Users Manual for the Cryogenic Array Spectrometer/Imager (CASPIR) on the MSSSO 2.3 m Telescope

Peter J. McGregor

June 5, 1997

Contents

1 Introduction

This manual describes the operation of CASPIR, the Cryogenic Array Spectrometer/Imager on the ANU 2.3 m telescope at Siding Spring Observatory. CASPIR uses a Santa Barbara Research Center (SBRC) CRC463 256×256 InSb detector array to provide direct imaging and spectroscopic capabilities in the 1–5 μm wavelength range. Two direct imaging focal plane scales of $0.5''$/pixel and $0.25''$/pixel are available, as well as long slit J, H, and K grisms giving two pixel resolving powers of ~ 500 through a $1''\times 128''$ slit, and IJ, JH, and HK cross-dispersed grisms giving two pixel resolving powers of ~ 1100 through a $1''\times 15''$ slit. Coronographic functions are also available, and imaging polarimetry is planned.

CASPIR operates within the overall infrared instrumentation environment which is familiar to past infrared users of the 2.3 m telescope, and which is described in a separate manual. Since most user demand is for a quick "How to do it" manual, I begin in §2 with a bare-bones description of getting the system on the air. Suitable observing procedures are discussed in more detail in §3. This is where you will find most of the procedural recipes you will need. The CASPIR hardware is described in greater detail in §4, while §5 documents the CASPIR control software. These sections contain reference material for the more serious user. Recommended data reduction procedures in IRAF are discussed in §6, §8, and §9. Performance figures, lists of photometric and spectroscopic standard stars, common infrared spectral features, and plots of terrestrial atmospheric transmission and filter transmissions can be found in the Appendices.

The AAO IRIS Users Manual contains valuable information about observing technique with infrared array cameras which is equally applicable to CASPIR. I recommend that CASPIR users also be familiar with the IRIS manual. Nomenclature for the array readout parameters is common between IRIS and CASPIR, so many of the concepts discussed in the IRIS manual also apply to CASPIR. However, the IRIS and CASPIR readout methods are numbered differently.

The CASPIR array is quite robust. It is not damaged by exposure to strong infrared illumination, and has little remnance. However, four warnings are in order:

- **THE ARRAY IS STATIC SENSITIVE SO UNDER NO CIRCUMSTANCES SHOULD A USER DISCONNECT THE CASPIR DEWAR FROM THE ACE2 DRIVE ELECTRONICS!**
- **THE HYBRID DETECTOR ARRAY CAN DELAMINATE AND THE CRYSTAL OPTICS MAY CRACK IF TEMPERATURE CYCLED FASTER THAN 20 °K/hour. THE DEWAR HAS BEEN DESIGNED TO PASSIVELY TEMPERATURE CYCLE AT THE MAXIMUM SAFE RATE. UNDER NO CIRCUMSTANCES SHOULD THE TEMPERATURE CONTROLLER BE USED TO HEAT THE ARRAY OR THE CAMERA MORE QUICKLY!**
- **THE ARRAY MUST BE STORED UNDER VACUUM AT ALL TIMES TO AVOID SURFACE CONTAMINATION. DO NOT BACK-FILL THE DEWAR WITH ANY GAS.**
- **HIGH PRESSURE HELIUM HOSES ARE ATTACHED TO THE DEWAR. DO NOT ROTATE THE INSTRUMENT ROTATOR OUTSIDE THE RANGE -270 TO +110 DEGREES.**

The Latex source files for this manual can be found in the directory p̃eter/latex/manuals/caspir on the MSO Sun network. The file manual.ps in that directory contains a postscript version of the manual. This file can also be obtained via anonymous ftp by typing:

```
ftp merlin.anu.edu.au
username: anonymous
password: type your internet id
cd pub/peter
prompt
mget manual*.ps.gz
bye
```

This manual is also available on the MSSSO WWW home page (http://msowww.anu.edu.au/home.html).

A CASPIR users email group exists for occassional dissemination of information about the instrument. Contact Peter McGregor on (06) 279 8033 or peter@mso.anu.edu.au for inclusion in this list, or for further information on CASPIR.

2 Getting Going Quickly

The infrared system must be started in the order listed below.

If you have not yet done so, start up the telescope control software from the telescope console. You need to configure the telescope for Cassegrain operation by issuing the following commands or including their equivalents in your startup procedure:

```
CONFIGURE SECONDARY IR_CASSEGRAIN
CONFIGURE INSTRUMENT_IDENT CASPIR
CONFIGURE FOCAL_STATION CASSEGRAIN
CONFIGURE EFFECTIVE_WAVELENGTH 2000.0
CONFIGURE GUIDE_WAVELENGTH 700.0
CONFIGURE ROTATOR_CW_LIMIT +110
CONFIGURE ROTATOR_CCW_LIMIT -270

ROTATOR/REFERENCE POSITION_ANGLE
ROTATOR  180
```

Now enable control of the telescope from MOPRA by typing:

```
ENLIST IR
```

into the *telescope console terminal.*

If you plan to use the Tip-Tilt secondary mirror enable telescope control from the Tip-Tilt system by typing:

```
ENLIST TT
```

into the *telescope console terminal.*

If you have previously saved a telescope configuration file (as described below) load it now and set the telescope aperture definition by typing:

```
CFILE/LOAD TEMP.CFILE
APERTURE A
```

To start the infrared instrument control software on MOPRA, first log on to the MOPRA workstation as user INFRARED (no password required so type a carriage return). This places you in the CASPIR data directory DATADISK:[INFRARED].

It is not normally necessary to down-load the LSI-11/23 software unless you are starting the system for the first time or recovering from a power failure. Refer to §3.1 if you have to do this.

Start up the infrared control software by typing:

```
IR_STARTUP
```

Answer "`N`" to the question about down-loading the LSI software - you should have already done that. Starting the system takes quite a while because it has many subprocesses to spawn. Be patient. When it has finished you will have a Status Display window and two image display windows (the Run Display and the Idle Display) on the workstation screen, and the Status Display will be showing the status of the DECnet links to the LSI-11/23. Wait until 'CASPIR : Relinquishing ownership' is printed in the lower part of the Status Display before proceeding.

You should leave the infrared system running for the duration of your run. All that is then required at the beginning of a night is to create a new data sub-directory (IR_DATA:) and reset the run number by typing:

```
STARTNEWNIGHT
```

Type:

```
_CASPIR
```

to bring up the CASPIR Status Display window and define the abbreviated control commands listed in the command procedure in IR_CASPIR:CASPIR.COM (see §5.2). This selects CASPIR as the active dewar and starts data taking in idle mode.

You should now be seeing an image of the array in the Idle Display window.

The CASPIR dewar uses a closed-cycle helium refrigerator to cool the camera and detector array - it does not need liquid nitrogen. Check that the array and camera body have reached their operating temperatures by looking for "Temperature Out-Of-Range" error reports in the CASPIR Status Display. To be doubly sure type:

```
TEMPERATURE/DISPLAY
```

The camera temperature should be ~ 60 K and the array temperature should be 32 K with a tolerance of 0.1 K.

Check that the IMB is configured correctly by typing:

```
IMB/DISPLAY
```

The dichroic mirror turret should be at position 'A' and the IMB X-Y stage at its 'home' position (X = 0.0 mm, Y = 0.0 mm).

Now return to the CASPIR display by typing:

```
CASPIR/DISPLAY
```

Configure the instrument for the type of measurement you want by typing one of the following:

```
FAST     - Direct imaging with the fast camera (0.5"/pixel).
SLOW     - Direct imaging with the slow camera (0.25"/pixel).
JGRISM   - Long slit J grism.
HGRISM   - Long slit H grism.
KGRISM   - Long slit K grism.
IJGRISM  - Short slit cross-dispersed IJ grism.
JHGRISM  - Short slit cross-dispersed JH grism.
HKGRISM  - Short slit cross-dispersed HK grism.
GRIDPOL  - Polarimetry with the wire grid.
PRISMPOL - Polarimetry with the Wollaston prism.
CORONA   - Coronograph imaging (0.5"/pixel).
```

If you are using one of the imaging modes, select the desired filter by typing `f` followed by a filter name from the following list:

```
J,          H,          K,          KP,         KN,         M,
HELIUM,     PGAMMA,     PBETA,      CONT1.6,    FEII,       AAOFEII,
H2O,        H2_1_0,     BRGAMMA,    CONT2.22,   H2_2_1,     CO,
ICE,        DUST3.28,   DUST3.4,    CONT3.6,    CONT4.0,    BRALPHA
```

For example:

```
F KN
```

Set the idle method, idle time, and idle cycles to typical values (for imaging in the JHK region) and repeats to one by typing:

```
IM 2
IT 0.3
IC 10
REP 1
```

Other values may be better suited to the particular measurement you are making. Refer to §5.2 to see how to set these parameters.

If you are using the Tip-Tilt system, log into MISTY as yourself or "user23" (password in the CCD temperature book), start OpenWindows, and start the Tip-Tilt software by typing:

```
tiptilt &
```

After the initialization has completed, go from idle mode to acquire mode by clicking on the "operate" button. Enable Tip-Tilt control and IMB X-Y stage motions from CASPIR DO files and in NOD mode by typing:

```
CASPIR/TIPTILT/STAGE
```

into the *CASPIR command terminal.*

If you are not using the Tip-Tilt system, disable Tip-Tilt control and IMB X-Y stage motions from CASPIR DO files by typing:

```
CASPIR/NOTIPTILT
```

into the *CASPIR command terminal.*

- Make sure the IMB dust slide is open. This must be done manually using the small grey handle on the IMB mounting flange adjacent to where CASPIR mounts on the IMB. The open and closed positions are clearly marked on the IMB mounting flange.

Now that the instrument is fully configured you are ready to acquire an object. Slew the telescope to a bright star at a zenith distance $\geq 20^\circ$ and perform the following alignments:

- The dewar should be tipped to point at the secondary mirror. Check the dewar alignment by driving the telescope out of focus and checking that the image of the primary mirror in the Idle Display is unvignetted. This can be done using either the normal direct imaging cold stop in position 2 of the Utility Wheel, or the alignment mask in position 1 of the Utility Wheel (see Table 18). Using the former, you see the full primary mirror aperture and must gauge whether the image is circular. Using the latter, you see the image through four small holes located at the periphery of the pupil mask and must gauge whether the four images have equal brightness. Either image display can be zoomed in by clicking on the window title, moving the cursor onto the image and repeatedly pressing the F2 key (see §5.3). Remember to reset the zoom by pressing the F3 key in the image part of the window, and then *click on the command input window again* to reconnect the keyboard to this window. Normally it will not be necessary to adjust the dewar alignment, but refer to §3.4 if you are forced to do this.

- Focus the star in the Idle Display, and center it in the middle of the array. This should also be done with a zoomed image display. Either use the F19 key in the Idle Display window to report the FWHM of the stellar image in pixels, or with the fast camera (0.5$''$ pixels) use the focussing mask in position 5 of the Utility Wheel (see Table 18) to form two images of the star and focus to minimise their separation (i.e., gauge by eye that the two images lie in the same image row). The Figdisp image displays deal only in *scaled* data, so set the Idle Display greyscale (CASPIR/IZMAX=...) so that the star image you measure is not saturated. Increments of 5 focus numbers usually produce satisfactory results. Activate the title bar cursor position readout using the F6 key in the Idle Display window. Use the cursor to locate the center of the array (pixel [128,128]) and position the star on the cursor.

- Calibrate the telescope coordinates at this position by typing:

  ```
  CALIBRATE POINTING
  ```

  into the *telescope console terminal.* The X and Y pointing coefficients should be approximately -30 and -11, respectively.

- The detector array should be aligned with its rows running E-W. Check that the instrument rotator is at the correct position angle by slewing the star in RA to the left and right of the array and noting the row numbers. Alter the nominal instrument rotator position angle by typing, e.g.:

  ```
  ROTATOR 179.5
  ```

  into the *telescope console terminal.*

- Calibrate the telescope aperture definition by typing:

  ```
  CALIBRATE APERTURE A
  ```

  into the *telescope console terminal.* You are required to drive the telescope to center the star on the central pixel. The telescope computer then rotates the Cassegrain instrument rotator by 120° and you recenter the star at the same pixel position. This locates the array center with respect to the instrument rotator axis, which is the optical axis of the telescope. You are then asked if you wish to define a slit orientation. Answer `YES` to this question and position the star at each end of the central array *row.* This is the grism slit direction. The instrument rotator will be returned to the original position at the end of this procedure.

- Recenter the star and calibrate the telescope coordinates again at this position by typing:

  ```
  CALIBRATE POINTING
  ```

  into the *telescope console terminal.*

- If you are using the grisms in Nod mode, select the grism slit by typing, e.g.:

  ```
  A LSLIT1
  ```

  into the *CASPIR command terminal.* Adjust the Idle Display to see the slit image and note the pixel coordinates of the slit center and the two nod positions you require. Remove the slit by typing:

  ```
  A FASTCLR
  ```

  and center the star on the slit-center pixel and redefine aperture A to this position by typing:

  ```
  APERTURE/HERE A
  ```

  into the *telescope console terminal.* Either move the star to the first nod position manually, or offset the telescope E-W by typing, e.g.:

  ```
  OFFSET/SCALE 10 0
  ```

  into the *telescope console terminal.* Define aperture N1 at this position by typing:

  ```
  APERTURE/HERE N1
  ```

  into the *telescope console terminal.* Manually move the star or offset the telescope to the second nod position and define aperture N2 at this position in a similar way. Reposition the star at slit-center again by typing:

  ```
  APERTURE A
  ```

  into the *telescope console terminal.*

- Drive the IMB X-Y stage to center the star in the Tip-Tilt sensor acquire field using the `IMB/XY_INCREMENT` command and the keypad arrow keys to move the stage. When the star is centered, exit from this by typing a `Q`, and zero the X-Y stage relative coordinates at that location by typing:

  ```
  IMB/XY_ZERO
  ```

  If necessary, focus the Tip-Tilt sensor image using the `IMB/FOCUS` command and the keypad up/down arrow keys. Exit from this by typing a `Q`.

- Define the IMB X-Y stage center to the telescope system by typing:

  ```
  CALIBRATE STAGE
  ```

  into the *telescope console terminal.* This asks you to define a guide box on the Tip-Tilt image display. To do this, place the cursor on the star and simultaneously press the keyboard "Shift" key and click the left mouse button. Respond to the question on the telescope console terminal by pressing "Return".

- Record the telescope setup by typing:

  ```
  CFILE/SAVE=ALL TEMP.CFILE
  ```

You are now ready to record data.

The orientation on the sky in each of the image displays should be as shown in Figure 1.

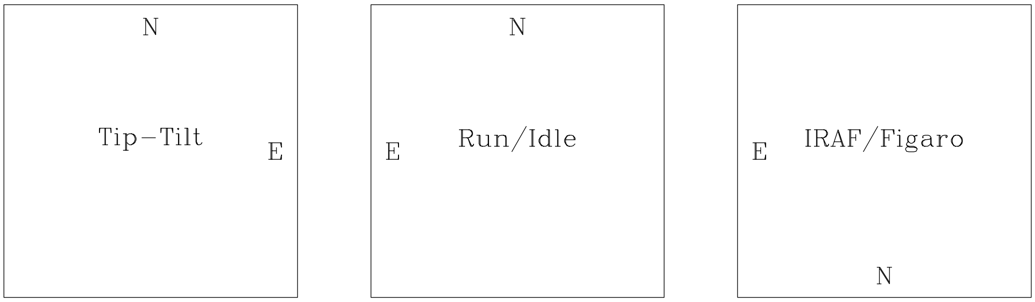


Figure 1: Orientation on the sky in the image displays (rotator P.A.=180°).

Standard stars are normally recorded in two frames offset by $\sim 30''$ asymmetrically placed about the center of the array. The shortest possible exposure times should be used for standard stars to avoid saturation. These are 0.2 sec in readout method 1, 0.3 sec in readout method 2, and 0.4 sec in readout method 3. The exposure time is set by typing:

```
CASPIR/TIME=time
```

The duration of the measurement, and hence signal-to-noise ratio, is defined by the number of coadd cycles which is set by typing:

```
CASPIR/CYCLES=cycle_count
```

A measurement is begun by typing:

```
CASPIR/RUN
```

Object measurements are normally mosaics including either separate sky frames or jittered object frames. The observation sequence is defined by entries in a DO file (see §5.2). A DO file for a typical observation can be found in IR_CASPIR:EXAMPLE.DO and has the following form:

```
!
! Example DO file for acquiring multiple CASPIR data frames.
!
DARK method=2 time=5 cycles=12 repeats=1
RUN ra=+120 dec=+120
RUN ra=   0 dec=+120
RUN ra=-120 dec=+120
RUN ra=+120 dec=   0
RUN ra=   0 dec=   0
RUN ra=-120 dec=   0
RUN ra=+120 dec=-120
RUN ra=   0 dec=-120
RUN ra=-120 dec=-120
DARK
```

Do files are read from the directory with logical name IR_DO. On startup, this is set to the default directory DATADISK:[INFRARED]. This can be changed to a private subdirectory by typing, e.g.:

```
DEFINE/JOB IR_DO DATADISK:[INFRARED.WOOD]
```

A DO file is executed by typing:

```
CASPIR/DO=filespec
```

A given set of coadd cycles can be repeated without moving the telescope by specifying a non-zero REPEATS:

```
CASPIR/REPEATS=repeat_count
```

Each coadd cycle is then written to disk as a separate file and displayed in the Run Display.

The data frames are stored as FITS files in the data directory with logical name IR_DATA which points to a sub-directory of DATADISK:[INFRARED]. The files are named ir*nnn*.fits where *nnn* is the run number. These files can also be accessed from MISTY in the directory /data/mopra/... The data values are normalised to the equivalent number of counts obtained in one integration time, i.e., one coadd cycle.

Once you are recording data you may wish to perform on-line processing on the displayed image.

Subtract a recorded sky frame from the Idle Display image by typing:

```
CASPIR/ISUBTRACT=filespec
```

Subtract a recorded sky frame from the Run Display image by typing:

```
CASPIR/SUBTRACT=filespec
```

Form a normalised flatfield frame in FITS format off-line using IRAF or FIGARO and divide the Idle Display image by this frame by typing:

```
CASPIR/IDIVIDE=filespec
```

Divide the Run Display image by a flatfield frame by typing:

```
CASPIR/DIVIDE=filespec
```

To see the mean coadded image of a set of repeats in the Run Display type:

```
CASPIR/SHOW=MEAN
```

To return to displaying the current frame in the Run Display type:

```
CASPIR/SHOW=CURRENT
```

To remove on-line processing type:

```
CASPIR/ISUBTRACT=NONE/IDIVIDE=NONE
CASPIR/SUBTRACT=NONE/DIVIDE=NONE
```

Dark frames use the exposure time specified by the TIME parameter and the cycles specified by the CYCLES parameter. These can be recorded by typing:

```
CASPIR/DARK
```

Bias frames use the minimum exposure time possible for the selected readout method and the cycles specified by the CYCLES parameter. These can be recorded by typing:

```
CASPIR/BIAS
```

3 Observing Procedures

This section describes recipes for a variety of procedures you may need to perform. A more complete description of the hardware and software commands can be found in §4 and §5.

3.1 Down-Loading The LSI-11/23 Program

It should only be necessary to down-load the LSI-11/23 software at the beginning of an observing run or after a power failure. To down-load the LSI-11/23 software type:

```
DOWN_LOAD
```

This takes about two minutes, and when successfully completed will print the following on the terminal window:

```
PASDBG V02.4
%PASDBG-I-NODSM No DSM - target not yet loaded

PASDBG>
%PASDBG-I-BOOT1 Loading Bootstrap
%PASDBG-I-BOOT2 Loading User Image. Please Wait.
PASDBG V02.4
      Target stopped at physical (00002056), virtual (002056): JMP @#2422
      Executing KERNAL code
      No process set, physical mapping in effect
PASDBG>
```

If it does not print this, the LSI-11/23 was probably already running and you have just bombed it! Don't panic, just type `DOWN_LOAD` again.

3.2 Down-Loading The ACE2 Program

The SBRC Array Control Electronics (ACE2) drive electronics for the detector array contains a timing generator with EEPROM resident firmware. It should not be necessary to down-load this code from the VAX. However, if circumstances conspire to make this necessary, first load the Logic Chip Array code by typing:

```
CASPIR/LCA
```

When this completes (after a couple of minutes) load the ACE2 timing program by typing:

```
CASPIR/TIMING=IR_CASPIR:SBRC256
```

This loads the timing program and two data banks through an RS-232 line and takes several minutes to complete.

If you have problems try pressing the reset button on the front panel of the ACE2 unit, wait until the green light starts flashing again, and repeat the above procedure.

3.3 CASPIR Status Displays

The CASPIR Status Display normally used by observers is the MAIN display. Two other Status Displays are also available. One is the VOLTAGES Status Display which shows the operating voltages and other parameters associated with the detector array. The other is the MISC Status Display which contains miscellaneous information such as the current grey scale ranges used in the Idle and Run image displays etc.

These display can be selected by typing any of:

```
CASPIR/DISPLAY
CASPIR/DISPLAY=VOLT
CASPIR/DISPLAY=MISC
```

3.4 Aligning The Dewar

The dewar should be adjusted so that the telescope exit pupil is matched to the internal cold stop. The positioning of the dewar is expected to be accurately reproducible in normal operation, so visual confirmation that the pupil image is unvignetted should be all that usually is required.

Acquire a bright star and drive the telescope out of focus so that you can clearly see the image of the telescope primary mirror. This is best done by zooming in on the image of the star in the Idle Display (see §5.3). The dewar should be tipped so that the image of the primary mirror is unvignetted. This can be done using either the normal direct imaging cold stop in position 2 of the Utility Wheel, or the alignment mask in position 1 of the Utility Wheel (see Table 18). Using the former, you see the full primary mirror aperture and must gauge whether the image is circular. Using the latter, you see the image through four small holes located at the periphery of the pupil mask and must gauge whether the four images have equal brightness. If the image ofthe primary mirror is vignetted, you will have to align the dewar. Switch MOPRA's console video to the monitor on the Cassegrain Access Platform by connecting the appropriate BNC cable to the BNC 'T' on one of the RGB inputs at the rear of MOPRA's monitor. Disable the console terminal screen saver from the Session Manager menu. Stop the instrument rotator and position CASPIR towards the Cassegrain Access Platform by typing:

```
ROTATOR/REFERENCE=STATIONARY
ROTATOR 0
```

Then go to the Cassegrain focus and tip the dewar using the three adjustments on the mount to the IMB until the out-of-focus image is circular. To do this, loosen the Allen bolt slightly, loosen the inner locking nut, and adjust the outer nut. When completed, retighten the Allen bolt, and the inner lock nut.

Return the Cassegrain instrument rotator to position angle mode by typing, e.g.:

```
ROTATOR/REFERENCE=POSITION_ANGLE
ROTATOR 179.5
```

3.5 Focusing

Focus the telescope using the image of a standard star in the Idle Display. Make sure that the display is not saturated using the `CASPIR/IZMAX=...` command, and use the F19 key in that display to measure the FWHM of the stellar image. $FWHM(true) = (FWHM(measured)^2 - 1)^{1/2}$ due the pixel sampling. Increments of 5 focus numbers usually produce satisfactory results. Smaller increments are required in very good seeing.

Alternatively, you can use any of the three focussing masks installed in the dewar: 1) When using the fast camera, use the focussing mask in position 5 of the Utility Wheel (see Table 18). This places two small holes at the pupil position. A prism over one hole displaces its image by $\sim 10''$ on the array. The result is two separated images of the star which move in the direction perpendicular to their separation (i.e., vertically on the Idle Display) as the telescope focus is adjusted. Correct focus corresponds to the minimum separation of these images (i.e., the two images lie in the same image row). 2) When using the fast camera, it is also possible to use the focussing mask in position 4 of the Utility Wheel (see Table 18). This is identical to the position 5 mask, but does not use a displacing prism. Correct focus is obtained by measuring the separation of the two images for at least two different focus values, and calculating the focus value corresponding to zero separation of the images. This mask is primarily used to calibrate the position 5 mask. 3) The Utility Wheel masks cannot be used with the slow camera which is also located in the Utility Wheel. To focus the slow camera, use the focus mask in position 16 of the Upper Filter Wheel (see Table 17). This is a two hole mask without displacing prism, like the second mask just described.

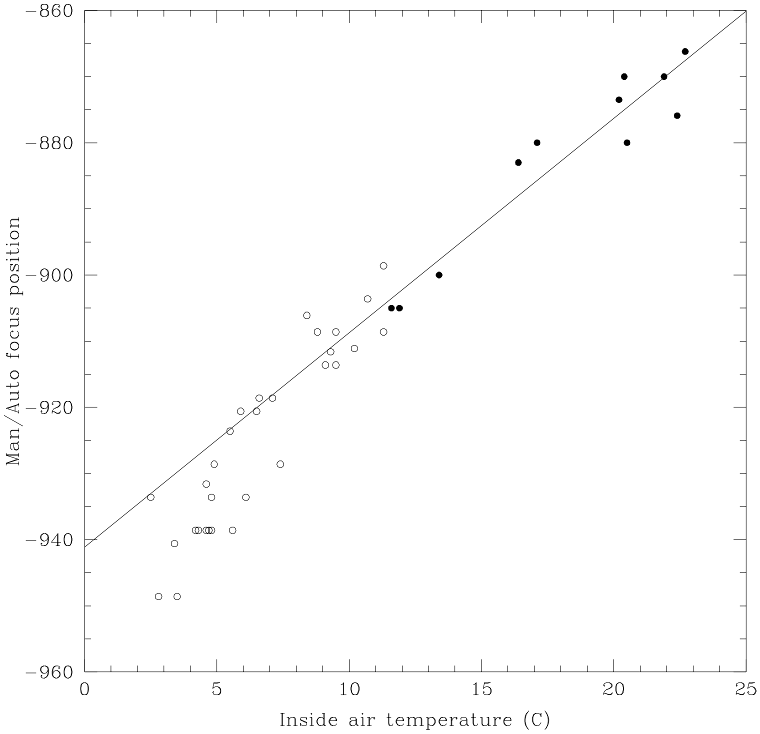


Figure 2: Temperature variation of telescope focus. The solid symbols are current measurements made since the Tip-Tilt system was installed. The open symbols are pre-Tip-Tilt measurements and have been offset by a constant in focus value to bring them into approximate agreement with the post-Tip-Tilt values. The solid line is a fit to the post-Tip-Tilt points only. The change in slope below $\sim 8°$C may not be real.

CASPIR has been designed so that usually there should be no need to adjust the focus for different filters. However, filters in the lower filter wheel operate in a converging beam when using the slow camera, so some refocussing may be needed. Any focus offset will be small.

The telescope focus is known to change with internal air temperature. Figure 2 shows the measured variation in manual/automatic focus numbers with inside air temperature. The fitted line is

$$Focus = 3.24T_{in} - 941.1$$

Small deviations from the fitted line may arise because of small mounting differencesfor the dewar, but relative focus changes can be accurately tracked using the fitted slope of 3.24 focus numbers per °C for temperatures above at least $\sim 8°$C.

In principle, the temperature dependence of the telescope focus can be removed by operating the focus control in compensated mode. This is achieved by typing the following command into the *telescope console terminal*:

```
CONFIGURE/FOCUS_CONTROL=COMPENSATED
```

or including its equivalent in your telescope startup procedure. In practice, 2.3 m telescope focus mechanism tends to lock-up when operated in this way, so its use is not recommended.

3.6 Monitoring Dewar Temperatures

The CASPIR detector array is actively maintained at a temperature of 32±0.1 K. The dewar body must be cold enough so that thermal emission from the camera does not rival the electrically generated dark current. In practice, the dewar body is cooled to ~ 60 K, but somewhat higher temperatures can be tolerated without significant performance degradation.

Temperature control is through the TEMPERATURE DCL command (see §5.4). The Temperature Status Display is selected by typing:

```
TEMPERATURE/DISPLAY
```

The array operating temperature and tolerance should be set by the technical staff using the commands:

```
TEMPERATURE/SET_POINT=32.0
TEMPERATURE/TOLERANCE=0.1
```

The tolerance is the threshold level permitted before a "Temperature-Out-Of-Range" error is reported.

The array and camera temperatures are continuously monitored while the infrared control software is running. These temperatures are recorded on disk and can be plotted at any time to see a history of the temperature fluctuations. The interval between temperature samples should be set by the technical staff using the command:

```
TEMPERATURE/INTERVAL=2.0
```

The time value is specified in minutes.

To plot the temperature fluctuation history on the workstation screen type:

```
TEMPERATURE/PLOT
```

This uses the values of XMINIMUM, XMAXIMUM, XAUTOSCALE, YMINIMUM, YMAXIMUM, and YAUTOSCALE listed in the Temperature Status Display. These values can be changed with the corresponding TEMPERATURE command.

A hardcopy of the temperature plot can be made by typing:

```
TEMPERATURE/HARDCOPY
```

Old temperature data in the disk file can be cleared by typing:

```
TEMPERATURE/CLEAR
```

The temperature controller can be reset by typing:

```
TEMPERATURE/RESET
```

3.7 Checking Array Performance

The performance of the array can be checked at the telescope by recording calibration frames. The read noise and dark current are determined by setting all wheels to their blank position. For the read noise measurement first record an average dark frame by typing:

```
CASPIR/DARK/TIME=0.3/CYCLES=100/METHOD=2
```

then record another dark frame with only one cycle:

```
CASPIR/DARK/TIME=0.3/CYCLES=1/METHOD=2,
```

subtract the average dark frame from this frame and determine the standard deviation of the pixel values. This is the read noise for two reads of the array (a difference of the end of the integration ramp and the reset voltage). The single-read read noise is the standard deviation of this frame divided by $\sqrt{2}$ and multipled by 9 e^-/ADU. Values of ~ 40 e^- are expected.

The dark current measurement is complicated by the long settling time (a few seconds) of the array after resetting. This means that it is not meaningful to subtract a short exposure dark frame from a long exposure dark frame to determine the dark current. To measure the dark current, record two long exposure dark frames of different duration with one cycle each, e.g.:

```
CASPIR/DARK/TIME=100/CYCLES=1/METHOD=2
CASPIR/DARK/TIME=50/CYCLES=1/METHOD=2,
```

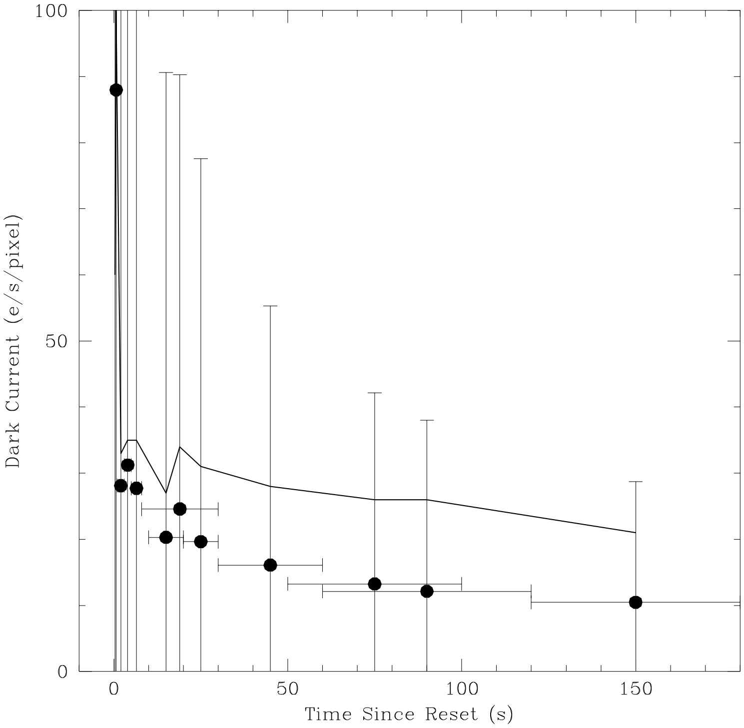


Figure 3: Dark current as a function of time since pixel reset. The plotted points are average dark current measurements formed by differencing dark exposures with durations indicated by the extent of the horizontal error bars. The vertical error bars indicate the standard deviation of dark current values across the array. The solid line is the 90th percentile of the cummulative dark current distribution for each measurement (i.e., 90% of pixels have a dark current lower than this value).

subtract the two frames and determine the mean pixel value. The dark current is the mean pixel value divided by the integration time difference between the frames and multipled by 9 e^-/ADU. *Mean* values of $\sim$ 13 e^-/s/pixel are expected from this measurement, but significant numbers of pixels have dark currents in excess of 50 e^-/s/pixel, as shown in Figure 3. For the 5 s integration time used in imaging observations, the average dark current is $\sim$ 30 e^-/s/pixel. For the longer integration times typical of spectroscopic observations, this value corresponds to the 90th percentile of the cummulative dark current distribution.

The signal strength can be checked by recording images of the standard stars listed in Appendix G. Measure the total sky-subtracted signal in the stellar image and convert to instrumental magnitudes using $m_{CASPIR} = -2.5 \log_{10}(ADU/sec)$. Correct for extinction using the mean extinction corrections listed in Appendix C and form the zenith zero point offsets for each filter, defined to be $m_{Std} - m_{CASPIR}$. These can be compared with the typical values listed in Appendix C.

Typical sky brightness figures are also listed in Appendix C. These can be checked using a dark-subtracted sky frame and the zero point offsets determined above, or the zero point offsets listed in Appendix C.

3.8 Flat Fielding

Dome flats are normally recorded through each filter with the flatfield lamp on and then off. The difference of these two is taken to be the response of the system to illumination through the telescope. Dome flats are recorded with the telescope at the zenith by illuminating the upper windscreen with incandescent lamps on the telescope top-end ring. Move the telescope to the zenith by typing:

```
ZENITH
```

into the *telescope console terminal*.

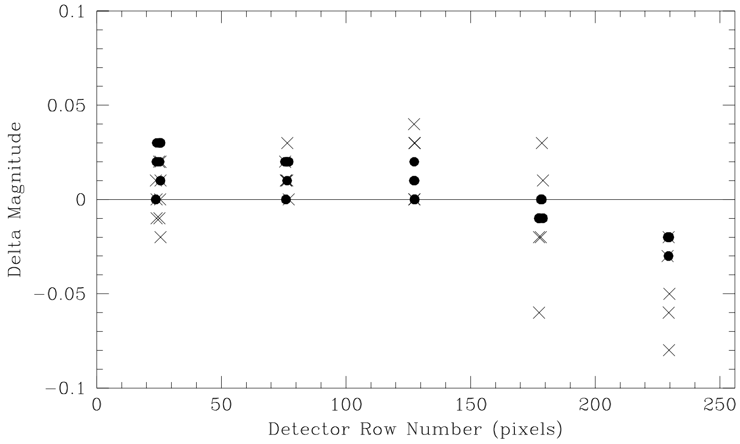


Figure 4: Sensitivity variation versus detector row number for Kn data reduced using a dome flat (*filled circles*) and a sky flat derived from the data (*crosses*). The data were obtained by recording images of a single star placed at different positions on the array in a 5 × 5 grid. Each cluster of points corresponds to measurements with the star at different column positions.

The upper windscreen is moved over the telescope by typing:

```
CONFIGURE WINDSCREEN_CONTROL CLOSED
```

into the *telescope console terminal.* The primary mirror cover must be open, and the dome lights off. The incandescent lamps are is controlled through the VAX commands:

```
SWITCH FLATFIELD_ILLUMINATION ON
SWITCH FLATFIELD_ILLUMINATION OFF
```

typed into the *telescope console terminal.* These can be equated with the DCL symbols `LON` and `LOFF` by typing:

```
LON  :== SWITCH FLATFIELD_ILLUMINATION ON
LOFF :== SWITCH FLATFIELD_ILLUMINATION OFF
```

into the *telescope console terminal* or including this in your telescope `STARTUP.COM` file. Wait until the lamp cools, i.e., the mean count level stabilizes, before recording the lamp off frame. The lamp intensity is set by adjusting the flatfield illumination control on the telescope console. There is also a switch on the top-end ring for enabling 4 or 8 of the lamps. Settings of ∼ 20% illumination (4 lamps) for broad band filters and ∼ 100% illumination (4 lamps) for narrowband filters work well for the 0.5″/pixel scale with an integration time of 0.4 sec. Use 40% illumination (4 lamps) for the 0.25″/pixel scale with broad band filters.

Return the upper windscreen to normal operation by typing:

```
CONFIGURE WINDSCREEN_CONTROL VERTICAL_ONLY_TRACKING
```

into the *telescope console terminal.*

Dome flats give better photometric accuracy than sky flats because a significant contribution to sky flats is due to thermal emission from the telescope at the longer wavelengths which is unrelated to the relative response of the array to light. A photometric performance comparison between dome flats and sky flats for the Kn filter is shown in Fig. 4. Despite their better photometric performance, there is still a residual sensitivity gradient vertically on the array of ∼ 0.05 mag amplitude. Horizontal gradients are generally ≤ 0.03 mag, as shown by the scatter in each cluster of filled circles. Better performance may be obtained by averaging dome flats taken with the instrument rotated by 180°.

3.9 Direct Imaging

Two focal plane scales are available for direct imaging; the fast camera with 0.5″/pixel, and the slow camera with 0.25″/pixel. The instrument can be configured for either of these by typing the commands `FAST` or `SLOW`. Direct imaging in the 3–4 μm window must be done with the 0.25″/pixel scale to avoid saturation on the background flux. Images can also be obtained at M using the 0.25″/pixel scale and the red leak in the Pβ narrow band filter to reduce the background intensity to a manageable level. Broad band filters are background noise limited at both scales, while some of the narrowest narrow band filters are marginally dark current/read noise limited.

Direct imaging is performed using the Direct_Imaging observing mode which is set by typing:

```
CASPIR/MODE=DIRECT_IMAGING
```

The preferred readout method for direct imaging is method 2. This method forms a difference between the end of the integration ramp and the reset level (see §4.3.2), so is immune to DC voltage drifts. However, the reset pedestal pattern is imprinted on the data in these method. It is essential to record dark and bias frames to permit linearization and remove the pedestal pattern.

It is often necessary to use readout method 1 for direct imaging in the 3–4 μm band and at M. This is the fastest readout method where the data are referenced directly to electrical ground (see §4.3.1). Method 1 is susceptible to DC voltage drifts because it does not perform a voltage difference. This is manifest as a column striping with a four column period which changes from frame to frame. The pattern can be characterized in clear sky regions and subtracted during data reduction, but a better alternative is to use readout method 2 when background levels permit.

Readout method 3 differences the signal level at the end and beginning of the integration ramp (see §4.3.3). Reset pedestal is not imprinted on the data in this method, but it is susceptible to DC drifts between the beginning and end of the integration interval. This is removed in readout method 4 (see §4.3.4) by additional samples of the reset level at the beginning and end of the integration period. Further performance characterisation of these methods is required.

In reducing your data (§6, §8, and §9), you will need bias frames and dark frames recorded with the same exposure time as each object frame and with the same readout method. These can be obtained by typing, e.g.:

```
CASPIR/DARK/TIME=5.0/CYCLES=10/METHOD=2
```

The minimum integration times in each readout method are listed in §4.3 (0.2 sec in method 1, 0.3 sec in method 2, 0.4 sec in method 3).

Three broad band K filters are available (see Table 19 and Appendix K). Kn is the preferred broad band K filter to use from SSO. Its short wavelength edge is similar to the original K filter, but its long wavelength edge is tailored to exclude much of the thermal emission in the long wavelength end of the original K band. K' was designed with the same goal for observation at Mauna Kea Observatory (Wainscoat & Cowie 1992, AJ, 103, 332). It extends to short wavelengths with poor transmission from SSO, so in practice it has a similar band pass to Kn from SSO, but the short wavelength edge is defined by vagaries of atmospheric transmission rather than the known properties of the filter. The K filter is the original broad band K filter. It is less sensitive than Kn due to the thermal contribution to the measured background flux, and should only be used when it is necessary to accurately reproduce data on the original broad band K system. The following transformation between K and Kn has been determined from model stellar atmosphere energy distributions and measured filter transmission curves:

$$Kn = K - 0.022(J - K).$$

It is not possible to use the broad band L filter without saturating on the thermal background at the shortest integration times and smallest pixel scale. The 3.6 μm continuum filter is used as a narrow band L filter substitute and is referred to below as nbL.

The red leak in the Pβ narrow band filter requires it to be used with a PK50 glass blocker. This is not mounted with the Pβ filter so that it can be used as an attentuator with the M filter. If the Pβ filter is selected by typing:

```
CASPIR/FILTER=PBETA
```

the PK50 blocker in the Lower Filter Wheel is automatically selected. If the Pβ filter is selected by an explicit upper filter wheel command, this will not be the case.

The AAO [Fe II] filter is centered slightly redward of the standard [Fe II] filter (see Appendix K). It should also be used with a PK50 blocker that is automatically selected if the filter is requested by typing:

```
CASPIR/FILTER=AAOFEII
```

Standard stars for direct imaging are listed in Appendix F. The IRIS standards in Table 21 are recommended for JHK imaging. The standard values are listed on the Carter SAAO system. Care should be exercised in selecting these standards as many of them may saturate the array in good seeing using the $0.5''$/pixel scale. Fainter equatorial JHK standards can be found in the UKIRT list (Table 22). The original MSSSO standards (McGregor 1994, PASP, 106, 508) are listed in Table 23. These are recommended for the 3–4 μm region and at M.

Sky subtraction is most demanding in the 3–4 μm band and at M. Since most of the background is thermal emission from the telescope, it is advisable to perform these observations away from the zenith where field rotation is slower. This is so that the view of the telescope structure seen by CASPIR changes only slowly during the observation sequence.

Direct imaging is usually performed as a dithered mosaic using the `CASPIR/DO=filespec` command (see §5.2). The actions performed during the execution of a DO file are controlled by two parameters, the TIPTILT parameter and the STAGE_OFFSET parameter. The values of both parameters are displayed in the MISC Status Display selected by typing:

```
CASPIR/DISPLAY=MISC
```

The value of the TIPTILT parameter is set by the `CASPIR/TIPTILT=...` command and the value of the STAGE_OFFSET parameter is set by the `CASPIR/STAGE_OFFSET=...` command (see §5.2).

If the TIPTILT parameter is set, the Tip-Tilt image correction system is operated during the execution of the DO file or in NOD mode. DO file parameters specify the type of correction to be used. If the STAGE_OFFSET parameter is set, the IMB X-Y stage is moved in response to each telescope offset to bring the specified reference star onto the Tip-Tilt sensor. The default action is to leave the correction subframe fixed with respect to the Tip-Tilt sensor. The geometry of the offset pattern is then set by the accuracy of the IMB X-Y stage settings, rather than the offsetting ability of the 2.3 m telescope which is the case if the Tip-Tilt system is not used. If the STAGE_OFFSET parameter is not set, the IMB X-Y stage is not moved in response to telescope offsets but the correction subframe is moved with respect to the Tip-Tilt sensor to reacquire the reference star. The former mode is suited to mosaics using large offsets. The latter may be preferred where more accurate offsets of small amplitude about the science object are required, since it is not subject to IMB X-Y stage setting errors. The operation of the Tip-Tilt system is more fully described in §3.13.

Before using the Tip-Tilt system in this way, it is necessary to calibrate the scale of the X-Y stage motions. Center a star in the CASPIR array and move the X-Y stage to center the same star in the Tip-Tilt sensor display by typing:

```
IMB/XY_INCREMENT
```

and using the keypad cursor keys to move the X-Y stage. Exit from this by typing a `Q`. Then zero the X-Y stage offsets at this position by typing:

```
IMB/XY_ZERO
```

Move the X-Y stage 20 mm East by typing:

```
IMB/Y=-20.0
```

and drive the telescope west to recenter the star in the Tip-Tilt sensor display. Record the position of the star in the CASPIR Idle Display. Repeat the procedure with the X-Y stage at Y=20.0 mm and determine the X-Y stage scale by adopting the nominal value for the CASPIR image scale ($0.5''$/pixel or $0.25''$/pixel). Determine the appropriate correction factor to the nominal X-Y stage scale ($5.0''$/mm) by dividing by 5.0, and input this correction factor by typing:

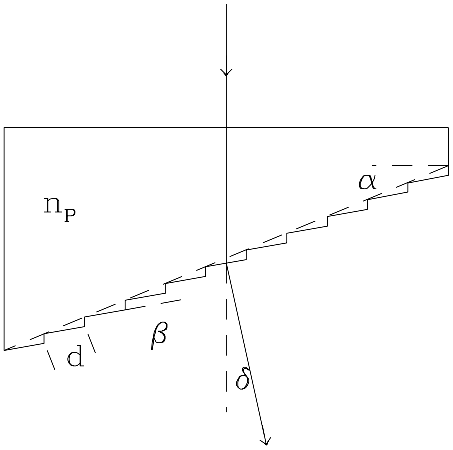


Figure 5: Optical diagram of a simple grism.

`CASPIR/XY_SCALE_FACTOR=factor`

The X-Y stage scale factor is normally about 1.055. The X-Y stage should now accurately define the requested mosaic pattern, and it should be possible to register the data frames using the adopted array pixel scale and the OFFRA and OFFDEC offsets recorded in the FITS file headers.

Tip-Tilt DO file commands are described in §5.2. In the simplest application, it is necessary to enable tip-tilt correction on object frames and disable tip-tilt correction when measuring sky frames. This is done by adding a *tiptilt* or *notiptilt* DO file command to each DO file line; *tiptilt* enables tip-tilt correction and *notiptilt* disables it. The type of Tip-Tilt correction must be specified at least in the first run of the DO file using the *tt_mode* command (typically *tt_mode=correct*).

Guide star acquisition procedures are described more fully in §3.13 and the guide star acquisition hardware are described in §4.5.

3.10 Long-Slit Grism Spectroscopy

A grism, or Carpenter prism, is a transmission grating mounted on a prism that has its angle chosen in such a way that the desired order of the grating passes through the grism undeviated. Figure 5 shows a schematic grism and the optical light path through it. We define α to be the prism angle, β to be the grating groove angle which is also the grating blaze angle in its reflection mode, δ to be the deflection angle, n_P to be the refractive index of the prism material, and d to be the grating groove spacing.

In the simplest case for a grism $\alpha = \beta$. Then consideration of the phase lag between adjacent facets of the grating in the prism material and external to the prism shows that the undeviated wavelength ($\delta = 0$) is given by:

$$N\lambda = (n_P - 1) d \sin\alpha,$$

where N is the order of the grating.

For deviated rays the grating equation becomes:

$$N\lambda = d[n_P \sin\alpha - \sin(\alpha - \delta)].$$

Geometrical ray trace shows that a ray with normal incidence passes undeviated ($\delta = 0$) when $\alpha = \beta$. That puts the grating blaze at $\delta = 0$. For α different from β or n_P different from the refractive index of the replicating resin used to produce the grating, the blaze is at a different wavelength, but the above grating equations remain valid.

Thus the grating groove spacing and the prism angle for a given prism material define the location of the spectrum on the detector, and the grating groove angle and resin index define the grating blaze function.

The long slit J, H, and K grisms in CASPIR provide two pixel resolving powers of $\sim$ 500 over each of the respective photometric passbands through a 1″× 128″ slit. Wider long slits in the Aperture Wheel can be used at the expense of spectral resolution. Grism spectra should be recorded at two positions along the slit in an ABBA sequence. This permits better sky subtraction than procedures which require interpolation of the sky flux. The object can be nodded between these two positions either by manually moving the telescope or by acquiring data in Nod mode. Nod mode has the advantages that nodding is performed automatically, the nod positions are defined as telescope apertures so are unaffected by changes in the instrument rotator angle, and the cumulative sum of the AB differences can be viewed in the Run Display. The longest possible integration time is required to overcome read noise. In practice, this means using an integration time of 180 sec in method 2.

To use the grisms, first configure CASPIR for direct imaging with the fast camera (0.5″/pixel scale) by typing `FAST`, and obtain an image of a star in the Idle Display. Select your long slit by typing, e.g.:

```
CASPIR/APERTURE=LSLIT1
```

Note the pixel positions of the center of the slit and the two desired nod positions, and then return to imaging the whole field by typing:

```
CASPIR/APERTURE=FASTCLR
```

Center the star on the slit-center pixel and redefine aperture A by typing:

```
APERTURE/HERE A
```

into the *telescope console terminal.* Manually move the star to the first nod position or offset the telescope EW by typing, e.g.:

```
OFFSET/SCALE 10.0 0.0
```

into the *telescope console terminal* and then define aperture N1 by typing:

```
APERTURE/HERE N1
```

into the *telescope console terminal.* Repeat this at the second nod position for aperture N2. Return the star to slit-center by typing:

```
APERTURE A
```

into the *telescope console terminal* and select Nod mode by typing:

```
CASPIR/MODE=NOD
```

into the CASPIR command terminal.

Spectroscopic observations are best performed using the Tip-Tilt system in either guide or correct mode. Operation of the Tip-Tilt system with CASPIR is more fully described in §3.13 and in the Tip-Tilt manual. To use the Tip-Tilt system for spectroscopic observations, roughly center the object on the slit-center pixel, then offset the IMB X-Y stage to the location of a suitable reference star by typing into the *telescope console terminal*, e.g.:

```
TIPTILT/OFFSET/SCALE -26.5 +10.5
```

if you know the reference star RA and Dec. offsets in arcsec on the sky, or

```
TIPTILT/COORD 12 26 25.9 -17 18 42 J2000
```

if you know the reference star coordinates, or

```
TIPTILT BS2015
```

if the reference star coordinates are in a telescope coordinate file, or

```
TIPTILT/TRACK
```

if you can use the optical image of the infrared object as the reference star, or

```
TIPTILT/HERE
```

if there is a suitable reference star within the Tip-Tilt acquire frame and you wish to drive the reference star to the correct subframe, or

```
TIPTILT/FIND
```

if there is a suitable reference star within the Tip-Tilt acquire frame and you wish to move the correct subframe to the pixel location of the reference star. Start correcting by typing:

```
TIPTILT/CORRECT
```

The Tip-Tilt system will pull the reference star to the center of the correct subframe, and hence may move the object out of the slit slightly. Recenter the object on the slit-center pixel by moving the Tip-Tilt sensor X-Y stage incrementally (using the above TIPTILT/OFFSET... commands) until the correct box center coincides with the slit-center pixel on the CASPIR array.

For small offsets ($\leq \pm 15''$) between the slit center and the N1 and N2 slit positions, it may be preferable to leave the IMB X-Y stage fixed and move the correction subframe on the Tip-Tilt sensor during each telescope offset. This is achieved by setting the TIPTILT parameter and unsetting the STAGE_OFFSET parameter by typing:

```
CASPIR/TIPTILT/NOSTAGE_OFFSET
```

Larger offsets with the long-slit grisms will require IMB X-Y stage motions:

```
CASPIR/TIPTILT/STAGE_OFFSET
```

Now select the appropriate slit, grism, and the fast camera lens, and place the filter wheels in clear positions by typing, e.g.:

```
CASPIR/APERTURE=LSLIT1/UTILITY=K_GRISM/UFILTER=CLEAR/LFILTER=CLEAR/LENS=FAST
```

or

```
KGRISM
```

The Idle Display image will change to a spectrum and you can begin taking data.

Grism data can be obtained in either the Direct_Imaging observing mode or the Nod observing mode. In Direct_Imaging mode, data frames are obtained singly with one frame recorded for each REPEAT requested. In Nod mode, successive exposures are obtained in an ABBA pattern at two positions on the sky defined by telescope focal plane *apertures* named N1 and N2. This permits accurate sky-subtraction by differencing the images. The number of AB pairs obtained is set by the REPEATS parameter which can be changed during data acquisition. If a `CASPIR/SHOW=CURRENT` command has been given, the current A-B difference is displayed in the Run Display. If the SHOW parameter has been set to MEAN with a `CASPIR/SHOW=MEAN` command, the average of the accummulated difference images is displayed in the Run Display. This allows the observer to assess the quality of the full dataset.

Data acquisition is started in Direct_Imaging or Nod mode by typing:

```
CASPIR/RUN
```

In Nod mode, each "repeat" consists of two runs (i.e., two recorded files) taken with the object at the N1,N2 or N2,N1 aperture positions. Set the "repeats" value to a large number initially, and reduce it to end the run.

The expected spectral images for common astronomical lines as well as Xenon and Argon arcs with each grism are shown in Figures 6 to 11. Tables of Xenon and Argon arc line wavelengths and OH airglow wavelengths (Oliva & Origlia 1992, A&A, 254, 466) can be found in Appendix J, as well as plots of extracted Xenon and Argon arcs for each grism. Xenon and Argon calibration lamps as well as an incandescent lamp are available in the calibration lamp module of the IMB. These are activated by typing any of:

```
IMB/CALIBRATION=XENON
IMB/CALIBRATION=ARGON
IMB/CALIBRATION=INCANDESCENT
```

It is recommended that lamp-on and lamp-off frames be obtained for the calibration lamps. The lamps can be switched off, without moving other components of the calibration lamp module but typing, e.g.:

```
IMB/XENON=OFF
```

The calibration lamps are switched off and the lamp select mirrors removed from the telescope beam by typing:

```
IMB/CALIBRATION=OFF
```

or just:

```
IMB/CALIBRATION
```

Wavelength calibration can also be achieved by measuring the compact planetary nebulae listed in Table 29 of Appendix J, or by recording mercury spectra of the fluorescent room lights.

Grism spectra are flat fielded using the incandescent lamp in the calibration lamp module. Record pairs of lamp on and lamp off frames, without moving the flip mirror between these frames. This can be done by typing:

```
IMB/CALIBRATION=INCANDESCENT
```

to turn the lamp on, and:

```
IMB/INCANDESCENT=OFF
```

to switch it off without moving the mirror, or by typing the DCL symbols `LON` and `LOFF` into MOPRA. Note that these abbreviations have a different effect to the same symbols typed into the telescope console terminal.

A flat spectrum object must be measured to remove terrestrial atmospheric absorption features from an object spectrum. A flux standard must also be measured to flux calibrate the object spectrum. Stars earlier in spectral type than F are preferred as calibrators for the grism spectra because they have few intrinsic spectral features, and the H^- ion bump around 1.6 μm is less pronounced than in G dwarfs. However, it is necessary to also record a spectrum of a K or M star in order to measure and remove the hydrogen absorption lines in the early-type star spectrum. Lists of suitable stars can be found in Appendix G. Plots of terrestrial atmospheric absorption can be found in Appendix M.

3.11 Short Slit Grism Spectroscopy

The short slit, cross-dispersed IJ, JH, and HK grisms provide two pixel resolving powers of $\sim$ 1100 through a $1'' \times 15''$ slit with complete wavelength coverage from 0.98 μm to 2.49 μm. Wider short slits in the Aperture Wheel can be used at the expense of spectral resolution.

The observing procedure for the short slit grisms is similar to the long slit grisms. More care is required in the placement of the two object positions along the short slit to avoid light loss at the slit ends while accurately measuring the sky flux at the other slit position. In practice, this means measuring spectra at two position displaced along the slit by $\pm 4''$ from its center.

The expected spectral images for common astronomical lines, airglow, Xenon and Argon arcs, with each grism are shown in Figures 12 to 17. Plots of extracted Xenon and Argon arc spectra for each order of each cross-dispersed grism are shown in Appendix J.

3.12 Coronographics

The coronograph mode in CASPIR is used to image faint emission near brighter objects with sizes comparable to the seeing disk. The coronograph does two things; first, it occults the direct light of the bright object over a region of the sky comparable to the seeing disk, and secondly, it blocks light from the bright object which is diffracted around the telescope secondary support structure.

This is achieved in CASPIR by selecting either the $2''$ or $5''$ diameter occulting disk in the Aperture Wheel (see Table 16), and selecting the pupil plane mask in the Utility Wheel (see Table 18). This means that the CASPIR coronograph can only be used with the fast camera ($0.5''$/pixel scale), as the slow camera is also located in the Utility Wheel. The size of the occulting disk is based on the expected extent of the faint emission being measured and the seeing, and is selected by typing, e.g.:

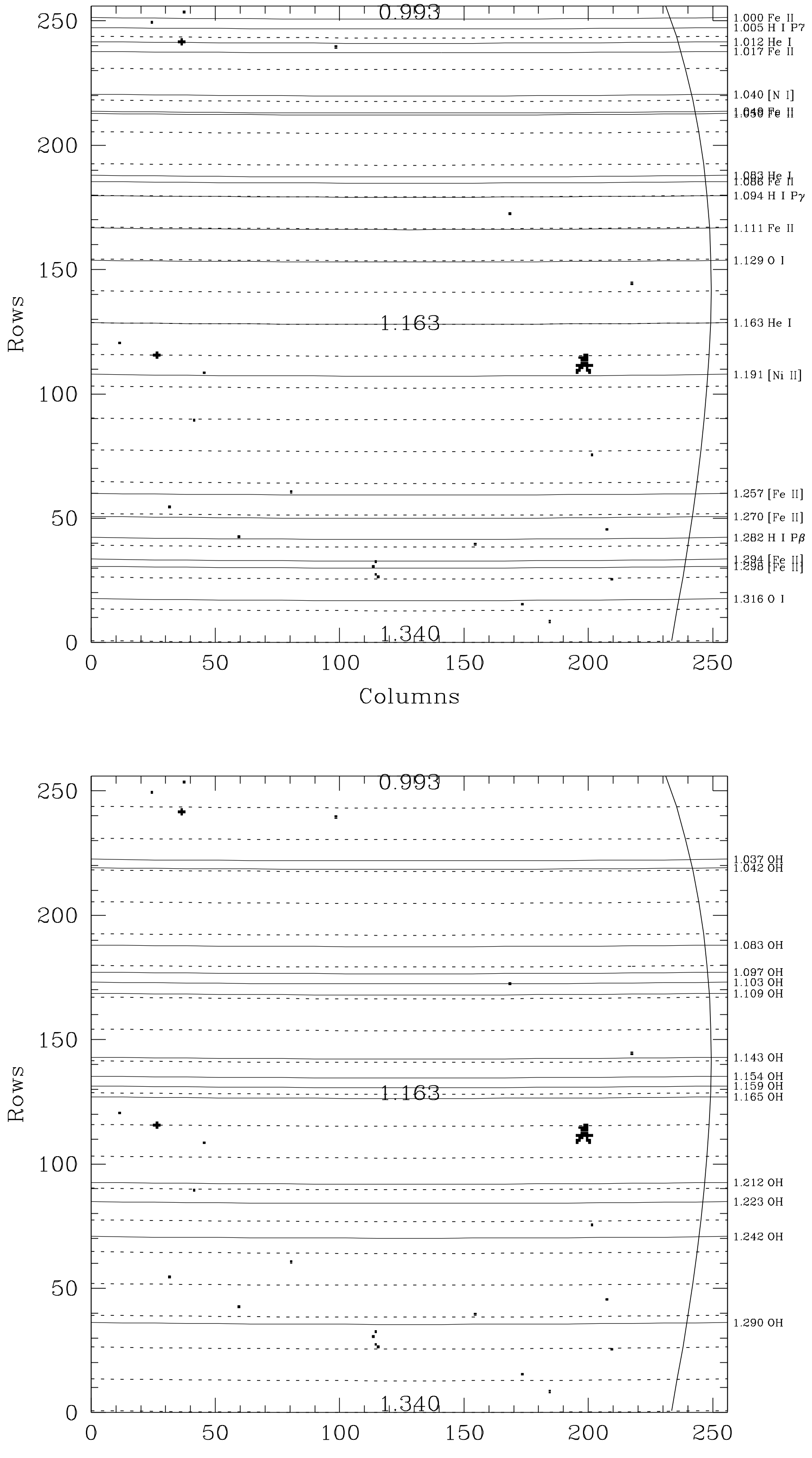
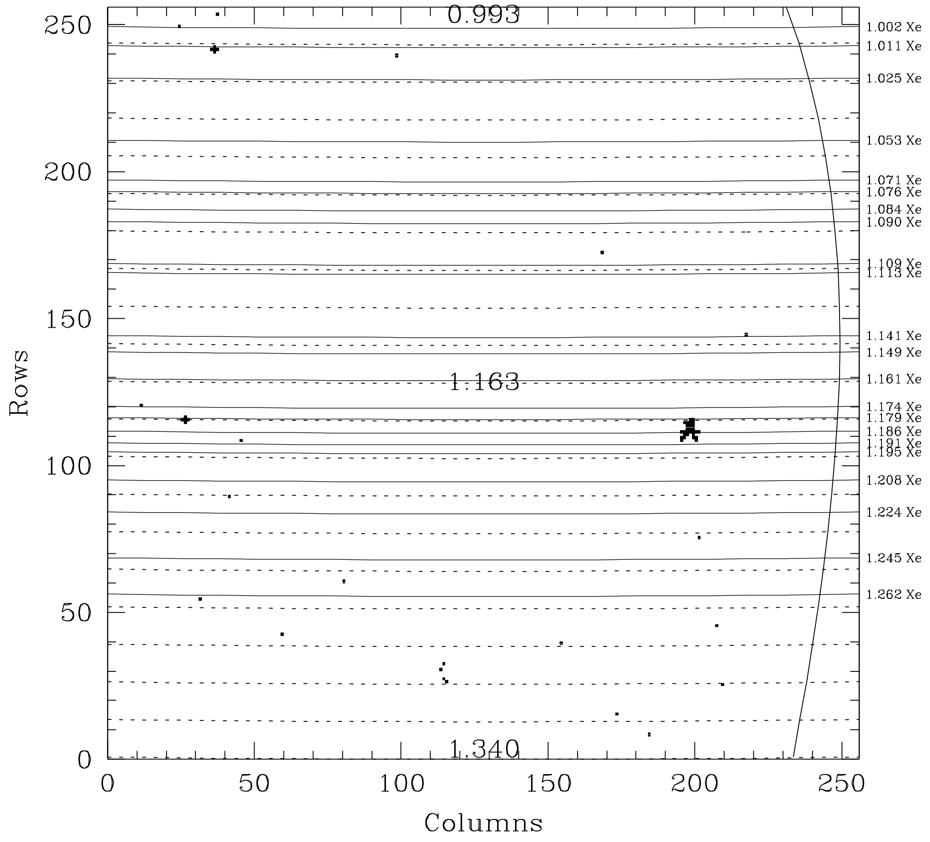


Figure 6: Predicted astronomical (*top*) and airglow (*bottom*) spectra for the *J* grism.



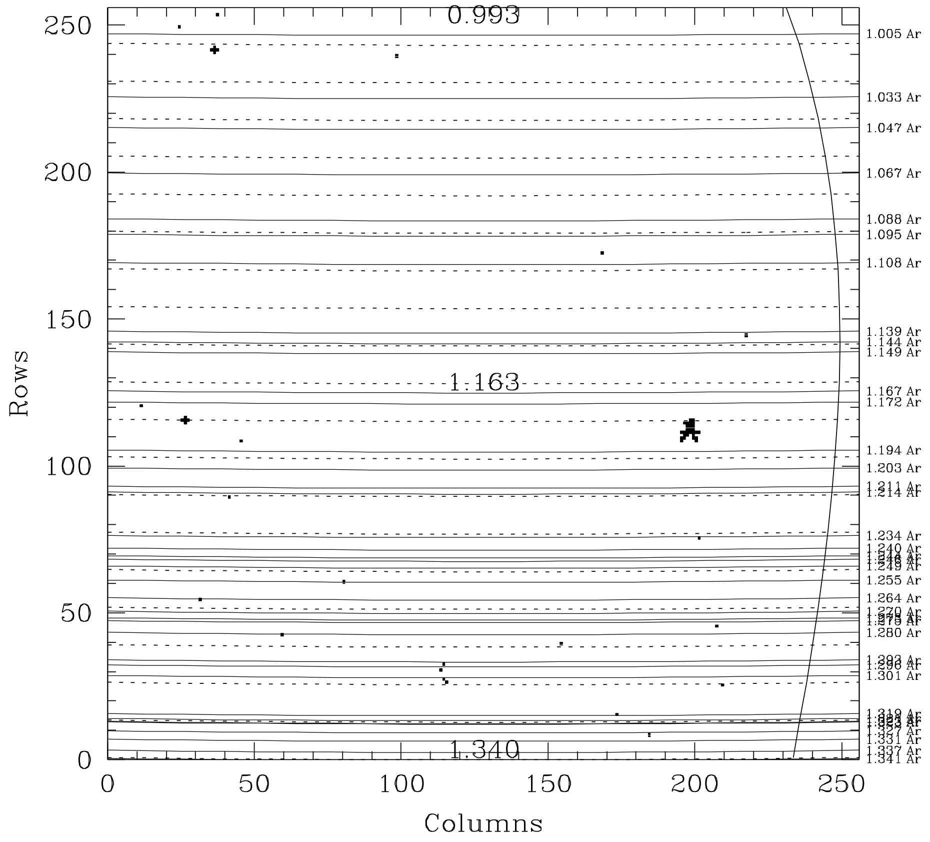


Figure 7: Predicted Xenon (*top*) and Argon (*bottom*) lamp spectra for the *J* grism.

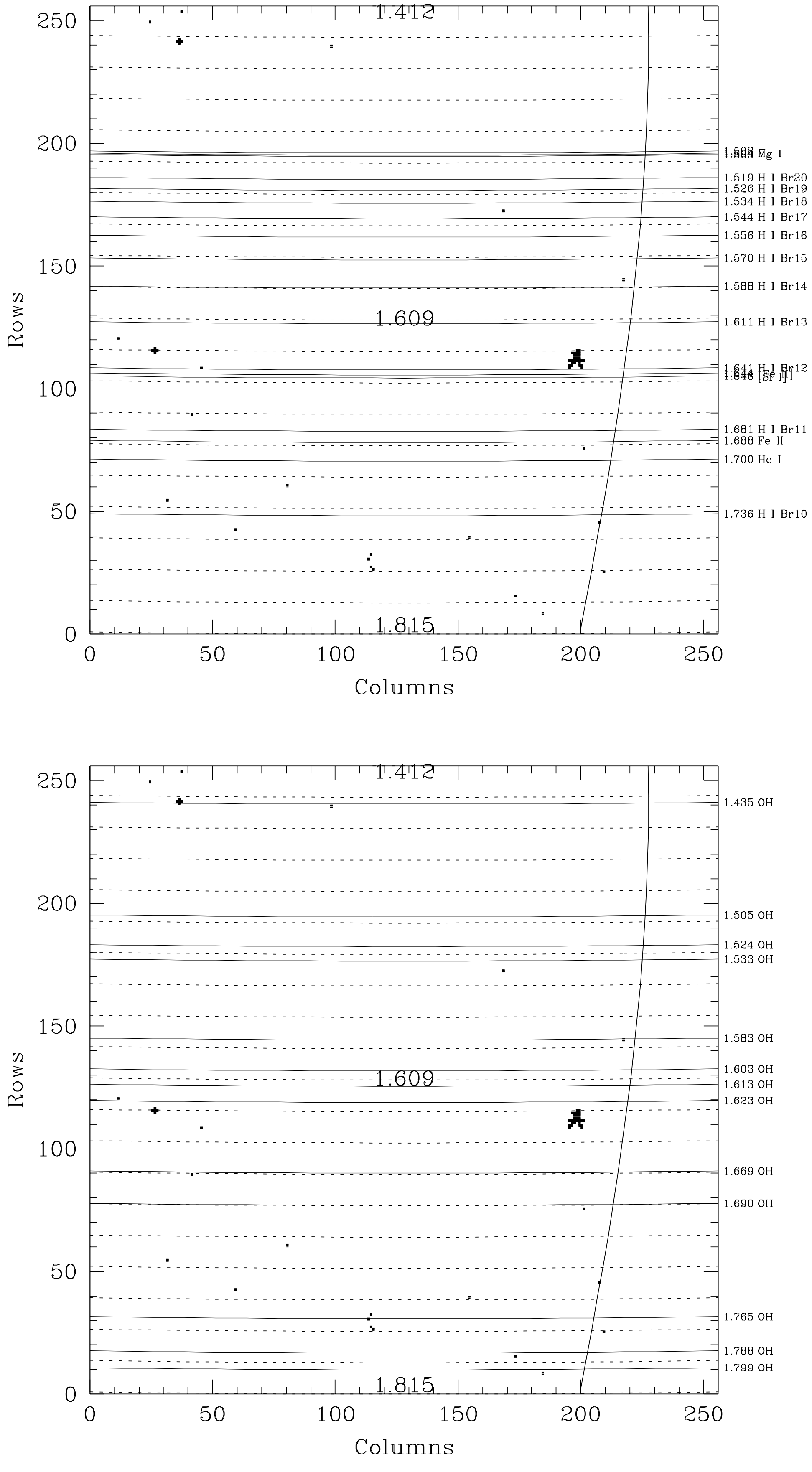


Figure 8: Predicted astronomical (*top*) and airglow (*bottom*) spectra for the *H* grism.

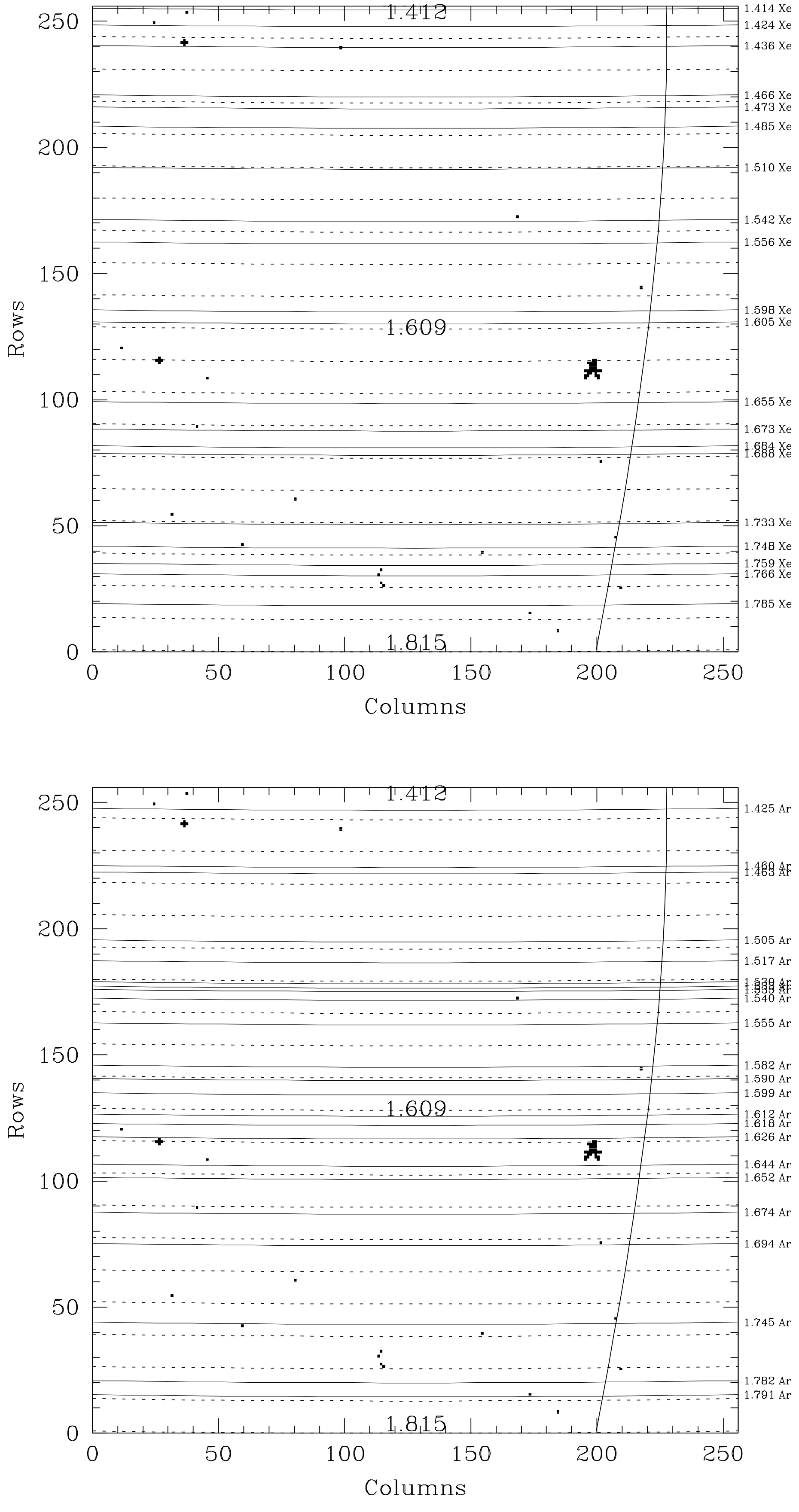


Figure 9: Predicted Xenon (*top*) and Argon (*bottom*) lamp spectra for the H grism.

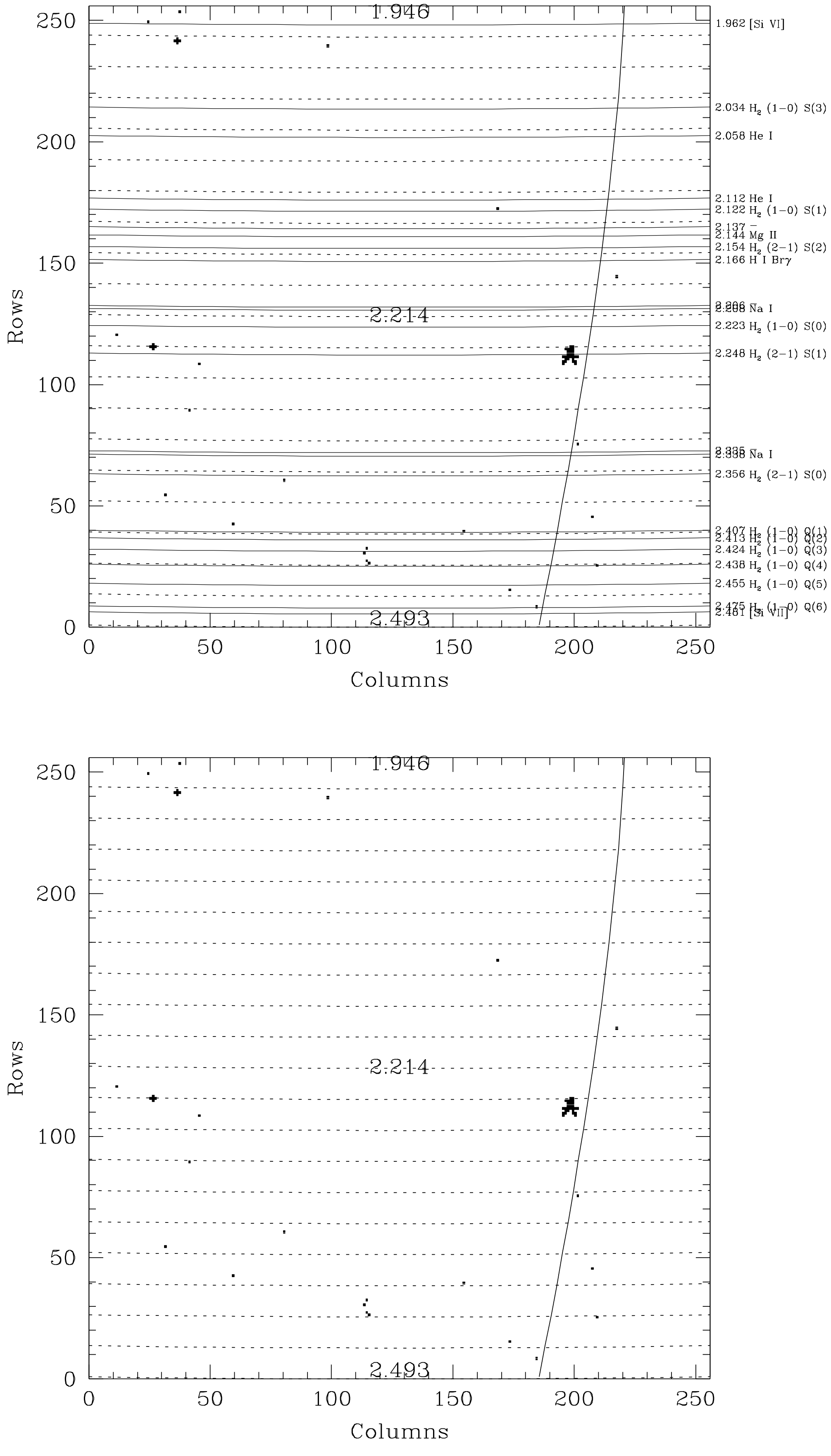


Figure 10: Predicted astronomical (*top*) and airglow (*bottom*) spectra for the K grism.

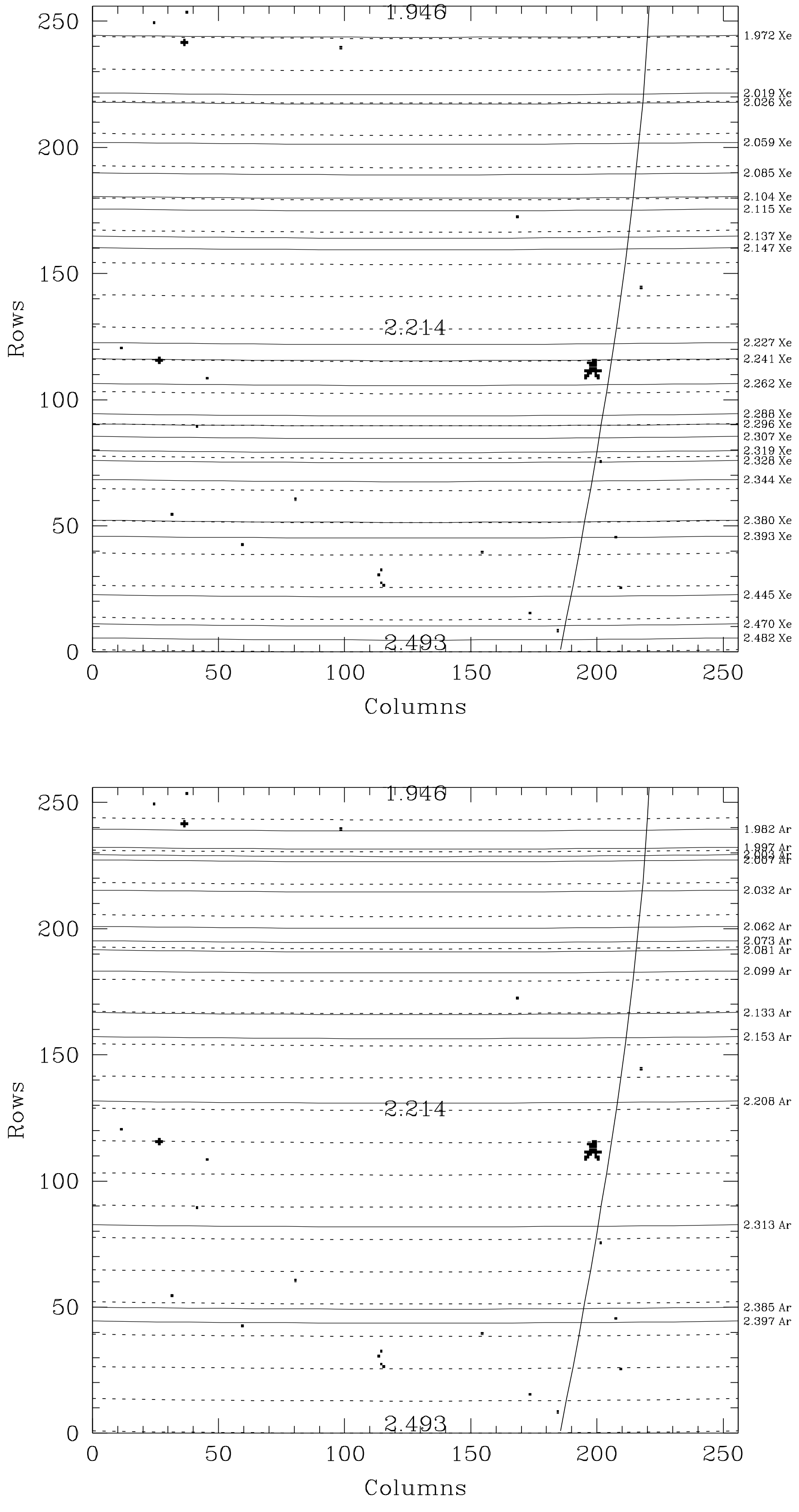


Figure 11: Predicted Xenon (*top*) and Argon (*bottom*) lamp spectra for the *K* grism.

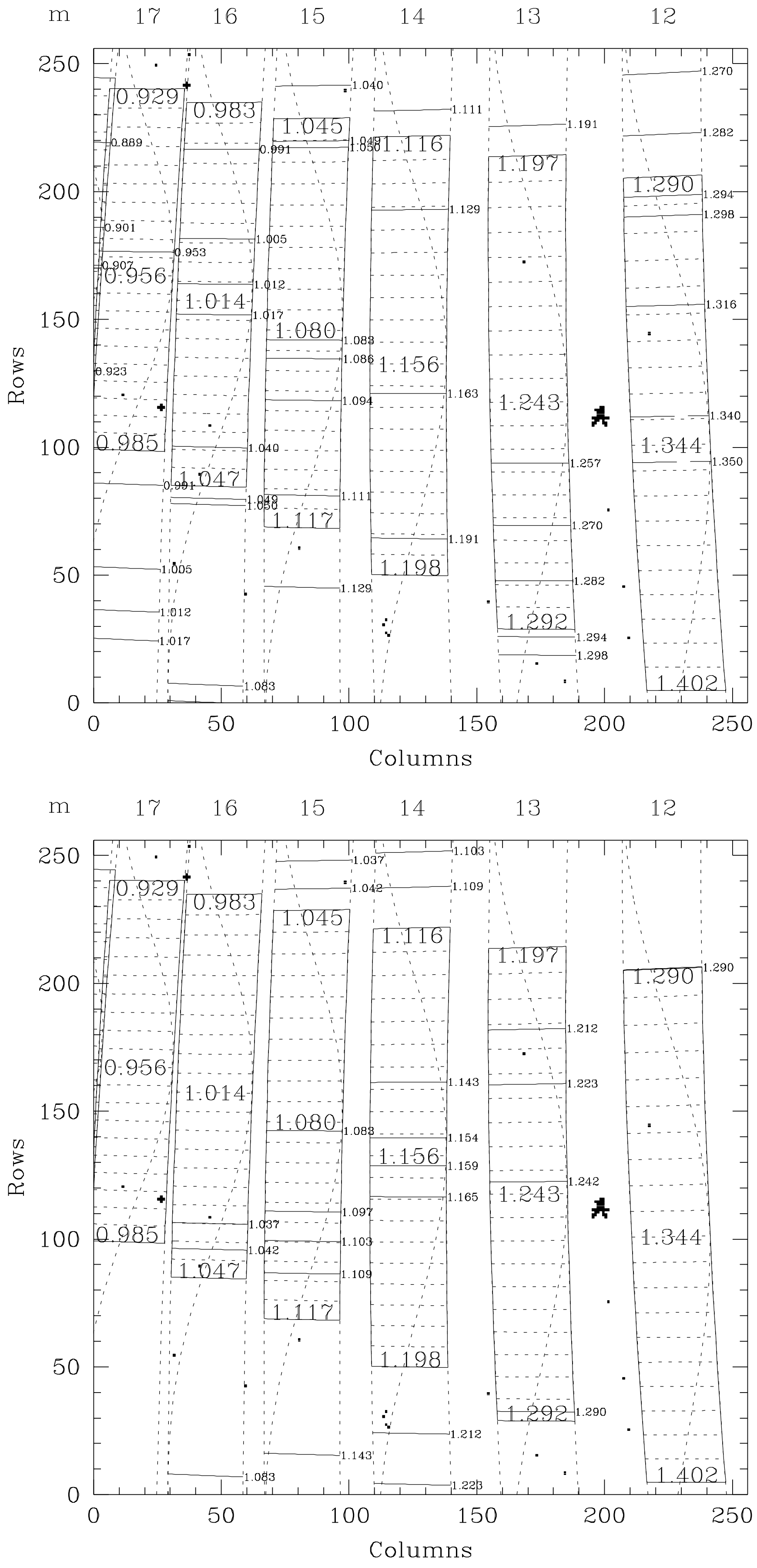


Figure 12: Predicted astronomical (*top*) and airglow (*bottom*) spectra for the *IJ* grism.

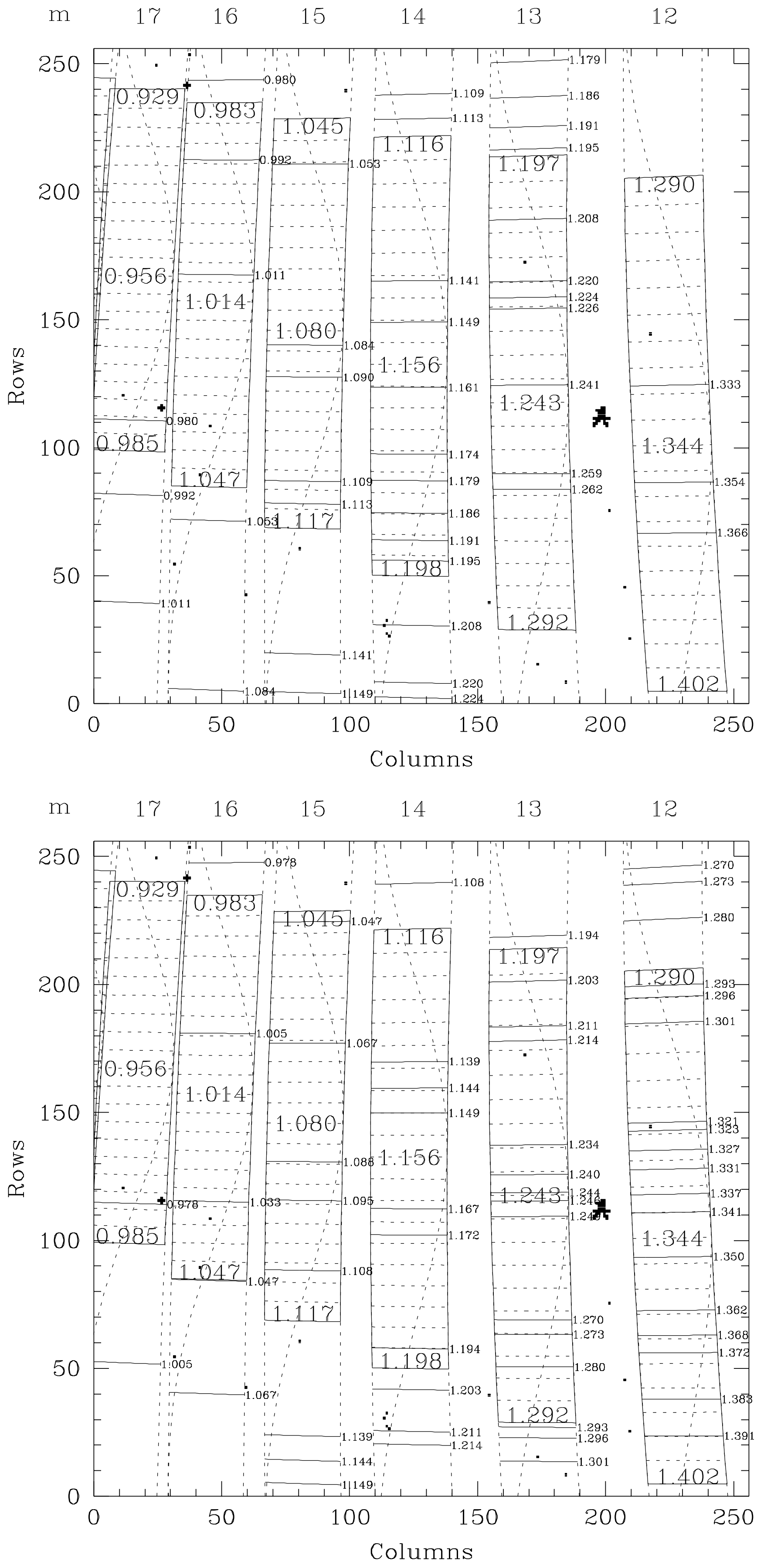


Figure 13: Predicted Xenon (*top*) and Argon (*bottom*) lamp spectra for the *IJ* grism.

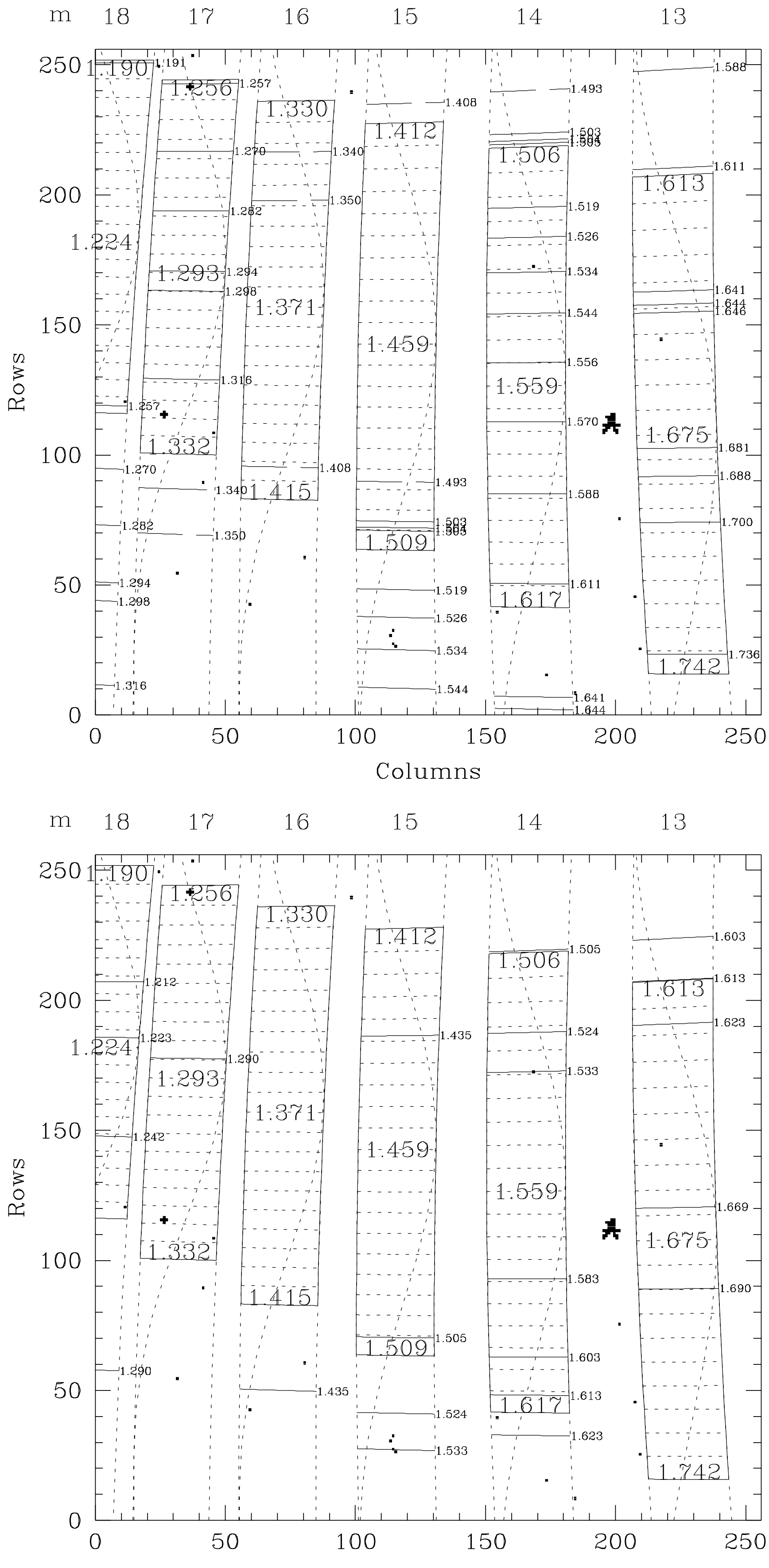


Figure 14: Predicted astronomical (*top*) and airglow (*bottom*) spectra for the JH grism.

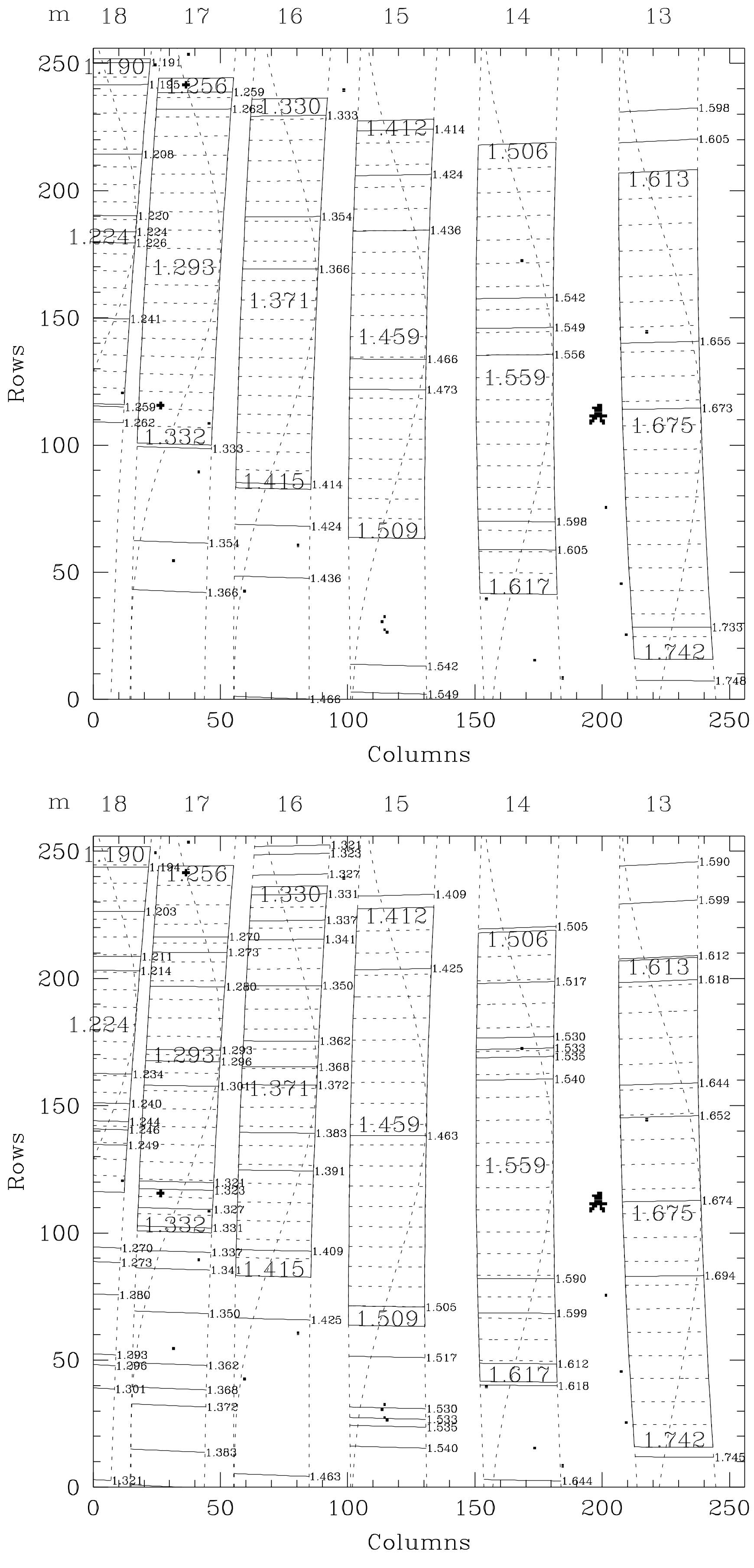


Figure 15: Predicted Xenon (*top*) and Argon (*bottom*) lamp spectra for the *JH* grism.

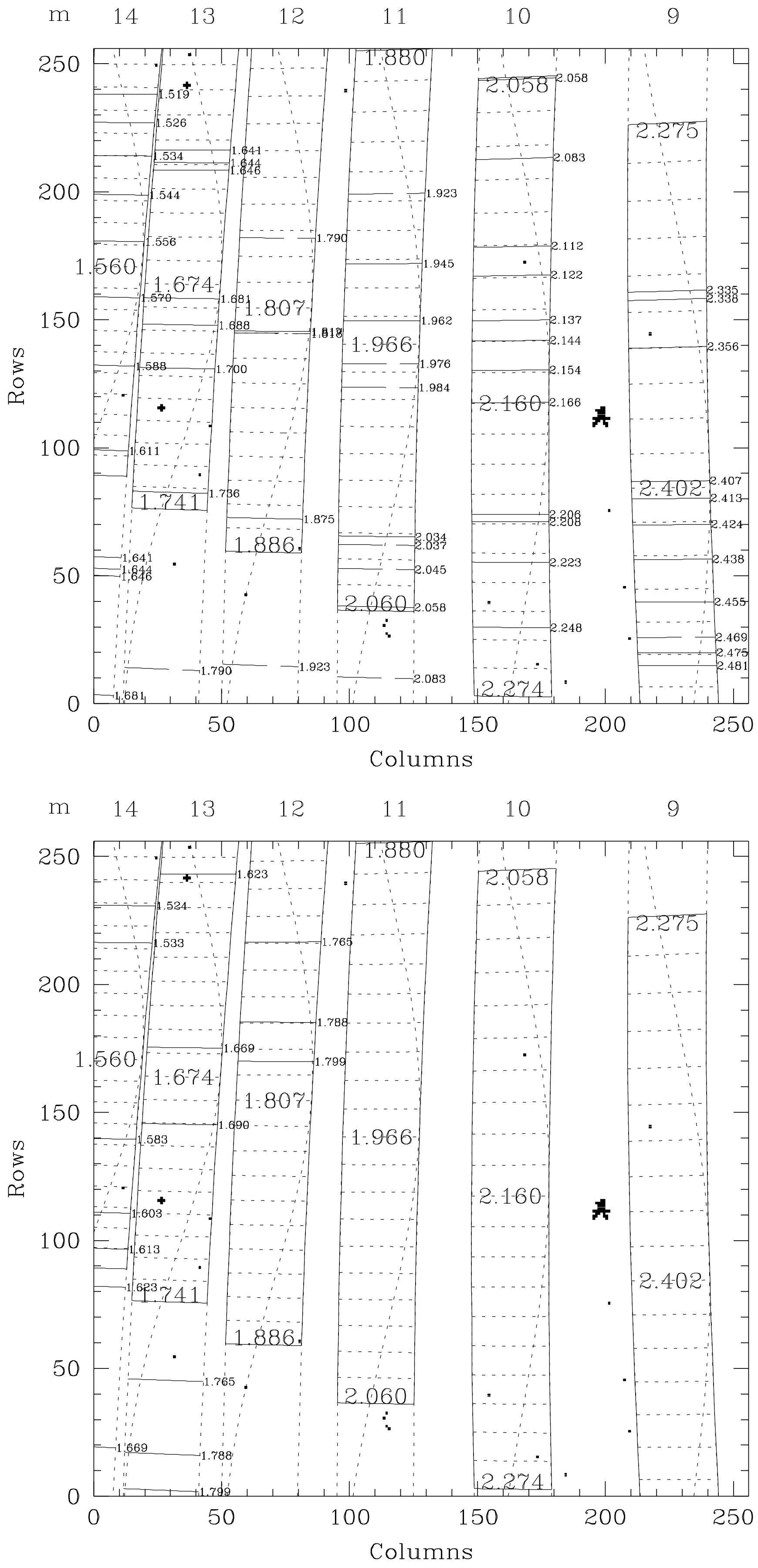


Figure 16: Predicted astronomical (*top*) and airglow (*bottom*) spectra for the HK grism.

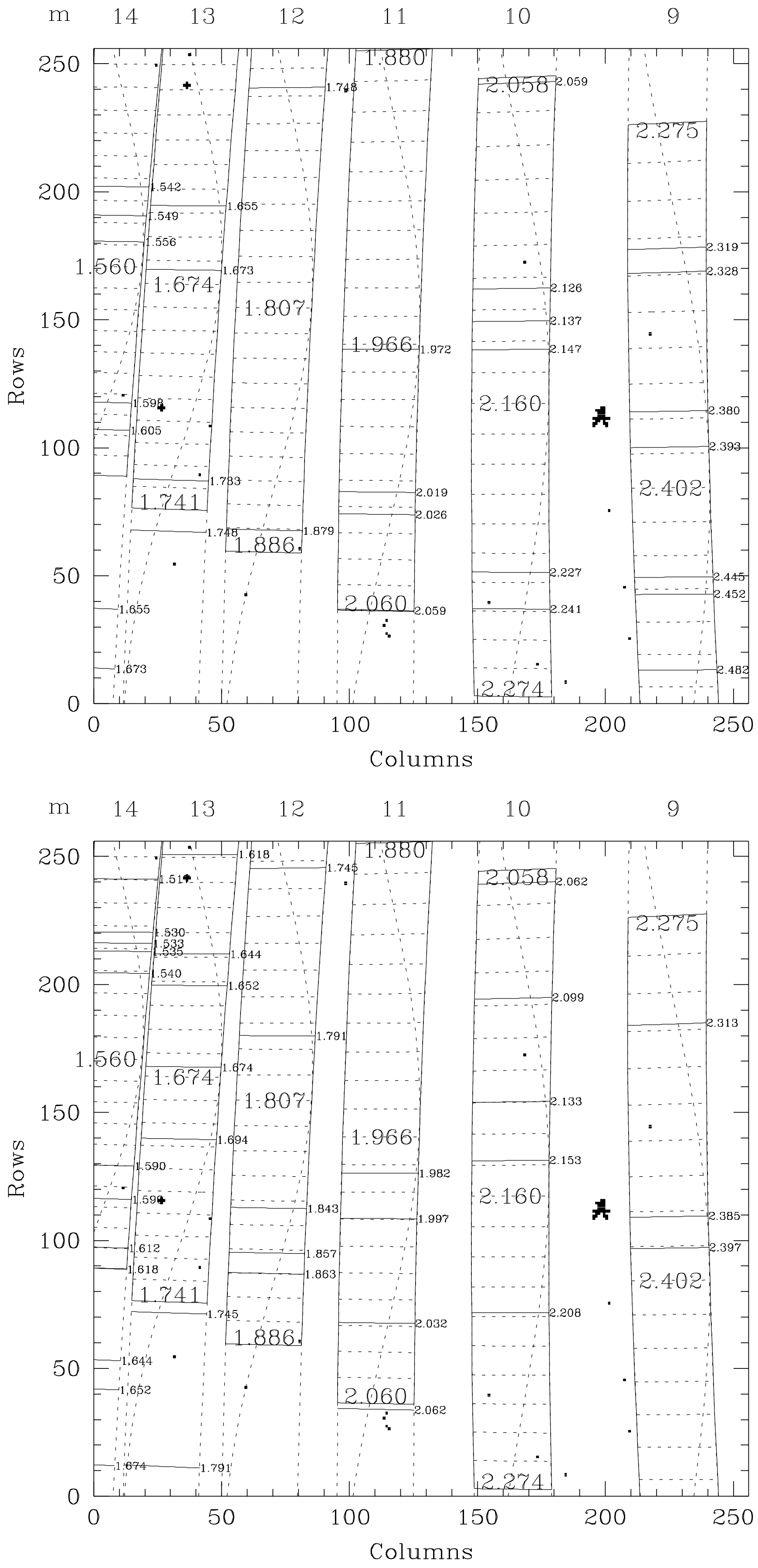


Figure 17: Predicted Xenon (*top*) and Argon (*bottom*) lamp spectra for the HK grism.

```
CASPIR/APERTURE=DISK2
```

Only one pupil plane mask is available. This is selected by typing:

```
CASPIR/UTILITY=MASK
```

Use of the coronograph masks in CASPIR is complicated by the alt-az nature of the 2.3 m telescope. Because the 2.3 m telescope has an alt-az mount, CASPIR is continuously rotated to maintain a fixed orientation with respect to the sky. The image of the secondary support structure then *rotates in the pupil plane*. The pupil plane mask is a Maltese Cross shaped baffle with each section of the cross having a half-angle of 15°. The mask has a fixed orientation with respect to the dewar. In using the coronograph pupil plane mask, it is desirable to set the instrument rotator position angle so that the secondary support structure remains vignetted for the longest time. If the parallactic angle is *increasing* set the instrument rotator position angle to the parallactic angle *plus* 15°. If the parallactic angle is *decreasing* set the instrument rotator position angle to the parallactic angle *minus* 15°. The secondary support structure will then be behind the pupil plane mask, but will move as the telescope tracks. The rate of motion depends on position on the sky. Consult Figure 9.9 in the 2.3 m Telescope Observer's Manual to estimate this speed. Field rotation at the Cassegrain focus is not monotonic and changes most rapidly near the zenith. Consequently, coronograph observations are best done away from the zenith.

3.13 Tip-Tilt Image Correction System

The Tip-Tilt sensor is mounted on the IMB X-Y stage behind a focal reducer that provides an image scale of $0.6''$/pixel (see Fig. 23). The stage has a travel of ± 31.3 mm in the f/18 ($5''$/mm) telescope beam, so an offset guide star is needed within a square field of $\sim 5.2'$ extent centered on the object. The Tip-Tilt CCD has 64×64 pixels, giving a full field of $38.4'' \times 38.4''$.

Operation of the Tip-Tilt system is fully described in the Tip-Tilt manual. Factors relevant to its operation with CASPIR are summarised below.

Give the Tip-Tilt system access to the telescope by typing:

```
ENLIST TT
CONFIGURE EFFECTIVE_WAVELENGTH 2000
CONFIGURE GUIDER_WAVELENGTH 700
```

into the *telescope console terminal*.

The Tip-Tilt software is run on MISTY under X Windows from any user account (your own or "user23"). Start the system by typing:

```
tiptilt &
```

After the initialization sequence completes, click on the "operate" button to select acquire mode. Correct and acquire integration times should be set to something less than 100 mS. When a suitable guide star is in the image display, select it by pressing "Shift" and clicking on the star with the left mouse button. The correct box is moved to this object, and tip-tilt correction is commenced by clicking on the "correct" button.

After the telescope and CASPIR have been properly configured, type:

```
CALIBRATE STAGE
```

into the *telescope console terminal* and follow the instructions. This procedure defines the IMB X-Y stage zero point and Tip-Tilt correct subframe to the telescope system.

Now enable use of the Tip-Tilt system and IMB X-Y stage motion from CASPIR DO files and in NOD mode by typing:

```
CASPIR/TIPTILT/STAGE_OFFSET
```

into the CASPIR command terminal.

Normally, the CASPIR array and the Tip-Tilt CCD will remain cofocal and no adjustment of the Tip-Tilt focus should be required. If focus adjustment is required, focus the telescope on the infrared array, then adjust the focus of the optical image in the Tip-Tilt display using the `IMB/FOCUS` command. Use the up and down arrows to change the focus of the acquistion unit focal reducer, and type `Q` to quit. *Do not move the telescope focus to focus the optical image.*

The Tip-Tilt sensor can be used in acquire mode for normal object acquisition. With the instrument rotator at a position angle of 180°, North is up and East to the right on the Tip-Tilt display, as shown schematically in Figure 1

To guide on an offset guide star, it is first necessary to offset the IMB X-Y stage to the location of a suitable star. The small size of the Tip-Tilt CCD field of view relative to the offset guide field makes it essential to pre-select suitable reference stars from charts of your fields. Procedures for doing this is described in §3.14. The Tip-Tilt systems allows the observer to specify reference stars to the telescope system by their coordinates, e.g.:

```
TIPTILT/COORD 12 34 46.5 -15 34 23 J2000
```

or from a telescope coordinate file, e.g., :

```
TIPTILT BS2015
```

or by their offsets in arcseconds on the sky, e.g.:

```
TIPTILT/OFFSET/SCALE 12.0 -3.4
```

or by typing:

```
TIPTILT/TRACK
```

if the object at the tracking coordinate (the infrared object) can be used as the reference star, or by typing:

```
TIPTILT/HERE
```

if there is a suitable reference star in the Tip-Tilt acquire frame and you wish to drive the reference star to the correct subframe, or

```
TIPTILT/FIND
```

if there is a suitable reference star in the Tip-Tilt acquire frame and you wish to move the correct subframe to the pixel location of the reference star.

When the Tip-Tilt system is correcting, the position of an object on the CASPIR array can be adjusted by translating the IMB X-Y stage using telescope `TIPTILT/OFFSET` command so that the object is dragged, by the Tip-Tilt system, to the desired infrared position. Measure the desired offset in arcseconds from pixel locations on the CASPIR array and apply this correction to the specified reference star offsets.

The Tip-Tilt system can also be controlled through the DO file used to acquire CASPIR data. The DO file commands controlling Tip-Tilt are:

```
tiptilt             - Turns on Tip-Tilt operation.
notiptilt           - Turns off Tip-Tilt operation.
stage_offset        - Enables IMB X-Y stage motion.
nostage_offset      - Disables IMB X-Y stage motion.
track_coord         - Track on a new object coordinate (i.e., RA, Dec.).
guide_coord         - Defines a new guide star coordinate (i.e., RA, Dec.).
gra_offset          - Defines guide star RA offset in arcsec on sky.
gdec_offset         - Defines guide star Dec. offset in arcsec on sky.
ttx                 - X coordinate of Tip-Tilt correct subframe center.
tty                 - Y coordinate of Tip-Tilt correct subframe center.
ttdx                - X size of Tip-Tilt correct subframe.
ttdy                - Y size of Tip-Tilt correct subframe.
acqx                - X coordinate of Tip-Tilt acquire subframe center.
acqy                - Y coordinate of Tip-Tilt acquire subframe center.
```

```
acqdx              - X size of Tip-Tilt acquire subframe.
acqdy              - Y size of Tip-Tilt acquire subframe.
tt_mode=correct    - Operates Tip-Tilt in correct mode.
tt_mode=guide      - Operates Tip-Tilt in guide mode.
tt_mode=acquire    - Operates Tip-Tilt in acquire mode.
tt_mode=recalibrate - Operates Tip-Tilt in recalibrate mode.
tt_atime           - Sets acquire mode integration time (ms).
tt_gtime           - Sets guide mode integration time (ms).
tt_ctime           - Sets correct mode integration time (ms).
tt_find            - Enables Auto-Acquire mode.
nott_find          - Disables Auto-Acquire mode.
tt_error           - Do not abort on Tip-Tilt error.
nott_error         - Abort DO file if Tip-Tilt errors encountered.
```

3.14 Preparing Offset Guide Star Charts

Convenient charts for identifying offset guide stars for CASPIR observations of southern objects can be obtained using the COSMOS database at the AAO, or the southern Digitised Sky Survey.

To access the COSMOS database, telnet to the COSMOS machine at Epping by typing:

```
telnet cosmos.aao.gov.au
username: cosmos
password: UKSTcosmos
```

Enter your object coordinates into a text file one object per line in free-format, e.g.,

```
cat > input.dat
08 06 30.24 -10 18 50.0
21 52 58.01 -69 55 40.4
<cnrtl>d
```

Start the COSMOS program and take the defaults on all the questions except for those listed below:

```
cosmos
>> Change default parameters (n)? y
>> Min, Max BJ magnitude (0.00 25.00): 0.0 20.0
>> No. plots across, down page (1 1): 5 3
>> Please select an output device: 1                (postscript)
>> Filename => output.ps
>> Text output filename (<CR> for none): output.dat
>> Input coordinate file (<CR> for none): input.dat   (coordinate file)
>> Equinox (J2000.0): B1950.0
>> Diameter of charts (6.0 arcmin): <CR>             (good size)
...
>> More plots (y)?: n
```

Now ftp the results (output.ps and output.dat) back to your home machine and print them. The COSMOS charts are contained in the file output.ps (e.g., Figure 18). The output.dat file is a text listing of source positions, brightnesses, etc. These can be used to calculate offsets to suitable guide stars in arcsec on the sky. The users guide for the COSMOS program can be found in the file /cosmos/disk1/doc/Userguide.tex. Contact Michael Drinkwater at the UKSTU for further information (mjd@aaocbn3.aao.gov.au).

The southern Digitised Sky Survey is best accessed via CDROM. The World Wide Web SkyView Basic (http://skyview.gsfc.nasa.gov/skyview.html) or STScI (http://stdatu.stsci.edu/dss/dss_form.html) nodes

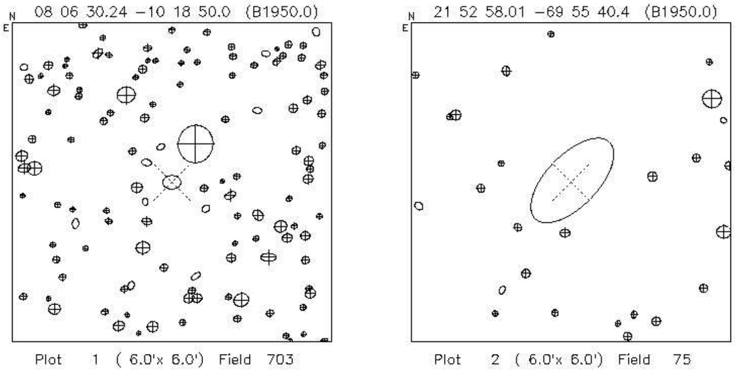


Figure 18: Typical COSMOS charts for 6′ × 6′ regions of sky.

can also be used, but these can be slow and the file headers differ from those of the CDROM versions. Convenient lists of stars from the Hubble Guide Star Catalog within a specified radius of an object (specified by name or coordinate) can be obtained from the ESO web site (http://archive.eso.org/gsc/gsc). SkyView Advanced (http://skyview.gsfc.nasa.gov/cgi-bin/v3.0/skyview_advanced.pl) can also be used to select Digitized Sky Survey images by specifying object names, overlay HST Guide Star Catalog stars as well as many other cataloged objects, and print the image and coordinates of overlayed objects in one streamlined, but slow, process.

To extract a Digitized Sky Survey image from CDROM type `getimage` and follow the instructions for loading the relevant CDROM disk.

When all the FITS files have been obtained, enter the filenames into a text file one per line, e.g.:

```
cat > files.dat
3c195.fits
2152-699.fits
<cntrl>d
```

Then form a postscript mosaic of these images using DSSPLOT (e.g., Figure 19) by typing:

```
dssplot files.dat
```

DSSPLOT is part of the CASPIR IRAF package. Refer to §6 for information on how to obtain copies of this package. Print the mosaic by typing, e.g.:

```
lpr -s -Plaser_d dssplot.ps
```

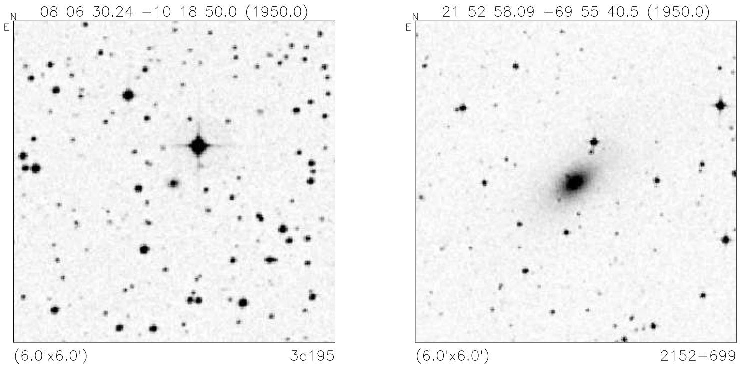


Figure 19: Typical southern Digitised Sky Survey charts formatted with DSSPLOT.

Positions of objects in the image can be obtained using IRAF. Load the STSDAS and GASP packages, then first form the RA/DEC world coordinate system for file image.fits by typing:

```
makewcs image
```

Then display the image and measure positions with the image cursor by typing:

```
display image 1
rimcursor wcs=world wxformat=%12.2H wyformat=%12.2h
```

Alternatively, if the (x,y) coordinates of the object are known, convert these to RA and DEC by typing:

```
xy2rd image x y
```

3.15 Data Archiving

CASPIR data files are written to the MOPRA data disk as FITS files. These files are accessible from MISTY in dated subdirectories of the directory /data/mopra/. Data files can be copied from MOPRA to MISTY by typing the following into MISTY, e.g.:

```
cp /data/mopra/10oct94/ir*.fits .
chmod -x *
```

Data are archived from MISTY to exabyte tape on drive ex0 (left drive) or ex1 (right drive). It is the responsibility of observers to provide their own exabyte tapes. Typically ~ 100 Mbytes of data are produced in a single night of direct imaging, so data from several nights can fit on one exabyte tape. Data files on MISTY can be archived in TAR format to an exabyte tape already containing data using the following example procedure:

```
allocate ex0                    (Allocate drive and insert tape in right drive.)
mt eom                          (Position tape at end-of-medium.)
mt nbsf 1                       (Backspace over one file.)
tar t                           (Read last TAR saveset on tape.)
tar t                           (Move over one end-of-file marker.)
cd /data/misty/...              (Go to your top level data directory.)
tar cv 10oct94/raw              (Archive data in subdirectory 10oct94/raw.)
mt nbsf 1                       (Backspace over the saveset.)
tar t                           (Check saveset written correctly.)
mt rewind                       (Rewind tape.)
deallocate ex0                  (Deallocate and remove tape.)
```

3.16 Shutting Down the System

Generally, it is advisable to leave the infrared system running at the end of a night. This allows array temperature logging to continue. The dewar should be left blanked off to avoid prelonged exposure to saturated light levels. Use the `STARTNEWNIGHT` command at the beginning of a new night to create a new dated data subdirectory and reset the run number.

To fully shut down the infrared system, type:

```
IR_SHUTDOWN
```

When all processes have stopped, and all but the command entry window have been removed from the workstation screen, click on the Session Manager (*key*) icon and select `Quit` in the Session menu. This logs the INFRARED process out of MOPRA.

3.17 Accessing the History File

An instrument history file exists for logging alterations to the instrument and for user comments. CASPIR users are encouraged to record their experiences in this file for the benefit of others. These comments will be incorporated into this manual where appropriate. To access the file, either to read it or add your comments to it, type:

```
HISTORY
```

This uses the VMS EDT editor in screen mode. To exit, type `<cntrl>Z` and then `EXIT` to update the file, or `QUIT` to leave the file unchanged. The file can also be accessed through the MSSSO WWW home page.

4 A Detailed Look at the Hardware

4.1 System Overview

CASPIR operates within the environment common to all infrared instrumentation on the 2.3 m telescope. A schematic overview of the CASPIR system is shown in Figure 20. All mechanical functions are controlled from MOPRA through a DECNET link to the LSI-11/23 located in the Cassegrain Instrumentation Rack in the Nasmyth Lab, and from this to the instrument control subrack mounted on the Instrument Mounting Box (IMB). The detector array clocks, biases, and signal processing are performed by the SBRC Array Control Electronics (ACE2) also mounted on the IMB, close to the CASPIR dewar. The ACE2 is controlled directly by MOPRA through a 9600 baud RS-232 connection. Data from the four detector output channels are digitised in the ACE2 using four 16-bit, 500 kHz Burr-Brown ADCs, and serialised using four transputer Link Adaptors. The serial data are transmitted from the Cassegrain focus to the Nasmyth Lab where four T800 transputers receive the data and process it as necessary. When the requested integration sequence completes, the data are transferred to MOPRA through a transputer link to Q-bus interface and are displayed on the workstation screen and stored on disk. The detector array temperature is controlled by a commercial controller located in the Nasmyth Lab. MOPRA communicates with this controller through an RS-232 line.

The following describes each section of this chain in detail.

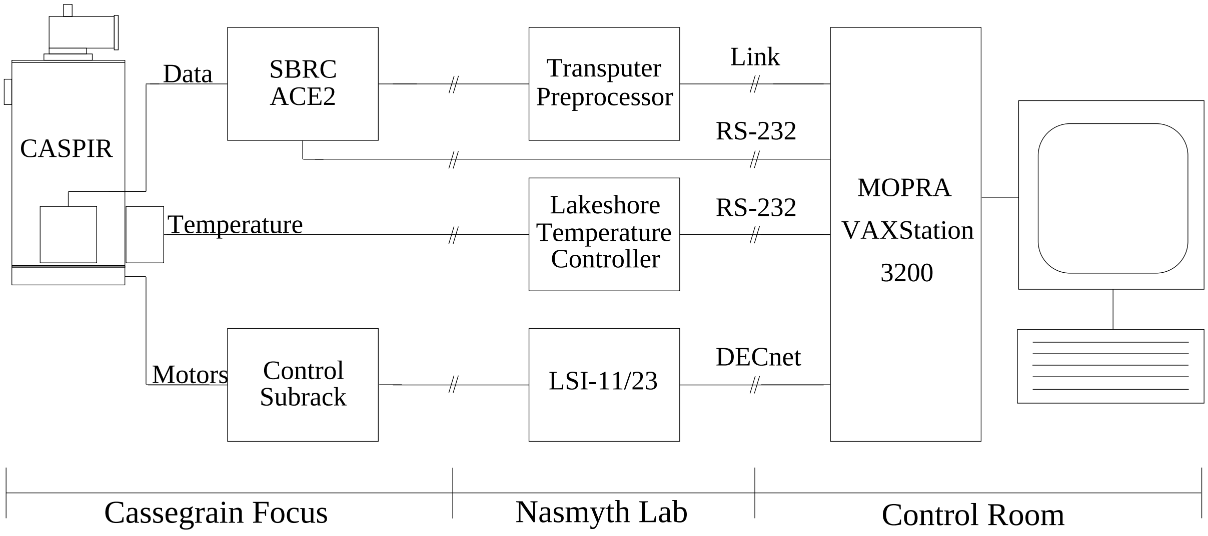


Figure 20: Overview of the CASPIR system showing connections between the dewar and MOPRA via the SBRC ACE2 drive electronics, the transputer preprocessor, the control subrack on the IMB, the LSI-11/23, and the Lakeshore temperature controller.

4.2 The CASPIR Dewar

CASPIR is a cryogenic reimaging camera with a 50 mm long, 10.4 mm diameter collimated beam section. The optical layout is shown in Figure 21, and the mechanical structure is shown in Figure 22. The camera body is cooled to $\sim$ 60 K by the first stage of a closed cycle helium refrigerator, and the detector array is cooled to $\sim$ 32 K by the second stage of the cooler. The dewar incorporates a novel design which uses five 16-position annular wheels mounted coaxially around the cooler to produce a compact vacuum system. The wheels are driven by motors located on the dewar base plate.

The CASPIR dewar mounts on port A of the IMB (Fig. 23). The rotatable dichroic mirror in the IMB directs the f/18 telescope beam to the dewar. The dewar window is a Sapphire/CaF$_2$ doublet which acts as a field lens to image the telescope exit pupil (the secondary mirror) onto an internal cold stop. A

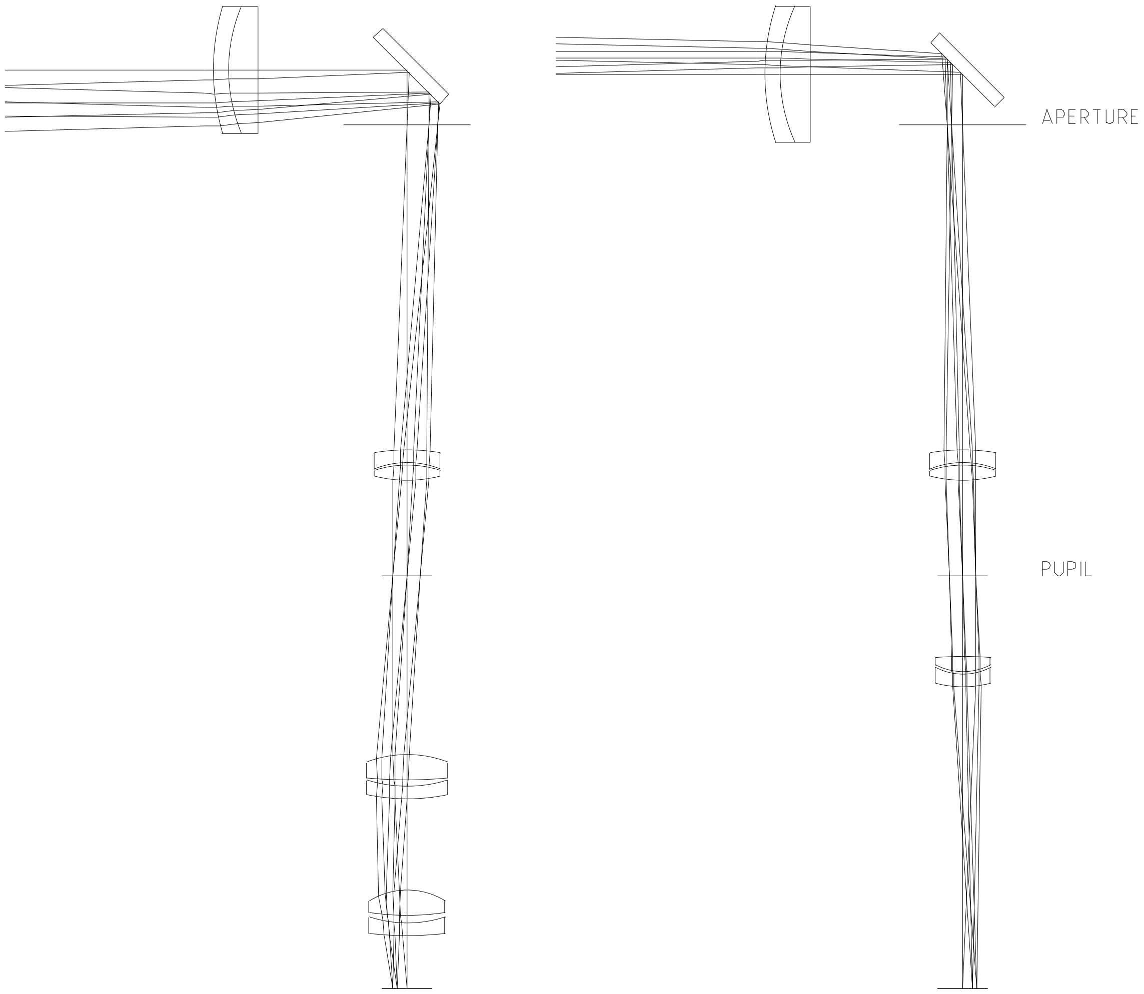


Figure 21: Layout of the CASPIR optics for the 0.5″/pixel scale (*left*) and the 0.25″/pixel scale (*right*). In both cases light enters at top left and passes through the field lens/dewar window, is reflected down to focus at the aperture wheel (marked APERTURE), passes through the collimator to the pupil position (marked PUPIL), and is brought to focus on the detector array by either the fast (*left*) or slow (*right*) camera.

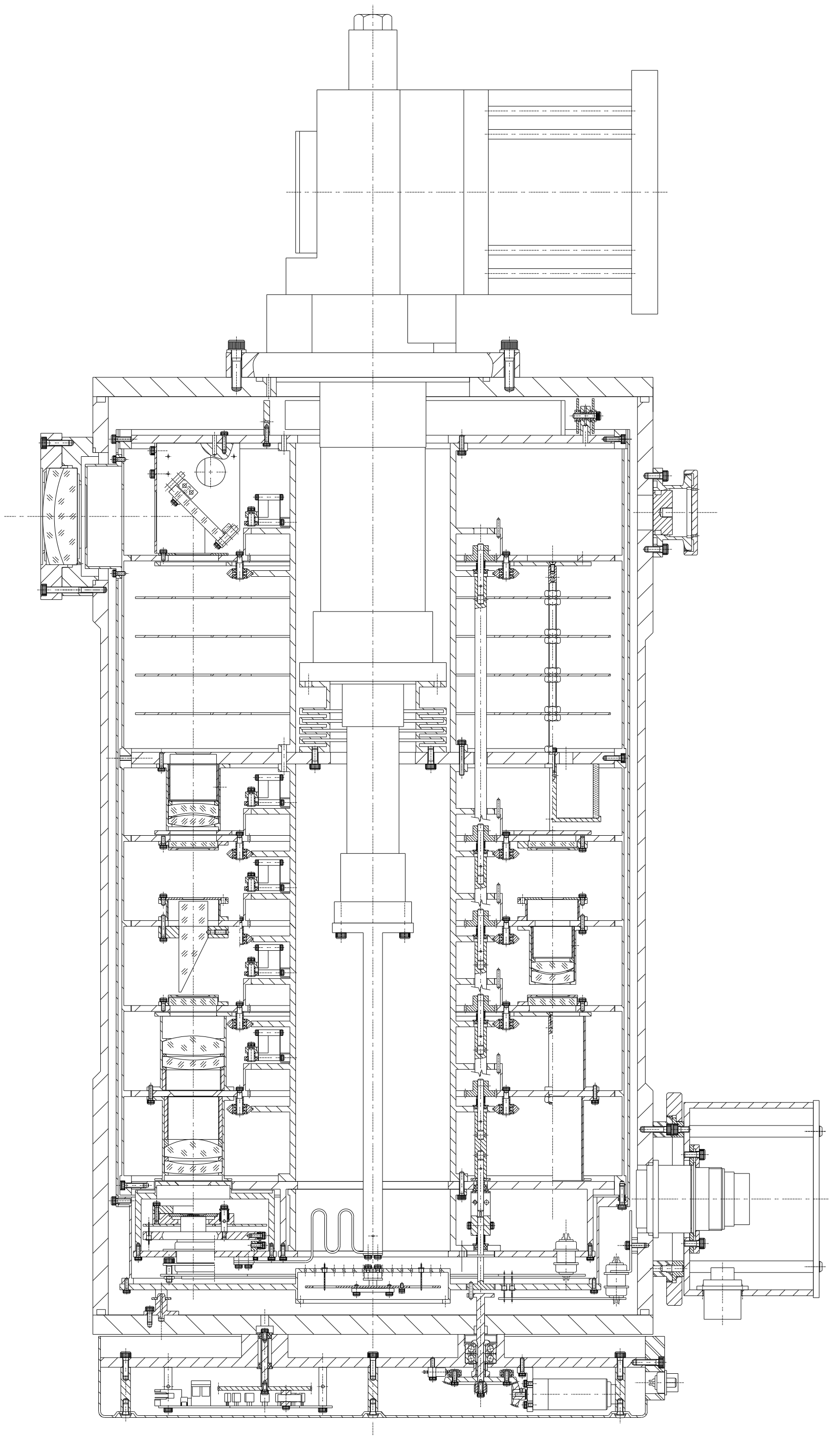


Figure 22: Assembly drawing of the CASPIR dewar. The annular wheels are located around the closed cycle helium refrigerator which is mounted on the dewar top plate. Motor drives for the wheels are located on the dewar base plate. The f/18 telescope beam enters from the left and passes through the dewar window/ field lens, the Aperture Wheel, collimator lens, Upper Filter Wheel, Utility Wheel, Lower Filter Wheel, and Lens Wheel to reach the detector at lower left. The dewar is shown configured with a cross-dispersed grism and the fast camera lenses in the optical beam. The slow camera lens is shown out of the beam to the right in the Utility Wheel.

cold gold-coated mirror then directs the beam down, parallel to the dewar axis. The telescope focus is located immediately below this mirror at the Aperture Wheel. The Aperture Wheel contains baffles for the 0.5″/pixel and 0.25″/pixel focal plane scales, a range of slits for the grisms, coronograph masks, and the field mask used for imaging polarimetry (Appendix E, Table 16). The diverging beam then passes to a fixed MgO/CaF$_2$ doublet collimator lens which produces the collimated beam section. Immediately below this, in the collimated beam, is the Upper Filter Wheel which contains the filters listed in Table 17 of Appendix E. Next is the Utility Wheel which is located at the pupil plane. This wheel contains the direct imaging cold stop, the MgO/CaF$_2$ doublet slow camera lens for the 0.25″/pixel focal plane scale, the six grisms, and the Wollaston prism polarimeter analysers (Appendix E, Table 18). Below the Utility Wheel is the Lower Filter Wheel which contains the filters listed in Table 19 of Appendix E. Note that some of the broadband filters require blocking filters located in the Lower Filter Wheel. Both filter wheels contain clear positions. The detector array should not be exposed to optical light while cold, so the software prevents both clear position being selected at the same time. Note also that the Lower Filter Wheel is located in an f/10.4 converging beam when the slow camera is used, so some refocusing between filters may be required. The final wheel is the Lens Wheel which contains the MgO/BaF$_2$ fast camera lenses for the 0.5″/pixel focal plane scale. These are rotated out of the beam when the slow camera is used. The detector array is located at the lower end of the dewar at the camera focus.

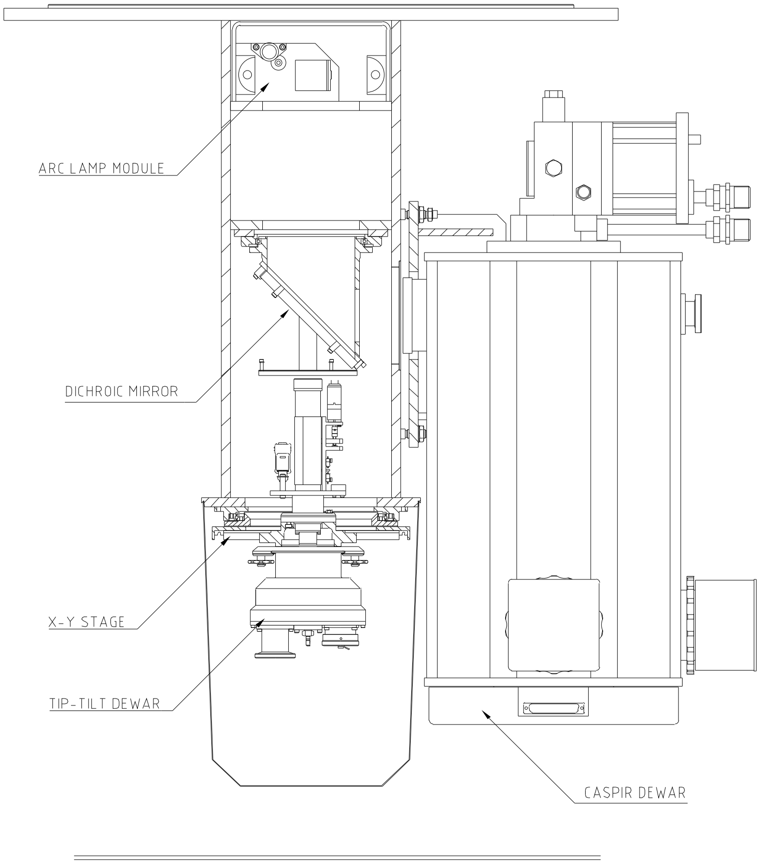


Figure 23: Schematic of CASPIR mounted on the IMB showing the CASPIR dewar, the dichroic mirror, the calibration lamp module, the IMB X-Y stage, and the Tip-Tilt dewar.

4.3 The Array and Its Read-out Methods

The detector is an SBRC CRC463 256×256 InSb array which is sensitive from ~ 0.9 μm to ~ 5.5 μm. The array has four output channels corresponding to four interlaced columns (12341234…). The array is controlled by the SBRC ACE2 drive electronics which is mounted close to the CASPIR dewar.

Communications with the ACE2 is through an RS-232 connection to MOPRA (Figure 20).

The CRC463 is a hybrid device in which the InSb detector material is bump-bonded to a silicon multiplexer through indium bumps. The multiplexer is a switched FET read-out device, which operates differently to a CCD. The circuit schematic is shown in Figure 24. Each pixel (or unit cell) contains four FETs; the two row select FETs and the reset FET (marked SW in Figure 24) are switches which can be thought of as closed when activated. The fourth FET (marked SF in Figure 24) acts as a source-follower amplifier which continuously samples the voltage on the detector node without affecting its value. Vgg provides a load for the unit cell source-follower FET. This load FET (marked SFL in Figure 24) is located in the column biasing circuitry. The output FET (also marked SF in Figure 24) acts as a second source-follower amplifier with its external 10 KΩ load resistor in the ACE2 electronics rack. The two column select FETs also act as switches.

Pixels in the array are sequentially addressed by pulsing column and row shift registers which activate the column and row select FET switches. Once a pixel is selected, the voltage on the detector node can be non-destructively read via the source-follower amplifier signal train, and the detector node voltage can then be optionally reset to Vdduc by activating the reset FET switch by pulsing the Φrst clock line. Note that the stored charge is not transferred across the array like a CCD. Instead each pixel is sequentially reset and read. This results in a time delay in the integration window across the array of one frame readout time between the first and last pixels.

The array readout scheme permits the use of a variety of readout methods which are now described.

4.3.1 Readout Method 1: Fast Sampling

In the fastest readout method, speed is considered more important than accuracy so we take only one sample per pixel and reference this voltage to electrical ground (Vss). The detector node voltage applicable in readout method 1 is shown schematically in Figure 25. The unit cell is reset, integrated, and sampled once at the end of the integration ramp.

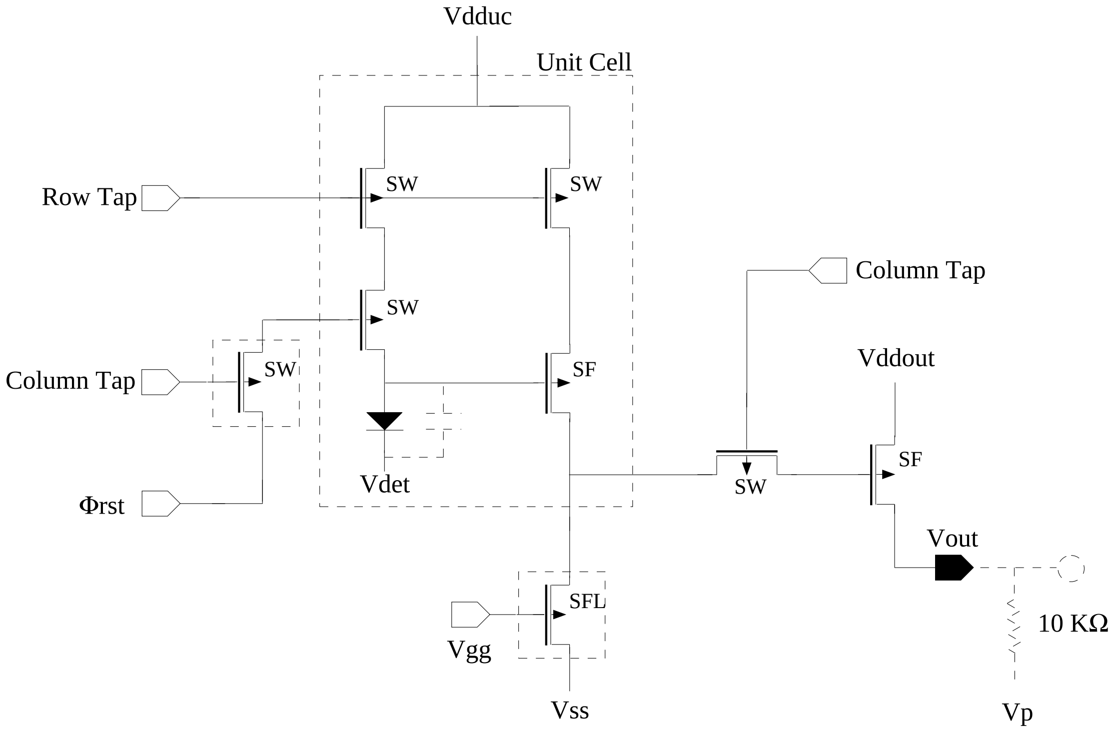


Figure 24: SBRC CRC463 detector array unit cell.

This method should be used for imaging in the 3–4 μm band and at M where the high thermal background flux significantly fills the detector wells in of order the frame readout time. In this situation, the dominant noise source is photon shot noise from the background flux, so readout noise is not an issue.

The minimum readout time for this method is 0.2 sec.

4.3.2 Readout Method 2: Relative Sampling

Under less extreme background conditions, significant improvement in stability can be made by referencing the signal level to the reset level, instead of electrical ground. This is done in readout method 2. The detector node voltage applicable to readout method 2 is shown schematically in Figure 26.

Note that the detector node voltage jumps when the reset FET is switched off, and this pedestal level is not removed in readout method 2. The pedestal level is different for each pixel in the array so this imprints a pedestal structure on the image, which is difficult to remove completely. The uncertainty in the value of this pedestal is known as kTC noise.

For direct imaging through broad band filters with high sky levels, the dominant noise source is still the photon shot noise of the background flux so readout method 2 gives acceptable performance.

The minimum readout time for this method is 0.3 sec.

4.3.3 Readout Method 3: Double-Correlated Sampling

The pedestal structure can be removed using a readout method which references the detector node voltage at the end of the integration to the voltage at the beginning of the integration. The detector node voltage applicable to readout method 3 is shown schematically in Figure 27.

In principle, this readout method is susceptible to electrical 1/f noise since it differences two samples separated in time by the duration of the integration. In practice, this is unlikely to be an important noise source.

This is the preferred readout method for broad band imaging because it does not imprint the pedestal pattern on the data.

The minimum readout time for this method is 0.4 sec.

4.3.4 Readout Method 4: Triple Correlated Sampling

The potential 1/f noise problem with readout method 3 can be overcome, at the expense of two more reads, by referring both the start and end reads to their respective reset levels. The detector node voltage applicable to readout method 4 is shown schematically in Figure 28.

Naively, this should be the most accurate readout method to adopt. However, we must now delve into the more obscure operating characteristics of the CRC463 array to see why other effects dominate.

4.3.5 Readout Method 5: Fowler Sampling

The FET switches in the CRC463 multiplexer are not perfect switches as assumed above, but instead have finite gate capacitances that act as sinks of charge that would otherwise remain on the detector node capacitance. The reset pedestal (i.e., the amount the detector node voltage jumps by when the reset is taken off) is due to a redistribution of charge from the detector node capacitance to the reset FET gate capacitance that occurs when the the reset FET gate voltage (i.e., the reset clock voltage) moves positive to switch the reset FET off. This amounts to $\sim$ 100 mV of lost detector reverse bias (or well depth). Similarly, a further $\sim$ 400 mV of detector bias is lost when the row and column select FETs are switched off to deselect the pixel. This constitutes a movement of $\sim$ 500 mV of charge off the detector node compared to the normal operating detector reverse bias that remains of only $\sim$ 200 mV. The *true* pedestal is therefore significantly larger than the reset pedestal seen if each pixel is reset and read on one pass through the array.

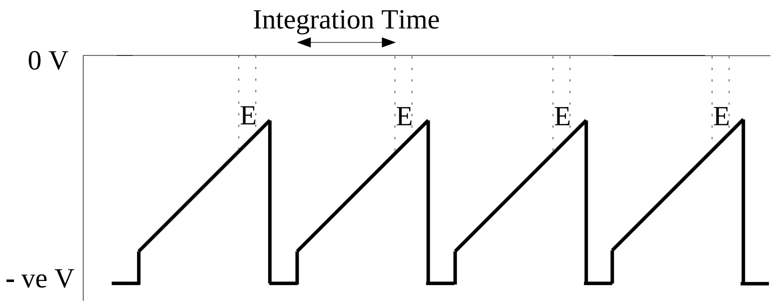


Figure 25: Detector node voltage applicable to readout method 1.

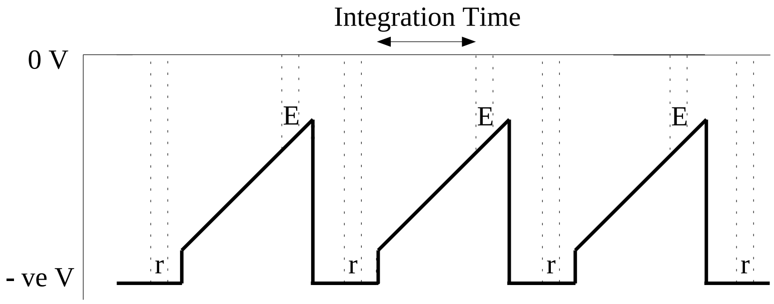


Figure 26: Detector node voltage applicable to readout method 2.

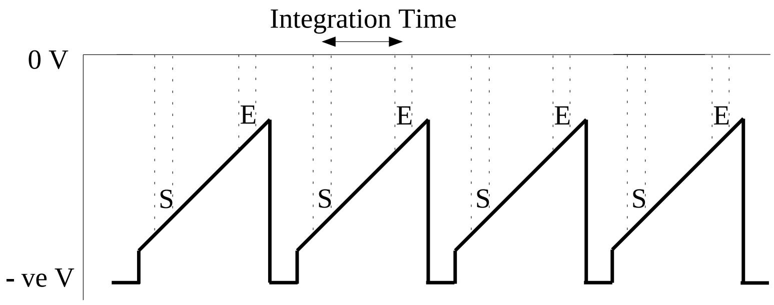


Figure 27: Detector node voltage applicable to readout method 3.

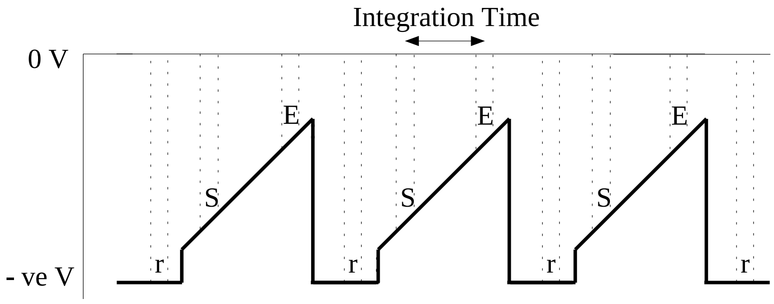


Figure 28: Detector node voltage applicable to readout method 4.

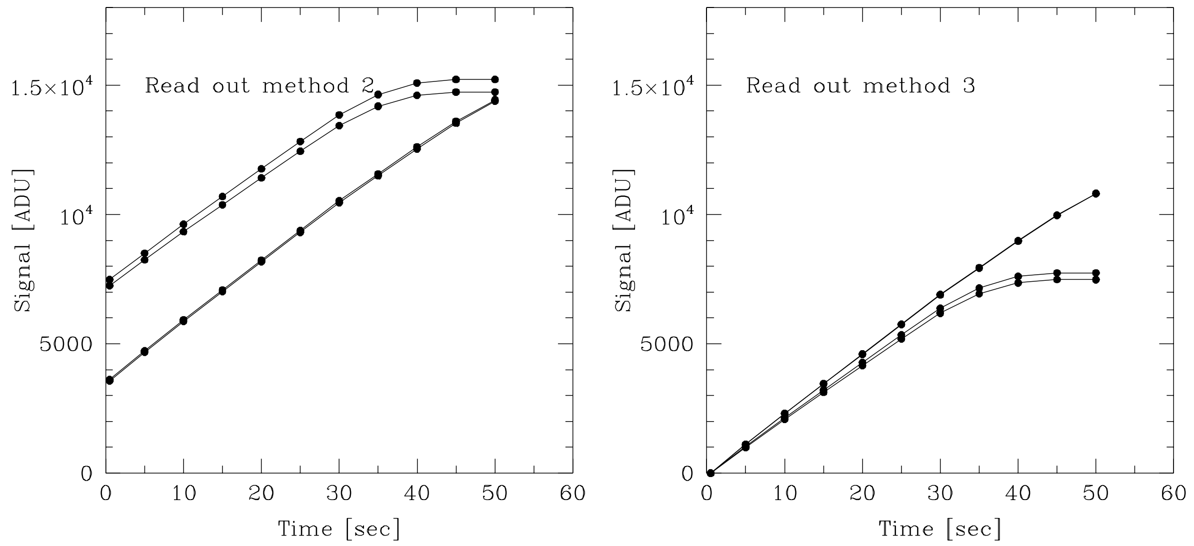


Figure 29: Raw linearity curves for readout method 2 (*left*) and readout method 3 (*right*). The signal levels for the four output amplifiers are plotted separately. Saturation occurs at a well depth of ~ 6500 ADU.

Fowler & Gatley (1990, ApJ, 353, L33) show that the read noise can be reduced by performing multiple non-destructive passes through the array at the beginning and end of the integration ramp. By resetting each pixel on one pass through the array, and sampling the detector node voltage on subsequent passes through the array, the *true* pedestal is removed from the data. Each time a pixel is selected charge is redistributed from the row and column select FETs back onto the detector node capacitance. Fowler claims that the read noise is predominantly due to the kTC noise associated with this charge redistibution. By performing multiple non-destructive passes through the array at the beginning and end of the integration, the read noise is reduced by the square root of the number of passes.

Readout Method 5 implements Fowler sampling in this way. The number of reads at each end of the integration is set by the FNDR parameter (`CASPIR/FNDR=...`). For applications where low read noise is required, at the expense of increased frame readout time, method 5 is the preferred readout method. This is likely to be the case when using the grisms.

4.3.6 Well Depth Considerations

The detector node capacitance for the CRC463 array is ~ 0.06 pF. The well depth is then proportional to the actual reverse bias voltage across the detector; $q = CV$. Consequently, a detector reverse bias of ~ 160 mV is required for a well depth of 60,000 e. Our array has an odd-even column effect which causes the applied detector reverse bias on even columns to be lower than that on odd columns. This means that even columns have well depths ~ 80% smaller than odd columns.

Raw linearity curves for readout methods 2 and 3 are plotted in Figure 29 for an applied reverse bias of 600 mV. These show that saturation becomes severe at signal levels $\geq$ 6500 ADU, corresponding to a well depth of 58500 e^-.

4.3.7 Linearity Correction

When the bias-subtracted linearity data in Figure 29 are plotted as signal rates (Figure 30), it is apparent that the CASPIR array has a quadratic non-linearity that must be allowed for during data reduction. The best description of this non-linearity is currently given by the equation:

$$Linear\ Counts = Raw\ Counts + 6.4 \times 10^{-6} \times (Raw\ Counts)^2$$

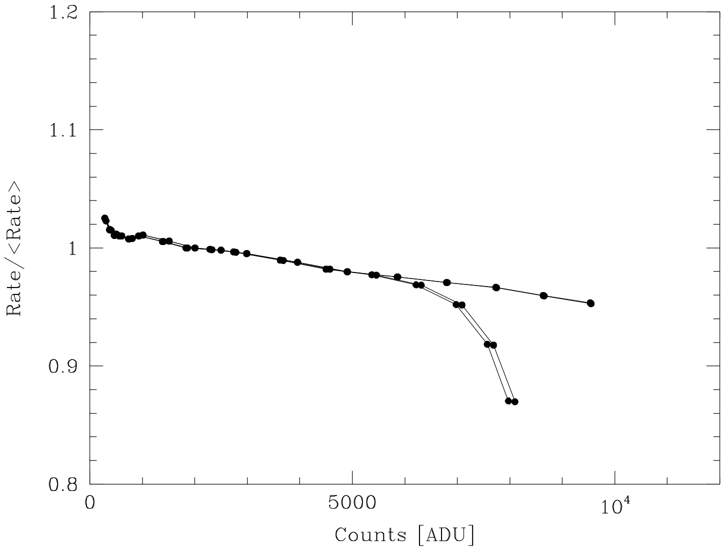


Figure 30: Raw linearity data for readout method 2 plotted as signal rate versus raw counts. The signal rates for the four output amplifiers are plotted separately. The raw data show a quadratic non-linearity.

It is possible that different quadratic coefficients apply to different pixels. Further investigation of this effect is required.

4.3.8 Setting Array Voltages

It should not be necessary for users to alter array voltages. However, the following description of the procedure is included for reference, and to describe some of the cosmetic features that indicate that adjustment is necessary.

Voltage adjustment is best done using the Idle Display and readout method 3. Ensure that the array has stabilized at its operating temperature of 32 K. All voltages are negative, but absolute values are discussed here, i.e., increasing a voltage means make it a bigger negative number. Look at something bright (the dome) with $0.5''$ pixels and the $5'' \times 15''$ grism slit so that the illuminated pixel saturate. Look for a dark vertical stripe down the full length of the array at the location of the slit. If this is seen, increase V3 to remove it. Now look for a brightening at the left hand side of the top array row in the Idle Display and a darkening of the middle of the bottom array row. If this is seen, decrease V3. V3 must be made small enough to remove the edge row effects, but large (i.e., negative) enough so as not to have vertical darkening around saturated objects. Now reduce Vgg(on) until the vertical darkening reappears, and increase it again so the vertical darkening has just disappeared.

The default array voltages are read from the file IR_CASPIR:ARRAY_PAR.DAT. This file must be edited if new array voltages are to be set on startup.

4.4 Transputer Preprocessor

CASPIR is designed to operate in the high background conditions encountered at long wavelengths. It uses four 16-bit 500 kHz analog-to-digital converters to digitize the data, with the rest of the data train being capable of sustained data rates of at least 2 μs/pixel. The requirement that individual frames be coadded at this data rate to build up the image means that the data cannot be input directly into MOPRA. Instead a transputer-based preprocessor is used.

A transputer is a fast microprocessor chip with considerable in-built parallelism and which uses four fast serial "links" for I/O. Each link can be connected to another transputer, or to an external device through a "Link Adaptor", which is essentially a bi-directional serial to parallel converter. This architecture has made transputers popular in parallel computing applications.

The CASPIR system uses four transputer link adaptors on the ADC cards to serialise the data at the Cassegrain focus. Four serial lines then bring the signals to the Nasmyth Lab where the transputer preprocessor is located. This consists of four T800 transputer boards which each have 1 Mbyte of memory and each are responsible for processing the data from one serial line. The current frame is DMAd into transputer memory at the same time that the previous frame is being coadded to an accumulation array where the summed image is stored. After the requested number of coadd cycles, the accumulated image is divided by the number of coadd cycles, optionally has a bias frame subtracted and is divided by a flatfield frame, and is copied to MOPRA via a transputer link to Q-bus interface with the four separate data channels correctly interlaced to form the final image.

The result of each sequence of coadd cycles is displayed on MOPRA's workstation screen and is stored on MOPRA's disk. The individual frames from each cycle are not normally saved (this only occurs in the occultation observing mode).

4.5 Instrument Mounting Box

All infrared dewars mount on a box attached to the Cassegrain focus of the 2.3 m telescope that is known as the Instrument Mounting Box (IMB; see Fig. 23). Two dewars can mount on the IMB at the same time and a dichroic mirror in the IMB can be positioned to direct infrared light from the telescope to either dewar. The IMB output ports are identified by the labels A–D. From the Cassegrain Access Platform, with the control electronics racks on your left, the port positions facing you is 'A', the one to your right (not used) is 'B', the back position is 'C', and the control electronics mount on face 'D'. A dichroic refexer directs the infrared beam to the selected IMB port while an acquisition system views the same field in optical light. Auxiliary modules can be mounted above the dichroic reflexer in the IMB. A calibration lamp module is available, and a polarimetry module is under construction.

A manual dust cover is located in the mounting flange at the top of the IMB. The open and closed positions are clearly marked on the flange, and *it should be used.*

4.5.1 Acquisition System

The IMB acquisition system contains the Tip-Tilt sensor mounted on an X-Y stage at the bottom of the IMB. This system views the telescope field in optical light through the dichroic reflexer, and allows offset guiding and selection of bright tip-tilt reference stars. The optical transmission function of the dichroic mirror is plotted in Figure 59 in Appendix L. The travel of the X-Y stage is $\sim \pm 31.2$ mm in each direction in the f/18 ($5''$/mm) telescope beam. A focussing unit mounted on the X-Y stage directly in front of the Tip-Tilt sensor changes the image scale, provides a pupil mask that acts as an optical sky baffle, and allows for focussing of the optical image independent of the infrared image.

4.5.2 Calibration Lamp Module

The calibration lamp module can be used to obtain wavelength calibration arc spectra. This is shown schematically in Figure 31. The module contains Xenon and Argon lamps as well as an incandescent lamp which may be useful for flatfielding. A rotary mirror is used to select one of the three lamps and a flip mirror is placed in the telescope beam to direct the lamp light to the detector.

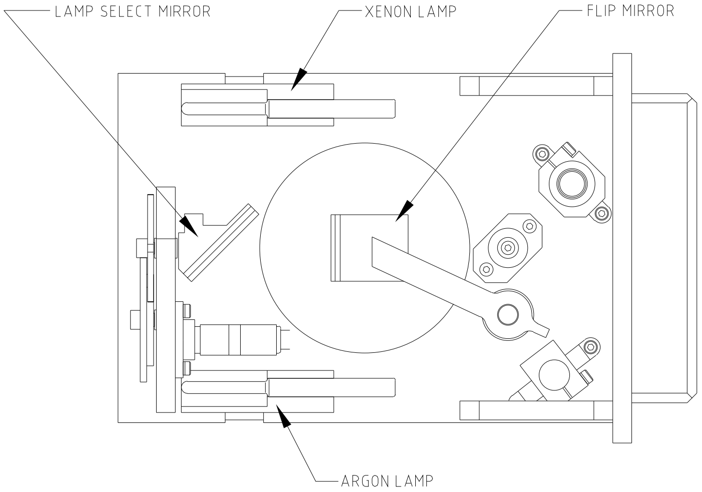


Figure 31: Schematic of the IMB calibration lamp module looking from above and showing the flip mirror, the lamp select mirror, and the xenon and argon lamps.

5 A Detailed Look at the Control Software

5.1 Control Environment

CASPIR is controlled by typing DCL commands into the Control window on the MOPRA workstation screen. A status window displays system parameters in its upper section and scrolls information in its lower section. Faults are displayed as flashing symbols on the bottom line of the Status Display window. Two image display windows are also provided. The upper display is the Idle Display, and the lower display is the Run Display. These both use a version of FIGDISP, the image display used with UNIX FIGARO. When no run is active, the system continuously takes data using idle readout parameters, and displays it in the Idle Display. This provides an almost real time display of the infrared sky which is useful for focusing and acquiring objects. When a data run is initiated (either by the CASPIR/RUN command or the CASPIR/DO command), the idle loop is interrupted and real integrations begin. On completion, the acquired data are displayed in the Run Display, and the system automatically returns to the idle loop.

The following sections describe this system in more detail. The CASPIR software is located in the directory with the logical name IR_CASPIR which has open read-only access.

5.2 The CASPIR Command

The CASPIR dewar is controlled through the CASPIR DCL command. The following subsections describe the command qualifiers used with the CASPIR command. When the infrared system is started, the command procedure in IR_CASPIR:CASPIR.COM is executed to make the composite definitions listed below. These are offerred to simplify the control operations. If any of these get inadvertantly redefined they can be deleted by typing, e.g.:

```
DELETE/SYMBOL FILTER
```

and then redefined by typing the appropriate line listed below.

```
f*ilter      :== caspir/filter=
uf*ilter     :== caspir/ufilter=
lf*ilter     :== caspir/lfilter=
a*perture    :== caspir/aperure=
u*tility     :== caspir/utility=
l*ens        :== caspir/lens=

mo*de        :== caspir/mode=
m*ethod      :== caspir/method=
t*ime        :== caspir/time=
c*ycles      :== caspir/cycles=
p*eriod      :== caspir/period=
re*peats     :== caspir/repeats=

im*ethod     :== caspir/imethod=
it*ime       :== caspir/it=
ic*ycles     :== caspir/icycles=
ip*eriod     :== caspir/iperiod=

r            :== caspir/run
b*ias        :== caspir/bias
d*ark        :== caspir/dark
do           :== caspir/do=
abort        :== caspir/abort

su*btract    :== caspir/subtract=
```

```
di*vide      :== caspir/divide=
isu*btract   :== caspir/isubtract=
idi*vide     :== caspir/idivide=

zmi*nimum    :== caspir/zminimum=
zma*ximum    :== caspir/zmaximum=
za*utoscale  :== caspir/zautoscale
izmi*nimum   :== caspir/izminimum=
izma*ximum   :== caspir/izmaximum=
iza*utoscale :== caspir/izautoscale

fa*st        :== caspir/apert=fastclr/util=clear/lens=fastcam/mode=direct
sl*ow        :== caspir/apert=fastclr/util=slowcam/lens=clear/mode=direct
jg*rism      :== caspir/apert=lslit1/ufilter=clear/util=j_grism/lfilter=clear-
                       /lens=fastcam/mode=direct
hg*rism      :== caspir/apert=lslit1/ufilter=clear/util=h_grism/lfilter=clear-
                       /lens=fastcam/mode=direct
kg*rism      :== caspir/apert=lslit1/ufilter=clear/util=k_grism/lfilter=clear-
                       /lens=fastcam/mode=direct
ijg*rism     :== caspir/apert=sslit1/ufilter=clear/util=ij_grism/lfilter=clear-
                       /lens=fastcam/mode=direct
jhg*rism     :== caspir/apert=sslit1/ufilter=clear/util=jh_grism/lfilter=clear-
                       /lens=fastcam/mode=direct
hkg*rism     :== caspir/apert=sslit1/ufilter=clear/util=hk_grism/lfilter=clear-
                       /lens=fastcam/mode=direct
grid*pol     :== caspir/apert=fastclr/ufilter=grid/util=clear/lens=fastcam-
                       /mode=polarimetry
pr*ismpol    :== caspir/apert=polar/util=wollaston/lens=fastcam/mode=polarimetry

j            :== caspir/filter=j/imethod=2/itime=5/icycles=1/method=2/time=5-
                       /cycles=12/repeats=1
h            :== caspir/filter=h/imethod=2/itime=5/icycles=1/method=2/time=5-
                       /cycles=12/repeats=1
k            :== caspir/filter=k/imethod=2/itime=5/icycles=1/method=2/time=5-
                       /cycles=12/repeats=1
kp           :== caspir/filter=kp/imethod=2/itime=5/icycles=1/method=2/time=5-
                       /cycles=12/repeats=1
kn           :== caspir/filter=kn/imethod=2/itime=5/icycles=1/method=2/time=5-
                       /cycles=12/repeats=1
nbl          :== caspir/filter=cont3.6/imethod=1/itime=0.2/icycles=50/method=1-
                       /time=0.2/cycles=300/repeats=1
Helium       :== caspir/filter=helium/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
PGamma       :== caspir/filter=pgamma/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
PBeta        :== caspir/filter=pbeta/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
Cont16       :== caspir/filter=cont1.6/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
FeII         :== caspir/filter=feii/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
AAOFeII      :== caspir/filter=aaofeii/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
H2O          :== caspir/filter=h2o/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
H2_1_0       :== caspir/filter=h2_1_0/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
```

```
BrGamma      :== caspir/filter=brgamma/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
Cont22       :== caspir/filter=cont2.2/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
H2_2_1       :== caspir/filter=h2_2_1/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
CONB         :== caspir/filter=co/imethod=2/itime=5/icycles=1/method=2-
                       /time=5/cycles=12/repeats=1
Ice          :== caspir/filter=ice/imethod=1/itime=0.2/icycles=50/method=1-
                       /time=0.2/cycles=300/repeats=1
Dust328      :== caspir/filter=dust3.28/imethod=1/itime=0.2/icycles=50/method=1-
                       /time=0.2/cycles=300/repeats=1
Dust34       :== caspir/filter=dust3.4/imethod=1/itime=0.2/icycles=50/method=1-
                       /time=0.2/cycles=300/repeats=1
Cont36       :== caspir/filter=cont3.6/imethod=1/itime=0.2/icycles=50/method=1-
                       /time=0.2/cycles=300/repeats=1
Cont40       :== caspir/filter=cont4.0/imethod=1/itime=0.2/icycles=50/method=1-
                       /time=0.2/cycles=300/repeats=1
BrAlpha      :== caspir/filter=bralpha/imethod=1/itime=0.2/icycles=50/method=1-
                       /time=0.2/cycles=300/repeats=1
```

5.2.1 CASPIR/APERTURE=position

Moves the aperture wheel to the specified position. The position may be specified by a number in the range 1–16, or by name. The position names are:

```
Blank,      FastClr,    SlowClr,
Sslit1,     Sslit1.5,   Sslit2,     Sslit5,     Sslit10,
Lslit1,     Lslit1.5,   Lslit2,     Lslit5,     Lslit10,
Disk2,      Disk5,      Polar
```

These names may be abbreviated.

5.2.2 CASPIR/UTILITY=position

Moves the utility wheel to the specified position. The position may be specified by a number in the range 1–16, or by name. The position names are:

```
Align,      Clear,      Wollastn,   SlowCam,    Mask,
J_grism,    H_grism,    K_grism,
IJ_grism,   JH_grism,   HK_grism,
Foccal,     Focus,      Hart2,      Hart1,      BigClear
```

These names may be abbreviated.

5.2.3 CASPIR/FILTER=desired_filter

Moves both filter wheels in combination to select the desired filter. This is equivalent to entering /UFILTER=pos1/LFILTER=pos2, where "pos1" and "pos2" make up a sensible combination. The desired_filter may be specified by name, which is one of the following:

```
Blank,             J,                 H,                 K,
KP,                KN,                L,                 M,
Helium (NB108),    PGamma (NB109),    PBeta (NB128),     Cont1.6,
FeII (NB164),      AAOFeII (NB165),   H2O (NB199),       H2_1_0 (NB212),
BrGamma (NB217),   Cont2.2 (NB222),   H2_2_1 (NB225),    CO (NB236),
Ice (NB310),       Dust3.28 (NB328),  Dust3.4 (NB340),   Cont3.6 (NB360),
Cont4.0 (NB400),   BrAlpha (NB405),   Grid,              Focus
```

These names may be abbreviated. Alternative names for a position are shown in parentheses. This qualifier cannot be specified with the /UFILTER qualifier or the /LFILTER qualifier.

5.2.4 CASPIR/UFILTER=position

Moves the upper filter wheel to the specified position. Normally, the two filter wheels are set using the /FILTER qualifier; this qualifier is provided to allow unusual settings of the upper filter wheel. The position may be specified by a number in the range 1–16, or by name. The position names are:

```
Blank,             Clear,             Helium (NB108)     PGamma (NB109),
PBeta (NB128),     FeII (NB164),      AAOFeII (NB165),   H2O (NB199),
H2_1_0 (NB212),    BrGamma (NB217),   Cont2.2 (NB222),   H2_2_1 (NB225),
CO (NB236),        Cont1.6,           Grid,              Focus
```

These names may be abbreviated. Alternative names for a position are shown in parentheses. This qualifier cannot be specified with the /FILTER qualifier.

5.2.5 CASPIR/LFILTER=position

Moves the lower filter wheel to the specified position. Normally, the two filter wheels are set using the /FILTER qualifier; this qualifier is provided to allow unusual settings of the lower filter wheel. The position may be specified by a number in the range 1–16, or by name. The position names are:

```
Blank,             Clear,             J,                 H,
KP,                KN,                K,                 L,
Ice (NB310),       Dust3.28 (NB328),  Dust3.4 (NB340),   Cont3.6 (NB360),
Cont4.0 (NB400),   BrAlpha (NB405),   M,                 PK50
```

These names may be abbreviated. Alternative names for a position are shown in parentheses. This qualifier cannot be specified with the /FILTER qualifier.

5.2.6 CASPIR/LENS=position

Moves the lens wheel to the specified position. The position may be specified by a number in the range 1–4, or by name. The position names are:

```
Blank,             FastCam,             Blank3,            Clear
```

These names may be abbreviated.

5.2.7 CASPIR/STATUS_NOW

The /STATUS_NOW qualifier causes CASPIR to interrogate the LSI-11/23 for the current wheel positions and their status and updates the Status Display accordingly.

5.2.8 CASPIR/[NO]REPORT

The /REPORT qualifier asks CASPIR to report (with a message to the IR status display) when each wheel arrives at its requested position. The /NOREPORT qualifier turns off wheel position reporting.

5.2.9 CASPIR/MODE=mode_number

Sets the observing mode to be used. The observing modes describe different ways in which the data-taking occurs, and may be specified as a number in the range 1–2, or by name. The observing mode names are:

```
Direct_Imaging,   Nod
```

In Direct_Imaging mode, single exposures are obtained for each run.

In Nod mode, successive exposures are obtained in an ABBA pattern at two positions on the sky defined by telescope focal plane *apertures* named N1 and N2. This is designed for use with the grisms. The number of AB pairs obtained is set by the REPEATS parameter which can be changed during data acquisition. If the SHOW parameter has been set to CURRENT with a `CASPIR/SHOW=CURRENT` command, the current A-B difference is displayed in the Run Display. If the SHOW parameter has been set to MEAN with a `CASPIR/SHOW=MEAN` command, the average of the accummulated difference images is displayed in the Run Display.

5.2.10 CASPIR/IMETHOD=method_number

Sets the integration method to be used when CASPIR is idling. This must be set as a value in the range 1–5, where the methods are as follows:

```
1 = Fast
2 = Absolute
3 = Double Correlated
4 = Triple Correlated
5 = Fowler Sampling
```

5.2.11 CASPIR/ICYCLES=cycle_count

Sets the number of coadd cycles to perform for each image CASPIR is to obtain when idling. Cycle_count should be an integer in the range 1–4095.

5.2.12 CASPIR/ITIME=time_value

Sets the integration time in seconds for each cycle, to be used when CASPIR is idling.

5.2.13 CASPIR/IFNDR=read_count

Sets the number of non-destructive reads performed at the beginning and end of an integration when using Fowler read-out methods, to be used when CASPIR is idling. This value is ignored for non-Fowler methods.

5.2.14 CASPIR/IPERIOD=time_value

Sets the read period (in units of seconds) for non-destructive reads within each integration cycle when using the linear fitting read-out method, to be used when CASPIR is idling. This value is not currently used (see /IFNDR instead).

5.2.15 CASPIR/METHOD=method_number

Sets the integration method to be used when CASPIR carries out its next run. This must be set as a value in the range 1–5, where the methods are as follows:

```
1 = Fast
2 = Absolute
3 = Double Correlated
4 = Triple Correlated
5 = Fowler Sampling
```

5.2.16 CASPIR/CYCLES=cycle_count

Sets the number of integration cycles to perform for each image CASPIR is to obtain on its next run. Cycle_count should be an integer in the range 1–4095.

5.2.17 CASPIR/TIME=time_value

Sets the integration time in seconds for each cycle, to be used on CASPIR's next run.

5.2.18 CASPIR/FNDR=read_count

Sets the number of non-destructive reads performed at the beginning and end of an integration when using Fowler read-out methods, to be used on CASPIR's next run. This value is ignored for non-Fowler methods.

5.2.19 CASPIR/PERIOD=time_value

Sets the read period (in units of seconds) for non-destructive reads within each integration cycle when using the linear fitting read-out method, to be used on CASPIR's next run. This value is not currently used (see /FNDR instead).

5.2.20 CASPIR/REPEATS=repeat_count

Sets the number of images to be obtained (i.e the number of data files to be written) at the next run. Each image consists of CYCLES coadds of frames with an integration time of TIME seconds.

5.2.21 CASPIR/RUN

The /RUN qualifier starts a run. A data file with name IRxxx (where xxx is the current run number) will be written at the end of the run. If REPEATS is set to more than one, more than one data file will be written, and xxx will be incremented for each one.

5.2.22 CASPIR/DARK

The /DARK qualifier takes a dark frame. That is, it starts a run, but it sets filter and aperture wheels to their blank positions to exclude light first. A file is written, just as for /RUN. The Filter and Aperture wheels are returned to their original positions when the run completes successfully.

5.2.23 CASPIR/BIAS

The /BIAS qualifier takes a bias frame. That is, it starts a run, but it sets filter and aperture wheels to their blank positions to exclude light first (just as does /DARK) and it sets integration time to the minimum possible for the selected readout method. A file is written, just as for /RUN. The Filter and Aperture wheels are returned to their original positions when the run completes successfully.

5.2.24 CASPIR/DO=filespec

This qualifier specifies a text file in the directory defined by the logical name IR_DO containing instructions for taking data frames automatically. On startup, IR_DO points to the default directory DATADISK:[INFRARED]. The file can also contain comment lines (lines beginning with the "!" character), which may appear anywhere in the file.

The file type, if not specified, is assumed to be ".DO".

The format of each instruction line is as follows:

```
COMMAND Object_Name RA_Offset Dec_Offset Method Cycles Time Fndr -
 Repeats Aperture Ufilter Utility Lfilter Lens Filter Period Tiptilt -
 Stage_Offset Track_Coord Guide_Coord GRA_Offset GDec_Offset TTX TTY -
 TTDX TTDY AcqX AcqY AcqDX AcqDY TT_Mode TT_ATime TT_GTime TT_CTime -
 TT_Find TT_Error
```

The syntax of the instruction lines is flexible. The COMMAND item must appear, and it must be one of "RUN", "BIAS" or "DARK". All other items are optional. Items may be separated by spaces and/or commas; if items are omitted, commas are required to identify the missing item (but note that COMMAND ,,,,, will interpret the commas as the object name). A "-" character at the end of a line indicates that the instruction is continued on the next line.

Items may also be specified non-positionally, using a ITEM_NAME=value syntax. This is the most convenient way of formatting an instruction when only a few items need be specified. For example:

```
RUN  Object_1, TIME = 15  CYCLES = 2  FILT=K
```

If the command is BIAS or DARK, then the Aperture, Ufilter, Utility, Lfilter, Lens and Filter items must not be specified. If the command is BIAS, the Time item must not be specified. If the command is RUN, the Filter item cannot be specified if either the Ufilter or Lfilter items is present.

The items in detail:

`COMMAND`	`"RUN", "BIAS" or "DARK".`
`Object_Name=`	`Character string.`
`RA_Offset=`	`Offset in Right Ascension to move telescope to, before taking data (arcseconds).`
`Dec_Offset=`	`Offset in Declination (arcseconds).`
`Method=`	`Integration (readout) method (integer, range 1-7).`
`Cycles=`	`Number of transputer co-add cycles.`
`Time=`	`Exposure time (seconds).`
`Fndr=`	`Number of Fowler non-destructive reads.`

```
Repeats=          Number of repeats of integration sequence.
Aperture=         Aperture wheel position.
Ufilter=          Upper Filter wheel position.
Utility=          Utility wheel position.
Lfilter=          Lower Filter wheel position.
Lens=             Lens wheel position.
Filter=           Combined Upper and Lower Filter wheel position.
Period=           Non-destructive read period (seconds) [not used].
Tiptilt           Enable Tip-Tilt operation.
NoTipTilt         Disable Tip-Tilt operation.
Stage_Offset      Enables IMB X-Y stage motion.
NoStage_Offset    Disables IMB X-Y stage motion.
Track_Coord=      Track on a new object coordinate specified as a text string
                    delimited by double quotes.  The string format is as for
                    the telescope TRACK/COORD command.  No object name can be
                    present; use the ``Object_Name'' DO file command instead.
                    The telescope returns to the original tracking coordinate
                    at the end of the DO file.
Guide_Coord=      Defines a new guide star coordinate specified as a text
                    string delimited by double quotes.  The string format is
                    as for the telescope TRACK/COORD command.  No object name
                    can be present.  The guide coordinates return to their
                    original values at the end of the DO file.
GRA_Offset=       Defines guide star offset in arcsec in RA as a floating point
                    number.  The guide coordinate returns to its original
                    value at the end of the DO file.
GDec_Offset=      Defines guide star offset in arcsec in Dec. as a floating
                    point number.  The guide coordinate returns to its original
                    value at the end of the DO file.
TTX=              X coordinate of Tip-Tilt correct subframe center in integer
                    units of CCD pixels.
TTY=              Y coordinate of Tip-Tilt correct subframe center in integer
                    units of CCD pixels.
TTDX=             X size of Tip-Tilt correct subframe in integer units of CCD
                    pixels.  Permitted values are 8, 10, 12, 16.
TTDY=             Y size of Tip-Tilt correct subframe in integer units of CCD
                    pixels.  Permitted values are 8, 10, 12, 16.
AcqX=             X coordinate of Tip-Tilt acquire subframe center in integer
                    units of CCD pixels.
AcqY=             Y coordinate of Tip-Tilt acquire subframe center in integer
                    units of CCD pixels.
AcqDX=            X size of Tip-Tilt acquire subframe in integer units of CCD
                    pixels.  Permitted values are 8, 10, 12, 16.
AcqDY=            Y size of Tip-Tilt acquire subframe in integer units of CCD
                    pixels.  Permitted values are 8, 10, 12, 16.
TT_Mode=          Tip-Tilt operation mode specified as one of ``correct'',
                    ``guide'', ``acquire'', or ``recalibrate''.  Tip-Tilt is
                    left in acquire mode at the end of the DO file.
TT_ATime=         Specifies acquire mode integration time in ms as a floating
                    point number.  Remains in effect when DO file completes.
TT_GTime=         Specifies guide mode integration time in ms as a floating
                    point number.  Remains in effect when DO file completes.
TT_CTime=         Specifies correct mode integration time in ms as a floating
                    point number.  Remains in effect when DO file completes.
TT_Find           Enables Auto-Acquire mode.
NOTT_Find         Disables Auto-Acquire mode.
TT_Error          Do not abort on Tip-Tilt errors.
```

```
NOTT_Error        Abort DO file if Tip-Tilt errors encountered.
```

5.2.25 CASPIR/[NO]TIPTILT

The /[NO]TIPTILT qualifier controls the use of the 2.3 m Cassegrain Tip-Tilt secondary mirror image correction system. The /TIPTILT qualifier enables control of tip-tilt image correction by DO file commands and in NOD mode. The /NOTIPTILT qualifier causes DO file tip-tilt commands and NOD mode tip-tilt commands to be ignored.

5.2.26 CASPIR/[NO]STAGE_OFFSET

If the TIPTILT parameter is set, the /STAGE_OFFSET qualifier causes the IMB X-Y stage to be moved in an opposite sense to the telescope during R.A. and Dec. offsets performed within a DO file. By doing so, the reference star is repositioned at the reference position on the tip-tilt sensor to allow guiding or correction on the same object. If the Tip-Tilt system is operated in guide or correct mode, the mosaic offsets will then be defined by the IMB X-Y stage positions, and accurate registration of the images should be possible using the OFFRA and OFFDEC parameters in the FITS file header. The /NOSTAGE_OFFSET qualifier disabled IMB X-Y stage motion. The Tip-Tilt system then attempts to move the correction subframe on the Tip-Tilt sensor to compensate for telescope offsets. If the TIPTILT parameter is not set, the STAGE_OFFSET parameter is ignored.

5.2.27 CASPIR/XY_SCALE_FACTOR=value

Sets the multiplicative scale factor applied to nominal IMB X-Y stage offsets to accurately move the X-Y stage by the required angular distance on the sky. The nominal image scale for the X-Y stage is $5''$/mm.

5.2.28 CASPIR/ABORT

The /ABORT qualifier aborts the current run and DO sequence.

5.2.29 CASPIR/ISUBTRACT=filename

Reads an image data file from IR_DATA: and downloads it to the transputers. They will subtract the image from every idle mode image that is uploaded to the VAX for display. This is used for sky subtraction. Specify a filename of 'none' to switch off subtraction.

5.2.30 CASPIR/IDIVIDE=filename

Reads an image data file from IR_DATA: and downloads it to the transputers. They will divide every idle mode image by this image before uploading it to the VAX for display. This is used for flatfield correction. Specify a filename of 'none' to switch off division.

5.2.31 CASPIR/IZMINIMUM=value

Lower bound for transputers to use when scaling idle mode data for display. This qualifier turns off idle Z autoscaling. It cannot be specified with the /ZAUTOSCALE qualifier.

5.2.32 CASPIR/IZMAXIMUM=value

Upper bound for transputers to use when scaling idle mode data for display. This qualifier turns off idle Z autoscaling. It cannot be specified with the /ZAUTOSCALE qualifier

5.2.33 CASPIR/[NO]IZAUTOSCALE

The /IZAUTOSCALE qualifier forces the transputers to calculate appropriate values for IZMINIMUM and IZMAXIMUM automatically. It cannot be specified with the /IZMINIMUM or /IZMAXIMUM qualifiers. The /NOIZAUTOSCALE qualifier turns off automatic calculation of minimum and maximum values.

5.2.34 CASPIR/SUBTRACT=filename

Reads an image data file from IR_DATA: and downloads it to the transputers. They will subtract the image from every run mode image that is uploaded to the VAX for display. This is used for sky subtraction. Specify a filename of 'none' to switch off subtraction. Data written to the data file does not have this subtraction performed.

5.2.35 CASPIR/DIVIDE=filename

Reads an image data file from IR_DATA: and downloads it to the transputers. They will divide every run mode image by this image before uploading it to the VAX for display. This is used for flatfield correction. Specify a filename of 'none' to switch off division. Data written to the data file does not have this subtraction performed.

5.2.36 CASPIR/ZMINIMUM=value

Lower bound for transputers to use when scaling run mode data for display. This qualifier turns off Z autoscaling. It cannot be specified with the /ZAUTOSCALE qualifier

5.2.37 CASPIR/ZMAXIMUM=value

Upper bound for transputers to use when scaling run mode data for display. This qualifier turns off Z autoscaling. It cannot be specified with the /ZAUTOSCALE qualifier

5.2.38 CASPIR/[NO]ZAUTOSCALE

The /ZAUTOSCALE qualifier forces the transputers to calculate appropriate values for ZMINIMUM and ZMAXIMUM automatically. It cannot be specified with the /ZMINIMUM or /ZMAXIMUM qualifiers. The /NOZAUTOSCALE qualifier turns off automatic calculation of minimum and maximum values.

5.2.39 CASPIR/SHOW=image_name

This qualifier selects the type of image that is to be displayed on the CASPIR Run Display. The image names available are:

```
CURRENT  - the most recently obtained frame.
MEAN     - the mean of all repeats in the current run so far.
```

When Nod mode is used, selecting CASPIR/SHOW=MEAN causes average of the accummulated difference images to be displayed.

5.2.40 CASPIR/DISPLAY [=status_screen]

Requests that the IR Status display change to the specified display screen. Allowed values for status_screen are:

```
COMMUNICATIONS  - the IR communications display
MAIN            - the CASPIR main display
MISC            - the CASPIR miscellaneous display
VOLTAGES        - the CASPIR SBRC voltages display
```

Specifying /DISPLAY without supplying a value for status_screen is equivalent to specifying /DISPLAY=MAIN

5.2.41 CASPIR/INFORMATION

Requests that a copy of the CASPIR Main and Miscellaneous display screens be written to the terminal.

5.2.42 CASPIR/OBJECT_NAME=[string]

Sets the object name for the current (or next) run to the string supplied. The object name appears on the main CASPIR display screen, and is written to the data file at the end of the exposure. If /OBJECT_NAME is not specified, the object name obtained from the telescope system is used. This is the name that was in the coordinate file, or the name that was specified in the coordinate string supplied to the TRACK/COORDINATE command. If no object name is obtained from the telescope system, a default name is generated.

If /OBJECT_NAME is specified without supplying a string, any previously specified object name is cancelled and the name obtained from the telescope system (or a default name) used instead.

5.2.43 CASPIR/VOLTAGES [=keyword]

Reads back the array voltages from the SBRC box, or switches them off, or back on. Allowed values for voltages_keyword are:

```
READ, ON, and OFF.
```

If /VOLTAGES is specified without a keyword, it is equivalent to /VOLTAGES=READ.

This qualifier cannot be specified with the /DETECTOR, /CSET, /BSET, /VPREAMP, /VSIGOFF or /VREFOFF qualifiers.

5.2.44 CASPIR/BSET=(bias_line=bias_voltage [,...])

Sets the specifed bias voltage(s) to the specified value(s). Allowed values for bias_line are:

```
VDDOUT_ON,  VDDOUT_OFF, VDDUC,      VGG_ON,     VGG_OFF,
VDET,       V3
```

This qualifier cannot be specified with the /VOLTAGES qualifier.

5.2.45 CASPIR/CSET=(clock_name=(high_voltage, low_voltage), [,...])

Sets the high and low voltages of the specified clock(s) to the specified values. Allowed clock names are:

```
PHI_SYNC_SLOW,    PHI_1_SLOW,       PHI_2_SLOW,
PHI_SYNC_FAST,    PHI_1_FAST,       PHI_2_FAST,
PHI_RESET
```

This qualifier cannot be specified with the /VOLTAGES qualifier.

5.2.46 CASPIR/DETECTOR=detector_state

The qualifier /DETECTOR=SHORTED sets the SBRC voltages to OFF, and shorts out the detector (leaving it in a electrically safe state). The qualifier /DETECTOR=ENABLED re-enables the detector for normal observing.

This qualifier cannot be specified with the /VOLTAGES, /BSET, or /CSET qualifiers.

5.2.47 CASPIR/VPREAMP=value

Sets the Preamp Reset voltage. This qualifier cannot be specified with the /VOLTAGES qualifier.

5.2.48 CASPIR/VREFOFF=value

Sets the Reference Offset voltage. This qualifier cannot be specified with the /VOLTAGES qualifier.

5.2.49 CASPIR/VSIGOFF=value

Sets the Signal Offset voltage. This qualifier cannot be specified with the /VOLTAGES qualifier.

5.2.50 CASPIR/[NO]DEBUG

Turns debugging messages on or off.

5.2.51 CASPIR/HIBERNATE

Causes CASPIR to relinquish ownership of the IR system and go to sleep.

5.2.52 CASPIR/INITIALIZE

Reloads SBRC voltages and analog settings from the array parameter file.

5.2.53 CASPIR/LCA

Downloads a new LCA file to the SBRC box.

5.2.54 CASPIR/TIMING=filename

Downloads a new timing file to the SBRC box.

5.2.55 CASPIR/RSPEED=readout_speed

Sets the readout speed to the value specified. The value must be in the range 0–4095.

5.2.56 CASPIR/[NO]DIFFERENCE_MODE

The /DIFFERENCE_MODE qualifier changes the operating mode of CASPIR to a diagnostic mode in which the Current array (or ICurrent array) is automatically copied directly into the Subtract array (or ISubtract array) at the time that it is uploaded to the VAX. Used in conjunction with the /CHANNEL_STATISTICS qualifier, this enables the transputers to generate statistics about the difference between the current frame and the previous frame.

The /NODIFFERENCE_MODE qualifier restores normal operation.

5.2.57 CASPIR/[NO]CHANNEL_STATISTICS

The /CHANNEL_STATISTICS qualifier enables transputer statistics calculations. As each frame is uploaded from the transputers to the VAX, the transputers calculate and upload basic statistics, which are broadcast to the messages display. Used in conjunction with the /DIFFERENCE_MODE qualifier this can be useful for noise comparison tests.

The /NOCHANNEL_STATISTICS qualifier disables these calculations (i.e., restores normal operation).

5.2.58 CASPIR/[NO]SLOG

The /SLOG qualifier causes transputer statistics to be written to a file in the data directory. The /NOSLOG qualifier disables this.

5.2.59 CASPIR/GAIN=gain_value

Sets the combination of Preamp and Postamp Gains to achieve the requested gain value. Allowed gain values are:

```
2, 5, 10, 20, 50, 100
```

This qualifier cannot be specifed with the /PREAMP_GAIN qualifier or the /POSTAMP_GAIN qualifier.

5.2.60 CASPIR/POSTAMP_GAIN=gain_value

Sets the postamp gain to the value specified. Allowed values are:

```
1, 2, 5, 10
```

This qualifier cannot be specifed with the /GAIN qualifier.

5.2.61 CASPIR/PREAMP_GAIN=gain_value

Sets the preamp gain to the value specified. Allowed values are:

```
2, 5, 10
```

This qualifier cannot be specifed with the /GAIN qualifier.

5.2.62 CASPIR/ADC_BW=bandwidth

Sets the ADC bandwidth to the value specified. Allowed values are:

```
LOW,        MEDIUM,     HIGH
```

5.2.63 CASPIR/[NO]SIMULATE

Sets the transputers to simulate mode.

5.2.64 CASPIR/SIM0=filename

Loads the file into the transputers' "Simulate 0" array.

5.2.65 CASPIR/SIM1=filename

Loads the file into the transputers' "Simulate 1" array.

5.2.66 CASPIR/SIM2=filename

Loads the file into the transputers' "Simulate 2" array.

5.2.67 CASPIR/SIM3=filename

Loads the file into the transputers' "Simulate 3" array.

5.2.68 CASPIR/SIM4=filename

Loads the file into the transputers' "Simulate 4" array.

5.2.69 CASPIR/SIM5=filename

Loads the file into the transputers' "Simulate 5" array.

5.2.70 CASPIR/PORT=port_number

Tells the system which IMB port CASPIR is mounted on. This is usually determined by interrogating the hardware on startup.

5.2.71 CASPIR/[NO]TELESCOPE

If the system is being run in isolation from the telescope, the /NOTELESCOPE qualifier should be used to avoid attempts to issue telescope control commands.

5.3 The FIGDISP Image Displays

The Idle and Run image displays are based on the FIGDISP program used with UNIX FIGARO. In essence, they operate in a way which will be familiar to FIGARO users. However, some modifications have been necessary in porting the program to VMS. Specifically, in the function key definitions which control the program, and in the way the window is activated.

Under VMS, you must click in the window to make it active. Since FIGDISP will pan the image to that position if you click in the display part of the window, it works better clicking in the window title bar. Similarly, you must remember to click in the command entry window again before entering CASPIR commands.

The FIGDISP functions and their binding in the infrared environment are listed below. Consult the FIGDISP manual for further explanation of what they do.

```
Left button   - Pan the image.
Middle button - Display an arbitrary line plot between start and end points.
Right button  - Manipulate the color look-up tables.
F2            - Zoom in.
F3            - Reset to normal zoom factors.
F4            - Zoom out.
PF1           - Zoom in X coordinates.
PF2           - Zoom out X coordinates.
PF3           - Zoom in Y coordinates.
PF4           - Zoom out Y coordinates.
F5            - Print help text.
F6            - Toggle cursor display.
F7            - Re-center image.
F8            - Toggle display of the location window.
F10           - Toggle display of the color map window.
F11           - Toggle display of the pixel value window.
F12           - Display a row plot in the line graphics window.
F13           - Print the whole image.
F14           - Print the visible portion of the image.
F16           - Inhibit keystroke interpretation until this key is pressed again.
F18           - Toggle color map inversion.
F19           - Toggle display of centroid/FWHM window for star near cursor.
F20           - Display a column plot in the line graphics window.
,             - Decrease number of pixels averaged for a line plot.
.             - Increase number of pixels averaged for a line plot.
/             - Reset number of pixels averaged for a line plot.
```

5.4 Temperature Control

The CASPIR detector array must be held accurately at its operating temperature of 32 K. This is achieve by the use of a Lakeshore Cryotronics Model 330 temperature controller which is located on top of the Cassegrain Instrument Rack in the 2.3 m Nasmyth Lab. This controller can be configured through front panel controls, or via RS-232 commands. While the infrared control software is running, a subprocess continually monitors both the array temperature, which is actively servoed to a preset value, and a second temperature sensor attached to the camera body. These functions are controlled through the following DCL TEMPERATURE commands:

5.4.1 TEMPERATURE/ABORT

Aborts an attempt to access the Lakeshore controller.

5.4.2 TEMPERATURE/[NO]DEBUG

Turns debugging messages on or off.

5.4.3 TEMPERATURE/DISPLAY [=status_screen]

Requests that the IR Status Display change to the specified display screen. Allowed values for status_screen are:

```
COMMUNICATIONS - the IR communications display
MAIN           - the main temperature display
```

Specifying /DISPLAY without supplying a value for status_screen is equivalent to specifying /DISPLAY=MAIN.

5.4.4 TEMPERATURE/[NO]REPORT

The /REPORT qualifier causes the data for each temperature sample to be typed in the scrolled section of the Status Display. The /NOREPORT qualifier stops reporting of the temperature values.

5.4.5 TEMPERATURE/INFORMATION

Requests that a copy of the TEMPERATURE Status Display screen be written to the terminal.

5.4.6 TEMPERATURE/STATUS_NOW

Immediately samples the array and camera temperatures and types the data in the scrolling section of the Status Display.

5.4.7 TEMPERATURE/RESET

Resets the Lakeshore Cryotronics Model 330 Temperature Controller and resets the array set point and tolerance to their default values.

5.4.8 TEMPERATURE/CLEAR

Clears old temperature data in the disk file where temperature samples are saved.

5.4.9 TEMPERATURE/INTERVAL=time_value

Sets the interval between samples for the continuous monitoring of the camera and detector array temperatures. The sample interval is specified in units of minutes.

5.4.10 TEMPERATURE/SET_POINT=temperature_value

Defines the set point temperature for controlling the detector array temperature. The set point temperature is specified in units of °K. The array should always be operated at a temperature of 32 K.

UNDER NO CIRCUMSTANCES SHOULD YOU USE THE TEMPERATURE CONTROLLER TO HEAT THE ARRAY QUICKLY. THE HYBRID DETECTOR ARRAY CAN DELAMINATE AND THE CRYSTRAL OPTICS MAY CRACK IF TEMPERATURE CYCLED FASTER THAN 20 °K/hour. THE DEWAR HAS BEEN DESIGNED TO PASSIVELY TEMPERATURE CYCLE AT THE MAXIMUM SAFE RATE.

If you have reason to change the array temperature, do so in steps of $\sim$ 10 K and wait until the array temperature stabilizes at each step.

5.4.11 TEMPERATURE/TOLERANCE=temperature_value

Defines the acceptable temperature range about the set point. If the array temperature deviates from the set point by more than the tolerance value, an error message is printed and a flashing warning indicator appears in the Status Display. The tolerance value is specified in units of °K. In normal operation this should be set to 0.1 °K.

5.4.12 TEMPERATURE/PLOT

Plots the history of temperature fluctuations on the screen using the current values of XMINIMUM, XMAXIMUM, XAUTOSCALE, YMINIMUM, YMAXIMUM, and YAUTOSCALE.

5.4.13 TEMPERATURE/HARDCOPY

Produces a hardcopy plot of the history of temperature fluctuations.

5.4.14 TEMPERATURE/[NO]LINE

Toggles plotting the temperature fluctuations with a line plot or as a histogram.

5.4.15 TEMPERATURE/XMINIMUM=time_value

Specifies the start time for a temperature fluctuation plot. This is specified in units of minutes prior to the present time.

5.4.16 TEMPERATURE/XMAXIMUM=time_value

Specifies the end time for a temperature fluctuation plot. This is specified in units of minutes prior to the present time.

5.4.17 TEMPERATURE/[NO]XAUTOSCALE

Causes the temperature fluctuation plot to be autoscaled in the time axis. All stored temperature data are displayed.

5.4.18 TEMPERATURE/YMINIMUM=temperature_value

Specifies the lower temperature limit of the temperature fluctuation plot in units of °K.

5.4.19 TEMPERATURE/YMAXIMUM=temperature_value

Specifies the upper temperature limit of the temperature fluctuation plot in units of °K.

5.4.20 TEMPERATURE/[NO]YAUTOSCALE

Causes the temperature fluctuation plot to be autoscaled in the temperature axis.

5.4.21 TEMPERATURE/GAIN=gain_value

Sets the Lakeshore temperature controller proportional gain parameter.

5.4.22 TEMPERATURE/RATE=rate_value

Sets the Lakeshore temperature controller derivative rate parameter.

5.4.23 TEMPERATURE/RSET=rset_value

Sets the Lakeshore temperature controller integral rset parameter.

5.5 The IMB Command

The IMB command qualifiers were fully described in the original Infrared Users Manual and are repeated here for completeness. The IMB includes the grism calibration lamp module which is controlled by the IMB command.

5.5.1 IMB/CONFIGURE

/CONFIGURE is generally issued by dewar subprocesses to set the turret to point to their dewar, and shift the X-Y stage to the position of the telescope aperture definition for that dewar. It can be initiated from the keyboard, but the telescope will not be offset to bring the star into the appropriate aperture as it is when the command is issued by the dewar subprocess.

5.5.2 IMB/TURRET=keyword

/TURRET sets the position of the turret on which the dichroic reflexer is mounted. This action directs the infrared beam from the telescope to the dewar to be used. The turret can be positioned in any one of four positions identified by the keywords A_POS (or 1), B_POS (or 2), C_POS (or 3), and IMB_POS (or 4). Dewars can only be mounted on the IMB ports corresponding to position keywords A_POS (or 1) and C_POS (or 3). CASPIR is mounted on IMB port position A. An IMB/TURRET=A_POS command is implicitly executed when a CASPIR command is first issued.

5.5.3 IMB/FOCUS

/FOCUS is used to control the focus function of the Tip-Tilt focusser unit mounted on the IMB X-Y stage. This optical focus is independent of the telescope focus which should be optimised for the infrared dewar. /FOCUS runs a routine which allows the user to control the Tip-Tilt focus using the up and down arrows on the control terminal keyboard. The focus is moved by a preset amount each time the arrow key is pressed. Limit switches ensure safe operation. Type `Q` to quit.

5.5.4 IMB/X_ABSOLUTE=integer_number

/X_ABSOLUTE sets the X-axis of the IMB X-Y stage carrying the Tip-Tilt sensor to the specified integer X-axis encoder number. Permitted integer values are in the approximate range of ±9000. Limit switches ensure safe operation.

5.5.5 IMB/Y_ABSOLUTE=integer_number

/Y_ABSOLUTE is the same as for /X_ABSOLUTE but applies to the Y-axis of the X-Y stage.

5.5.6 IMB/XY_ZERO

/XY_ZERO defines the zero point of the relative coordinate system for the IMB X-Y stage to be the current absolute (X,Y) position. This relative coordinate system is in units of millimeters in the f/18 beam of the telescope (as the focal ratio converter moves with the X-Y stage) and would normally be zeroed on the position of the center of the infrared array. Offset guide stars can then be found from known offsets in arcsec (the plate scale at f/18 is nominally 5.0″/mm).

5.5.7 IMB/X=real_number

/X sets the IMB X-Y stage carrying the Tip-Tilt sensor to the specified X coordinate in mm relative to a zero point defined with the /XY_ZERO qualifier.

5.5.8 IMB/Y=real_number

/Y is the same as for /X but applies to the Y-axis of the X-Y stage.

5.5.9 IMB/XY_HOME

/XY_HOME returns the IMB X-Y stage to the defined zero position of the relative coordinate system. This qualifier can be used to return the Tip-Tilt sensor from the position of an offset guide star to the infrared position.

5.5.10 IMB/XY_INCREMENT

/XY_INCREMENT runs a routine which allows the position of the IMB X-Y stage to be controlled from the control terminal keyboard using the four arrow keys. The space bar is used to toggle fast and slow motion controls. This qualifier is used for interactive adjustment of the X-Y stage position, such as when centering the Tip-Tilt sensor on a star.

5.5.11 IMB/CALIBRATION=keyword

/CALIBRATION automatically configures the calibration lamp module for measurements of each lamp. The available keywords are ARGON, XENON, INCANDESCENT, and OFF. /CALIBRATION=OFF turns off the calibration lamps and reconfigures the module for observing celestial objects. This is the default qualifier value, i.e., this is the action taken in response to IMB/CALIBRATION.

5.5.12 IMB/ARGON=[ON/OFF]

/ARGON turns on or off the argon lamp in the calibration lamp module.

5.5.13 IMB/XENON=[ON/OFF]

/XENON turns on or off the xenon lamp in the calibration lamp module.

5.5.14 IMB/INCANDESCENT=ON/OFF]

/INCANDESCENT turns on or off the incandescent lamp in the calibration lamp module.

5.5.15 IMB/LAMP_SELECT=keyword

/LAMP_SELECT positions the lamp select mirror in the calibration lamp module to point to the appropriate lamp. The lamp select keywords are ARGON, XENON, and INCANDESCENT.

5.5.16 IMB/FLIP_MIRROR=[IN/OUT]

/FLIP_MIRROR moves the calibration lamp module flip mirror in and out of the telescope beam. This mirror directs light from the calibration lamps to the infrared detector and Tip-Tilt sensor.

5.5.17 IMB/DISPLAY=keyword

/DISPLAY selects the IMB status display screen to be put on the top half of the instrument status screen. The startup communications display is available by specifying IMB/DISPLAY=COMMUNICATIONS.

5.5.18 IMB/INFORMATION

/INFORMATION produces a copy of the IMB status display screen on the control terminal screen. This is useful for determining the IMB status without overwriting the normal instrument status display.

5.5.19 IMB/STATUS_NOW

/STATUS_NOW queries the IMB for its current status without altering any settings. This qualifier is used to confirm that the status display is showing the true settings.

5.5.20 IMB/[NO]REPORT

/[NO]REPORT toggles a flag which defines whether or not some explanatory messages will be broadcast to IR_BROADCAST . If /NOREPORT has been selected, error conditions are flagged only as highlighted and cryptic messages in the IMB status display (which may not be visible at the time).

5.5.21 IMB/ABORT

/ABORT causes the current operation to be terminated.

5.5.22 IMB/[NO]DEBUG

/[NO]DEBUG toggles a flag which defines whether or not various diagnostic messages are broadcast to IR_BROADCAST during normal operation. As the name suggests, this qualifier would not normally be used.

5.6 The Telescope Paddle

A telescope paddle appears on the MOPRA workstation screen during system startup (if ENLIST IR has been typed). This paddle consists of a 3×3 grid with NSEW boxes labelled accordingly. The first mouse button (the left one for a righthanded setup) is used to offset the telescope by clicking on the appropriate box. All eight outer boxes respond in the obvious way. The first mouse button does not respond to clicks in the central square. The default telescope offset is 1.0 arcsec. This offset can be increased in factors of two by clicking the second (middle) mouse button in the central square. Similarly, it is decreased by clicking the third mouse button in the central square. The second and third mouse buttons do not respond to clicks in any other squares.

6 Imaging Data Reduction

6.1 Introduction

CASPIR produces images of the infrared sky in one passband at a time. These observations normally consist of a number of object and sky frames acquired through the execution of a DO file. Typical observing sequences would:

1) Record a few frames of one object with small spatial offsets between frames to counter ghosts and bad pixels, and to improve spatial sampling of the images.

2) Record many frames of the same object with a dither pattern of offsets to build up long exposures.

3) Record spatial mosaics of dithered sets of images with limited overlap between frames to cover large regions of sky.

These observing sequences naturally lead to the definition of a *dataset* as the set of related observations of a given object in one filter. In the extreme case, a dataset may contain only a single exposure. Different datasets may require different reduction strategies, depending on the nature of the observing sequence employed. The reduction of most datasets will follow the path:

1) Create BIAS and DARK frames, and linearize object and sky frames.

2) Create dome FLAT frames, and remove pixel-to-pixel sensitivity variations.

3) Create background SKY frames, and subtract sky background from object frames.

4) Define relative spatial offsets between each object frame in the dataset.

5) Combine all object frames in a dataset into a single image suitable for analysis, using bad pixel masks to exclude bad pixels.

Users are cautioned that infrared imaging datasets often present a greater data reduction challenge than optical CCD images both due to the superior performance of optical CCD detectors (lower dark current, read noise, and pixel-to-pixel sensitivity variations) and especially due to the extreme background-limited nature of most infrared imaging observations. The results at each step in the reduction process should be carefully examined and problems understood before proceeding. Many problems can be solved by the exclusion of bad images from the data sets.

The reduction procedures described here use the local MSSSO CASPIR package running in IRAF. The procedures (and this description) are based heavily on the SQIID package and its documentation (written by Mike Merrill at NOAO), but have been adapted at MSSSO for CASPIR reductions. The CASPIR package is available via ftp to merlin.anu.edu.au. You can retrieve it by typing:

```
ftp merlin.anu.edu.au
log in as ‘anonymous’
use your email address as password
cd pub/peter/
get caspir.tar.gz
bye
```

Then put the following lines in your *loginuser.cl* file.

```
set caspirdir = ‘‘home$scripts/caspir/’’
set caspirdb  = ‘‘home$scripts/caspir/database/’’
task $caspir = "caspirdir$caspir.cl"
caspir
```

These define the IRAF variables *caspirdir* and *caspirdb* to point to your CASPIR package directory and a convenient database directory, respectively, then define the *CASPIR* package and load it automatically on starting IRAF. You also need to include the line

```
unlimit descriptors
```

in your *.cshrc* file. This lets you handle a larger number of files in forming mosaics.

6.2 Preparations

CASPIR writes FITS format data files at the telescope which can be reduced in this form if your IRAF handles FITS files directly. Otherwise, the FITS files must be converted to IRAF *.imh* files before reduction can begin. To do this, restore all the data files for one night to a disk directory, start IRAF, and type:

```
files *%.fits%% > allfiles
rfits @allfiles//.fits * @allfiles
delete @allfiles//.fits
```

to convert FITS files to IRAF *.imh* files and remove the FITS files from disk.

In any event, you need to create a list of all the data file names so type:

```
files *%.fits%% > allfiles
```

if you are working directly on the FITS files.

List processing is fundamental to efficient data reduction, and will be used extensively in what follows. The `csplist` task is a convenient list generation utility for the reduction of CASPIR datasets. The `csplist` task has the following parameters.

```
                                  I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = csplist

keyword =                 list  List key type
value   =                   kn  List key value
images  =              @ifiles  List of images to search
(first_i=                ir001) First image in list
(number =                   21) Number of images in output list
(delta  =                    1) File number increment
(suffix =                     ) File name suffix
(mode   =                    q)
```

The following examples illustrate the capabilities of this task:

To generate a file containing a sequence of five filenames starting with *ir153*, incremented by two, and having the suffix *t*, type:

```
csplist list first=ir153 num=5 delta=2 suffix=t > tfiles
```

Then *tfiles* contains the names:

```
ir153t
ir155t
ir157t
ir159t
ir161t
```

as can be seen by typing any one of the following:

```
type tfiles
head tfiles
tail tfiles
```

To select all frames in the list file *allfiles* recorded with method 2, and write the filenames to a new list file *m2files* with a *t* appended, type:

```
csplist method 2 images=@allfiles suffix=t > m2files
```

To select all frames in the list file *allfiles* obtained with the Kn filter, and write the filenames to a new list file *knfiles* with a *t* appended, type:

```
csplist filter kn images=@allfiles suffix=t > knfiles
```

To select all frames in the list file *allfiles* obtained with the HK grism, and write the filenames to a new list file *hkfiles* with a *t* appended, type:

```
csplist grism HK_grism images=@allfiles suffix=t > hkfiles
```

To select all frames in the list file *allfiles* with a header exposure time string of `5.0`, and write the filenames to a new list file *5files* with a *t* appended, type:

```
csplist time 5.0 images=@allfiles suffix=t > 5files
```

To select all dark frames in the list file *allfiles*, and write the filenames to a new list file *dfiles* with a *t* appended, type:

```
csplist dark images=@allfiles suffix=t > dfiles
```

Two more general purpose tasks are mentioned before we begin the reduction: `cspdisplay` sequentially displays a list of images and is useful for quickly gaining a feel for the quality of a dataset. `csppeek` sequentially displays a list of images after a specified dark frame has been subtracted from each frame. This task is useful for quickly assessing raw data that are dominated by the pedestal pattern until a dark frame has been subtracted. These tasks have the following parameters:

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspdisplay

images  =                       List of input images
(zscale =                  yes) Autoscale display?
(z1     =                     ) Minimum level to be displayed
(z2     =                     ) Maximum level to be displayed
(statist=                   no) Calculate statistics?
(movie  =                   no) Continuous movie mode?

(verbose=                  yes) Verbose output?
next_ima=                  yes  Next image?
(imglist=                     )
(mode   =                   ql)
```

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = csppeek

images  =                ir168  List of input images
dark    =                ir366  Dark frame to use
(zscale =                  yes) Autoscale display?
(z1     =                   0.) Minimum level to be displayed
(z2     =                6500.) Maximum level to be displayed

(verbose=                  yes) Verbose output?
next_ima=                  yes  Next image?
(imglist=                     )
(mode   =                   ql)
```

6.3 Forming BIAS and DARK Frames

Proper data reduction requires accurate correction for the electrical offsets introduced by the data acquisition system (BIAS frames), the small additive effects of internal illumination, charge generation, and charge leakage (DARK frames), the large additive effects of sky illumination (SKY frames), and the multiplicative effects of position dependent pixel sensitivity (FLAT frames). Implicit in this is the need to correct for non-linearities in the responsivity of the detector array.

BIAS and DARK calibration frames are required for the linearity correction, so their creation is the first step in the data reduction process.

6.3.1 BIAS Frames

BIAS frames are defined to be dark exposures of the minimum duration possible for a given read-out method. The nature of the CASPIR array prevents us obtaining zero length exposures. BIAS frames will normally have been recorded with the `CASPIR/BIAS` command. The stability of BIAS frames over the duration of a night is questionable, so caution dictates that sets of BIAS frames be recorded at the beginning and end of each night. Intermittent problems with reading out the array make it advisable to record several bias frames. The quality of these should be checked visually using the `csppeek` task, and acceptable frames combined using the `cspcombine` task. For example,

```
cspcombine ir001,ir002,ir003 bias average
```

averages the three raw bias frames ir00[1-3], and writes the result to the file *bias*.

The `cspcombine` task has the parameters listed below. The *comb_opt* parameter defines how the frames are combined. This should be *average* if the number of bias exposures is less than about 5 and *median* if greater than about 5.

```
                                  I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspcombine

images  =    ir001,ir002,ir003  List of raw input images
output  =                 bias  Combined output image
(comb_op=             average)  Type of combine operation

(verbose=                 yes)  Verbose output?
(imglist=                    )
(mode   =                  ql)
```

6.3.2 DARK Frames

DARK frames should be obtained for each exposure time used during a night. These are used in the linearity correction routine to remove dark current and exposure time dependent electrical offset effects. The same stability concerns associated with BIAS frames also apply to DARK frames. Cautious observes may intersperse DARK frame measurements with object frames. Sets of DARK frames of the same exposure time can also be combined with the `cspcombine` task, for example,

```
cspcombine ir004,ir005,ir006 dark5 average
```

could be used to average four 5 sec DARK frames and write the result to the file *dark5*.

6.4 Linearity Correction

The response of the CASPIR detector array to light has a quadratic form which must be allowed for before accurate correction of other additive and multiplicative effects can be achieved. CASPIR data are linearized by subtracting a BIAS frame from the data, applying the quadratic correction, subtracting a linearized DARK frame, converting the data units from ADUs to electrons, dividing by the exposure time to produce a signal rate in electrons/sec, and flipping the image vertically to match the orientation on the data acquisition displays.

A convenient environment in which to conduct this and the remainder of the basic imaging reduction is provided by the `redimage` task. The `redimage` task is a multifunction procedure which operates along the lines of the `ccdproc` task in noao.imred.ccdred. `redimage` overwrites the input images at each stage of the reduction so it is useful to make a copy of the raw data files before proceeding. This can be done by typing

```
imcopy @allfiles @allfiles//r
```

To linearize all the images obtained with a 5 sec exposure time, first form a list file of the image filenames using the `csplist` task by typing:

```
csplist time 5.0 images=@allfiles > 5files
```

Now use `epar` to set the `redimage` parameters as listed below.

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redimage

(images =              @5files) List of CASPIR inputimages
(mosfile=                     ) Mosaic filename

(linear =                  yes) Linearize data?
(flatten=                   no) Divide by flatfield?
(skysub =                   no) Sky subtract?
(fixbad =                   no) Fix known bad pixels?
(mosaic =                   no) Mosaic image set?
(coord  =                   no) Add coordinate grid?
(display=                   no) Display result?
(phot   =                   no) Measure photometry?

(bias   =                 bias) Bias frame to use
(dark   =                dark5) Dark frame to use
(flatfil=                     ) Flatfield frame to use
(statsec=      [50:200,50:200]) Image section for computing statistics
(obstype=                  all) Type of observation made
(subtype=                  all) Type of sky subtraction to use
(scale  =                  yes) Scale sky to match object?
(skyfile=                  sky) Sky frame to use
(nrun   =                    4) Number of frames for running sky subtraction
(destrip=                   no) Subtract column pattern after sky subtraction
(badtype=               mosaic) Type of bad pixel correction
(badfile=     caspirdir$caspir) Bad pixel file
(mostype=                blind) Type of mosaic to make
(xoffset=                   0.) X offset of centroid star from object
(yoffset=                   0.) Y offset of centroid star from object
(cboxsiz=                    9) Size of automatic mode centroiding box
(radius =                  40.) Radius of object aperture in pixels
(buffer =                   1.) Background buffer width in pixels
(width  =                  20.) Width of background annulus in pixels

(verbose=                  yes) Verbose output?
(imglist=                     )
```

```
(skylist=                    )
(mode   =                  ql)
```

The flags *linear*, *flatten*, *skysub*, *fixbad*, *mosaic*, *coord*, *display*, and *phot* define the reduction steps that will be performed. The remainder of the parameters are used in the execution of these basic functions. The parameters relevant to the linearization of a particular dataset are *dark* which specifies the single DARK frame to be used for the entire dataset, and *bias* which specifies the single BIAS frame to be used for the entire dataset. Note that the DARK frame must have the same exposure time as the objects, so observations of different exposure times must be linearised separately using multiple calls to the `redimage` task. Run `redimage` by exiting `epar` using the *:g* command. `redimage` makes a copy of the linearised data in files with the suffix "l" appended. These can be used to replace the working files if subsequent processing steps must be repeated, e.g., by typing:

```
imdelete @5files
imcopy @5files//l @5files
```

It is most convenient to linearize all observations obtained during a given night at this stage of the reduction. A typical sequence might be:

```
csplist time 0.3 images=@allfiles > 03files
redimage images=@03files linear+ bias=bias dark=dark03

csplist time 5.0 images=@allfiles > 5files
redimage images=@5files linear+ bias=bias dark=dark5
```

6.5 Flatfielding

The creation of suitable FLAT and SKY frames is more difficult than for BIAS and DARK frames, but they are crucial to the quality of the final images. Different approaches may be necessary for different types of CASPIR imaging data. Compared to optical band CCD observations, most broadband observations with CASPIR are extremely background limited. Furthermore, the background in the near-infrared is variable at many temporal and spatial scales. Since infrared sources are often much fainter than the broadband sky background, very precise removal of the sky signal is required. Narrowband CASPIR images with both pixel scales and J images with the $0.25''$ pixels have lower sky backgrounds and present different data reduction challenges.

The primary goal in flatfielding images is to correct for pixel-to-pixel sensitivity variations across the array, so that the relative intensities of objects imaged in different parts of the array are accurately recorded. Flattening the sky background is a secondary effect, although this should also be achieved if the array responds similarly to stellar continuum light and sky emission. Two flatfielding strategies are possible: A set of sky images can be combined to form a sky FLAT frame, or images of an illuminated screen within the dome can be combined to form a dome FLAT frame. Better photometric accuracy is achieved for CASPIR data using dome flats because telescope thermal emission is removed by differencing *lamp on* and *lamp off* pairs. The energy distribution of the lamp probably also matches that of stars better than the sky background, which is dominated by line emission shortward of about 2.2 μm.

Dome flats should be measured in sets of *lamp on* and *lamp off* pairs for each filter and image scale required. Dome FLAT frames can be created from linearized data with the `cspflat` task. The inputs required are a list of *lamp on* frames, a list of *lamp off* frames, and an output filename. For example,

```
cspflat ir007,ir009,ir011 ir008,ir010,ir012 flat_kn comb_opt=average
```

averages the *lamp on* frames ir007-11 and the *lamp off* frames ir008-12, takes their difference, then normalizes the median pixel value of the difference to unity, and writes the resulting dome FLAT frame to the file *flat_kn*.

The `cspflat` task has the parameters listed below.

```
                                 I R A F
                  Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspflat

ons     =    ir007,ir008,ir009  List of lamp ON frames
offs    =    ir008,ir010,ir012  List of lamp OFF frames
flat    =              flat_kn  Output flatfield frame
(comb_op=              average) Type of combine operation
(statsec=      [50:200,50:200]) Image section for calculating statistics

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

The *comb_opt* parameter should be *average* if the number of on or off exposures is less than about 5 and *median* if greater than about 5. The *statsec* default should generally be satisfactory.

All frames obtained with a particular filter and image scale can be flatten together by unsetting the *linear* flag in `redimage`, setting the *flatten* flag, and setting the *flatfile* parameter to the appropriate FLAT frame filename. Run `redimage` from the command line or by exiting `epar` via the *:g* command. `redimage` makes a copy of the flattened data in files with the suffix "f" appended. A typical sequence might be:

```
csplist filter j images=@allfiles > jfiles
redimage images=@jfiles linear- flatten+ flatfile=flat_j

csplist filter h images=@allfiles > hfiles
redimage images=@hfiles linear- flatten+ flatfile=flat_h

csplist filter kn images=@allfiles > knfiles
redimage images=@knfiles linear- flatten+ flatfile=flat_kn
```

6.6 Sky Subtraction

The strong and variable near-infrared background has contributions from OH airglow in the J, H, and K bands, moonlight (either directly or reflected off clouds) especially in the J band, and from thermal emission from the telescope and sky in the K and L bands which varies with temperature and humidity. Although the 10–30% variations in background caused by these factors do not strongly limit the S/N of observations (except at K and L for large changes in temperature), they greatly complicate both the creation of mosaics of large regions and accurate surface photometry of objects with extents comparable to CASPIR's field of view. For such observing programs, it is best to obtain sufficient object exposures (and intermixed sky exposures if necessary) to create a SKY frame for each dataset. For programs with single or a few observations of many objects, a sky calibration based on observations of several objects, possibly combined with subtracting a fitted surface from the final image, is the best that can be accomplished. These grouped observations could be treated as one dataset for the purposes of sky subtraction. It is useful to remember that variable airglow can cause the sky background to vary at H by a factor of 2 and at J by 40% on hour timescales.

SKY frames for a dataset are created using the `redimage` task by setting the *skysub* flag, and supplying values to the *obstype*, *subtype*, *scale*, *skyfile*, *nrun*, and *destripe* parameters. *obstype* defines the type of sky observations in the dataset. *obstype=all* indicates that all images in the dataset are to be included in the creation of SKY frames. *obstype=oso* indicates that the first image in the dataset is an object image, and this is followed by a sequence of an off-source sky image and an object image, ending with an object image. Only the off-source sky images will be included in the creation of SKY frames. *obstype=sos* indicates that the first image in the dataset is an off-source sky image, followed by object and off-source sky image pairs, ending with a sky image. Only the off-source sky images will be included in the creation of SKY frames. *obstype=soos* indicates that the dataset consists of sequences of sky, object, object, sky frames. Only the off-source sky images will be included in the creation of SKY frames. *obstype=osso* indicates that the dataset consists of sequences of object, sky, sky, object frames. Only the off-source sky images will be included in the creation of SKY frames. *obstype=nod* indicates that the dataset consists of object frames where the object has been nodded between two locations on the array in an ABBA sequence. Only the B position frames are used to create the A position SKY frame, and the A position frames to create the B position SKY frame. *obstype=radio*, *obstype=gc*, and *obstype=brc* are patterns used for specialised observing sequences. It is likely that these patterns will include most observing sequences in user defined DO files. `redimage` can be extended to include other sky types if this proves necessary.

Standard star measurements recorded in pairs with the star displaced on the array can be processed by selecting *obstype=standard*. This is a special type requiring exactly two input images. An output image is formed by subtracting the second (*sky*) image of the standard star from the first (*object*) image of the standard star. A permanent output file is produced with the name `stdnnn_mmm` where `nnn` is the number of the first standard star image and `mmm` is the number of the second standard star image. This sky-subtracted standard star image can be automatically processed in each the following steps except that mosaicing and creating a coordinate grid will be ignored. These steps are not applicable to this image. It is most likely that users will fix bad pixels and then measure aperture photometry on the standard star image after sky subtracting.

The *subtype* parameter in `redimage` defines the type of sky subtraction that is performed. *subtype=all* defines that all sky images in the dataset will be included in the creation of a single SKY frame, which is then scaled to the median pixel value of each object image if *scale=yes*, and subtracted from them. This is adequate for small datasets where the total time span of the observation is less than about 20 minutes. Larger datasets need to be subdivided into smaller units, with individual SKY frames. This is achieved by setting *subtype=running*. This causes a SKY frame to be formed for each object image in the dataset from the median of *nrun* sky images taken immediately before and after the object image. The object image itself is not included in the running median. The SKY frame created for each object image is then scaled to the median pixel value of the object image, if *scale=yes*, and subtracted from it. In each ofthese cases, the last formed sky frame is saved in the file named “sky”. *subtype=file* defines that the file specified by the parameter *skyfile* will be used as the sky frame for the dataset. This frame is scaled to the median pixel value of each object image, if *scale=yes*, before being subtracted.

The *destripe* parameter in `redimage` determines whether a residual column bias pattern is to be defined and subtracted from each image after normal sky subtraction. Usually this will not be necessary. However, *nbL* images obtained with readout method 1 suffer from DC drifts in the bias levels of the four output amplifiers between the object and sky frames that are manifest as a residual column bias pattern with four pixel period that is often not removed by normal sky subtraction. When the *destripe* parameter is set, `redimage` determines the shape of this bias pattern by projecting the image in the column direction to a 1D spectrum, and then subtracting this spectrum off each row in the image.

Individual datasets must be sky subtracted separately. It is most convenient to form a list file containing the names of all the images in the dataset and use `redimage` to process them. This can be done using `csplist` by typing, e.g.:

```
delete tfiles
csplist list first=ir054 num=7 > tfiles ; tail tfiles
```

or by explicitly listing the file names, e.g:

```
delete tfiles
cat > tfiles
ir054
ir055
ir056
ir057
ir058
```

```
ir059
ir060
^D
```

A typical **redimage** parameter list for sky subtracting a single *oso* dataset in the list file *tfiles* using a running median SKY frame subtraction is shown below.

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redimage

(images =             @tfiles) List of CASPIR input images
(mosfile=                   ) Mosaic filename

(linear =                  no) Linearize data?
(flatten=                  no) Divide by flatfield?
(skysub =                 yes) Sky subtract?
(fixbad =                  no) Fix known bad pixels?
(mosaic =                  no) Mosaic image set?
(coord  =                  no) Add coordinate grid?
(display=                  no) Display result?
(phot   =                  no) Measure photometry?

(bias   =                bias) Bias frame to use
(dark   =               dark5) Dark frame to use
(flatfil=             flat_kn) Flatfield frame to use
(statsec=      [50:200,50:200]) Image section for computing statistics
(obstype=                 oso) Type of observation made
(subtype=             running) Type of sky subtraction to use
(scale  =                 yes) Scale sky to match object?
(skyfile=                 sky) Sky frame to use
(nrun   =                   4) Number of frames for running sky subtraction
(destrip=                  no) Subtract column pattern after sky subtraction
(badtype=              mosaic) Type of bad pixel correction
(badfile=     caspirdir$caspir) Bad pixel file
(mostype=               blind) Type of mosaic to make
(xoffset=                  0.) X offset of centroid star from object
(yoffset=                  0.) Y offset of centroid star from object
(cboxsiz=                   9) Size of automatic mode centroiding box
(radius =                 40.) Radius of object aperture in pixels
(buffer =                  1.) Background buffer width in pixels
(width  =                 20.) Width of background annulus in pixels

(verbose=                 yes) Verbose output?
(imglist=                   )
(skylist=                   )
(mode   =                  ql)
```

6.7 Fixing Bad Pixels

For single observation data sets, or minimally overlapped mosaics, it is necessary to correct bad pixels by interpolation. In heavily overlapped mosaics, bad pixels can be allowed for when these mosaics are combined. However, in both cases it is necessary to attach a bad pixel file to each image before correction can be achieved.

Bad pixels can be interpolated using the **`noao.proto.fixpix`** or **`imedit`** tasks. Bad pixels are specified to these routines in an ascii bad pixel file which is described in the *help instruments* man pages. The file consists of lines describing rectangular regions of the image. The regions are specified by four numbers giving the starting and ending columns followed by the starting and ending rows, for example,

```
# CASPIR - untrimmed
25 25 111 111
108 108 87 113
256 256 1 256
1 256 1 1
185 190 240 245
```

If there is a comment line in the file containing the word *untrimmed*, the coordinates of the bad pixel regions apply to the original image, rather than a sub-section. The file caspirdir$caspir.bad contains the standard CASPIR bad pixel list in this format. It is possible that users will wish to add other bad pixels to their own versions of this list.

Mosaics are combined with the powerful **`imcombine`** task which uses more sophisticated bad pixel mask images. These are associated with an image through the 'BPM' header entry for the image. A bad pixel mask image is a pixel list file (.pl extension). It is treated like an image file and can be viewed with **`display`** and altered with **`imedit`** etc. A bad pixel mask image is created from an ascii bad pixel file using **`noao.imred.ccdred.badpiximage`**. The following example shows how to form the bad pixel mask image *caspir.pl* from the bad pixel file *caspir.bad.*

```
noao
imred
ccdred
cp caspirdir$caspir.bad .
badpiximage caspir.bad ir001 caspir
imcopy caspir caspir.pl
imdelete caspir
```

The file *ir001* can be any CASPIR data file. It is used as a template to define the size of the bad pixel mask image. Good pixels have a value of 1 and bad pixels have a value of 0 in the bad pixel mask image.

The **`cspmask`** task can also be used to create a bad pixel list file and a bad pixel mask image directly from a CASPIR image (typically a FLAT frame) by defining upper and lower rejection thresholds. The **`epar`** listing for **`cspmask`** is shown below.

```
                                        I R A F
                         Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspmask

input   =             sflat_kn  Input images
output  =         newcaspir.pl  Clipped output images
lower_li=                  0.8  Lower limit for in/exclusion
upper_li=                  1.2  Upper limit for in/exclusion
(in_valu=                   1.) Replacement value inside range
(out_val=                   0.) Replacement value outside range
(section=               [*,*]) Image section for replacement
(trimlim=           [0:0,0:0]) trim limits around edge

(verbose=                  yes) Verbose output?
(outlist=                     )
(mode   =                   ql)
```

To apply the appropriate bad pixel correction using the `redimage` task, set the *fixbad* flag and nominate the type of correction and the bad pixel filename using the *badtype* and *badfile* parameters. *badtype=interpolate* causes `fixpix` to be used to interpolate over bad pixels. *badtype=mosaic* causes the bad pixel mask image filename to be associated with each object image, but actual correction of bad pixels is deferred until the mosaic is combined. The *badfile* parameter should not include the file extension (*.bad* or *.pl*). `redimage` will append this depending on the type of bad pixel correction selected. Consequently, it is advisable to maintain a *.bad* and a *.pl* copy of each bad pixel file used.

If all else fails, use `imedit` to interactively 'fix' bad pixels by defining a circular aperture and replacing the pixel values within the circle, e.g.:

```
imedit input output radius=5 width=5
```

6.8 Removing "Cosmic Rays"

The many hot pixels in the CASPIR array often leave a "snow" of residual hot and cold pixels in the sky subtracted images. This is especially serious at J where the sky level is initially lower. These hot and cold pixels occur at random locations so cannot be removed using a fixed bad pixel mask. The `cspclean` task uses the IRAF `cosmicrays` task to first clean the hot pixels assuming they look like cosmic rays, then invert the image, and clean the cold pixels again as if they were cosmicrays. Any automated cleaning routine should be used with caution so some experimentation is required to set the threshold levels to appropriate values. This can be done using the "training" features build into `cosmicrays`. Consult the `cosmicrays` documentation (by typing `help cosmicrays`) for more details. A typical `epar` listing for `cspclean` is shown below.

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspclean

images  =              @tfiles  List of input images
(outputs=          @tfiles//c) List of output images

(coldpix=                 yes) Also clean cold pixels?
(train  =                 yes) Train cosmic-ray/object discriminant?
(thresho=                 0.2) Cosmic ray detection threshold above mean
(fluxrat=                  7.) Flux ratio threshold percentage

(zscale =                 yes) Autoscale display?
(z1     =                    ) Minimum level to be displayed
(z2     =                    ) Maximum level to be displayed

(display=                  no) Display cleaned images?
(verbose=                 yes) Verbose output?
(imglist=                    )
(mode   =                  ql)
```

6.9 Preliminary Mosaicing

Mosaicing is the most complex part of infrared imaging data reduction. Several crude levels of mosaicing are provided in the `redimage` task. Discussion of full interactive mosaicing is deferred to §7. To mosaic a dataset using the `redimage` task, set the *mosaic* flag, enter the mosaic output filename in the *mosfile* parameter, and define the mosaicing type using the *mostype* parameter.

Selecting *mostype=blind* causes the object images in the dataset to be combined at their nominal offsets from the base position, as specified in the DO file used to acquire the data and as recorded in the image header entries 'offra' and 'offdec'. This type of mosaic is generally useful for a first look, or for minimally overlapped mosaics where blind offsetting is all that can be achieved.

Selecting *mostype=manual* causes the object images to be display at their nominal offsets so that the user can mark the location of a suitable reference point with the image display cursor. The reference point should be located within each of the images in the dataset, but need not correspond to a particular object. No automatic centroiding is performed on the marked position, so this option is most suitable for noisy images where the centering determination is subjective. The *xoffset* and *yoffset* parameters specify the position of the reference object relative to the base position of the mosaic.

Selecting *mostype=auto* is useful if there is a moderately unresolved reference object in the mosaic, and this source is in each object image of the dataset. This will often be the case for dithered observations of a single object. When *mostype=auto* is selected, the nominal offsets are corrected by centroiding on the reference object in each frame using the IRAF `proto.imcntr` task. The `redimage` parameter *cboxsize* defines the size of the centroiding box used. This option produces excellent results for suitable datasets with a moderately unresolved reference object. Some care should be exercised in deciding whether centroiding has been successful. This can usually be gauged from the appearance of off-center stars in the mosaic. The *xoffset* and *yoffset* parameters specify the position of the reference object relative to the base position of the mosaic.

Observations obtained with the *radio.do* pattern, described above, require special treatement to estimate the *nbL* image offsets from offsets determined from interspersed Kn images of the same object. This is achieved by selecting *mostype=radio*.

These options provide a convenient way of assessing mosaiced data at the telescope and of gauging the result of the data reduction steps performed so far, before committing significant effort to the more involved full mosaicing.

6.10 Coordinate Overlays

A world coordinate (RA and DEC) system can be defined for a mosaic image produced with the `redimage` task by setting the *coord* flag. The coordinate system is defined from the base position of the mosaic stored in the image header entries *meanra* and *meandec*, and the maximum RA offset and the minimum DEC offset used in combining the mosaic and stored in the mosaic header entries *moffra* and *moffdec* when `redimage` forms the mosaic.

If the *coord* and *display* flags are set when `redimage` is run, an RA and DEC coordinate grid is overlaid on the mosaic image when it is displayed. This may be helpful for identifying objects in large mosaics and for determining the scale of a mosaic.

The `images.tv.wcslab` task can be used to overlay the world coordinate grid at any time when the mosaic image is redisplayed. Note that this does not work with SAOIMAGE under Solaris 2, and the `wcslab` command must currently be issued twice when using the XIMTOOL display under Solaris 2.

Once the world coordinate system grid has been defined, RA and DEC positions of selected objects can be obtained by typing

```
rimcursor wcs=world
```

Use the image display cursor to select objects and type any key to print the coordinates. Exit `rimcursor` by typing <cntrl>d with the cursor in the image display.

6.11 Quick-Look Aperture Photometry

The IRAF `imexam` or `noao.digiphot.apphot.qphot` tasks can be used from `redimage` to measure quick aperture photometry for a mosaic image by setting the *phot* flag in `redimage`. This is especially useful for quick-look assessment at the telescope. Currently `redimage` is hardwired to use `imexam`. A circular aperture radius is defined by the *radius* parameter. This is surrounded by a buffer of *buffer* pixels, and a sky annulus *width* pixels wide. Calibrated photometry can be obtained by running the same procedure on standard stars and manually applying the necessary offset.

Objects are selected using the image display cursor and a radial profile is plotted and photometry calculated by typing "r". Help on other `imexam` commands can be obtained by typing "?". `imexam` is exited by typing "q".

7 Full Mosaicing

7.1 Introduction

The following procedures describe how to mosaic large datasets of minimally overlapped CASPIR images, or partially overlapped datasets that cannot easily be handled using the simple mosaicing function available in `redimage`. The tasks described are modified (and henced renamed) versions of the SQIID mosaicing tasks provided by Mike Merrill. This description is based heavily on the SQIID mosaicing description, with minor modifications to reflect CASPIR specific features.

7.2 Building a Database from a Dataset

Following reduction of the individual data frames discussed in §6, each dataset to be mosaiced must be converted into a *database*. As with datasets, each database contains the observations of a single field or target in a single passband. The database construct will be used to bring the individual exposures together into the desired final image (dither or mosaic).

The `cspmosaic` task is used to gather observations of a single object into a database. Each database consists of a text file and an image containing a mosaic (with no overlap) of the images in the database. Hence the disk storage requirements grow during this stage of the processing. If possible, retain the individual images and calibration frames on the disk since iteration of the processing is often necessary and usually involves the recreation of the FLAT or SKY frame and the reprocessing of the individual images.

Note that `cspmosaic` calls the `noao.nproto.irmosaic` task which is also part of the `noao.imred.irred` package loaded by the `caspir` package. `cspmosaic` is really just a pre- and post-processor for `irmosaic`, initializing the registration database files.

A dataset of processed images listed in the file *image.lis* is assembled into a database by typing, e.g.:

```
cspmosaic @image.lis imagemos 3 4
```

This will create a database mosaic, *imagemos*, that is able to contain up to 12 input images. The user must specify dimensions of the database mosaic which are large enough to contain all of the images in the input list and which, typically, is approximately square to facilitate display with the image display tool.

The `cspmosaic` task has a number of parameters which should be set as indicated in the "epar" listing below:

```
                                  I R A F
                   Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspmosaic

images  =          @image.lis  List of input images
mosfile =            imagemos  Mosaic filename
nxsub   =                   3  Number of subrasters in x
nysub   =                   4  Number of subrasters in y
(null_in=                    ) List of missing input images

(corner =                  ll) Starting corner for the mosaic
(directi=                 row) Starting direction for the mosaic
(raster =                  no) Raster scan?
(trim_se=               [*,*]) Input image section used in output image
(nimcols=               INDEF) Number of columns in the output image
(nimrows=               INDEF) Number of rows in the output image
(oval   =              -1000.) Mosaic border pixel value
```

```
(median =                   no) Compute the median of each subraster?
(median_=               [*,*]) Input image section used for median
(subtrac=                   no) Subtract median from each subraster?
(tran   =                   no) Apply transformation to input images?
(task_tr=             geotran) Type of image transform to use
(db_tran=                    ) Name of database file output by GEOMAP
(co_tran=                    ) Name of coordinate file input to GEOTRAN
(geom_tr=              linear) GEOTRAN transformation geometry
(max_tra=                 yes) Offset GEOTRAN to save maximum image?
(interp_=              linear) GEO(IMLIN)TRAN interpolant
(bound_t=             nearest) GEO(IMLIN)TRAN boundary
(const_t=                   0.) GEO(IMLIN)TRAN constant boundary extension value
(flux_tr=                 yes) Conserve flux during GEO(IMLIN)TRAN?
(save_tr=                   no) Save intermediate GEO(IMLIN)TRAN images?
(save_ir=                   no) Save IRMOSAIC database file?

(verbose=                 yes) Verbose output?
(imglist=                    )
(mode   =                   ql)
```

The input image list is specified as an list file. The output file name, *mosfile* (without extension), will be the rootname of both the database mosaic image (with the extension .imh or .fits) and the database text file (with the extension .mdb). The images must all be the same size.

The *nxsub* and *nysub* parameters specify the dimensions of the database mosaic. When there will be unfilled cells in the mosaic, a list of the missing images must be provided in the parameter *null_input*. For example, if the dataset contains 10 images, a 3 by 4 mosaic could be specified. Then *null_input* should be `11,12` or `11-12`. If their are no null images, set *null_input* to `""` (a `" "` will cause the task to abort!). The image numbering refers to the postion of the image in the input list.

The images in the input list will be tiled into a mosaic with 1-pixel boundaries (value determined by *oval*) according to the selected prescription. The parameter *corner*, which indicates where to start tiling the images from the input list and the parameter *direction*, which indicates the direction (row or column) to proceed with the tiling operation, should be set to the values which describe the way you have ordered your data in the input list. A natural choice might be to set *corner* to *ll* (lowerleft) and *direction* to *row*. Then the images in the database mosaic would be numbered starting with the lower left image as *1* and proceeding by row. For example,

```
9 10 11 12
5  6  7  8
1  2  3  4
```

are the image numbers in the above example. The options to subtract the median and to transform the image should be set to ”no” since these steps are done elsewhere. Setting *median=yes* calculates and reports the image statistics. However, occasionally (for reasons unknown), `irmosaic` can take an inordinately long time to perform these calculations.

The parameters *task_tran*, *db_tran*, *co_tran*, *geom_tran*, *max_tran*, *interp_tran*, *bound_tran*, *const_tran*, *flux_tran* are used to geometrically transform the images prior to storage in the mosaic. Normally one saves the data as is and defers image transforms to later stages.

7.3 Specifying the Relative Spatial Offsets

To combine a database of images into a single, final image, the relative offsets between the individual images in the database must be determined. IRAF does not yet have a general image registration task and many of the tools which are available are tailored to tiling images sets taken in a fixed grid pattern with minimal overlap (the images are not combined: each successive image covers up its neighbors in the overlap region).

The **caspir** package contains a set of image registration tools designed to facilitate image registration and combination. The image registration process naturally separates into the following steps:

1) Determine the relative spatial offsets between images.

2) Link these relative offsets into a single map which contains the offset of each image relative to the origin of the final image.

3) Combine the images into a single image.

These tools generate a database which links the untouched processed data (generally stored as mosaics using `cspmosaic`) via a prescription which describes how each image is the be transformed, shifted, and masked to make a composite image. The input images (in the database mosaics) are not modified during this process; rather, each tool in turn inserts the necessary information into the database text files. When required, temporary copies of the images are created, modified, and discarded at task completion. One can edit the prescription as required to meet the special needs of each data set. Tools are provided for merging registration data which share a common image into larger databases. Ultimately, the images are combined according to the database prescription using the powerful IRAF task `imcombine`.

7.3.1 Interactive Specification of the Offsets for Grid Data

The interactive determination of the offsets is accomplished by identifying common sources in the images in the database mosaic and requires an IRAF image display tool (e.g., ximtool). Since registration of grids of images with minimal overlap between adjacent images (taken to cover large area) and heavily overlapped images which share a common overlap region (taken to reach faint magnitudes) require different strategies, there are two sets of tools to accomplish this task:

1) The `cspmark` and `cspmate` tools are best suited for dataset grids.

2) The `cspmatch` task is best suited for multiply-overlapped datasets.

These tools produce a common database which can be used by subsequent steps in the registration process. In addition, the `cspmerge` task, discussed below, allows you to merge databases from both types of data into a common database (e.g., to bring the second members of dithered pairs for grid data in registration with the first members of the pair).

Grid data are most easily handled using the `cspmark` task. To use this task, the images must be ordered in the `cspmosaic` image so that overlapping images are adjacent to one another. A typical "epar" listing for `cspmark` is shown below:

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspmark

mosfile =             imagemos  Mosaic filename
(append =                  yes) Append to existing coordinate file?

(zscale =                  yes) Autoscale display?
(z1     =                INDEF) Minimum level to be displayed
(z2     =                INDEF) Maximum level to be displayed

(mark   =               circle) Type of mark
(size   =                   5.) Size of mark
(label  =                  yes) Label each mark?
(cbox   =                   7.) Size of centering box

(verbose=                  yes) Verbose output?
```

```
(coolist=                    )
(mode   =                  ql)
```

Enter the `cspmark` task by typing:

```
cspmark imagemos
```

Using the image cursor successively mark images which appear in adjacent frames: the data must be paired such that each member of the pair corresponds to the position of the selected object in an adjacent frame. The overall order in which the object pairs are selected is unimportant. Avoid very bright stars (which might be saturated) and stars at the edge of the subrasters (whose position can be influenced by the one pixel gap between adjacent sub-rasters). Hopefully, all edge pairs contain at least one object within their common overlap region. If not, subsequent tasks may estimate the offset from other pairs in the same column or row, or from other rows or columns (if desperate!).

The cursor file produced by `cspmark` is the basis file for the `cspmate` task, which collects and averages the spatial offsets between adjacent frames and links them into a common map. Enter the `cspmate` task by typing:

```
cspmate imagemos
```

The `cspmate` task employs many of the conventions of the `iralign/irmatch1(2)d` IRAF tasks. A typical "epar" listing for `cspmate` is shown below:

```
                                    I R A F
                     Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspmate

mosfile =            imagemos  Mosaic filename
(link   =                  no) Read linkage paths from .lnk file?
(nxrsub =               INDEF) Index of X reference subraster
(nyrsub =               INDEF) Index of Y reference subraster
(guess  =                 yes) Guess missing links from average values?
(new_ori=                 yes) Move origin to lower left corner?
(trimlim=         [0:0,0:0]) Trim limits for input subrasters

(tran   =                  no) GEOTRAN subrasters before IMCOMBINE?
(db_tran=                    ) Name of database file output by GEOMAP
(geom_tr=              linear) GEOTRAN transformation geometry
(max_tra=                 yes) Offset GEOTRAN to save maximum image?
(interp_=              linear) GEOTRAN interpolant
(bound_t=             nearest) GEOTRAN boundary
(const_t=                  0.) GEOTRAN constant boundary extension value
(flux_tr=                 yes) Conserve flux during GEOTRAN?

(shift_i=              linear) IMSHIFT interpolant

(verbose=                 yes) Verbose output?
(mode   =                  ql)
```

mosfile is the name of the `cspmosaic` mosaic image to be registered. By default (*link=no*), the linkage path for each subraster is computed along two orthogonal paths and the average linkage is used: one path proceeds along the row to the reference subraster row, then along the column; the other path proceeds along the column and then along the row. If *link=yes* is specified, a linkage file (called imagemos.lnk in this example) is used to determine the linkage paths for each subraster. Since arbitrary linkage paths are allowed, one can accommodate problem images which are not linked on sufficient sides. You need to walk each piece to the same final link (one path per line), giving the path position of each image you trespass on the way from each subraster to the number of the reference subraster declared by *nxrsub* and *nyrsub*. Here are three sample formats for `cspmate` link files for the 3×4 mosaic in the `cspmosaic` example above and *nxrsub=2* and *nyrsub=2*:

```
Tile order:     9 10 11 12
                5  6  7  8
                1  2  3  4

File1:          File2:          File3:

1 2 6           1 5 6           1 2 6
2 6             2 6             2 6
3 2 6           3 7 6           3 2 6
4 3 2 6         4 8 7 6         4 8 7 6
5 6             5 6             5 6
6               6               6
7 6             7 6             7 6
8 7 6           8 7 6           8 7 6
9 10 6          9 5 6           9 10 6
10 6            10 6            10 6
11 10 6         11 7 6          11 7 6
12 11 10 6      12 8 7 6        12 8 7 6
```

File1 proceeds along the row to the reference subraster row, then along the column; *File2* proceeds along the column, then along the row; *File3* contains a variety of linkages to avoid missing links.

nxrsub and *nyrsub* are the column and row indices, respectively, of the reference subraster. These default to the central subraster if set to INDEF. If *guess=yes*, links which are absent from the database are estimated on the basis of the average value for the link along the row or column where the link is missing. Setting *guess = no* prevents the use of average links when none exists. Setting *new_origin=yes* tells the task to find the size of the combined image in the database and shift the implied origin of the database to include all of the images by putting the database origin in the lower left corner of the dataset. *new_origin=no* does not reset the origin from wherever it happens to be. *trimlimits* specifies in section notation ([left:right,top:bottom]) the number of columns or rows to trim off each edge of each input subraster before inserting it in the output image. The default is to trim 1 column or line at each edge. The input images are not touched; rather the database is marked to exclude these edge regions from the final image. Setting *tran=yes* requests that the task transform the database coordinates according to the **`geotran`** conventions and to mark the database so that the images will be geotransformed during the combination process. Setting *tran=no* leaves things alone. *db_tran*, *geom_tran*, *max_tran*, *interp_tran*, *bound_tran*, *const_tran*, *flux_tran* are parameters employed by **`geotran`** and should be left at their default values. They are ignored when *tran=no*. *shift_interp* specifies the type of interpolant used to shift the subrasters. This uses the **`imshift`** conventions (*linear*, *nearest*, *poly3*, *poly5*, and *spline3* are allowed); *linear* is the perferred choice.

As the XY offset data are being collected, `cspmate` signals the presence of mis-matched object pairs as follows:

```
#Note: non-adjacent pair:482.06 212.9 514. 218.
```

If you see this message (which generally means that one of a pair of positions is missing), the linkage will be flawed. You need to examine your mosaic file at the reported coordinate location, fix the problem (by editing out the bad position or inserting a missing position from a pair with `cspmark`), and rerun `cspmate`.

During linkage operation `cspmate` signals missing links and the action taken:

```
#DBL Note: no data for link | r 2,3 |
#DBL Note: using row_ave para_laps 3  for link | r 2,3 |
#DBL Note: no data for link | c 2,1 |
```

```
#DBL Note: using row_ave perp_laps 1  for link | c 2,1 |
#DBL Note: no data for link | c 2,2 |
#DBL Note: using row_ave perp_laps 2  for link | c 2,2 |
#DBL Note: null links not used in pairs
```

Note: `cspmate`, which uses the output from the `cspmark` task is set up to operate on mosaics no larger than 10 in X or Y. (IRAF scripts do not handle arrays well and larger arrays eat up too much space on the stack.)

7.3.2 Interactive Specification of the Offsets for Multiply-Overlapped Data

Many datasets are either irregularly or multiply-overlapped and cannot be put into a simple grid. The `cspmatch` task is designed to accommodate datasets which share an object in common. In many instances, the entire dataset will share a common object and `cspmatch` can be run once on the entire dataset. In other cases, subsets of data will share a common object and the dataset can be broken into a series of multiply-overlapped images. Then `cspmatch` can be run on each subset and on pairs of images which link each subset and the `cspmerge` task (discussed below) can be used to merge the data into a single database for the entire subset. For example,

```
cspmatch imagemos "1-10|1"
```

will permit the user to interactively indentify a number of point sources in image 1 and then a single source which appears in each of images 1 to 10. Prior to running this task it is advisable to examine the database mosaic image to identify a single point source which is present on all of the images. A typical "epar" listing for `cspmatch` is shown below:

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspmatch

mosfile =            imagemos  Input mosaic filename or @list of images
frames  =              1-25|1  Mosaic frame nums.|ref. num.|ref. mosaic
(cdbfile=                   ) Output composite database filename
(trimlim=          [0:0,0:0]) Trim limits for input subrasters

(coord_i=                   ) Input initial coordinate file
(in_shif=                   ) Initial ref/images shift file
(ra_offs=                   ) Ref/images RA offset [##.#(E|W)]
(dec_off=                   ) Ref/images DEC offset [##.#(N|S)]
(scale  =              0.242) Offset scale in units/pixel

(bigbox =                11.) Size of coarse search box
(boxsize=                 7.) Size of final centering box
getoffse=                 yes  Do you want to get subraster offsets?

(tran   =                 no) GEOTRAN subrasters before IMCOMBINE?
(db_tran=                   ) Name of database file output by GEOMAP
(geom_tr=             linear) GEOTRAN transformation geometry
(max_tra=                yes) Offset GEOTRAN to save maximum image?
(interp_=             linear) GEOTRAN interpolant
(bound_t=            nearest) GEOTRAN boundary
(const_t=                 0.) GEOTRAN constant boundary extension value
(flux_tr=                yes) Conserve flux during GEOTRAN?

(zscale =                yes) DISPLAY using zscale?
(z1     =                 0.) Minimum greylevel to be displayed
```

```
(z2     =                1000.) Maximum greylevel to be displayed
(format =                  no) Fancy file format using AWK

(verbose=                 yes) Verbose output?
compute_=                 yes  Do you want to [re]compute image size?
(list1  =                    )
(list2  =                    )
(list3  =                    )
(mode   =                  ql)
```

mosfile is the name of the `cspmosaic` mosaic image to be registered. *frames* is a specially formatted string which tells which images to register and what image to register them against. The images are identified by their path order in the `cspmosaic` database (MOS_XXX lines, where XXX is the path number). The format for *frames* consists of up to three fields separated by |. (Note, because of the use of the | delimiter, the *frames* string must be enclosed in quotes). The first field indicates the range of images to be registered; the second field indicates the number of the reference image these images are to be referenced to; the third field (when present) gives the name of the `cspmosaic` image where the reference image can be found. By default, the images are all from the same database; inclusion of the third field allows you to register images against another image not in the current database. Since the CASPIR registration database files describe each frame in a single line beginning with "COM_XXX", where XXX is the order of the image in the list, these frame numbers are often be refered to as COM numbers. The syntax for the range portion of the *frames* string consists of positive integers, "-" (minus), "*", "," (comma), and whitespace. The commas and whitespace are ignored and may be freely used for clarity. The remainder of the string consists of sequences of three fields. The first field is the beginning of a range, the second is a "-", and the third is the end of the range. The following examples illustrate the range syntax:

```
Range   Result

1-10    1 2 3 4 5 6 7 8 9 10
1,5,9   1 5 9
1-3,5   1 2 3 5
*       1 to the number of cspmosaic subrasters read from the database
        Warning:  since this number is the original size of the
        cspmosaic mosaic, it may not include all the images in a merged
        dataset.
```

The following examples illustrate the full *frames* syntax:

frames = "1-4|2" registers images 1,2,3,4 against image 2 in the same mosaic.

frames = "1-4|2|mos2" registers the same images against image 2 in the mosaic mos2.

cdbfile is the name of the composite database file generated. If none is specified, it defaults to the *mosfile* name. *trimlimits* specifies in section notation ([left:right,top:bottom]) the number of columns or rows to trim off each edge of each input subraster before inserting it in the output image. The default is to trim 1 column or line at each edge. The input images are not touched; rather the database is marked to exclude these edge regions from the final image. Setting *tran=yes* requests that the task transform the database coordinates according to the `geotran` conventions and to mark the database so that the images will be geotransformed during the combination process. Setting *tran=no* leaves things alone. *db_tran*, *geom_tran*, *max_tran*, *interp_tran*, *bound_tran*, *const_tran*, *flux_tran* are parameters employed by `geotran` and should be left at their default values. They are ignored when *tran=no*. The scaling of the image display during the interactive phases of the `cspmatch` task may be automatic if the parameter *zscale=yes*, otherwise the images will be scaled to fill the range between the values of the parameters *z1* and *z2*. It is often best to set the parameter *verbose=yes*.

7.4 Merging Registration Files Into Larger Databases

`cspmate/cspmatch` and `cspmerge` allow you to operate in larger domains. If you assemble the data in smaller mosaics, you can pull them together using `cspmatch` to link the individual mosaics and `cspmerge` to put it together into a single prescription. As noted above, `cspmatch` will accept pieces from different mosaics. The format can be summarized as follows:

```
"Range of included image COM#'s | reference COM# | mosaic name of reference"
```

Note that the final | and final field are omitted if they are from the same mosaic.

To merge composite databases, enter the names of the separate composite database files (one per line) into a file (e.g., totalmos.lis) and use `cspmerge` to merge them into a single file (e.g., totalmos) as follows:

```
cspmerge @totalmos.lis totalmos
```

Note: You must feed the information to `cspmerge` in the proper order when you organize the list of filenames: each reference frame must be found within the list of frames which has accummulated from the composite database filenames earlier in the list. A typical "epar" listing for `cspmerge` is shown below:

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspmerge

comfiles=       @totalmos.lis  List of composite database filenames
mergedfi=            totalmos  Output composite database filename
(subset =                  no) Keep only COM_000 and mos_name entries?
(mos_nam=                    ) Mosaic name for included COM entries

(renumbe=                 yes) Renumber secondary referenced frames?
(verbose=                 yes) Verbose output?

compute_=                 yes  Do you want to recompute image size?
(list1  =                    )
(list2  =                    )
(mode   =                  ql)
```

comfiles is the list of composite database files you wish to merge. This is either a comma delimited inline list or an "@list" filename with the files listed one per line. Remember to feed the information to `cspmerge` in the proper order when you organize the list of filenames: Each reference frame must be found within the list of frames which has accummulated from the files earlier in the list. *mergedfile* is the name of resultant composite database file. If some of the *comfiles* include references to reference images outside the dataset which you do not want to include in the *mergedfile*, set *subset=yes*. The task will then only include those images which have the rootname *mos_name*. *mos_name* is ignored if *subset=no*. Set *renumber=yes* if you want to automatically renumber COM# after the first file, so they cannot conflict with earlier COM#. Each new file is renumbered to begin where the previous file left off.

After all files have been accepted into the database, you will be prompted:

```
Do you want to recompute image size? (yes)
```

Answer *yes* if you wish to have the task find the new size of the combined image in the database and shift the implied origin of the database to include all of the images by putting the database origin in the lower left corner of the dataset. Answer *no* if you want to leave things as they are.

7.5 Creating the Final Images

Following the construction of the database files containing the offset and transformation information, the final images are created with the task `cspmakeit`. `cspmakeit` follows the submitted registration prescription and transforms (`geotransform`), and spatially shifts (`imshift`) copies of the input database images and presents these copies to the IRAF `imcombine` task along with the integer spatial offsets necessary for assembling the final image. In this task all of the transformations are actually applied. For example,

```
cspmakeit imagemos image
```

will create an IRAF image *image* from the *imagemos* database files.

Whenever you run `cspmakeit`, it checks to see if there is a common overlap region for the dataset. If there is no overlap region, it issues a warning:

```
#WARNING: overlap section: [463:253,456:254] is unphysical!
```

A typical "epar" listing for `cspmakeit` is shown below:

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspmakeit

mosfile =             imagemos  Mosaic filename
comfile =                image  Composite image filename
(frame_n=                 all) Frame numbers to include in mosaic

(trimlim=           [2:2,2:2]) Trim limits for input subrasters
(registe=                  no) Maintain input image origin and size
(common =                none) Pre-combine common offset
(comb_op=             average) Type of combine operation
(reject_=                none) Type of pixel rejection operation
(lthresh=               -200.) Rejection floor for imcombine and stats
(hthresh=              65000.) Rejection ceiling for imcombine and stats
(blank  =              -1000.) Value if there are no pixels
(setpix =                  no) Run SETPIX on data?
(maskima=     caspirdir$caspir) Bad pixel image mask
(svalue =         -100000000.) Setpix value (<< lthreshold)
(fixpix =                  no) Run FIXPIX on data?
(fixfile=     caspirdir$caspir) Bad pixel file in FIXPIX format

(make_st=                  no) IMSTACK images prior to IMCOMBINE?
(apply_z=                  no) Apply zeropoint prior to IMCOMBINE?
(save_im=                  no) Save images IMCOMBINED via imstack?
(do_comb=                 yes) IMCOMBINE (or overlay) final image?

(size   =                  no) Compute image size?
(shift_i=              linear) IMSHIFT interpolant
(bound_s=             nearest) IMSHIFT boundary
(const_s=                  0.) IMSHIFT constant for boundary extension
(gxshift=                  0.) Global xshift for final image
(gyshift=                  0.) Global yshift for final image
(goverla=                    ) Global overlap section (overrides all else)
(gsize  =                    ) Global image size (overrides all else)
(weight =                none) Image weights
(mclip  =                  no) Use median, not mean, in clip algorithms
(pclip  =                -0.5) pclip: Percentile clipping parameter
(nlow   =                   1) minmax: Number of low pixels to reject
(nhigh  =                   1) minmax: Number of high pixels to reject
(lsigma =                  3.) Lower sigma clipping factor
(hsigma =                  3.) Upper sigma clipping factor
```

```
(sigscal=                 0.1) Tolerance for sigma clipping scaling correction
(grow   =                   0) Radius (pixels) for 1D neighbor rejection
(expname=                    ) Image header exposure time keyword
(rdnoise=                  0.) ccdclip: CCD readout noise (electrons)
(gain   =                  1.) ccdclip: CCD gain (electrons/DN)

(verbose=                 yes) Verbose output?

answer  =                 yes  Do you want to continue?
compute_=                 yes  Do you want to [re]compute image size?
(list1  =                    )
(list2  =                    )
(mode   =                  ql)
```

mosfile is the composite database file corresponding to the image you wish to assemble. The database files output by `cspmate`, `cspmatch`, or `cspmerge` are acceptable. Remember that you can edit COM-line prescriptions contained in these files when necessary to get your desired result. *comfile* is the name of the output image file. *trimlimits* specifies in section notation the number of columns or rows to trim off each edge of each input subraster before inserting it in the output image. The default is to trim 2 columns or lines at each edge. This compensates for the 2 pixel border trashed (i.e., made up) by the *imshift* operations. The input images are not touched; rather the database is marked to exclude these edge regions from the final image. However, the images the trimmed portions of the image will be excluded during the image overlap statistics. Normally, *trimlimits* are cumulative in the database. This *trimlimits* is not. It just communicates to the task generating the overlap regions the message that the edges are flawed so do not count them as useful during the overlap computations. The `imcombine` task trims the edges of the output image at the top and right to the miminal size required. Consequently final image size can vary. Setting *register=yes* restores images to the full size requested in *mosfile*. Setting *register=no* leaves the output image of `imcombine` alone.

If your dataset contains images which share a common overlap region, you can use *common* to select the statistic you want to use to determine the z offsets between images. It can be either *mean*, *median*, or *mode*. This feeds the *zero* parameter in `imcombine`. *comb_opt* specifies the type of combining operation performed on the final set of pixels (after offsetting, thresholding, and rejection). The choices are *average* and *median*. The median uses the average of the two central values when the number of pixels is even. *reject_opt* specifies the type of rejection operation performed on the pixels remaining after offsetting, masking and thresholding. The rejection choices are:

```
none      - No rejection
minmax    - Reject the nlow and nhigh pixels
ccdclip   - Reject pixels using CCD noise parameters
crreject  - Reject only positive pixels using CCD noise parameters
sigclip   - Reject pixels using a sigma clipping algorithm
avsigclip - Reject pixels using an averaged sigma clipping algorithm
pclip     - Reject pixels using sigma based on percentiles
```

minmax is a conservative choice. See the help page for `imcombine` for discussion of the alternatives. Depending on the choice of *reject_opt*, the parameters from *weight* through *gain* listed above may be better served by choices other than those shown.

lthreshold is the lower limit for inclusion in `imstats` during intensity offset operations and for inclusion in the final image in `imcombine` during threshold operations. When using *setpix=yes* you must be sure to exclude the mask regions, which will be set to *svalue*, from the statistics. You might consider choosing a higher value to improve image statistics by restricting the range. However, be sure to keep this limit safely below the loweset real data in your image! *hthreshold* is the upper limit for inclusion in `imstats` during intensity offset operations and for inclusion in the final image in `imcombine` during threshold operations. You might consider choosing a lower value to limit the effects of bright stars and improve image statistics by restricting the range. `imcombine` thresholds its input pixels prior to any scaling, rejection, and combining; if either *lthreshold=INDEF* or *hthreshold=INDEF* the thresholds are not used.

blank is the value given to output pixel locations where no input pixels have survived the threshold and rejection algorithms. Since the over-lap region includes the edges of the frame, it is best to mask the images when computing intensity offsets and combining the images into a composite image. *setpix=yes* will mask the images using the mask *maskimage* before calculating overlap statistics. `cspmakeit` works on image copies, so the original images remain untouched. *svalue* is the value given to masked pixels. The large negative number shown assures that any output pixel which is generated through subsequent image shift and geotransformed from masked input pixels stays recognizably negative compared to good pixels so that such pixels can be thresholded from the final image. When using such a *svalue*, you must remember to exclude this value by choice of lowerlimit from statistics.

By default, *do_combine=yes* and the images are combined into a single composite image using all the available pixels. If you would rather emulate the tiling operations of the `iralign/irmatch1(2)d` tasks and have each succesive image cover up the overlap regions with prior images in the prescription, set *do_combine=no*. *shift_interp*, *bound_shift*, and *const_shift* are used internally by `imshift` and should remain at their indicated default values.

The query parameter *compute_size* should be set to *no*. The trimlimits should be [2:2,2:2] to exclude the edges which will have been affected by the transformation.

The parameters *lthreshold* and *hthreshold* should be set to include the range of all good pixels in all images. For example, the range -100 to 20000 would certainly be safe for images which have been optimally sky-subtracted. Setting these to closer tolerences may improve the precision of the common median determination. The parameters *lthreshold* and *hthreshold* also limit the range of pixels values which will be included in assembly of the final image. The limits should certainly be set to exclude pixels flagged as bad (i.e., *svalue* after masking) and pixels with unreasonable values.

7.6 Handling Larger Images

Assembling grids beyond order 6 × 6 can be a daunting task. The larger the grid, the more likely there will be weak or missing links in the registration process. At some point, one needs to worry about cumulative effects. Furthermore, `cspmate`, which uses the output from the `cspmark` task is set up to operate on mosaics no larger than 10 in X or Y. (IRAF scripts do not handle variable arrays well and larger arrays eat up too much space on the stack.) The techniques summaried above are well suited for minimally-overlapped spatial grids up to 6 × 6 in size. What is the best way to register larger images? The answer begins with it depends...!

You have a number of choices, since the database generated by `cspmate/cspmatch` does not really care where the individual frames are. Here are some recipes for linking datasets composed of dithered pairs of a 3 × 3 grid (arranged as separate 3 × 3 grids arranged vertically into a 3 × 6 mosaic), which is extensible to larger situations:

1) The plan ahead option. Include a key piece of an adjacent frame inside a 3 × 6 grid (make a 3 × 7 with the additional pieces in the top row - remember that some of the entries to `cspmosaic` can be "null". Then use `cspmatch` followed by `cspmerge` to handle the overlapped piece and bring them all to the same universe. You can still do this by creating a new mosaic with the same number of frames in the X direction as your original. Then you can reuse your `cspmark` output and run `cspmate` again with *nx_sub* and *ny_sub* set to 3. Then you run `cspmatch` on the additonal piece to get the link to the next 3 × 3 grid and use `cspmerge` to put it all together.

2) Use the option in `cspmatch` which allows the matched frames to be in separate `cspmosaic` mosaics. Match frame pairs for each mosaic that way and use `cspmerge` to put it together.

3) Make a `cspmosaic` mosaic of `cspmakeit` combined mosaics. Here you need to get crafty, since `cspmosaic` only accepts pieces of the same size. You can use `mkpattern` in the `noao.artdata` package to make an image big enough to fit any of the pieces and then `imcopy` each `cspmakeit` frame to the larger template. You should use `imreplace` to set all the bad and border pixels to that large negative number the *setpix* option uses (e.g., -1.0E+08; they have been set to *blank* by `cspmakeit`). Then use `cspmosaic` to make the new mosaic and `cspmark/cspmate` or `cspmatch` to link them. Do not use the *setpix* option (you took care of that when you did `cspmakeit` before; now you do not have a proper mask

image) or the *tran* options (you have already done that during `cspmakeit`) along the way in `cspmatch`, `cspmate`, or `cspmakeit`.

There is no clear best way to go. Options 1 & 2 rely on a single overlapping frame for the link, while option 3 allows you to use several. However, if the 3 × 3 grids are not put together well (because of weak or missing links), option 3 might lead to contradictions at the edges.

7.7 CASPIR Image Composite Database Format

The `caspir` package generates composite databases according to a simple format. The position of each individual image is descibed by a COM-line (a line beginning with "COM"). Commenting out a COM-line (by putting a "#" in front) eliminates that image from the final combined image. A sample database file and a description of the COM-line follows:

```
#DBM Wed 15:56:15 15-Jan-92 CSPMERGE: mosn10_024k.cdb
#DBM    master_file     mosn10_024k.mdb
#DBM    master_ref      mosn10_024k[258:513,258:513]
#DBM    merge_file      mosn10_024k.cdb
#DBM    merge_file      mosn10_024k_10.cdb
#DBM    merge_file      mosn10_024k_11.cdb
#DBM    merge_file      mosn10_024k_12.cdb
#DBM    merge_file      mosn10_024k_13.cdb
#DBM    merge_file      mosn10_024k_14.cdb
#DBM    merge_file      mosn10_024k_15.cdb
#DBM    merge_file      mosn10_024k_16.cdb
#DBM    merge_file      mosn10_024k_17.cdb
#DBM    merge_file      mosn10_024k_18.cdb
#DB # Wed 14:23:16 15-Jan-92:
#DB begin       mosn10_024k
#DB     trimsection     [*,*]
#DB     medsection      [*,*]
#DB     ncols           256
#DB     nrows           256
#DB     nxsub           3
#DB     nysub           8
#DB     nxoverlap       -1
#DB     nyoverlap       -1
#DB     corner          ll
#DB     order           row
#DB     raster          no
#DB     oval            10000.
#DB     nsubrasters     24
#DB  Wed 14:23:37 15-Jan-92:
#DB     null_input      23-24
#DB     mosaic          mosn10_024k
#DB     median_compute  yes
#DB     median_subtract no
#DBL Wed 15:27:57 15-Jan-92:
#DBL    info_file       _Tgmh9352es.ctr
#DBL    nxrsub          2
#DBL    nyrsub          2
#DBL    ref_image       mosn10_024k[258:513,258:513]
#DBL    ref_nim         5
#DBG Wed 15:28:10 15-Jan-92:
#DBG    basis_info      mosn10_024k.ctr.1
#DBG    lap_basis       center
```

```
#DBG    trimlimits      [4:3,8:0]
#DBT    mos_transform   no
#DBM    do_tran         no
#DBM    out_sec         [1:727,1:703]
#DBM    overlap_sec     [475:252,455:255]
COM_000 mosn10_024k[258:513,258:513]   5 253 9 256  245  220  0.00  0.00 0.00 |
COM_001 mosn10_024k[1:256,1:256]       5 253 9 256   21    4  0.44 -0.31 0.00 |
COM_002 mosn10_024k[258:513,1:256]     5 253 9 256  241    0  0.32  0.22 0.00 |
COM_003 mosn10_024k[515:770,1:256]     5 253 9 256  462    0 -0.39 -0.30 0.00 |
COM_004 mosn10_024k[1:256,258:513]     5 253 9 256   25  224 -0.47  0.17 0.00 |
COM_005 mosn10_024k[258:513,258:513]   5 253 9 256  245  220  0.00  0.00 0.00 |
COM_006 mosn10_024k[515:770,258:513]   5 253 9 256  466  220 -0.42 -0.48 0.00 |
COM_007 mosn10_024k[1:256,515:770]     5 253 9 256   28  445 -0.08 -0.19 0.00 |
COM_008 mosn10_024k[258:513,515:770]   5 253 9 256  248  442  0.26 -0.13 0.00 |
COM_009 mosn10_024k[515:770,515:770]   5 253 9 256  469  439  0.01  0.24 0.00 |
COM_010 mosn10_024k[1:256,772:1027]    5 253 9 256    0    4 -0.34  0.11 0.00 |
COM_011 mosn10_024k[258:513,772:1027]  5 253 9 256  220    1 -0.28 -0.23 0.00 |
COM_012 mosn10_024k[515:770,772:1027]  5 253 9 256  439    0  0.47  0.23 0.00 |
COM_013 mosn10_024k[1:256,1029:1284]   5 253 9 256    2  225  0.41 -0.39 0.00 |
COM_014 mosn10_024k[258:513,1029:1284] 5 253 9 256  223  220 -0.03  0.48 0.00 |
COM_015 mosn10_024k[515:770,1029:1284] 5 253 9 256  443  220  0.24 -0.07 0.00 |
COM_016 mosn10_024k[1:256,1286:1541]   5 253 9 256    6  445  0.11  0.21 0.00 |
COM_017 mosn10_024k[258:513,1286:1541] 5 253 9 256  226  442  0.05  0.25 0.00 |
COM_018 mosn10_024k[515:770,1286:1541] 5 253 9 256  447  440 -0.15 -0.42 0.00 |
```

Each image has a ”COM-line”, which is arranged as follows:

Col. 1: COM path identification. Unless renumbered, the _XXX corresponds to the original path position in the `cspmos` database. 'COM_000' marks the reference image.

Col. 2: Actual name of the subraster, including image section, giving the location where this piece of the dataset can be found within the mosaic image produced by `cspmosaic`.

Col. 3 – Col. 6: xmin, xmax, ymin, ymax. The subsection of the original image subraster which will be included in the final image. The cumulative effects of the *trimlimits* parameters are reflected here.

Col. 7 – Col. 8: The x and y coordinates of the integer location of the subraster in the final image. The `imshift`ed subraster will be offset to this integer location in the final image.

Col. 9 – Col. 10: The x and y coordinates of the fraction location of the subraster in the final image. The subraster will be `imshift`ed by this amount prior to image combination.

Col. 11: The intensity offset for the subraster which will be added prior to image combination (not cumulative - applies to image only).

Col. 12: An end-of-line marker designed to frustrate the system daemons which want to suppress any LF at the end of a line in columns 79 or 80 (thereby merging the COM-lines into one line!)

Note: Buried deep in the UNIX/IRAF system is a ”daemon” which silently decides ”The line is too long, I must silently fix it!”. This ”feature” is activated within the *.login* file (and elsewhere) when the environmental variable *wrap* is set. Lines which will be 80 characters long are optionally given an automatic LF, so that you need not worry about such issues when you are typing. This feature will break COM-lines and raise all sorts of havoc within the CASPIR registration database files!

8 Long-Slit Grism Data Reduction

8.1 Introduction

CASPIR produces near-infrared spectra in both long slit and cross-dispersed formats. This section deals with the reduction of long-slit grism data. These observations normally consist of a number of object and sky frames acquired through the execution of a DO file, or via the nodding observing mode. Typical observing sequences would:

1) Record off-source sky spectra for extended objects, and object spectra with the object placed at different positions along the slit to counter ghosts and bad pixels.

2) Record nodded pairs of frames with an unresolved or slightly resolved object placed at two positions along the slit to permit sky subtraction.

3) Record sets of frames with the object placed at a number of positions along the slit to permit sky subtraction and to counter ghosts and bad pixels.

A spectroscopic *dataset* is therefore naturally defined as a set of related observations of a given object with a particular grism. The reduction of most long-slit grism datasets will follow the path:

1) Create BIAS and DARK frames, and linearize object and sky frames.

2) Subtract sky background from object frames, and combine all object frames in the dataset to a single spectral image.

3) Create FLAT frames for each grism, and remove pixel-to-pixel sensitivity variations.

4) Fix known and random bad pixels.

5) Apply a geometrical transformation to align the dispersion direction with image columns, align the spatial direction with image rows, and perform the wavelength calibration.

6) Correct for non-uniform illumination along the slit.

7) Extract one dimensional spectra from the combined spectral images with appropriate background subtraction in the slit direction to remove residual sky features.

8) Flux calibrate the one dimensional spectra.

9) Correct for absorption features in the standard star spectrum, inexact cancellation of terrestrial atmospheric absorption features, and slit losses in the standard star measurement.

Users are cautioned that infrared spectroscopy presents greater challenges than optical spectroscopy. The infrared sky makes a significant contribution to deep infrared spectroscopic observations and must be removed using frequent sky observations. Terrestrial atmospheric absorption is also strong in the near-infrared (see Figure 60 to 63 in Appendix M) and must be removed through division by a measurement of a featureless star obtained close to the object measurement in both time and position on the sky. The quality of the final spectrum frequently depends on the accuracy of this correction. Spectroscopic observations will normally use long integration times that increase the importance of dark current as a noise source. Pixels that saturate due to their high dark current are not removed by sky subtraction and must be treated as bad pixels.

The reduction procedures described here use the local MSSSO CASPIR package running in IRAF. Refer to §6 for instructions on how to obtain this package. Users are advised to familiarize themselves with the general procedures available within IRAF for spectral reduction by reading the documents *A User's Guide to CCD Reductions with IRAF* and *A User's Guide to Reducing Slit Spectra with IRAF*. Compressed postscript versions of these documents are available via anonymous ftp to iraf.noao.edu in the files *iraf/docs/ccduser2.ps.Z* and *iraf/docs/spect.ps.Z*.

8.2 Forming BIAS and DARK Frames

Spectroscopic data require the same corrections for electrical offsets and charge leakage as required for imaging data. BIAS and DARK frames for spectroscopic data reduction are formed in exactly the same way as for imaging data using the `cspcombine` task. Refer to §6 for descriptions of these procedures.

8.3 Linearity Correction

Spectroscopic observations must also be linearized as described in §6. A convenient environment in which to conduct this and the remainder of the basic long-slit grism reduction is provided by the `redgspec` task. The `redgspec` task is the spectroscopic equivalent of the `redimage` task used for imaging data reduction. For example, to linearize a set of images obtained with a 180 sec exposure time, first form a list file of the image filenames using the `csplist` task by typing:

```
csplist time 180 images=@allfiles > 180files
```

`redgspec` overwrites the input images so first copy the input images to temporary files. This can be done by typing:

```
imcopy @180files @180files//t
```

Now use `epar` to set the `redgspec` parameters as listed below.

```
                                           I R A F
                            Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redgspec

(images =            @180files) List of CASPIR input images
(spectru=                     ) Base name of spectrum file

(linear =                  yes) Linearize data?
(combine=                   no) Combine individual 2D images?
(flatten=                   no) Divide by flatfield?
(fixbad =                   no) Fix known bad pixels?
(clean  =                   no) Interactively clean additional pixels?
(transfo=                   no) Geometrically transform and subset?
(illumin=                   no) Correct non-uniform slit illumination?
(extract=                   no) Extract 1D spectra?
(fluxcal=                   no) Flux calibrate spectra?
(flatdiv=                   no) Divide by flat spectrum star?
(plot   =                   no) Plot spectrum?

(bias   =               dark03) Bias frame to use
(dark   =              dark180) Dark frame to use
(obstype=                 abba) Type of observation made
(zerosec=     [200:250,10:240]) Zero level image section
(flatfil=                     ) Flatfield frame to use
(badfile=      caspirdir$grism) Bad pixel file
(badtype=               interp) Type of bad pixel correction
(illfile=                     ) Illumination frame to use
(reffile=                     ) Comparison extraction reference file
(fluxspe=                     ) Flux calibration spectrum to use
(flatspe=                     ) Flat spectrum star file to use

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

The flags *linear*, *combine*, *flatten*, *fixbad*, *clean*, *transform*, *illumination*, *extract*, *fluxcal*, *flatdiv*, and *plot* define the reduction steps that will be performed. The remainder of the parameters are used in the execution of these basic functions.

The parameters relevant to the linearization of a particular dataset are *bias* and *dark*. These are used in the same way as described in §6 for `redimage`.

8.4 Defining The Geometrical Transformation

Spectra recorded with the long-slit grisms in CASPIR have tilted slit images which may vary along the spectrum. This distortion must be corrected in order to accurately align the dispersion direction with the image columns and the spatial direction with image lines. Files containing fits to these geometrical distortions for each grism are distributed along with the IRAF CASPIR package. However, it is advisable to define new transformations for each observing run.

Curvature in the spectral direction can be traced using sky-subtracted images of stellar spectra placed at different positions along the slit. Spectra at 11 evenly-spaced positions along the long-slit are adequate. Slit tilt is traced using spectral images of arc lamps. These also serve to establish the wavelength calibration.

First, form a SKY frame by median combining the individual stellar spectral images, then form the stellar curvature reference frame by subtracting this SKY frame from the star images. Then, form xenon and/or argon arc lamp frames by subtracting *lamp on* and *lamp off* pairs, according to the following example:

```
delete tfiles
csplist list first=ir078 num=11 > tfiles ; tail tfiles
cspcombine @tfiles sky_k comb_opt=median
cspflat @tfiles sky_k star_k

cspflat ir005,ir006 ir007,ir008 xenon_k
cspflat ir001,ir002 ir003,ir004 argon_k
```

Note that the geometrical transformation is best defined using frames that have not been flatfielded.

The geometrical transformation for a particular grism is defined using the `cspgtrans` task which has the parameters listed below.

```
                                I R A F
                  Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspgtrans

curve   =              star_k  Curvature reference frame to use
xenon   =             xenon_k  Xenon lamp frame to use
argon   =             argon_k  Argon lamp frame to use

(verbose=                 yes) Verbose output?
profile =                      Enter the profile section to use
(mode   =                  ql)
```

The *curve* parameter defines the stellar curvature reference frame name, the *xenon* parameter defines the xenon arc lamp filename, and the *argon* parameter defines the argon arc lamp filename. At least one arc lamp frame must be specified. Line lists for the xenon and argon arc lamps are distributed with the IRAF CASPIR package in the files *xenon.dat* and *argon.dat*.

The `cspgtrans` task first displays the curvature reference frame, and an average profile through the first, middle, or last ten lines of the image, as specified by the *profile* parameter, is displayed in the graphics display using the `noao.twodspec.identify` task. Mark the position of the star by using the cursor and typing 'm'. Enter the appropriate column number, and type 'q' to exit this section. `cspgtrans` then uses `noao.twodspec.reidentify` to trace the spectrum. Answer 'yes' to the question *Do you want to save to database?*. The `cspgtrans` task then displays the xenon arc lamp spectum image (if one was specified) and uses `noao.twodspec.identify` to display an average profile through the central three columns (along the dispersion). Referring to the arc lamp spectra in Figs. 38–40 of Appendix J, type 'm' to mark the locations of a few emission lines and enter their wavelengths in Angstroms. Then type 'f' to obtain a preliminary fit to the wavelength calibration. Type 'q' to exit the fit routine, and then 'l' to automatically locate other arc lines. Delete erroneous identifications by typing 'd'. Use the window commands 'w t' and 'w b' to change the top and bottom plot values, and 'w a' to autoscale the plot. Fit the wavelength calibration again, and type 'q' to exit the fit routine and another 'q' to exit the identify routine. **cspgtrans** then uses **noao.twodspec.reidentify** to trace the slit images. The **cspgtrans** task then repeats the identification process for the argon arc lamp image (if one was specified). Answer 'yes' to *Fit interactively (yes)?*, and remove erroneous data points and points off the ends of the slit using the 'd' key; typing 'd' followed by a 'p' deletes a single point, typing 'd' followed by an 'x' or a 'y' deletes all points at that constant x or y. The fit is best displayed by looking at the residuals as a function of x position; type 'x' followed by 'x', 'y' followed by 'r', and then 'r' to redisplay the plot. Redo the fit by typing 'f'. Display the fit itself by typing 'x' 'x', 'y' 'y', and then 'r' to redisplay the plot. When a satisfactory fit has been obtained, exit the fit routine by typing 'q'. Then answer 'yes' to *Write coordinate map to the database (yes)?*.

The fit parameters are stored in a local subdirectory named *database/* of the current directory, and in the database directory pointed to by the IRAF *database$* environment variable. The x and y fits for a particular grism are stored in files with names like *fcK_grism_10x* and *fcK_grism_10y* in those directories.

8.5 Combining Individual Images

OH airglow line emission is a problem for near-infrared spectroscopy. This emission is bright, especially in the H band, and varies on timescales of $\sim$ 10 minutes. It is therefore necessary to obtain frequent sky exposures, either by offsetting an object along the spectrograph slit, or by recording spectra at off-source sky positions. These observations must now be combined into single object and sky images. Generally, spectroscopic datasets contain fewer observations than imaging datasets, with the exposure times for each observation being longer. Object and sky frames are therefore combined by simple differencing and averaging, rather than by forming median sky frames as is done for imaging data.

Spectroscopic data sets are sky subtracted, and the object images combined, using the **redgspec** task by unsetting the *linear* flag, setting the *combine* flag, and supplying values for the *spectrum*, *obstype*, and *zerosection* parameters. *spectrum* is the base name of the combined spectrum files. *obstype* defines the type of observation in the dataset. *obstype=abba* indicates that the object was nodded between two position along the slit while frames were recorded in an ABBA sequence. Differencing each AB pair produces positive and negative spectra in the object image that are averaged and output to a file named by appending *.oim* to the base spectrum name. 'A beam' and 'B beam' sky images are also formed by averaging the B and A beam object frames, respectively, and these images are output to files named by appending *.aim* and *.bim*, respectively, to the base name. Refer to Figure 32 to trace the file name conventions used. The *zerosection* parameter specifies an image section that is used to sample the off-slit background level in these sky images. This DC level is subtracted from the sky images. Sky images are carried throughout the reduction and can be used to define the illumination profile of the spectrograph slit and to improve the wavelength calibration on long exposure frames. If this is to be done, it is advisable to record DARK frames of the same duration close in time to the sky frames. *obstype=soos* indicates that the dataset consists of sequences of sky, object, object, sky images, where the sky images are recorded with the slit positioned off the object. *obstype=osso* indicates that the dataset consists of sequences of object, sky, sky, object frames, where the sky frames are recorded with the slit positioned off the object. Averaged object and sky images are formed for both these observation types and are output to files named by appending *.oim* and *.sim*, respectively, to the base name. In both cases, the *zerosection* parameter specifies an image section that is used to subtract a DC level from the combined sky image. *obstype=comparison* indicates that the dataset is to be combined to form a comparison observation (e.g., an arc lamp image or a twilight sky image). All images in the dataset are averaged and the result is output to a file named by appending *.cim* to the base name. The *obstype* parameter is written to each output file header and is used in subsequent processing of the dataset. No allowance is made for drifts in the position of the object along the slit during the observations.

A typical **redgspec** parameter list for combining a single *abba* dataset in the list file *tfiles* is shown below. The sky subtracted and combined object image will be output to the file *sp150.oim*.

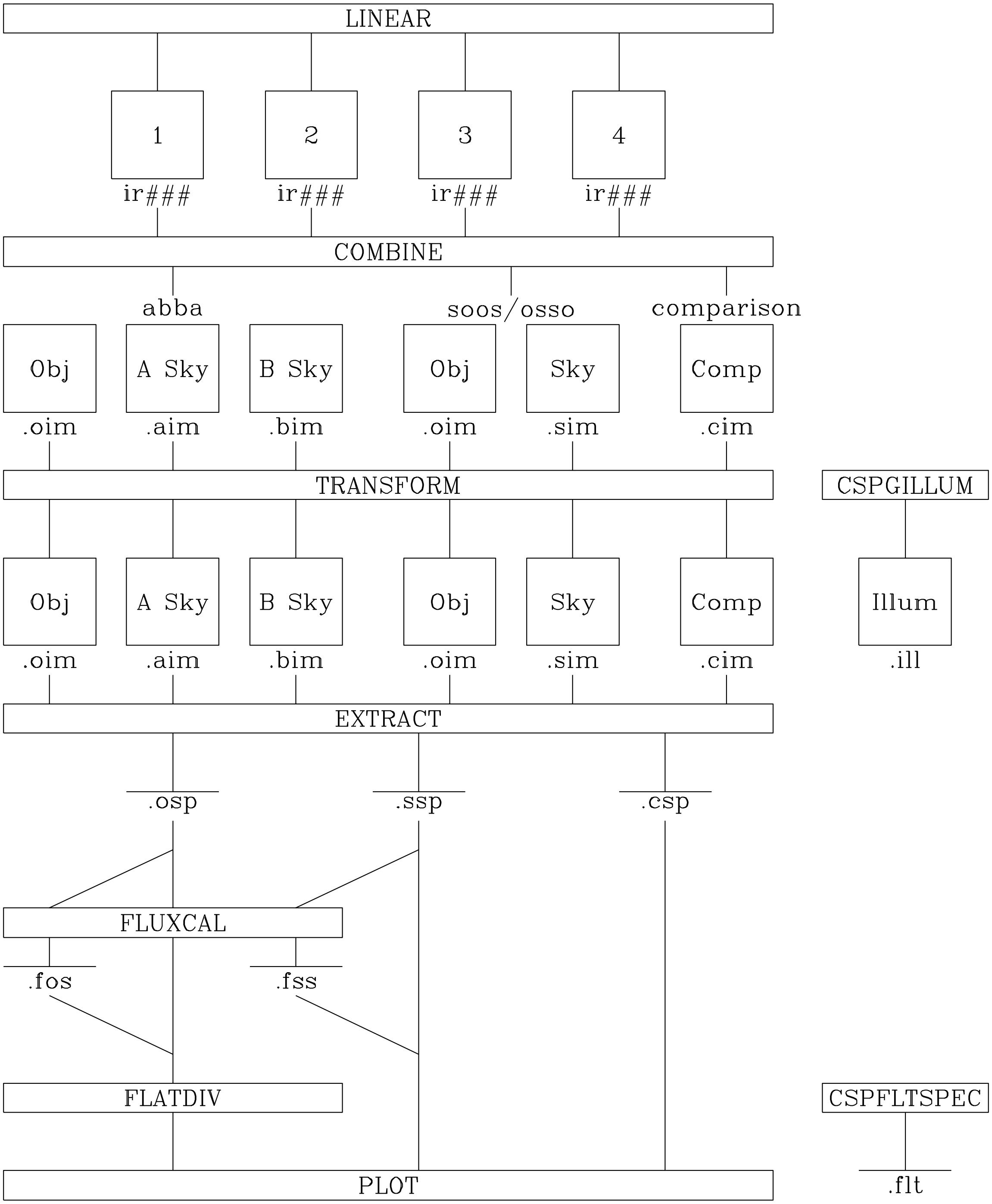


Figure 32: File name conventions used in the long-slit grism reduction.

```
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redgspec

(images =             @tfiles) List of CASPIR input images
(spectru=               sp150) Base name of spectrum file

(linear =                  no) Linearize data?
(combine=                 yes) Combine individual 2D spectra?
(flatten=                  no) Divide by flatfield?
(fixbad =                  no) Fix known bad pixels?
(clean  =                  no) Interactively clean additional pixels?
(transfo=                  no) Geometrically transform and subset?
(illumin=                  no) Correct non-uniform slit illumination?
(extract=                  no) Extract 1D spectra?
(fluxcal=                  no) Flux calibrate spectra?
(flatdiv=                  no) Divide by flat spectrum star?
(plot   =                  no) Plot spectrum?

(bias   =                bias) Bias frame to use
(dark   =             dark180) Dark frame to use
(obstype=                abba) Type of observation made
(zerosec=     [200:250,10:240]) Zero level image section
(flatfil=                    ) Flatfield frame to use
(badfile=      caspirdir$grism) Bad pixel file
(badtype=              interp) Type of bad pixel correction
(illfile=                    ) Illumination frame to use
(reffile=                    ) Comparison extraction reference file
(fluxspe=                    ) Flux calibration spectrum to use
(flatspe=                    ) Flat spectrum star file to use

(verbose=                 yes) Verbose output?
(imglist=                    )
(mode   =                  ql)
```

8.6 Flatfielding

Spectroscopic FLAT frames are derived from sets of *lamp on* and *lamp off* pairs for each grism. These are obtained using the incandescent lamp in the Comparison Lamp Module. The FLAT frames are formed in the same way as the FLAT frames for imaging datasets by differencing and then combining the linearized *lamp on* and *lamp off* pairs using the `cspflat` task. The inputs required are a list of *lamp on* frames, a list of *lamp off* frames, and an output filename. For example,

```
cspflat ir007,ir009,ir011 ir008,ir010,ir012 flat_k comb_opt=average
```

averages the *lamp on* frames ir007–11 and the *lamp off* frames ir008–10, takes their difference, then normalizes the median pixel value of the difference in the image section specified by the *statsec* parameter to unity, and writes the resulting FLAT frame to the file *flat_k*. The *statsec* parameter should be set to the image section corresponding to the slit-center. No attempt is made to correct for the spectral distribution of the lamp or any non-uniformity in the slit illumination by the lamp.

The `cspflat` task has the parameters listed below.

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspflat
```

```
ons     =    ir007,ir009,ir011 List of lamp ON frames
offs    =    ir008,ir010,ir012 List of lamp OFF frames
flat    =               flat_k Output flatfield frame
(comb_op=             average) Type of combine operation
(statsec=     [100:150,10:240]) Image section for computing statistics

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

The *comb_opt* parameter should be *average* if the number of on or off exposures is less than about 5 and *median* if greater than about 5.

The object, sky, and comparison images for the specified base spectrum name are flattened by unsetting the *combine* flag in `redgspec`, setting the *flatten* flag, and setting the *flatfile* parameter to the appropriate FLAT frame filename.

8.7 Fixing Known Bad Pixels

Spectroscopic datasets usually contain only a small number of frames so that bad pixels must be corrected by interpolation, and this interpolation should ideally be constrained to occur only in the spectral direction. The longer integration times used for spectroscopic datasets also demand the use of a more comprehensive bad pixel file than for imaging datasets. Procedures for defining an ascii bad pixel file were outlined in §6. The same bad pixel file used with `noao.proto.fixpix` can be used for spectroscopic data, but it is not possible to define the interpolation direction using `fixpix`. To do this, it is necessary to use the IRAF `imedit` task and specify a bad pixel file that can be used as the cursor input file to `imedit`. Rectangular regions are specified in this file by cursor records defining the corners of the rectangle. An *l* cursor command specifies interpolation between nearest image lines, so that interpolation occurs in the spectral direction. An example of such a file is listed below.

```
 25 111 1 l
 25 111 1 l
108  87 1 l
108 113 1 l
256   1 1 l
256 256 1 l
  1   1 1 l
256   1 1 l
185 240 1 l
190 245 1 l
```

Files of this format are identified within the CASPIR package by a *.bpx* extension. The standard CASPIR spectroscopic bad pixel list plus a large number of high dark current pixels are contained in the file *caspirdir$grism.bpx* in this format. If the *l* cursor command were changed to an *f* in this file, `imedit` would interpolate in the shorter dimension of each rectangle and the operation would be equivalent to that of `fixpix`.

To apply a bad pixel correction using the `redgspec` task, set the *fixbad* flag and nominate the bad pixel filename and the type of correction using the *badfile* and *badtype* parameters. *badtype=interpolate* causes `imedit` to be used to interpolate over the bad pixels listed in a *.bpx* file. This is the preferred choice for spectroscopic data. *badtype=fixpix* causes `fixpix` to be used to interpolate over bad pixels listed in a *.bad* file. This is included for consistency with the imaging reduction procedure `redimage`. As with `redimage`, the *badfile* parameter should not include the file extension (*.bpx*, *.bad*, or *.pl*). `redgspec` will append this.

8.8 Interactively Cleaning Bad Pixels

The longer integration times used in recording spectroscopic datasets make cosmic rays and random hot pixels more of a problem than for imaging datasets. These undesirable features must be interactively removed before they are smeared when the curved spectrum is straightened.

The `redgspec` task can be used to interactively clean bad pixels by setting the *clean* flag. This invokes the IRAF `imedit` task to first clean the object image (*.oim* file extension) and the associated sky images (*.aim*, *.bim*, or *.sim* file extensions). After the image to be cleaned has been displayed, center the image display cursor on the bad pixel and type *l*. Type *l* again to correct a single bad pixel, or move to another pixel and type *l* again to correct a rectangular region of bad pixels. Type *q* to terminate cleaning the current image and move to cleaning the next image.

Users should become familiar with the zoom and pan functions of `ximtool`. The IRAF `imedit` task does not function properly with `saoimage` operating under Solaris 2.

8.9 Applying The Geometrical Transformation

Once the geometrical transformation has been defined and all processing dependent on the original geometrical pattern of the image has been completed, it is a simple matter to apply the geometrical transformation to straighten the spectrum and align slit images with image lines.

The current geometrical transformations are applied to images in a dataset using the `redgspec` task by setting the *transform* flag. The current transformations are the transformations defined by the fit files located in the directory pointed to by the IRAF environment variable *database$*. The wavelength calibration is stored in the transformed file header.

8.10 Slit Illumination Correction

The spectrograph slits in CASPIR are machined slots in separate thin metal plates, and as such are expected to vary slightly in width along their lengths. The sensitivity variations introduced by these width variations are partially removed by the flatfield correction, but the flatfield frames also potentially suffer from non-uniform illumination by the flatfield lamp. Geometrically transformed spectral images of blank sky are needed to accurately define the illumination profile of the spectrograph slit. These frames can be formed from spectroscopic observations of the twilight sky for each grism and through each slit used, or by combining deep off-source sky measurements taken as program observations.

Slit illumination correction images for each long-slit grism are formed from geometrically transformed sky frames, or comparison frames in the case of twilight sky measurements, using the `cspgillum` task, which calls the `noao.twodspec.illum` task. The inputs required are a list of the base names of the SKY frames, and the base name of the output illumination files. For example,

```
cspgillum @skyfiles illum_k
```

The output illumination function file names are formed by appending *.ill* to the specified output base name.

The `cspgillum` task has the parameters listed below. The *comb_opt* parameter defines the way in which the individual sky frames in the list are combined. *comb_opt* should be *average* if the number of sky images is less than about 5 and *median* if greater than about 5. The *statsec* parameter defines the image section within the sky frame over which the illumination profile is computed. This should be set to the region of the image illuminated by the spectrum.

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspgillum
```

```
skies   =           @skyfiles  List of base sky frame names
illfile =             illum_k  Output illumination frame

(comb_op=             average) Type of combine operation
(statsec=           [1:230,*]) Image section for computing profile

(verbose=                 yes) Verbose output?
(imglist=                   )
(mode   =                  ql)
```

You are asked `Determine illumination interactively for illfile.ill (yes):`. Answering *yes* to this question causes an average spectrum to be plotted in the graphics display. You are required to mark the range of the bin that will be used for determining the average profile along the spatial direction. The default is to use the entire spectrum, but this can be changed using cursor commands in the graphics display window. The available commands are listed below. Type *q* to proceed to fitting the spatial profile.

```
                Set Illumination Bins

?       Print options
i       Clear the sample ranges
q       Exit interactive curve fitting
s       Set bins with the cursor
I       Interrupt task immediately

The parameters are listed or set with the following commands which may be
abbreviated.  To list the value of a parameter type the command alone.

:bins value             Illumination bins
:show                   Show the values of all the parameters
```

You are then asked the question `Determine illumination interactively for illfile.ill[1:230,*] at bin 1 (yes):`. Answer *yes* to this question and the spatial profile is plotted in the graphics display window. A fit to the profile is made using the IRAF `icfit` task. The parameters of the fit can be changed interactively using the interactive curve fitting cursor commands listed below. Type *d* to delete a point. Type *f* to perform the fit. Type *r* to redraw the graph. The fitting function can be changed by typing, e.g., *:function chebyshev.* The order of the fit can be changed by typing, e.g., *:order 2.* The number of samples being averaged to form the fitted data can be changed by typing, e.g., *:naverage 2.* The values of all fit parameters can be seen by typing *:show.* Type *q* to exit the interactive curve fitting task when a suitable fit has been obtained.

```
1. INTERACTIVE CURVE FITTING CURSOR OPTIONS

?       Print options
a       Add point to constrain fit
c       Print the coordinates and fit of point nearest the cursor
d       Delete data point nearest the cursor
f       Fit the data and redraw or overplot
g       Redefine graph keys.  Any of the following data types may be along
        either axis.
            x  Independent variable     y  Dependent variable
            f  Fitted value             r  Residual (y - f)
            d  Ratio (y / f)            n  Nonlinear part of y
h-l     Graph keys.  Defaults are h=(x,y), i=(y,x), j=(x,r), k=(x,d), l=(x,n)
o       Overplot the next graph
q       Exit the interactive curve fitting.  Carriage return will also exit.
r       Redraw graph
```

```
s       Set sample range with the cursor
t       Initialize the sample range to all points
u       Undelete the deleted point nearest the cursor
w       Set the graph window.  For help type 'w' followed by '?'.
x       Change the x value of the point nearest the cursor
y       Change the y value of the point nearest the cursor
z       Delete sample region nearest cursor
I       Interrupt task immediately


2. INTERACTIVE CURVE FITTING COLON COMMANDS

The parameters are listed or set with the following commands which may be
abbreviated.  To list the value of a parameter type the command alone.

:show [file]            Show the values of all the parameters
:vshow [file]           Show the values of all the parameters verbosely
:xyshow [file]          Show the x, y fit, and y data values
:errors [file]          Print the errors of the fit (default STDOUT)
:function [value]       Fitting function (chebyshev, legendre, spline3, spline1)
:grow [value]           Rejection growing radius
:naverage [value]       Sample averaging or medianing window
:order [value]          Fitting function order
:low_reject [value]     Low rejection threshold
:high_reject [value]    High rejection threshold
:niterate [value]       Number of rejection iterations
:sample [value]         Sample ranges
:markrej [value]        Mark rejected points?

Additional commands are available for setting graph formats and manipulating
the graphics.  Use the following commands for help.

:/help                  Print help for graph formatting option
:.help                  Print help for general graphics options


3. INTERACTIVE CURVE FITTING GRAPH KEYS

The graph keys are h, i, j, k, and l.  The graph keys may be redefined to
put any combination of axes types along either graph axis with the 'g' key.
To define a graph key select the desired key to redefine and then specify
the axes types for the horizontal and vertical axes by a pair of comma
separated types from the following:

d  Ratio (y / f)
f  Fitted values
r  Residuals of fit (y - f)
n  Nonlinear part of data (linear component of fit subtracted)
x  Independent variable
y  Dependent variable (data being fit)
```

The object, sky, and comparison images for a dataset can be corrected for non-uniform slit illumination by setting the *illumination* flag in `redgspec`, and setting the *illfile* parameter to the appropriate illumination correction base filename. A typical `redgspec` parameter list for applying the slit illumination correction in the file *illum_k* to the spectrum with the base name *sp175* is shown below.

```
                                   I R A F
```

```
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redgspec

(images =             @tfiles) List of CASPIR input images to reduce
(spectru=               sp175) Base name of spectrum file

(linear =                  no) Linearize data?
(combine=                  no) Combine individual 2D spectra?
(flatten=                  no) Divide by flatfield?
(fixbad =                  no) Fix known bad pixels?
(clean  =                  no) Interactively clean additional pixels?
(transfo=                  no) Geometrically transform and subset?
(illumin=                 yes) Correct non-uniform slit illumination?
(extract=                  no) Extract 1D spectra?
(fluxcal=                  no) Flux calibrate spectra?
(flatdiv=                  no) Divide by flat spectrum star?
(plot   =                  no) Plot spectrum?

(bias   =                bias) Bias frame to use
(dark   =             dark180) Dark frame to use
(obstype=                osso) Type of observation made
(zerosec=      [190:195,10:90]) Zero level image section
(flatfil=              flat_k) Flatfield frame to use
(badfile=      caspirdir$grism) Bad pixel file
(badtype=              interp) Type of bad pixel correction
(illfile=             illum_k) Illumination frame to use
(reffile=                    ) Comparison extraction reference file
(fluxspe=                    ) Flux calibration spectrum to use
(flatspe=                    ) Flat spectrum star file to use

(verbose=                 yes) Verbose output?
(imglist=                    )
(mode   =                  ql)
```

8.11 Extraction of 1D Spectra

We now have an averaged two-dimensional image of the long-slit grism spectrum. For most applications, we want to extract a one-dimensional spectrum from this image. In general, residual sky emission lines will also be present in the image. This is because the sky emission line spectrum varies on shorter timescales than our integration time. This sky background is removed during the extraction process by linear interpolation along the slit direction.

One-dimensional spectra are extracted using the **redgspec** task by setting the *extract* flag, and optionally defining a value for the *reffile* parameter. The **redgspec** task uses the **apall** task in the IRAF **noao.twodspec.apextract** package to perform the extraction and background subtraction interactively. It is recommended that users become familiar with the workings of this package. The available cursor commands are listed below. Generally, you will want to edit the extraction aperture for each object by setting *reffile=""*. However, this may be difficult for extremely weakly-exposed spectra and is inappropriate for comparison spectra. In these cases, you can use a previously defined extraction aperture from a reference spectrum. If a reference spectrum is to be used, set the *reffile* parameter to the filename of the reference spectrum.

```
                  APEXTRACT CURSOR KEY SUMMARY

?  Print help            a  Toggle all flag          b  Set background(s)
```

```
c  Center aperture(s)    d  Delete aperture(s)      e  Extract spectra
f  Find apertures        g  Recenter aperture(s)    i  Set aperture ID
j  Set beam number       l  Set lower limit(s)      m  Mark and center aperture
n  New uncentered ap.    o  Order the ap. numbers   q  Quit
r  Redraw graph          s  Shift aperture(s)       t  Trace aperture(s)
u  Set upper limit(s)    w  Window graph            y  Y level limit(s)
z  Resize aperture(s)    .  Nearest aperture        +  Next aperture
-  Previous aperture     I  Interrupt

                 APEXTRACT COLON COMMAND SUMMARY

:apertures      :apidtable      :avglimits      :b_function     :b_grow
:b_high_reject  :b_low_reject   :b_naverage     :b_niterate     :b_order
:b_sample       :background     :bkg            :center         :clean
:database       :extras         :gain           :image          :line
:llimit         :logfile        :lower          :lsigma         :maxsep
:minsep         :npeaks         :nsubaps        :nsum           :order
:parameters     :peak           :plotfile       :r_grow         :radius
:read           :readnoise      :saturation     :shift          :show
:skybox         :t_function     :t_grow         :t_high_reject  :t_low_reject
:t_naverage     :t_niterate     :t_nsum         :t_order        :t_sample
:t_step         :t_width        :threshold      :title          :ulimit
:upper          :usigma         :weights        :width          :write
:ylevel         :t_nlost

                APEXTRACT CURSOR KEYS

?    Print help
a    Toggle the ALL flag
b an Set background fitting parameters
c an Center aperture(s)
d an Delete aperture(s)
e an Extract spectra (see APSUM)
f    Find apertures up to the requested number (see APFIND)
g an Recenter aperture(s) (see APRECENTER)
i  n Set aperture ID
j  n Set aperture beam number
l ac Set lower limit of current aperture at cursor position
m    Define and center a new aperture on the profile near the cursor
n    Define a new aperture centered at the cursor
o  n Enter desired aperture number for cursor selected aperture and remaining
     apertures are reordered using apidtable and maxsep parameters
     (see APFIND for ordering algorithm)
q    Quit
r    Redraw the graph
s an Shift the center(s) of the current aperture to the cursor position
t ac Trace aperture positions (see APTRACE)
u ac Set upper limit of current aperture at cursor position
w    Window the graph using the window cursor keys
y an Set aperture limits to intercept the data at the cursor y position
z an Resize aperture(s) (see APRESIZE)
.  n Select the aperture nearest the cursor to be the current aperture
+  c Select the next aperture (in ID) to be the current aperture
-  c Select the previous aperture (in ID) to be the current aperture
I    Interrupt task immediately.  Database information is not saved.

The letter a following the key indicates if all apertures are affected when
```

```
the ALL flag is set.  The letter c indicates that the key affects the
current aperture while the letter n indicates that the key affects the
aperture whose center is nearest the cursor.

                        APEXTRACT COLON COMMANDS

:show [file]       Print a list of the apertures (default file is STDOUT)
:parameters [file] Print current parameter values (default file is STDOUT)
:read [name]       Read apertures from database (default to the current image)
:write [name]      Write apertures to database (default to the current image)

The remaining colon commands are task parameters and print the current
value if no value is given or reset the current value to that specified.
Use :parameters to see current parameter values.
```

The extraction process proceeds slightly differently for the different observation types defined by the observation type header entry. If the observation type is *abba*, the positive object spectrum is extracted interactively, then the corresponding sky spectrum is automatically extracted, and these steps are repeated for an inverted version of the negative object spectrum. For the *osso* and *soos* observation types, the object spectrum is extracted interactively, then the sky spectrum is automatically extracted. For *comparison* spectra, the extraction occurs automatically using the extraction aperture defined by the reference spectrum. The extraction and background aperture definitions used for each object spectrum become the default definitions for extracting the next spectrum. Generally all that is required is to recenter the extraction aperture on the new spectrum.

The extraction process for each spectrum begins by asking `Edit apertures for infile.oim? (yes):`. Answering *yes* to this question allows the user to interactively change the default extraction and background subtraction apertures using the `apedit` task. The full profile perpendicular to the dispersion axis is plotted in the graphics display and the location of the default extraction aperture is indicated, if one is defined. Type *m* to mark the location of the first extraction aperture at the centroid of the profile peak near the cursor location. Type *n* to mark the first extraction aperture at the cursor location without centroiding. Type *s* to shift a predefined aperture to a different location, and optionally centroid the aperture at the new location in response to the question asked. Type *c* to centroid a predefined aperture. On weakly exposed spectra, the object may not be detectable in the full slit profile. If emission features are present, plot the slit profile only around an emission line by decreasing the number of dispersion lines summed by typing, e.g., *:nsum 20*, and selecting the location of the cut across the spectrum by typing *:line nnn*, where *nnn* is the line number where the feature occurs. To change the lower bound of the extraction aperture, position the cursor at the new position and type *l*, or type *:lower -4* to explicitly set to a value of -4. To change the upper bound of the extraction aperture, position the cursor at the new position and type *u*, or type *:upper 4* to explicitly set to a value of 4. Alternatively, you can set the width of the extraction aperture using the height of the cursor as a threshold to define new upper and lower bounds and type *y*. Type *r* to redraw the graph. Define new background sample regions explicitly by typing, e.g., *:b_sample -8:-5,5:8*, or type *b* to change the background subtraction sample regions using the cursor. The cursor commands then available are those of the interactive curve fitting task `icfit` that were listed earlier. Type *z* to delete the sample region nearest the cursor. Type *s* to define one side of a new sample region, and *s* again to define the other side. Type *:sample -8:-5,5:8* to set the background subtraction sample regions explicitly from within `icfit`. To change the order of the fit type *:order 1*. Type *f* for a new fit. Type *r* to redraw the graph. Type *q* to exit from the interactive curve fitting task. When the extraction and background apertures have been defined, type *q* to exit the aperture editor.

Answer *yes* to the question `Write apertures for infile.oim to database (yes):` to save the definition. Then answer *yes* to the question `Extract aperture spectra for infile.oim? (yes):` to perform the extraction. Answer *yes* to the question `Review extracted spectra from infile.oim? (yes):` to display the extracted one-dimensional spectrum. Since we have only one aperture, answer *yes* to the question `Review extracted spectrum for aperture 1 from infile.oim (yes):`. Type *q* to proceed. Then type a carriage return to the question `Output image name [use # to skip output] (infile.oim.0001):`. The `redgspec` task will rename this file.

Each extracted spectrum is stored in an IRAF multispec format file named by appending *.osp*, *.ssp*, or *.csp* to the base spectrum name for the object, sky, or comparison spectrum, respectively. The aperture definitions for each extracted spectrum are stored in a *database/* sub-directory of the current directory in files with names like *apinfile.oim.*

8.12 Flux Calibration

The near-infrared spectrum is strongly affected by terrestrial atmospheric absorption. This is corrected for, and the extracted object spectra placed on an absolute flux scale, by dividing by the observed spectrum of a flux calibrator star and multiplying by the absolute flux distribution of the calibrator. Ideally, each object measurement would be accompanied by a similar measurement of a nearby featureless flux calibrator taken as close as possible in time to the object observation and with the same spectral resolution. In practice, the flux calibrator will be at some distance from the object on the sky and will contain intrinsic absorption features. Our approach is to flux calibrate with the best available flux calibrator and then to correct for any shortcomings in the flux calibrator by dividing by a 'flat spectrum' star. It is necessary to record spectra of the flux calibrator with the same slit width as the object in order to accurately cancel terrestrial atmospheric absorption, and it is advisable to also record spectra of the flux calibrator with a very wide slit if absolute flux calibration is required. The narrow slit measurement is used for the initial flux calibration and cancellation of terrestrial atmospheric absorption features, and the wide slit spectrum is used later to derive a correction for slit losses.

The choice of suitable flux calibrators is often difficult due to the range of intrinsic absorption features present in stellar spectra. Theoretical spectra for the Kurucz $\log g = 4.5$ model atmospheres are plotted in Figures 34 to 37 of Appendix H. While these may not accurately reproduce molecular features, they are certainly a good guide to the types and strengths of absorption features present in the near-infrared spectra of main-sequence stars. Early-type stars have the smoothest continua and should be used when the features of interest cover a broad wavelength range. However, early-type stars have hydrogen absorption lines which must be accurately measured, especially if these are features of interest in the object spectra. F and early G dwarfs have relatively weak hydrogen lines and are sufficiently common to allow examples to be found near most objects. However, their spectra in the J band are contaminated by weak absorption lines which may be problematical. Dwarf stars later than mid G have CO first-overtone absorption beyond 2.3 μm and weak absorption throughout their near-infrared spectra. These should be avoided for the purpose of flux calibration. However, late K and early M dwarfs lack significant hydrogen absorption so they can be usefully employed in measuring the strength of hydrogen absorption in early-type flux calibrators.

The above considerations were used in forming the list of spectroscopic flux calibrators in Table 24 of Appendix G. Most stars in this list have accurately determined near-infrared photometry on a well-defined photometric system, and as such are useful flux calibrators. Ideally, the flux distributions of these stars would be known. However, this is not the case. Instead, we are forced to model the shape of the flux distributions for these stars. The `redgspec` task uses two model types; a blackbody distribution parameterised by a color temperature, and approximations to the Kurucz $\log g = 4.5$ flux distributions parameterised by the model effective temperature. An interstellar extinction can also be applied to the model distribution. Blackbody models can be used for early-type stars, but Kurucz models should be preferred for mid- and late-type stars where the continuum distributions deviate significantly from blackbodies. The model distributions are normalised at K using a magnitude calculated from the model flux distribution, the CASPIR K filter profile, the predicted transmission function of the CASPIR anti-reflection coatings, and the theoretical atmospheric transmission function shown in Appendix M.

Model flux distributions are calculated using the `cspflux` task. This task has the parameters listed below. The *fctype* parameter defines whether *blackbody* or *kurucz* models are used. The *kmag* parameter defines the K magnitude normalization to be used, and should be set to the K magnitude of the flux calibrator star. The *temp* parameter specifies the blackbody color temperature, or the Kurucz model effective temperature to be used. The *av* parameter defines the visual extinction in magnitudes to be applied to the model flux distribution. The `cspflux` task outputs the J, H, and K magnitudes, $J-K$ and $H-K$ colors, and K band normalisation constant for the specified model. Different model parameters should be tried until a satisfactory fit to the J, H, and K magnitudes of the flux calibrator star has been found. The model $J-K$ and $H-K$ colors listed in Table 1 help in converging on this solution.

Table 1: Model Near-Infrared Colors

		Kurucz		Blackbody				Kurucz		Blackbody	
Temp	SpT	$J-K$	$H-K$	$J-K$	$H-K$	Temp	SpT	$J-K$	$H-K$	$J-K$	$H-K$
3500	M2V	0.974	0.222	0.804	0.324	11500		-0.081	-0.040	-0.013	-0.011
3750		0.916	0.167	0.716	0.288	12000	B8V	-0.088	-0.030	-0.026	-0.016
4000	K7V	0.873	0.113	0.641	0.257	12500	B7V	-0.095	-0.045	-0.037	-0.021
4250		0.792	0.072	0.575	0.230	13000	B6V	-0.104	-0.048	-0.048	-0.025
4500	K4V	0.701	0.056	0.518	0.207	14000	B5V	-0.116	-0.052	-0.066	-0.033
4750		0.604	0.053	0.467	0.186	15000	B4V	-0.121	-0.058	-0.082	-0.039
5000	K2V	0.524	0.044	0.423	0.168	16000	B3V	-0.129	-0.053	-0.095	-0.045
5250		0.453	0.034	0.383	0.151	17000		-0.136	-0.062	-0.108	-0.051
5500	G6V	0.392	0.028	0.347	0.137	18000		-0.150	-0.070	-0.119	-0.055
5750		0.350	0.038	0.314	0.123	19000	B2V	-0.148	-0.057	-0.127	-0.058
6000	G0V	0.306	0.033	0.285	0.111	20000		-0.164	-0.073	-0.136	-0.062
6250		0.266	0.030	0.258	0.100	21000		-0.170	-0.078	-0.145	-0.067
6500	F5V	0.215	0.015	0.234	0.090	22000	B1V	-0.186	-0.084	-0.149	-0.067
6750		0.187	0.013	0.211	0.081	23000		-0.182	-0.076	-0.157	-0.071
7000	F2V	0.161	0.015	0.191	0.073	24000		-0.203	-0.090	-0.161	-0.072
7250		0.136	0.008	0.172	0.065	25000	B0.5V	-0.213	-0.100	-0.167	-0.075
7500	F0V	0.105	0.004	0.154	0.058	26000		-0.216	-0.097	-0.171	-0.076
7750		0.079	-0.007	0.138	0.051	27000	B0V	-0.214	-0.102	-0.178	-0.081
8000	A7V	0.059	-0.006	0.123	0.045	28000		-0.221	-0.097	-0.184	-0.085
8250		0.033	-0.008	0.109	0.039	29000		-0.230	-0.103	-0.180	-0.078
8500	A5V	0.019	-0.016	0.096	0.034	30000		-0.241	-0.112	-0.190	-0.086
8750		0.010	-0.008	0.083	0.028	31000		-0.246	-0.112	-0.188	-0.083
9000	A2V	-0.002	-0.011	0.072	0.024	32000		-0.250	-0.114	-0.195	-0.087
9250		-0.013	-0.010	0.061	0.019	33000		-0.251	-0.117	-0.192	-0.083
9500	A1V	-0.017	-0.011	0.050	0.015	34000		-0.251	-0.107	-0.208	-0.098
9750		-0.029	-0.010	0.041	0.011	35000		-0.254	-0.118	-0.207	-0.095
10000	A0V	-0.036	-0.020	0.032	0.007	37500		-0.255	-0.109	-0.205	-0.089
10500		-0.054	-0.023	0.015	0.000	40000		-0.254	-0.115	-0.212	-0.094
11000	B9V	-0.062	-0.030	0.000	-0.005						

```
                                 I R A F
                   Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspflux

fctype  =                    k  Type of flux calibration to use
kmag    =                  4.7  K magnitude of flux calibrator
temp    =                 5500  Adopted stellar temperature
(av     =                   0.) Visual extinction.

(verbose=                  yes) Verbose output?
(mode   =                   ql)
```

The `redgspec` task searches the file *caspirdir$fluxstds.dat* to locate model parameters for the flux calibrator star using the object name header entry as the search parameter. Entries in this file have the format shown below where the columns are the object name in uppercase characters, the model type (*b* for blackbody, *k* for Kurucz), the K magnitude, the temperature, the A_V value, and the K band normalisation constant. Entries for new flux calibration stars should be added to this file when suitable model parameters have been found using the `cspflux` task. Model parameters are prompted for if they are not found in the *caspirdir$fluxstds.dat* file.

```
HD216009  b  7.947 10000 0. 4.4555796155286E-12
```

Table 2: Adopted Zero Magnitude Flux Densities

Filter	λ_c (μm)	F_λ (erg/s/cm^2/Å)	F_ν (Jy)
J	1.239	3.109×10^{-10}	1592
H	1.649	1.149×10^{-10}	1042
Kn	2.132	4.541×10^{-11}	688
K	2.192	4.098×10^{-11}	657

```
Y5117    k  3.078  4000 0. 1.7494077560988E-12
Y5584    k  3.382  4000 0. 1.3221814130991E-12
BS8477   k  4.700  5500 0. 4.5171744088401E-13
```

The model flux densities are in units of F_λ in erg/s/cm^2/Å for consistency with other IRAF spectral reduction packages. The absolute flux calibration of the magnitude system is based on the normalization derived by Bersanelli, Bouchet, & Falomo (1991, A&A, 252, 854) and effective wavelengths for the CASPIR broadband filters calculated for a 10000 K blackbody spectrum. These effective wavelengths and the zero magnitude flux densities are listed in Table 2.

Flux calibration is achieved by dividing the object spectrum by the observed spectrum of the flux calibrator and multiplying by the absolute flux spectrum modelled for the flux calibrator. This is done in the `redgspec` task by setting the *fluxcal* flag and specifying the base name of the flux calibrator file in the *fluxspec* parameter. No correction is applied for airmass differences between the object and flux calibrator; it is assumed that the observations were made at similar airmasses in order to optimise terrestrial atmospheric absorption correction. The flux calibrated object spectrum is stored in a file named by appending *.fos* to the base spectrum name and the flux calibrated sky spectrum is stored in a file named by appending *.fss* to the base spectrum name. Comparison spectra are not flux calibrated.

8.13 Division By A Flat Spectrum Star

Several details of the flux calibration process have been ignored so far; we have not removed spectral features in the flux calibrator star, we have not allowed for slit losses in the measurement of the flux calibrator, and we have assumed that terrestrial atmospheric absorption features were accurately removed during the flux calibration process. Each of these points can be addressed by applying a multiplicative wavelength-dependent correction to the object spectrum which we generically call a ‘flat spectrum star’ correction.

The correction for spectral features in the flux calibrator is derived from a measurement of a star lacking these features. Generally, a late-type star is used to correct for features in an early type star, and vice-versa. The ratio of the continuum star spectrum to the flux calibrator spectrum is formed, a fitted continuum is multiplicatively removed, and all regions in the resultant spectrum except for the features of interest are set to unity. This minimises the noise added to the corrected spectrum, and prevents other spectral features in the continuum star being imprinted on the corrected spectrum.

Slit losses in the measurement of the flux calibrator must be corrected for in order to place the object observation on an absolute flux scale. This correction is formed by flux calibrating a wide slit measurement of the flux calibrator with the same narrow slit measurement used to flux calibrate the object spectrum. The overall shape of the calibrated wide slit spectrum will be severely affected by poor cancellation of terrestrial atmospheric absorption, but the level in clear regions defines the multiplicative slit correction constant to be applied to the object spectrum.

A correction for residual terrestrial atmospheric absorption is formed from a measurement of a ‘flat spectrum’ star located near the object of interest. The ‘flat spectrum’ star measurement is flux calibrated with the same calibrator measurement used for the object spectrum and any intrinsic spectral features removed. The absorption correction is again formed by multiplicatively removing a fitted continuum and setting featureless regions of the correction spectrum to unity.

The `cspfltspec` task is used to form the 'flat spectrum star' correction to be applied. The parameters for this task are listed below. *flatspec* is the base name of the flat spectrum star. The correction can be based either on the flux calibrated object spectrum (*.fos* file extension) of this name or the unfluxed object spectrum (*.osp* file extension), and the correction spectrum is stored in a file named by appending *.flt* to this base name. The *constant* parameter defines the scaling constant by which the derived correction spectrum is divided. Since `redgspec` divides by the correction spectrum, the object spectrum is multiplied by this constant. This will normally be the value of the correction for slit losses, or unity if no slit loss correction is required.

```
                                   I R A F
                     Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspfltspec

flatspec=                sp163  Flat spectrum star file to use
(constan=                  1.0) Divisor constant

(verbose=                  yes) Verbose output?
(mode   =                    q)
```

The 'flat spectrum star' correction is formed by first fitting the continuum of the specified object spectrum interactively using the IRAF `icfit` task. The default sample region is the whole spectrum. This region can be deleted by typing *z* and new sample regions chosen to avoid spectral features by positioning the cursor at the start position and typing *s* and then repositioning the cursor at the end position and typing *s* again. Redo the fit by typing *f*, and replot the spectrum by typing *r*. The order of the fit is changed by typing *:order 3*. Type *?* for help on the cursor key functions, and type *q* to quit `icfit` when a satisfactory continuum fit has been obtained.

The `cspfltspec` task then plots the ratioed spectrum in the graphics display using the IRAF `splot` task. Users should become familiar with the many features of this task listed below. Specifically for the moment, set regions away from the features of interest to unity by positioning the Y cursor at 1.00, the X cursor at the start of the region to set, and typing *x*. Move the cursor in X to the end of the region to set while keeping the Y cursor value at 1.00 and type *x* again. Repeat as necessary.

When a suitable correction spectrum has be constructed, remember to type *i* to save the correction spectrum to the output file from within `splot`. The `cspfltspec` task cannot do this for you. Type *q* to quit.

Once the 'flat spectrum star' correction has been formed, object spectra can be divided by this correction using the `redgspec` task by setting the *flatdiv* flag and specifying the base name of the flat spectrum correction file in the *flatspec* parameter.

8.14 Plotting The Final Spectrum

Now that your labors have been rewarded with a fully reduced spectrum, you will want to look at it. This can be done using the `redgspec` task by setting the *plot* flag. This calls the IRAF `splot` task which allows interactive viewing and analysis of the spectrum. Users should consult the help pages for this task for a full description of its capabilities (type *help splot* | *lpr*). Type *a* to expand and autoscale the plot to a data range given by two cursor positions. Type *w* to window the graph. Type *b* to toggle setting the plot baseline to zero rather than autoscaling. Type *c* to clear all windowing and redraw the full spectrum. Type *e* to measure the equivalent width directly from the data. Type *h* to measure the equivalent width assuming a Gaussian profile. Type *k* to mark two continuum points and fit a single Gaussian function. The reported flux is divided by 1000 to convert to W cm^{-2}. Type *d* to mark two continuum points and fit multiple Gaussian functions. Type - to subtract the fit from the spectrum. Type *t* to fit a function to the spectrum using the IRAF `icfit` task. Type *m* to compute the mean, RMS, and signal-to-noise ratio over a region marked by two cursor positions. Type *l* to convert from F_ν to F_λ units. Type *n* to convert from F_λ to F_ν units. Type *p* to define a linear wavelength scale. Type *u* to adjust the wavelength scale interactively. Type *v* to convert to a velocity scale. Type *j* to change the data values using the cursor. Type *s* to boxcar smooth the spectrum. Type *f* to do arithmetic function manipulations. Type *i* to save any modifications to a file. Type *g* to get a new spectrum. Type *o* to overplot a spectrum. Type *r* to redraw the plot. Type *:hist yes/no* to enable/disable histogram line type plotting. Type = to make a hardcopy of the plot. Type *q* to exit.

The full set of `splot` cursor commands, and the standard IRAF cursor mode commands that are also available, are listed below.

```
                         SPLOT CURSOR COMMANDS

? - This display                          r - Redraw the current window
/ - Cycle thru short help on stat line    s - Smooth (boxcar)
a - Autoexpand between cursors            t - Fit continuum (see below)
b - Toggle base plot level to 0.0         u - Adjust coordinate scale
c - Clear and redraw full spectrum        v - Velocity scale (toggle)
d - Deblend lines using Gaussians         w - Window the graph
e - Equiv. width, integ flux, center      x - Connects 2 cursor positions
f - Arithmetic functions: log, sqrt...    y - Plot std star flux from calib file
g - Get new image and plot                z - Expand x range by factor of 2
h - Equivalent widths (see below)         ) - Go to next spectrum in image
i - Write current image as new image      ( - Go to previous spectrum in image
j - Fudge a point to Y-cursor value       # - Select new line/aperture
k - Gaussian fit to single line           % - Select new band
l - Convert to F-lambda                   $ - Toggle wavelength/pixel scale
m - Mean, RMS, snr in marked region       - - Subtract deblended fit
n - Convert to F-nu                       , - Down slide spectrum
o - Toggle overplot of following plot     . - Up slide spectrum
p - Convert to wavelength scale           I - Interrupt task immediately
q - Quit and exit                   <space> - Cursor position and flux

For 'h' key: Measure equivalent widths
a - Left side for width at 1/2 flux       l - Left side for continuum = 1
b - Right side for width at 1/2 flux      r - Right side for continuum = 1
c - Both sides for width at 1/2 flux      k - Both sides for continuum = 1

For 't' key: Fit the continuum with ICFIT and apply to spectrum
    / = normalize by the continuum fit
    - = subtract the continuum fit (residuals)
    f = replace spectrum by the continuum fit
    c = clean spectrum of rejected points
    n = do the fitting but leave the spectrum unchanged
    q = quit without fitting or modifying spectrum

For 'u' key: Adjust the coordinate scale by marking features
    d = apply doppler correction to bring marked feature to
        specified coordinate
    l = set linear (in wavelength) coordinates based on two marked features
    z = apply zero point shift to bring marked feature to
        specified coordinate

The colon commands do not allow abbreviations.

:# <comment>      - Add comment to log file
:dispaxis <val>   - Change summing parameter for 2D images
:log              - Enable logging to save_file
:nolog            - Disable logging to save_file
```

```
:nsum <val>       - Change summing parameter for 2D images
:show             - Show full output of deblending and equiv. width measurments
:units <value>    - Change coordinate units (see below)

:auto [yes|no]    - Enable/disable autodraw option
:zero [yes|no]    - Enable/disable zero baseline option
:xydraw [yes|no]  - Enable/disable xydraw option
:hist [yes|no]    - Enable/disable histogram line type option
:nosysid [yes|no] - Enable/disable system ID option
:wreset [yes|no]  - Enable/disable window reset for new spectra option
:flip [yes|no]    - Enable/disable dispersion coordinate flip
:overplot [yes|no]- Enable/disable permanent overplot mode


                               UNITS

The units are specified by strings having a unit type from the list below
along with the possible preceding modifiers, "inverse", to select the
inverse of the unit and "log" to select logarithmic units. For example "log
angstroms" to plot the logarithm of wavelength in Angstroms and "inv
microns" to plot inverse microns.  The various identifiers may be
abbreviated as words but the syntax is not sophisticated enough to
recognized standard scientific abbreviations such as mm for millimeter.

           angstroms - Wavelength in Angstroms
          nanometers - Wavelength in nanometers
        millimicrons - Wavelength in millimicrons
             microns - Wavelength in microns
         millimeters - Wavelength in millimeters
          centimeter - Wavelength in centimeters
              meters - Wavelength in meters
               hertz - Frequency in hertz (cycles per second)
           kilohertz - Frequency in kilohertz
           megahertz - Frequency in megahertz
            gigahertz - Frequency in gigahertz
                 m/s - Velocity in meters per second
                km/s - Velocity in kilometers per second
                  ev - Energy in electron volts
                 kev - Energy in kilo electron volts
                 mev - Energy in mega electron volts
                   z - Redshift

The velocity and redshift units require a trailing value and unit defining the
velocity zero point.  For example to plot velocity relative to
a wavelength of 1 micron the unit string would be:

        km/s 1 micron


                      SET GRAPH WINDOW COMMANDS

a  Autoscale x and y axes
b  Set bottom edge of window
c  Center window at cursor position
d  Shift window down
e  Expand window (mark lower left and upper right of new window)
f  Flip x axis
```

```
g  Flip y axis
j  Set left edge of window
k  Set right edge of window
l  Shift window left
m  Autoscale x axis
n  Autoscale y axis
p  Pan x and y axes about cursor
r  Shift window right
t  Set top edge of window
u  Shift window up
x  Zoom x axis about cursor
y  Zoom y axis about cursor
z  Zoom x and y axes about cursor


                     STANDARD IRAF CURSOR MODE COMMANDS

Cursor Mode Keystrokes

        A                       draw and label the axes of current viewport
        B                       backup over last instruction in frame buffer
        C                       print the cursor position
        D                       draw a line by marking the endpoints
        E                       expand plot by setting window corners
        F                       set fast cursor (for HJKL)
        H                       step cursor left
        J                       step cursor down
        K                       step cursor up
        L                       step cursor right
        M                       move point under cursor to center of screen
        P                       zoom out (restore previous expansion)
        R                       redraw the screen
        T                       draw a text string
        U                       undo last frame buffer edit
        V                       set slow cursor (for HJKL)
        W                       select WCS at current position of cursor
        X                       zoom in, X only
        Y                       zoom in, Y only
        Z                       zoom in, both X and Y
        <                       set lower limit of plot to the cursor y value
        >                       set upper limit of plot to the cursor y value
        \                       escape next character
        :                       set cursor mode options
        :!                      send a command to the host system
        =                       shorthand for :.snap (make graphics hardcopy)
        0                       reset and redraw
       1-9                      roam


Cursor Mode Commands:

        :.axes[+-]              draw axes of viewport whenever screen is redrawn
        :.case[+-]              enable case sensitivity for keystrokes
        :.clear                 clear alpha memory (e.g, this text)
        :.cursor n              select cursor
        :.gflush                flush plotter output
        :.help                  print help text for cursor mode
```

```
:.init                  initialize the graphics system
:.markcur[+-]           mark cursor position after each cursor read
:.off [keys]            disable selected cursor mode keys
```

9 Cross-Dispersed Grism Data Reduction

9.1 Introduction

This section deals with the reduction of cross-dispersed grism data. The procedures for doing so are similar to those described for long-slit grism data (§8), so readers should be familar with that material before proceeding.

The types of spectroscopic datasets obtained with the cross-dispersed grisms are constrained by the short length of the slits used, and by the extent of the object being measured. The reduction of most cross-dispersed grism datasets will follow the path:

1) Create BIAS and DARK frames, and linearize object and sky frames.

2) Subtract sky background from object frames, and combine all object frames in the dataset to a single spectral image.

3) Create FLAT frames for each grism, and remove pixel-to-pixel sensitivity variations.

4) Fix known and random bad pixels.

5) Apply a geometrical transformation to align the dispersion direction with image columns, align the spatial direction with image rows, and perform the wavelength calibration.

6) Correct for non-uniform illumination along the slit.

7) Extract one dimensional spectra from the combined spectral images with appropriate background subtraction in the slit direction to remove residual sky features.

8) Flux calibrate the one dimensional spectra.

9) Merge the individual grism orders into a single spectrum.

10) Correct for absorption features in the standard star spectrum, inexact cancellation of terrestrial atmospheric absorption features, and slit losses in the standard star measurement.

The reduction procedures described here continues to use the local MSSSO CASPIR package running in IRAF. Refer to §6 for instructions on how to obtain this package. Users are again advised to familiarize themselves with the general procedures available within IRAF for spectral reduction by reading the documents *A User's Guide to CCD Reductions with IRAF* and *A User's Guide to Reducing Slit Spectra with IRAF*. Compressed postscript versions of these documents are available via anonymous ftp to iraf.noao.edu in the files *iraf/docs/ccduser2.ps.Z* and *iraf/docs/spect.ps.Z*.

9.2 Forming BIAS and DARK Frames

Spectroscopic data require the same corrections for electrical offsets and charge leakage as required for imaging data. BIAS and DARK frames for spectroscopic data reduction are formed in exactly the same way as for imaging data using the `cspcombine` task. Refer to §6 for descriptions of these procedures.

9.3 Linearity Correction

Spectroscopic observations must also be linearized as described in §6. A convenient environment in which to conduct this and the remainder of the basic cross-dispersed grism reduction is provided by the `redxspec` task. The `redxspec` task is the cross-dispersed grism equivalent of the `redimage` task used for imaging data reduction and the `redgspec` used for long-slit grism reduction. For example, to linearize a set of images obtained with a 180 sec exposure time, first form a list file of the image filenames using the `csplist` task by typing

```
csplist time 180 images=@allfiles > 180files
```

`redxspec` overwrites the input images so copy the input images to temporary files and work on these. This can be done by typing

```
imcopy @180files @180files//t
```

Now use `epar` to set the `redxspec` parameters as listed below.

```
                                  I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redxspec

(images =              @tfiles) List of CASPIR input images
(spectru=                     ) Base name of spectrum file

(linear =                  yes) Linearize data?
(combine=                   no) Combine individual 2D spectra?
(flatten=                   no) Divide by flatfield?
(fixbad =                   no) Fix known bad pixels?
(clean  =                   no) Interactively clean additional pixels?
(transfo=                   no) Straighten orders and subset?
(illumin=                   no) Correct non-uniform slit illumination?
(extract=                   no) Extract 1D spectra?
(fluxcal=                   no) Flux calibrate spectra?
(merge  =                   no) Merge spectrum segments?
(flatdiv=                   no) Divide by flat spectrum star?
(plot   =                   no) Plot merged spectra?

(bias   =                 bias) Bias frame to use
(dark   =              dark180) Dark frame to use
(obstype=                 abba) Type of observation made
(zerosec=      [190:195,10:90]) Zero level image section
(flatfil=                     ) Flatfield frame to use
(badfile=      caspirdir$grism) Bad pixel file
(badtype=               interp) Type of bad pixel correction
(illfile=                     ) Illumination frame to use
(reffile=                     ) Comparison extraction reference file
(fluxspe=                     ) Flux calibration spectrum to use
(weights=                     ) Merge weighting function file to use
(flatspe=                     ) Flat spectrum star file to use

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

The flags *linear*, *combine*, *flatten*, *fixbad*, *clean*, *transform*, *illumination*, *extract*, *fluxcal*, *merge*, *flatdiv*, and *plot* define the reduction steps that will be performed. The remainder of the parameters are used in the execution of these basic functions.

The parameters relevant to the linearization of a particular dataset are *bias* and *dark*. These are used in the same way as described in §6 for `redimage`.

9.4 Defining The Geometrical Transformation

Spectra recorded with the cross-dispersed grisms in CASPIR have curved orders and the tilts of the slit images vary along each order. These distortions must be corrected in order to accurately align the dispersion direction with the image columns and the spatial direction with image lines. Files containing fits to these geometrical distortions for each grism are distributed along with the IRAF CASPIR package. However, it is advisable to define new transformations for each observing run.

Curvature in the spectral direction can be traced using a sky-subtracted image of a stellar spectrum. A single object spectrum near slit center is sufficient for cross-dispersed data where geometrical distortions along the short slits are minimal. Slit tilt is traced using spectral images of arc lamps. These also serve to establish the wavelength calibration.

First form a stellar curvature reference frame by subtracting suitable linearized star and sky images and xenon and/or argon arc lamp frames by subtracting *lamp on* and *lamp off* pairs, for example using `cspflat`:

```
cspflat ir011,ir014 ir012,ir013 star_jh
cspflat ir005,ir006 ir007,ir008 xenon_jh
cspflat ir001,ir002 ir003,ir004 argon_jh
```

Note that the geometrical transformation should be defined using frames that have not been flatfielded.

The geometrical transformation for a particular grism is defined using the `cspxtrans` task which has the parameters listed below.

```
                                I R A F
                  Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspxtrans

curve   =              star_jh  Curvature reference frame to use
xenon   =             xenon_jh  Xenon lamp frame to use
argon   =             argon_jh  Argon lamp frame to use

(verbose=                 yes) Verbose output?
continue=                       Process this order?
profile =                       Enter the profile section to use
(mode   =                  ql)
```

The *curve* parameter defines the curvature reference frame name, the *xenon* parameter defines the xenon arc lamp filename, and the *argon* parameter defines the argon arc lamp filename. At least one arc lamp frame must be specified. Line lists for the xenon and argon arc lamps are distributed with the IRAF CASPIR package in the files *xenon.dat* and *argon.dat*.

The `cspxtrans` task treates each order of cross-dispersed spectral data separately by first extracting a subsection around the location of each order and then analysing that subsection. The curvature reference subimage is displayed first, and an average profile through the first, middle, or last ten lines of the image, as specified by the *profile* parameter, is displayed in the graphics display using the `noao.twodspec.identify` task. Mark the position of the star by using the cursor and typing 'm'. Enter the appropriate column number (1, 18, 26, 34, 51 for 0, 25, 50, 75, 100% positions across the order), and type 'q' to exit this section. `cspxtrans` then uses `noao.twodspec.reidentify` to trace the spectrum. Answer 'yes' to the question *Write coordinate map to the database (yes)?*. The `cspxtrans` task then displays the xenon arc lamp spectum sub-image (if one was specified) and uses `noao.twodspec.identify` to display an average profile through the central three columns (along the dispersion). Referring to the arc lamp spectra in Figs. 41–55 of Appendix J, type 'm' to mark the locations of a few emission lines and enter their wavelengths in Angstroms. Then type 'f' to obtain a preliminary fit to the wavelength calibration. Type 'q' to exit the fit routine, and then 'l' to automatically locate other arc lines. Delete erroneous identifications by typing 'd'. Use the window commands 'w t' and 'w b' to change the top and bottom plot values, and 'w a' to autoscale the plot. Fit the wavelength calibration again, and type 'q' to exit the fit routine and another 'q' to exit the identify routine. `cspxtrans` then uses `noao.twodspec.reidentify` to trace the slit images. The `cspxtrans` task then repeats the identification process for the argon arc lamp sub-image (if one was specified). Answer 'yes' to *Fit interactively (yes)?*, and remove erroneous data points and points off the ends of the slit using the 'd' key; typing 'd' followed by a 'p' deletes a single point, typing 'd' followed by an 'x' or a 'y' deletes all points at that constant x or y. The fit is best displayed by looking at the residuals as a function of x position; type 'x' followed by 'x', 'y' followed by 'r', and then 'r' to redisplay the plot. Redo the fit by typing 'f'. Display the fit itself by typing 'x' 'x', 'y' 'y', and then 'r' to redisplay the plot. When a satisfactory fit has been obtained, exit the fit routine by typing 'q'. Then answer 'yes' to *Write coordinate map to the database (yes)?*. This procedure is repeated for each order of the cross-dispersed grism.

The fit parameters are stored in a local subdirectory named *database/* of the current directory, and in the database directory pointed to by the IRAF *database$* environment variable. The x and y fits for a particular grism are stored in files with names like *fcJH_grism_10x* and *fcJH_grism_10y* in those directories.

9.5 Combining Individual Images

Cross-dispersed grism data sets are sky subtracted, and the object images combined, using the **redxspec** task by unsetting the *linear* flag, setting the *combine* flag, and supplying values for the *spectrum*, *obstype*, and *zerosection* parameters. *spectrum* is the base name of the combined spectrum files. *obstype* defines the type of observation in the dataset. *obstype=abba* indicates that the object was nodded along the slit while frames were recorded in an ABBA sequence. Differencing each AB pair produces positive and negative spectra in the object image that are averaged and output to a file named by appending *.oim* to the base spectrum name. 'A beam' and 'B beam' sky images are also formed by averaging the B and A beam object frames, respectively, and these images are output to files named by appending *.aim* and *.bim*, respectively, to the base name. Refer to Figure 33 to trace the file name conventions used. The *zerosection* parameter specifies an image section that is used to sample the inter-order background level in these sky images. This DC level is subtracted from the sky images. Sky images are carried throughout the reduction and can be used to define the illumination profile of the spectrograph slit and to improve the wavelength calibration on long exposure frames. If this is to be done, it is advisable to record DARK frames of the same duration close in time to the sky frames. *obstype=soos* indicates that the dataset consists of sequences of sky, object, object, sky images, where the sky images are recorded with the slit positioned off the object. *obstype=osso* indicates that the dataset consists of sequences of object, sky, sky, object frames, where the sky frames are recorded with the slit positioned off the object. Averaged object and sky images are formed for both these observation types and are output to files named by appending *.oim* and *.sim*, respectively, to the base name. In both cases, the *zerosection* parameter specifies an image section that is used to subtract a DC level from the combined sky image. *obstype=comparison* indicates that the dataset is to be combined to form a comparison observation (e.g., an arc lamp image or a twilight sky image). All images in the dataset are averaged and the result is output to a file named by appending *.cim* to the base name. The *obstype* parameter is written to each output file header and is used in subsequent processing of the dataset. No allowance is made for drifts in the position of the object along the slit during the observations.

A typical **redxspec** parameter list for combining a single *abba* dataset in the list file *tfiles* is shown below. The sky subtracted and combined object image will be output to the file *sp150.oim*.

```
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redxspec

(images =            @tfiles) List of CASPIR input images
(spectru=              sp150) Base name of spectrum file

(linear =                 no) Linearize data?
(combine=                yes) Combine individual 2D spectra?
(flatten=                 no) Divide by flatfield?
(fixbad =                 no) Fix known bad pixels?
(clean  =                 no) Interactively clean additional pixels?
(transfo=                 no) Straighten orders and subset?
(illumin=                 no) Correct non-uniform slit illumination?
```

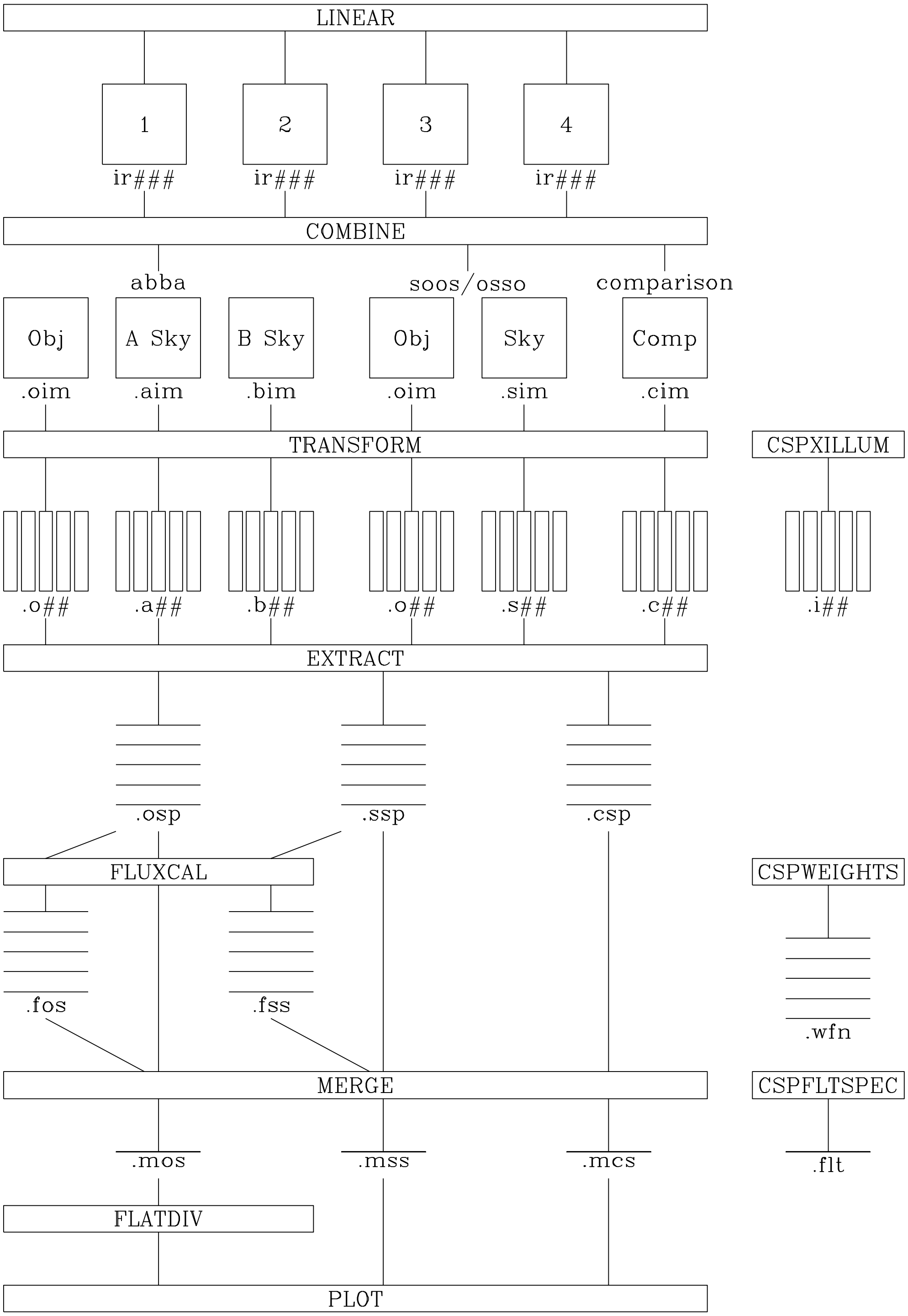


Figure 33: File name conventions used in the cross-dispersed grism reduction.

```
(extract=                   no) Extract 1D spectra?
(fluxcal=                   no) Flux calibrate spectra?
(merge  =                   no) Merge spectrum segments?
(flatdiv=                   no) Divide by flat spectrum star?
(plot   =                   no) Plot merged spectra?

(bias   =                 bias) Bias frame to use
(dark   =              dark180) Dark frame to use
(obstype=                 abba) Type of observation made
(zerosec=      [190:195,10:90]) Zero level image section
(flatfil=                     ) Flatfield frame to use
(badfile=      caspirdir$grism) Bad pixel file
(badtype=               interp) Type of bad pixel correction
(illfile=                     ) Illumination frame to use
(reffile=                     ) Comparison extraction reference file
(fluxspe=                     ) Flux calibration spectrum to use
(weights=                     ) Merge weighting function file to use
(flatspe=                     ) Flat spectrum star file to use

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

9.6 Flatfielding

Spectroscopic FLAT frames are derived from sets of *lamp on* and *lamp off* pairs for each grism. These are obtained using the incandescent lamp in the Comparison Lamp Module. The FLAT frames are formed in the same way as the FLAT frames for imaging datasets by differencing and then combining the linearized *lamp on* and *lamp off* pairs using the `cspflat` task. The inputs required are a list of *lamp on* frames, a list of *lamp off* frames, and an output filename. For example,

```
cspflat ir007,ir009,ir011 ir008,ir010,ir012 flat_jh comb_opt=average
```

averages the *lamp on* frames ir007–11 and the *lamp off* frames ir008–10, takes their difference, then normalizes the median pixel value of the difference in the image section specified by the *statsec* parameter to unity, and writes the resulting FLAT frame to the file *flat_jh*. The *statsec* parameter should be set to the image section corresponding to the central strip of one of the orders. No attempt is made to correct for the spectral distribution of the lamp or any non-uniformity in the slit illumination by the lamp.

The `cspflat` task has the parameters listed below.

```
                                  I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspflat

ons     =    ir007,ir009,ir011  List of lamp ON frames
offs    =    ir008,ir010,ir012  List of lamp OFF frames
flat    =              flat_jh  Output flatfield frame
(comb_op=              average) Type of combine operation
(statsec=     [150:170,50:200]) Image section for computing statistics

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

The *comb_opt* parameter should be *average* if the number of on or off exposures is less than about 5 and *median* if greater than about 5.

The object, sky, and comparison images for the specified base spectrum name are flattened by unsetting the *combine* flag in `redxspec`, setting the *flatten* flag, and setting the *flatfile* parameter to the appropriate FLAT frame filename.

9.7 Fixing Known Bad Pixels

The bad pixel correction procedure is the same as described for long-slit grism reductions (§8).

To apply a bad pixel correction using the `redxspec` task, set the *fixbad* flag and nominate the bad pixel filename and the type of correction using the *badfile* and *badtype* parameters. *badtype=interpolate* causes `imedit` to be used to interpolate over the bad pixels listed in a *.bpx* file. This is the preferred choice for spectroscopic data. *badtype=fixpix* causes `fixpix` to be used to interpolate over bad pixels listed in a *.bad* file. This is included for consistency with the imaging reduction procedure `redimage`. As with `redimage`, the *badfile* parameter should not include the file extension (*.bpx*, *.bad*, or *.pl*). `redxspec` will append this.

9.8 Interactively Cleaning Bad Pixels

The interactive cleaning procedure is the same as described for long-slit grism reductions (§8).

The `redxspec` task can be used to interactively clean bad pixels by setting the *clean* flag. This invokes the IRAF `imedit` task to first clean the object image (*.oim* file extension) and the associated sky images (*.aim*, *.bim*, or *.sim* file extensions). After the image to be cleaned has been displayed, center the image display cursor on the bad pixel and type *l*. Type *l* again to correct a single bad pixel, or move to another pixel and type *l* again to correct a rectangular region of bad pixels. Type *q* to terminate cleaning the current image and move to cleaning the next image.

9.9 Applying The Geometrical Transformation

Once the geometrical transformation has been defined and all processing dependent on the original geometrical pattern of the image has been completed, it is a simple matter to apply the geometrical transformation to straighten the spectral orders and align slit images with image lines.

The current geometrical transformations are applied to images in a dataset using the `redxspec` task by setting the *transform* flag. The current transformations are the transformations defined by the fit files located in the directory pointed to by the IRAF environment variable *database$*. Each order of the object, sky, and comparison images, if present, are transformed separately and subsetted into separate files, with separate wavelength calibrations stored in their headers. The separate file names are formed by appending *.o##*, *.a##*, *.b##*, *.s##*, or *.c##* (depending on whether the observation type header entry is *abba*, *soos*, *osso*, or *comparison*) to the base spectrum name, where *##* is the number of the spectral order.

9.10 Slit Illumination Correction

The slit illumination correction procedure for cross-dispersed grism data is similar to that described for long-slit grism reductions (§8).

Slit illumination correction images for each order of cross-dispersed grism data are formed from geometrically transformed sky frames, or comparison frames in the case of twilight sky measurements, using the `cspxillum` task, which calls the `noao.twodspec.illum` task. The inputs required are a list of the base names of the SKY frames, and the base name of the output illumination files. For example,

```
cspxillum @skyfiles illum_jh
```

The output illumination function file names are formed by appending *.i##* to the specified output base name, where *##* is the number of the spectral order.

The `cspxillum` task has the parameters listed below. The *comb_opt* parameter defines the way in which the individual sky frames in the list are combined. *comb_opt* should be *average* if the number of sky images is less than about 5 and *median* if greater than about 5. The *statsec* parameter defines the image section within the sky frame over which the illumination profile is computed. This should be set to the region of the image illuminated by the orders.

```
                                 I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspxillum

skies   =            @skyfiles  List of base sky frame names
illfile =             illum_jh  Output illumination frame

(comb_op=              average) Type of combine operation
(statsec=            [15:40,*]) Image section for computing profile

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

For each order of cross-dispersed grism data, you are asked `Determine illumination interactively for illfile.i13 (yes):`. Answering *yes* to this question causes an average spectrum to be plotted in the graphics display. You are required to mark the range of the bin that will be used for determining the average profile along the spatial direction. The default is to use the entire spectrum, but this can be changed using cursor commands in the graphics display window. The available commands are listed in §8. Type *q* to proceed to fitting the spatial profile.

You are then asked the question `Determine illumination interactively for illfile.i13[15:40,*] at bin 1 (yes):`. Answer *yes* to this question and the spatial profile is plotted in the graphics display window. A fit to the profile is made using the IRAF `icfit` task. The parameters of the fit can be changed interactively using the interactive curve fitting cursor commands listed below. Type *d* to delete a point. Type *f* to perform the fit. Type *r* to redraw the graph. The fitting function can be changed by typing, e.g., *:function chebyshev.* The order of the fit can be changed by typing, e.g., *:order 2.* The number of samples being averaged to form the fitted data can be changed by typing, e.g., *:naverage 2.* The values of all fit parameters can be seen by typing *:show.* Type *q* to exit the interactive curve fitting task when a suitable fit has been obtained.

The object, sky, and comparison images for a dataset can be corrected for non-uniform slit illumination by setting the *illumination* flag in `redxspec`, and setting the *illfile* parameter to the appropriate illumination correction base filename. A typical `redxspec` parameter list for applying the slit illumination correction in the file *illum_jh* to spectra with the base name *sp175* is shown below.

```
                                 I R A F
                    Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = redxspec

(images =              @tfiles) List of CASPIR input images to reduce
(spectru=                sp175) Base name of spectrum file

(linear =                   no) Linearize data?
(combine=                   no) Combine individual 2D spectra?
(flatten=                   no) Divide by flatfield?
(fixbad =                   no) Fix known bad pixels?
(clean  =                   no) Interactively clean additional pixels?
(transfo=                   no) Straighten orders and subset?
(illumin=                  yes) Correct non-uniform slit illumination?
(extract=                   no) Extract 1D spectra?
```

```
(fluxcal=                   no) Flux calibrate spectra?
(merge  =                   no) Merge spectrum segments?
(flatdiv=                   no) Divide by flat spectrum star?
(plot   =                   no) Plot merged spectra?

(bias   =                 bias) Bias frame to use
(dark   =              dark180) Dark frame to use
(obstype=                 osso) Type of observation made
(zerosec=      [190:195,10:90]) Zero level image section
(flatfil=              flat_jh) Flatfield frame to use
(badfile=      caspirdir$grism) Bad pixel file
(badtype=               interp) Type of bad pixel correction
(illfile=             illum_jh) Illumination frame to use
(reffile=                     ) Comparison extraction reference file
(fluxspe=                     ) Flux calibration spectrum to use
(weights=                     ) Merge weighting function file to use
(flatspe=                     ) Flat spectrum star file to use

(verbose=                  yes) Verbose output?
(imglist=                     )
(mode   =                   ql)
```

9.11 Extraction of 1D Spectra

We now have an averaged two-dimensional spectral image for each order of the cross-dispersed grisms. For most applications, we want to extract one-dimensional spectra from these images. In general, residual sky emission lines will also be present in these images. This is because the sky emission line spectrum varies on shorter timescales than our integration time. This sky background is removed during the extraction process by linear interpolation along the slit direction.

One-dimensional spectra are extracted using the `redxspec` task by setting the *extract* flag, and optionally defining a value for the *reffile* parameter. The `redxspec` task uses the `apall` task in the IRAF `noao.twodspec.apextract` package to perform the extraction and background subtraction interactively. It is recommended that users become familiar with the workings of this package. The available cursor commands are listed in §8. Generally, you will want to edit the extraction aperture for each object by setting *reffile=""*. However, this may be difficult for extremely weakly-exposed spectra and is inappropriate for comparison spectra. In these cases, you can use a previously defined extraction aperture from a reference spectrum. If a reference spectrum is to be used, set the *reffile* parameter to the filename of the reference spectrum. Avoid setting *reffile=last* to use the `apextract` *last* feature when extracting cross-dispersed grism spectra where each order is extracted sequentially.

The extraction process proceeds slightly differently for the different observation types defined by the observation type header entry. If the observation type is *abba*, the positive object spectrum is extracted interactively, then the corresponding sky spectrum is automatically extracted, and these steps are repeated for an inverted version of the negative object spectrum. For the *osso* and *soos* observation types, the object spectrum is extracted interactively, then the sky spectrum is automatically extracted. For *comparison* spectra, the extraction occurs automatically using the extraction aperture defined by the reference spectrum. The extraction begins with the lowest spectral order in the image and proceeds through each order. The extraction and background aperture definitions used for each object spectrum become the default definitions for extracting the next order. Generally all that is required is to recenter the extraction aperture on the new order.

The extraction process for each order begins by asking `Edit apertures for infile.o13? (yes):`. Answering *yes* to this question allows the user to interactively change the default extraction and background subtraction apertures using the `apedit` task. The full profile perpendicular to the dispersion axis is plotted in the graphics display and the location of the default extraction aperture is indicated, if one is defined. Type *m* to mark the location of the first extraction aperture at the centroid of the profile peak near the cursor location. Type *n* to mark the first extraction aperture at the cursor location without centroiding. Type *s* to shift a predefined aperture to a different location, and optionally centroid the aperture at the new location in response to the question asked. Type *c* to centroid a predefined aperture. On weakly exposed spectra, the object may not be detectable in the full slit profile. If emission features are present, plot the slit profile only around an emission line by decreasing the number of dispersion lines summed by typing, e.g., *:nsum 20*, and selecting the location of the cut across the spectrum by typing *:line nnn*, where *nnn* is the line number where the feature occurs. To change the lower bound of the extraction aperture, position the cursor at the new position and type *l*, or type *:lower -4* to explicitly set to a value of -4. To change the upper bound of the extraction aperture, position the cursor at the new position and type *u*, or type *:upper 4* to explicitly set to a value of 4. Alternatively, you can set the width of the extraction aperture using the height of the cursor as a threshold to define new upper and lower bounds and type *y*. Type *r* to redraw the graph. Define new background sample regions explicitly by typing, e.g., *:b_sample -8:-5,5:8*, or type *b* to change the background subtraction sample regions using the cursor. The cursor commands then available are those of the interactive curve fitting task `icfit` that are listed in §8. Type *z* to delete the sample region nearest the cursor. Type *s* to define one side of a new sample region, and *s* again to define the other side. Type *:sample -8:-5,5:8* to set the background subtraction sample regions explicitly from within `icfit`. To change the order of the fit type *:order 1*. Type *f* for a new fit. Type *r* to redraw the graph. Type *q* to exit from the interactive curve fitting task. When the extraction and background apertures have been defined, type *q* to exit the aperture editor.

Answer *yes* to the question `Write apertures for infile.o13 to database (yes):` to save the definition. Then answer *yes* to the question `Extract aperture spectra for infile.o13? (yes):` to perform the extraction. Answer *yes* to the question `Review extracted spectra from infile.o13? (yes):` to display the extracted one-dimensional spectrum for this grism order. Since we have only one aperture, answer *yes* to the question `Review extracted spectrum for aperture 1 from infile.o13 (yes):`. Type *q* to proceed. Then type a carriage return to the question `Output image name [use # to skip output] (infile.o13.0001):`. The `redxspec` task will rename this file.

The extracted spectra for each order are stored in a single IRAF multispec format file named by appending *.osp*, *.ssp*, or *.csp* to the base spectrum name for the object, sky, or comparison spectra, respectively. These spectra can be inspected individually using the IRAF `splot` task and the *)* and *(* cursor commands to cycle through the orders. The aperture definitions for each order are stored in a *database/* sub-directory of the current directory in files with names like *apinfile.o13*.

9.12 Flux Calibration

The flux calibration procedure for cross-dispersed grism data is similar to that described for long-slit grisms in §8. The approach is to flux calibrate with the best available flux calibrator and to correct for any shortcomings in the flux calibrator by dividing by a 'flat spectrum' star after the flux calibrated spectral orders have been merged into a single spectrum. Suitable spectroscopic flux calibrators are listed in Table 24 of Appendix G.

The `redxspec` task uses the two model flux distributions discussed in §8; a blackbody distribution parameterised by a color temperature, and approximations to the Kurucz $\log g = 4.5$ flux distributions parameterised by the model effective temperature. Model flux distributions are calculated using the `cspflux` task as described in §8. The `redxspec` task searches the same *caspirdir$fluxstds.dat* file to locate model parameters for the flux calibrator star using the object name header entry as the search parameter. Model parameters are prompted for if they are not found in the *caspirdir$fluxstds.dat* file.

Flux calibration is achieved by dividing the object spectrum by the observed spectrum of the flux calibrator and multiplying by the absolute flux spectrum modelled for the flux calibrator. This is done in the `redxspec` task by setting the *fluxcal* flag and specifying the base name of the flux calibrator file in the *fluxspec* parameter. No correction is applied for airmass differences between the object and flux calibrator; it is assumed that the observations were made at similar airmasses in order to optimise terrestrial atmospheric absorption correction. The flux calibrated object spectra are stored in a file named by appending *.fos* to the base spectrum name and the flux calibrated sky spectra are stored in a file named by appending *.fss* to the base spectrum name. Comparison spectra are not flux calibrated.

9.13 Merging Spectral Segments

We now want to merge the individual segments for each order of the grism into a single spectrum. The echellogram produced by the cross-dispersed grisms is such that there is considerable overlap in wavelength from one order to the next, but the instrumental sensitivity at a particular wavelength in different orders can be quite different due to the shape of the blaze profile. These differences lead to different noise levels in the flux calibrated spectra, even though the absolute levels of the individual flux calibrated segments should match. Optimal combination of the segments is performed using weighting functions for each order that are proportional to the wavelength-dependent instrumental sensitivity. The FLAT frame is a suitable origin for these weighting functions.

Weighting functions are derived from the FLAT frame using the `cspweights` task which has the parameters listed below. The *flatfile* parameter defines the flatfield frame to use. The *weights* parameter specifies the base name of the output weighting function. The weighting function will have *.wfn* appended to this name. The FLAT frame is first combined as a *comparison* image, then the known bad pixels are fixed and you are given the opportunity to interactively clean remaining bad pixels. The cleaned image is geometrically transformed and a one dimensional spectrum is extracted from each order by averaging the columns specified by the *range* parameter. These spectra are normalized by dividing by the median value of the spectrum of the first order, and the normalized weighting functions are stored in the IRAF multispec format output file and are plotted in the graphics display.

```
                                  I R A F
                      Image Reduction and Analysis Facility
PACKAGE = caspir
   TASK = cspweights

flatfile=             flat_jh  Flatfield frame to use
weights =               wt_jh  Base name of weighting function

(range  =               15:35) Range of columns to average
(zerosec=      [190:195,10:90]) Zero level image section

(verbose=                 yes) Verbose output?
(mode   =                  ql)
```

Once the weighting functions for a grism have been formed, the individual object, sky, and comparison spectra for each order can be merged into single spectra using the `redxspec` task by setting the *merge* flag and using the *weights* parameter to define the base name of the weighting function file. Flux calibrated object and sky spectra (*.fos* and *.fss* file extensions) will be merged if they exist. Otherwise, the extracted object and sky spectra (*.osp* and *.ssp* file extensions) will be merged. The individual segments for each object order are first overplotted in the graphics display so that the user can assess how well they are matched. The weighted average is then formed, and the process is repeated first for the sky spectra and then for any comparison spectra having the specified base spectrum name and *.csp* file extension. The merged object spectra are stored in a file with *.mos* appended to the base spectrum name. The merged sky spectra are stored in a file with *.mss* appended to the base spectrum name. The merged comparison spectra are stored in a file with *.mcs* appended to the base spectrum name.

9.14 Division By A Flat Spectrum Star

Spectral features in the flux calibrator star, slit losses in the measurement of the flux calibrator, and residual terrestrial atmospheric absorption features are removed by applying a multiplicative wavelength-dependent correction to the merged spectra which we generically call a 'flat spectrum star' correction. The `cspfltspec` task is used to form the 'flat spectrum star' correction based on the merged object spectrum (*.mos* file extension) of a featureless standard. The procedure is described in §8. The correction spectrum is stored in a file named by appending *.flt* to the base name.

Once the 'flat spectrum star' correction has been formed, object spectra can be divided by this correction using the **`redxspec`** task by setting the *flatdiv* flag and specifying the base name of the flat spectrum correction file in the *flatspec* parameter.

9.15 Plotting The Final Spectrum

You can look at the final spectrum using the **`redxspec`** task by setting the *plot* flag. This calls the IRAF **`splot`** task which allows interactive viewing and analysis of the spectrum. Users should consult the help pages for this task for a full description of its capabilities (type *help splot* | *lpr*), or refer to the abbreviated description in §8.

APPENDICES

A Error Recovery

Hardware errors should be reported to the technical staff at SSO. Software errors should be reported to peter@mso.anu.edu.au and/or mickb@mso.anu.edu.au and explained with as much detail as possible.

A.1 Infrared System Software

Most software problems should be cleared by shutting down the whole system and starting again. To do this type:

```
IR_SHUTDOWN
```

When all the windows, except the command entry window, have been removed restart the system according to the instructions in §2. This takes considerable time. It is often quicker to stop only the offending process and restart it if you know which process is at fault. The subprocesses associated with the infrared system, and their functions are listed in Table 3. The subprocesses running at any time can be listed by typing:

```
SHOW PROCESS/SUB
```

Any of the subprocesses listed in Table 3 can be stopped using the STOP DCL command, e.g.:

```
STOP IR_CASPIR
```

Table 3: Infrared System Subprocesses

Subprocess	Function
IR_CASPIR	Controls CASPIR dewar and data taking.
IR_TEMPERATURE	Controls the Lakeshore Temperature Controller and temperature logging.
IR_STATUS	Controls the Status Display.
IR_IDLE_DISPLAY	Idle mode FIGDISP image display.
IR_RUN_DISPLAY	Run mode FIGDISP image display.
IR_PLOT_DISPLAY	Line graphics display used for plotting temperature data.
IR_IMB	Controls Instrument Mounting Box functions.
IR_PADDLE	Controls the N/S/E/W paddle on the workstation screen.
IR_RESPONSE	Receives response messages from the LSI-11/23.
DEWAR_COMMUN	Controls dewar communications with the LSI-11/23.
IMB_COMMUN	Controls IMB communications with the LSI-11/23.

Individual infrared system subprocesses can be restarted using the commands:

```
START_CASPIR
START_TEMPERATURE
START_IDLE
START_RUN
START_PLOT
START_PADDLE
```

The transputer coadder can be restarted by typing:

```
@IR_TRANSPUTER:START_TRANSPUTER
```

A.2 SBRC ACE-2 Drive Electronics

The SBRC ACE-2 drive electronics are mounted on the side of the IMB. If the ACE-2 hangs and MOPRA cannot communicate with it, it may be necessary to press the black reset button on the front panel of the ACE-2.

A.3 MOPRA System Software

If a system error occurs, the workstation screen can change to 'console' mode with a black background and a similar terminal format. If this occurs, it can be reset to the normal Xwindows format by simultaneously typing <ctrl> <shift> F2, where F2 is the F2 function key at the top of the keyboard.

A.4 Lakeshore Temperature Controller

If the 'Array Temperature Out-of-Range' warning appears, you should check that the helium refrigerator is running, that the high pressure helium hoses are not fouled, and that the electrical cable is plugged into the cooler head on the dewar. The array temperature can fluctuate if the cooler operation is erratic and the Lakeshore Temperature Controller frequently wants to autotune the control loop parameters by ramping the temperature up and down around the set point. The Lakeshore controller is located in the Nasmyth Lab, usually on top of the helium compressor. The 'Tune' message flashes on the Lakeshore front panel when it is autotuning. If this problem occurs, report the condition to the SSO technical staff who should investigate the cause of the erratic behavior. In the meantime, it may be possible to limp on by powering off and on the Lakeshore controller until it decides not to autotune for a while.

A.5 Console Room Lights

If the console room incandescent lights go out, reset the circuit breaker in the telescope console, behind the telescope command entry terminal. To do this go to the back of the console and open the blue door at the MOPRA end of the console. The breaker is in the second compartment up from the bottom and it is the one at the left hand end.

B VMS/UNIX Equivalents

Table 4: VMS Equivalents of Common UNIX Commands

UNIX	VMS
mkdir subdir	create/dir [.subdir]
rmdir subir	set prot=[o:rwed] subdir.dir delete subdir.dir;*
cd /disk/dir/subdir/	set default disk:[dir.subdir]
cd ..	set default [-]
pwd	show default
ls /disk/dir/subdir/file.ext	directory disk:[dir.subdir]file.ext
ls * > dir.lis	dir/output=dir.lis *.*
ls -laFq *	dir/date/size *.*
rm *	delete *.*;*
more file.ext	type/page file.ext
cp file.ext .	copy file.ext *
mv file.ext file.new	rename file.ext file.new
chmod u+x file.ext	set protection=(o:e) file.ext
lpr file.ext	print file.ext
df	show device/full datadisk
grep string file.ext	search file.ext string
alias fred 'cd subdir'	fred :== set def [.subdir]
setenv here /disk/dir/subdir/	define/job here disk:[dir.subdir]
source file.csh	@file.com
man	help

C System Performance

The best empirical estimate of the system performance is the observation that for imaging with $0.5''$ pixels after 6 hr of on-source integration, objects spread over $\sim 2''$ with $Kn \sim 19.5$ mag are detectable with a signal-to-noise ratio of ~ 5, depending on how they are measured. This is confirmed by similar observations with 4 min on-source integration times reaching $Kn \sim 17.0$ mag with similar signal-to-noise ratio.

The following describes measurements of basic system parameters, and then calculations of the theoretical performance based on these parameters. These calculations can be used to estimate system performance in other configurations, but should be normalized by comparison with the above *observed* sensitivities.

System zero point offsets are based on the total ADUs in a sky-subtracted stellar image after correction for airmass effects and are defined by the equation $ZP = m_{Std} + 2.5\log_{10}(ADU/sec)$. Typical values of the zero point offsets for each filter (mainly with the $0.5''$ pixel scale) are listed in Table 5. These can be used to calculate the total signal expected on an object of a given brightness or the signal/pixel on an object of a given surface brightness.

Table 5: Typical Zero Points

Filter	Zero Point
J	21.6
H	21.6
K	20.8
K'	20.6
Kn	20.5
M	11.7
MSO [Fe II]	18.6
H_2 1-0 S(1)	18.0
H I Brγ	17.6
2.21 μm Continuum	19.1
CO (Δv=2)	18.5
3.28 μm Dust	16.6
3.60 μm Continuum	17.3
4.00 μm Continuum	16.6
H I Brα	16.3

Typical background brightnesses measured with CASPIR are listed in Table 6. The expected background photon fluxes can be calculated from the tabulated background brightnesses and the system zero point offsets.

Table 6: Background Brightnesses (mag/arcsec^2)

Filter	IRPS 1984	IRIS 1993	CASPIR Nov 1993	CASPIR Mar 1993	PICNIC Aug 1994	CASPIR Apr 1995	CASPIR Jun 1996	CASPIR Jan 1997
J	15.5	15.0	18.7	...	...	15.2	...	15.2
H	14.5	13.7	14.6	...	...	...	...	14.1
K	11.5	12.5	11.6	11.7	...	...	...	...
K'	...	13.7	12.5	12.6	...	...	...	...
Kn	...	13.2	12.4	12.5	13.1–13.9	12.5	12.9	12.0
2.21 μm Continuum	...	...	12.9	...	...	...	...	...
CO (Δv=2)	...	...	10.7	...	...	...	...	...
3.28 μm Dust	...	...	3.1	...	...	...	...	...
3.60 μm Continuum	...	...	3.8	...	...	3.8	...	...
4.00 μm Continuum	...	...	2.6	...	...	...	...	...
H I Brα	...	...	2.0	...	...	...	...	...

The noise in an image is a combination of photon shot noise from the sky and telescope, photon shot noise from the object, shot noise from the dark current, read noise, and other systematic noise sources that are difficult to quantify. For small signals, the noise per pixel can be estimated from the equation

$$Noise = \sqrt{RN^2 + T \times (i_b + i_d)}$$

where RN is the read noise in e$^-$, T is the integration time in sec, i_b is the background signal in e$^-$/sec, and i_d is the dark current in e$^-$/sec. The read noise for the double sample readout methods (methods 2–4, and method 5 with FNDR=1) is $\sim$ 60 e$^-$. The dark current is typically $<$ 30 e$^-$/s/pixel for most of the array, but there are a significant number of detectors with dark currents of $>$ 50 e$^-$/s/pixel (see Fig. 3).

With these data, theoretical performance figures for CASPIR can be calculated from the measured background brightness and the camera throughput as quantified by the system zero point.

For example, for a Kn background brightness of 12.4 mag/arcsec^2 and a Kn zero point offset of 20.5 mag, the Kn background flux for 0.5$''$ pixels is

$$10^{(ZP - m_{Std})/2.5}/4 = 434 \quad ADU/sec/pixel$$

In a 5 sec integration, the background count is $\sim$ 2170 ADU/pixel, or 19550 e$^-$/pixel (1 ADU = 9 e$^-$). The shot noise of this background signal is $\sqrt{19550} = 140 e^-$ which dominates the typical readout noise of 60 e$^-$. Consequently, Kn images with 0.5$''$ pixels and an integration time of 5 sec should be background limited. The total noise per cycle is $\sim \sqrt{60^2 + 19550} \sim$ 152 e$^-$/pixel or 152/9 = 16.9 ADU/pixel which is reduced to 4.9 ADU/pixel when 12 cycles are averaged. The measured value is $\sim$ 5 ADU/pixel. We assume here that sufficient sky frames are averaged so that sky subtraction is essentially noiseless.

For a 5σ detection of an object spread over $n \times n$ pixels, we require an average signal in each of these n^2 pixels of five times the noise per pixel. The total object signal is then $n^2 \times 5 \times 4.9$ ADU. This can be converted to a Kn magnitude after dividing by the integration time of 5 sec and using the Kn zero point offset of 20.5 mag. In this way, we can estimate limiting magnitudes at Kn for a range of seeing or object sizes. The results of these calculations are shown in detail in Table 7.

Table 7: Performance Predictions at Kn (0.5$''$/pixel)

Image Size		5σ Total Signal	Mag	Time to 20 mag
(arcsec)	(pixels)	(ADU/5 sec)	(1 min, 5:1)	(min)
$1'' \times 1''$	2×2	98	17.3	145
$1.5'' \times 1.5''$	3×3	220	16.4	760
$2'' \times 2''$	4×4	390	15.8	2290
$5'' \times 5''$	10×10	2439	13.8	91200

Predicted performance figures for 5σ detections in 1 min of on-source integration in different seeing conditions for various filters are listed in Table 8 for the 0.5$''$/pixel scale and in Table 9 for the 0.25$''$/pixel scale. The 1 min integration time does not include time for sky measurements and the dead time between frames of $\sim$ 20 sec. It is recommended to limit individual frames to 1 min exposures, effectively making the elapsed time $\sim$ 80 sec, so that an adequate number of sky frames can be obtained in the timescale of $\sim$ 15 min on which the sky level is observed to change significantly. If off-source sky measurements are necessary, it is recommended that equal time be spent on the object and sky positions.

Relative performance figures for each filter are of interest in deciding which passband is most sensitive for a particular observation. These calculations for the 0.5$''$/pixel scale in 1.5$''$ seeing and an integration time of 5 sec with 12 cycles are listed in Table 10 for a 15.0 mag star with zero color (S/N$_{HotStar}$), a typical unreddened late-type star with K = 15.0 mag, $J - K$ = 1.0, and $H - K$ = 0.2 (S/N$_{CoolStar}$), and a typical AGN power law spectrum with $S_\nu \propto \nu^{-1.5}$ and K = 15.0 mag (S/N$_{AGN}$).

Performance figures for the grisms can be estimated assuming a slit transmission $\tau_{Slit} = 0.5$ and grism transmissions, τ_{Grism}, as shown in Tables 11 & 12. For example, consider an observation using the HK grism and a 1$''$ (2 pixel) wide slit of an object spread over 2$''$ ($n_Y = 4$ pixels) along the slit and recorded in two frames ($n_{Frames} = 2$) each with an integration time T = 180 sec and with the object placed at

Table 8: Predicted System Performance (0.5″/pixel)

Filter	Time (sec)	Cycles	RN^2 $(e^-)^2$	Background Signal (e^-)	Dark Signal (e^-)	5σ, 1 min Magnitude			
						$1'' \times 1''$	$1.5'' \times 1.5''$	$2'' \times 2''$	$5'' \times 5''$
J	5.0	12	3600	3100	150	19.0	18.1	17.5	15.5
H	5.0	12	3600	7100	150	18.8	17.9	17.3	15.3
K	5.0	12	3600	53850	150	17.1	16.2	15.6	13.6
K'	5.0	12	3600	19550	150	17.4	16.5	15.9	13.9
Kn	5.0	12	3600	19550	150	17.3	16.4	15.8	13.8
[Fe II]	10.0	6	3600	900	300	16.6	15.7	15.1	13.1
H_2O	10.0	6	3600	3810	300	15.7	14.9	14.2	12.2
Cont2.2	10.0	6	3600	6800	300	16.7	15.8	15.2	13.2
CO	10.0	6	3600	29660	300	15.4	14.6	13.9	12.0

Table 9: Predicted System Performance (0.25″/pixel)

Filter	Time (sec)	Cycles	RN^2 $(e^-)^2$	Background Signal (e^-)	Dark Signal (e^-)	5σ, 1 min Magnitude			
						$1'' \times 1''$	$1.5'' \times 1.5''$	$2'' \times 2''$	$5'' \times 5''$
J	5.0	12	3600	775	150	17.7	16.8	16.2	14.2
H	5.0	12	3600	1775	150	17.6	16.8	16.1	14.2
K	5.0	12	3600	13460	150	16.2	15.3	14.7	12.7
K'	5.0	12	3600	4890	150	16.4	15.5	14.9	12.9
Kn	5.0	12	3600	4890	150	16.3	15.4	14.8	12.8
[Fe II]	10.0	6	3600	224	300	15.2	14.3	13.7	11.7
H_2O	10.0	6	3600	978	300	14.5	13.6	13.0	11.0
Cont2.2	10.0	6	3600	1700	300	15.5	14.6	14.0	12.0
CO	10.0	6	3600	7420	300	14.5	13.7	13.0	11.0
Cont3.28	0.3	200	3600	706500	9	10.0	9.1	8.5	6.5
nbL	0.3	200	3600	706500	9	10.7	9.8	9.2	7.2

different positions along the slit in both images. The spectral resolution at 2.2 μm is 2.2/2200 = 0.001 μm/pixel, or a factor of $\Lambda = 0.33/0.001 = 330$ lower than for Kn. In the spectral direction, each pixel sees signal from an area of sky $A_{Sky} = 1'' \times 0.5'' = 0.5$ arcsec^2, dispersed by a factor of Λ more than for Kn, but reduced in flux by τ_{Grism}. The background current per pixel (averaged over features in the sky emission spectrum) is therefore

$$10^{(Z.P.-m_{Bkg})/2.5} \times A_{Sky} \times \frac{\tau_{Grism}}{\tau_{Kn}} \times \frac{Gain}{\Lambda} = 3.2 \quad e^-/sec/pixel.$$

Here we have used the observed Kn background brightness, m_{Bkg}, of 12.4 mag/arcsec^2, and zero point offset, $Z.P.$, of 20.5 mag, and conversion between electrons and ADU, $Gain$, of 9 e$^-$/ADU. The noise per pixel is then

$$Noise = \sqrt{60^2 + 180 \times (3.2 + 10)} = \sqrt{3600 + 2304} = 77 \quad e^-/pixel$$

where we use a read noise of 60 e$^-$ and an average long-integration dark current of $\sim$ 10 e$^-$/s/pixel (see Fig. 3). We see from this that shot noise from the dark current makes a dominant contribution to the total noise, and that integration times of order 180 sec are required to minimise the read noise contribution. Integration times significantly longer than this are not recommended because sky intensity variations make accurate sky subtraction increasingly difficult, and significant numbers of hot pixels saturate as the integration time is increased further. Normally, spectra are recorded as a nodded pair to allow sky subtraction, and preferably as an ABBA sequence. In the case where a single sky frame is subtracted from an object frame to perform the sky subtraction, the total noise per pixel is increased by $\sqrt{2}$ because the sky frame has the same noise per pixel as the object frame. For our example, the final noise becomes 123 e$^-$/pixel.

Table 10: Relative Performances for Different Objects With K = 15 mag

Filter	S/N$_{HotStar}$	S/N$_{CoolStar}$	S/N$_{AGN}$
J	85	34	14
H	73	60	28
K	15	15	15
Kn	18	18	17

We define a 5σ detection per pixel by requiring a signal-to-noise ratio of 5 per pixel after averaging n_Y pixels along the slit and averaging the n_{Frames} object frames. The average object signal per pixel in the dispersion direction is then

$$Signal = 5 \times Noise/\sqrt{n_Y}/\sqrt{n_{Frames}} = 193 \quad e^-/pixel$$

The equivalent Kn imaging signal rate would be

$$Kn\ Signal = \frac{193}{180} \times \frac{\tau_{Kn}}{\tau_{Grism}} \times \frac{\Lambda}{Gain} \times \frac{n_Y^2}{\tau_{Slit}} = 9450 \quad ADU/sec$$

which corresponds to a Kn brightness of

$$Kn = 20.5 - 2.5\log(9450) = 10.6 mag$$

From this we predict that a signal-to-noise ratio of 50:1 can be achieved with the HK grism on a Kn = 8.1 mag object in the continuum in 6 min of on-source integration. Similar calculations for each of the grisms are presented in Tables 11 & 12. Note that integrations with the K grism are limited to 120 sec duration by the background flux at 2.4 μm.

The 5σ line detection sensitivity in the same time can be estimated by assuming the line occupies two pixels in the dispersion direction. The line flux is then $4.54 \times 10^{-14}/10^{(Kn(50\sigma)+2.5)/2.5} \times \lambda(\mu\mathrm{m})/1100 = 5.2 \times 10^{-21}$ W cm^{-2}.

Table 11: Predicted Long-Slit Grism Performance

Grism	Time (sec)	τ_{Grism}	Λ	RN^2 (e$^-$)^2	Background Signal (e$^-$)	Dark Signal (e$^-$)	Noise / Frame (e$^-$)	50σ, 4 min Magnitude	5σ, 4 min Line Flux (W cm^{-2})
J	120	0.53	176	3600	738	1200	74	11.1	2.8×10^{-21}
H	120	0.43	164	3600	1051	1200	76	10.9	1.7×10^{-21}
K	120	0.25	150	3600	1738	1200	81	9.2	4.2×10^{-21}

Table 12: Predicted Cross-Dispersed Grism Performance

Grism	Time (sec)	τ_{Grism}	Λ	RN^2 (e$^-$)^2	Background Signal (e$^-$)	Dark Signal (e$^-$)	Noise / Frame (e$^-$)	50σ, 6 min Magnitude	5σ, 6 min Line Flux (W cm^{-2})
IJ	180	0.08	387	3600	76	1800	74	8.7	1.2×10^{-20}
JH	180	0.14	360	3600	234	1800	75	9.3	3.3×10^{-21}
HK	180	0.12	330	3600	569	1800	77	8.1	5.2×10^{-21}

The signal-to-noise ratio achived with the HK grism has been determined empirically to be given by

$$(S/N)^{-1} \sim \sqrt{(0.067 T_{int} 10^{(9.5-K)/2.5} \sqrt{cycles}\sqrt{runs})^{-2} + (134)^{-2}}$$

This reproduces the predicted HK grism sensitivity in Table 12.

D Miscellaneous Near-Infrared Data

Typical atmospheric extinction corrections for SSO are listed in Table 13, and values for the standard interstellar extinction law from Rieke & Lebofsky (1985, ApJ, 288, 618) are listed for reference in Table 14. Adopted values for the near-infrared broadband zero magnitude flux calibration are listed in Table 15. These are obtained from a 11200 K blackbody normalized to $F_\lambda(\lambda = 5550\text{Å}) = 3.44 \times 10^{-12}$ W cm^{-2} μm^{-1} (Bersanelli, Bouchet, & Falomo 1991, A&A, 252, 854) giving

$$F_\nu = 5513.15/\lambda^3[\exp(1.2848/\lambda) - 1]$$

where F_ν is flux density in Jy and λ is wavelength in μm.

Table 13: Atmospheric Extinction

Filter	mag/airmass
J	0.12
H	0.08
K	0.10
L	0.19
M	0.20
H_2O 2.00 μm	0.11
Continuum 2.21 μm	0.11
CO 2.34 μm	0.19

Table 14: Standard Interstellar Extinction Law

Filter	A_λ/A_V
U	1.531
B	1.324
V	1.000
R	0.748
I	0.482
J	0.282
H	0.175
K	0.112
L	0.058
M	0.023
N	0.052

Table 15: Adopted Zero Magnitude Flux Densities

Filter	λ_c (μm)	F$_\nu$ (Jy)	F$_\lambda$ (W cm^{-2} μm^{-1})
J	1.239	1592	3.11×10^{-13}
H	1.649	1042	1.15×10^{-13}
Kn	2.132	688	4.54×10^{-14}
K	2.192	657	4.10×10^{-14}
nbL	3.592	277	6.44×10^{-15}
M	4.777	164	2.15×10^{-15}

E Wheel Contents

The contents of the five wheels are listed below.

Table 16: Aperture Wheel Contents

Position	Keyword	Content
1	Blank	Blank
2	Lslit1	$1.0'' \times 128''$ slit
3	Disk5	$5.0''$ occulting disk
4	Lslit1.5	$1.5'' \times 128''$ slit
5	Lslit2	$2.0'' \times 128''$ slit
6	SlowClr	$0.25''$/pixel baffle
7	Lslit5	$5.0'' \times 128''$ slit
8	Lslit10	$10.0'' \times 128''$ slit
9	Polar	Three $20'' \times 120''$ slits (for polarimetry)
10	Sslit10	$10.0'' \times 15''$ slit
11	Sslit5	$5.0'' \times 15''$ slit
12	FastClr	$0.5''$/pixel baffle
13	Sslit2	$2.0'' \times 15''$ slit
14	Sslit1.5	$1.5'' \times 15''$ slit
15	Disk2	$2.0''$ occulting disk
16	Sslit1	$1.0'' \times 15''$ slit

Table 17: Upper Filter Wheel Contents

Position	Keyword	Alternative Keyword	Filter	λ_c (μm)	$\Delta\lambda$ (μm)
1	Blank	...	Blank	...	...
2	Clear	...	Clear	...	...
3	Helium	nb108	He I 10830	1.082	0.011
4	PGamma	nb109	H I Pγ	1.093	0.010
5	PBeta	nb128	H I Pβ	1.282	0.015
6	FeII	nb164	MSO [Fe II] + PK50	1.647	0.018
7	AAOFeII	nb165	AAO [Fe II]	1.650	0.015
8	H2O	nb199	H_2O	1.996	0.050
9	H2_1_0	nb212	H_2 1–0 S(1)	2.120	0.027
10	BrGamma	nb217	H I Brγ	2.170	0.022
11	Cont2.2	nb222	Continuum	2.210	0.094
12	H2_2_1	nb225	H_2 2–1 S(1)	2.249	0.024
13	CO	nb236	CO (Δv = 2)	2.343	0.088
14	Cont1.6	...	Continuum	1.580	0.012
15	Grid	...	Wire Grid Analyser	...	...
16	Focus	...	Two-hole focus mask	...	...

Table 18: Utility Wheel Contents

Position	Keyword	Content
1	Align	Four hole dewar alignment mask
2	Clear	Direct imaging cold stop
3	IJ_grism	IJ cross-dispersed grism
4	Foccal	Two-hole focus mask
5	Focus	Two-hole focus mask with prism
6	H_grism	H grism
7	SlowCam	Slow camera lens ($0.25''$/pixel)
8	JH_grism	JH cross-dispersed grism
9	Hart2	Low resolution Hartmann mask
10	Hart1	High resolution Hartmann mask
11	J_grism	J grism
12	Mask	Coronograph pupil mask
13	BigClear	Oversize imaging cold stop
14	HK_grism	HK cross-dispersed grism
15	Wollaston	Wollaston polarimeter analyser
16	K_grism	K grism

Table 19: Lower Filter Wheel Contents

Position	Keyword	Alternative Keyword	Filter	λ_c (μm)	$\Delta\lambda$ (μm)
1	Blank	...	Blank	...	...
2	Clear	...	Clear	...	...
3	J	...	J	1.275	0.282
4	H	...	H	1.672	0.274
5	KP	...	K' + PK50	2.124	0.337
6	KN	...	Kn + PK50	2.165	0.33
7	K	...	K	2.224	0.394
8	L	...	L'	3.821	0.602
9	Ice	nb310	3.08 μm H_2O ice	3.077	0.102
10	Dust3.28	nb328	3.28 μm Dust emission	3.299	0.074
11	Dust3.4	nb340	3.4 μm Dust emission	3.415	0.072
12	Cont3.6	nb360	3.6 μm Continuum	3.592	0.078
13	Cont4.0	nb400	4.0 μm Continuum	3.990	0.052
14	BrAlpha	nb405	H I Brα	4.051	0.054
15	M	...	M	4.777	0.65
16	PK50	...	2 mm PK50	...	...

Table 20: Lens Wheel Contents

Position	Keyword	Content
1	Blank	Blank
2	FastCam	Fast Camera Lens ($0.5''$/pixel)
3	Blank3	Blank
4	Clear	Clear

F Photometric Standards

CASPIR can measure stars fainter than $K \sim 8.2$ mag with $0.5''$ pixels in direct imaging mode in seeing conditions of 1–2″. The IRIS standard star list contains many stars in this range that are suitable for JHK imaging. These stars are listed in Table 21 with standard values on the Carter SAAO system (Carter, B. S., & Meadows, V. S. 1995, MNRAS, 276, 734). Care should be taken to ensure that bright standards do not saturate the array. This is especially problematical at J. The fainter equatorial JHK standards from UKIRT can also be used. These are listed in Table 22. Transformations equations to the Caltech system of Elias et al. (1982, AJ, 87, 1029) are:

$$K_{CIT} = K_{UKIRT} - 0.018 \times (J - K)$$
$$(J - K)_{CIT} = 0.936 \times (J - K)_{UKIRT}$$
$$(H - K)_{CIT} = 0.960 \times (H - K)_{UKIRT}$$
$$(J - H)_{CIT} = 0.820 \times (J - H)_{UKIRT}$$

Transformations from the Caltech system to the original MSSSO and AAO systems are given in McGregor (1994, PASP, 106, 508).

In the 3–4 μm band, and at M must brighter standards are required. The original MSSSO infrared photometric standards (McGregor 1994, PASP, 106, 508) can be used at these wavelengths. They are listed in Table 23.

The 2.3 m telescope coordinate file in MAIA::[PETER.OBSERVE]STAND.COORD contains coordinates for stars in these lists.

Table 21: IRIS Photometric Standards (Carter System)

Star	R.A. (2000) Dec.		μ_α (s/yr)	μ_δ (″/yr)	SpT	V	J	H	K	L
HD590	00 10 16.8	-18 51 47	...	...	F2	10.7	9.195	8.969	8.947	...
HD1274	00 16 36.9	-63 51 35	...	...	G5	9.8	8.781	8.412	8.352	...
HD7644	01 15 34.9	-45 26 42	...	...	F6	10.3	9.487	9.239	9.199	...
HD8864	01 27 29.4	+04 27 44	-0.0018	+0.003	A5	8.9	8.631	8.510	8.474	...
HD15189	02 26 26.5	-13 52 44	+0.0036	-0.047	G0	9.2	8.460	8.159	8.126	...
HD15274	02 27 45.6	+08 51 30	+0.0025	+0.018	F5	8.6	8.490	8.276	8.250	...
HD15911	02 31 45.4	-51 39 43	+0.0009	+0.043	A0	9.4	9.452	9.462	9.472	...
HD17040	02 43 40.7	-17 28 55	-0.0015	+0.018	F7	9.22	9.401	9.141	9.107	...
SA94-251	02 57 46.9	+00 16 05	...	...	...	...	9.131	8.426	8.305	...
SA94-702	02 58 13.6	+01 10 52	...	...	...	...	9.246	8.434	8.289	...
HD18847	03 01 24.5	-19 59 13	-0.0014	-0.019	F5	9.1	8.992	8.686	8.653	...
HD20223	03 13 25.7	-43 21 58	+0.0016	+0.016	A9	8.7	8.824	8.673	8.663	...
HD24849	03 55 41.2	-35 14 53	-0.0034	-0.019	F3	9.7	8.802	8.530	8.489	...
HD29250	04 35 13.0	-29 38 13	+0.0017	+0.026	A4	8.7	9.465	9.361	9.354	...
HD37567	05 38 53.9	-12 46 34	+0.0006	+0.011	B9	8.7	8.997	8.990	8.993	...
HD38872	05 45 55.1	-52 44 22	+0.0015	+0.033	A7	8.7	8.136	7.985	7.960	...
HD39944	05 54 43.2	-25 34 32	-0.0004	-0.096	G1	9.2	8.465	8.144	8.104	...
HD40348	05 58 07.0	-02 33 28	-0.0012	+0.017	A0	9.0	8.926	8.895	8.892	...
HD52467	06 59 19.7	-42 14 16	-0.0004	+0.005	B5	8.5	8.637	8.659	8.699	...
HD56189	07 14 22.3	-38 10 10	...	...	F3	10.3	9.141	8.910	8.873	...
HD62388	07 43 15.0	-12 24 01	+0.0000	-0.029	A0	8.9	8.727	8.691	8.670	...
HD62998	07 46 07.6	-16 34 39	-0.0020	+0.018	F6	9.2	8.593	8.323	8.294	...
HD71264	08 26 18.1	-05 51 49	-0.0011	-0.011	A0	8.6	8.612	8.565	8.538	...
HD84090	09 41 26.2	-42 06 34	-0.0026	-0.013	A3	9.0	8.568	8.506	8.493	...
HD84503	09 45 08.5	-26 16 31	-0.0019	+0.005	F2	9.0	8.849	8.638	8.579	...
HD88449	10 11 40.3	-15 25 25	-0.0037	-0.006	F5	9.3	8.522	8.257	8.223	...
HD94949	10 57 49.2	+09 01 10	...	...	F8	9.7	8.267	7.968	7.938	...
HD100501	11 33 48.1	-29 21 39	-0.0014	-0.005	A9	9.1	9.305	9.119	9.087	...
HD105116	12 06 05.2	-45 53 24	-0.0011	-0.012	A2	9.0	8.153	8.050	8.032	...
HD106807	12 17 05.7	-49 30 02	-0.0035	-0.018	A1	8.8	8.707	8.645	8.637	...
HD106973	12 18 09.3	-01 10 02	...	...	F8	10.7	9.148	8.875	8.836	...
HD114895	13 13 58.3	-35 09 09	+0.0009	+0.011	A3	8.8	8.252	8.135	8.101	...
HD122414	14 02 58.1	-49 32 28	-0.0048	-0.030	F5	9.0	8.536	8.281	8.224	...
HD129349	14 43 10.3	-37 54 23	...	...	F2	9.8	9.077	8.861	8.802	...
HD129540	14 43 13.7	-02 57 29	-0.0027	-0.037	A2	8.7	8.466	8.283	8.247	...
HD130035	14 47 21.1	-44 27 10	-0.0016	-0.018	F0	9.2	8.648	8.461	8.427	...
HD136879	15 26 50.3	-65 57 34	+0.0001	-0.028	A0	9.0	8.659	8.560	8.528	...
HD147778	16 24 26.0	-17 44 42	+0.0003	-0.001	F0	9.1	8.453	8.151	8.088	...
HD148332	16 27 23.3	-01 22 27	...	...	F5	9.5	8.480	8.218	8.174	...
HD159402	17 36 40.2	-44 33 52	+0.0015	+0.018	B8	8.2	8.102	8.113	8.140	...
HD169588	18 26 50.0	-35 22 14	...	...	A0	...	8.734	8.720	8.713	...
DM-597287	18 32 07.9	-59 27 42	...	...	F9	...	8.872	8.594	8.548	...
HD177619	19 08 34.4	-55 41 13	+0.0029	-0.069	F7	9.7	8.584	8.312	8.278	...
HD193727	20 22 15.4	-16 06 49	...	...	F0	9.6	8.977	8.826	8.783	...
HD194107	20 25 36.6	-45 46 36	...	...	G5	9.9	8.772	8.395	8.352	...
HD202964	21 20 21.4	-38 24 17	...	...	F3	9.1	8.624	8.286	8.243	...
HD207288	21 48 15.6	-17 37 10	...	...	G8	9.9	8.825	8.369	8.315	...
HD210427	22 10 51.1	-26 54 03	...	...	G1	10.6	9.245	8.895	8.852	...
HD210863	22 13 26.3	-08 13 44	-0.0028	-0.049	G0	9.3	8.590	8.272	8.234	...
HD212874	22 27 19.5	+04 02 51	...	...	A2	10.0	9.077	8.921	8.890	...
HD214497	22 38 44.4	-14 48 48	...	...	F6	10.0	9.237	8.951	8.906	...
HD216009	22 49 51.2	-44 25 25	+0.0011	-0.003	A0	8.1	7.988	7.949	7.947	...
HD218814	23 11 42.6	-56 47 23	+0.0015	+0.013	A6	9.7	9.334	9.242	9.227	...
HD221462	23 32 27.3	-24 55 54	-0.0035	-0.025	G3	8.7	8.630	8.282	8.219	...

Table 22: UKIRT Photometric Standards (UKIRT System)

Star	R.A. (2000)	Dec.	*J*	*H*	*K*	*L*
FS1	00 33 54.4	-12 07 56	13.429	13.048	12.967	...
FS2	00 55 09.8	00 43 14	10.713	10.504	10.466	...
FS3	01 04 21.5	04 13 40	12.600	12.725	12.822	...
FS4	01 54 37.6	00 43 05	10.556	10.304	10.264	...
FS5	01 54 34.5	-06 46 02	12.335	12.340	12.342	...
FS6	02 30 16.4	05 15 55	13.239	13.305	13.374	...
FS7	02 57 21.0	00 18 44	11.105	10.977	10.940	...
FS8	02 57 46.6	00 16 07	9.079	8.442	8.313	...
FS9	02 58 13.3	01 10 56	9.150	8.424	8.266	...
FS10	03 48 50.0	-00 58 26	14.749	14.870	14.919	...
FS11	04 52 58.7	-00 14 34	11.354	11.294	11.278	...
FS12	05 52 27.4	15 53 23	13.681	13.807	13.898	...
FS13	05 57 07.5	00 01 17	10.517	10.182	10.135	...
FS14	07 24 14.4	-00 33 00	14.108	14.182	14.261	...
FS15	08 51 06.0	11 43 50	12.778	12.420	12.360	...
FS16	08 51 15.2	11 49 24	12.971	12.669	12.631	...
FS17	08 51 19.6	11 52 14	12.681	12.343	12.270	...
FS18	08 53 35.4	-00 36 34	10.814	10.553	10.522	...
FS19	10 33 43.1	-11 41 36	13.565	13.654	13.796	...
FS20	11 07 59.9	-05 09 18	13.353	13.404	13.473	...
FS21	11 37 05.6	29 47 59	12.948	13.031	13.132	...
FS33	12 57 02.3	22 01 54	14.017	14.162	14.240	...
FS23	13.41 44.0	28 29 50	12.997	12.446	12.374	...
FS24	14 40 06.8	00 01 42	10.904	10.772	10.753	...
FS25	15 38 33.2	00 14 14	10.231	9.826	9.756	...
FS26	16 37 00.5	-00 34 45	8.830	8.127	7.972	...
FS27	16 40 41.6	36 21 09	13.494	13.181	13.123	...
FS28	17 44 06.6	-00 25 05	10.745	10.644	10.597	...
FS35	18 27 13.5	04 03 05	12.231	11.846	11.757	...
FS34	20 42 34.5	-20 04 38	12.819	12.919	12.989	...
FS29	21 52 25.3	02 23 21	13.175	13.271	13.346	...
FS30	22 41 44.6	01 12 36	11.923	11.979	12.015	...
FS31	23 12 21.4	10 47 04	13.798	13.919	14.039	...
FS32	23 16 12.4	-01 50 36	13.459	13.576	13.664	...

Table 23: MSSSO Photometric Standards (MSSSO System)

Star	R.A. (2000) Dec.		μ_α (s/yr)	μ_δ (″/yr)	SpT	V	J	H	K	L
Y5817	00 05 24.4	-37 21 26	0.4733	-2.337	M4	8.63	5.282	4.742	4.529	4.356
BS33	00 11 15.8	-15 28 05	-0.0056	-0.264	F7	4.89	3.936	3.679	3.646	3.628
BS77	00 20 04.2	-64 52 30	0.2685	1.167	F9	4.23	3.165	2.870	2.832	2.811
Y392	01 52 49.0	-22 26 06	0.0598	0.004	M1	8.7	6.062	5.391	5.223	5.113
BS612	02 04 29.4	-29 17 49	0.0008	0.010	B9	4.69	4.972	5.024	5.073	5.114
BS740	02 32 05.1	-15 14 41	-0.0053	-0.117	F4	4.75	3.859	3.622	3.589	3.576
BS818	02 45 06.1	-18 34 21	0.0229	0.042	F6	4.47	3.595	3.384	3.344	3.335
Y642	03 06 26.7	+01 57 57	0.0245	-0.897	M0	9.10	6.478	5.815	5.674	5.596
Y1181	05 11 40.5	-45 01 16	0.6156	-5.734	M0	8.86	5.818	5.297	5.073	4.887
Y1255	05 31 27.3	-03 40 39	0.0506	-2.103	M1	7.98	4.775	4.075	3.886	3.766
BS1983	05 44 27.8	-22 26 54	-0.0212	-0.373	F6	3.60	2.689	2.450	2.419	2.415
BS2015	05 44 46.5	-65 44 08	-0.0042	0.007	A7	4.35	3.858	3.749	3.723	3.711
BS2020	05 47 17.1	-51 03 59	0.0005	0.087	A5	3.85	3.558	3.501	3.489	3.476
BS2085	05 56 24.2	-14 10 04	-0.0034	0.136	F1	3.71	3.080	2.935	2.908	2.898
BS2451	06 37 45.6	-43 11 45	-0.0006	-0.005	B8	3.17	3.330	3.359	3.381	3.391
BS3314	08 25 39.6	-03 54 23	-0.0047	-0.027	A0	3.90	3.914	3.921	3.930	3.950
Y2267	09 31 19.6	-13 29 18	0.0500	0.059	M4	10.04	6.401	5.797	5.554	5.369
BS3842	09 38 01.4	-43 11 27	0.0022	-0.035	G8	5.50	3.947	3.493	3.409	3.354
BS3871	09 44 12.1	-27 46 10	-0.0037	0.030	A8	4.79	3.696	3.327	3.255	3.217
V569	10 12 17.6	-03 44 43	-0.0105	-0.232	M2	9.30	5.903	5.256	5.034	4.892
BS4102	10 24 23.7	-74 01 54	-0.0044	-0.031	F2	4.00	3.327	3.166	3.140	3.136
BS4450	11 33 00.1	-31 51 27	-0.0162	-0.042	G7	3.54	1.996	1.535	1.448	1.390
BS4638	12 11 39.1	-52 22 06	-0.0038	-0.019	B3	3.96	4.325	4.397	4.449	4.501
BS4773	12 32 28.0	-72 07 58	-0.0104	-0.009	B5	3.87	4.181	4.253	4.303	4.357
BS4802	12 37 42.1	-48 32 28	-0.0187	-0.008	A2	3.86	3.744	3.720	3.710	3.706
Y2951	12 50 43.5	-00 46 05	-0.0029	-0.395	M0	8.51	5.789	5.117	4.957	4.883
BS4989	13 14 14.7	-59 06 12	-0.0339	-0.161	F7	4.92	3.985	3.725	3.684	3.676
BS5028	13 20 35.7	-36 42 44	-0.0283	-0.089	A2	2.75	2.703	2.697	2.697	2.699
BS5249	13 58 40.7	-44 48 13	-0.0024	-0.024	B2	3.87	4.343	4.438	4.509	4.574
Y3296	14 34 16.7	-12 31 13	-0.0233	0.599	M4	11.36	6.879	6.279	5.986	5.756
Y3375B	14 57 26.6	-21 24 44	0.0731	-1.713	M2	7.91	4.797	4.155	3.938	3.768
Y3501	15 32 13.1	-41 16 35	-0.1022	-1.020	M4	9.30	5.668	5.034	4.792	4.606
Y3746	16 30 18.0	-12 39 48	-0.0048	-1.173	M4	10.10	5.962	5.387	5.115	4.887
BS6147	16 31 08.2	-16 36 46	-0.0037	-0.038	G8	4.28	2.781	2.366	2.274	2.225
Y3845	16 55 28.9	-08 20 10	-0.0542	-0.877	M3	8.98	5.241	4.663	4.420	4.221
BS6378	17 10 22.6	-15 43 29	0.0026	0.095	A2	2.43	2.293	2.286	2.275	2.269
Y3958	17 28 40.2	-46 53 45	0.0555	-0.876	M4	9.36	5.722	5.136	4.888	4.688
Y3992	17 37 03.4	-44 19 11	-0.0637	-0.931	M5	11.2	6.583	5.940	5.658	5.419
Y4338	18 49 50.0	-23 50 12	0.0503	-0.207	M4	10.95	6.229	5.673	5.380	5.123
BS7340	19 21 40.3	-17 50 50	-0.0018	0.024	F0	3.93	3.491	3.396	3.371	3.356
Y4794	20 13 53.3	-45 09 47	0.0726	-0.133	M0	7.97	5.109	4.465	4.279	4.154
BS7773	20 20 39.7	-12 45 33	0.0011	-0.018	B9	4.76	4.814	4.848	4.854	4.852
Y4924	20 42 18.4	-52 41 56	0.0074	-1.067	K7	8.83	6.307	5.651	5.504	5.411
BS7950	20 47 40.5	-09 29 45	0.0022	-0.032	A1	3.77	3.705	3.703	3.697	3.681
Y5117	21 17 15.0	-38 52 06	-0.2787	-1.153	M0	6.67	3.910	3.240	3.078	2.968
Y5190	21 33 34.0	-49 00 32	-0.0055	-0.798	M1	8.68	5.304	4.707	4.482	4.304
BS8278	21 40 05.4	-16 39 45	0.0131	-0.022	F0	3.68	3.173	3.069	3.045	3.025
Y5243	21 46 35.9	-57 42 11	0.0120	-0.873	K7	8.80	6.267	5.617	5.464	5.379
Y5358	22 09 39.9	-04 38 28	0.0693	-0.027	M3	10.12	6.526	5.875	5.626	5.441
Y5475	22 38 33.5	-15 18 00	0.1634	2.236	M6	12.18	6.569	5.955	5.591	5.275
Y5546	22 53 17.1	-14 15 45	0.0656	-0.631	M5	10.10	5.941	5.321	5.044	4.827
BS8709	22 54 38.9	-15 49 15	-0.0029	-0.022	A3	3.27	3.113	3.081	3.067	3.057
Y5572	23 00 16.0	-22 31 28	-0.0658	0.062	M1	7.90	5.295	4.639	4.486	4.394
Y5584	23 05 52.0	-35 51 12	0.5575	1.330	M2	7.34	4.212	3.601	3.382	3.220
BS8848	23 17 25.7	-58 14 08	-0.0032	0.089	F1	3.99	3.200	3.001	2.967	2.945

G Spectroscopic Standards

Spectroscopic standards should be chosen to have featureless spectra and, preferably, to have known photometric magnitudes. Often it is necessary to use a star close to the object in airmass and position on the sky in order to accurately cancel atmospheric absorption features. A large list of spectroscopic standard stars is then useful. Such a list is reproduced in Table 24. These stars are taken from a variety of sources (MSSSO photometric standards, IRPS/FIGS G dwarfs spectroscopic standards, UKIRT spectroscopic standards, NASA Infrared Catalog, Bright Star Catalog) and have correspondingly uncertain photometric magnitudes. The IRPS/FIGS G dwarf spectroscopic standards are to be preferred, but these and F dwarfs have hydrogen (Paschen and Brackett) absorption that should be allowed for during data reduction. One approach is to measure a later type star to determine the hydrogen line strength in the standard, and then remove this feature before dividing object spectra by the corrected standard star spectrum.

Photometric magnitudes come from the following refereences: M = McGregor (1994, PASP, 106, 508), C = Carter (1990, MNRAS, 242, 1), B = Bouchet, Manfroid, & Schmider (1991, A&A Suppl., 91, 409), A = Allen & Cragg (1983, MNRAS, 203, 777). Stars with magnitudes listed but lacking a reference annotation in Table 24 are taken from the NASA Catalog, and their photometry should be consider uncertain at the ±0.05 mag level. Other stars lacking measured photometric magnitudes should be used only as flat spectrum stars to remove terrestrial absorption features; flux calibration should be obtained separately.

As a last resort, bright stars from the Ephemeris can be used, but generally these have unknown infrared magnitudes.

The file MAIA::[PETER.OBSERVE]STAND.COORD also contains coordinates for the these stars.

Table 24: Composite List Of Bright Spectroscopic Standards

Star	R.A. (2000)	Dec.	μ_α (s/yr)	μ_δ ($''$/yr)	SpT	V	J	H	K	L	Ref
BS9095	00 02 57.5	-20 02 46	+0.0077	+0.075	F6V	6.25	...	...	...	...	
BS9088	00 02 10.1	+27 04 56	+0.0630	-0.985	G2V	5.75	4.37	3.95	3.87	...	
BS32	00 10 38.7	-73 13 29	+0.0305	+0.019	F2V+F6V	6.64	...	...	...		
BS33	00 11 15.8	-15 28 05	-0.0056	-0.264	F7V	4.89	3.94	3.68	3.65	3.63	M
BS35	00 01 43.9	-35 07 59	+0.0135	+0.126	F4V	5.25	...	...	...	...	
BS39	00 13 14.1	+15 11 01	+0.0002	-0.007	B2IV	2.84	3.35	3.47	3.52	3.58	B
BS77	00 20 04.2	-64 52 30	+0.2685	+1.167	F9V	4.23	3.17	2.87	2.83	2.81	M
BS88	00 22 51.7	-12 12 34	+0.0266	+0.065	G2V	6.39	5.27	4.95	4.88	...	A
BS100	00 26 12.1	-43 40 48	+0.0098	+0.035	A7V	3.94	3.64	3.55	3.54	3.48	C
BS142	00 35 14.8	-03 35 34	+0.0274	-0.021	F8V	5.20	...	...	...	...	
BS145	00 35 54.7	+13 12 24	-0.0098	-0.184	F7V	6.41	...	...	...	...	
BS147	00 35 41.0	-48 00 04	+0.0044	-0.098	F6V	5.51	...	...	...	...	
BS187	00 42 28.4	-65 28 05	+0.0093	+0.048	F6V	5.39	...	...	...	...	
BS225	00 48 58.6	+16 56 26	-0.0001	-0.200	F8V	5.07	...	...	...	...	
BS314	01 05 51.3	+04 54 34	+0.0018	-0.114	F6V	7.25	...	...	...	...	
BS366	01 14 24.0	-07 55 23	+0.0082	+0.277	F5V	5.13	...	...	...	...	
BS368	01 14 49.1	-00 58 26	-0.0011	+0.209	F5V	5.70	...	...	...	...	
BS370	01 15 11.1	-45 31 54	+0.0633	+0.190	F8V	4.96	4.00	3.71	3.67	3.64	C
BS443	01 31 39.0	-45 34 32	-0.0004	+0.012	A2V	6.17	6.05	6.03	6.03	...	C
BS447	01 32 36.3	-49 43 40	-0.0033	-0.071	F4V	6.28	...	...	...	...	
BS448	01 33 42.8	-07 01 31	+0.0118	-0.077	G2IV	5.76	4.67	4.35	4.28	...	A
BS506	01 42 29.3	-53 44 26	+0.0193	-0.086	F8V	5.52	...	...	...	...	
BS512	01 37 55.6	-82 58 30	+0.0654	+0.129	G2V	5.86	4.79	4.52	4.44	4.37	B
BS531	01 49 35.0	-10 41 11	-0.0103	-0.091	F3III	4.67	...	3.90	3.89	...	
BS535	01 49 48.8	-38 24 14	-0.0007	+0.238	F8V	6.37	...	...	...	...	
Y392	01 52 49.0	-22 26 06	+0.0598	+0.004	M1V	8.7	6.06	5.39	5.22	5.11	M
BS544	01 53 04.8	+29 34 44	+0.0008	-0.229	F6IV	3.41	2.51	...	2.25	...	
BS573	01 57 00.0	-51 45 58	+0.0383	+0.255	F6-7V	6.10	...	...	...	...	
BS612	02 04 29.4	-29 17 49	+0.0008	+0.010	B9.5p	4.69	4.97	5.02	5.07	5.11	M
BS624	02 09 23.1	+17 13 28	+0.0099	-0.177	F5V	6.39	...	...	...	...	
BS638	02 11 22.2	-10 03 08	-0.0019	-0.171	F5V	6.01	...	...	...	...	
BS646	02 12 48.0	+21 12 39	+0.0115	+0.007	F5V	5.27	...	...	...	...	
BS674	02 16 30.6	-51 30 44	+0.0102	-0.022	B8V-IV	3.56	3.78	3.83	3.87	3.89	C
BS705	02 21 45.1	-68 39 34	-0.0079	+0.008	A3V	4.09	4.00	3.97	3.96	3.96	C
BS718	02 28 09.5	+08 27 36	+0.0025	-0.004	B9III	4.28	4.38	4.43	4.42	4.44	B
BS721	02 26 59.1	-47 42 14	+0.0022	-0.005	B5IV	4.25	4.50	4.54	4.59	...	C
BS740	02 32 05.1	-15 14 41	-0.0053	-0.117	F4IV	4.75	3.86	3.62	3.59	3.58	M
BS755	02 33 54.6	-51 05 37	-0.0007	-0.026	F6V	6.24	...	...	...	...	
BS763	02 36 37.8	+12 26 52	+0.0189	-0.081	F7V	5.68	...	...	...	...	
BS772	02 36 58.5	-34 34 42	-0.0015	-0.266	G5IV	5.79	4.63	4.33	4.26	...	A
BS777	02 38 18.6	-30 11 40	+0.0076	-0.083	F4V	5.83	...	...	...	...	
BS784	02 40 12.3	-09 27 11	-0.0106	-0.084	F6V	5.78	...	...	...	...	
BS818	02 45 06.1	-18 34 21	+0.0229	+0.042	F6V	4.47	3.60	3.38	3.34	3.34	M
BS823	02 43 26.6	-66 42 52	+0.0189	-0.066	F5V	6.26	...	...	...	...	
BS869	02 56 26.1	+18 01 23	+0.0193	-0.207	F6V	5.63	...	...	...	...	
Y642	03 06 26.7	+01 57 57	+0.0245	-0.897	M0V	9.10	6.48	5.82	5.67	5.60	M
BS919	03 02 23.5	-23 37 28	-0.0107	-0.051	A4IV	4.09	3.78	3.68	3.67	3.65	C
BS962	03 12 46.4	-01 11 46	+0.0129	-0.063	F8V	5.06	...	...	...	...	
BS996	03 19 21.6	+03 22 13	+0.0178	+0.098	G5Vv	4.83	3.65	3.35	3.27	...	A
BS1006	03 17 46.1	-62 34 32	+0.1934	+0.661	G3–5V	5.54	4.39	4.06	4.00	...	A
BS1013	03 20 45.1	-26 36 23	+0.0029	+0.027	F7V	6.39	...	...	...	...	
BS1076	03 30 13.5	-41 22 12	-0.0012	-0.175	F7V	6.12	...	...	...	...	
BS1093	03 33 56.8	-31 04 49	-0.0020	+0.065	F5V	6.20	...	...	...	...	
BS1101	03 36 52.3	+00 24 06	-0.0157	-0.481	F9V	4.28	3.22	...	2.90	...	
BS1140	03 44 48.1	+24 17 22	+0.0009	-0.043	B7IV	5.46	5.52	5.50	5.51	...	

Table 24: - *cont'd*

Star	R.A. (2000)	Dec.	μ_α (s/yr)	μ_δ (″/yr)	SpT	V	J	H	K	L	Ref
BS1144	03 45 09.7	+24 50 21	+0.0015	-0.044	B8V	5.64	5.78	5.81	5.84	...	
BS1165	03 47 29.0	+24 06 18	+0.0014	-0.044	B7IIIe	2.87	2.93	2.94	2.94	2.92	
BS1233	03 59 40.6	+10 19 51	+0.0114	+0.008	F5V	6.37	...	...	...	...	
BS1239	04 00 40.8	+12 29 25	-0.0005	-0.009	B3V+A4IV	3.47	3.63	3.67	3.68	3.69	B
BS1249	04 02 36.7	-00 16 08	+0.0097	-0.248	F5V	5.38	...	...	...	...	
BS1291	04 08 33.9	-45 51 54	+0.0072	+0.018	F2V	6.59	5.87	5.64	5.61	...	C
BS1294	04 07 21.6	-64 13 21	+0.0322	+0.328	G3V	6.38	5.22	4.90	4.84	...	A
BS1302	04 10 50.5	-41 59 37	+0.0169	+0.067	A9V	4.93	4.29	4.11	4.08	4.07	C
BS1309	04 13 33.0	+07 42 58	-0.0003	+0.009	F2V+F5V	5.29	4.55	...	4.40	...	
BS1316	04 12 31.6	-44 22 06	+0.0035	+0.006	K3–4III	6.71	4.24	3.45	3.31	3.20	C
BS1319	04 15 46.2	+15 24 02	+0.0080	-0.027	F5V	6.32	...	...	...	...	
BS1347	04 17 53.6	-33 47 54	+0.0049	-0.006	B9V	3.56	3.85	...	3.87	...	...
BS1380	04 24 05.7	+17 26 38	+0.0077	-0.037	A7V	4.80	4.48	4.43	4.43	4.39	
BS1404	04 25 19.1	-44 09 39	+0.0025	+0.070	F6V	6.39	...	...	...	...	
BS1473	04 38 09.4	+12 30 39	+0.0067	-0.010	A6V	4.27	4.02	...	3.96	3.93	
BS1502	04 40 33.6	-41 51 50	-0.0135	-0.078	F2V	4.45	3.86	...	3.67	...	...
BS1538	04 48 32.4	-16 19 47	-0.0002	+0.036	F6V	5.77	...	...	...	...	
BS1545	04 49 42.2	-13 46 10	-0.0083	-0.165	F5V	6.26	...	...	...	...	
BS1552	04 51 12.3	+05 36 18	-0.0003	+0.001	B2III	3.69	4.03	4.08	4.15	4.20	C
BS1606	04 53 05.6	-72 24 27	-0.0117	+0.275	F6V	6.28	...	...	...	...	
BS1656	05 07 27.0	+18 38 42	+0.0378	+0.019	G4V	5.00	3.79	3.42	3.37	3.26	
BS1687	05 11 19.1	-02 29 26	+0.0045	+0.009	F5V	5.90	...	...	...	...	
Y1181	05 11 40.5	-45 01 16	+0.6156	-5.734	M0V	8.86	5.82	5.30	5.07	4.89	M
BS1748	05 19 35.2	-01 24 43	-0.0008	-0.005	B1.5V	6.35	6.66	...	6.74	...	
BS1765	05 21 45.7	-00 22 57	-0.0003	-0.001	B2IV-V	4.73	5.08	...	5.22	5.22	
BS1785	05 23 11.9	-26 42 21	+0.0018	+0.009	F6V	6.49	...	...	...	...	
Y1255	05 31 27.3	-03 40 39	+0.0506	-2.103	M1V	7.98	4.78	4.08	3.89	3.77	M
BS1852	05 32 00.3	-00 17 57	-0.0002	-0.001	B0III	2.23	2.75	2.84	2.90	2.90	
BS1855	05 31 55.8	-07 18 06	-0.0005	-0.006	B0V	4.62	5.15	5.29	5.40	5.55	
BS1912	05 33 44.2	-54 54 08	+0.0064	+0.012	F8V	6.43	...	...	...	...	
BS1931	05 33 43.5	-02 39 28	-0.0002	+0.001	O9V	3.81	4.41	4.45	4.52	4.57	
BS1935	05 37 44.6	-28 41 22	-0.0030	+0.051	F4V	5.31	...	...	...	...	
BS1937	05 38 53.0	-07 12 47	-0.0012	-0.054	A4V	4.80	4.53	...	4.47	4.35	
BS2007	05 48 34.9	-04 05 40	+0.0037	-0.216	G4V	5.97	4.83	4.53	4.45	...	A
BS2015	05 44 46.5	-65 44 08	-0.0042	+0.007	A7V	4.35	3.86	3.75	3.72	3.71	M
BS2020	05 47 17.1	-51 03 59	+0.0005	+0.087	A5V	3.85	3.56	3.50	3.49	3.48	M
BS2022	05 37 08.8	-80 28 09	+0.1107	+1.064	G1V	5.65	...	...	...	...	
BS2047	05 54 22.9	+20 16 34	-0.0133	-0.086	G0V	4.41	3.39	3.06	3.02	2.92	
BS2056	05 53 06.8	-33 48 05	-0.0008	+0.033	B5V	4.87	5.14	...	5.35	...	
BS2085	05 56 24.2	-14 10 04	-0.0034	+0.136	F1III	3.71	3.08	2.94	2.91	2.90	M
BS2158	06 04 40.1	-45 04 44	-0.0075	+0.255	F4V	5.93	...	...	...	...	
BS2186	06 09 47.8	-22 46 27	+0.0054	+0.066	F6V	5.71	...	...	...	...	
BS2220	06 14 50.8	+19 09 23	-0.0068	-0.190	F6V	5.20	...	...	...	...	
BS2290	06 20 06.1	-48 44 28	+0.0233	-0.267	G3V	6.60	5.52	5.21	5.15	...	A
BS2318	06 24 43.9	-28 46 48	-0.0124	-0.117	G0V	6.39	5.28	4.99	4.92	4.89	B
BS2348	06 25 43.6	-48 10 38	-0.0011	-0.031	B9V	5.76	5.84	5.85	5.87	...	C
BS2354	06 24 26.4	-63 25 44	-0.0009	-0.104	G3III	6.45	5.37	5.04	5.00	...	C
BS2400	06 31 18.2	-51 49 34	+0.0107	+0.095	F8V	5.60	...	...	...	...	
BS2451	06 37 45.6	-43 11 45	-0.0006	-0.005	B8III	3.17	3.33	3.36	3.38	3.39	M
BS2548	06 49 54.5	-46 36 52	-0.0008	+0.373	F5V	5.14	4.30	4.05	4.01	3.98	C
BS2579	06 52 47.0	-43 58 33	-0.0011	+0.000	B8V	6.46	6.63	6.62	6.64	...	C
BS2626	06 58 41.7	-45 46 04	-0.0011	-0.021	A0V	6.22	6.24	6.23	6.24	...	C
BS2637	07 00 42.6	-28 29 22	-0.0008	-0.036	F5V	6.27	...	...	...	...	
BS2643	07 03 30.4	+29 20 14	+0.0121	-0.827	G4V	5.93	4.89	4.55	4.52	...	
BS2653	07 03 01.4	-23 50 00	-0.0005	-0.001	B3Iab	3.02	3.21	3.25	3.26	3.20	

Table 24: - *cont'd*

Star	R.A. (2000)	Dec.	μ_α (s/yr)	μ_δ (″/yr)	SpT	V	J	H	K	L	Ref
BS2667	07 03 57.2	-43 36 29	-0.0106	+0.385	G3V	5.54	4.46	4.15	4.08	...	B
BS2668	07 03 58.8	-43 36 42	-0.0110	-0.119	K0V	6.79	5.51	5.10	5.01	4.97	B
BS2779	07 19 47.7	+07 08 35	+0.0053	-0.053	F8V	5.91	...	...	...	...	
BS2835	07 26 50.2	+21 32 09	-0.0225	-0.024	F6V	6.54	...	...	...	...	
BS2845	07 27 09.0	+08 17 21	-0.0036	-0.040	B8Ve	2.90	3.00	3.05	3.03	...	B
BS2868	07 29 21.8	-14 59 57	-0.0131	-0.258	F7V	6.05	...	...	...	...	
BS2882	07 30 42.3	-37 20 23	-0.0088	+0.039	G4V	6.65	5.55	5.24	5.18	...	A
BS2883	07 32 05.7	-08 52 52	-0.0064	-0.161	F5V	5.90	...	...	...	...	
BS3034	07 48 05.1	-25 56 14	-0.0010	+0.003	B0Ve	4.50	4.38	4.26	4.09	3.72	
BS3079	07 52 15.6	-34 42 19	-0.0163	+0.240	F5V	5.01	...	...	...	...	
BS3113	07 57 40.1	-30 20 04	-0.0008	+0.007	A2Vv	4.79	4.34	4.23	4.21	4.15	C
BS3131	07 59 52.0	-18 23 58	-0.0006	-0.046	A2Vn	4.61	4.40	4.34	4.33	4.32	C
BS3138	07 57 46.9	-60 18 12	+0.0694	+0.117	G0V	5.59	4.57	4.24	4.21	4.17	C
BS3176	08 07 45.8	+21 34 54	+0.0015	-0.074	G1V	6.14	4.20	3.91	3.83	...	B
BS3202	08 10 39.8	-13 47 57	-0.0170	+0.052	F6V	5.54	...	...	...	...	
BS3271	08 20 13.1	-00 54 34	+0.0035	-0.096	F9V	6.18	...	...	...	...	
BS3274	08 17 55.8	-59 10 01	-0.0057	-0.034	F5V	6.42	...	...	...	...	
BS3299	08 25 49.8	+17 02 46	-0.0133	-0.156	F6V	6.14	...	...	...	...	
BS3314	08 25 39.6	-03 54 23	-0.0047	-0.027	A0V	3.90	3.91	3.92	3.93	3.95	M
BS3398	08 35 28.1	-07 58 56	-0.0020	+0.016	A1p	5.72	5.80	5.81	5.81	...	
BS3421	08 37 19.9	-40 08 51	-0.0275	+0.029	G4V	6.55	5.51	5.22	5.16	...	A
BS3454	08 41 05.2	+03 23 55	-0.0013	-0.005	B3V	4.30	4.70	4.82	4.87	5.05	
BS3465	08 44 45.0	+10 04 54	-0.0010	-0.021	A1p	5.66	5.83	5.85	5.89	...	
BS3522	08 52 35.8	+28 19 51	-0.0365	-0.239	G8V	5.95	4.59	4.14	4.07	3.98	
BS3570	08 55 11.9	-54 57 56	+0.0041	-0.083	F6V	5.71	...	...	...	...	
BS3578	08 58 43.8	-16 07 58	+0.0162	+0.214	F6V	5.86	4.71	4.41	4.38	...	
BS3650	09 12 17.5	+14 59 46	-0.0361	+0.242	G9V	6.51	5.17	4.75	4.69	4.59	
BS3670	09 13 34.5	-47 20 19	-0.0021	+0.001	B9Ve	5.92	5.93	5.94	5.94	...	C
BS3672	09 14 08.0	-44 08 46	-0.0042	+0.000	B6IV	5.85	6.09	6.13	6.17	...	C
BS3674	09 14 24.4	-43 13 39	-0.0025	+0.008	B4V	5.25	5.49	5.54	5.58	...	C
BS3712	09 17 17.2	-68 41 22	-0.0193	-0.025	F4V	5.39	...	...	...	...	
BS3759	09 29 08.8	-02 46 08	+0.0084	-0.018	F6V	4.60	...	...	...	...	
BS3842	09 38 01.4	-43 11 27	+0.0022	-0.035	G8II	5.50	3.95	3.49	3.41	3.35	M
BS3871	09 44 12.1	-27 46 10	-0.0037	+0.030	A8V+F7	4.79	3.70	3.33	3.26	3.22	M
BS3961	10 04 08.4	+03 12 04	-0.0052	-0.101	F4V	6.45	...	...	...	...	
BS3991	10 10 05.8	-12 48 58	-0.0089	-0.119	F5V	5.31	...	...	...	...	
BS4005	10 12 37.8	-19 09 13	-0.0169	-0.121	F6V	6.44	...	...	...	...	
V569	10 12 17.6	-03 44 43	-0.0105	-0.232	M2V	9.30	5.90	5.26	5.03	4.89	M
BS4013	10 13 24.7	-33 01 55	-0.0289	+0.056	G1V	6.38	5.35	5.07	5.01	...	A
BS4023	10 14 44.1	-42 07 19	-0.0135	+0.038	A2V	3.85	3.76	3.74	3.73	3.73	C
BS4030	10 16 32.2	+23 30 11	-0.0149	+0.031	G2IV	5.97	4.79	4.46	4.40	4.42	B
BS4039	10 17 14.5	+23 06 22	-0.0296	-0.105	F8V	5.82	4.80	4.52	4.49	...	
BS4061	10 18 37.5	-56 06 36	-0.0302	+0.124	F6V	5.81	...	...	...	...	
BS4079	10 23 14.5	+05 41 39	-0.0162	-0.075	F6V	6.54	...	...	...	...	
BS4101	10 27 38.9	+09 45 45	+0.0004	-0.002	A0p	6.04	6.08	6.10	6.12	...	
BS4102	10 24 23.7	-74 01 54	-0.0044	-0.031	F2IV	4.00	3.33	3.17	3.14	3.14	M
BS4133	10 32 48.6	+09 18 24	-0.0006	-0.006	B1Ib	3.85	4.18	4.22	4.26	4.27	
BS4157	10 36 04.5	-26 40 30	+0.0005	-0.066	F5V	6.29	...	...	...	...	
BS4167	10 37 18.0	-48 13 33	-0.0159	-0.020	F4IV+F3	3.84	3.28	3.14	3.11	3.09	C
BS4213	10 44 26.6	-72 26 38	-0.0374	+0.034	F6V	6.27	...	...	...	...	
BS4281	10 59 41.0	+11 42 21	-0.0158	+0.036	F5V	6.53	...	...	...	...	
BS4369	11 16 58.1	-07 08 07	-0.0009	-0.012	A8IV	6.14	5.91	5.77	5.79	5.72	
BS4373	11 17 39.1	-34 44 14	-0.0008	-0.002	F4V	6.45	...	...	...	...	
BS4413	11 25 43.2	-63 58 22	-0.0469	-0.083	F7V	5.17	...	...	...	...	
BS4455	11 34 21.9	+03 03 37	-0.0123	-0.107	F5V	5.77	...	...	...	...	

Table 24: - *cont'd*

Star	R.A. (2000)	Dec.	μ_α (s/yr)	μ_δ (″/yr)	SpT	V	J	H	K	L	Ref
BS4488	11 38 40.0	-13 12 07	+0.0060	+0.114	F7V	5.48	...	...	...	...	
BS4520	11 45 36.4	-66 43 43	-0.0162	+0.033	A7III	3.64	3.34	3.25	3.23	3.21	C
BS4523	11 46 31.0	-40 30 01	-0.1347	+0.396	G5V	4.91	3.77	3.38	3.32	...	A
BS4570	11 56 43.8	-47 04 21	-0.0126	+0.013	F5V	6.26	...	...	...	...	
BS4600	12 03 39.5	-42 26 03	+0.0294	-0.122	F6V	5.15	4.36	4.12	4.09	4.03	C
BS4620	12 08 14.6	-48 41 34	-0.0027	-0.020	B9V	5.34	5.30	5.29	5.28	...	C
BS4638	12 11 39.1	-52 22 06	-0.0038	-0.019	B3V	3.96	4.33	4.40	4.45	4.50	M
BS4657	12 15 10.5	-10 18 45	+0.0020	-1.023	F5V	6.11	...	...	...	...	
BS4689	12 19 54.3	-00 40 00	-0.0043	-0.022	A2IV	3.89	3.81	3.78	3.78	3.77	C
BS4743	12 28 02.3	-50 13 51	-0.0029	-0.022	B2V	3.91	4.36	4.44	4.51	4.51	C
BS4757	12 29 51.8	-16 30 56	-0.0148	-0.143	B9V	2.95	3.03	3.04	3.06	3.04	C
BS4773	12 32 28.0	-72 07 58	-0.0104	-0.009	B5V	3.87	4.18	4.25	4.30	4.36	M
BS4802	12 37 42.1	-48 32 28	-0.0187	-0.008	A2V	3.86	3.74	3.72	3.71	3.71	M
BS4828	12 41 53.0	+10 14 08	+0.0057	-0.095	A0V	4.88	...	4.69	4.68	4.69	
Y2951	12 50 43.5	-00 46 05	-0.0029	-0.395	M0V	8.51	5.79	5.12	4.96	4.88	M
BS4883	12 51 41.8	+27 32 26	-0.0010	-0.013	G0III	4.94	3.73	3.44	3.36	...	B
BS4891	12 53 11.1	-03 33 11	-0.0174	-0.006	F5V	6.11	...	...	...	...	
BS4903	12 54 58.4	-44 09 07	-0.0210	-0.229	G1V	5.89	4.87	4.58	4.51	...	A
BS4935	13 03 46.0	-20 34 59	+0.0099	+0.013	F7V	5.58	4.60	4.28	4.26	...	
BS4983	13 11 52.3	+27 52 41	-0.0603	+0.879	G0V	4.26	3.19	2.92	2.88	2.87	
BS4989	13 14 14.7	-59 06 12	-0.0339	-0.161	F7IV	4.92	3.99	3.73	3.68	3.68	M
BS5000	13 16 44.8	-65 08 17	-0.0152	-0.058	F5V	6.07	...	...	...	...	
BS5028	13 20 35.7	-36 42 44	-0.0283	-0.089	A2V	2.75	2.70	2.70	2.70	2.70	M
BS5072	13 28 25.7	+13 46 43	-0.0164	-0.581	G2.5V	4.98	3.71	3.32	3.25	3.21	
BS5082	13 33 14.8	-77 34 05	-0.1041	-0.114	F6V	6.48	...	...	...	...	
BS5107	13 34 41.5	-00 35 46	-0.0191	+0.036	A3V	3.37	...	3.08	3.06	3.06	
BS5128	13 38 42.0	-29 33 39	-0.0060	-0.073	F5V	5.83	...	...	...	...	
BS5132	13 39 53.2	-53 27 59	-0.0025	-0.017	B1III	2.30	2.84	2.97	3.02	3.04	B
BS5249	13 58 40.7	-44 48 13	-0.0024	-0.024	B2V	3.87	4.34	4.44	4.51	4.57	M
BS5270	14 02 31.7	+09 41 11	-0.0134	-0.066	F8IV	6.20	4.33	3.77	3.69	...	
BS5304	14 10 23.9	+25 05 30	-0.0017	-0.064	F9IV	4.83	3.87	...	3.54	3.47	
BS5356	14 19 00.7	-25 48 56	-0.0275	+0.347	F5V	5.87	...	...	...	...	
BS5384	14 23 15.2	+01 14 30	+0.0148	-0.481	G1V	6.27	5.12	4.77	4.71	...	A
BS5387	14 23 06.7	+25 20 17	-0.0121	+0.066	F5V	6.22	...	...	...	...	
BS5412	14 30 08.5	-45 19 18	-0.0045	-0.043	B8Vn	5.50	5.62	5.64	5.65	...	C
BS5447	14 34 40.7	+29 44 42	+0.0144	+0.129	F2V	4.46	3.70	3.51	3.49	3.47	
BS5453	14 37 53.1	-49 25 32	-0.0031	-0.022	B5V	4.05	4.38	4.44	4.49	4.56	C
BS5455	14 36 59.7	-12 18 20	-0.0594	+0.360	F5V	6.20	...	...	...	...	
BS5457	14 39 10.9	-46 35 03	-0.0178	-0.213	F7V	6.07	5.17	4.90	4.86	...	C
BS5471	14 41 57.5	-37 47 37	-0.0020	-0.036	B3V	4.00	4.39	4.47	4.52	4.56	C
BS5494	14 46 29.0	-47 26 28	-0.0022	-0.018	A1V	5.74	5.62	5.59	5.58	...	C
BS5511	14 46 14.9	+01 53 34	-0.0076	-0.031	A0V	3.72	3.70	...	3.67	3.67	
BS5530	14 50 41.1	-15 59 50	-0.0070	-0.072	F4IV	5.15	4.42	4.21	4.16	4.10	B
Y3375B	14 57 26.6	-21 24 44	+0.0731	-1.713	M2V	7.91	4.80	4.16	3.94	3.77	M
BS5568	14 57 27.9	-21 24 56	+0.0746	-1.740	K4V	5.74	3.83	3.24	3.17	3.08	
BS5570	14 57 10.9	-04 20 47	-0.0069	-0.158	F0V	4.49	3.88	...	3.67	3.63	
BS5571	14 58 31.8	-43 08 02	-0.0034	-0.043	B2III	2.68	3.17	3.26	3.33	3.38	C
BS5586	15 00 58.3	-08 31 08	-0.0045	-0.009	B9.5V	4.92	...	4.68	4.68	4.66	
BS5634	15 07 18.0	+24 52 09	+0.0136	-0.171	F5V	4.93	4.12	3.90	3.88	3.89	
BS5646	15 11 56.0	-48 44 16	-0.0097	-0.049	B9.5Vne	3.87	3.91	3.92	3.93	3.91	C
BS5699	15 21 48.1	-48 19 03	-0.1621	-0.271	G4V	5.65	4.51	4.16	4.10	...	A
BS5712	15 23 09.2	-36 51 30	-0.0015	-0.025	B4V	4.54	4.90	4.95	5.00	5.02	
BS5747	15 27 49.7	+29 06 20	-0.0137	+0.083	F0p	3.68	3.36	3.28	3.27	3.28	
BS5758	15 30 55.4	+08 34 45	+0.0022	-0.004	F4Vw	6.57	...	...	...	...	
BS5803	15 39 56.3	-59 54 30	-0.0161	-0.220	F6V	5.95	...	...	...	...	

Table 24: - *cont'd*

Star	R.A. (2000)	Dec.	μ_α (s/yr)	μ_δ (″/yr)	SpT	V	J	H	K	L	Ref
BS5816	15 38 40.0	-08 47 28	+0.0017	-0.022	F6V	6.48	...	...	...	...	
BS5867	15 46 11.2	+15 25 18	+0.0047	-0.049	A2IV	3.67	3.47	...	3.42	3.41	
BS5868	15 46 26.5	+07 21 11	-0.0151	-0.068	G0V	4.43	3.41	3.06	3.00	...	A
BS5923	15 56 13.8	-31 47 09	+0.0029	-0.002	F6V	6.29	...	...	...	...	
BS5928	15 56 53.0	-29 12 50	-0.0006	-0.021	B2IV-V	3.88	4.35	4.42	4.47	4.50	
BS5993	16 06 48.3	-20 40 09	-0.0007	-0.024	B1V	3.96	4.02	4.05	4.09	4.14	C
BS5996	16 07 03.3	-14 04 16	-0.0179	+0.021	G4IV-V	6.32	5.24	4.93	4.87	...	A
BS6012	16 09 55.1	-18 20 27	-0.0060	-0.079	F4V	6.47	...	...	...	...	
BS6094	16 24 01.2	-39 11 35	+0.0067	-0.008	G5V	5.40	4.31	4.00	3.93	...	A
BS6095	16 21 55.1	+19 09 11	-0.0033	+0.042	A9III	3.75	3.19	...	3.02	2.98	
BS6117	16 25 24.9	+14 02 00	+0.0030	-0.063	B9p	4.57	...	4.59	4.52	4.53	
BS6141	16 30 12.4	-25 06 54	-0.0005	-0.024	B2V	4.79	5.02	5.08	5.11	5.19	
BS6165	16 35 52.9	-28 12 58	-0.0006	-0.025	B0V	2.82	3.55	3.51	3.59	3.56	
BS6171	16 36 21.3	-02 19 29	+0.0303	-0.315	K2V	5.75	4.34	3.91	3.86	...	
BS6310	17 00 09.4	-24 59 21	+0.0045	-0.059	F4V	5.75	...	...	...	...	
BS6314	17 03 08.6	-53 14 13	-0.0001	-0.143	F6V	5.29	...	...	...	...	
BS6328	17 01 09.5	+27 11 47	-0.0012	-0.064	F5V	6.55	...	...	...	...	
BS6353	17 05 32.1	-00 53 32	+0.0000	-0.002	B1V	5.64	5.28	5.33	5.29	5.35	
BS6371	17 10 42.2	-44 33 27	-0.0031	-0.056	G8+K0III	5.08	3.60	3.11	3.04	3.01	C
BS6416	17 19 03.1	-46 38 02	+0.0952	+0.218	G8–K0V	5.48	3.94	3.44	3.35	3.31	C
BS6441	17 20 34.1	-19 19 58	-0.0108	-0.103	G3IV	6.52	5.53	5.25	5.18	...	A
BS6454	17 22 37.9	-35 54 36	+0.0067	+0.111	F7V	6.47	...	...	...	...	
BS6496	17 27 02.0	-12 30 45	+0.0023	-0.065	F7V	6.21	...	...	...	...	
BS6500	17 31 05.9	-60 41 01	-0.0065	-0.094	B8Vn	3.62	3.77	3.81	3.83	3.86	C
BS6541	17 33 22.7	+19 15 24	-0.0022	-0.093	F6V	5.64	...	...	...	...	
BS6548	17 34 36.6	+09 35 12	+0.0002	-0.008	A2V	5.81	5.72	...	5.65	5.66	
BS6537	17 35 39.4	-46 30 20	-0.0027	-0.034	A0V	4.59	4.53	4.51	4.51	...	C
BS6572	17 41 16.1	-46 55 19	+0.0007	-0.009	A0V	5.79	5.73	5.71	5.71	...	C
BS6601	17 43 46.9	-07 04 46	-0.0003	-0.008	B1.5V	6.30	5.56	5.41	5.35	5.29	
BS6629	17 47 53.5	+02 42 26	-0.0016	-0.074	A0V	3.75	3.65	3.64	3.64	3.68	
BS6676	17 54 14.0	+11 07 49	-0.0050	-0.173	F5Vn	6.38	...	...	...	...	
BS6733	18 03 04.8	-08 10 50	+0.0017	-0.039	F5V	5.94	...	...	...	...	
BS6736	18 03 52.3	-24 21 38	+0.0002	+0.002	O8If	5.97	5.80	5.77	5.77	...	C
BS6748	18 06 23.6	-36 01 11	+0.0091	+0.014	G5V	5.95	4.92	4.63	4.57	...	A
BS6751	18 12 34.4	-73 40 18	-0.0109	-0.229	F5V	5.85	...	...	...	...	
BS6758	18 05 43.2	+12 00 14	-0.0007	+0.001	A7p	7.04	6.91	6.81	6.87	7.01	
BS6771	18 07 20.9	+09 33 50	-0.0042	+0.081	A4IV	3.73	3.48	...	3.42	3.36	
BS6797	18 09 53.9	+03 07 11	+0.0012	-0.192	F5V	5.69	...	...	...	...	
BS6823	18 15 12.8	-20 23 17	-0.0002	+0.000	O9II	5.95	5.92	5.89	5.90	5.90	
BS6828	18 19 40.1	-63 53 13	+0.0073	-0.285	F9V	6.18	...	...	...	...	
BS6907	18 27 49.4	-29 48 59	-0.0001	+0.032	F9V	5.92	...	...	...	...	
BS6917	18 25 58.7	+29 49 44	+0.0018	-0.022	A2IV	5.83	5.67	...	5.64	5.59	
BS7034	18 43 51.2	-06 49 07	+0.0030	-0.056	F7V	6.31	...	...	...	...	
BS7038	18 45 18.5	-21 00 05	+0.0019	-0.020	F5V	6.36	...	...	...	...	
BS7061	18 45 39.6	+20 32 47	-0.0008	-0.334	F6V	4.19	3.32	...	3.06	3.03	
BS7167	18 58 46.8	+13 54 24	-0.0003	-0.051	F0p	5.89	5.47	5.38	5.35	5.34	
BS7213	19 06 19.8	-52 20 27	+0.0035	-0.115	F7V	5.16	...	...	...	...	
BS7230	19 05 41.0	-15 39 37	-0.0003	-0.006	B9V	5.97	5.97	5.98	5.97	5.97	
BS7235	19 05 24.5	+13 51 48	-0.0005	-0.095	A0Vn	2.99	2.91	...	2.90	2.89	
BS7236	19 06 14.8	-04 52 57	-0.0014	-0.088	B9V	3.44	3.60	3.66	3.66	3.66	B
BS7253	19 06 37.6	+28 37 43	+0.0057	+0.087	F0III	5.55	5.02	4.87	4.85	...	C
BS7280	19 11 30.8	+26 44 09	+0.0016	-0.034	F5V	6.36	...	...	...	...	
BS7330	19 21 29.8	-34 59 02	+0.0086	-0.098	G5V	6.48	5.38	5.05	4.97	...	A
BS7340	19 21 40.3	-17 50 50	-0.0018	+0.024	F0IV	3.93	3.49	3.40	3.37	3.36	M
BS7354	19 22 48.3	+09 54 46	+0.0008	+0.097	F6V	6.35	...	...	...	...	

Table 24: - *cont'd*

Star	R.A. (2000)	Dec.	μ_α (s/yr)	μ_δ (″/yr)	SpT	V	J	H	K	L	Ref
BS7393	19 30 34.4	-55 06 36	+0.0043	-0.012	F5V	6.30	...	...	...	...	
BS7446	19 36 53.4	-07 01 39	+0.0000	-0.004	B1III	4.96	5.01	5.04	5.06	5.05	B
BS7454	19 37 34.3	-14 18 06	-0.0075	-0.142	F5V	5.47	...	...	...	...	
BS7631	20 00 20.2	-33 42 14	+0.0108	-0.305	F7V	5.66	...	...	...	...	
BS7644	20 05 32.6	-67 19 15	+0.1461	-0.680	G3V	6.07	4.97	4.62	4.57	...	A
BS7658	20 03 44.2	-22 35 44	-0.0030	+0.022	F6V	6.45	...	...	...	...	
BS7710	20 11 18.2	-00 49 17	+0.0024	+0.007	B9III	3.23	3.35	3.37	3.37	3.37	B
Y4794	20 13 53.3	-45 09 47	+0.0726	-0.133	M0V	7.97	5.11	4.47	4.28	4.15	M
BS7749	20 19 17.8	-47 34 49	+0.0198	-0.182	F5V	6.13	...	...	...	...	
BS7773	20 20 39.7	-12 45 33	+0.0011	-0.018	B9V	4.76	4.81	4.85	4.85	4.85	M
BS7779	20 22 27.4	-42 02 59	+0.0032	-0.091	A0V	5.59	5.58	5.58	5.58	...	C
BS7787	20 23 53.1	-42 25 23	+0.0000	+0.025	A5V	5.64	5.26	5.15	5.12	...	C
BS7855	20 34 11.6	-13 43 16	+0.0050	+0.072	F6V	6.13	...	...	...	...	
BS7875	20 40 02.4	-60 32 56	+0.0419	-0.569	F8V	5.12	...	...	...	...	
BS7906	20 39 38.2	+15 54 43	+0.0045	+0.000	B9IV	3.77	3.85	...	3.88	3.84	
BS7914	20 40 45.1	+19 56 07	+0.0087	+0.306	G5V	6.45	5.36	5.02	4.97	...	
Y4924	20 42 18.4	-52 41 56	+0.0074	-1.067	K7V	8.83	6.31	5.65	5.50	5.41	M
BS7950	20 47 40.5	-09 29 45	+0.0022	-0.032	A1V	3.77	3.71	3.70	3.70	3.68	M
BS7973	20 49 37.7	+12 32 43	+0.0038	+0.101	F5V	5.98	...	...	...	...	
BS7982	20 51 25.6	-05 37 35	+0.0064	+0.001	F5V+F7V	5.99	...	...	...	...	
BS8031	20 59 59.5	-36 07 45	+0.0082	-0.040	F5V	6.11	...	...	...	...	
BS8042	21 02 12.5	-43 00 07	+0.0054	-0.100	K0IV	6.63	5.52	5.20	5.12	5.05	B
BS8056	21 03 02.9	+01 31 55	-0.0079	-0.049	F5V	6.25	...	...	...	...	
BS8075	21 05 56.7	-17 13 58	+0.0058	-0.056	A1V	4.07	4.07	4.04	4.04	4.01	C
BS8097	21 10 20.5	+10 07 53	+0.0040	-0.152	F0p	4.69	4.28	4.18	4.13	4.13	
Y5117	21 17 15.0	-38 52 06	-0.2787	-1.153	M0V	6.67	3.91	3.24	3.08	2.97	M
Y5190	21 33 34.0	-49 00 32	-0.0055	-0.798	M1V	8.68	5.30	4.71	4.48	4.30	M
BS8278	21 40 05.4	-16 39 45	+0.0131	-0.022	F0p	3.68	3.17	3.07	3.05	3.03	M
BS8283	21 41 32.8	-14 02 51	-0.0084	-0.304	G1V+G0V	5.18	4.02	3.69	3.61	...	B
Y5243	21 46 35.9	-57 42 11	+0.0120	-0.873	K7V	8.80	6.27	5.62	5.46	5.38	M
BS8402	22 03 18.7	-02 09 19	+0.0011	-0.010	B7IV	4.69	4.83	4.84	4.80	...	
BS8430	22 07 00.6	+25 20 42	+0.0221	+0.028	F5V	3.76	2.94	2.72	2.66	2.63	B
BS8431	22 08 22.9	-32 59 19	+0.0061	-0.033	A2V	4.50	4.38	4.35	4.35	4.34	C
BS8457	22 11 02.3	-21 13 57	+0.0087	-0.030	F6V	6.09	...	...	...	...	
BS8467	22 12 43.7	-04 43 14	-0.0036	-0.031	F7V	6.39	...	...	...	...	
BS8477	22 14 38.5	-41 22 54	+0.0500	-0.788	G5V	6.23	5.12	4.77	4.70	...	A
BS8514	22 20 55.8	+08 11 13	+0.0031	+0.028	F6V	6.17	...	...	...	...	
BS8524	22 23 07.9	-45 55 42	+0.0226	-0.046	F3III-IV	5.62	4.93	4.71	4.67	...	C
BS8531	22 24 56.3	-57 47 51	+0.0183	-0.339	G3IV	5.32	4.18	3.87	3.76	3.75	B
BS8551	22 27 51.5	+04 41 44	+0.0054	-0.306	K0III	4.79	3.01	2.38	2.30	2.23	C
BS8573	22 30 38.7	-10 40 41	+0.0000	-0.027	A0IV	4.82	4.95	4.97	4.95	4.96	
BS8576	22 31 30.3	-32 20 46	+0.0053	-0.012	A0V	4.29	4.27	4.27	4.27	4.26	C
BS8597	22 35 21.3	-00 07 03	+0.0059	-0.051	B9IV-V	4.02	4.18	...	4.22	4.22	
BS8629	22 40 47.9	-03 33 15	+0.0000	-0.037	F6V	6.31	...	...	...	...	
BS8634	22 41 27.6	+10 49 53	+0.0054	-0.008	B8V	3.40	3.51	...	3.56	3.59	
BS8635	22 42 36.8	-47 12 39	+0.0008	-0.321	G0V	5.98	4.93	4.60	4.53	...	C
BS8641	22 41 45.3	+29 18 27	-0.0004	-0.022	A1IV	4.79	4.81	...	4.82	...	
BS8658	22 46 07.9	-48 58 44	+0.0207	-0.045	F9V	6.62	5.52	5.18	5.11	...	A
BS8665	22 46 41.5	+12 10 22	+0.0159	-0.493	F6III-IV	4.2	3.22	...	2.92	2.86	
BS8700	22 53 37.8	-48 35 53	+0.0218	-0.073	G0V	6.04	5.07	4.74	4.72	4.63	B
BS8701	22 54 39.5	-70 04 26	-0.0076	+0.073	G2IV	6.04	4.98	4.68	4.60	...	B
BS8709	22 54 38.9	-15 49 15	-0.0029	-0.022	A3V	3.27	3.11	3.08	3.07	3.06	M
BS8717	22 55 13.6	+08 48 58	+0.0052	+0.019	A1V	4.90	4.90	...	4.90	4.93	
BS8729	22 57 27.9	+20 46 08	+0.0145	+0.063	G2IV	5.49	4.36	4.03	3.97	...	
Y5572	23 00 16.0	-22 31 28	-0.0658	+0.062	M1V	7.90	5.30	4.64	4.49	4.39	M

Table 24: - *cont'd*

Star	R.A. (2000)	Dec.	μ_α (s/yr)	μ_δ ($''$/yr)	SpT	V	J	H	K	L	Ref
BS8781	23 04 45.6	+15 12 19	+0.0043	-0.038	B9V	2.49	2.53	2.55	2.53	2.51	B
Y5584	23 05 52.0	-35 51 12	+0.5575	+1.330	M2V	7.34	4.21	3.60	3.38	3.22	M
BS8843	23 16 57.6	-62 00 05	+0.0251	-0.026	F7V	5.66	...	...	...	...	
BS8845	23 15 57.8	+24 46 16	+0.0068	+0.010	F5V	6.60	...	...	...	...	
BS8848	23 17 25.7	-58 14 08	-0.0032	+0.089	F1III	3.99	3.20	3.00	2.97	2.95	M
BS8859	23 18 09.8	-40 49 29	+0.0117	-0.124	F5V	5.53	...	...	...	...	
BS8905	23 25 22.7	+23 24 15	+0.0140	+0.043	F8III	4.40	...	3.07	3.00	2.97	
BS8907	23 26 36.4	-52 43 18	+0.0036	+0.131	F4V	5.52	...	...	...	...	
BS8911	23 26 55.9	+01 15 20	+0.0057	-0.092	A0p	4.94	4.91	4.97	4.98	4.97	
BS8931	23 31 31.4	-04 05 15	+0.0115	-0.185	F8V	6.49	...	...	...	...	
BS8959	23 37 50.9	-45 29 33	+0.0066	-0.009	A2V	4.74	4.58	4.55	4.53	4.48	C
BS8984	23 42 02.7	+01 46 48	-0.0087	-0.147	A7V	4.50	4.10	...	4.00	3.94	
BS8999	23 44 28.8	-26 14 48	-0.0052	-0.011	F4V	6.17	...	...	...	...	
BS9016	23 48 55.5	-28 07 49	+0.0080	-0.101	A0V	4.57	4.57	4.55	4.54	4.55	C

H Kurucz Model Stellar Spectra

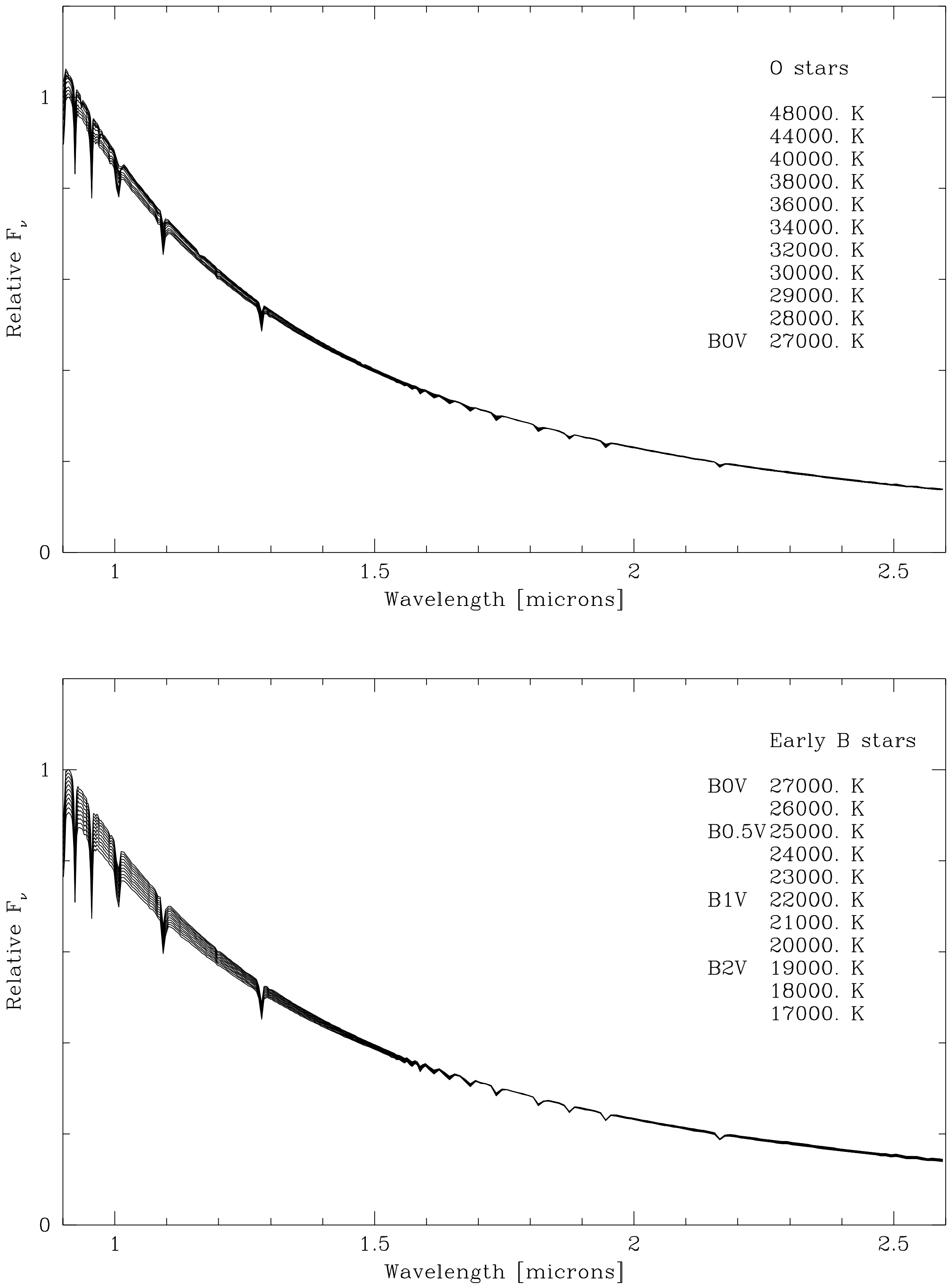
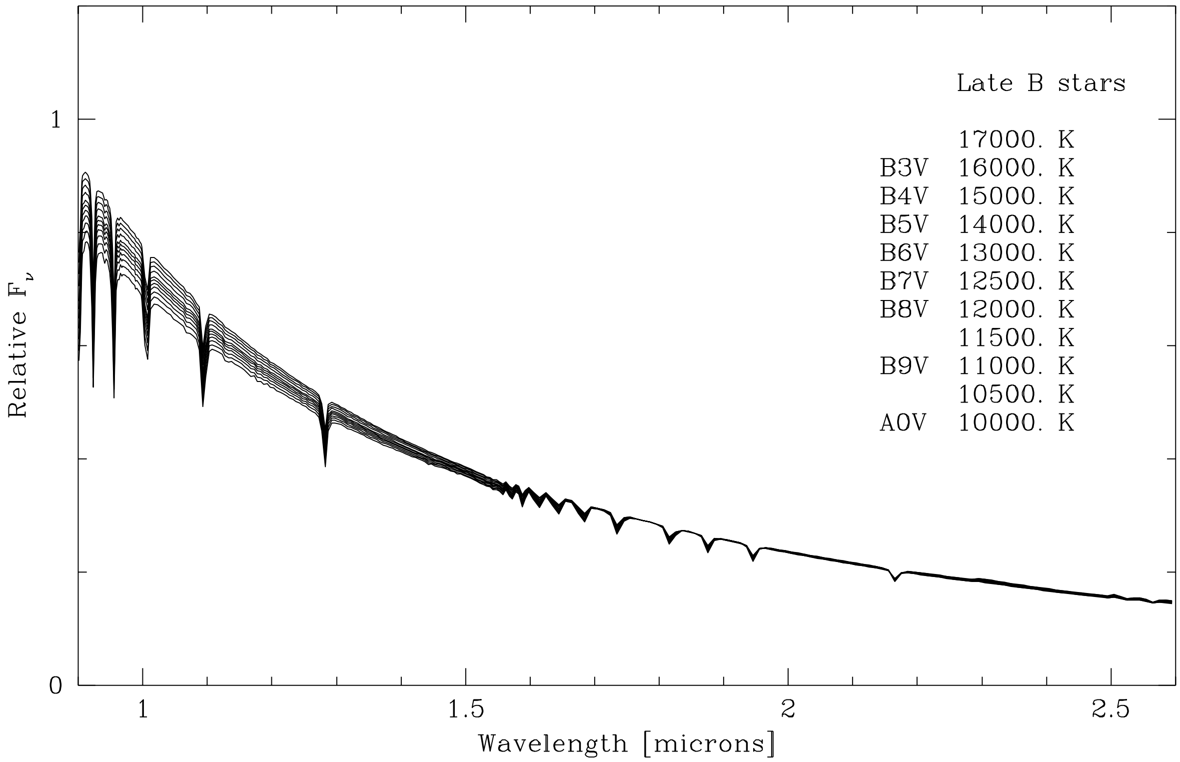


Figure 34: Kurucz $\log g = 4.5$ model stellar spectra.



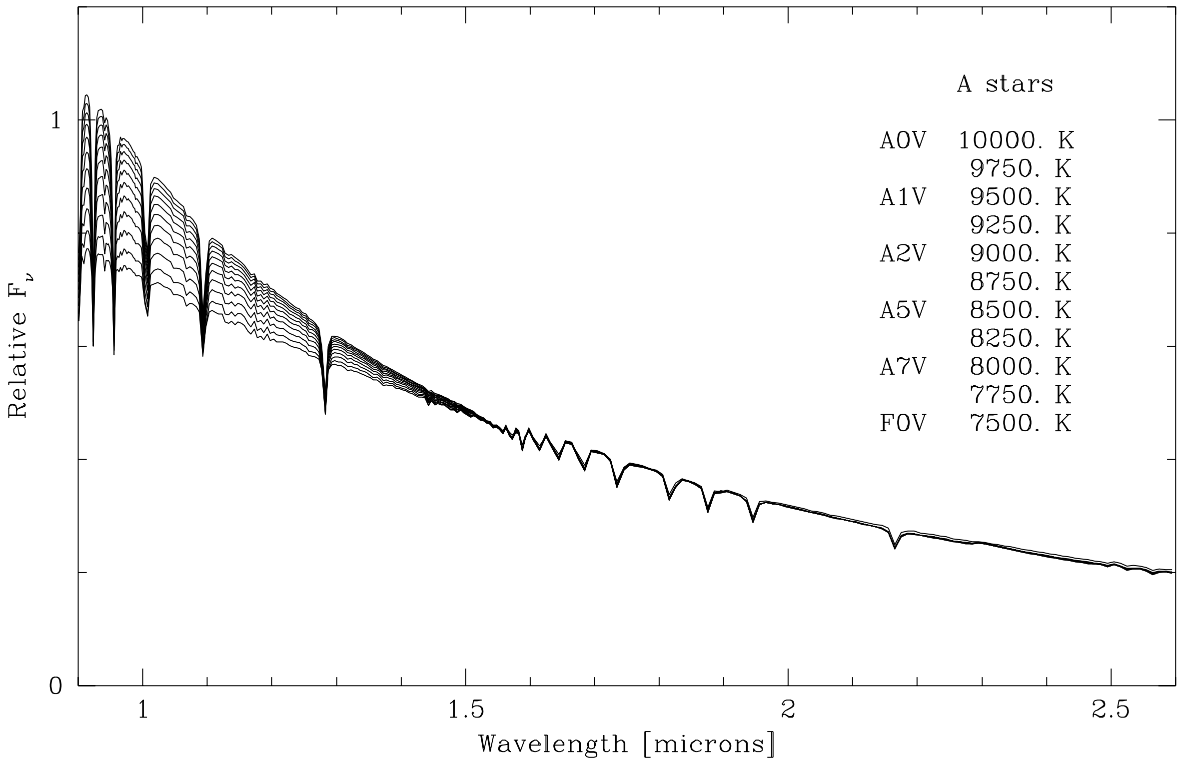
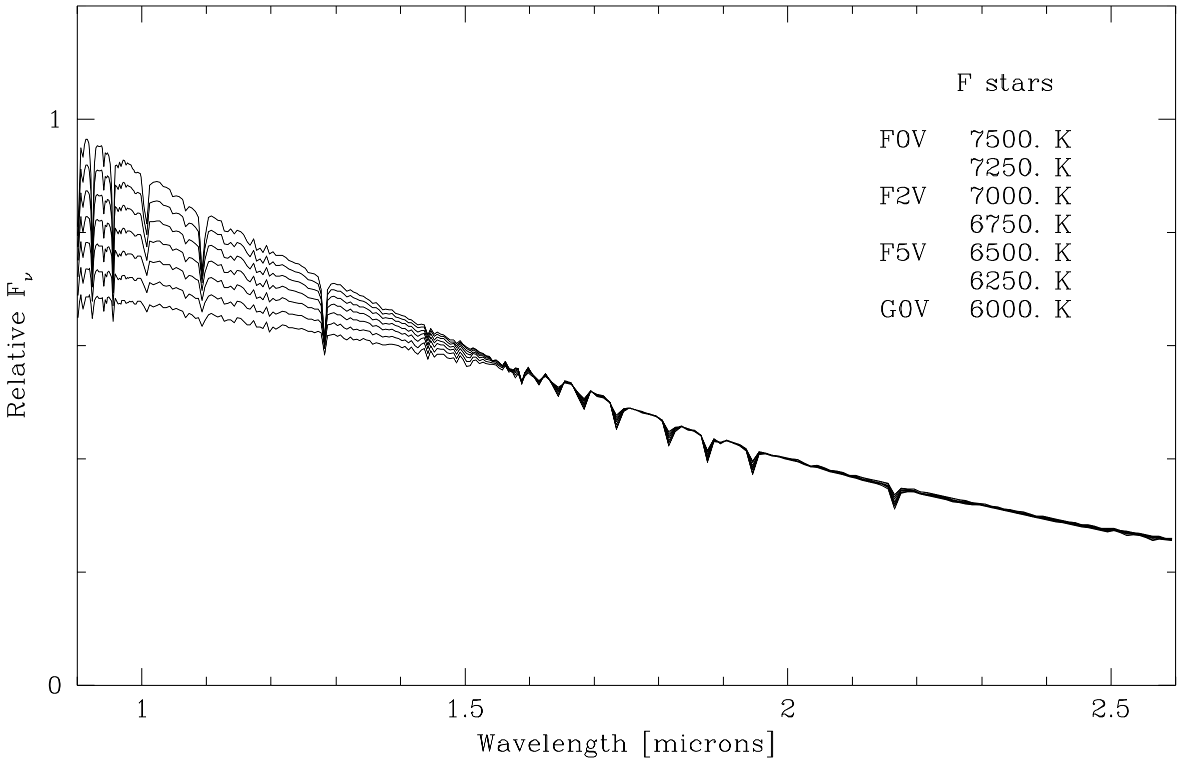


Figure 35: Kurucz $\log g = 4.5$ model stellar spectra.



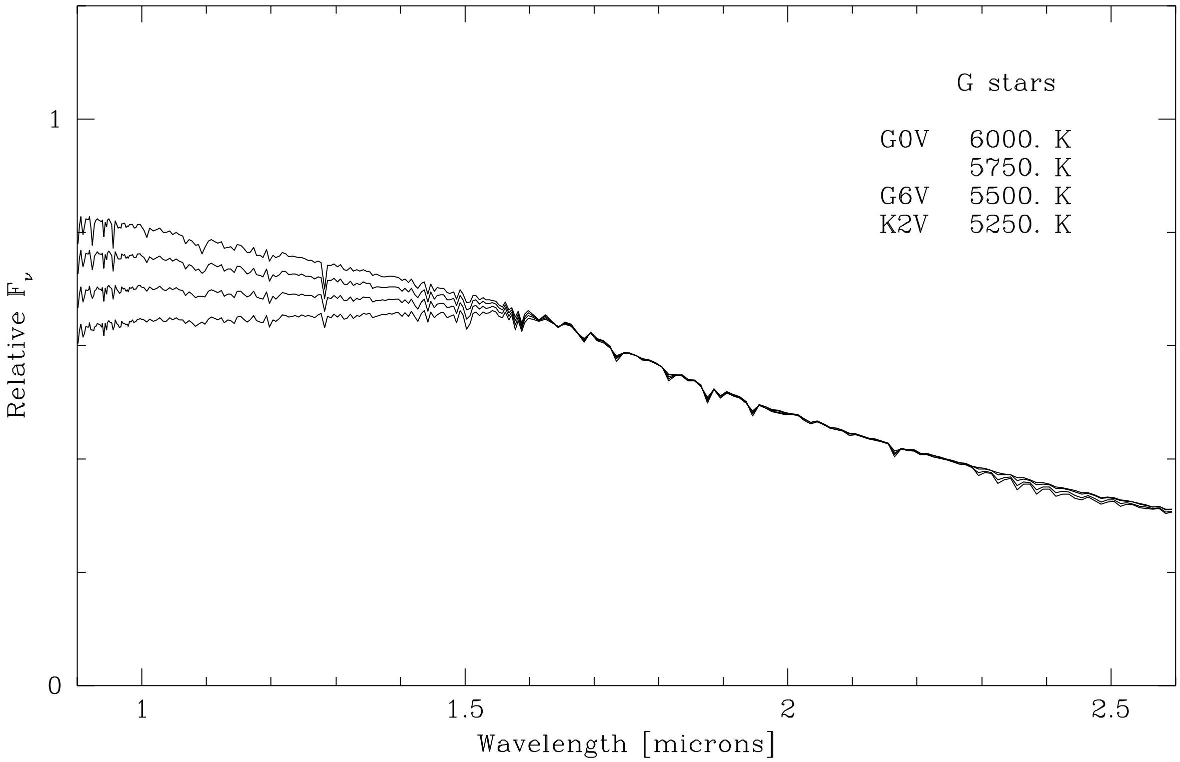
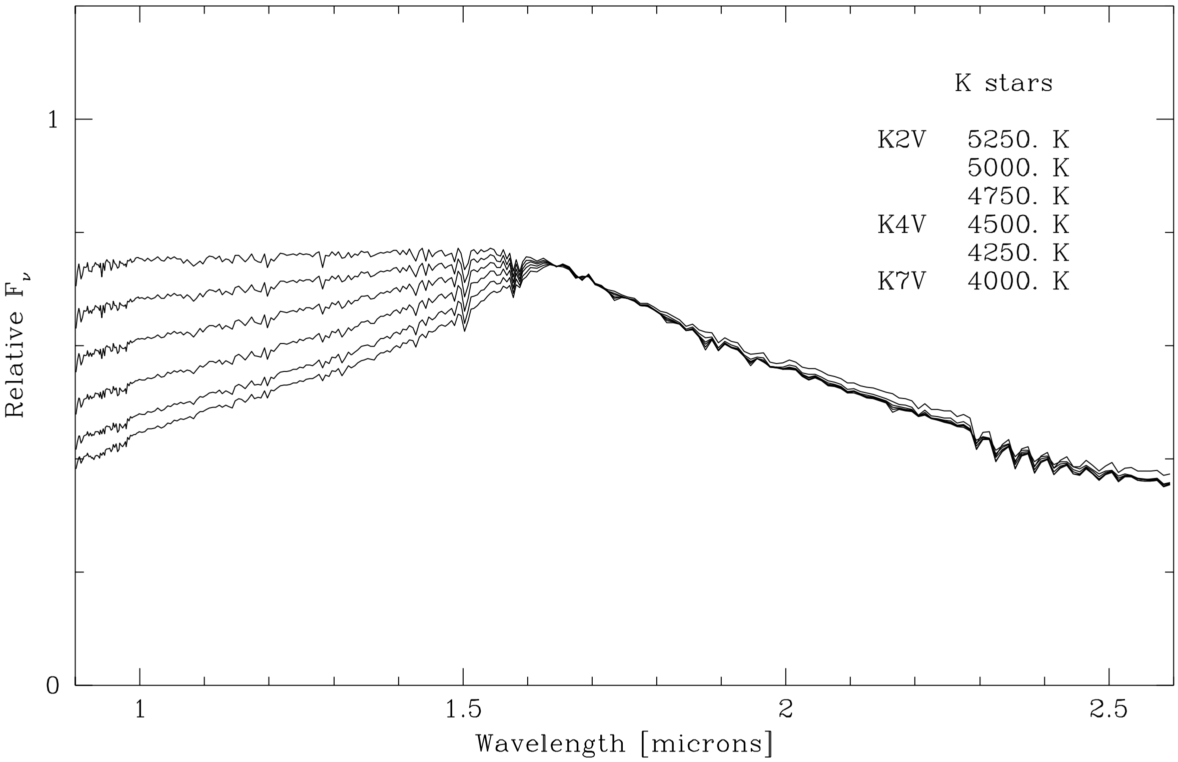


Figure 36: Kurucz $\log g = 4.5$ model stellar spectra.



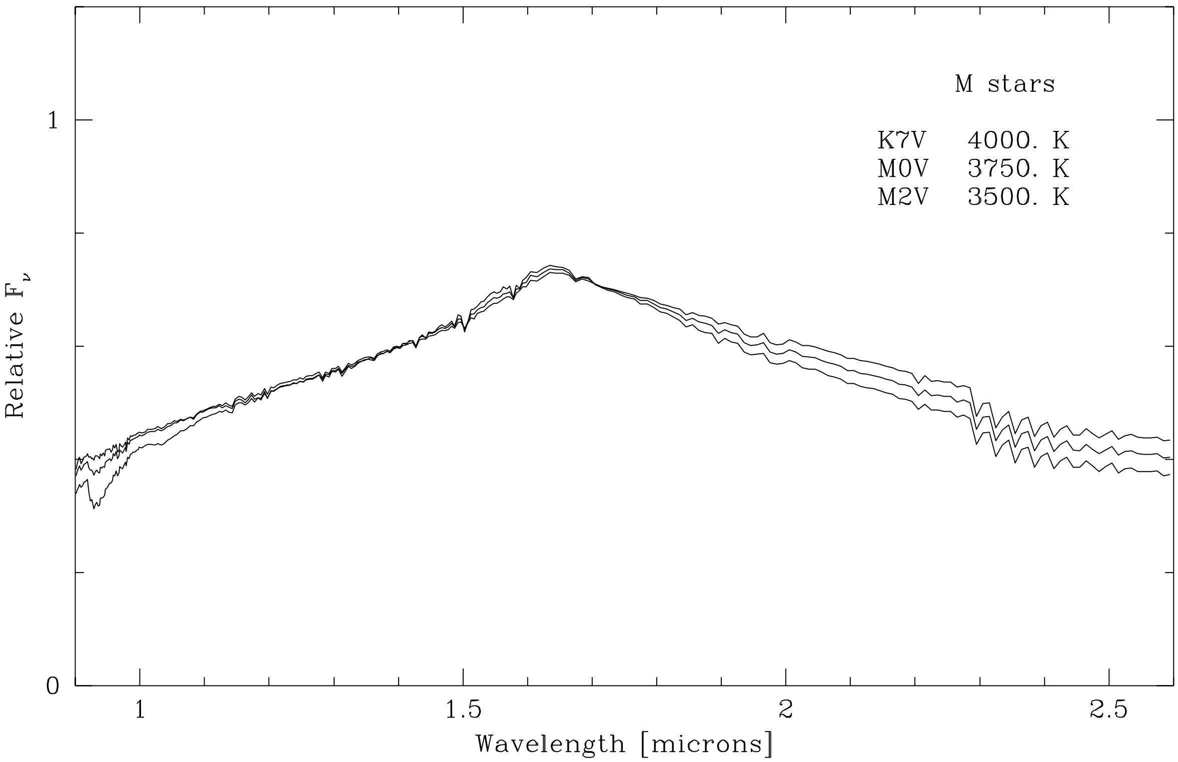


Figure 37: Kurucz $\log g = 4.5$ model stellar spectra.

I Common Infrared Spectral Features

Table 25: Infrared Spectral Features

λ_{air} (μm)	Identification
0.991272	[S VIII] (2p^5 $^2P^0_{3/2} -^2 P^0_{1/2}$)
0.999756	Fe II
1.00494	H I Pδ
1.01236	He I
1.0174	Fe II
1.03998	[N I]
1.0300	[S II]
1.0490	Fe II
1.0501	Fe II
1.0747	[Fe XIII]
1.0798	[Fe XIII]
1.082909	He I
1.083025	He I ($2^3P - 2^3S$)
1.083034	He I
1.0863	Fe II
1.09381	H I Pγ
1.11126	Fe II
1.1287	O I
1.16264	He I
1.1883	[P II]
1.1910	[Ni II]
1.233	H_2 3–1 S(1)
1.25235	[S IX] 329 eV
1.2521	[Fe II] (a$^6D_{3/2}$–a$^4D_{1/2}$)
1.2527	He I ($3^3S - 4^3P^0$)
1.2567	[Fe II] (a$^6D_1$–a$^4d_7$)
1.270	[Fe II]
1.28181	H I Pβ
1.294	[Fe II]
1.298	[Fe II]
1.313	H_2 4–2 S(1), 3–1 Q(1,2,3)
1.3164	O I
1.321	[Fe II]
1.4305	[Si X]
1.476	He II 9–6
1.502499	Mg I ($^3S -^3 P^0$)
1.504024	Mg I ($^3S -^3 P^0$)
1.504770	Mg I ($^3S -^3 P^0$)
1.51918	H I Br20
1.522	[Fe II]
1.52606	H I Br19
1.530	Hg I (telluric)
1.533	[Fe II]
1.53418	H I Br18
1.54389	H I Br17
1.55565	H I Br16
1.56	^{12}CO (3–0)
1.57007	H I Br15
1.572	He II 13–7
1.58	^{12}CO (4–1)
1.58805	H I Br 14
1.599	[Fe II]
1.60	^{12}CO (5–2)
1.6022	H_2 6–4 Q(1)
1.607	[Si I]
1.61093	H I Br13
1.6131	H_2 5–3 O(3)
1.62	^{12}CO (6–3)
1.64	^{12}CO (7–4)
1.64072	H I Br12
1.6435	[Fe II] (a$^4D_{7/2}$–a$^4F_{9/2}$)
1.6454	[Si I]
1.66	^{12}CO (8–5)
1.664	[Fe II]
1.677	[Fe II] (a$^4F_{7/2}$–a$^4D_{1/2}$)
1.68065	H I Br11
1.688	Fe II
1.692	He II 12–7
1.700247	He I ($4^3D - 3^3P$)
1.736	C IV 9–8
1.73621	H I Br10
1.77	C_2
1.81741	H I Br9
1.8358	H_2 1–0 S(5)
1.87510	H I Pα
1.94456	H I Br8
1.9499	H_2 2–1 S(5)
1.95	H_2O vapor
1.9576	H_2 1–0 S(3)
1.96287	[Si VI] (2p^5 $^2P^0_{3/2} -^2 P^0_{1/2}$) 205.1 eV
1.99	Ca I
2.0041	H_2 2–1 S(4)
2.0338	H_2 (1–0) S(2)
2.040	[Al IX] 330.2 eV
2.047	[Fe II] ($a^4P - a^2P$)
2.058130	He I ($2^1P - 2^1S$)
2.061	Fe II ($c^4F - z^4F^0$)
2.0735	H_2 2–1 S(3)
2.089	Fe II ($c^4F_{3/2} - z^4F^0_{3/2}$)
2.112007	He I ($4^3S - 3^3P$)
2.112143	He I
2.113203	He I ($4^1S - 3^1P$)
2.1218	H_2 (1–0) S(1)
2.137	Mg II ($5p^2P_{3/2} - 5s^2S_{1/2}$)
2.144	Mg II ($5p^2P_{1/2} - 5s^2S_{1/2}$)
2.1451	[Fe III] ($^3G_3 -^3 H_4$)
2.1542	H_2 (2–1) S(2)
2.16553	H I Brγ
2.189	He II 7–10
2.205644	Na I ($4^2S - 4^2P^0$)
2.208367	Na I ($4^2S - 4^2P^0$)
2.2178	[Fe III] ($^3G_5 -^3 H_6$)

Table 25: - *cont'd*

λ (μm)	Identification
2.2233	H_2 (1–0) S(0)
2.2420	[Fe III] ($^3G_4 -^3 H_4$)
2.2477	H_2 (2–1) S(1)
2.26	Ca I
2.295	^{12}CO (2–0)
2.32141	[Ca VIII] (3p $^2P^0_{1/2} -^2 P^0_{3/2}$) 147.4 eV
2.324	^{12}CO (3–1)
2.334841	Na I
2.337913	Na I
2.345	^{13}CO (2–0)
2.3479	[Fe III] ($^3G_5 -^3 H_5$)
2.354	^{12}CO (4–2)
2.3556	H_2 (2–1) S(0)
2.374	^{13}CO (3–1)
2.385	^{12}CO (5–3)
2.3865	H_2 3–2 S(1)
2.404	^{13}CO (4–2)
2.4066	H_2 (1–0) Q(1)
2.4134	H_2 (1–0) Q(2)
2.414	^{12}CO (6–4)
2.42	C IV 10–9
2.4237	H_2 (1–0) Q(3)
2.434	^{13}CO (5–3)
2.4375	H_2 (1–0) Q(4)
2.446	^{12}CO (7–5)
2.4547	H_2 (1–0) Q(5)
2.465	^{13}CO (6–4)
2.4754	H_2 (1–0) Q(6)
2.479	^{12}CO (8–6)
2.48266	[Si VII] (2p^4 $^3P_2 -^3 P_1$) 246.5 eV
2.5254	H I Pf16
2.5636	H I Pf15
2.6119	H I Pf14
2.62520	H I Brβ
2.6744	H I Pf13
2.7575	H I Pf12
2.84	[Si IX]
2.8722	H I Pf11
2.88	[Al V] 153.8 eV
3.02713	[Mg VIII] (2p $^2P^0_{1/2} -^2 P^0_{3/2}$) 265.9 eV
3.0384	H I Pf10
3.08	H_2O ice
3.09	He II 7–6
3.2	[Ca IV]
3.2349	H_2 (1–0) O(5)
3.28	PAH dust
3.28	C IV 11–10
3.2961	H I Pfδ
3.317	H_3^+ $1,5,3_{+1}$–4,3
3.40	PAH dust
3.413	H_3^+ $1,4,0_{-1}$–3,0
3.5006	H_2 (1–0) O(6)
3.534	H_3^+ $1,4,3_{-1}$–3,3
3.6267	H_2 0–0 S(15)

Table 25: - *cont'd*

λ (μm)	Identification
3.6550	[Al VI] 190.5 eV
3.704	[A VII]
3.7395	H I Pfγ
3.7750	[S IX]
3.8071	H_2 (1–0) O(7)
3.8468	H_2 0–0 S(13)
3.9346	[Si IX] 303 eV
3.953	H_3^+ $1,1,0_{-1}$–1,0
3.9654	[Mg V]
3.986	H_3^+ $1,3,0_{-1}$–3,0
4.046	H_3^+ $1,5,0_{-1}$–5,1
4.049	He II 10–8
4.05116	H I Brα
4.16	[Ca V]
4.1813	H_2 0–0 S(11)
4.350	H_3^+ $1,2,3_{+1}$–3,3
4.492	[Mg IV]
4.508	H_3^+ $1,3,3_{+1}$–4,3
4.510	H_3^+ $1,3,4_{+1}$–4,4
4.65251	H I Pfβ
4.65	^{12}CO (1–0)
4.684	H_3^+ $1,4,5_{+1}$–5,5
4.6946	H_2 0–0 S(9)
5.5112	H_2 0–0 S(7)

J Wavelength Calibration Data

Table 26: Xenon Arc Lines

λ_{air} (μm)	Identification
0.930664	Xe I
0.937476	Xe I
0.941201	Xe I
0.944534	Xe I
0.949707	Xe I
0.9513379	Xe I
0.958514	Xe I
0.968532	Xe I
0.970099	Xe I
0.971816	Xe I
0.9799699	Xe I
0.9923192	Xe I
1.0023711	Xe I
1.0084800	Xe I
1.0107362	Xe I
1.0125452	Xe I
1.0188365	Xe I
1.0251037	Xe I
1.0484814	Xe I
1.0527861	Xe I
1.0706783	Xe I
1.0758898	Xe I
1.0838335	Xe I
1.0895324	Xe I
1.1085241	Xe I
1.11272	Xe I
1.11627	Xe I
1.112149	Xe I
1.112892	Xe I
1.13096	Xe I
1.14151	Xe I
1.14913	Xe I
1.16141	Xe I
1.17424	Xe I
1.17935	Xe I
1.18580	Xe I
1.19122	Xe I
1.19531	Xe I
1.20848	Xe I
1.2203818	Xe I
1.2235243	Xe I
1.2257765	Xe I
1.2409131	Xe I
1.2451547	Xe I
1.2590202	Xe I
1.2623391	Xe I
1.3331868	Xe I
1.3544152	Xe I
1.3657055	Xe I
1.3814410	Xe I
1.3919611	Xe I
1.4050741	Xe I
1.4142444	Xe I
1.4240959	Xe I
1.4364987	Xe I
1.4424	Xe I
1.4503	Xe I
1.4661	Xe I
1.4732805	Xe I
1.4850	Xe I
1.5060	Xe I
1.5099725	Xe I
1.5278	Xe I
1.5418394	Xe I
1.5490971	Xe I
1.5557128	Xe I
1.5979536	Xe I
1.6053281	Xe I
1.6554	Xe I
1.6728150	Xe I
1.6834541	Xe I
1.6883069	Xe I
1.7325767	Xe I
1.7365086	Xe I
1.74784	Xe I
1.75900	Xe I
1.76568	Xe I
1.8788128	Xe I
1.97169	Xe I
2.0187190	Xe I
2.0262242	Xe I
2.05128	Xe I
2.05933	Xe I
2.08426	Xe I
2.08846	Xe I
2.10408	Xe I
2.11109	Xe I
2.11459	Xe I
2.12151	Xe I
2.1373073	Xe I
2.1470089	Xe I
2.2269836	Xe I
2.2406818	Xe I
2.2618283	Xe I
2.28779	Xe I
2.2964776	Xe I
2.3022418	Xe I
2.3073456	Xe I
2.3105265	Xe I
2.3193332	Xe I
2.3279541	Xe I
2.3443639	Xe I
2.34439	Xe I
2.3796466	Xe I
2.3934491	Xe I
2.4446	Xe I
2.4702317	Xe I
2.4824712	Xe I

Table 27: Argon Arc Lines

λ_{air} (μm)	Identification
0.9784503	Ar I
1.0052059	Ar I
1.0309139	Ar I
1.0332725	Ar I
1.0470054	Ar I
1.050647	Ar I
1.052932	Ar I
1.067355	Ar I
1.073387	Ar I
1.0759165	Ar I
1.077335	Ar I
1.088096	Ar I
1.095074	Ar I
1.107887	Ar I
1.1106464	Ar I
1.13937	Ar I
1.1441912	Ar I
1.14676	Ar I
1.14881	Ar I
1.15803	Ar I
1.16687	Ar I
1.17195	Ar I
1.17332	Ar I
1.1884463	Ar I
1.18966	Ar I
1.1943285	Ar I
1.2026648	Ar I
1.2112324	Ar I
1.2139737	Ar I
1.2343392	Ar I
1.2402828	Ar I
1.2439321	Ar I
1.2456114	Ar I
1.2487663	Ar I
1.2554324	Ar I
1.2596209	Ar I
1.2596276	Ar I
1.2621619	Ar I
1.2638480	Ar I
1.2702280	Ar I
1.2733418	Ar I
1.2746232	Ar I
1.2802737	Ar I
1.2933196	Ar I
1.2956658	Ar I
1.3008264	Ar I
1.3213991	Ar I
1.3228104	Ar I
1.3230897	Ar I
1.3272635	Ar I
1.3313209	Ar I
1.3367110	Ar I
1.3406513	Ar I
1.3406586	Ar I
1.3499406	Ar I
1.3504190	Ar I
1.3544205	Ar I
1.3573618	Ar I
1.3599333	Ar I
1.3622659	Ar I
1.3678549	Ar I
1.3718577	Ar I
1.3828321	Ar I
1.3828394	Ar I
1.3866396	Ar I
1.3866998	Ar I
1.3910556	Ar I
1.3992808	Ar I
1.4093640	Ar I
1.4249193	Ar I
1.4595733	Ar I
1.4596471	Ar I
1.4634414	Ar I
1.4634504	Ar I
1.4975	Ar I
1.5046503	Ar I
1.5172691	Ar I
1.5301881	Ar I
1.5301970	Ar I
1.5329344	Ar I
1.5348516	Ar I
1.5349253	Ar I
1.5402640	Ar I
1.5446772	Ar I
1.5555460	Ar I
1.5735	Ar I
1.5816777	Ar I
1.5899687	Ar I
1.5989491	Ar I
1.6122	Ar I
1.6180023	Ar I
1.6264070	Ar I
1.6436575	Ar I
1.6519867	Ar I
1.6549306	Ar I
1.6550400	Ar I
1.6740078	Ar I
1.6940584	Ar I
1.7401908	Ar I
1.7444903	Ar I
1.7445248	Ar I
1.7823991	Ar I
1.7914629	Ar I
1.7914726	Ar I
1.8185749	Ar I
1.8231349	Ar I
1.8348006	Ar I
1.8427765	Ar I
1.8428392	Ar I
1.8429455	Ar I
1.8485653	Ar I
1.8485663	Ar I

Table 27: - *cont'd*

λ_{air} (μm)	Identification
1.8486723	Ar I
1.8564219	Ar I
1.8632289	Ar I
1.8745	Ar I
1.9124	Ar I
1.9175	Ar I
1.9817508	Ar I
1.9965730	Ar I
2.0025672	Ar I
2.0068932	Ar I
2.0317011	Ar I
2.0616229	Ar I
2.0733634	Ar I
2.0735350	Ar I
2.0811042	Ar I
2.0986111	Ar I
2.1332885	Ar I
2.1534207	Ar I
2.2039561	Ar I
2.2077181	Ar I
2.2113	Ar I
2.225414	Ar I
2.2533597	Ar I
2.3133204	Ar I
2.3845035	Ar I
2.3966518	Ar I
2.477662	Ar I
2.477785	Ar I

Table 28: Airglow Lines

λ_{air} (μm)	Identification
1.08293	OH
1.08296	OH
1.08313	OH
1.269	O_2
1.50487	OH
1.50514	OH
1.50648	OH
1.52368	OH
1.53282	OH
1.54279	OH
1.58260	OH
1.58289	OH
1.58382	OH
1.60264	OH
1.61242	OH
1.62309	OH
1.66846	OH
1.66878	OH
1.66981	OH
1.68990	OH
1.70041	OH
1.71190	OH
1.76450	OH
1.76483	OH
1.76600	OH
1.79890	OH
2.04072	OH
2.1802	OH
2.2742	OH

Table 29: Compact Planetary Nebulae

Object	R.A. (1950) Dec.		Size ($''$)	log $F_{H\beta}$ (erg cm^{-2} s^{-1})
J320	05 02 48.6	+10 38 25	6.2	-11.37
IC2165	06 19 24.2	-12 57 40	7.7	-10.87
M1–14	07 25 46.0	-20 06 58	5.0	-11.51
He2–5	07 46 01.1	-51 07 41	3.0	-11.24
IC2621	10 58 23.5	-64 58 47	5.0	-11.10
PB8	11 30 57.5	-56 49 43	5.0	-11.41
MY CN 18	13 35 54.4	-67 07 33	4.0	-11.20
He2–97	13 41 24.0	-71 13 47	<5	-11.3
NGC5315	13 50 12.7	-66 16 06	6.1	-10.4
He2-118	15 02 55.2	-42 48 24	<5	-11.1
NGC5873	15 09 38.0	-37 56 16	7.0	-11.2
He2–131	15 31 54.0	-71 45 00	6	-10.17
He2–138	15 51 19.2	-66 00 26	7	-10.6
PC11	16 33 37.1	-55 36 25	<5	-11.45
He2–182	16 49 49.3	-64 09 39	3	-11.08
H2–1	17 01 19.4	-33 55 05	4	-11.45
M1–26	17 42 45.0	-30 11 02	4.8	-11.11
H1–35	17 45 54.6	-34 21 59	2	-11.38
M2–17	17 49 09.6	-17 35 34	7.2	-11.5
FG3	17 56 44.4	-38 49 45	2	-10.9
M3–21	17 59 08.0	-36 38 55	<5	-11.12
SWST1	18 12 58.8	-30 53 10	1.3	-10.3
CN3–1	18 15 10.7	+10 08 02	5	-10.95
CN1–5	18 25 57.0	-31 32 00	7	-11.3
NGC6644	18 29 30.0	-25 10 08	2.6	-11.0
IC4776	18 42 34.1	-33 23 52	7.7	-10.5
HB7	18 52 23.8	-32 19 49	4	-11.25
NGC6741	19 00 02.0	-00 31 12	7.8	-11.5
IC4846	19 13 44.9	-09 08 06	2.0	-11.33
IC1297	19 13 57.6	-39 42 12	7	-11.3
NGC6790	19 20 24.5	+01 25 02	7.4	-11.0
NGC6803	19 28 53.5	+09 57 00	5.6	-11.15
NGC6807	19 32 03.4	+05 34 30	2	-11.41
IC4997	20 17 51.0	+16 34 27	1.6	-10.8

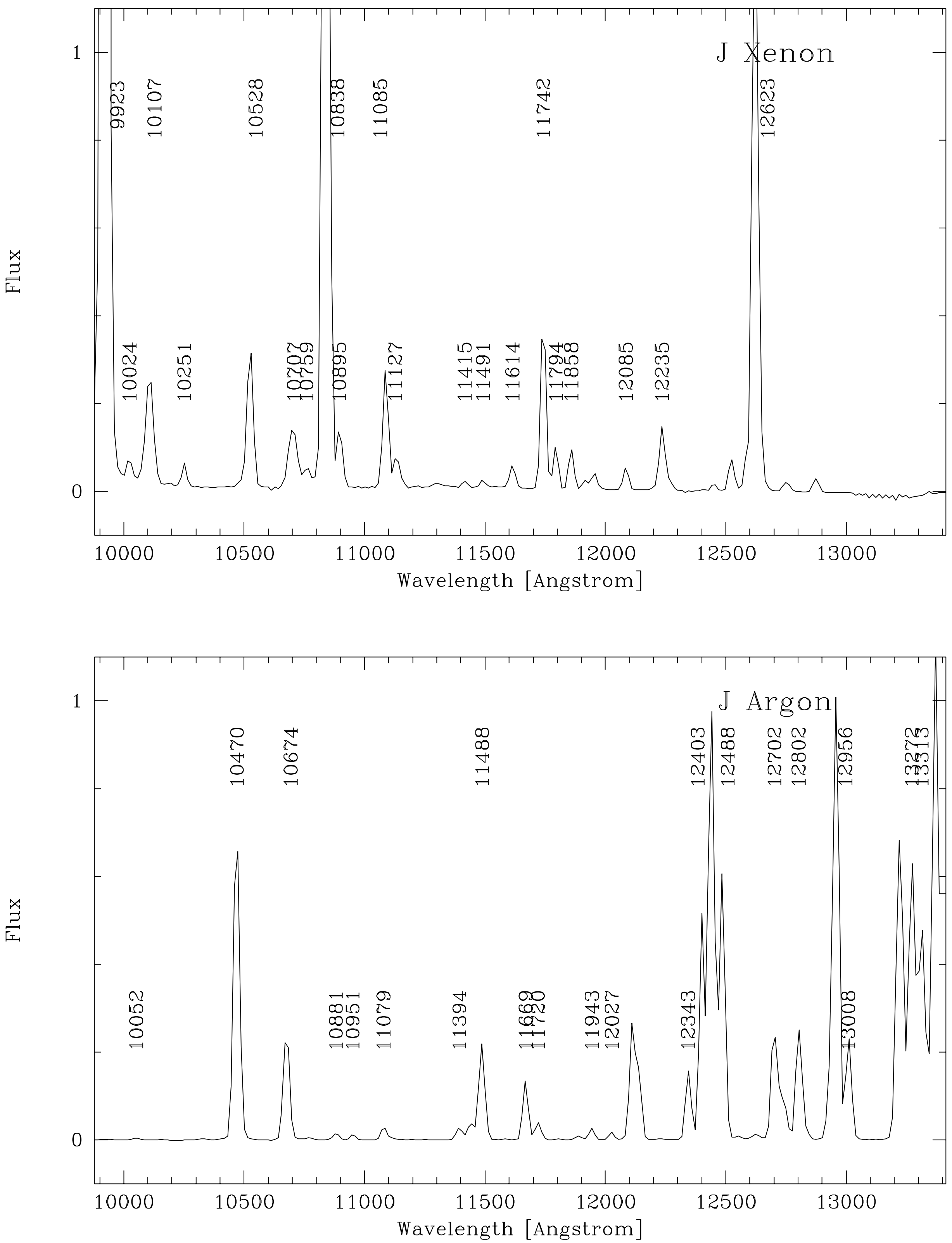


Figure 38: Xenon and Argon arc spectra for *J* grism.

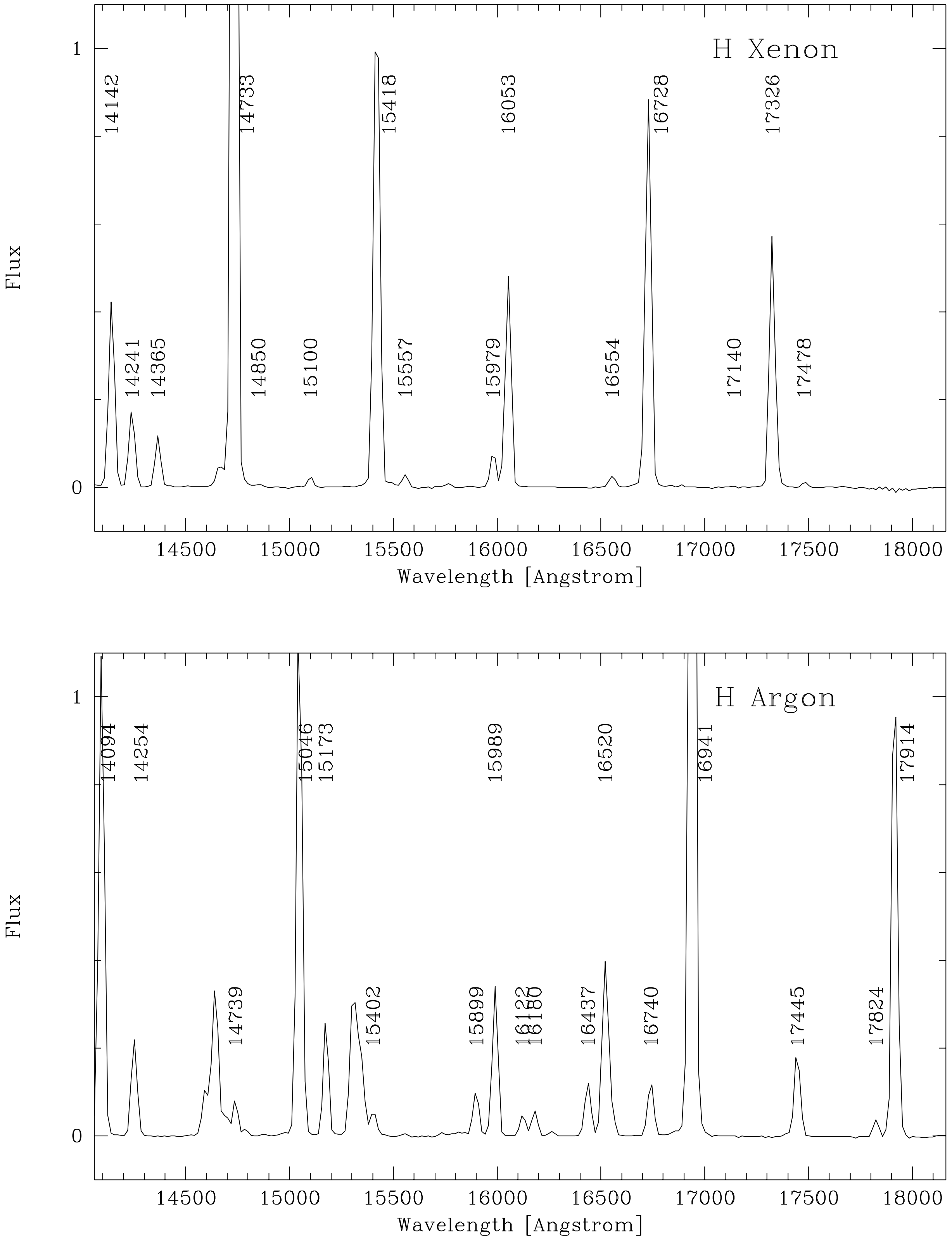


Figure 39: Xenon and Argon arc spectra for *H* grism.

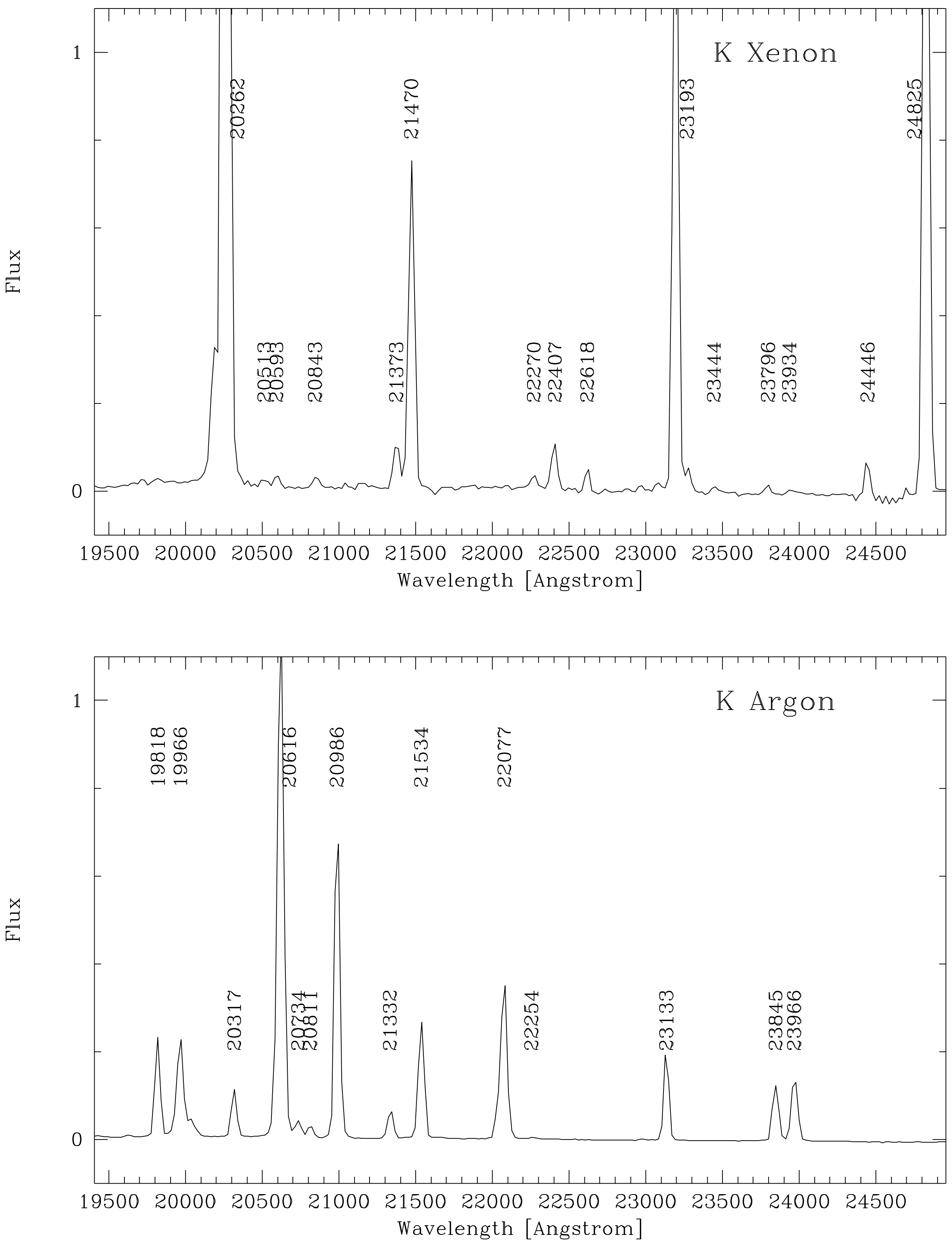
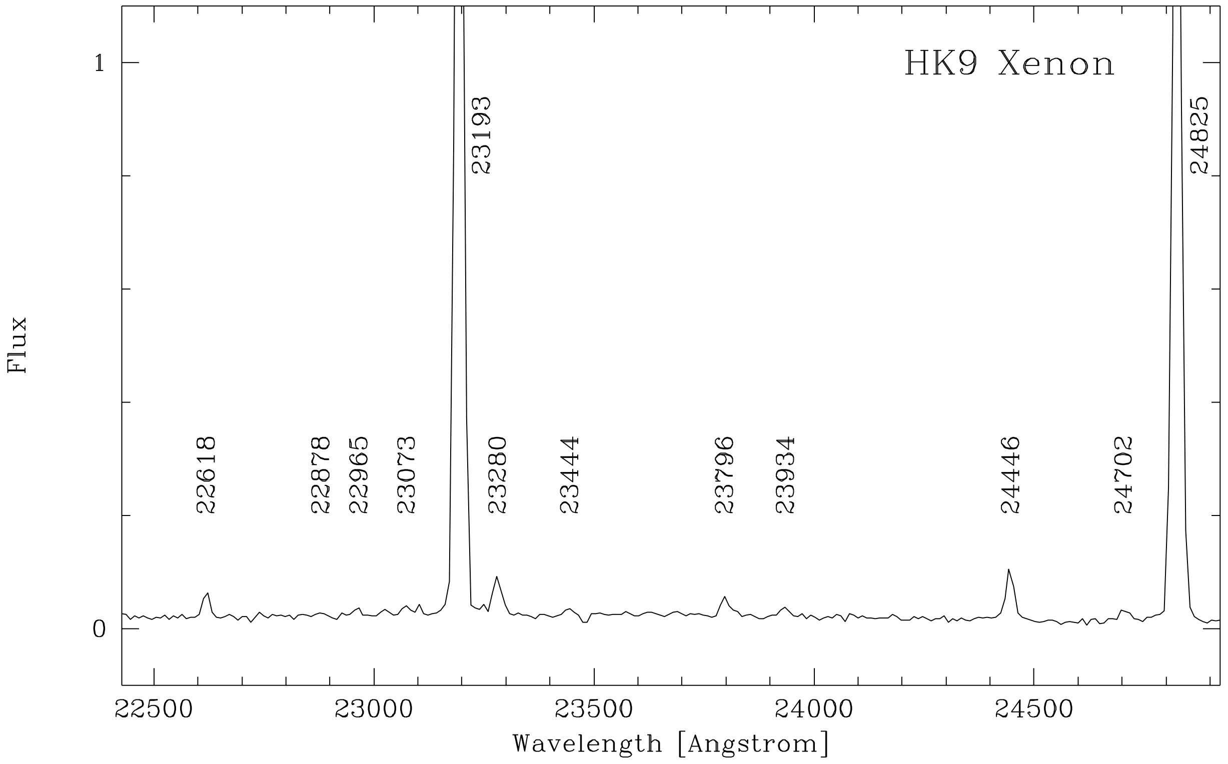


Figure 40: Xenon and Argon arc spectra for *K* grism.



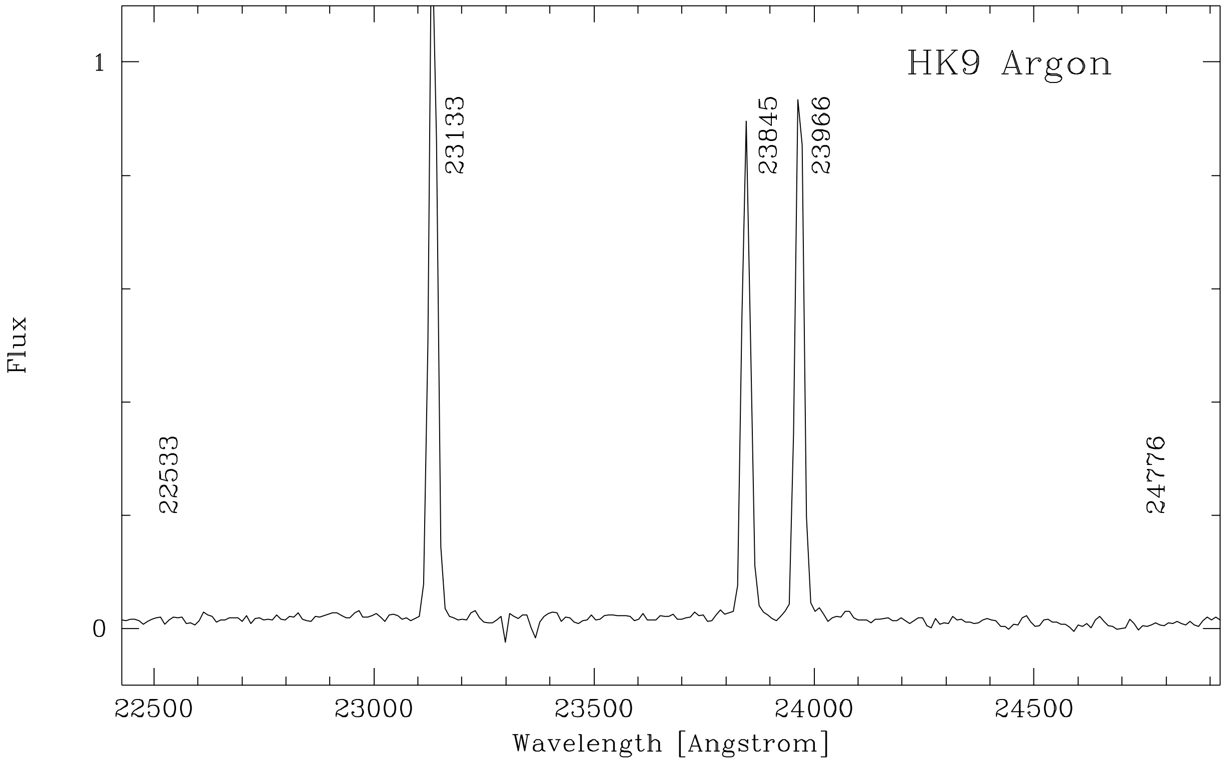
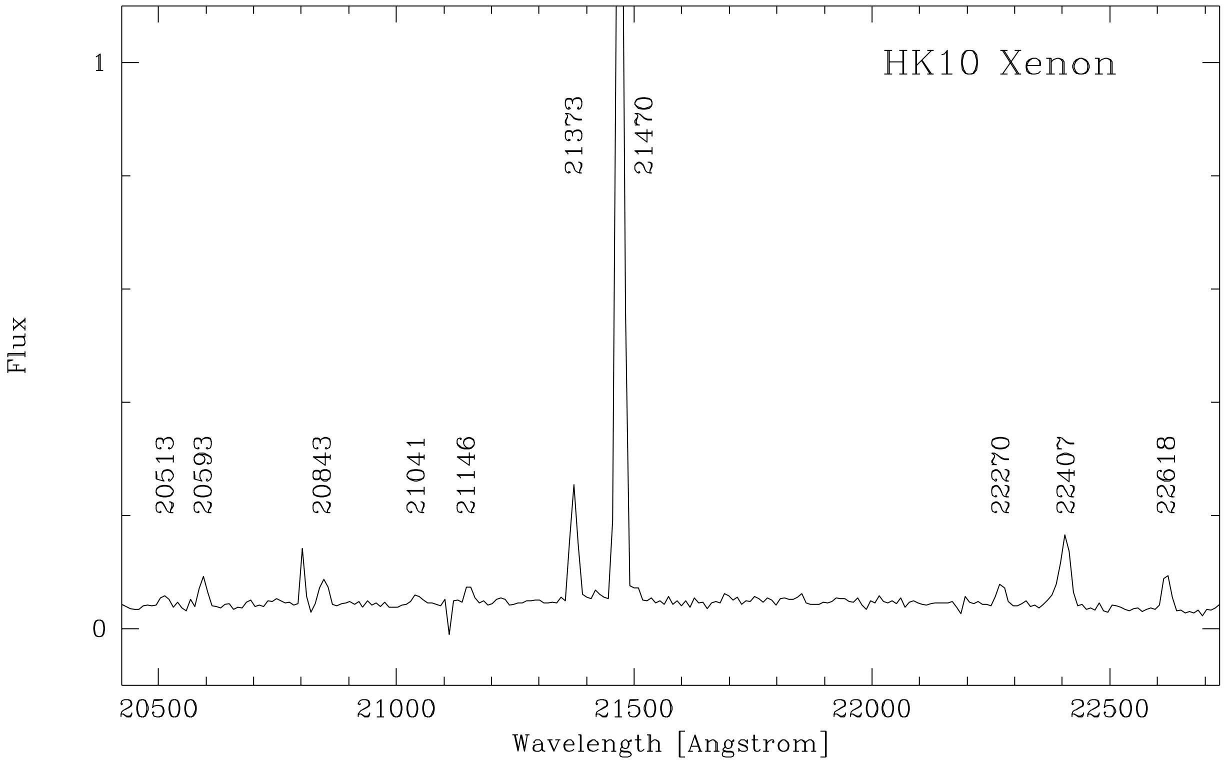


Figure 41: Xenon and Argon arc spectra for HK grism order 9.



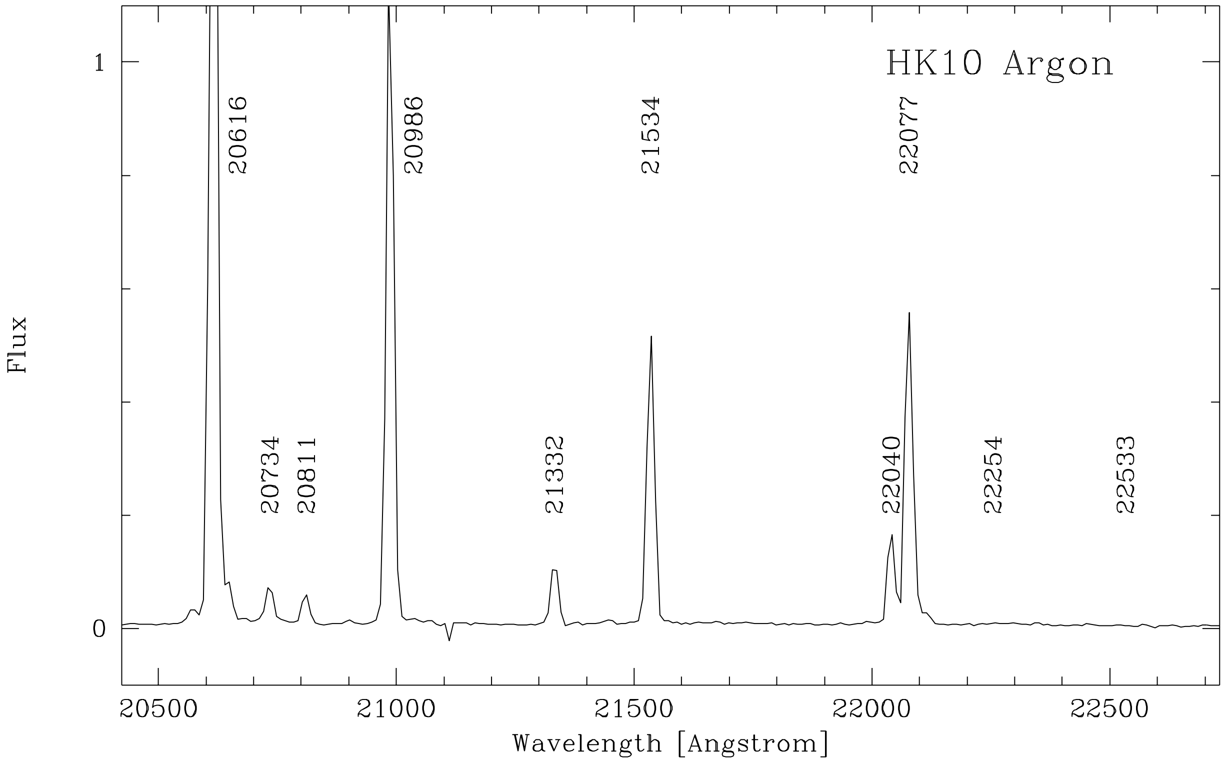
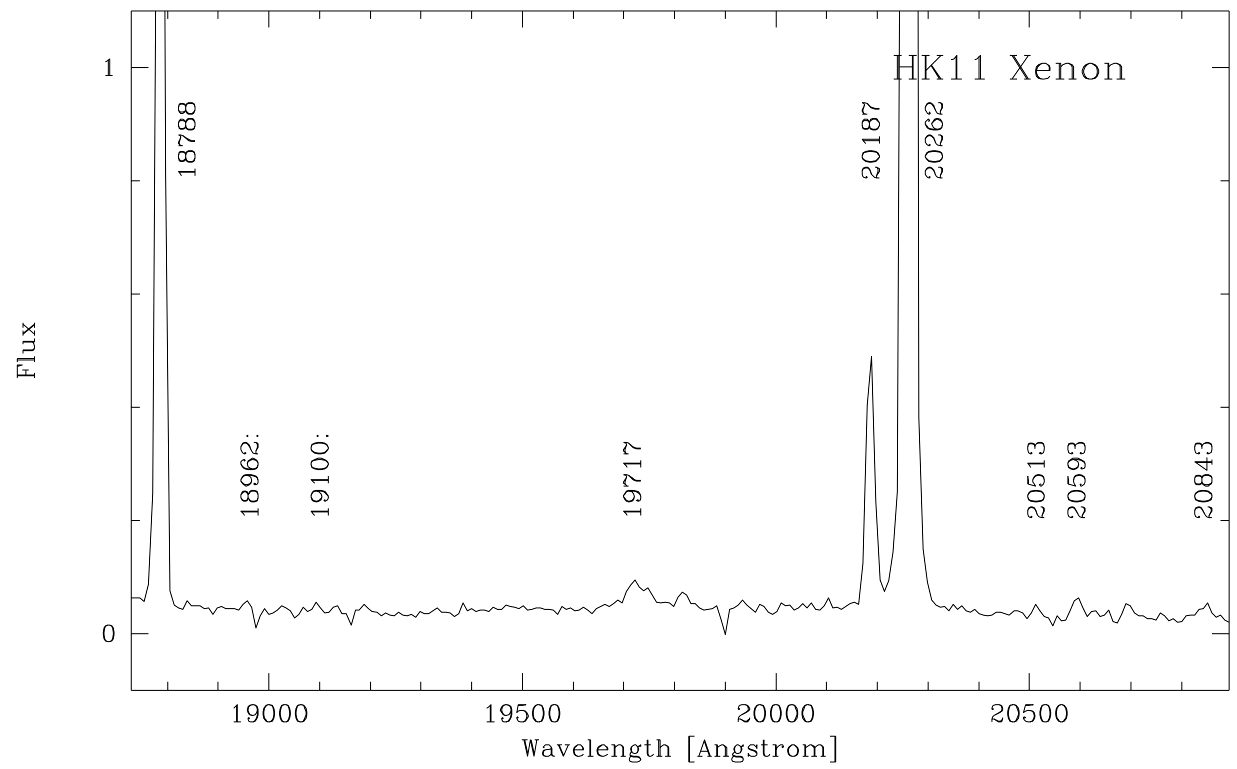


Figure 42: Xenon and Argon arc spectra for HK grism order 10.



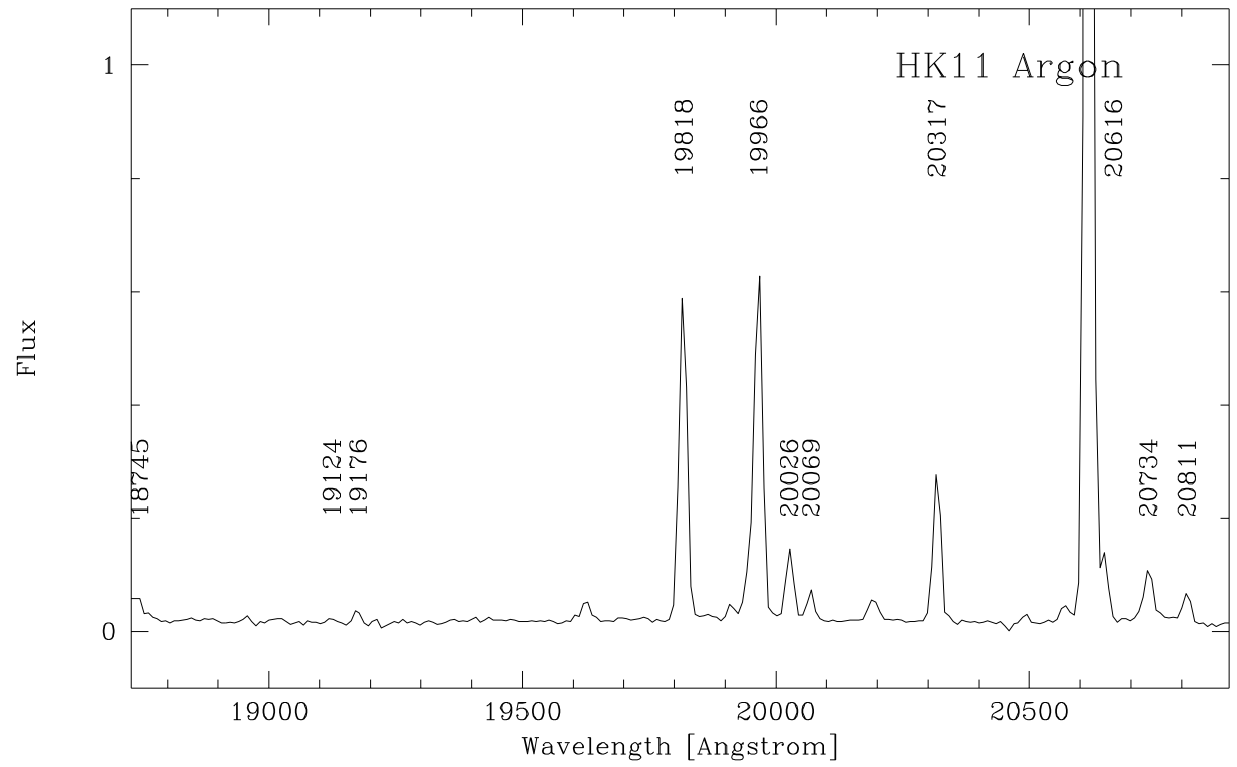


Figure 43: Xenon and Argon arc spectra for HK grism order 11.

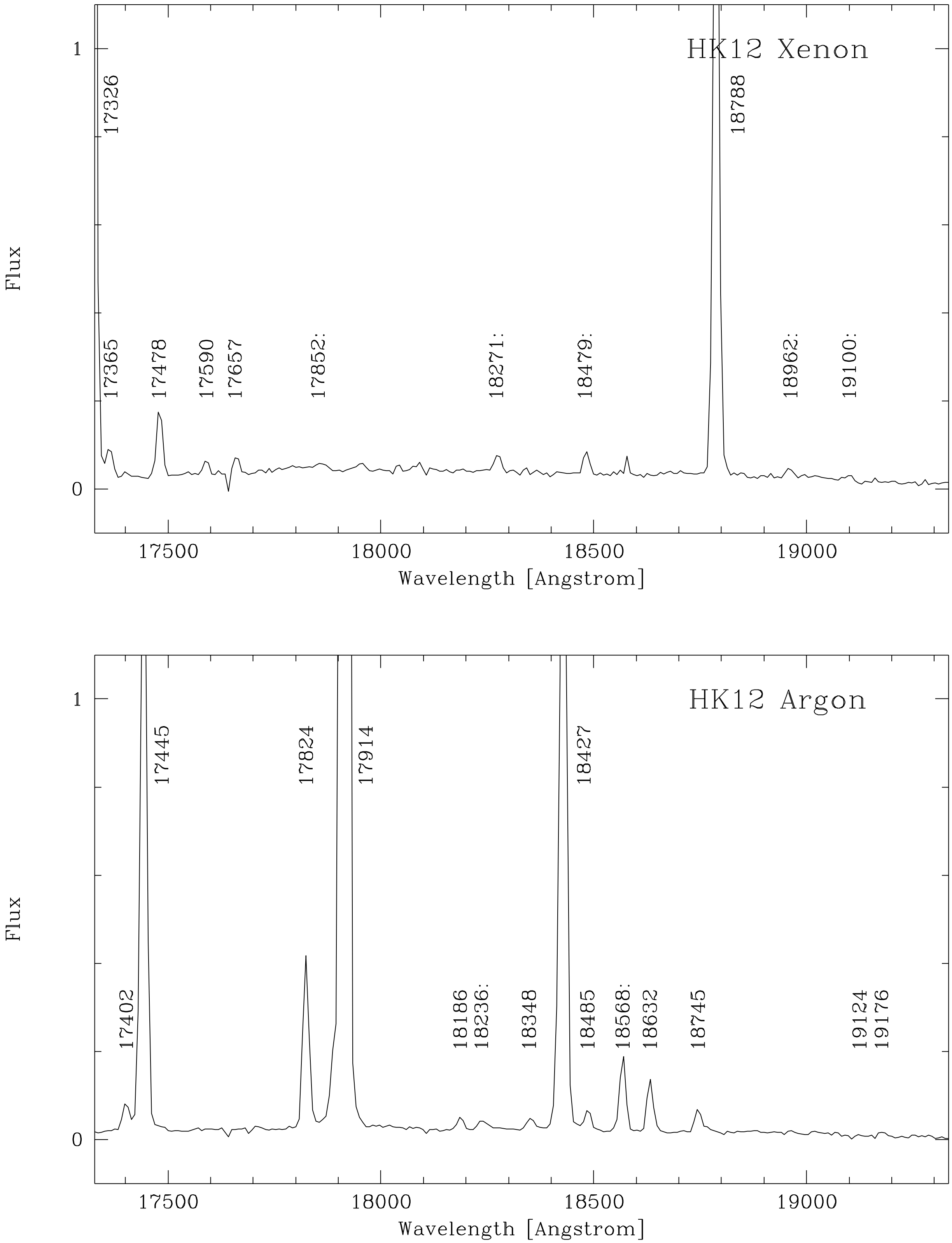
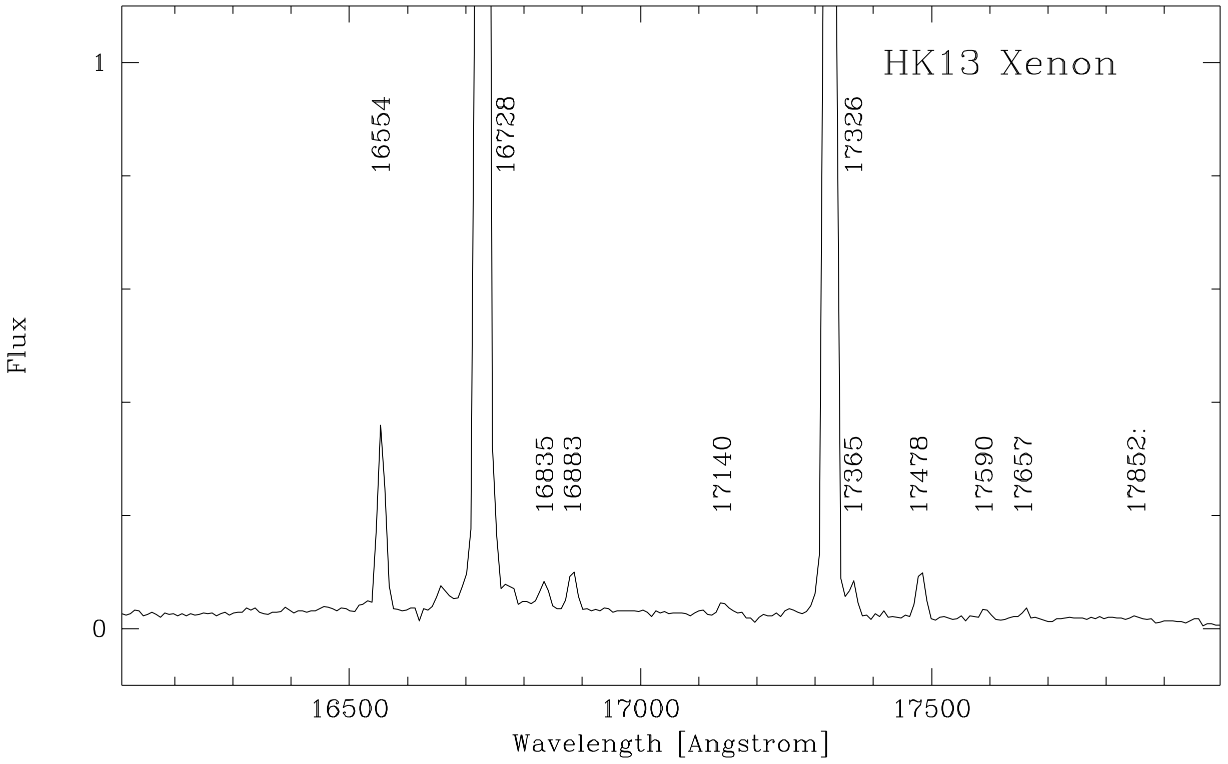


Figure 44: Xenon and Argon arc spectra for HK grism order 12.



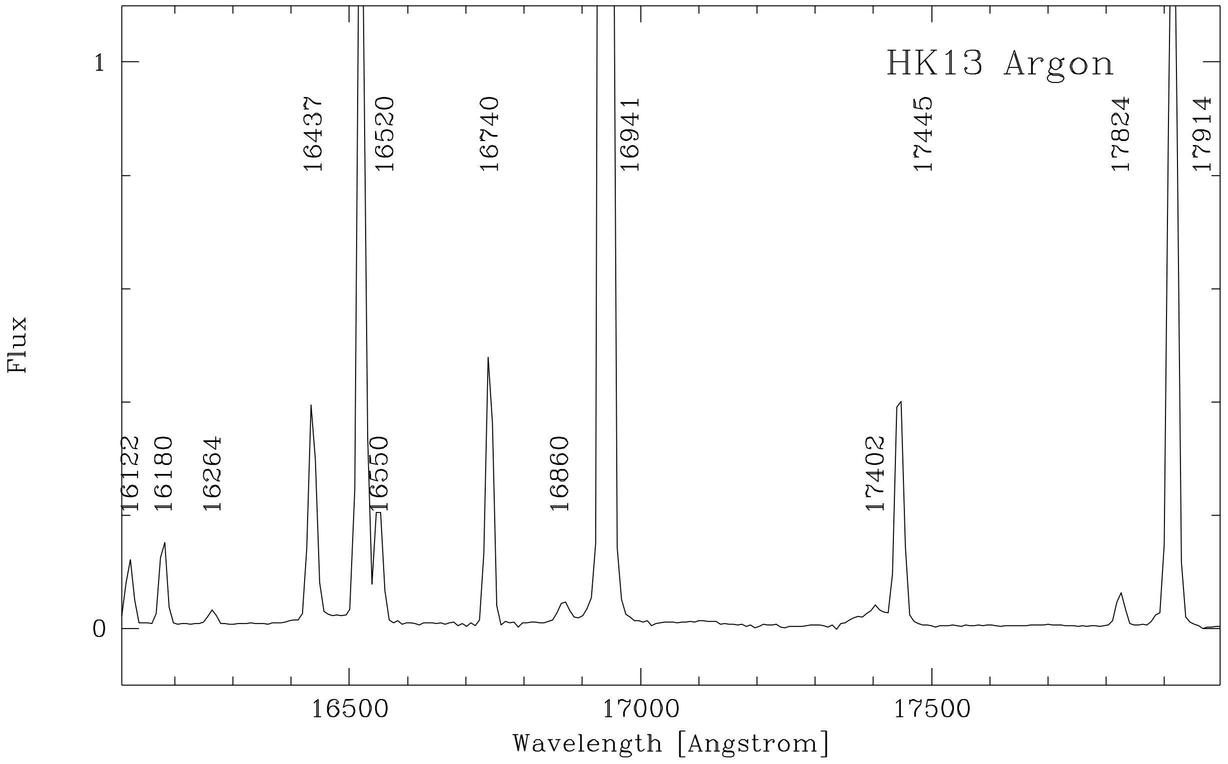
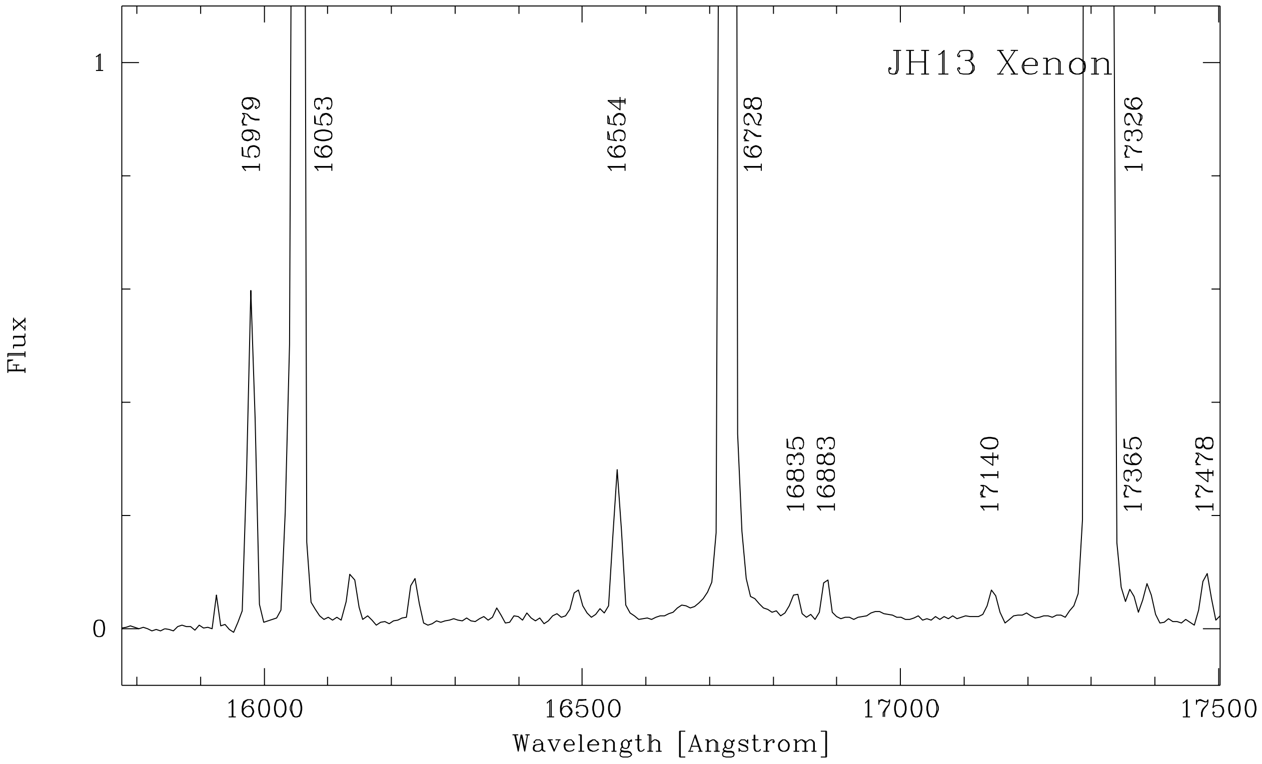


Figure 45: Xenon and Argon arc spectra for HK grism order 13.



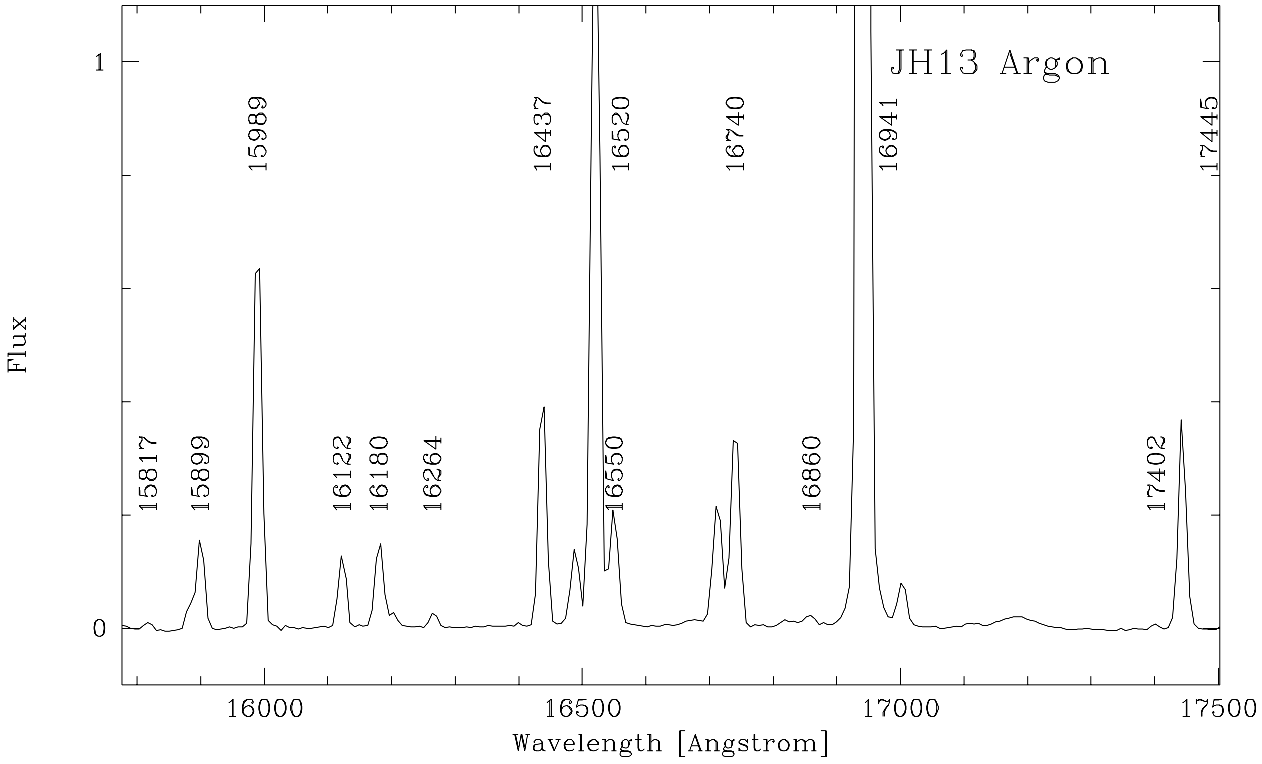


Figure 46: Xenon and Argon arc spectra for JH grism order 13.

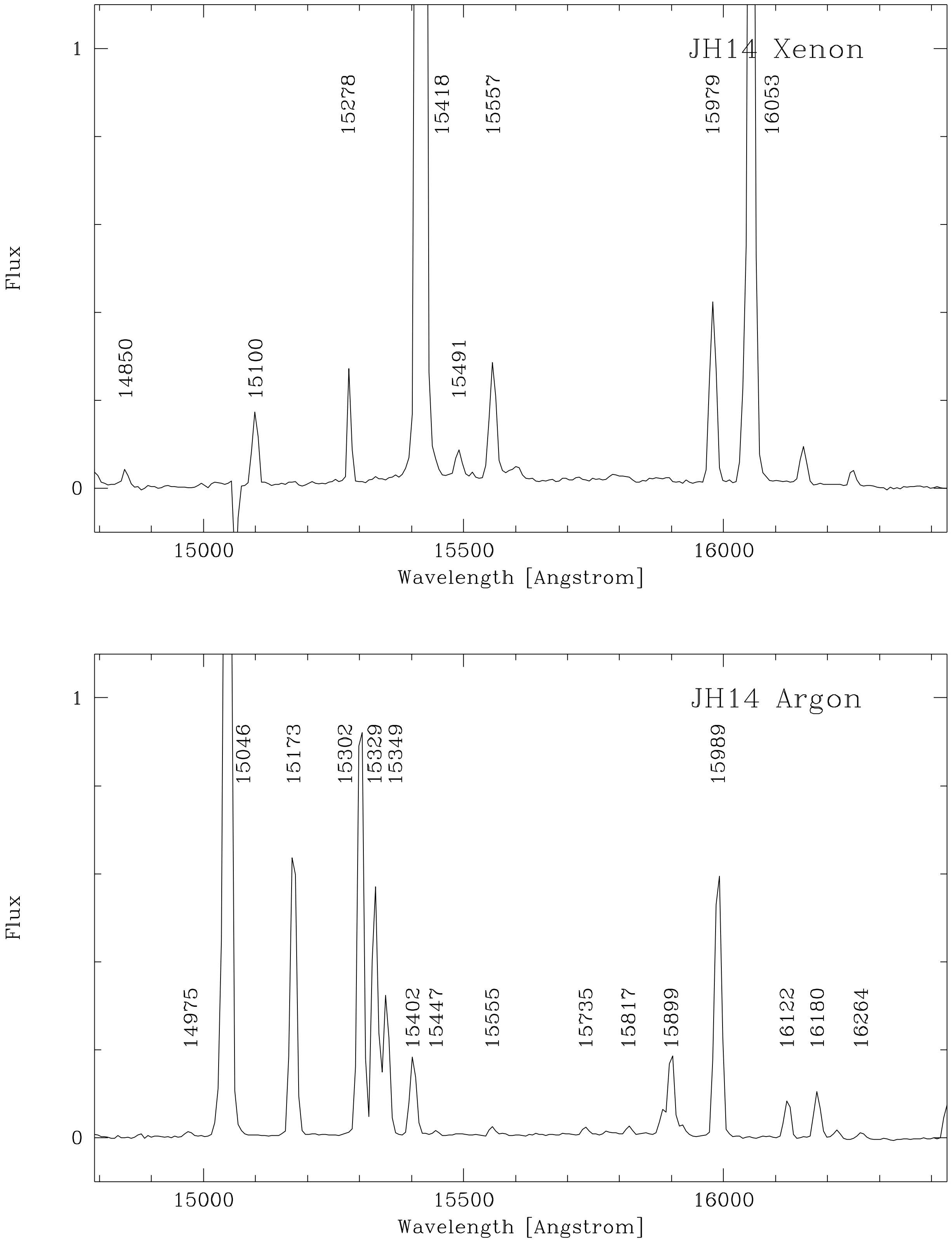
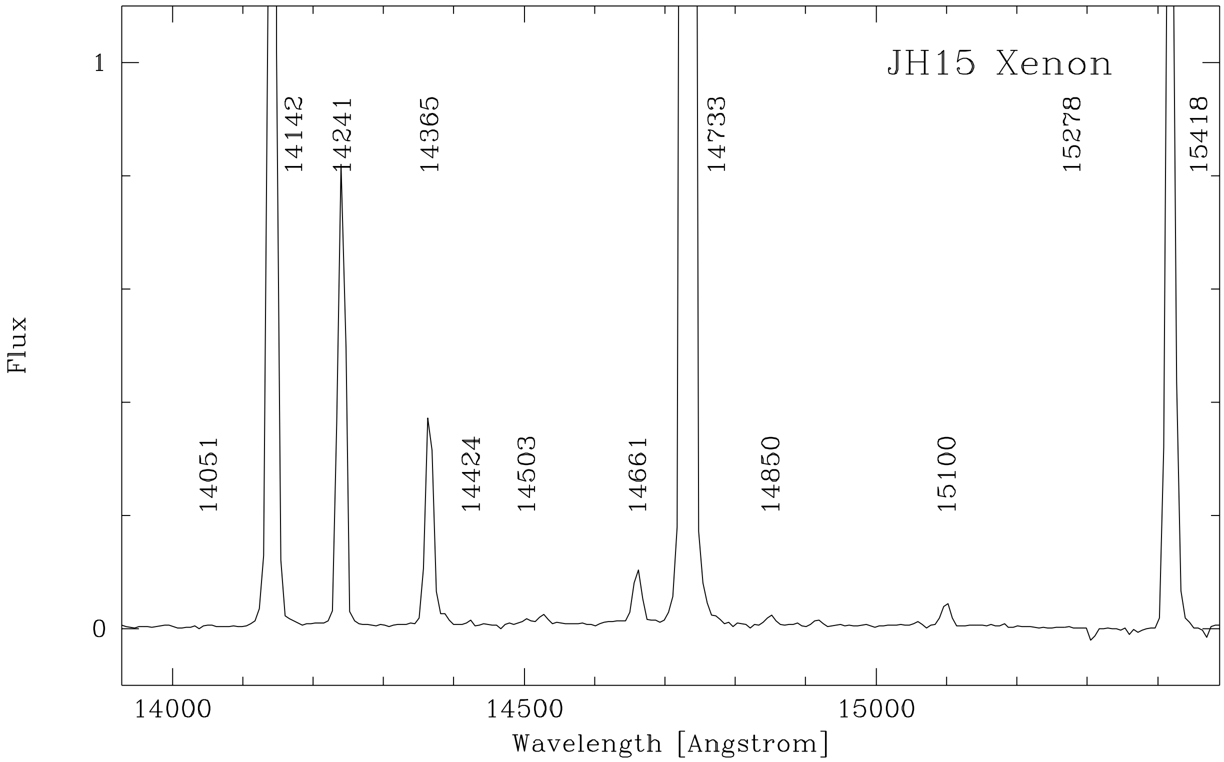


Figure 47: Xenon and Argon arc spectra for JH grism order 14.



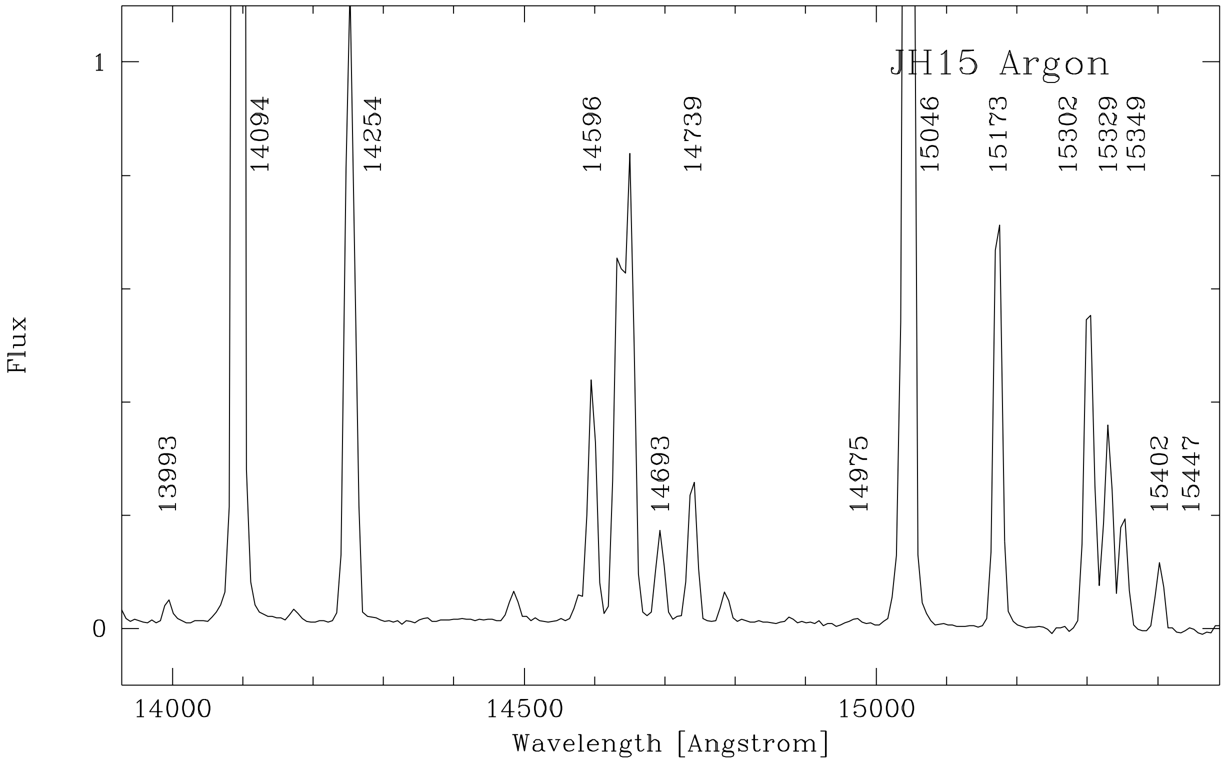
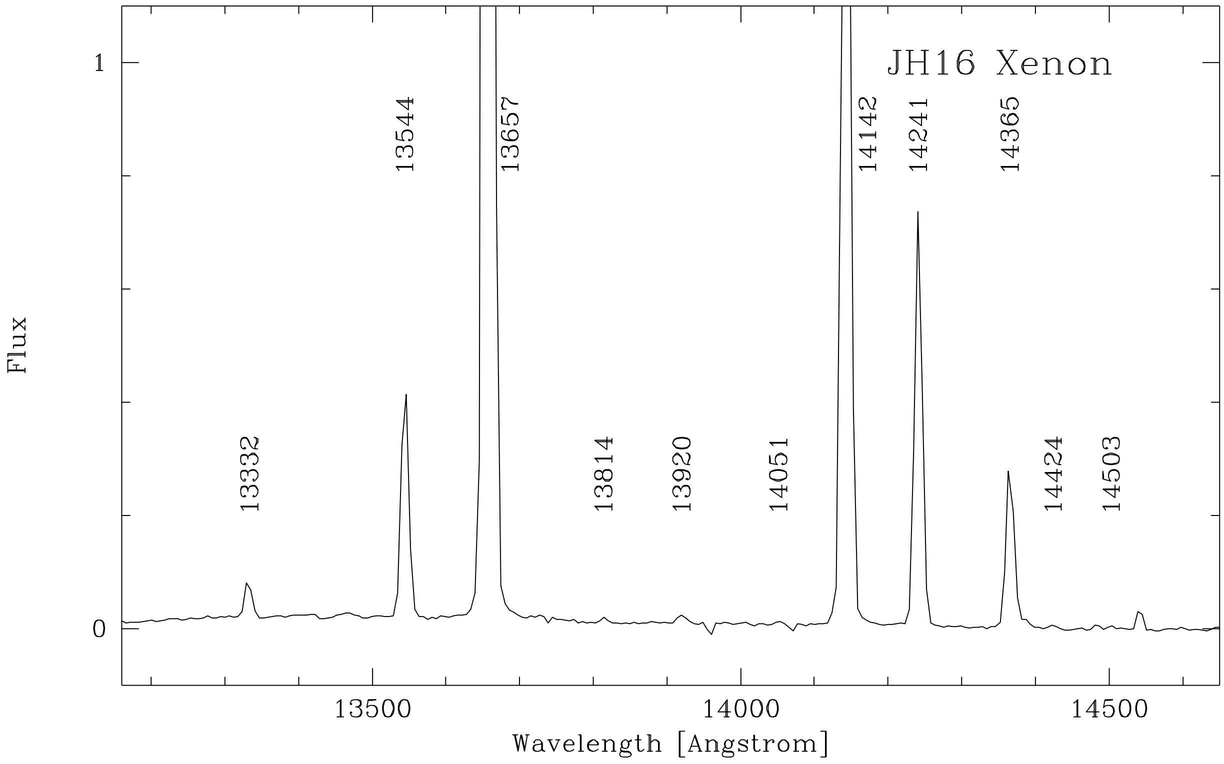


Figure 48: Xenon and Argon arc spectra for JH grism order 15.



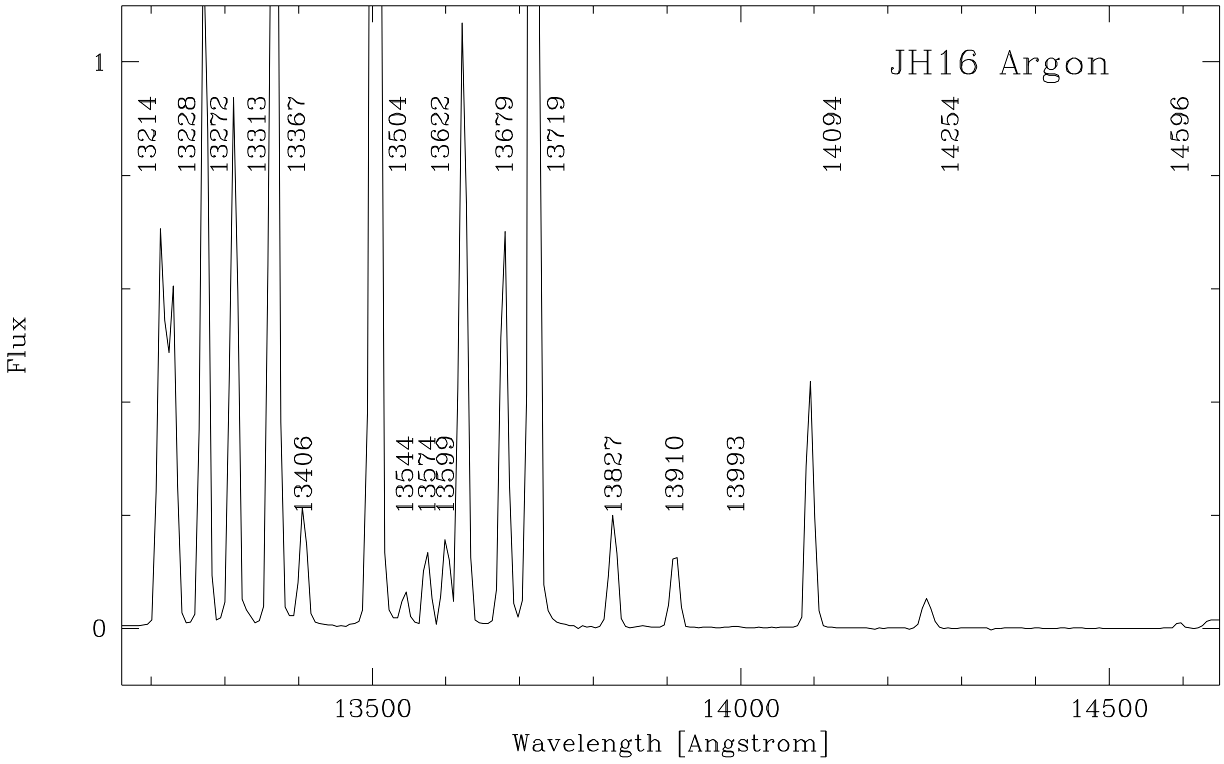
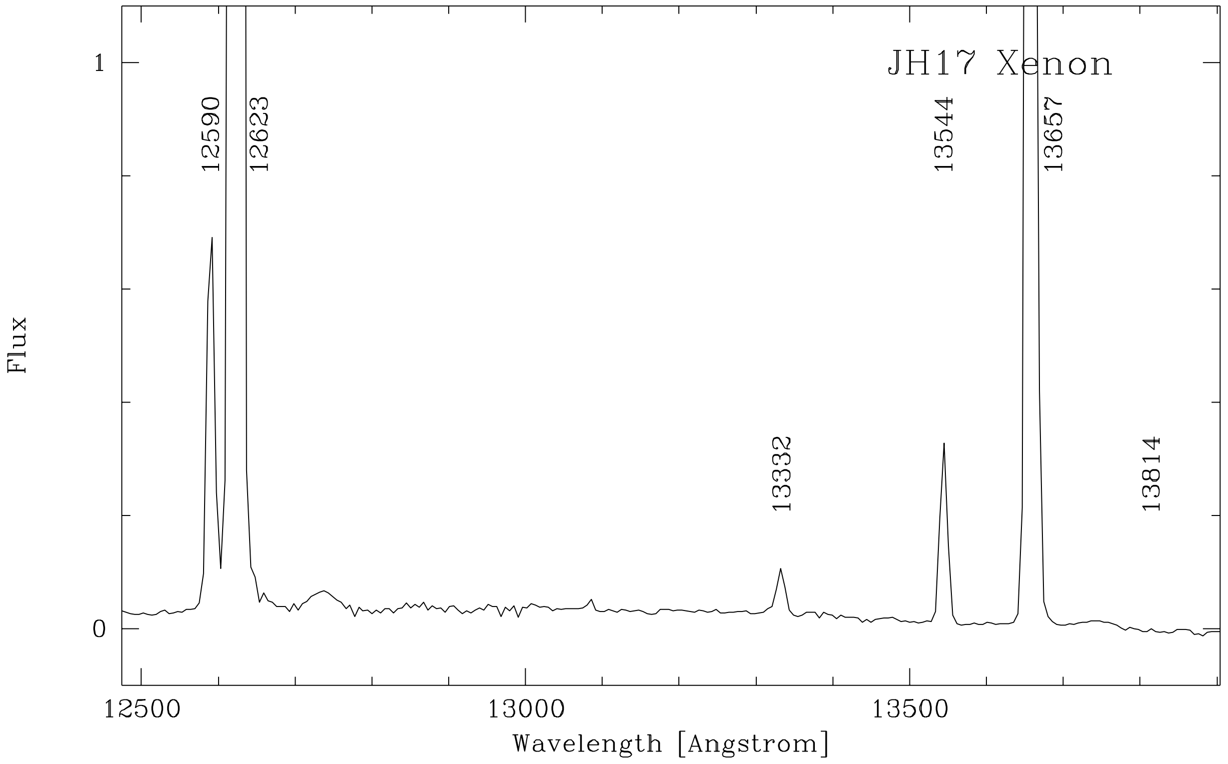


Figure 49: Xenon and Argon arc spectra for JH grism order 16.



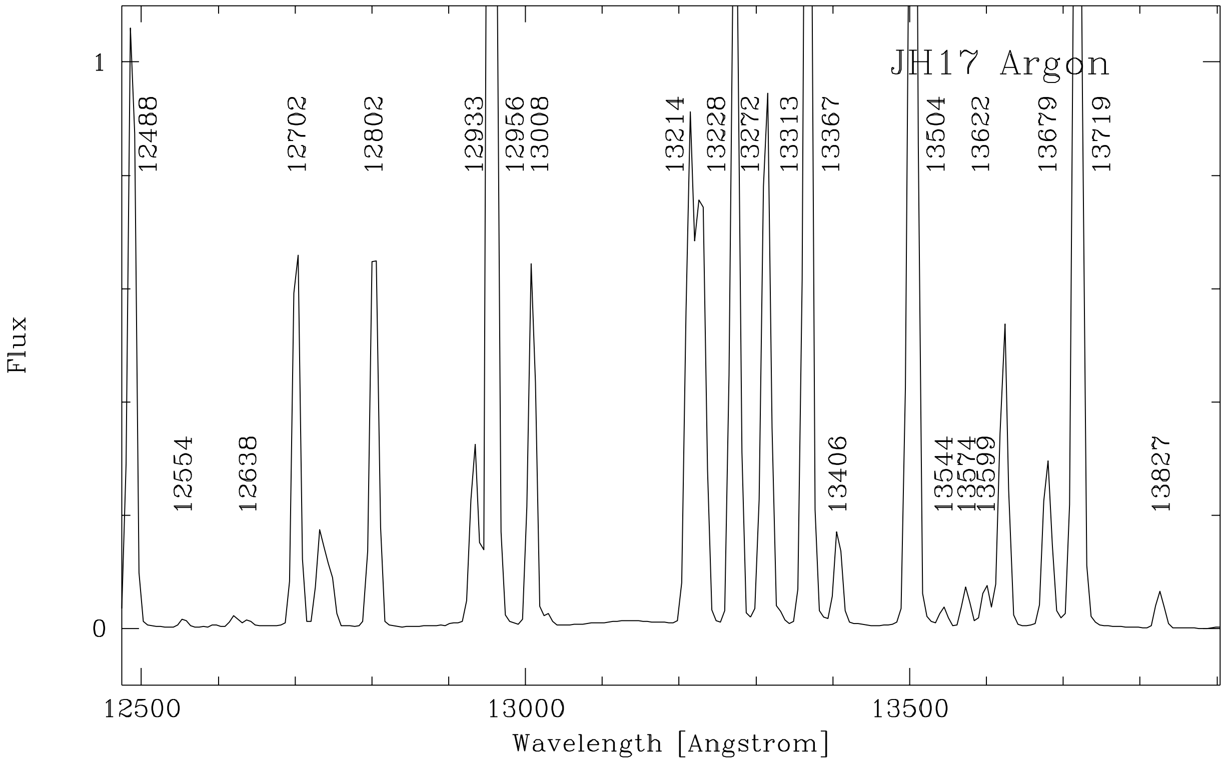
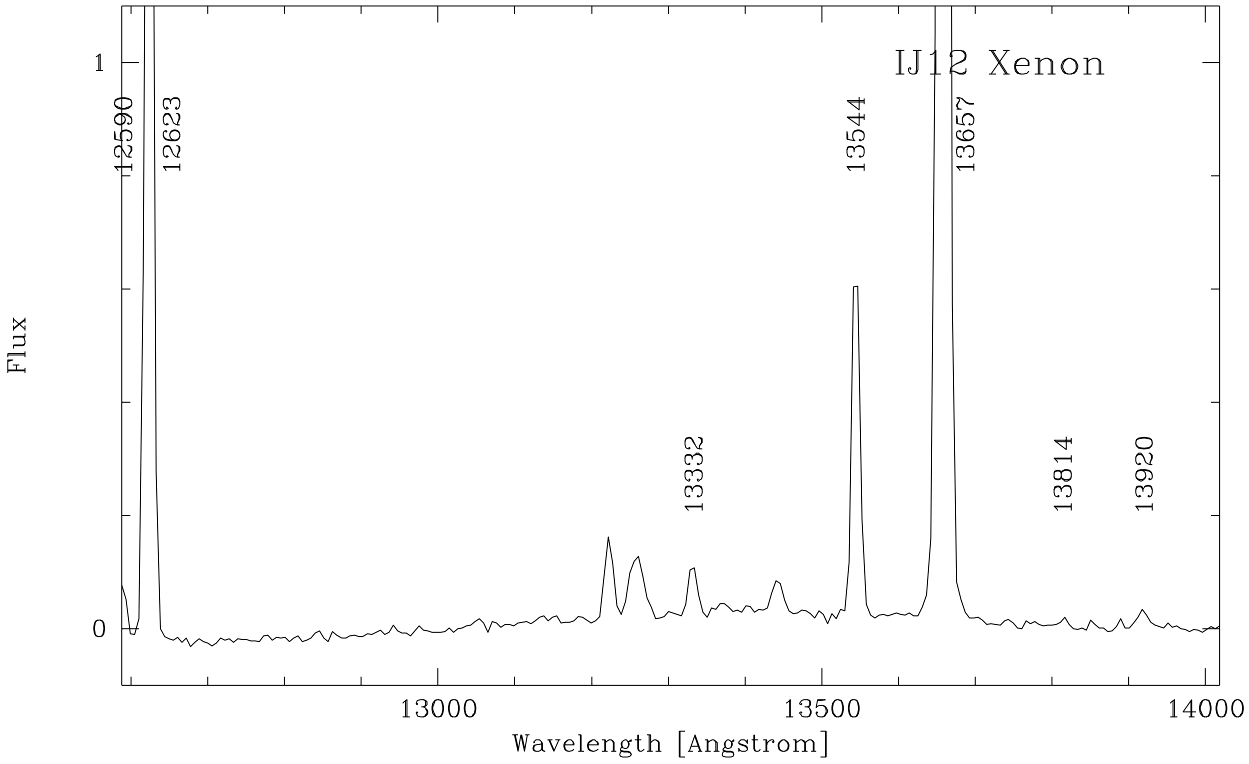


Figure 50: Xenon and Argon arc spectra for JH grism order 17.



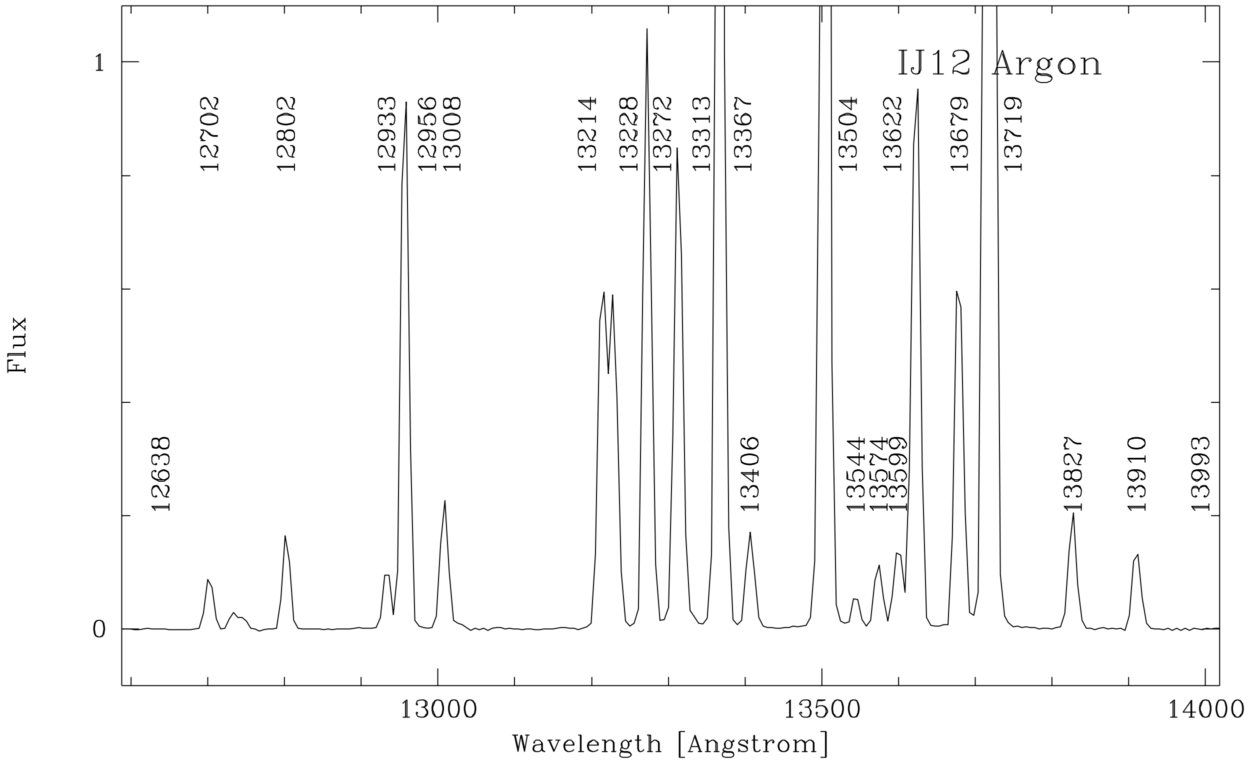
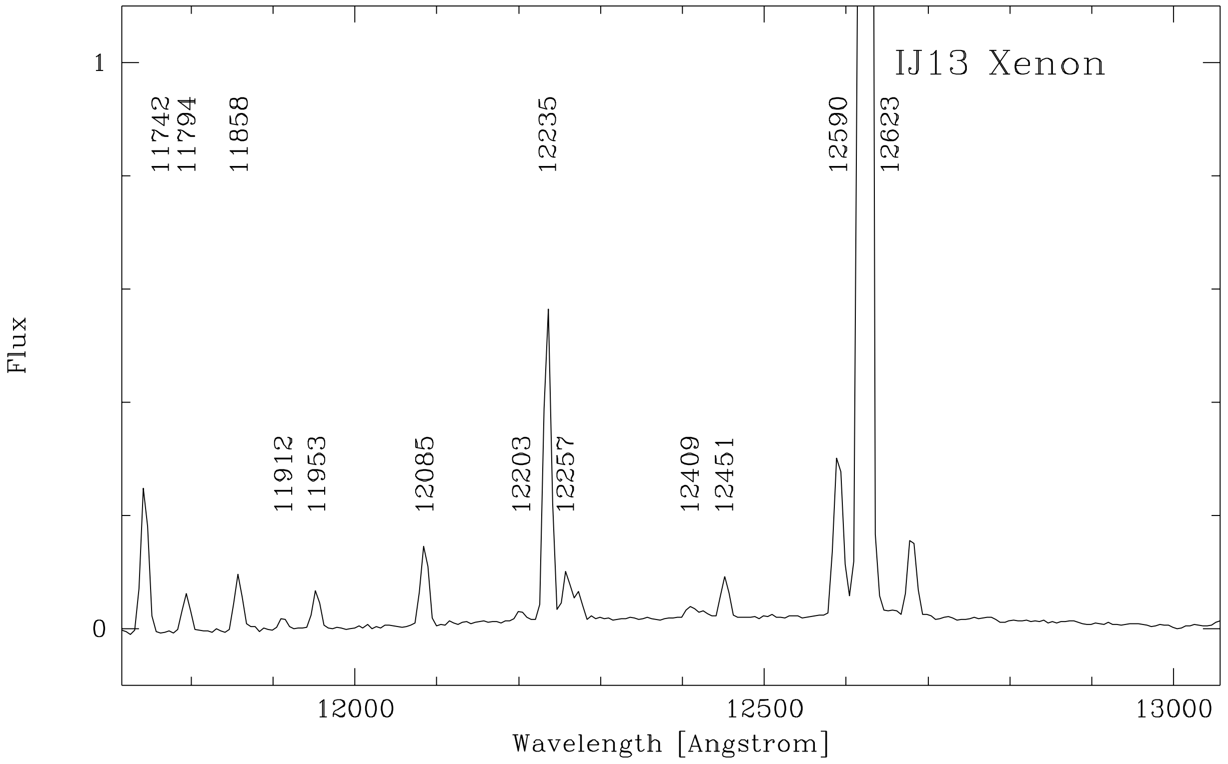


Figure 51: Xenon and Argon arc spectra for *IJ* grism order 12.



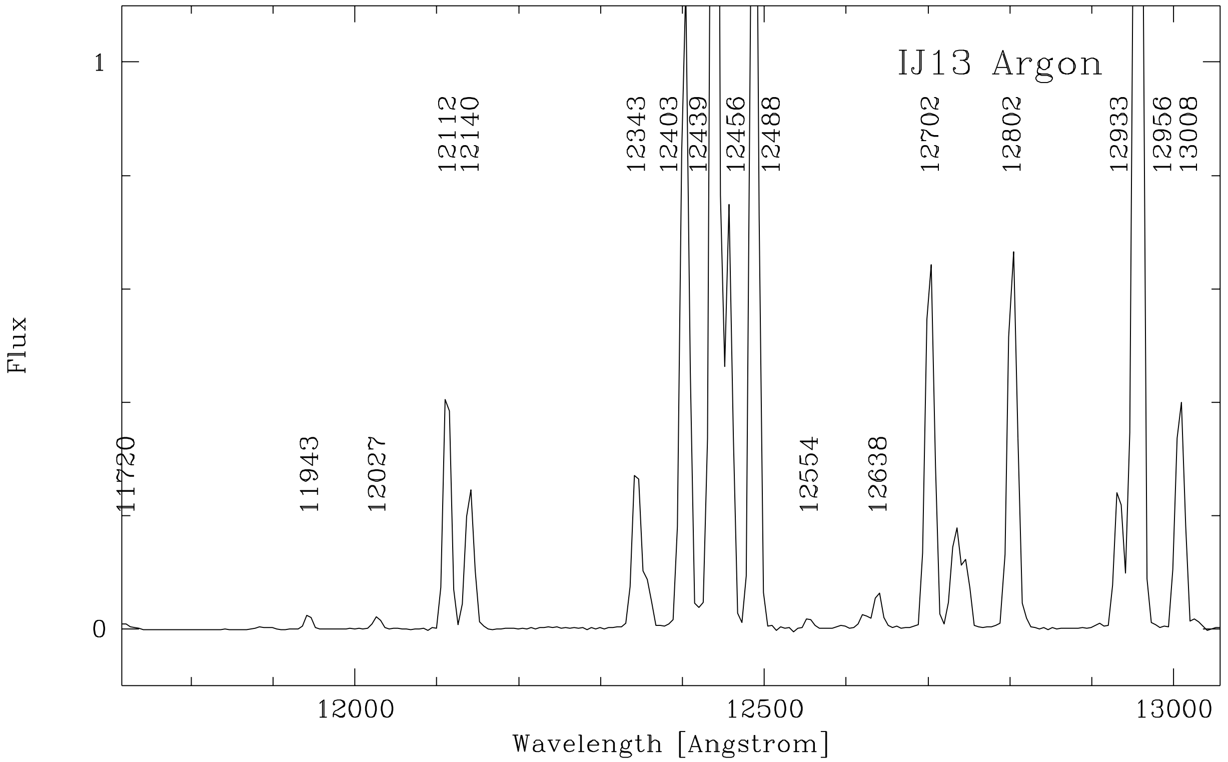
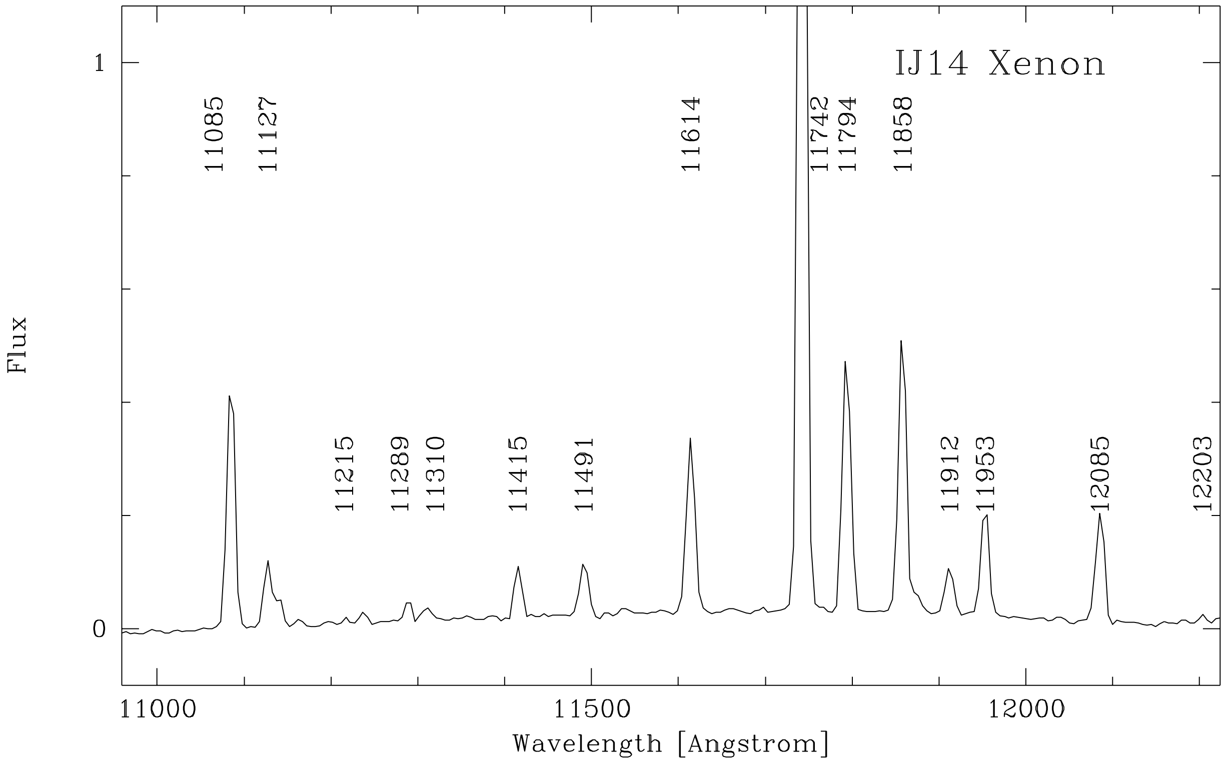


Figure 52: Xenon and Argon arc spectra for *IJ* grism order 13.



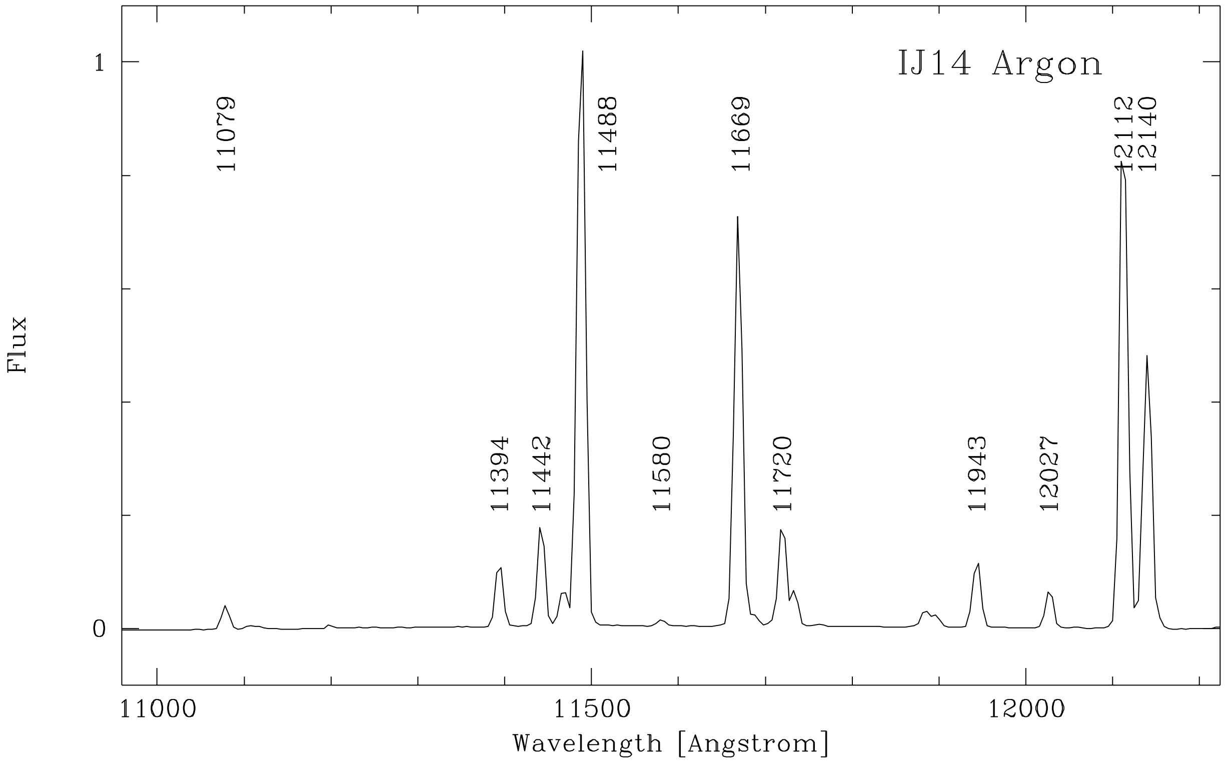
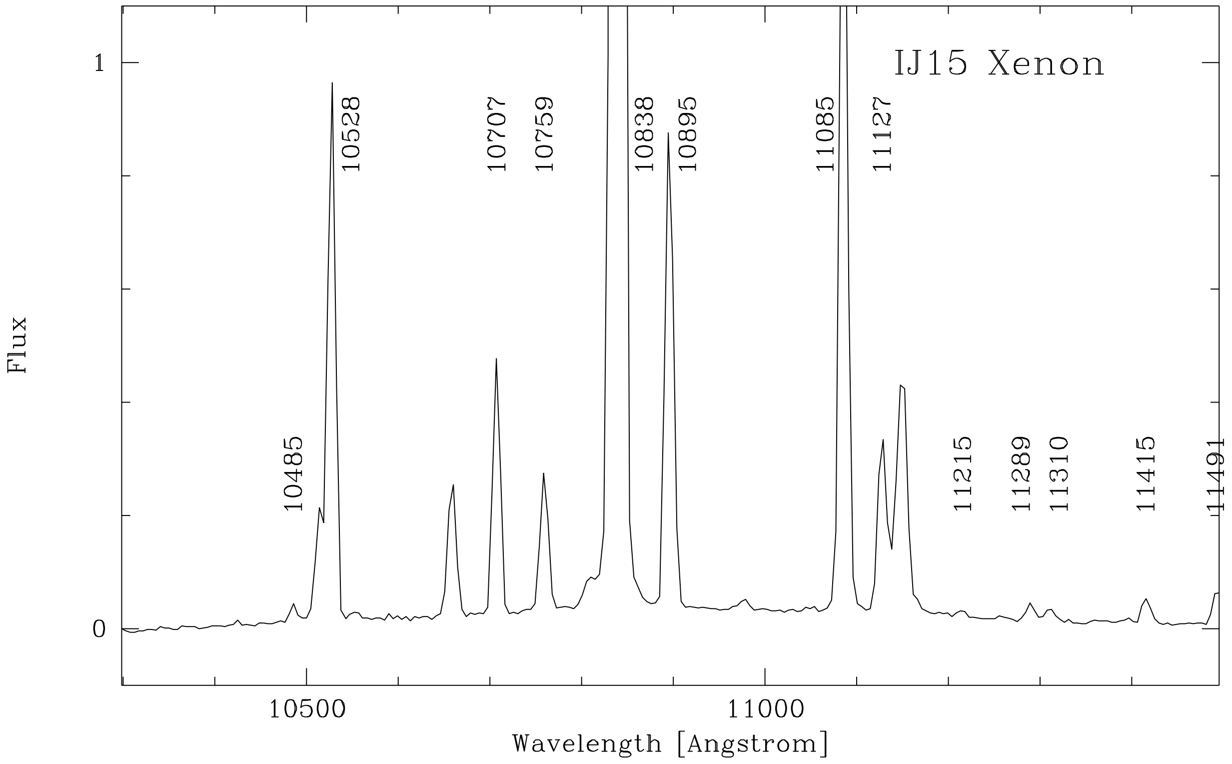


Figure 53: Xenon and Argon arc spectra for *IJ* grism order 14.



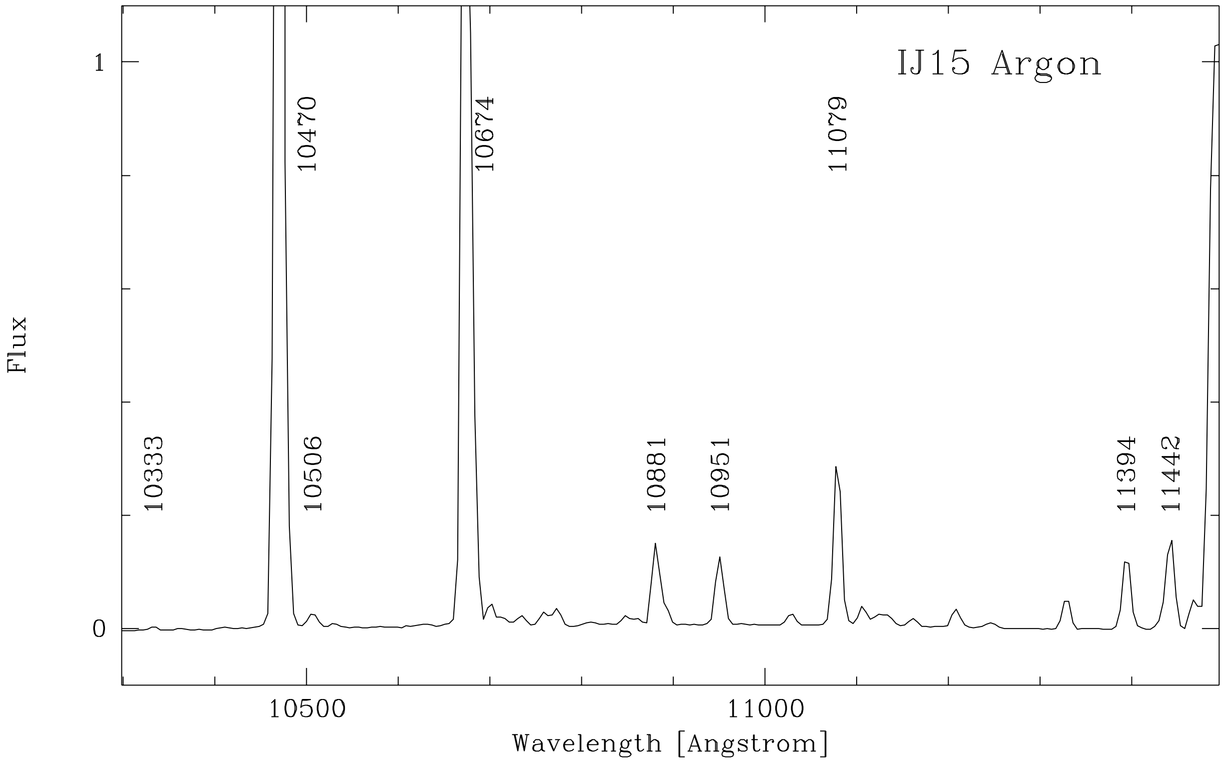
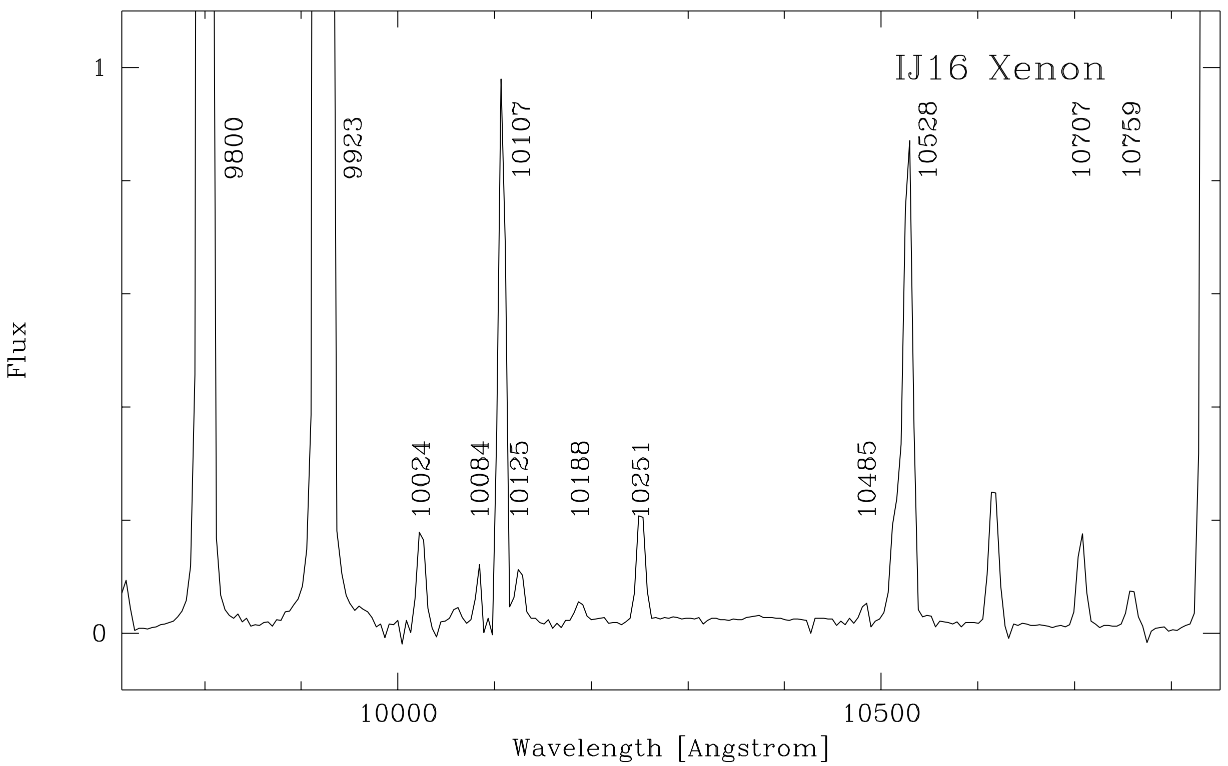


Figure 54: Xenon and Argon arc spectra for *IJ* grism order 15.



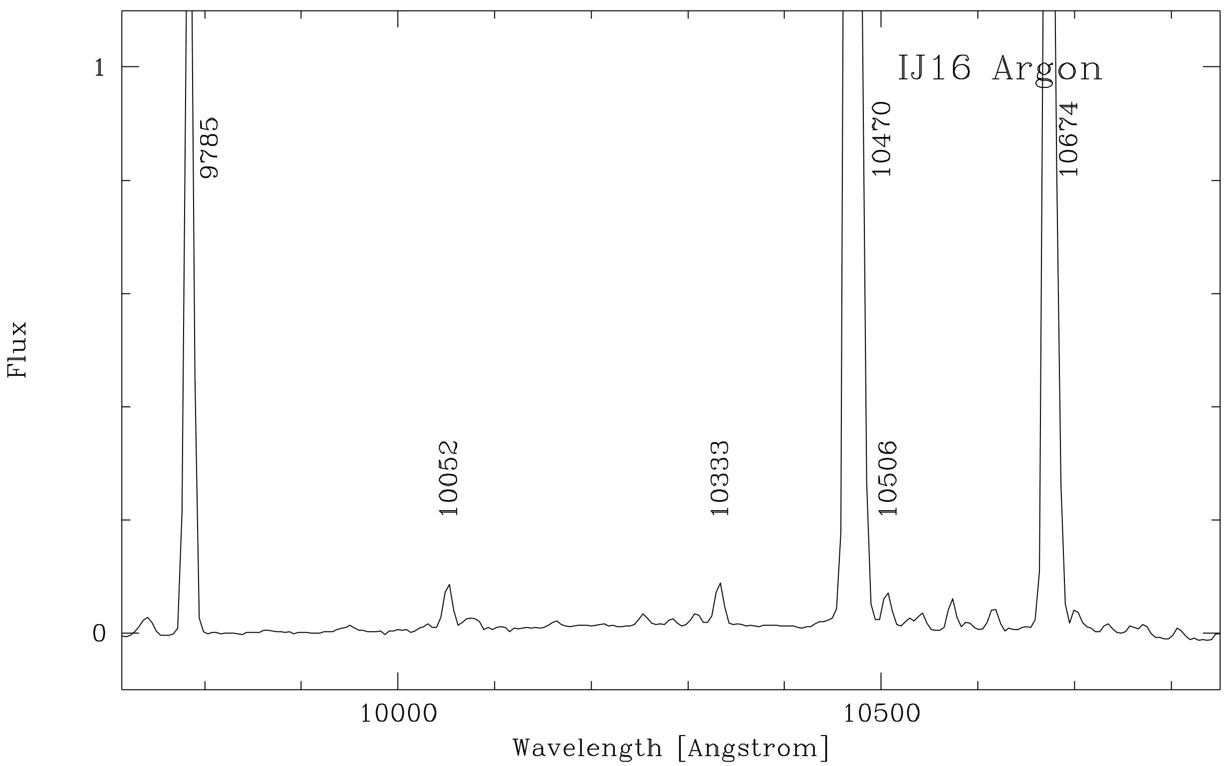


Figure 55: Xenon and Argon arc spectra for *IJ* grism order 16.

K Filter Transmission Functions

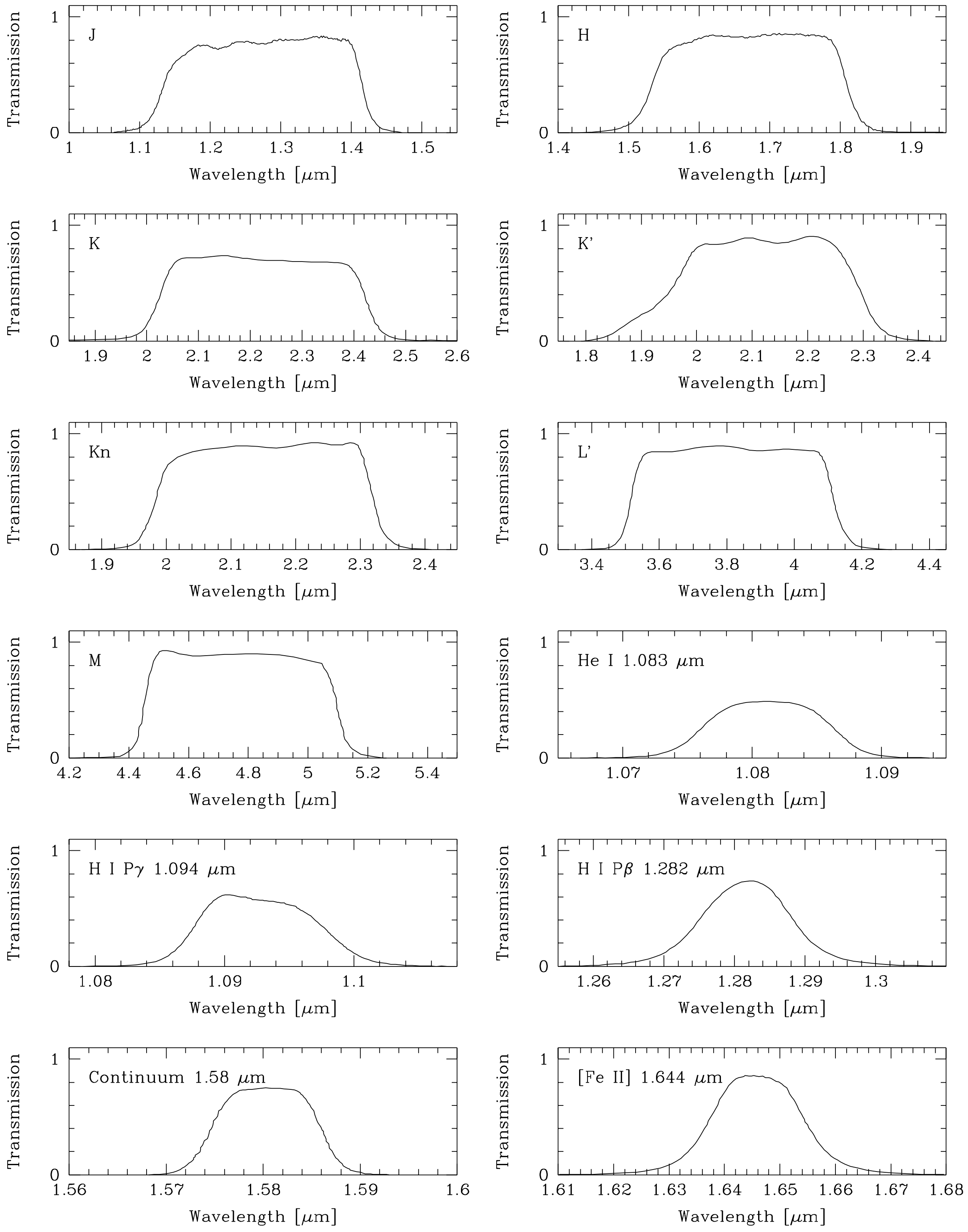


Figure 56: Filter Transmission Functions.

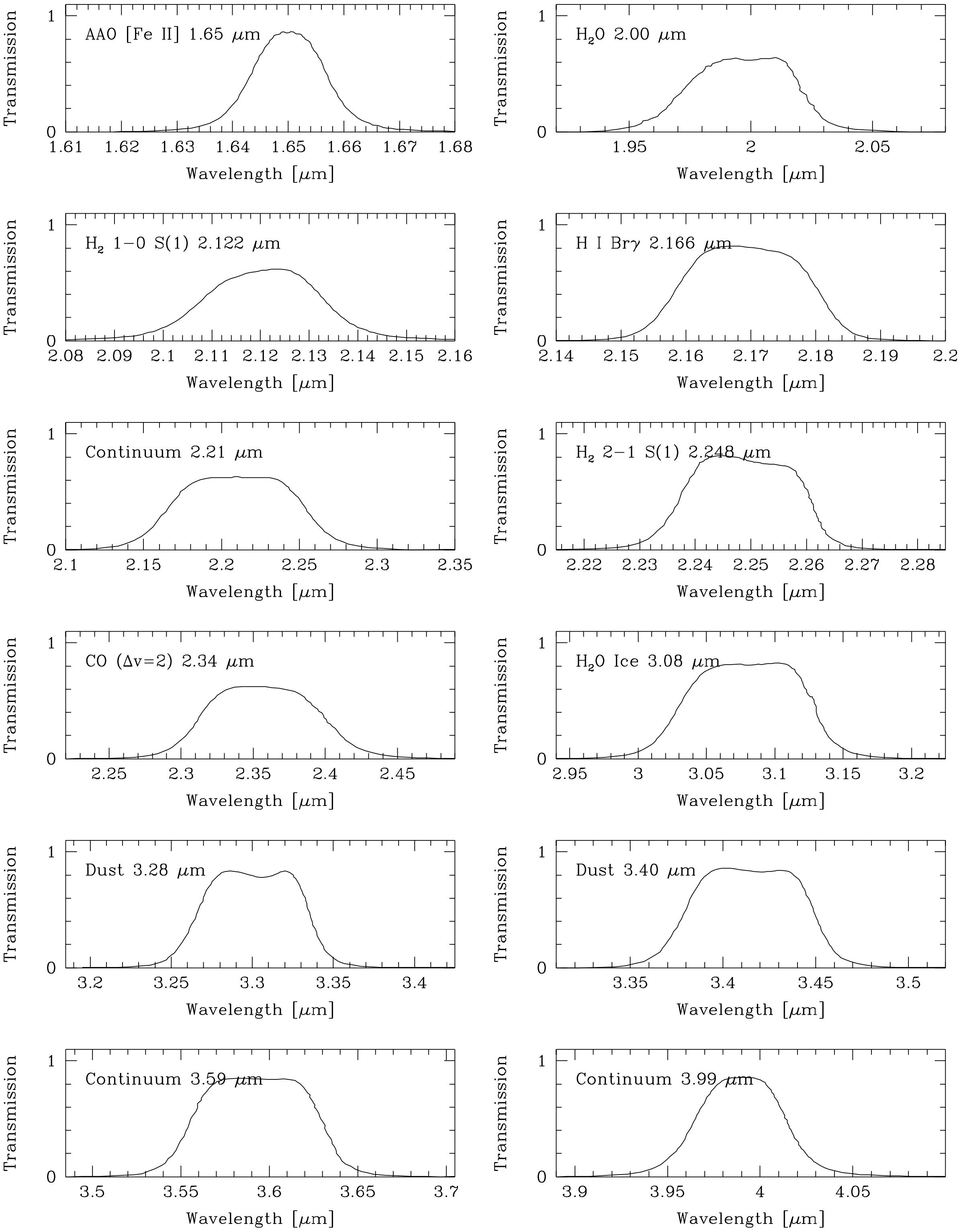


Figure 57: Filter Transmission Functions.

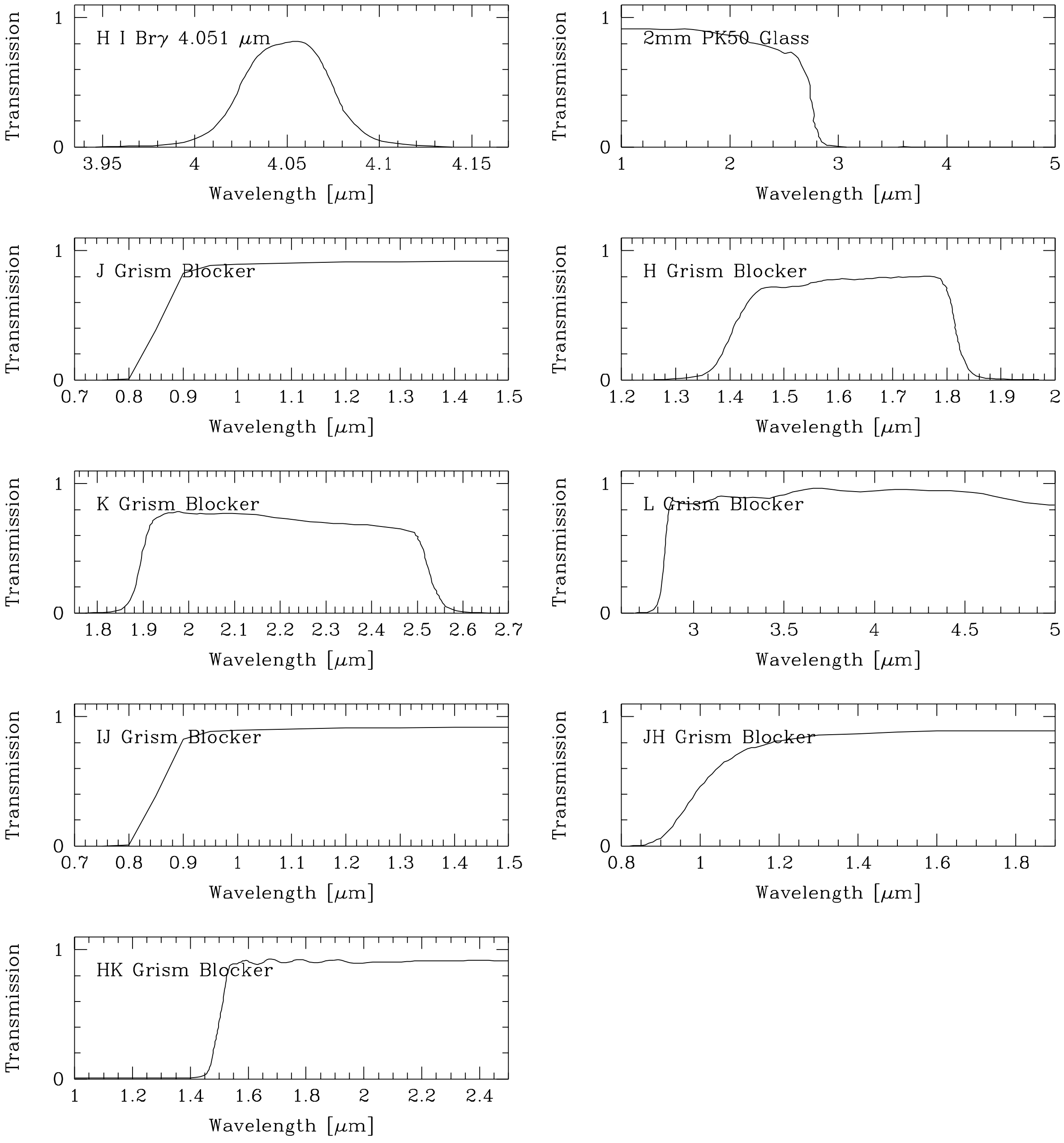


Figure 58: Filter Transmission Functions.

L Dichroic Mirror Transmission

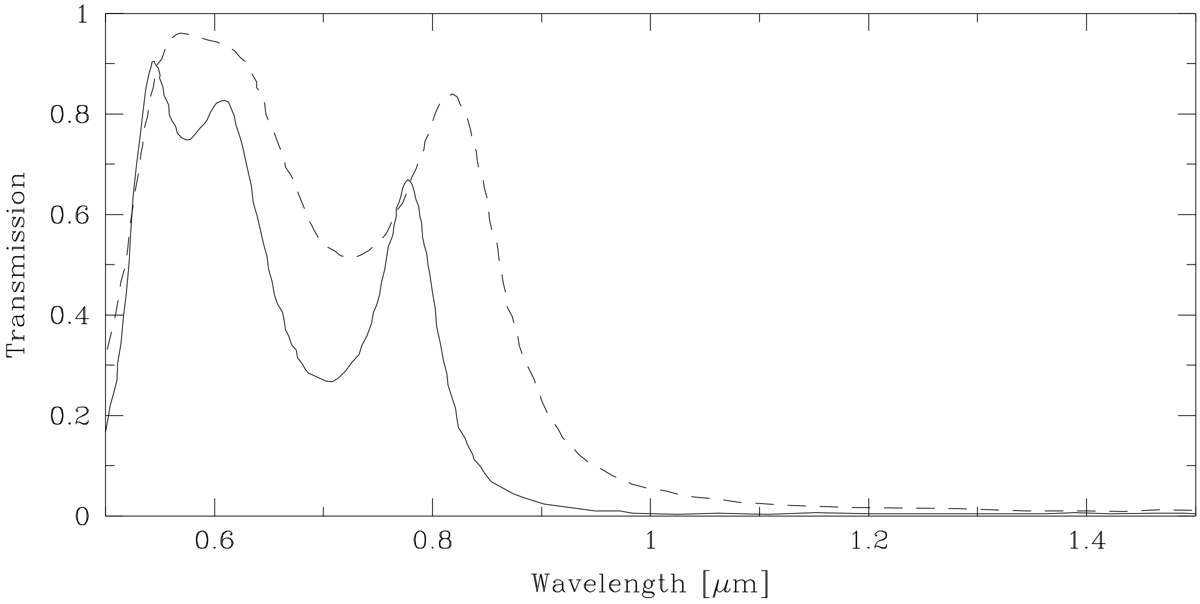


Figure 59: Transmission of the IMB dichroic mirror for the S (*solid line*) and P (*dashed line*) polarizations.

M Terrestrial Atmospheric Transmission

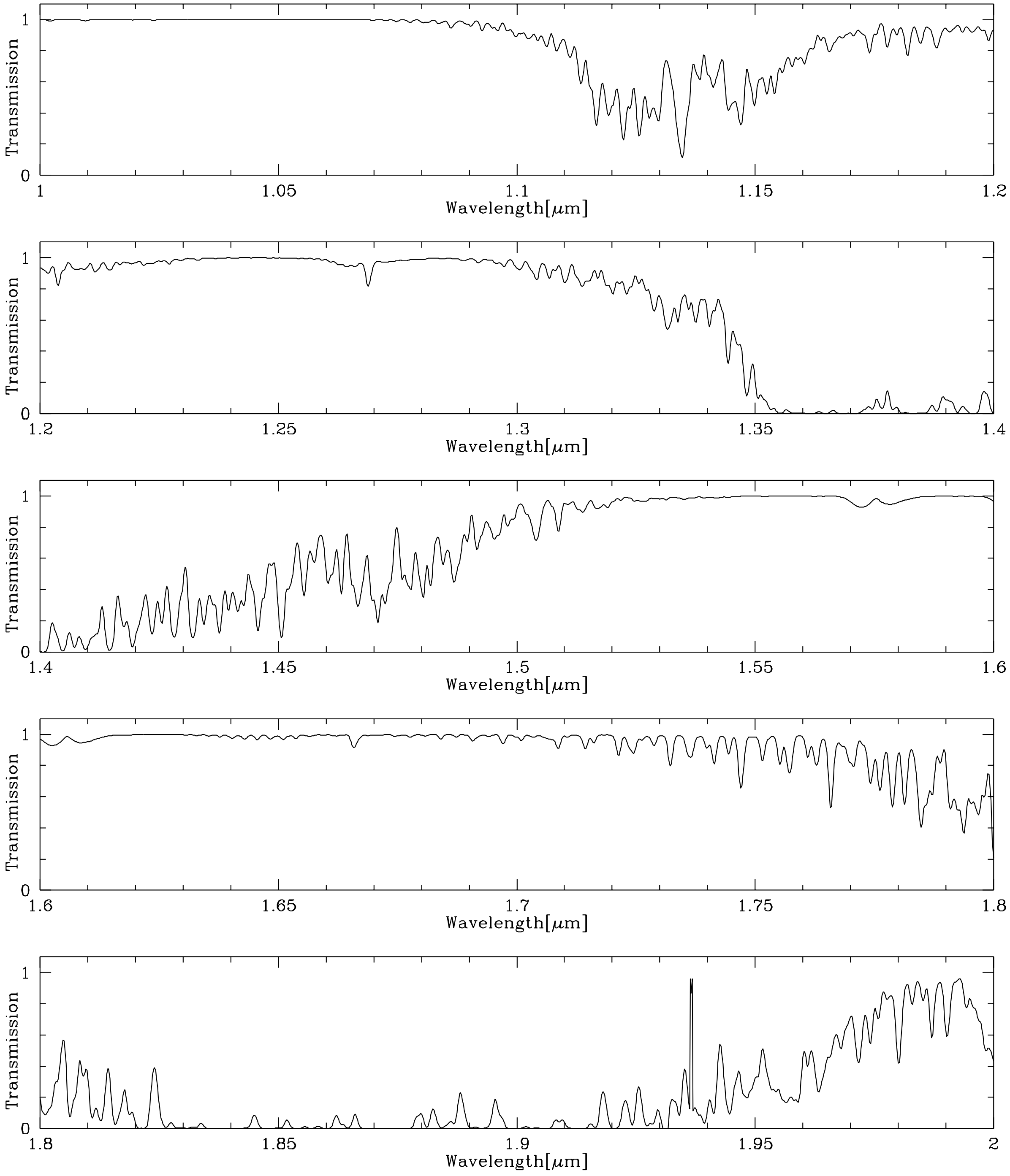


Figure 60: Terrestrial Atmospheric Transmission at SSO.

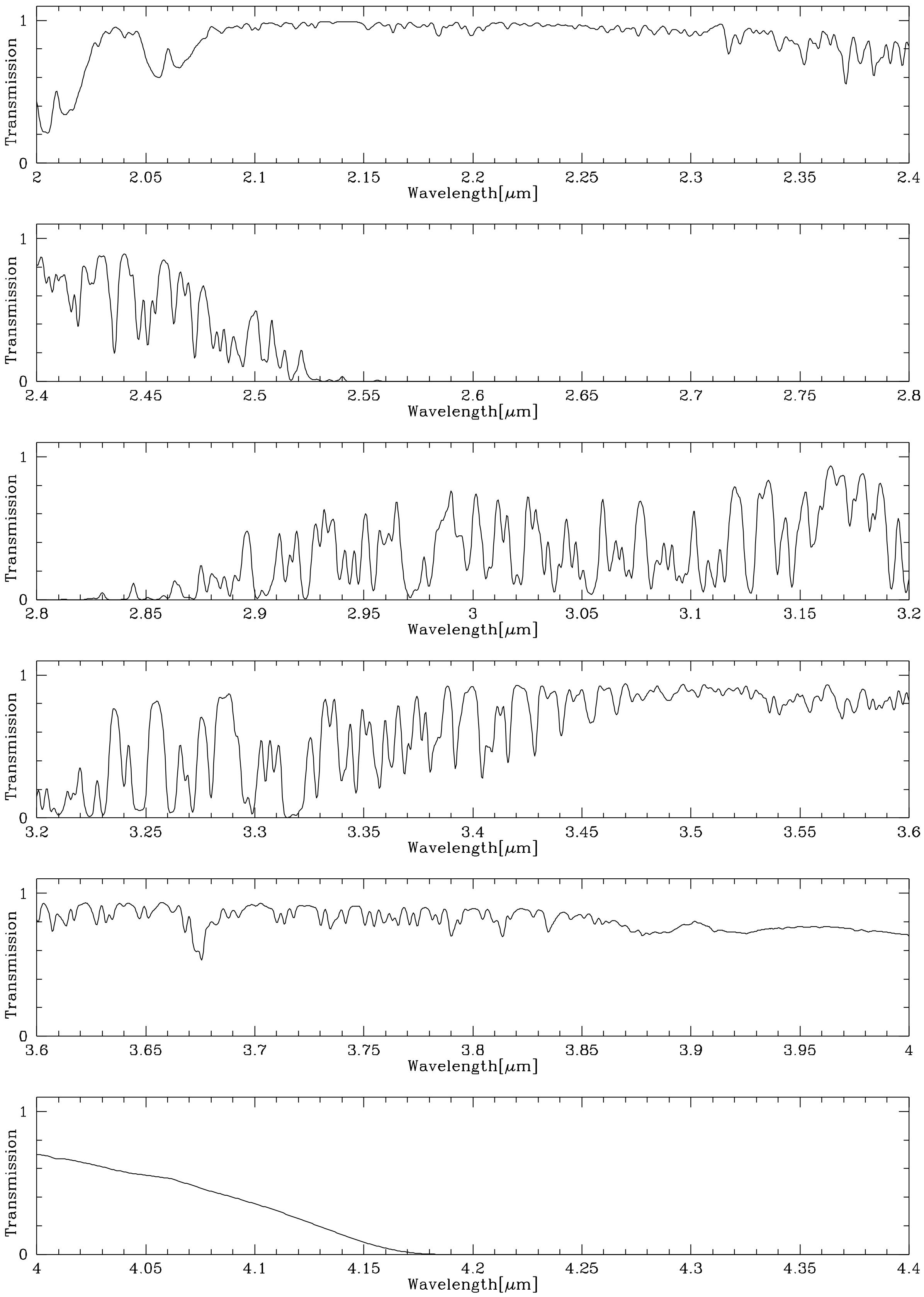


Figure 61: Terrestrial Atmospheric Transmission at SSO.

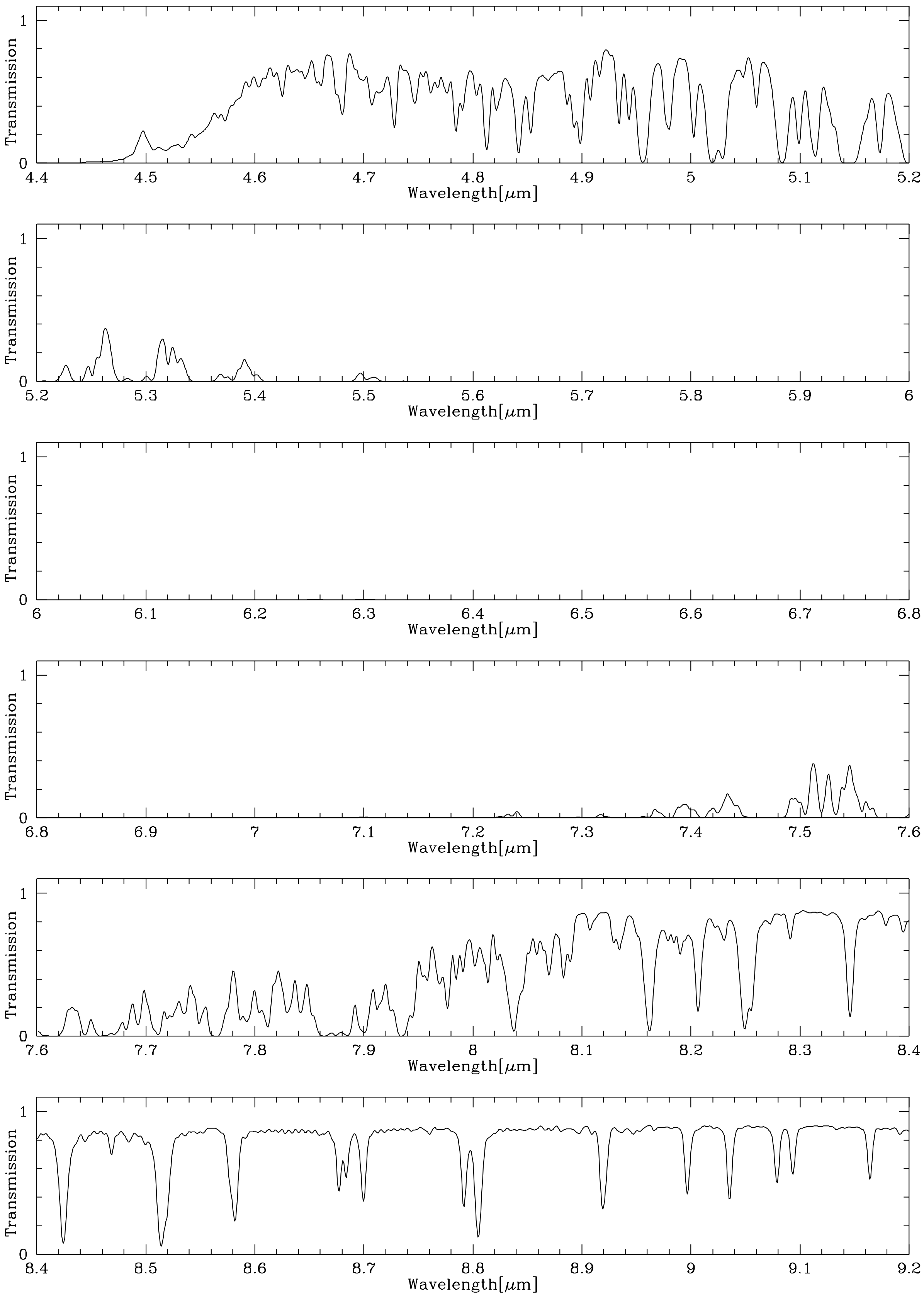


Figure 62: Terrestrial Atmospheric Transmission at SSO.

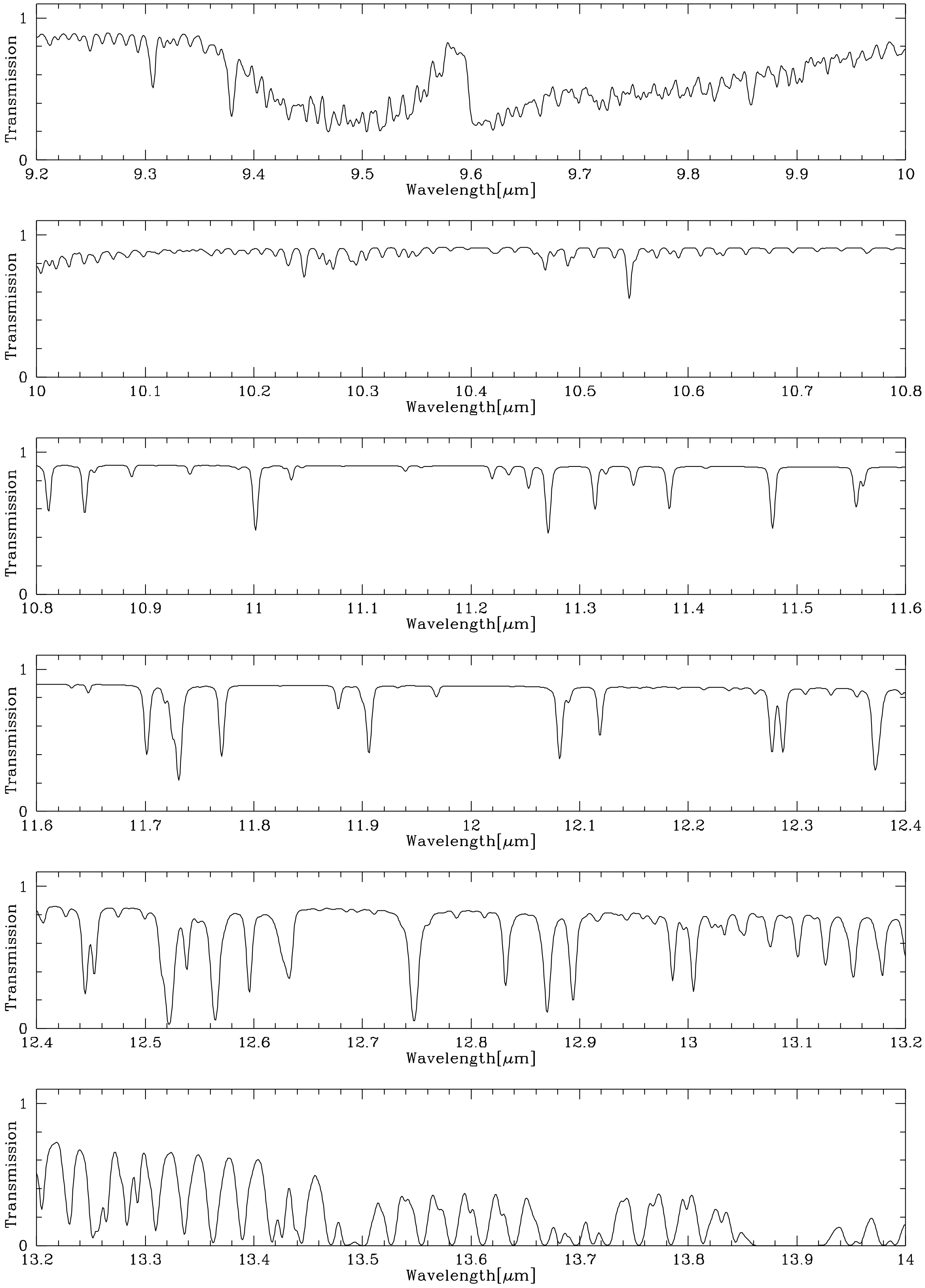


Figure 63: Terrestrial Atmospheric Transmission at SSO.