Physics 629 Lab 4 Due: December 8, 2004

Multi-Object Spectroscopy: The Systemic Velocity and Line-of-Sight Velocity Dispersion of M56

Overview

With very few exceptions (such as gravitational lensing studies) our knowledge of the masses of star clusters, galaxies and galaxy clusters relies on radial velocity measurements. Until relatively recently, measurements of this sort were carried out sequentially, one object at a time. During the past decade, multi-object spectrographs have become commonplace at most major optical observatories, greatly increasing our ability to accumulate large radial velocity samples in short observing runs. In this lab, you will reduce and analyze spectra taken with one such instrument: Hydra, a multi-fiber spectrograph on the WIYN 3.5m telescope at Kitt Peak National Observatory. Using this data, you will measure radial velocities for roughly one hundred stars in the direction of the Galactic globular cluster M56. Using a subset of these velocities, you will determine the systemic velocity and velocity dispersion of this cluster with several different statistical estimators.

Obviously, this lab does not require you to take any observations. Instead, you may download the data directly from the course webpage, and immediately begin the analysis using IRAF. **Be aware that the analysis for this lab is significantly more time-consuming than any of the previous ones, so do not put off starting on it.**

Background and Procedure

M56 (= NGC6779) is a poorly studied globular cluster in the direction of the inner Galaxy. With Galactic coordinates of $(l,\ b) \simeq (63^\circ,\ 8^\circ)$, there is severe contamination from disk and outer bulge stars along this line of sight (as you can see from Figure 1). On July 19, 1996, my collaborators and I observed this field with Hydra. A thorough description of this instrument may be found at the following URL:

`http://www.noao.edu/kpno/manuals/hydraman/hydrawiynmanual.html`

It is wise to read the manual carefully before beginning the analysis. Likewise, you may want to read the document "A User's Guide to Reducing Slit Spectra with IRAF" by Massey, Valdes & Barnes which is available from the course website: spectra_guide.ps. Hydra is *not* a slit spectrograph, but much of the analysis closely resembles that for slit spectra. There is a nice IRAF tutorial dealing with the the extraction and calibration of slit spectra. It is also available from the course website: exer211.tar.gz. Finally, it wouldn't hurt to read the paper,

> `A Survey of Galaxy Redshifts. I. Data Reduction Techniques,`
> `by J. Tonry and M. Davis: 1979, AJ, 84, 1511.`

where the cross-correlation method that we'll use in this lab is discussed in detail.

Very briefly, Hydra is a multi-object spectrograph in which ∼100 optical fibers isolate light from small regions in the WIYN focal plane, and relay it to a bench-mounted spectrograph. Figure 2 gives a schematic representation of Hydra with the fibers "configured" for observation. For the observations considered here, a 316 l/mm echelle grating was used with an order selecting filter to isolate the approximate spectral region $4983 \lesssim \lambda \lesssim 5252$ Å, at a linear dispersion of ~ 0.13 Å pixel^{-1}. In this configuration, the spectrograph has a resolving power of $R \sim 16,000$, so it easy to measure radial velocities to a precision of better than 1 km s^{-1} from these spectra.

Table 1: Some Properties of the M56 Field

Right Ascension	RA(J2000)	19:16:35.5
Declination	DEC(J2000)	+30:11:05
Constellation		Lyra
Gal. longitude	l	62.66 deg
Gal. latitude	b	8.33 deg
Field Diameter		~45 arcmin
Cluster Reddening	E(B-V)	0.20 mag
Cluster Distance	D	10.1 kpc

Some basic information about the Hydra field shown in Figure 1 may be found in Table 1. Stars within this field were first selected from images taken with the KPNO 0.9m telescope, and their astrometric positions measured to a precision of $\pm\, 0''\!.3$. A subset of these stars were then targeted for observation with Hydra. The scientific goals of this program were two-fold: (1) measure radial velocities for cluster members and improve upon existing measurements of the cluster's systemic velocity and line-of-sight velocity dispersion; and (2) carry out a quasi-serendipitous search for "moving groups" of disk, bulge or halo stars along this line of sight. Note that the data you'll be analyzing comprise only a subset of the spectroscopic data for this field.

Before downloading the data for this lab, make sure that you have ~60 MB of free space in your IRAF directory. Then go to the course website and download the file lab4.tar. Unpack the file with the command, "tar xvf lab4.tar", and gunzip the various fits images. You should have the following files:

OBS.LOG	observing log for observations
obj0075.fits	Hydra spectra of program stars in the M56 field
comp0076.fits	Hydra spectra of Th-Ar comparison lamp (used to wavelength-calibrate obj0075.fits)
dflat0098.fits	Hydra spectral dome flats
obj0153.fits	Hydra spectrum of IAU radial velocity standard star, HD222368
comp0154.fits	Hydra spectrum of Th-Ar comparison lamp (used to wavelength-calibrate obj0153.fits)

The goal here is to measure heliocentric radial velocities from the raw stellar spectra in obj0075.fits. The first step in this process is to find and trace the fiber spectra in dflat0098.fits, where the various fibers are well illuminated and have continuous spectra (two important considerations for finding/tracing the fiber spectra). Once you have extracted the dome spectra from this image, you can do the same for obj0075.fits and comp0076.fits using the dome spectra as a reference. Note that comp0076.fits contains spectra of the Th-Ar comparison lamp taken immediately after the observations of the program field (obj0075.fits). Using the extracted comparison lamp spectra, you will determine a "dispersion solution" for each fiber. Using this dispersion solution (*i.e.*, the relation between wavelength and pixel position along the spectrum), you will wavelength-calibrate the extracted program spectra. The final reduction step is to remove the continuum level from the program spectra. The this entire procedure is repeated for obj0153.fits and comp0154.fits. The reduction of these last two files will give a "template" spectrum for HD222368, a radial velocity standard star. Measuring the shift in wavelength of each object spectrum relative to this template spectrum will yield the radial velocity of that object.

Analysis

1. Pre-Processing

There is no need to pre-process the images, as they have already been overscan-corrected, bias-subtracted and trimmed. Each image measures 1000 × 2047 pixels.

2. Extracting the Spectra:

Using the NOAO.TWODSPEC.APEXTRACT.APALL task, find the various apertures in dflat0098.fits (see Figures 3 and 4). Be sure to run APALL interactively. The objective here is to find, trace, edit, and extract the ∼100 apertures in this image. Extracting a region of width ±2 pixels centered on each aperture is adequate. A 10th-order Legendre polynomial should do a reasonable job as a fitting function (Figure 5). There is no need to "sky-subtract" the spectra since the sky is many magnitudes fainter than the program stars.

Once you have extracted the apertures for dflat0098.fits (see Figure 6), use this image as a reference for the extraction of the apertures from obj0075.fits, comp0076.fits, obj0153.fits, and obj0154.fits. For these images, simply "recenter" the apertures and extract them (*i.e.*, there's no need to find and trace the apertures again). The extracted files should be in "multispec" format and will be named something like dflat0098.ms.fits and have dimensions $2047 \times N_a$, where N_a is the number of apertures.

3. Cosmic Ray Removal:

As you've probably noticed, your extracted spectra (particularly for obj0075.fits) contain numerous cosmic rays (Figure 7). Use the NOAO.ONEDSPEC.CONTINUUM task to remove these cosmic rays by fitting a low-order polynomial to the continuum. Reject points that lie more than, say, 4σ above the fitted continuum; be careful to exclude the stellar absorption lines in the fit! Do this for each aperture of obj0075.fits, obj0153.fits and dflat0098.fits. See Figure 8 for an example of a spectrum after cosmic ray cleaning.

4. Flat-fielding the Spectra:

As with imaging data, we need to remove the pixel-to-pixel variations in sensitivity along the extracted spectrum. We may do this with our dome spectra. Create a normalized spectrum for each aperture in dflat0098.fits using the NOAO.ONEDSPEC.CONTINUUM task by fitting a low-order polynomial to the "continuum" of the extracted dome spectra and then taking the ratio of the data and best-fit curve. Using the IMARITH task, flat-field the extracted spectra from obj0075.fits and obj0153.fits using this normalized spectra. (The difference between the pre- and post-flatfielded spectra will be slight.)

5. Wavelength Calibration:

Use NOAO.ONEDSPEC.IDENTIFY task to identify the various Thorium and Argon emission lines in one aperture of comp0075.ms.fits. You should be able to identify about 40 different lines in this aperture (Figure 9). Since you'll need to know the wavelengths of the various lines, you will want to consult NOAO's online spectral atlas:

`http://www.noao.edu/kpno/specatlas/`

A fifth order Legendre polynomial should give you a reasonable calibration between wavelength and pixel position. The rms scatter about the best-fit relation should be less than about 0.01 Å. Once you have identified the lines in this single aperture, you may determine the dispersion solution for the remaining apertures much more efficiently using the NOAO.ONEDSPEC.REIDENTIFY task. Use this first aperture as the reference aperture when running REIDENTIFY.

Repeat this exercise for obj0153.ms.fits. Note that for this image, only a single aperture is illuminated (by our standard star, of course). Run the NOAO.ONEDSPEC.REFSPECTRA task, giving comp0076.ms.fits and comp0154.ms.fits as the reference spectra for obj0075.ms.fits and obj0153.ms.fits, respectively. You may now wavelength-calibrate obj0075.ms.fits and obj0153.ms.fits by running the NOAO.ONEDSPEC.DISPCOR task.

6. Continuum Subtraction:

Your spectra for the M56 field stars and the radial velocity standard star have now been identified, extracted, cleaned of cosmic rays, flat-fielded, and wavelength calibrated. One important step remains before we can measure radial velocities: continuum subtraction. Once again, use the CONTINUUM task to fit a low-order polynomial to the continuum of each spectrum (remembering to avoid the absorption lines in the fit), and subtract off the fitted curves (see Figure 10). Repeat this exercise for the spectrum of the standard star.

7. Cross-Correlation:

Before cross-correlating the object spectra against that of the standard star, we need to update the header of the template spectrum. In performing the cross-correlation, IRAF can determine the heliocentric radial velocity of each program object only if it knows the heliocentric radial velocity of the standard star (since the cross-correlation method gives only the velocity *difference* between the two spectra). Use the IMAGES.IMUTIL.HEDIT task to add the keyword "VHELIO = 5.6" to the header of the template spectrum. This is the known radial velocity of HD222368, taken from the Astronomical Almanac.

Using the NOAO.RV.FXCOR task, cross-correlate each object spectrum against that of the template. There is no need to continuum-subtract the spectra since we have already done this, but you will want to Fourier filter the two spectra in order to remove low and high-frequency power that does *not* come from the absorption lines in the spectra. Edit the parameter file for the NOAO.RV.FILTPARS so that you are using a ramp filter to do this. Experiment with the values of the CUTON, CUTOFF, FULLON and FULLOFF parameters until you get the best (*i.e.*, highest) cross-correlation peak. See Figure 12 for a representative cross-correlation function. What values did you use for the CUTON, CUTOF, FULLON and FULLOFF parameters?

After you have settled on the best choice for these parameters, run the FXCOR task, outputing the results to an ascii file. Include a copy of this file in your lab report. The heliocentric radial velocities for each program object are recorded in this file, measured relative to HD222368.

6. Systemic Velocity and Line-of-Sight Velocity Dispersion:

You've now measured radial velocities for a sample of cluster and field stars along this line of sight; plot a histogram of these radial velocities over the range –200 to +200 km s^{-1}, in bins of 10 km s^{-1}. What do you find for the approximate mean radial velocity of the cluster? With an arrow, indicate the location of the cluster on your radial velocity histogram. (It is fair to consult published radial velocity studies of this cluster to help guide your choice, but be sure to cite these papers.) For a globular cluster of this luminosity and central concentration, the radial velocity dispersion is expected to be (roughly!) $\sigma \sim 4$ km s^{-1}. Using this fact, and your rough estimate for the mean velocity, isolate a sample of stars that you consider to be probable or certain members of M56. Include a list of these stars in your report, identifying them by fiber number and radial velocity. What velocity range did you adopt for the cluster?

Using these radial velocities, calculate the cluster's systemic velocity and radial velocity dispersion. The traditional way of doing this is to simply measure the mean and standard deviation of your sample of radial velocities. There are, however, more sophisticated statistical estimators for these parameters (*i.e.*, the *location* and *scale* in statistical parlance).

Read the following paper carefully.

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Measures of Location and Scale for Velocities in Clusters of Galaxies:
A Robust Approach, by T. Beers, K. Flynn & K. Gebhardt: 1990, AJ, 100, 32
```

These authors describe a number of different estimators for the location and scale. Run the program /home/pryor/util/rostat/rostat to determine the following estimators for your sample of M56 radial velocities (the program gives many other quantities, we will use just these):

- Mean and Standard Deviation (mean and sdev)
- Median and Median Absolute Deviation (median and sig-mad)
- Biweight and Biweight Scale (biwt and s-biwt)

The program expects an input file containing the velocity and velocity uncertainty for each star in the sample, with one star per line. Answer the question about the number of simulations with 10000. The results appear in the file rostat.out. Quote your values of the location and scale to one decimal place. Also give the bootstrap estimates of the one-sigma (68%) uncertainties for the mean, standard deviation, biweight, and biweight scale. This is the first of the four uncertainties given for each estimator (the other three are the boundaries of the 90%, 95%, and 99% confidence intervals). [The Fortran source code for Rostat is available in the same directory if you wish to compile it on a computer other than the Suns. If you do so, you will also have to copy the data files and edit rostat.f to change the path to those files.]

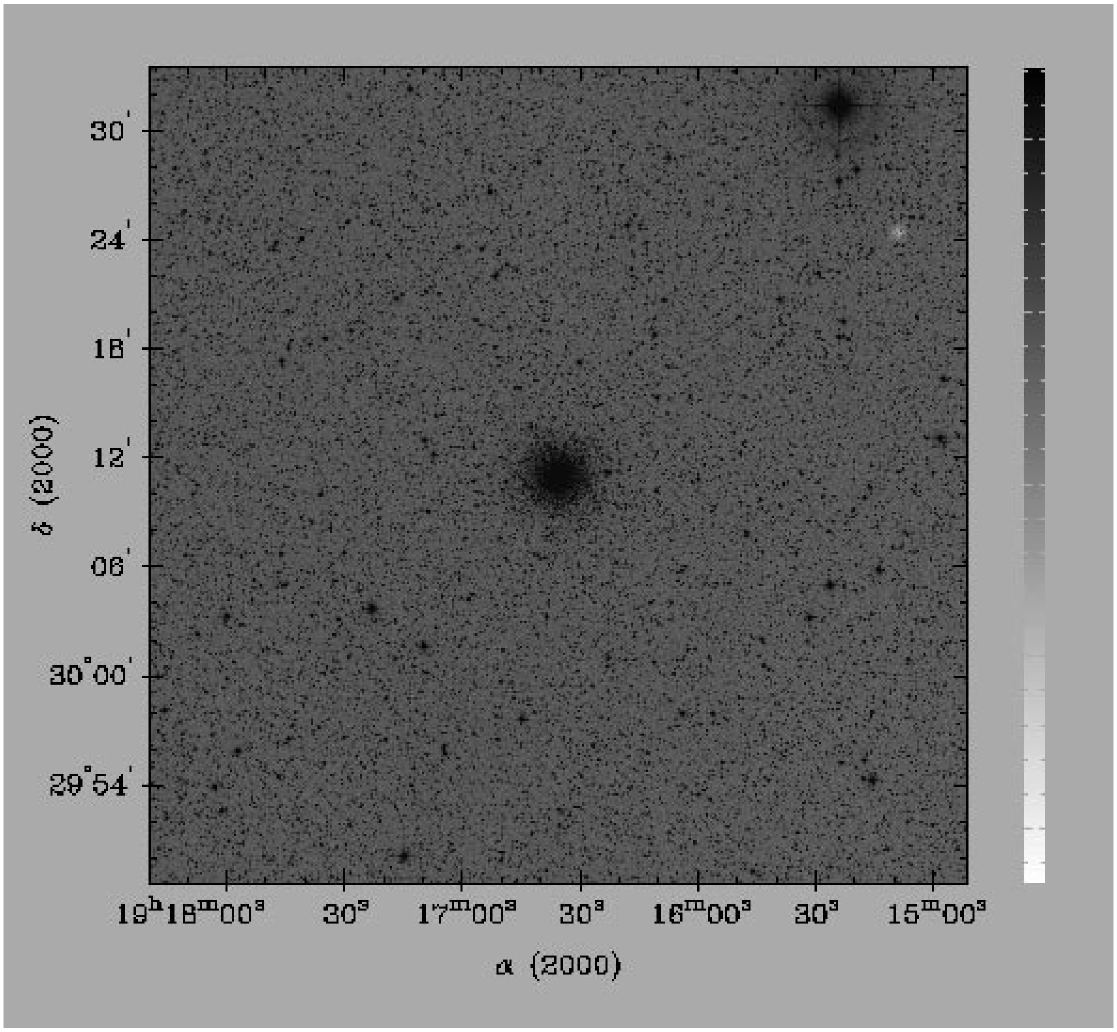
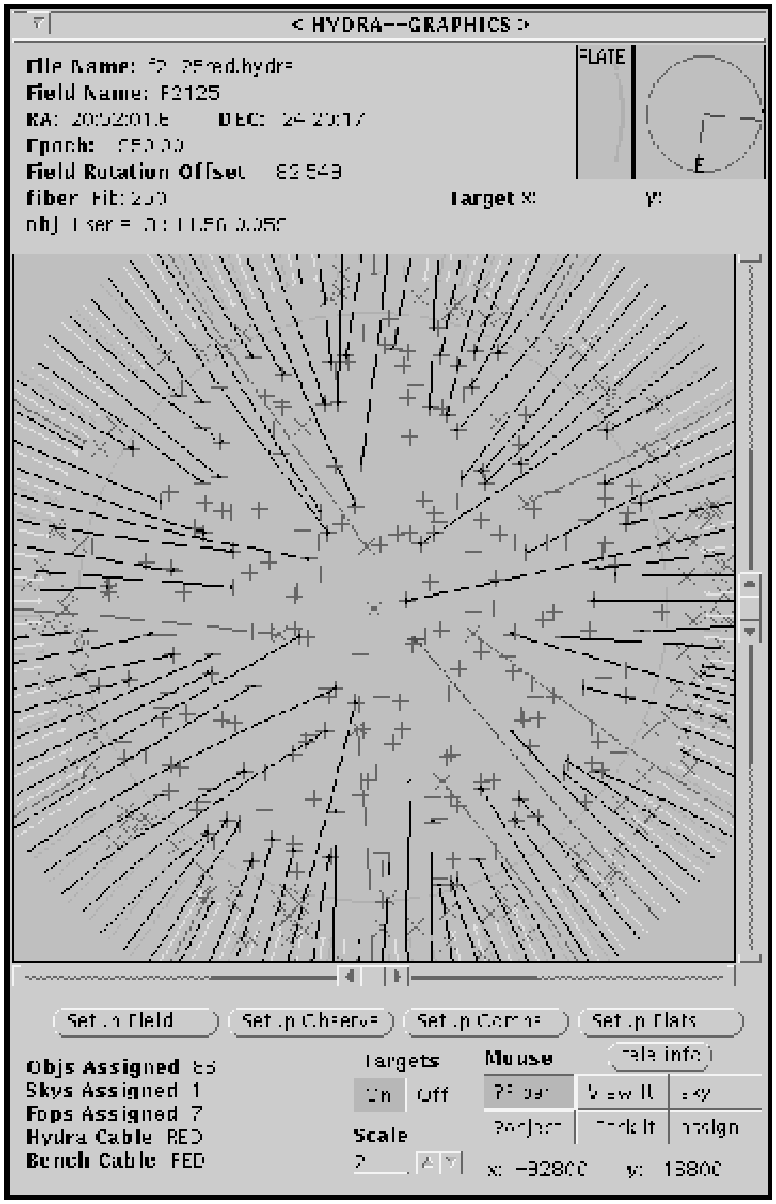


Figure 1: Image of the M56 field from Second Generation Palomar Observatory Sky Survey. The image measures $45' \times 45'$. North is at the top, east is to the left. The image obj0075.fits contains echelle spectra for ~ 100 stars in this field.



Field Name: F2125
Field Rotation Offset
fiber
Target X:
Y:
Objs Assigned 65
Skys Assigned 1
Fops Assigned 7
Hydra Cable RED
Bench Cable RED
Scale 2
x: -32800 y: 13800

Figure 2: View of the Hydra graphics window, taken from the instrument user's manual (Barden & Armandroff 1995). In this view, Hydra has been configured for observations.

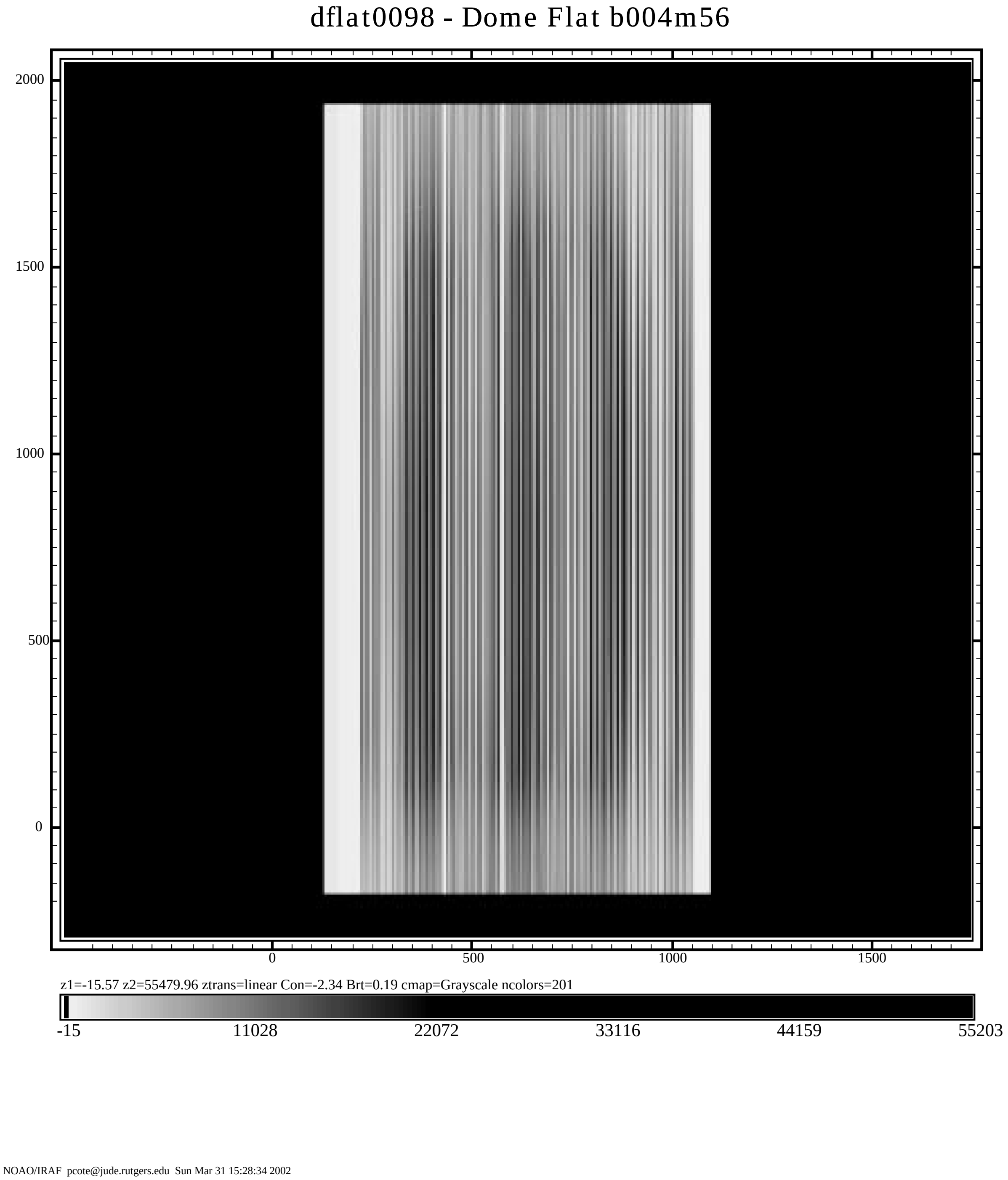
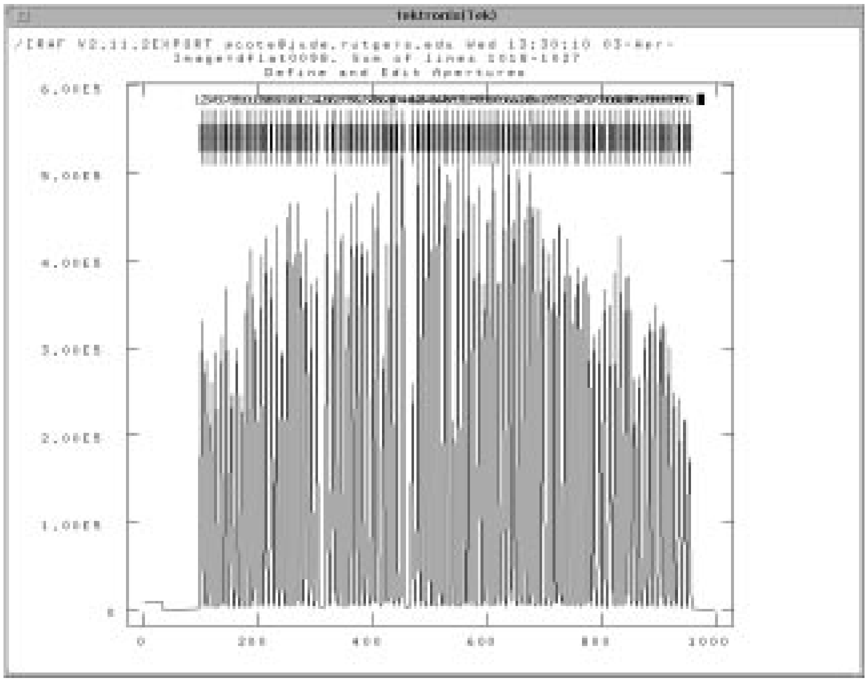
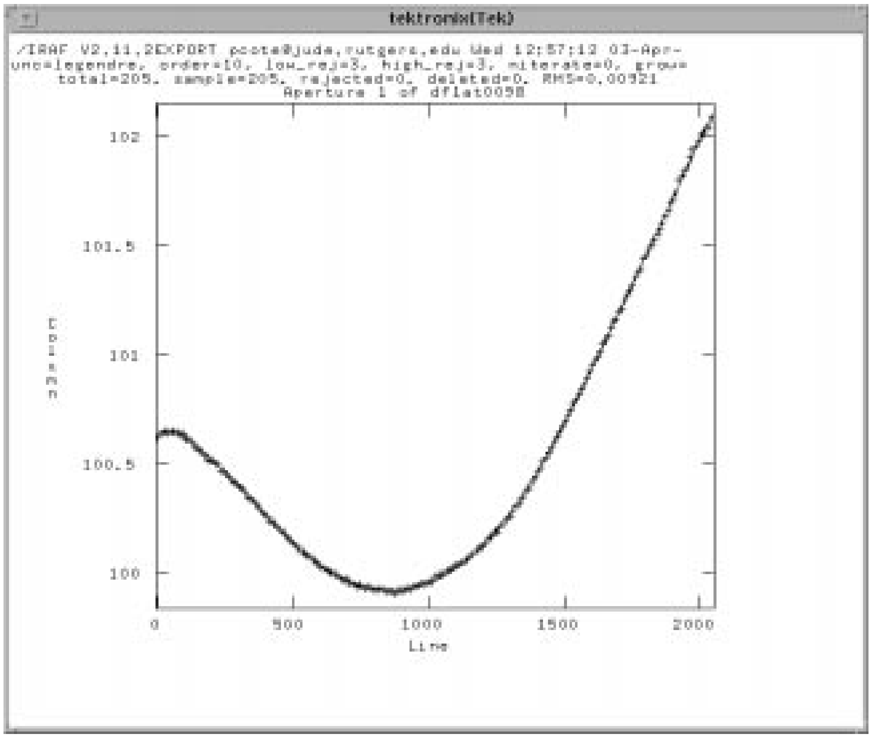


Figure 3: Dome spectra (dflat0098.fits) for the fiber configuration used to observe the M56 field. There are about one hundred spectra in this image, with the spectral dispersion axis running vertically. Red wavelengths are located at the bottom of the image, blue wavelengths are at the top.



```
/IRAF V2.11.2EXPORT pcote@jude.rutgers.edu Wed 13:30:10 03-Apr-
          Image=dflat0098, Sum of lines 1018-1027
                Define and Edit Apertures
```

Figure 4: A cross sectional view of the dome flats shown in the previous figure. This view is perpendicular to the dispersion axis, so that each spike corresponds to the spectrum from an individual fiber. The tickmarks at the top indicate fiber spectra (*i.e.*, *apertures*) which have been found using the NOAO.TWODSPEC.APEXTRACT.APALL task.



```
/IRAF V2.11.2EXPORT pcote@jude.rutgers.edu Wed 12:57:12 03-Apr-
unc=legendre, order=10, low_rej=3, high_rej=3, niterate=0, grow=
    total=205, sample=205, rejected=0, deleted=0, RMS=0.00921
                Aperture 1 of dflat0098
```

Figure 5: Traced dome spectrum for aperture #1 of dflat0098.fits. The dotted line shows the best-fit 10th-order Legendre polynomial. This plot was also made with the APALL task.

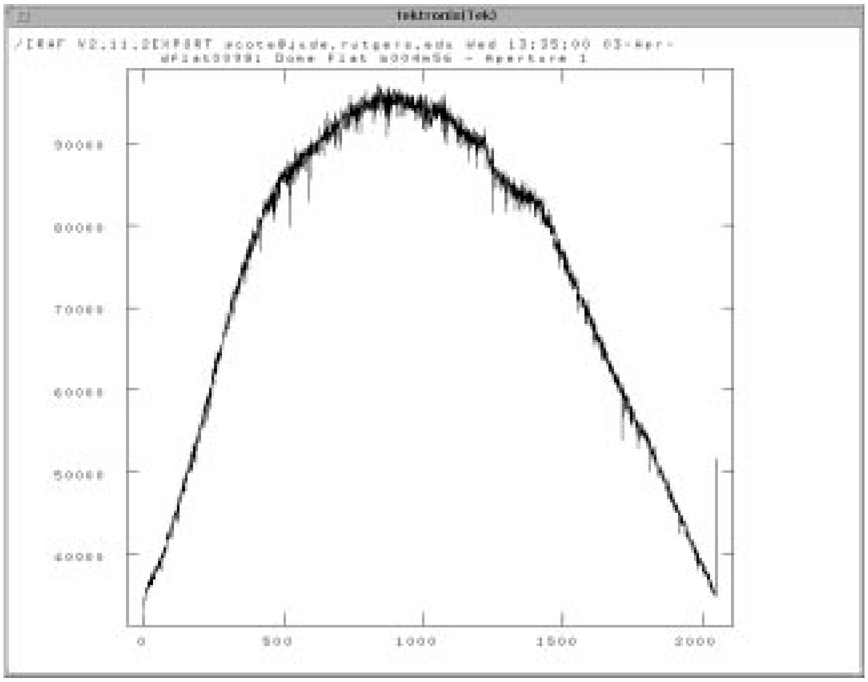


Figure 6: Extracted dome spectrum for aperture #1 of dflat0098.fits, produced with the APALL task. A region of width ± 2 pixels perpendicular to the dispersion direction and centered on the spectrum has been extracted.

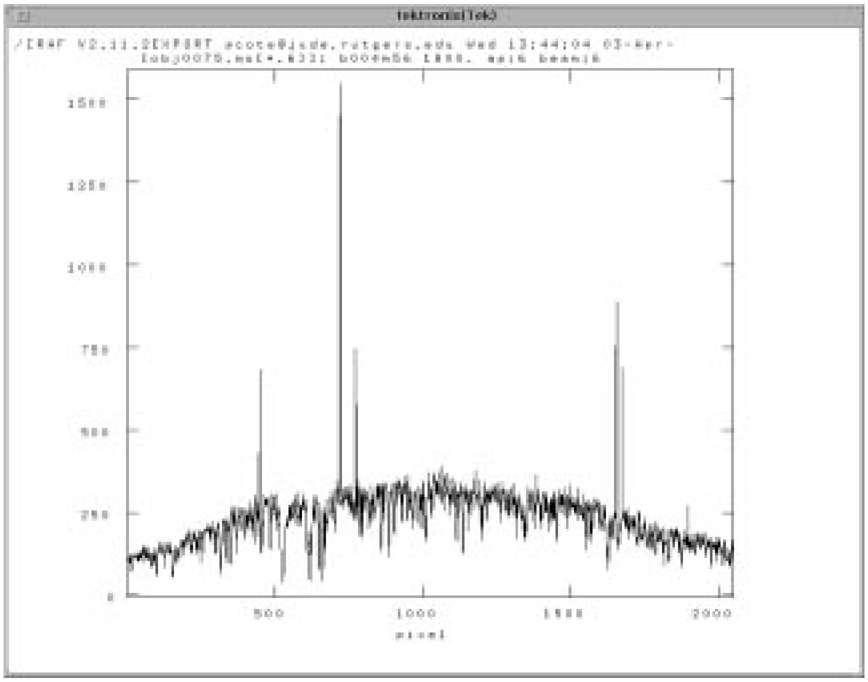


Figure 7: Extracted spectrum for aperture #6 of obj0075.fits. Note the sharp "spikes" superimposed on the continuum. These are cosmic rays which have been extracted along with the stellar (absorption) spectrum. The NOAO.ONEDSPEC.CONTINUUM task was used to produce this plot.

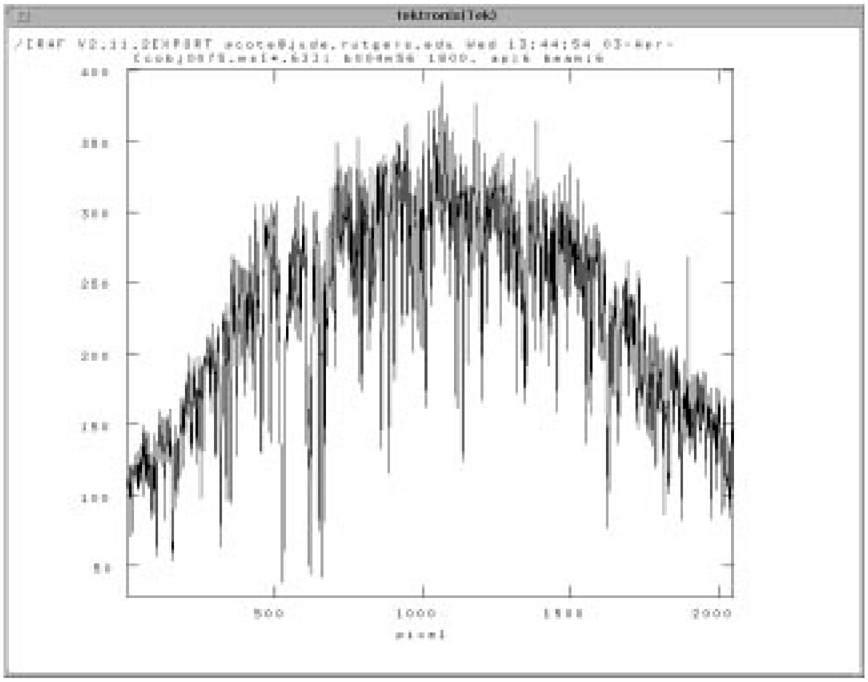


Figure 8: Extracted spectrum for aperture #6 of obj0075.fits after cosmic ray removal with the CONTINUUM task.

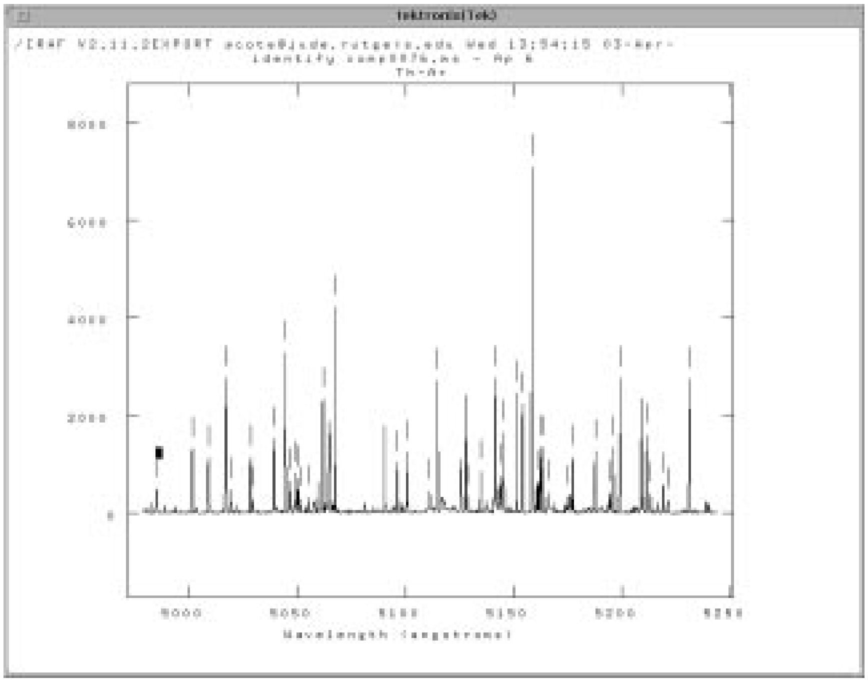


Figure 9: Wavelength-calibrated Th-Ar spectrum for aperture #6 of comp0076.fits. Emission lines in this spectrum have been identified using the NOAO.ONEDSPEC.IDENTIFY task.

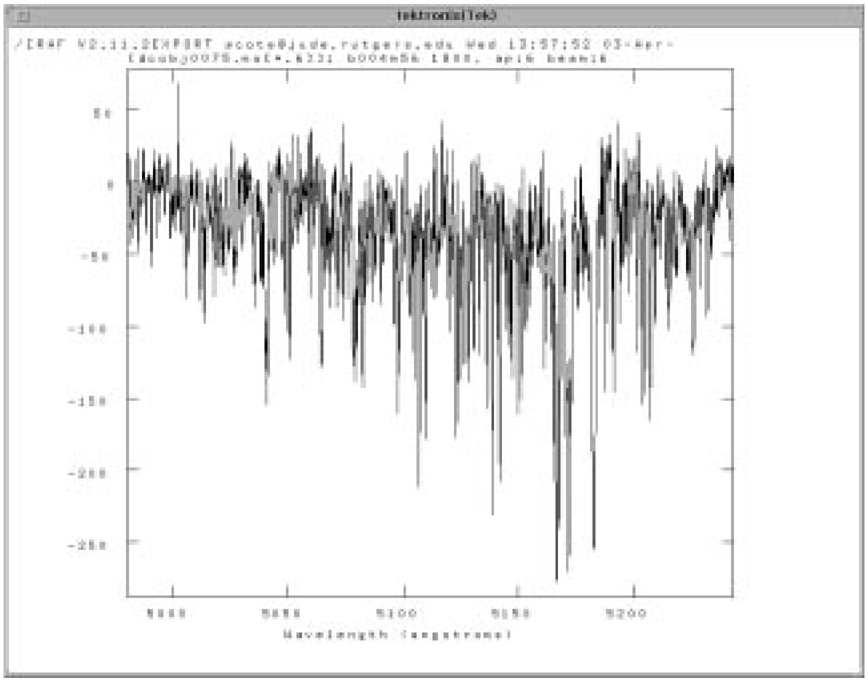


Figure 10: Wavelength-calibrated, continuum-subtracted spectrum for aperture #6 of obj0075.fits. This plot was produced with the CONTINUUM task.

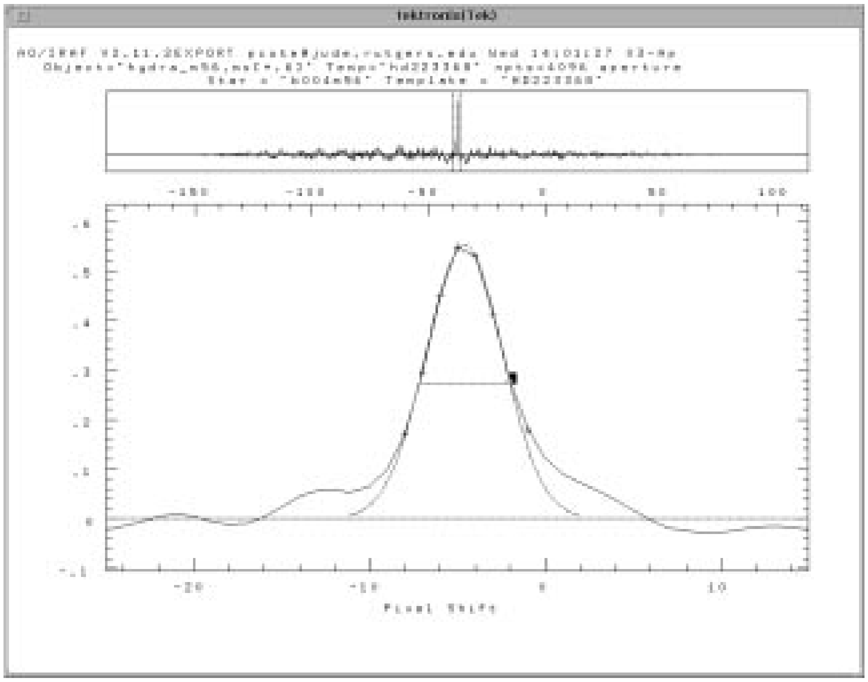


Figure 12: Cross-correlation function aperture #6 of obj0075.fits, using HD222368 (obj0153.fits) as a radial velocity template. Both the object and template spectra have been Fourier filtered with a ramp filter. The Gaussian that best fits the cross-correlation function is overlaid.