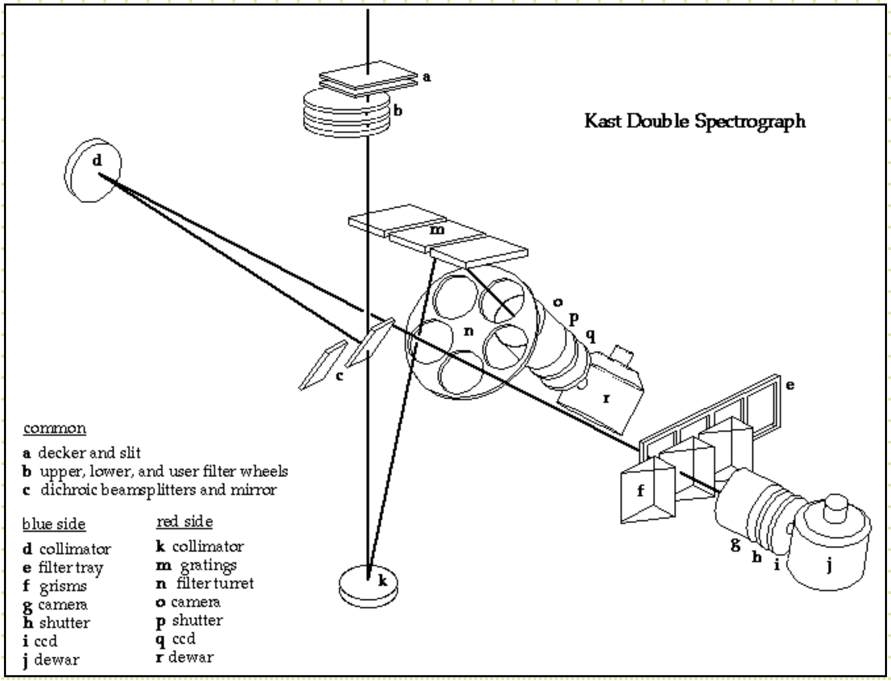
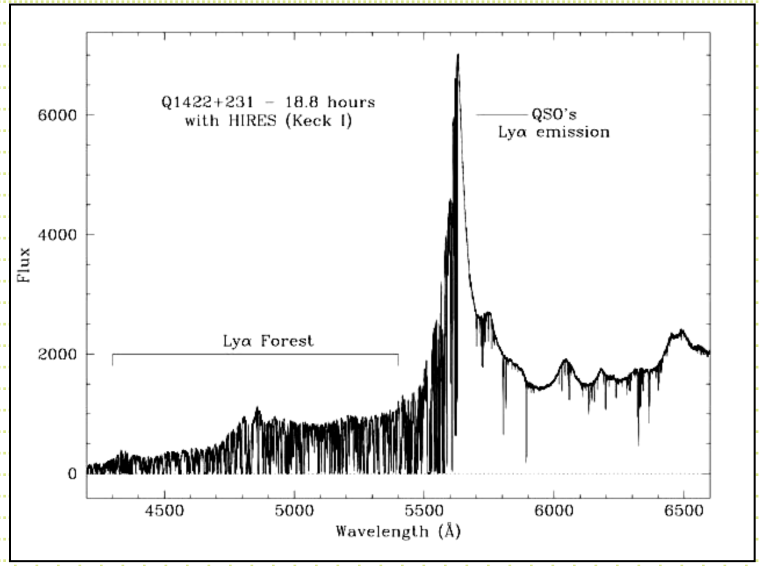
Spectra





- Bowen, 1962, Astronomical Techniques, pg 34.
- Pogge, 1992, ASP Conf. Ser.#23, pg.160

What are spectra good for?

- Astrophysics!
  - Radial velocities
    - Stellar kinematics
    - Discovering extra-solar planets
    - Stellar/neutron star/stellar black hole masses
    - Stellar rotation
    - Rotation curves and velocity dispersion of galaxies to determine mass and mass distribution
    - Measuring the motions of galaxies in clusters
    - Measuring the expansion of the Universe

What are spectra good for?

- Physical properties of gas
  - Temperature, density, chemical composition
- Physical properties of stars
  - Surface temperature
  - Surface pressure (mass/radius)
  - Chemical composition

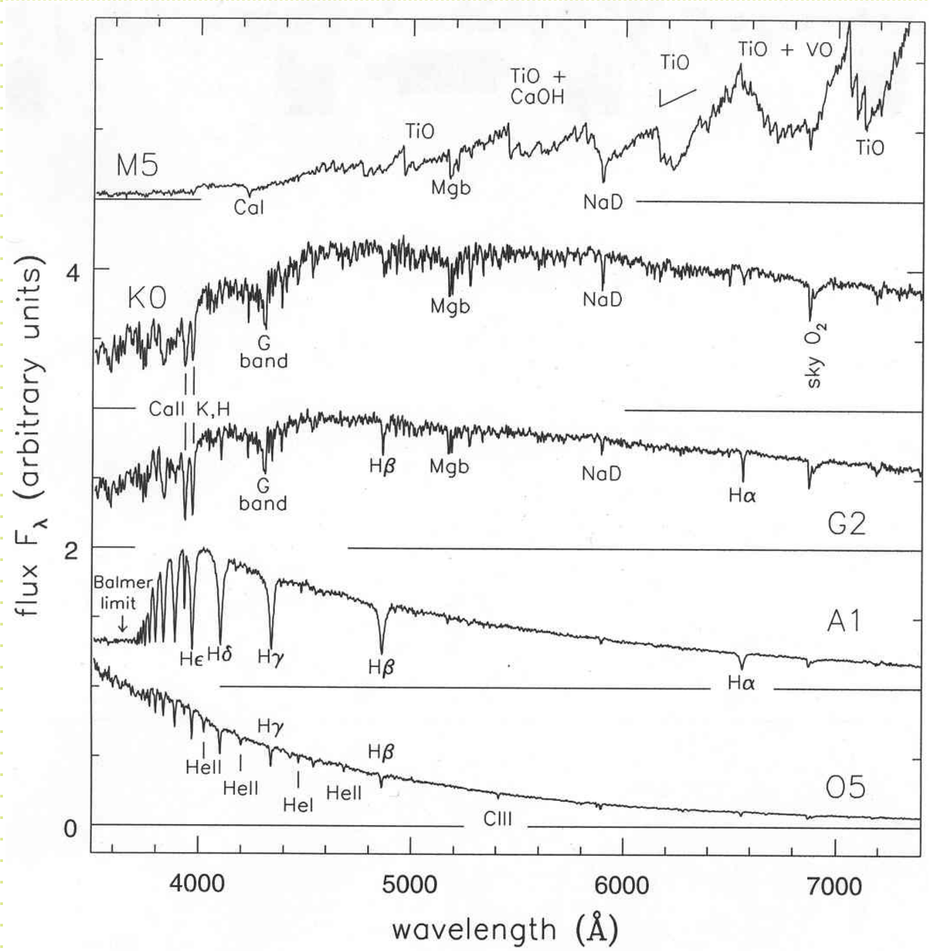


Figure 1.1 Optical spectra of main-sequence stars with roughly the solar chemical composition. From the top in order of increasing surface temperature, the stars have spectral classes M5, K0, G2, A1, and O5 – G. Jacoby *et al.*, spectral library.

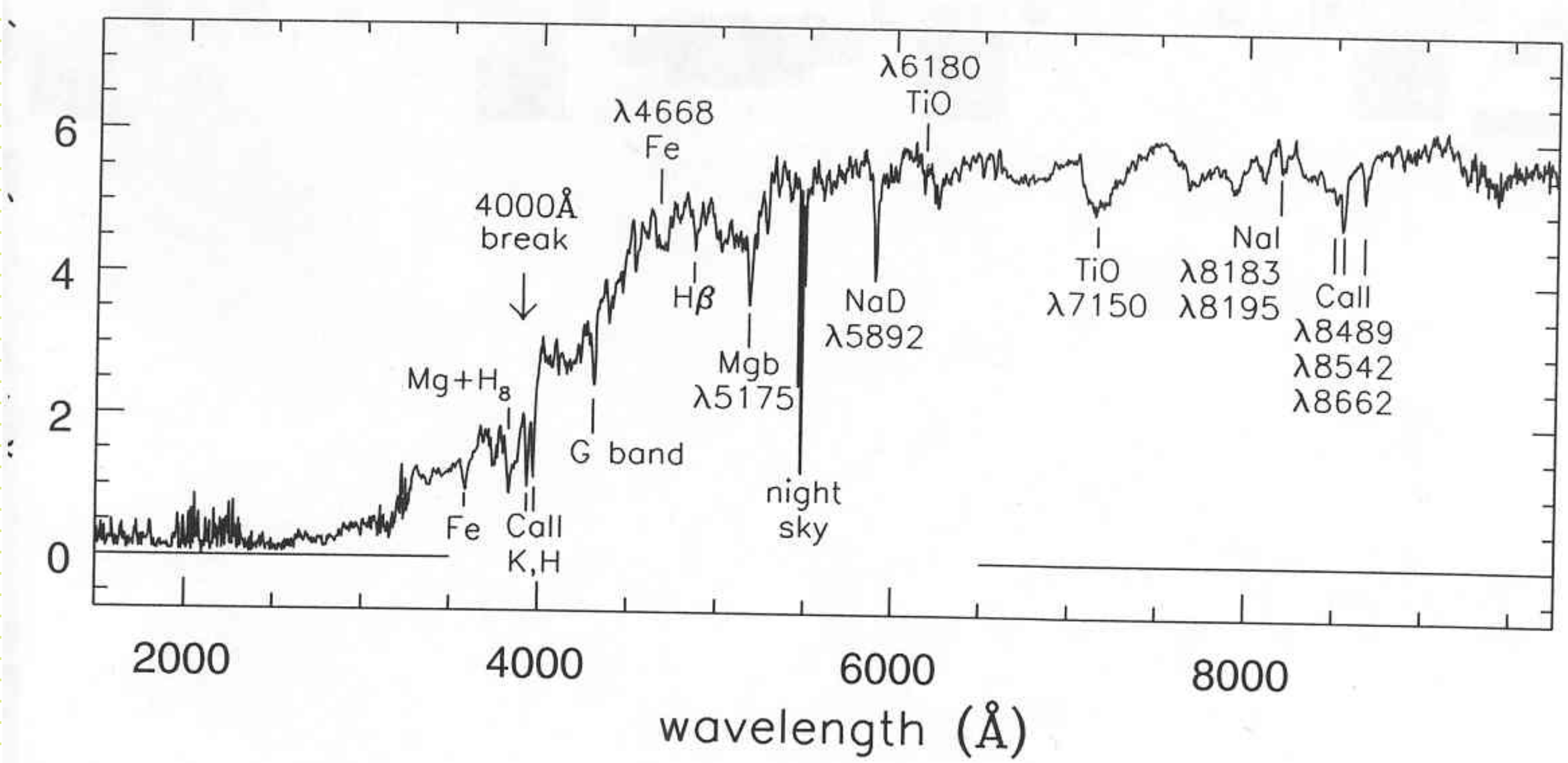
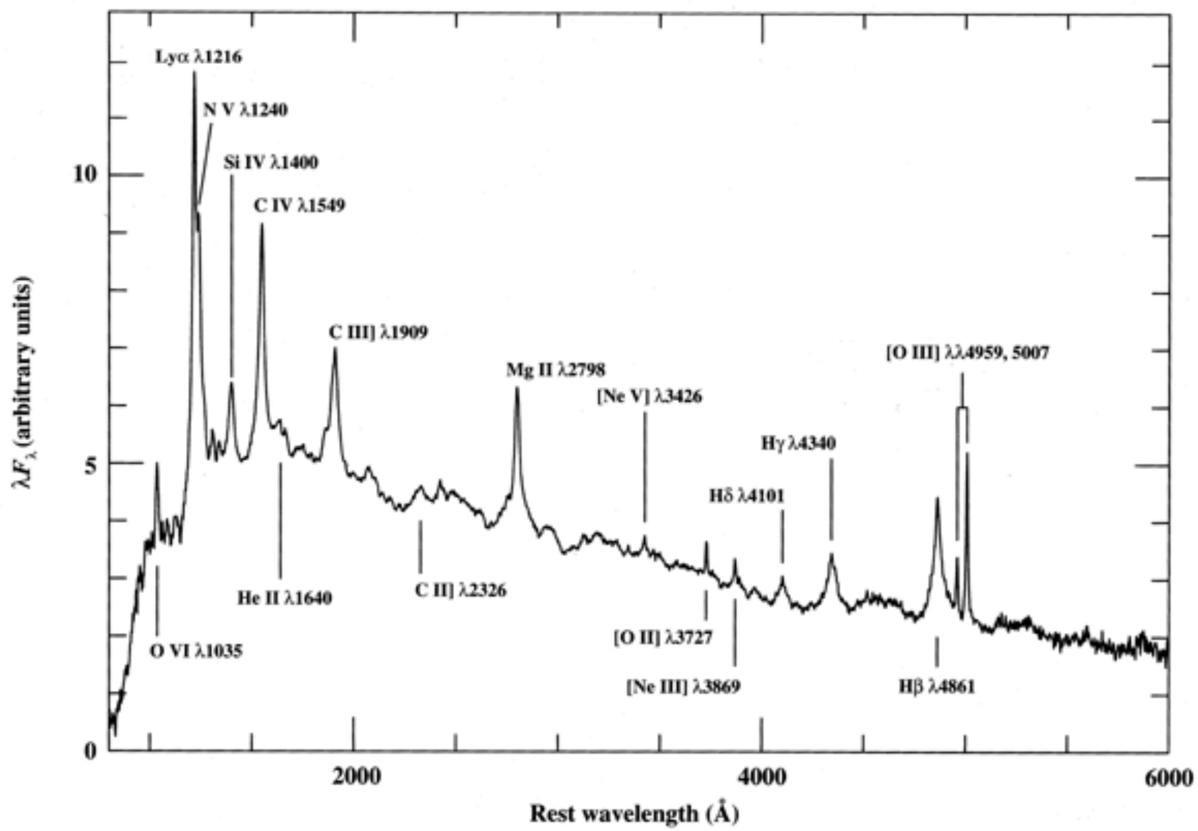


Figure 6.17 Spectrum of an elliptical galaxy; compare with the
in Figure 1.1, and those of disk galaxies in Figure 5.24 – A. Kir



Lyα λ1216
N V λ1240
Si IV λ1400
C IV λ1549
C III] λ1909
Mg II λ2798
[Ne V] λ3426
[O III] λλ4959, 5007
Hγ λ4340
Hδ λ4101
He II λ1640
C II] λ2326
[O II] λ3727
[Ne III] λ3869
Hβ λ4861
O VI λ1035
λF_λ (arbitrary units)
0
5
10
2000
4000
6000
Rest wavelength (Å)

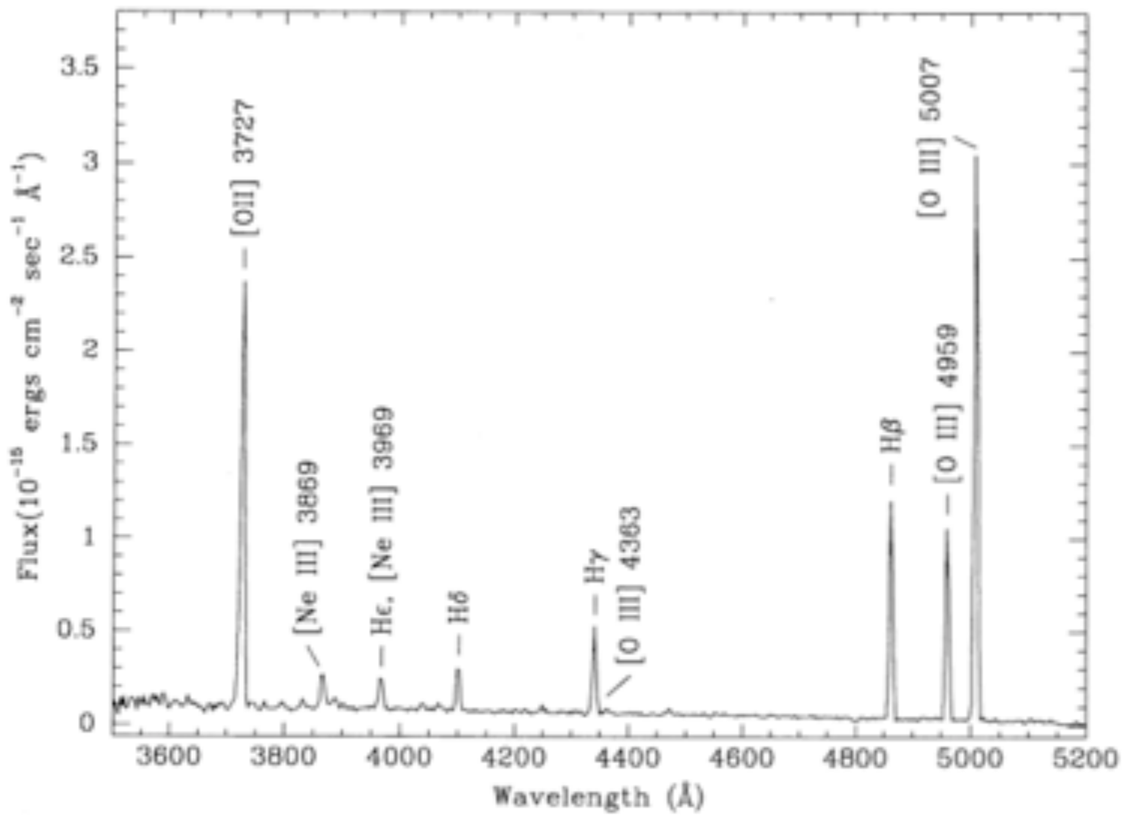
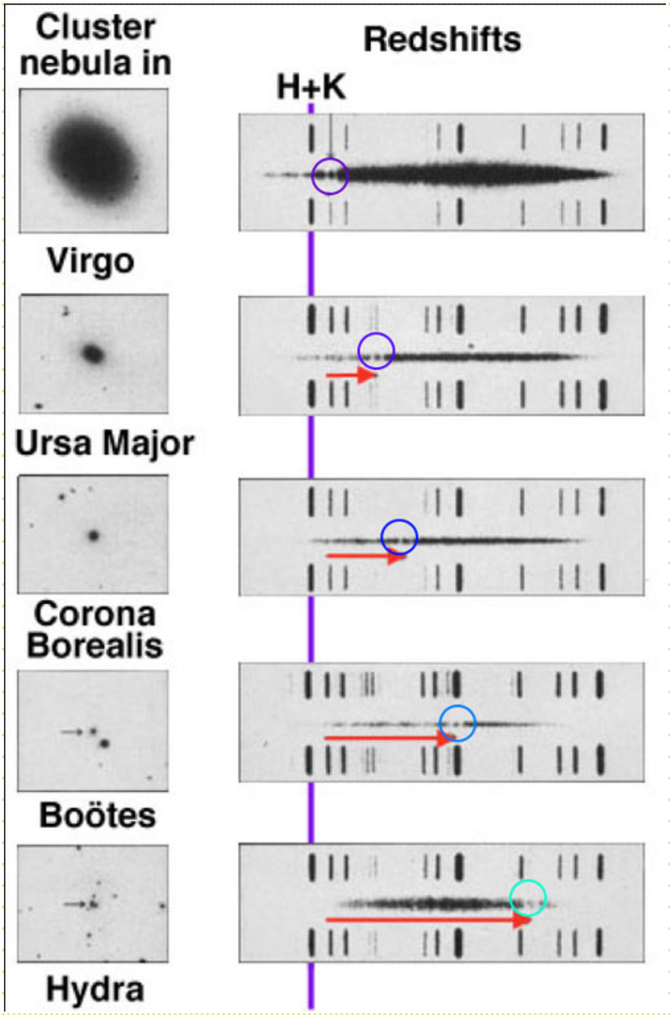
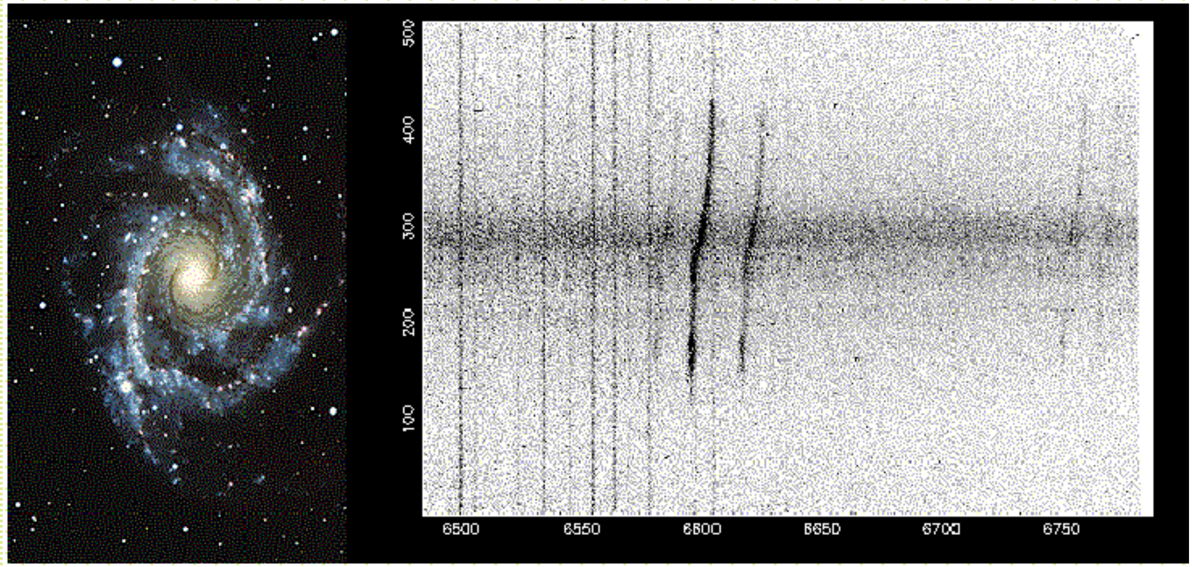
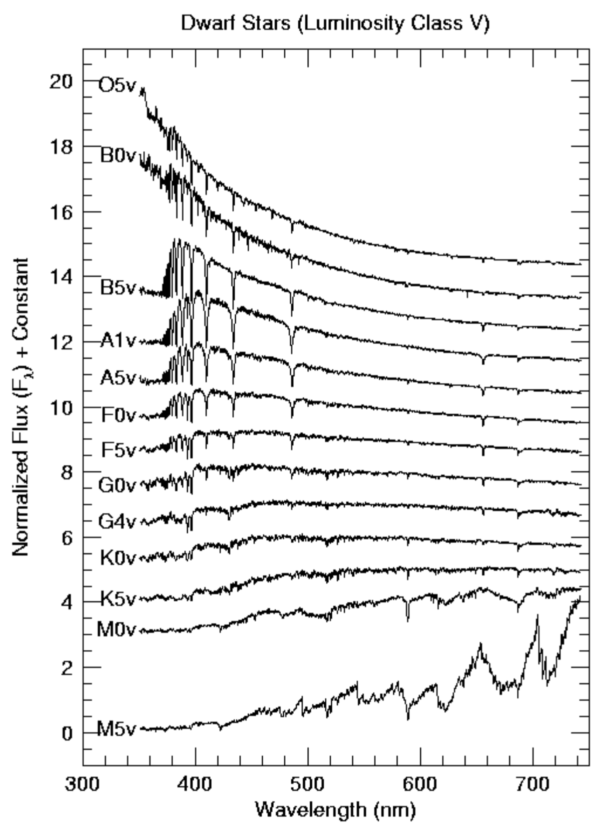


FIG. 1.—Spectrum of region No. 2 in NGC 2541 obtained in the long-slit mode. Emission lines targeted for measurement are labeled.


Cluster nebula in
Redshifts
H+K
Virgo
Ursa Major
Corona Borealis
Boötes
Hydra

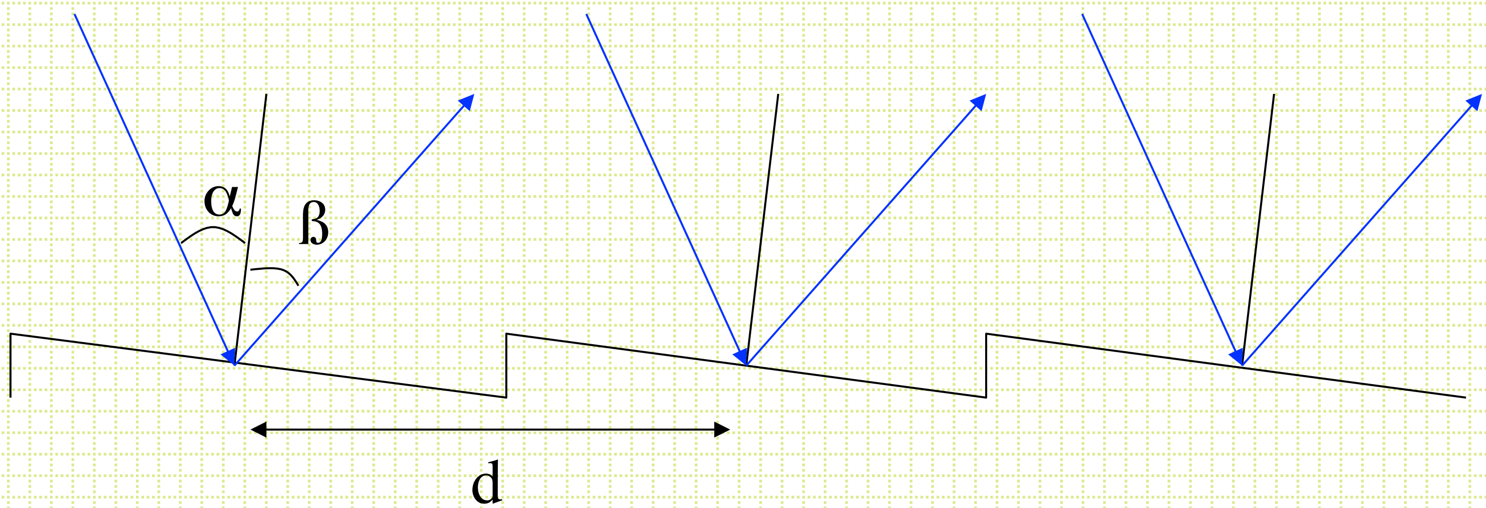

500
400
300
200
100
6500
6550
6600
6650
6700
6750


Dwarf Stars (Luminosity Class V)
Normalized Flux (F_λ) + Constant
Wavelength (nm)
O5v
B0v
B5v
A1v
A5v
F0v
F5v
G0v
G4v
K0v
K5v
M0v
M5v
0
2
4
6
8
10
12
14
16
18
20
300
400
500
600
700

Dispersing Elements

- Most common is probably the *reflecting diffraction grating*.
- Grating equation: $m\lambda = d[\sin(\alpha) + \sin(\beta)]$

order groove spacing



Grating dispersion

- Think of the Young Double-slit experiment with many slits very closely spaced together (100 - 10,000+ lines/mm) and for non-monochromatic light - same constructive/destructive interference phenomenon from path-length differences.
- Note: ruling gratings is not easy! Spacing tolerance is ~1nm. Richardson has a machine in a room kept a constant temperature to 0.01˚C

- Differentiate the grating equation wrt outgoing angle and get the *angular dispersion*

$$\frac{d\beta}{d\lambda} = \frac{m}{d\cos(\beta)}$$

- The *linear dispersion* is:

$$\frac{d\lambda}{dx} = \frac{d\lambda}{d\beta}\frac{d\beta}{dx} = \frac{d\cos(\beta)}{mF_{camera}}$$

in camera focal plane

Å/mm α d/m

order

lines/mm

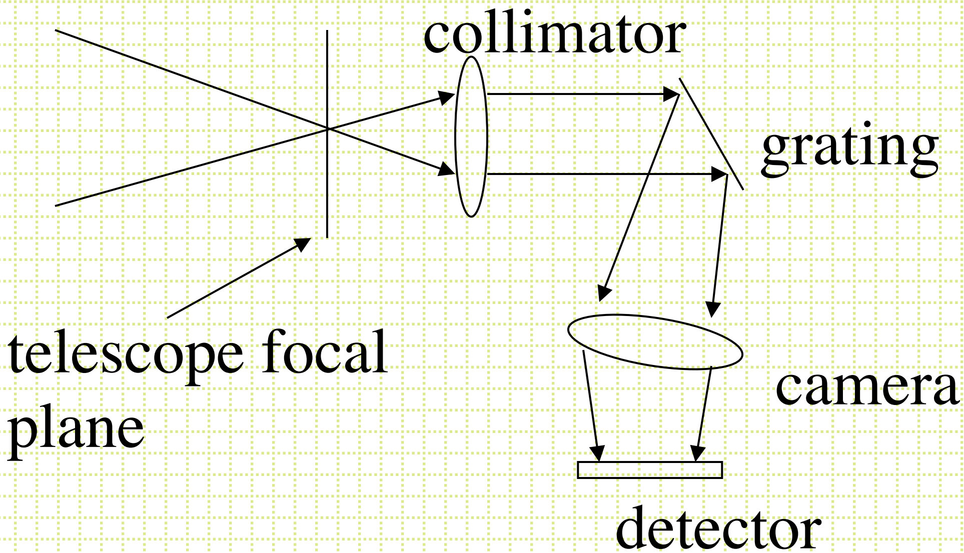
$$F_{camera} = \frac{dx}{d\beta} \equiv \text{camera focal length}$$

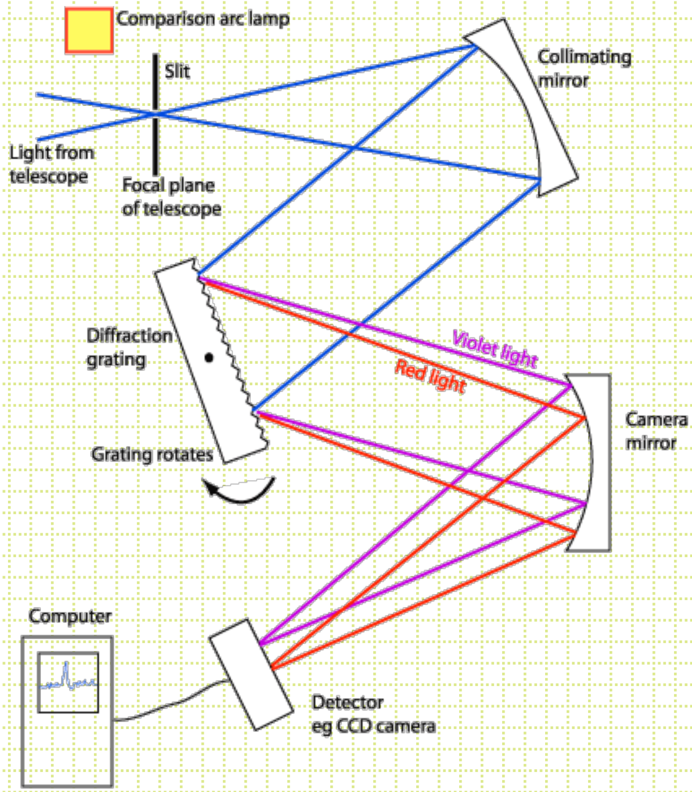
Transmission gratings

- There are also different versions of transmission gratings.
  - Transmission grating
  - *Grisms* - add a prism for *zero-deviation* transmission dispersion
  - *Volume Phase Holographic Gratings*: VPH - use modulations of the index of refraction rather than surface structures to produce dispersion. High efficiency.

Spectrometers

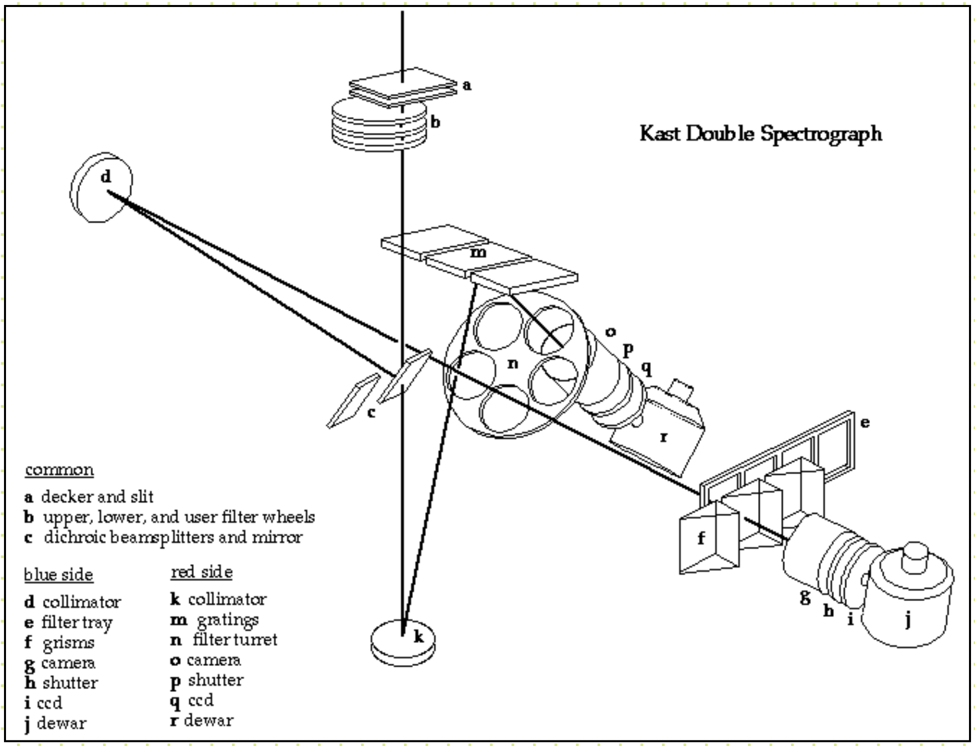
- Gratings require collimated (parallel beam) light so the basic long-slit spectrometer:





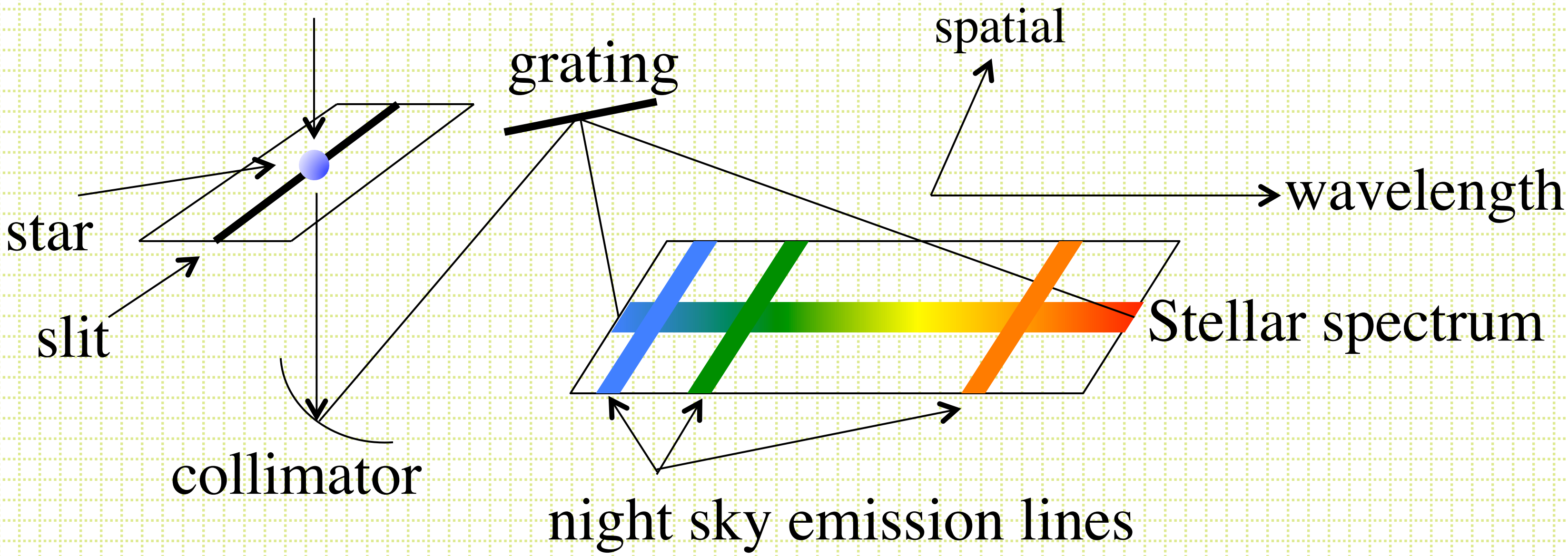
A Schematic Diagram of a Slit Spectrograph

Double Spectrometers

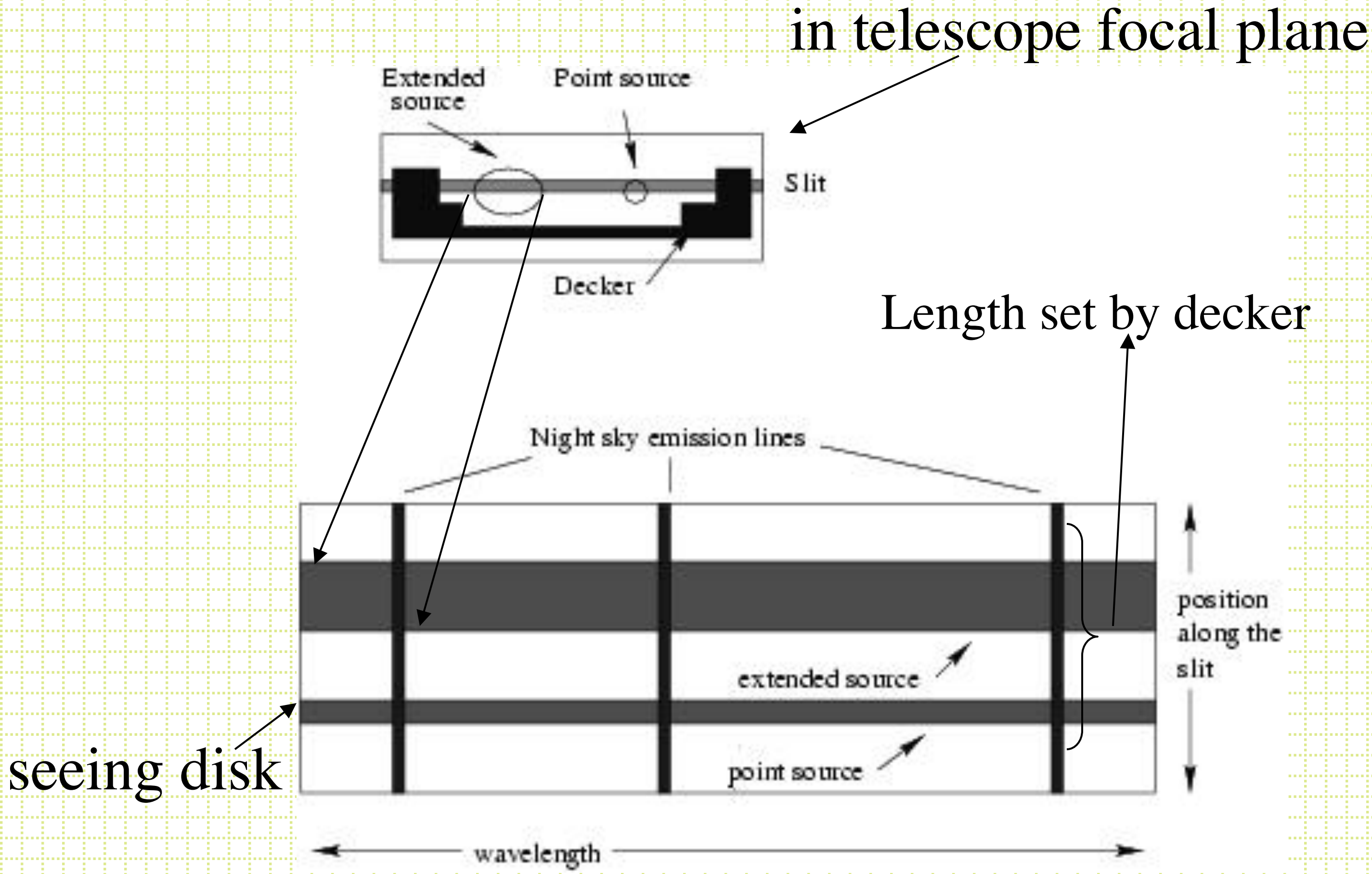


- Two-arm spectrometers developed to optimize throughput
- Glasses, coatings matched for:
  - 320nm – 550nm
  - 550nm – 1000nm
- Beam split with dichroic

Long-slit Spectra Geometry



In the *camera* focal plane there is the *dispersion direction* perpendicular to the slit and the *spatial direction* along the slit. Slit *width* affects spectral resolution



in telescope focal plane
Extended source
Point source
Slit
Decker
Length set by decker
Night sky emission lines
position along the slit
extended source
point source
seeing disk
wavelength

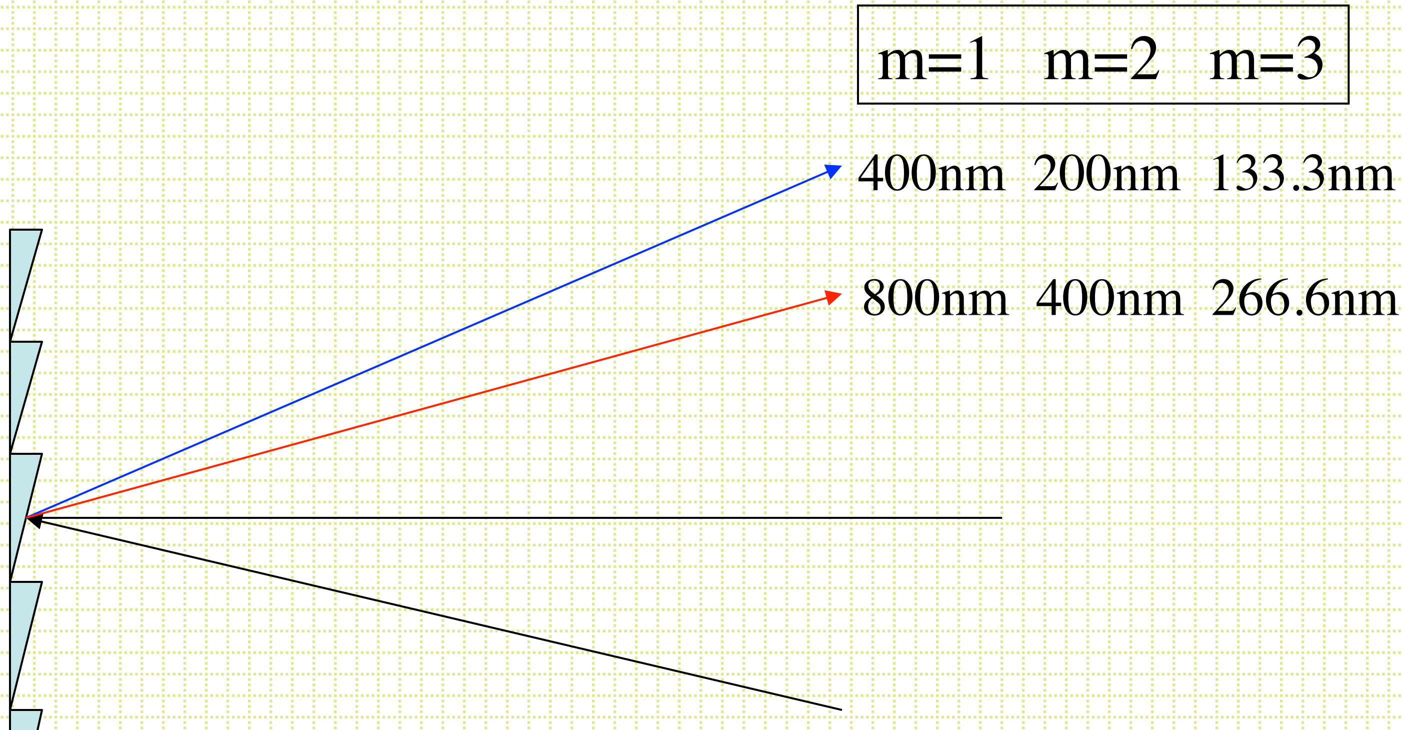
Spectral Resolution

- $R=\lambda/\Delta\lambda$
- For slit spectral, depends on slit width and grating choice.
- Examples:
  - V filter: 5500Å/1000Å=5.5
  - LRIS-R: 1″ ~4 pixels FWHM
    - 150 l/mm grating: R~6500/20 ~325
    - 600 l/mm grating: R~6500/5 ~1300
    - 1200 l/mm grating: R~6500/2.6 ~2600

LRIS (Keck Obs WWW page)

Grating Name	Grooves (l/mm)	Blaze Wave (Å)	Dispersion (Å/pix)	Spectral coverage (Å/2048 pix)
150/7500	150	7500	4.8	9830
300/5000	300	5000	2.55	5220
400/8500	400	8500	1.86	3810
600/5000	600	5000	1.28	2620
600/7500	600	7500	1.28	2620
600/10000	600	10000	1.28	2620
831/8200	831	8200	0.93	1900
900/5500	900	5500	0.85	1740
1200/7500	1200	7500	0.64	1310

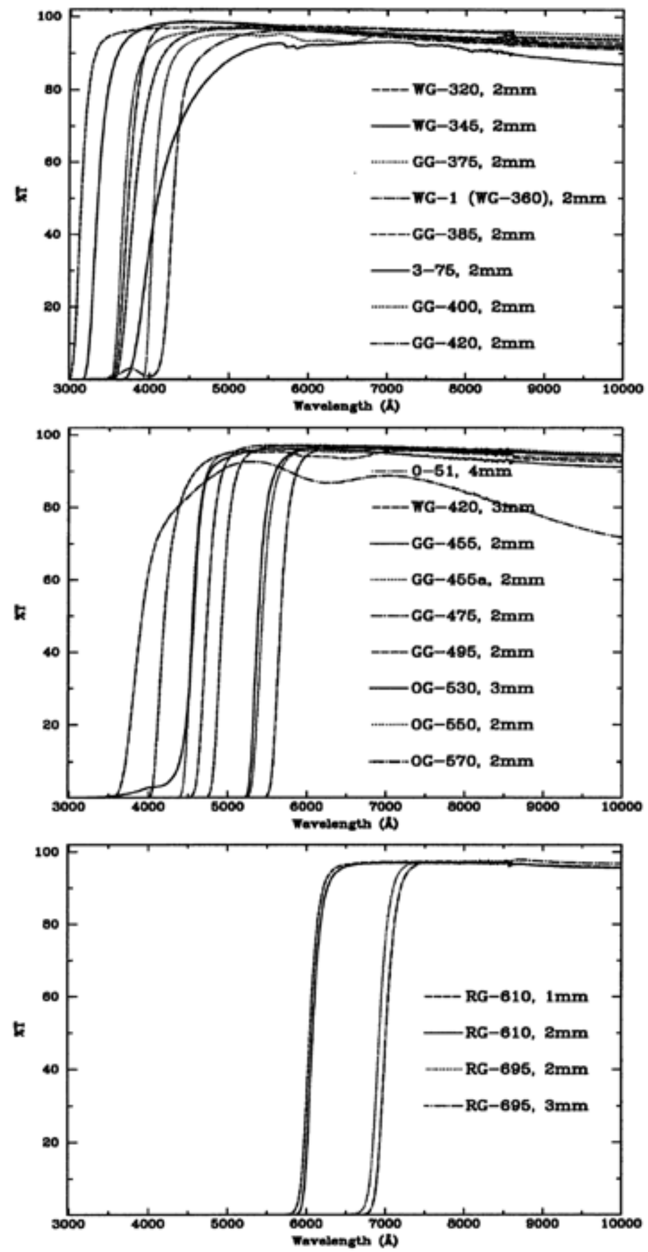
Orders and blocking filters



For order n, at λ_n there is also order m light with wavelength $\lambda_m=(n/m)\lambda_n$

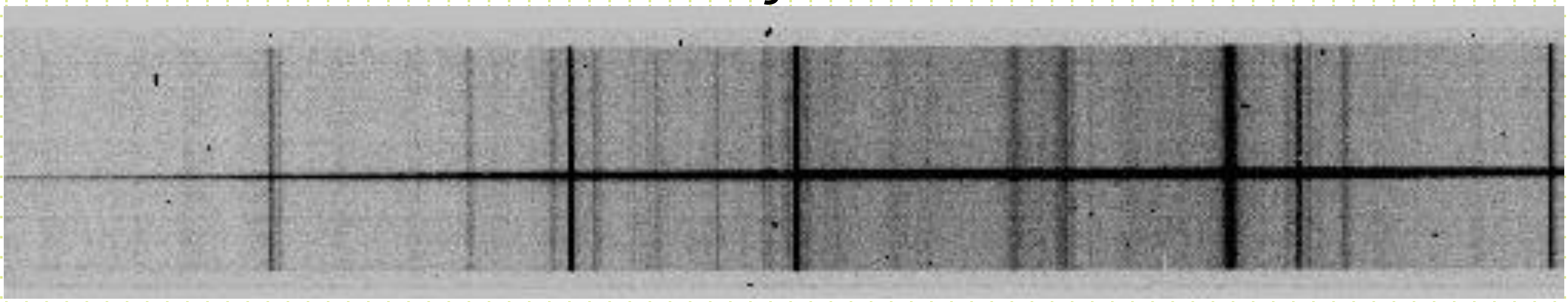
- For higher orders with $\lambda<310$nm it's not an issue as the atmosphere cuts out all the light (can still be an issue for calibration sources).
- But, if you are working in the red (>640nm) in 1st order, you need to block the 2nd order light.
- If you are working in a higher order, may need to block red light from lower orders.

KPNO 2.1m Goldcam blue blocking filters



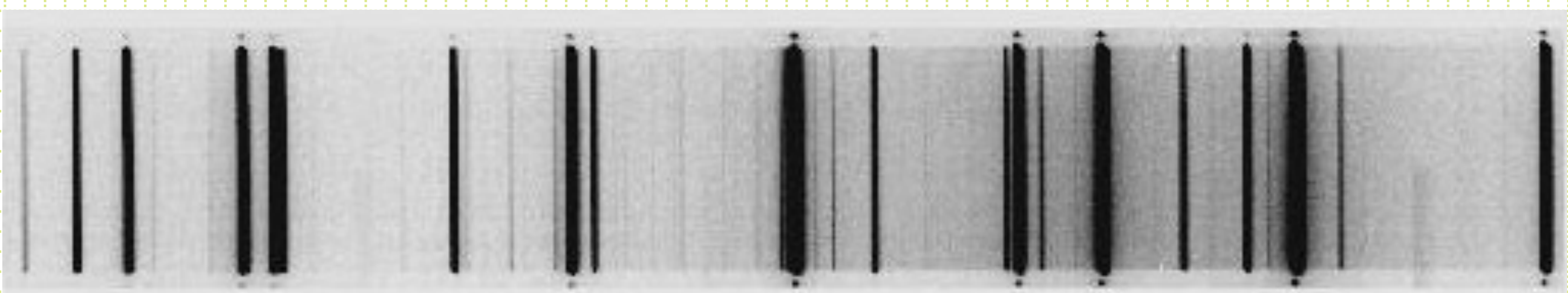
- Grating tilt for wavelength
- Grating efficiency
- Dichroics and double spectrometers

Star+sky



Quartz lamp flat

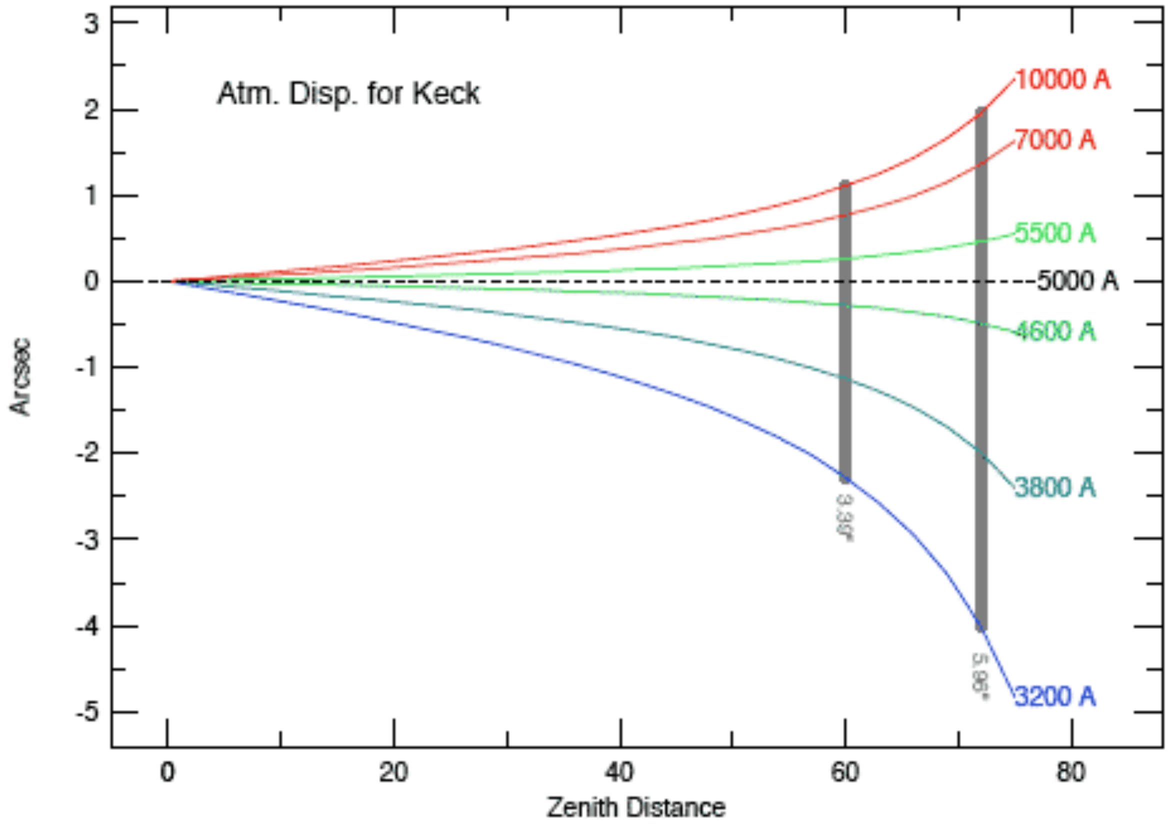
HgCdNe line lamps



Note about Observing

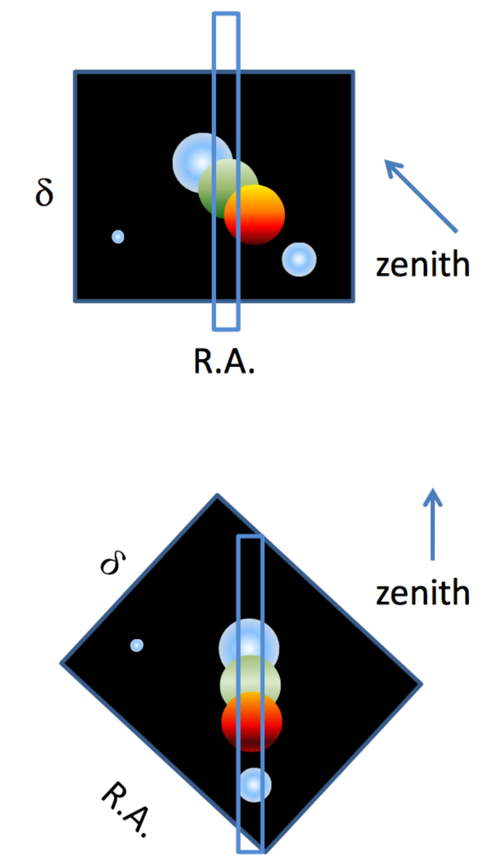
- If spectrometer is not flexure compensated, the usual procedure is to obtain a line lamp spectrum (or two) and flat-field spectrum (or two) at the position of your program object. Sometimes even bracket the program exposures with arcs and flats.
- Depending on program, observe:
  - Flux standard
  - Radial velocity standard
  - Hot rapid rotator to identify terrestrial atmospheric absorption
- If no ADC, pay attention to position angle!

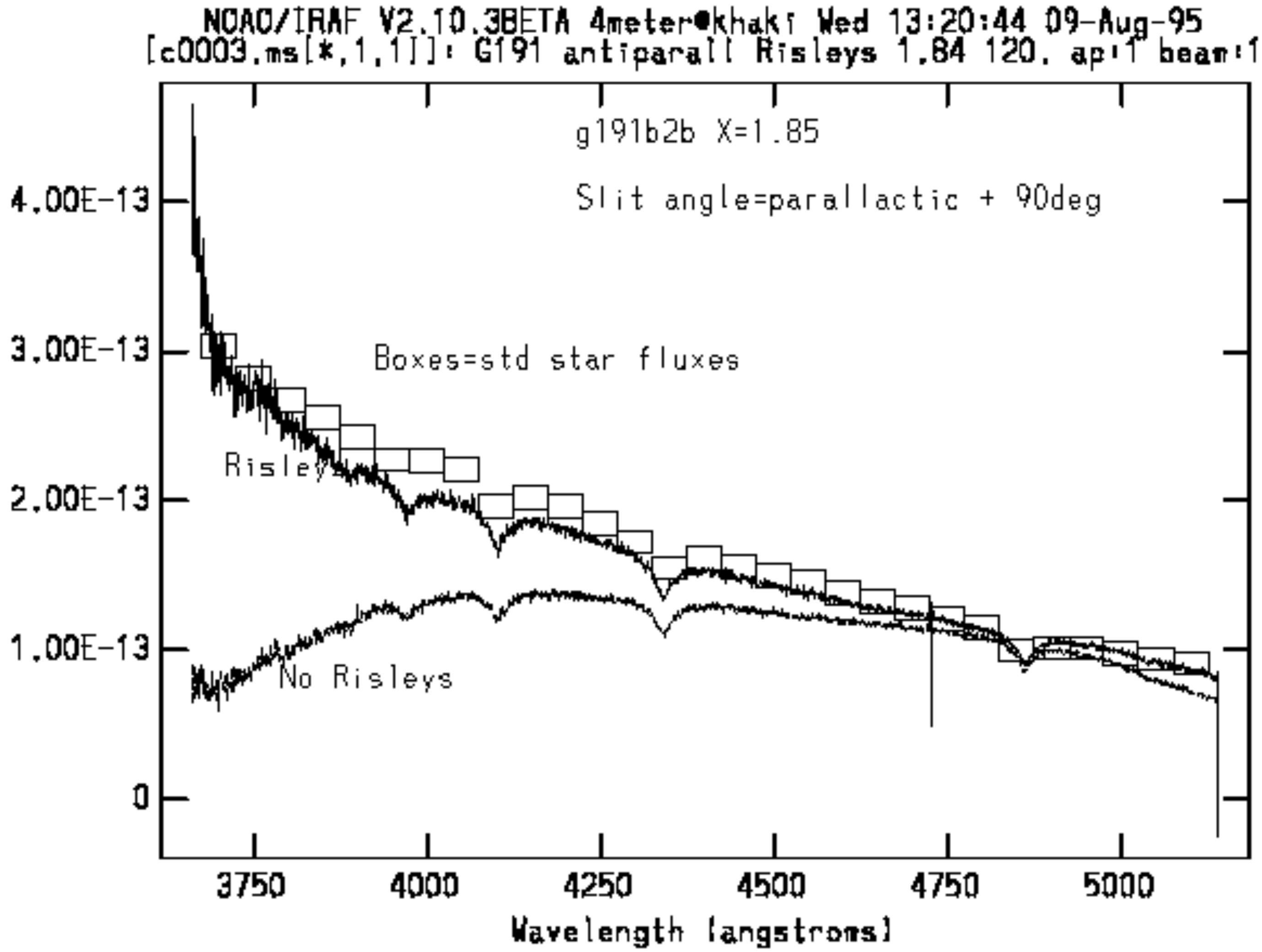
Atmospheric Dispersion



Parallactic Angle

- The "parallactic" angle is perpendicular to the horizon and allows you to capture all the light in an atmospheric-dispersed object (but increasingly displaced along the slit with increasing airmass)




NOAO/IRAF V2.10.3BETA 4meter@khaki Wed 13:20:44 09-Aug-95
[c0003.ms[*,1,1]]: G191 antiparall Risleys 1.84 120. ap:1 beam:1
g191b2b X=1.85
Slit angle=parallactic + 90deg
Boxes=std star fluxes
Risleys
No Risleys
4.00E-13
3.00E-13
2.00E-13
1.00E-13
0
3750
4000
4250
4500
4750
5000
Wavelength (angstroms)

Spectral Reduction Procedures

- There are good introductions/cookbooks available from the IRAF folks. The introduction to spectral reductions is at the class WWW site.
- There are many ways to accomplish most tasks. Will run through a basic approach to reducing long slit spectra.

- Steps:
  - Bias and overscan correction
  - Flat-fielding
    - Note: need to remove large-scale variations in the spectral dimension
  - Identify location of the spectrum
  - Identify location of sky samples
  - Extract spectrum
    - Trace
    - Collapse lines
    - Interpolate sky and subtract
  - Use stellar aperture to extract arc spectrum
    - Note: sometimes do the flat-fielding here
  - Fit pixel-wavelength map and apply to spectrum
  - Derive flux calibration and apply to spectrum

- Packages in noao.twodspec.apextract
  – Need to set the dispersion axis

Dispersion axis

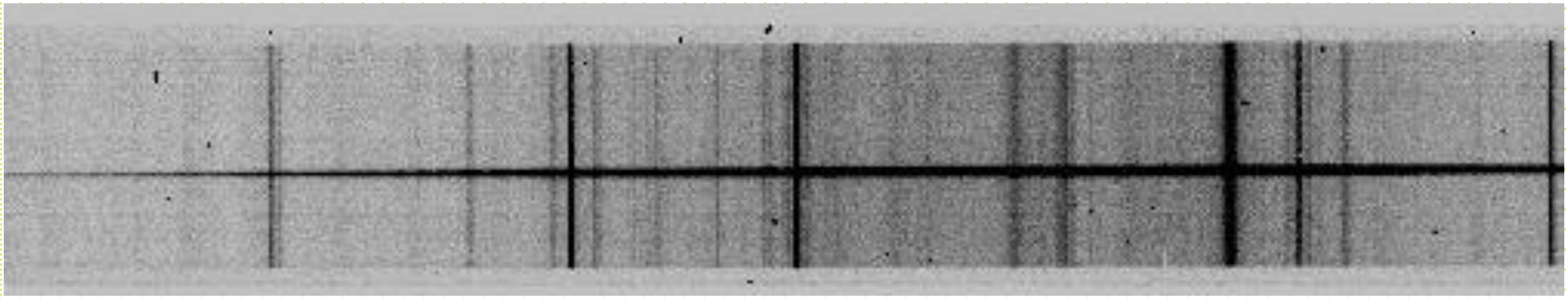
```
tw>epar apextract

    PACKAGE = twodspec
    TASK = apextract

(dispaxi=                1) Dispersion axis (1=along lines, 2=along columns)
(databas=         database) Database
(verbose=               no) Verbose output?
(logfile=                 ) Text log file
(plotfil=                 ) Plot file
(version= APEXTRACT V3.0: August 1990)
(mode   =               ql)
($nargs =                0)
```

- noao.twod.apextract

tw> apex

apall	apedit	apflatten	apnormalize	apscatter
apdefault@	apfind	apmask	aprecenter	apsum
apdemos.	apfit	apnoise	apresize	aptrace

apall combines parameter files for all the rest of the tasks



Dispersion axis along lines (`1’ to IRAF)

PACKAGE = apextract
TASK = apall

```
input   =                     List of input images
(output =                   ) List of output spectra
(apertur=                   ) Apertures
(format =       multispec) Extracted spectra format
(referen=                   ) List of aperture reference images
(profile=                   ) List of aperture profile images

(interac=                yes) Run task interactively?
(find   =                yes) Find apertures?
(recente=                yes) Recenter apertures?
(resize =                yes) Resize apertures?
(edit   =                yes) Edit apertures?
(trace  =                yes) Trace apertures?
(fittrac=                yes) Fit the traced points interactively?
(extract=                yes) Extract spectra?
(extras =                yes) Extract sky, sigma, etc.?
(review =                yes) Review extractions?
```

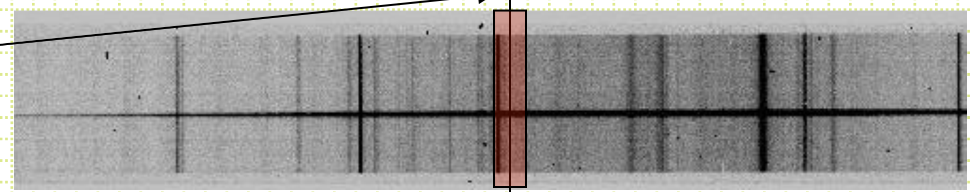
Multispec: star, sky, S/N

Useful for arcs/faint spectra/ discontinuous spectra

Usually "no"

keep spectrum, sky and S/N in 3-d output fits file

Default is center



(line = INDEF) Dispersion line

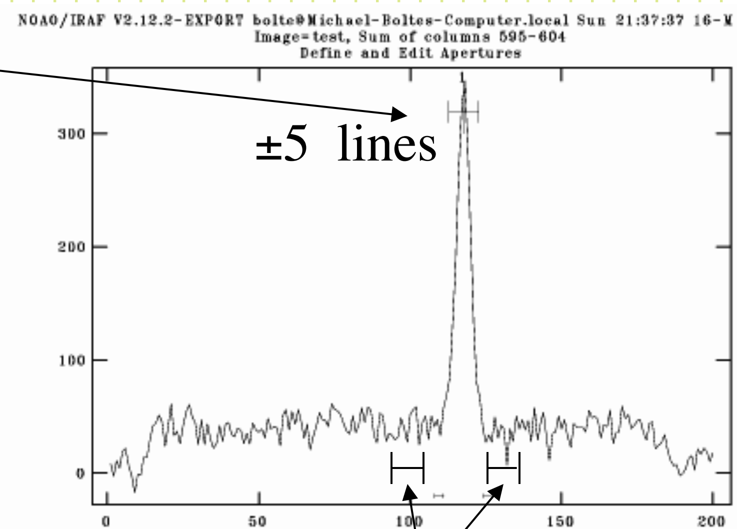
(nsum = 10) Number of dispersion lines to sum or median

DEFAULT APERTURE PARAMETERS

(lower = -5.) Lower aperture limit relative to center

(upper = 5.) Upper aperture limit relative to center

(apidtab=) Aperture ID table (optional)



DEFAULT BACKGROUND PARAMETERS

(b_funct= chebyshev) Background function

(b_order= 1) Background function order

(b_sampl= -10:-6,6:10) Background sample regions

(b_naver= -3) Background average or median

(b_niter= 0) Background rejection iterations

(b_low_r= 3.) Background lower rejection sigma

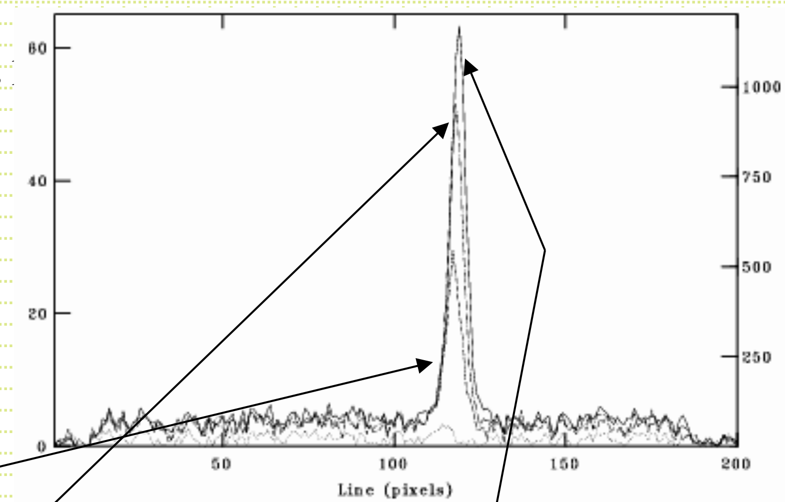
(b_high_= 3.) Background upper rejection sigma

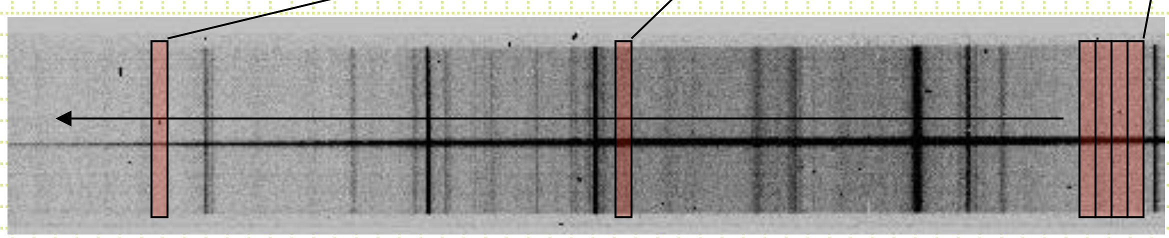
(b_grow = 0.) Background rejection growing radius

APERTURE CENTERING PARAMETERS
AUTOMATIC FINDING AND ORDERING PARAMETERS
RECENTERING PARAMETERS
RESIZING PARAMETERS
TRACING PARAMETERS

Skipping the details of these for now

(t_nsum = 10) Number of dispersion lines to sum
(t_step = 10) Tracing step
(t_nlost= 3) Number of consecutive times profile is
(t_funct= legendre) Trace fitting function
(t_order= 2) Trace fitting function order
(t_sampl= *) Trace sample regions
(t_naver= 1) Trace average or median
(t_niter= 0) Trace rejection iterations
(t_low_r= 3.) Trace lower rejection sigma
(t_high_= 3.) Trace upper rejection sigma
(t_grow = 0.) Trace rejection growing radius





Trace finds the `y' position of the peak as a function of x position

```
(backgro=                fit) Background to subtract      (none,average,median,min,fit)
(skybox =                  1) Box car smoothing length for sky
(weights=               none) Extraction weights (none|variance)
(pfit   =              fit1d) Profile fitting type (fit1d|fit2d)
(clean  =                yes) Detect and replace bad pixels?
(saturat=            31000.) Saturation level
(readnoi=                 0.) Read out noise sigma (photons)
(gain   =                 1.) Photon gain (photons/data number)
(lsigma =                 4.) Lower rejection threshold
(usigma =                 4.) Upper rejection threshold
(nsubaps=                  1) Number of subapertures per aperture
```

Example Extraction

cl>apall b188 output=b188.ms

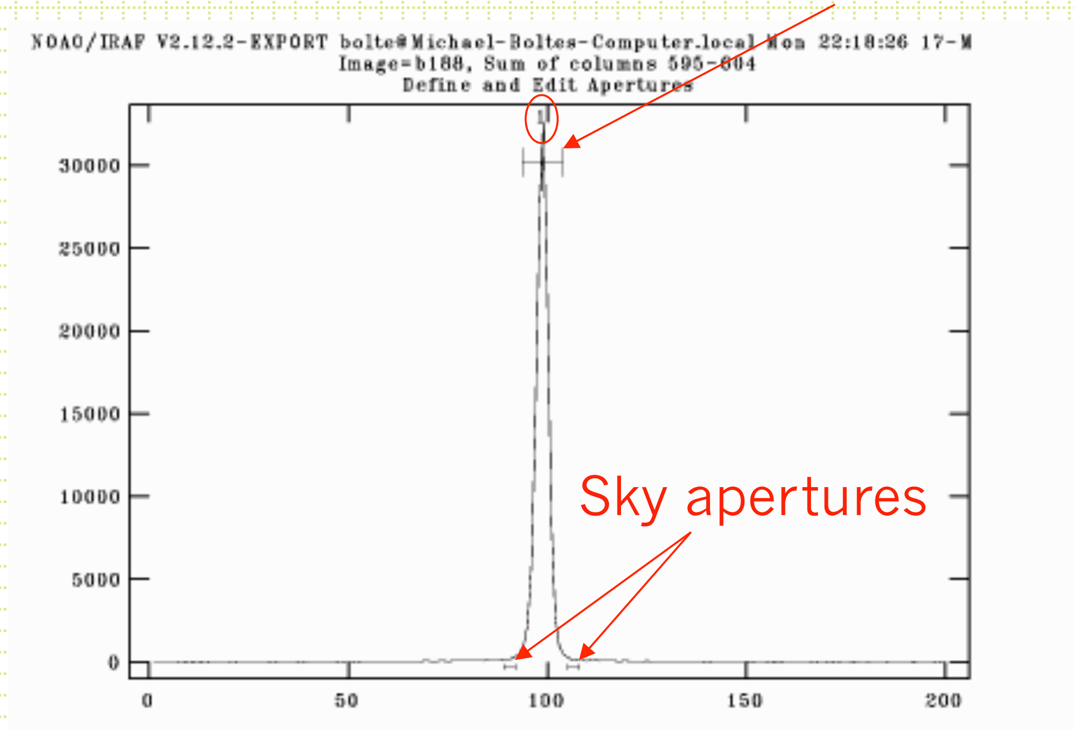
Find apertures for b188? (yes):

Number of apertures to be found automatically (1):

Edit apertures for b188? (yes):

Commonly used options:

- ? -- help
- l -- set lower ap limit
- u -- set upper ap limit
- b -- to tweak sky aperture
- w -- window the plot
  - ? -- window help
  - e -- expand plot
- q -- happy, continue



`b' option:

Commonly-used commands:

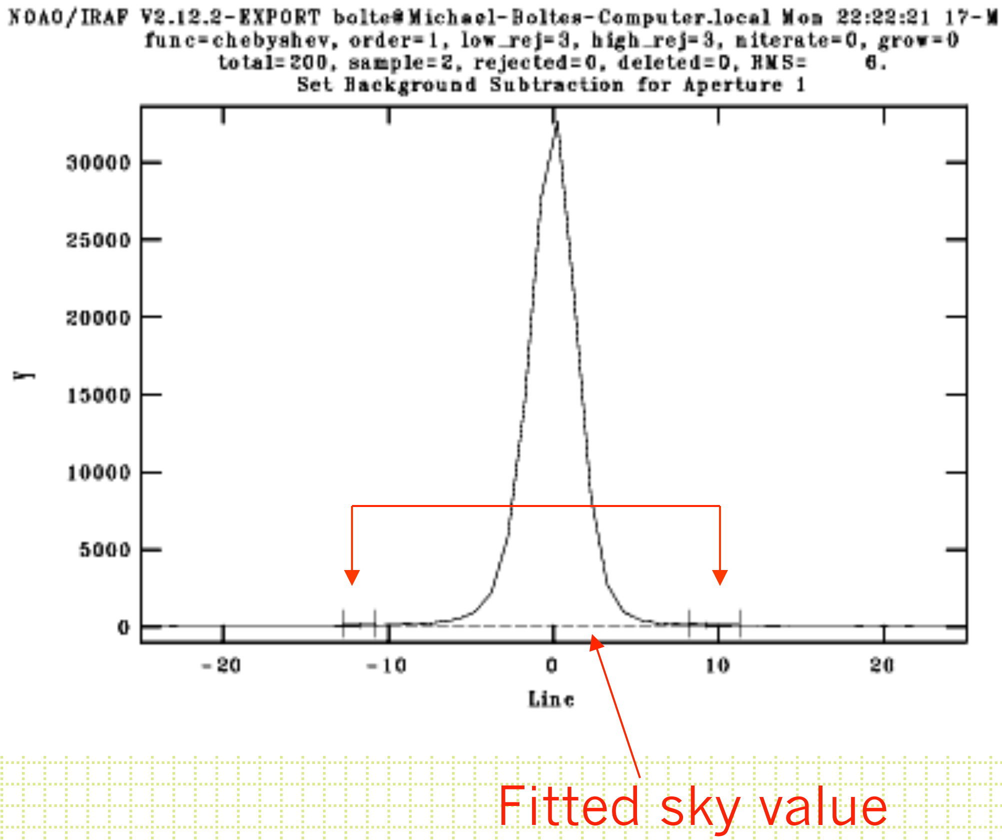
z -- deletes nearest aperture

s -- define new aperture

f -- redo fit

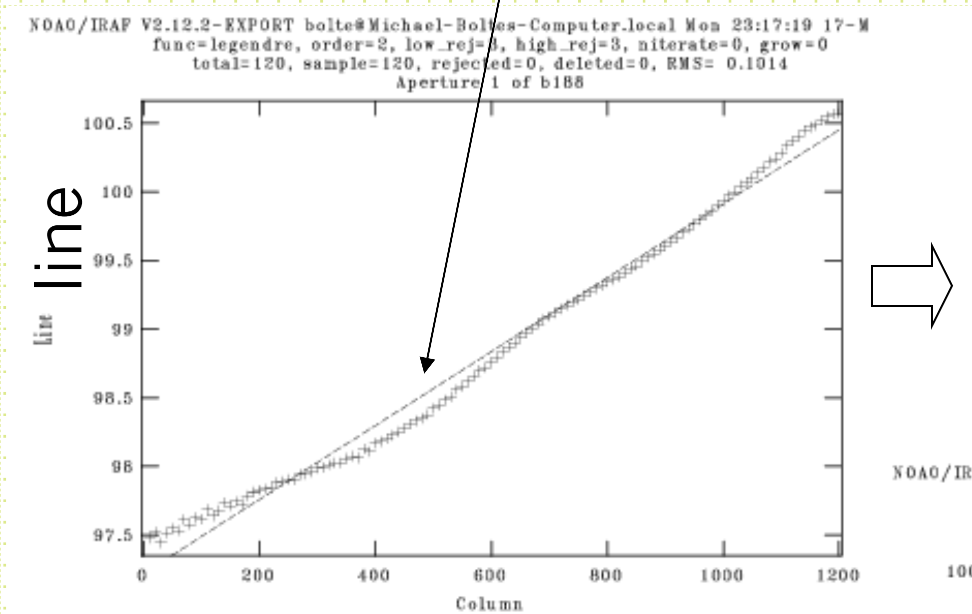
:order n -- set order of fit

q -- accept fit and go to previous panel



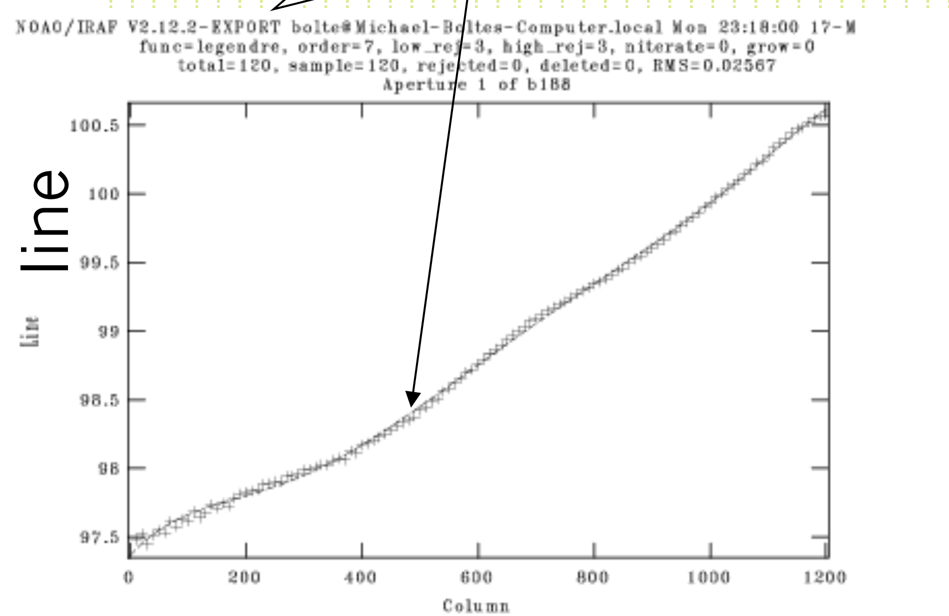
Trace:

order 2 fit



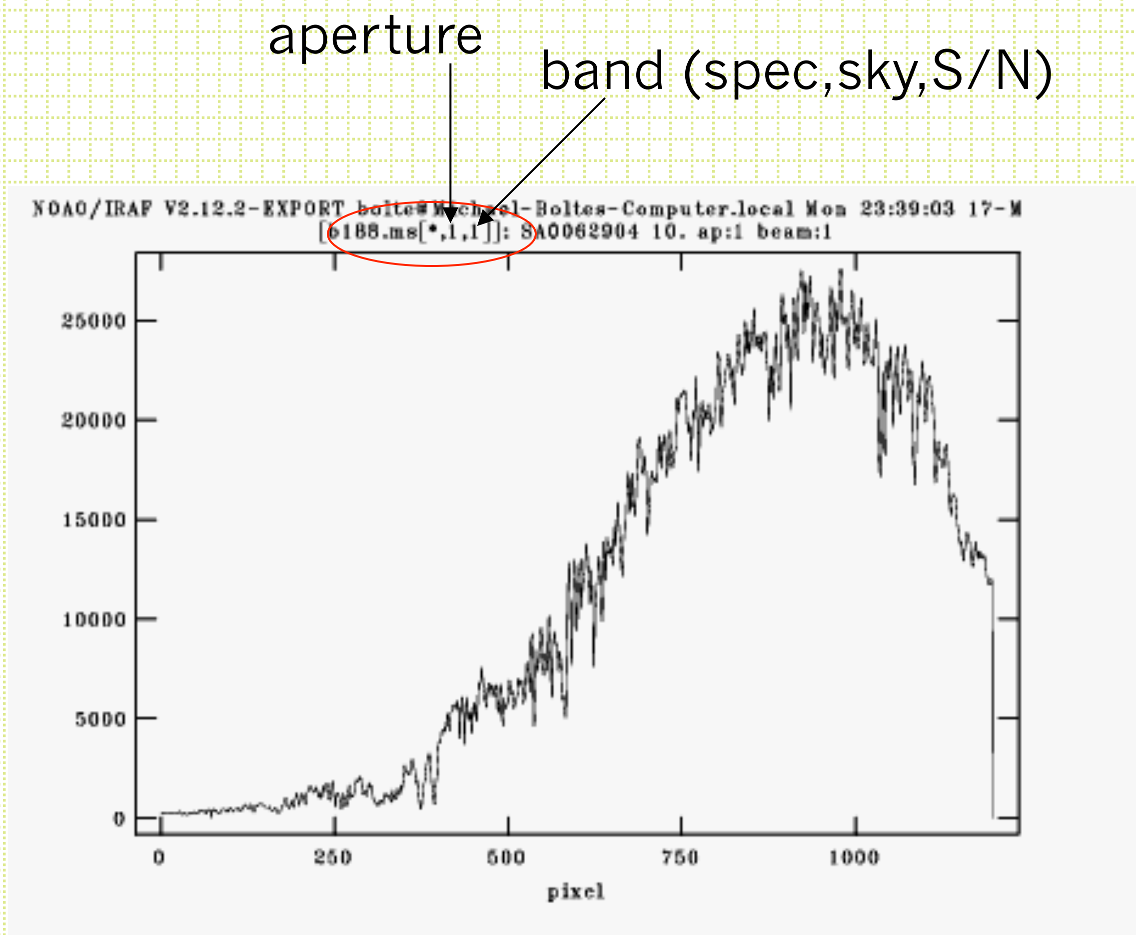
:o 7
f

order 7 fit



Splot:

cl>splot b188.ms

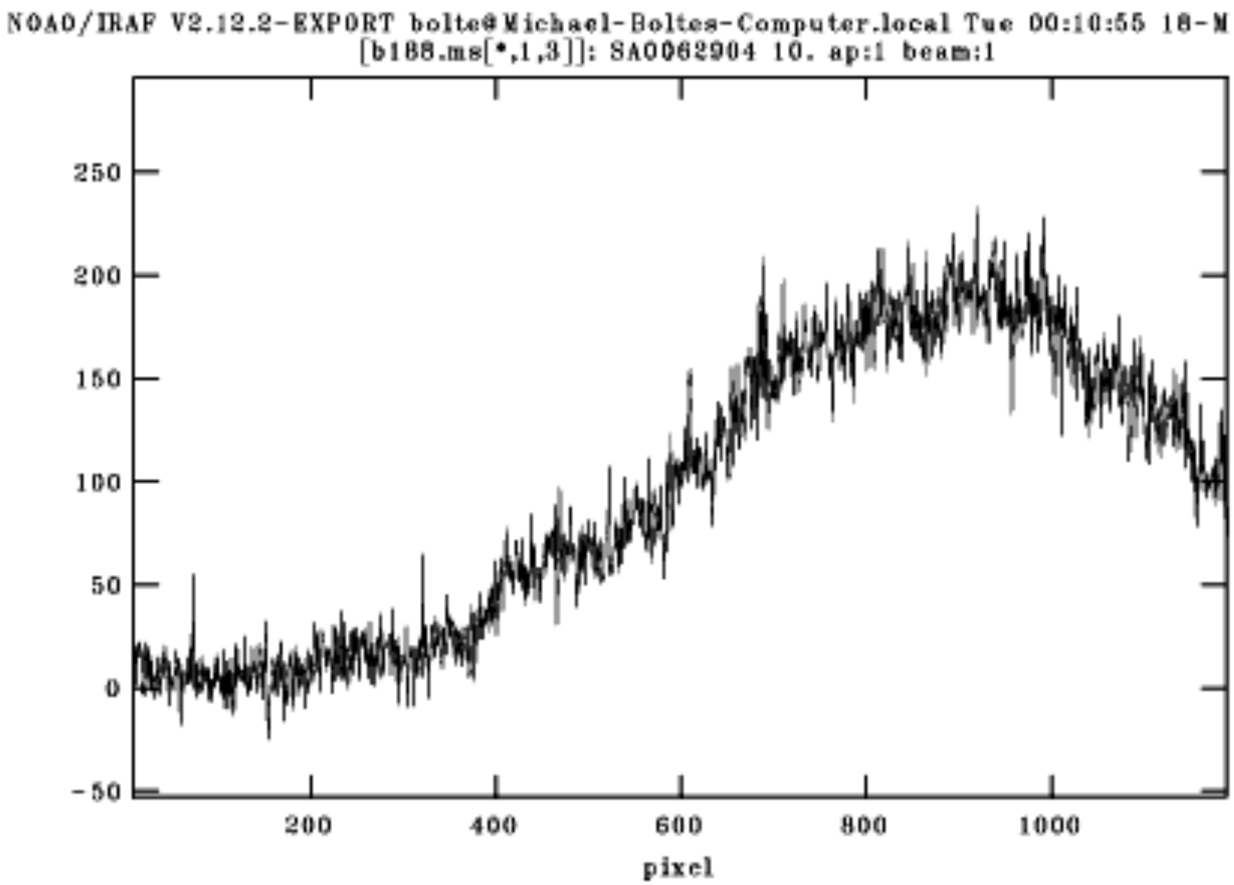


Extracted spectrum in pixel space

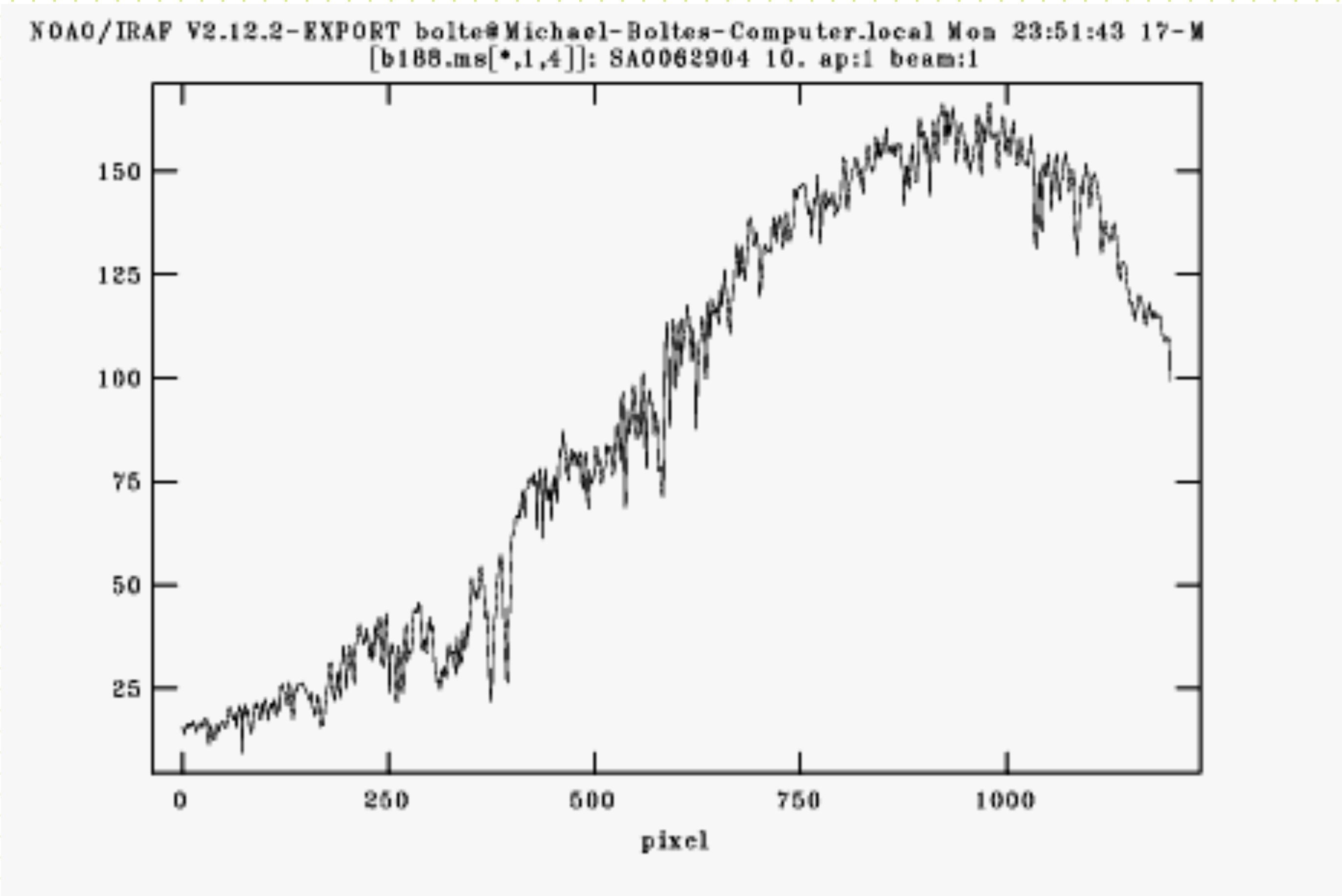
Common splot options:

- ? -- lists all the options
- %-- select new band
- m-- gives statistics
- e-- eq. width, line centers
- s-- smooth
- t-- fit continuum
- w--window plot

Sky

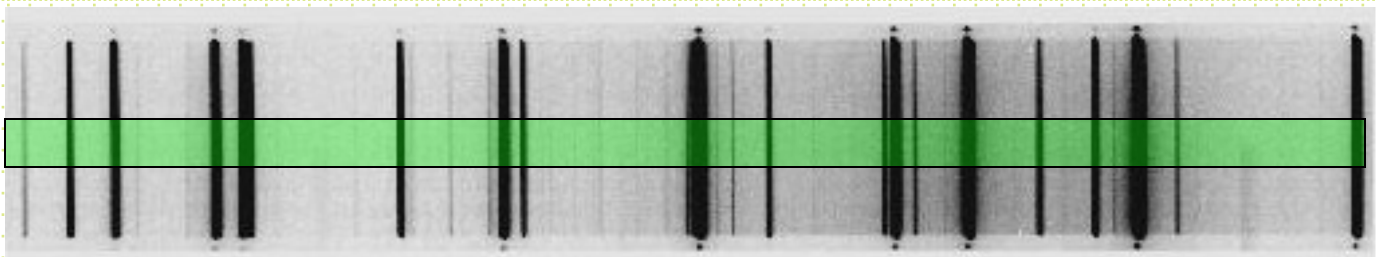

NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 00:10:55 18-M
[b188.ms[*,1,3]]: SA0062904 10. ap:1 beam:1
250
200
150
100
50
0
-50
200
400
600
800
1000
pixel

Band #4: S/N

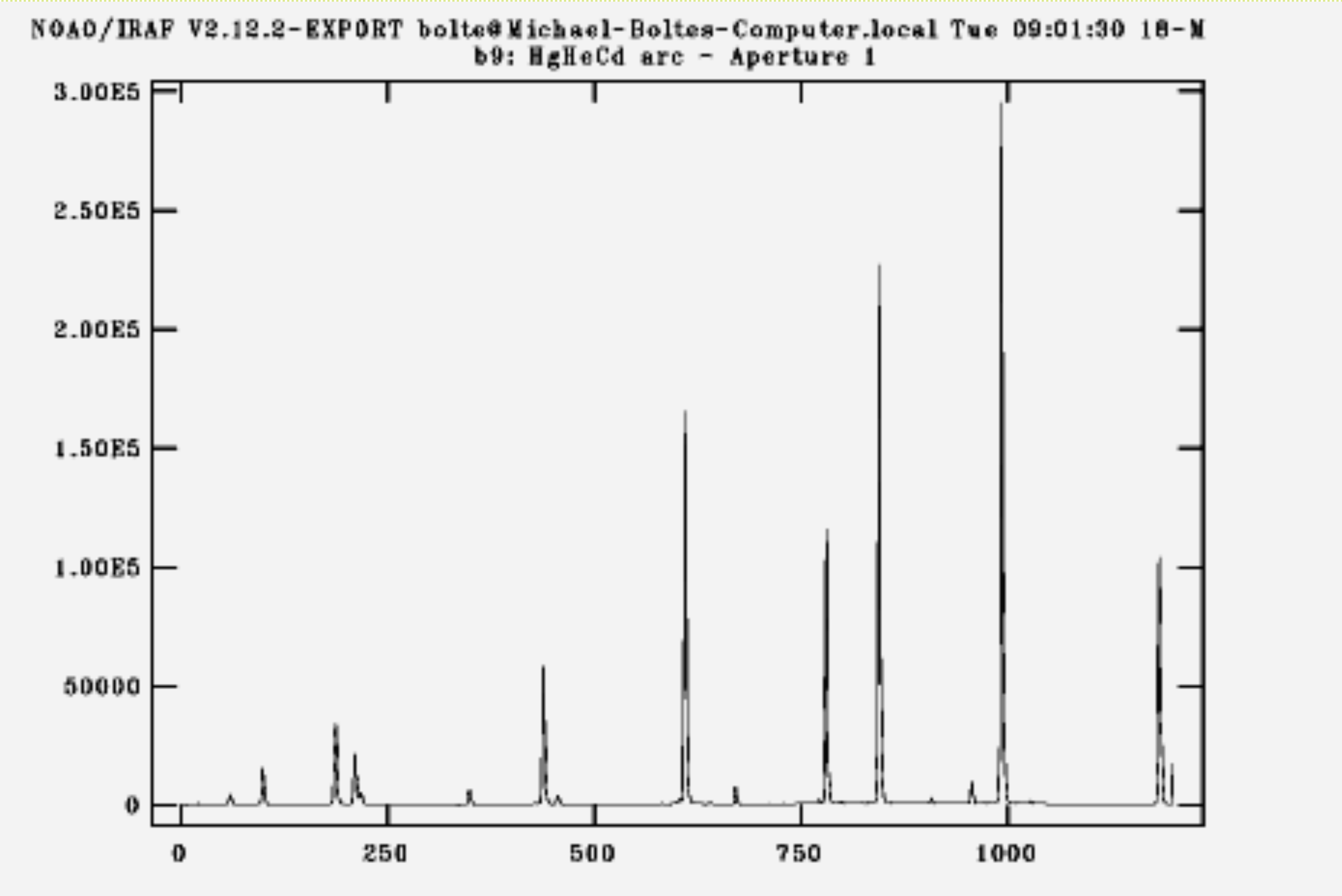

NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Mon 23:51:43 17-M
[b188.ms[*,1,4]]: SA0062904 10. ap:1 beam:1
150
125
100
75
50
25
0
250
500
750
1000
pixel

Line Lamps

- Use a pre-defined aperture, trace for extracting arcs. Lines are often tilted or curved.



cl>apall arc output=arc.ms ref=b188 find- trace- background=none

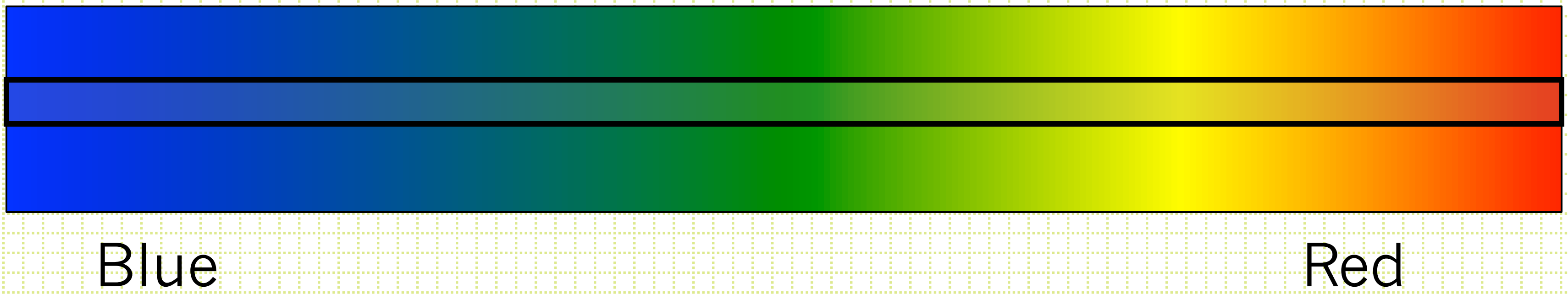


Sometimes fit a master arc taken in the afternoon and use arcs taken adjacent to program objects to make a zeropoint shift to the wavelength solution.

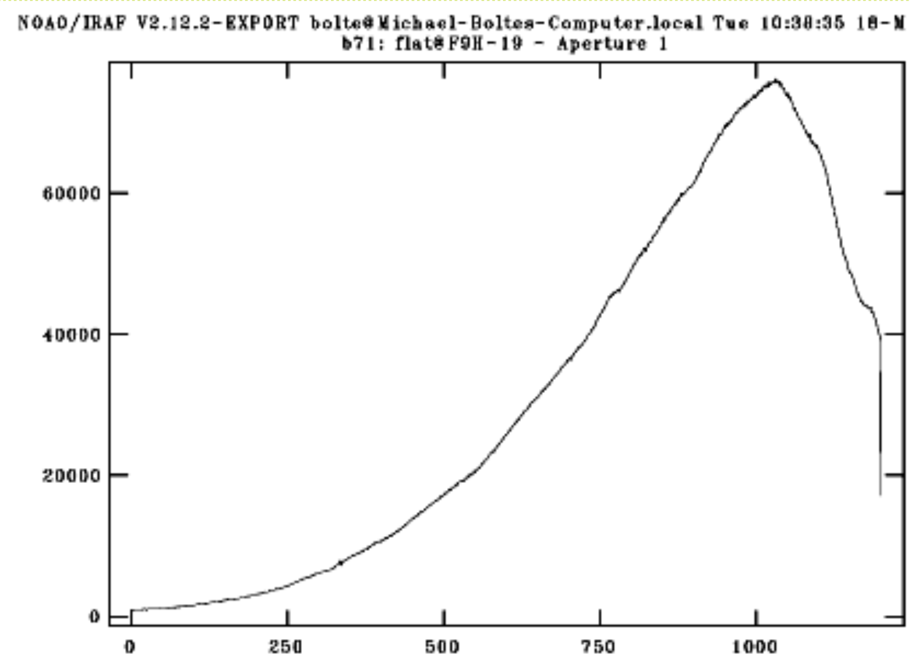
Flat-fields

- Can flat-field original frames in 2-D format, but more commonly, the flat-field image is extracted with the same aperture as the program object.
- In the spirit of flat-fielding for direct images, you would like a source that is uniform in the spatial direction AND has a flat spectrum. In practice, all flat-field lamps (usually a hot quartz lamp) have a strong spectral (continuum) signature.
- So, usually extract flat, then fit a function in the spectral direction and divide this out to leave the pixel-to-pixel response.

Quartz lamp



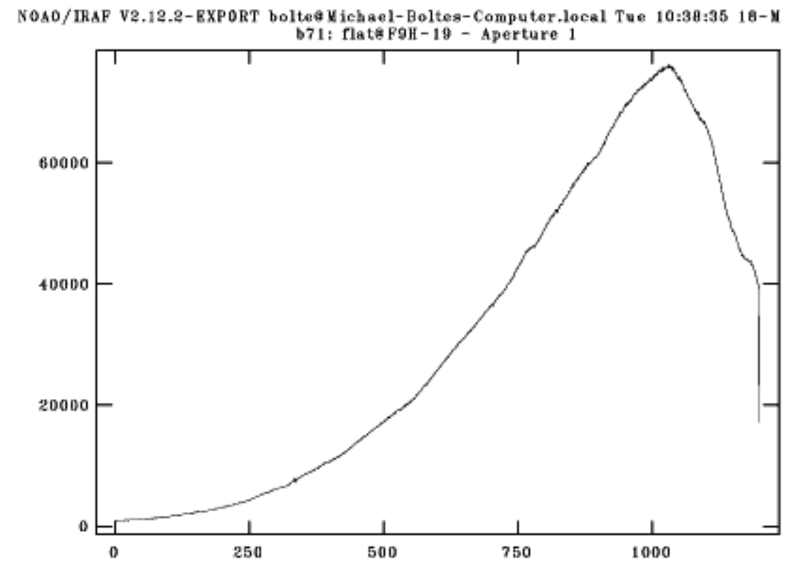
Blue
Red

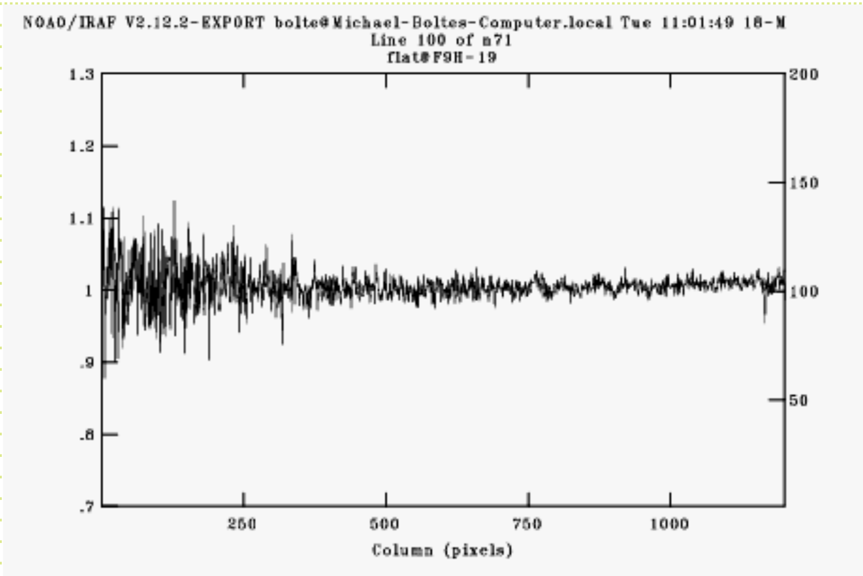


NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 10:38:35 18-M
b71: flat@F9H-19 - Aperture 1
60000
40000
20000
0
0
250
500
750
1000

Can do any of the following:

(1) Divide by extracted flat and normalized later
(2) Fit extracted flat and normalize, then divide
(3) Use twod.longslit.response and approximate the aperture (returns normalized, extracted flat response from 2-D spectrum

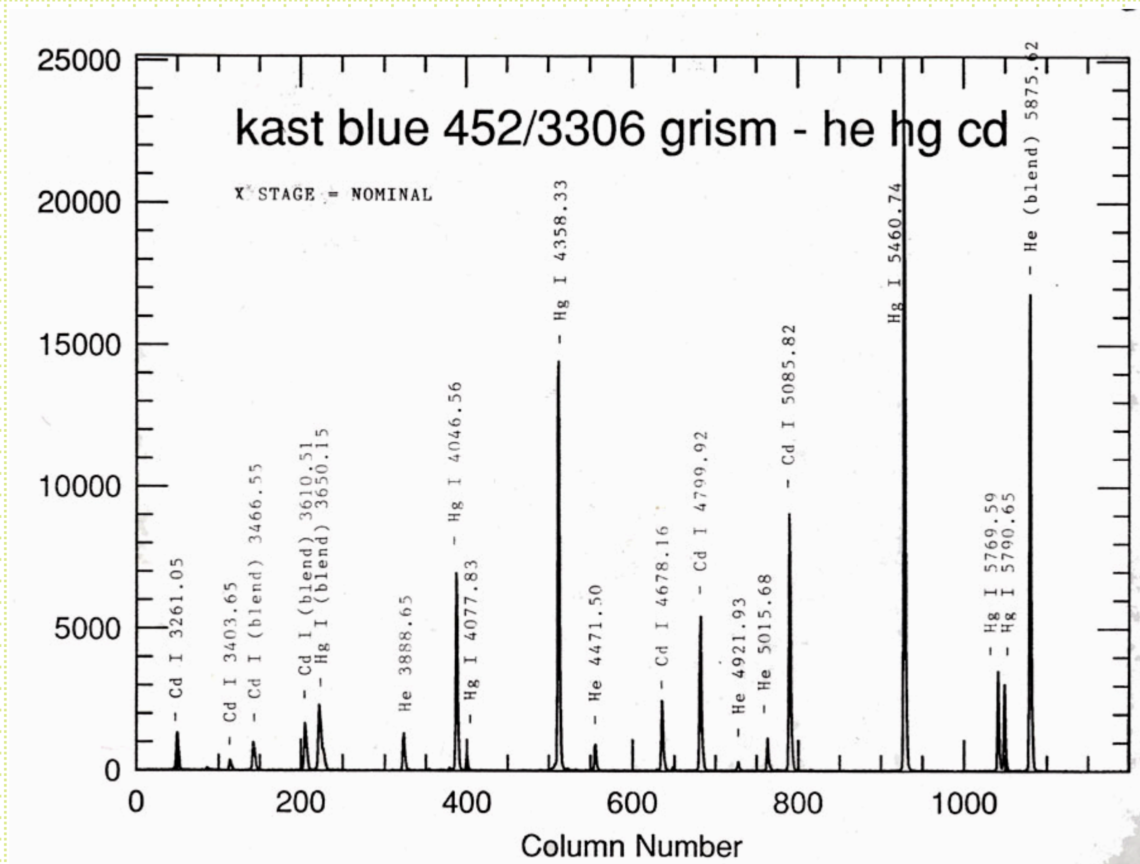




Wavelength Calibration

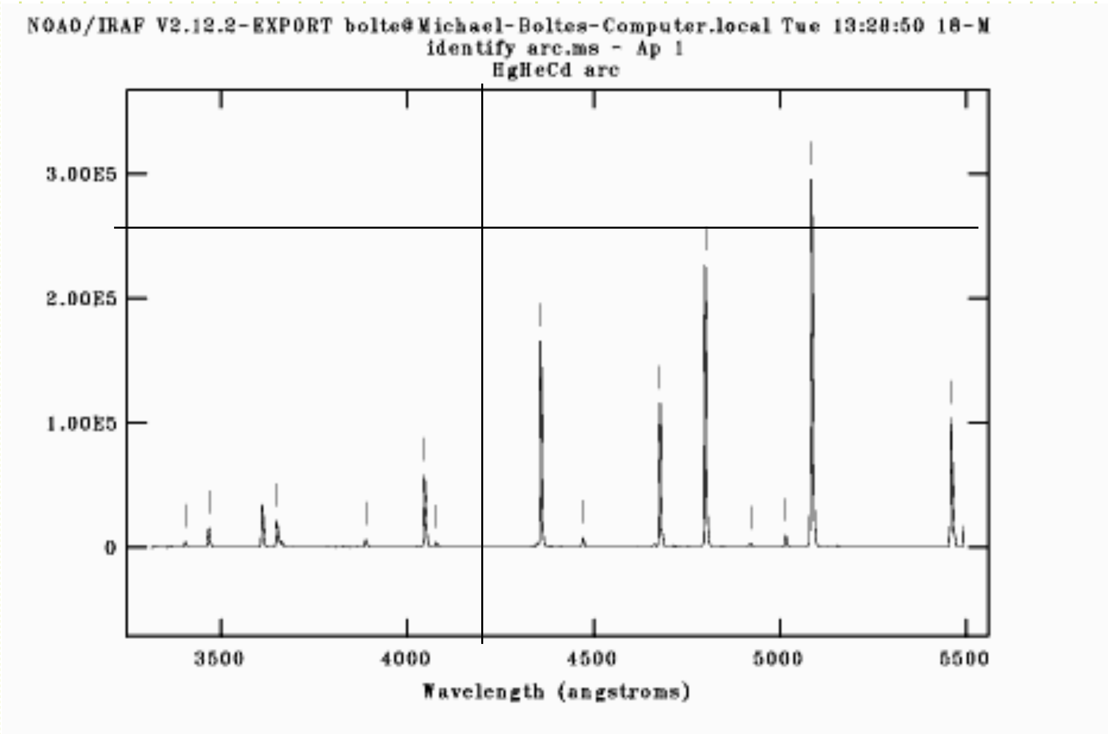
- Identify the lines in your lamp-line spectrum
- Fit line centers, derive function to map pixel scale to wavelength scale
- Associate arc+solution with program spectra
- Apply the `dispersion' solution, usually writing a short version of the solution to the header

Example, from Lick KAST WWW pages



- IRAF wavelength fitting routine:
  - noao.oned.*identify*

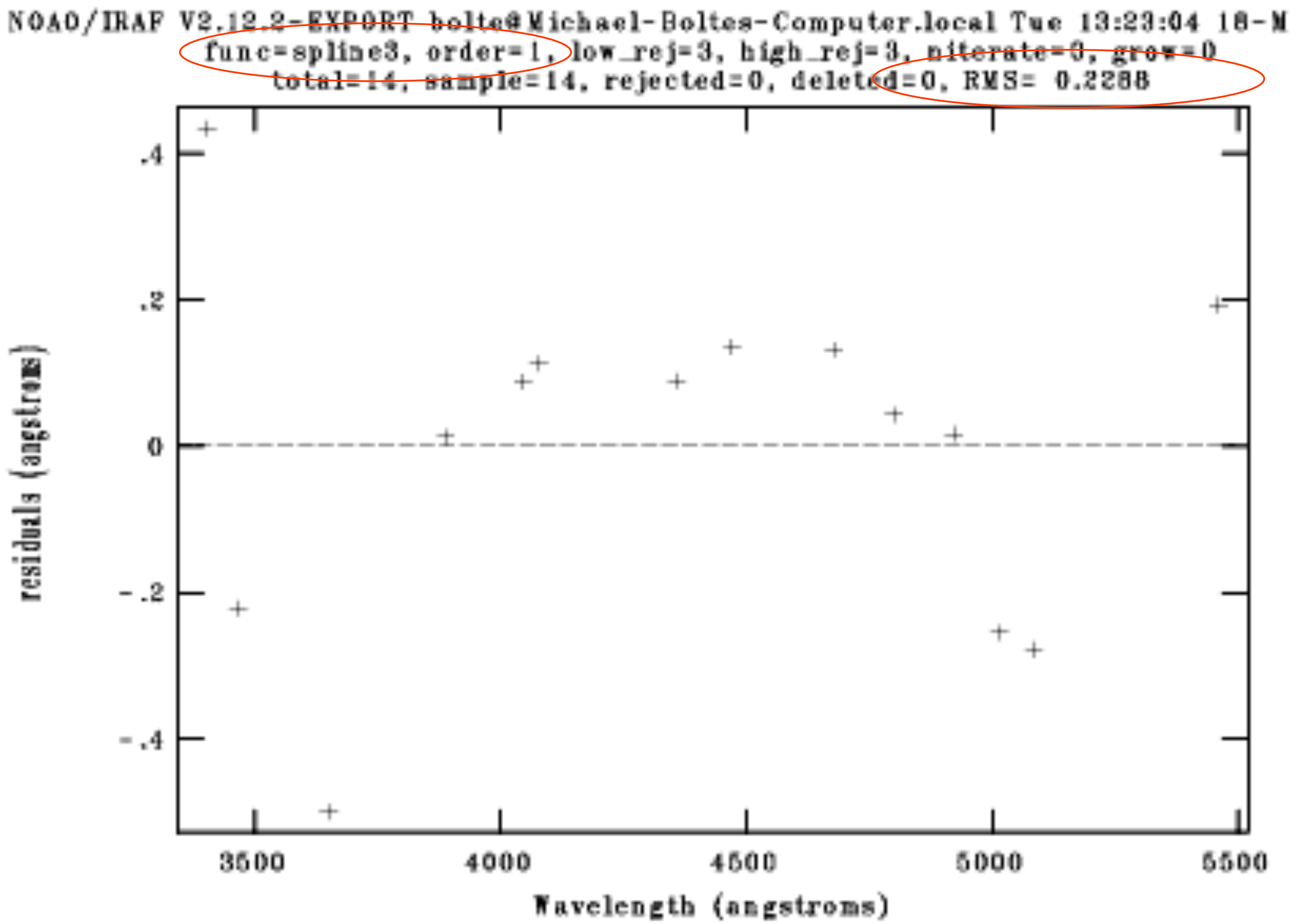
```
PACKAGE = onedspec
   TASK = identify

images  =                        Images containing features to be identified
(section=         middle line) Section to apply to two dimensional images
(databas=             database) Database in which to record feature data
(coordli= linelists$idhenear.dat) User coordinate list (typically user uses their own list)
(units  =                    ) Coordinate units
(nsum   =                  10) Number of lines/columns/bands to sum in 2D image
(match  =                 -3.) Coordinate list matching limit
(maxfeat=                  50) Maximum number of features for automatic identif
(zwidth =                100.) Zoom graph width in user units
(ftype  =            emission) Feature type
(fwidth =                  4.) Feature width in pixels
(cradius=                  5.) Centering radius in pixels
(thresho=                  0.) Feature threshold for centering
(minsep =                  2.) Minimum pixel separation
(functio=             spline3) Coordinate function
(order  =                   1) Order of coordinate function
(sample =                   *) Coordinate sample regions
```

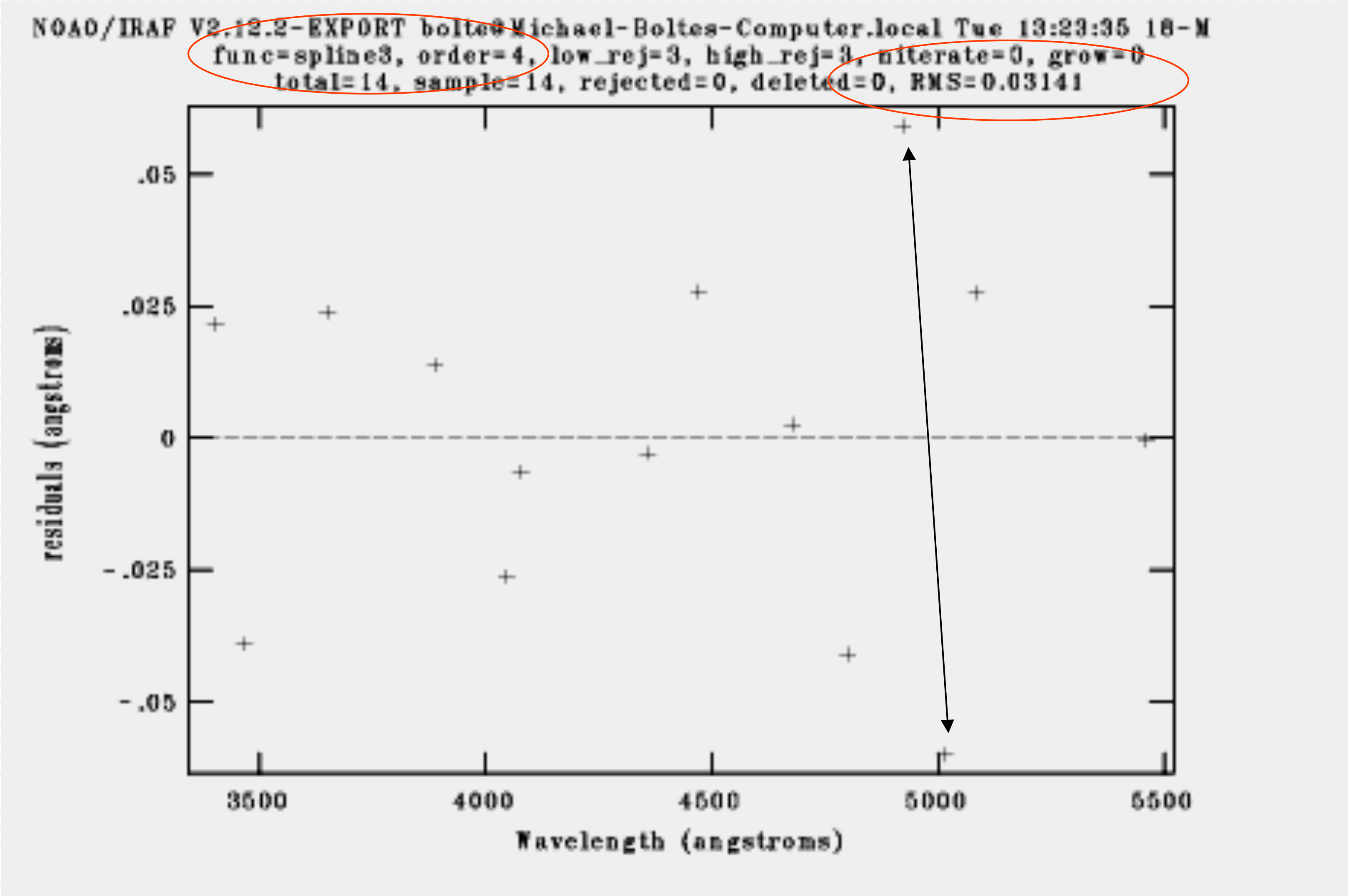


First *identify* window

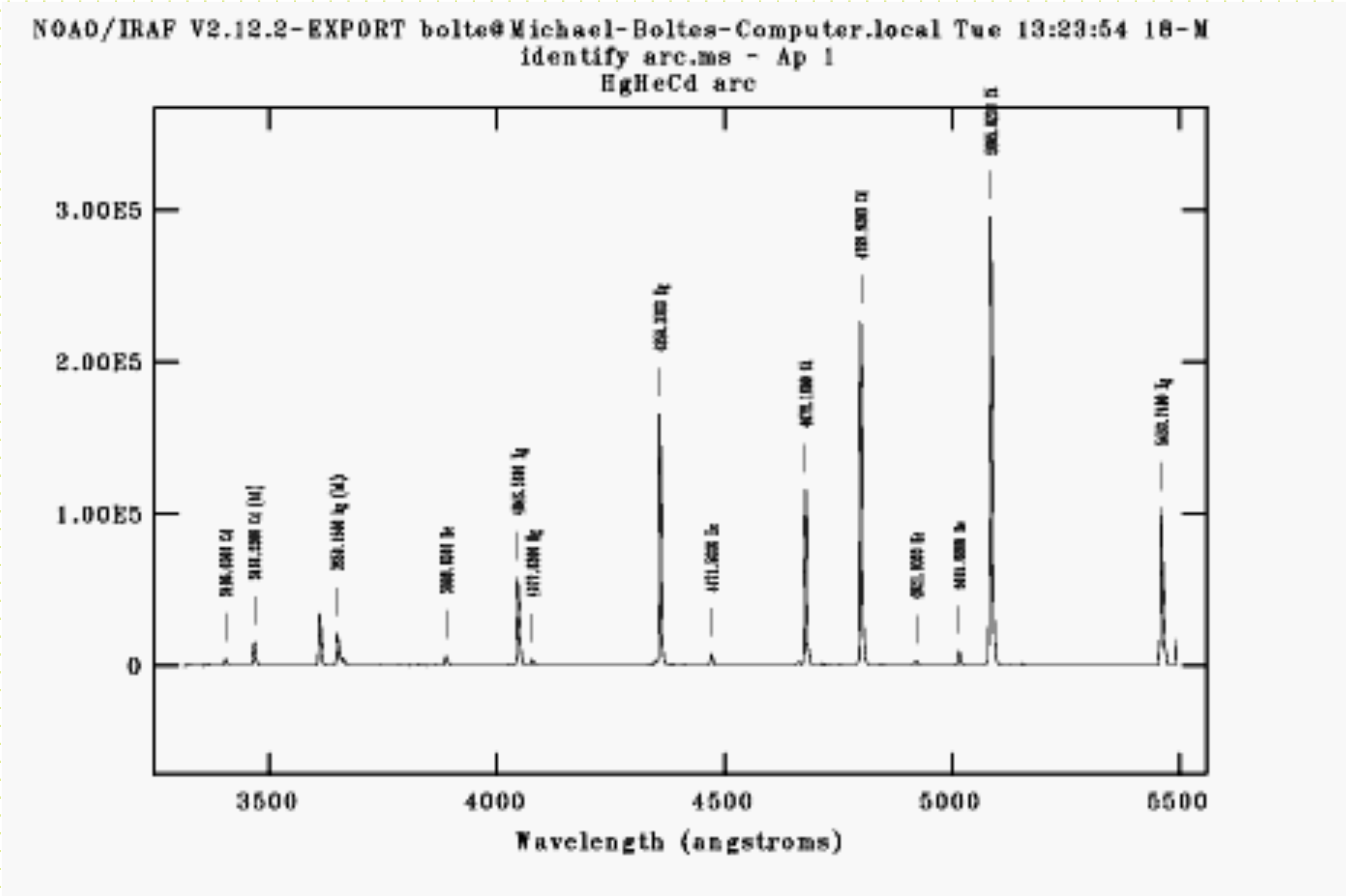
Commonly-used commands:

? -- help
m -- mark a line
c -- center next feature
l -- locate the rest of the lines
d -- delete a line
f -- fit (brings up new window)
w -- window


NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 13:23:04 18-M
func=spline3, order=1, low_rej=3, high_rej=3, niterate=0, grow=0
total=14, sample=14, rejected=0, deleted=0, RMS= 0.2288
residuals (angstroms)
Wavelength (angstroms)
.4
.2
0
-.2
-.4
3500
4000
4500
5000
5500


NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 13:23:35 18-M
func=spline3, order=4, low_rej=3, high_rej=3, niterate=0, grow=0
total=14, sample=14, rejected=0, deleted=0, RMS=0.03141
.05
.025
0
-.025
-.05
residuals (angstroms)
3500
4000
4500
5000
5500
Wavelength (angstroms)

:label both


NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 13:23:54 18-M
identify arc.ms - Ap 1
HgHeCd arc
3.00E5
2.00E5
1.00E5
0
3500
4000
4500
5000
5500
Wavelength (angstroms)

Applying wavelength solution

```
PACKAGE = onedspec
   TASK = refspectra

input   =   extracted_spectrum  List of input spectra
(referen=                  arc) List of reference spectra
(apertur=                     ) Input aperture selection list
(refaps =                     ) Reference aperture selection list
(ignorea=                  yes) Ignore input and reference apertures?
(select =               interp) Selection method for reference spectra
(sort   =                   jd) Sort key
(group  =                  ljd) Group key
(time   =                   no) Is sort key a time?
(timewra=                  17.) Time wrap point for time sorting
(overrid=                   no) Override previous assignments?
(confirm=                  yes) Confirm reference spectrum assignments?
(assign =                  yes) Assign the reference spectra to the input spectr
(logfile=       STDOUT,logfile) List of logfiles
(verbose=                   no) Verbose log output?
answer  =                       Accept assignment?
(mode   =                   ql)
```

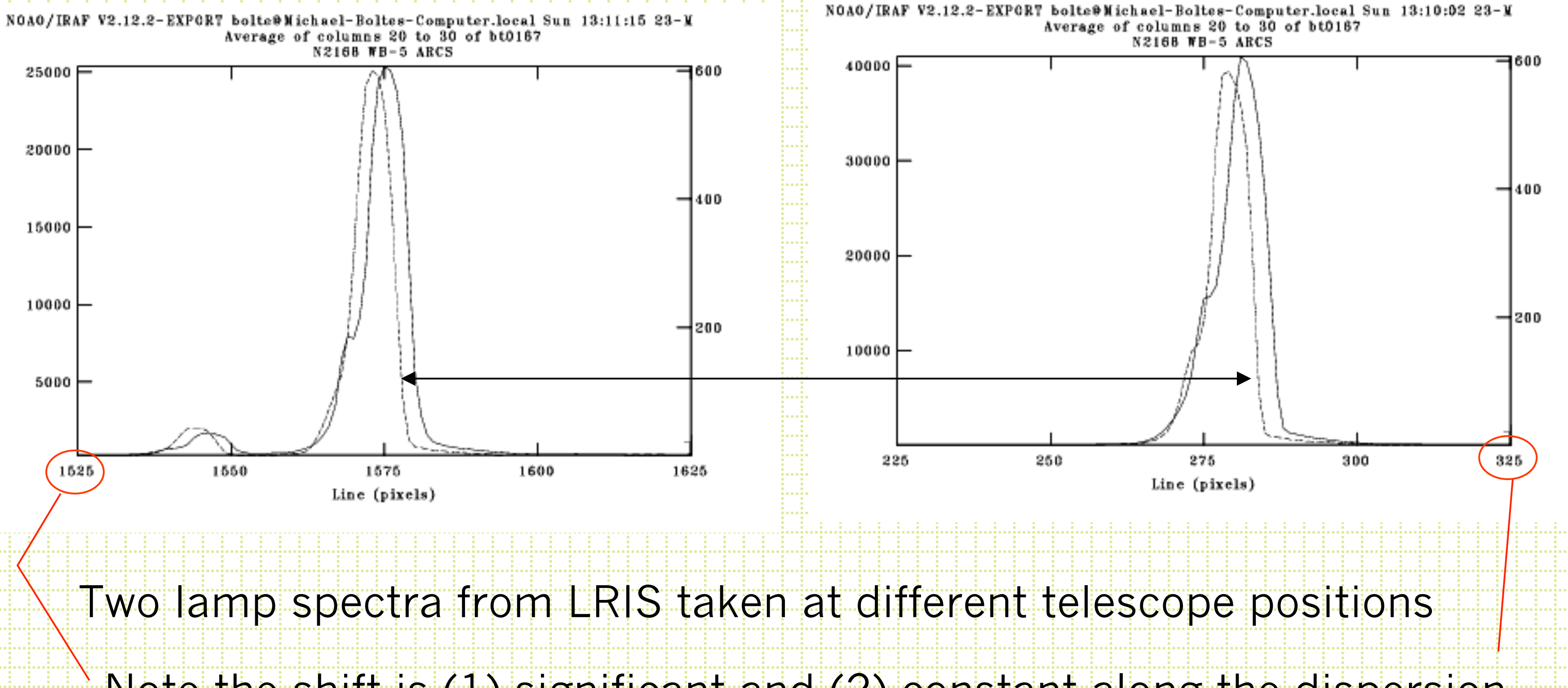
Sophisticated auto assignment options (select, sort, group, time, timewra)

Last step: apply dispersion solution. In IRAF, done in header

```
PACKAGE = onedspec
   TASK = dispcor

input   =                       List of input spectra
output  =                       List of output spectra
(lineari=                   yes) Linearize (interpolate) spectra?
(databas=              database) Dispersion solution database
(table  =                      ) Wavelength table for apertures
(w1     =                 INDEF) Starting wavelength
(w2     =                 INDEF) Ending wavelength
(dw     =                 INDEF) Wavelength interval per pixel
(nw     =                 INDEF) Number of output pixels
(log    =                    no) Logarithmic wavelength scale?
(flux   =                   yes) Conserve flux?
(samedis=                    no) Same dispersion in all apertures?
(global =                    no) Apply global defaults?
(ignorea=                    no) Ignore apertures?
(confirm=                    no) Confirm dispersion coordinates?
(listonl=                    no) List the dispersion coordinates only?
(verbose=                   yes) Print linear dispersion assignments?
```

```
cl>dispcor b188.ms w188.ms
b188.ms: REFSPEC1 = 'arc.ms 1.'
w188.ms: ap = 1, w1 = 3312.038, w2 = 5494.508, dw = 1.820242, nw = 1200
```

Flexure

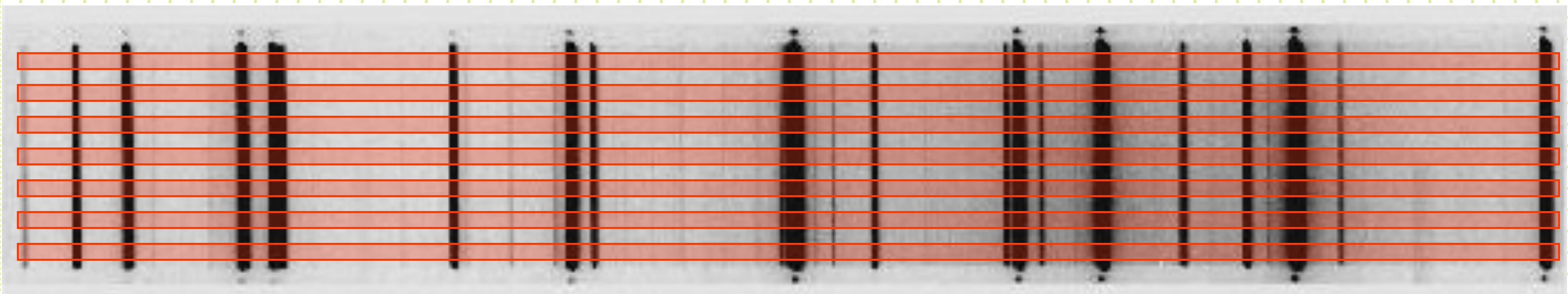


Two lamp spectra from LRIS taken at different telescope positions

Note the shift is (1) significant and (2) constant along the dispersion

reidentify allows a quick/automatic refitting of arcs taken during the night. Can also use single arc solution from afternoon calibrations and apply a zeropoint (wavelength) shift for each program spectrum based on night sky line positions

Short reidentify aside



- Can *reidentify* the line lamp spectrum at a range of line values (in a single spectrum)
- Use *fitcoords* to take the fit as a function of line number plus *transform* to remap the 2D image to be rectilinear in dispersion-spatial.
- Useful for long-slit work with resolved objects.

Flux Calibration

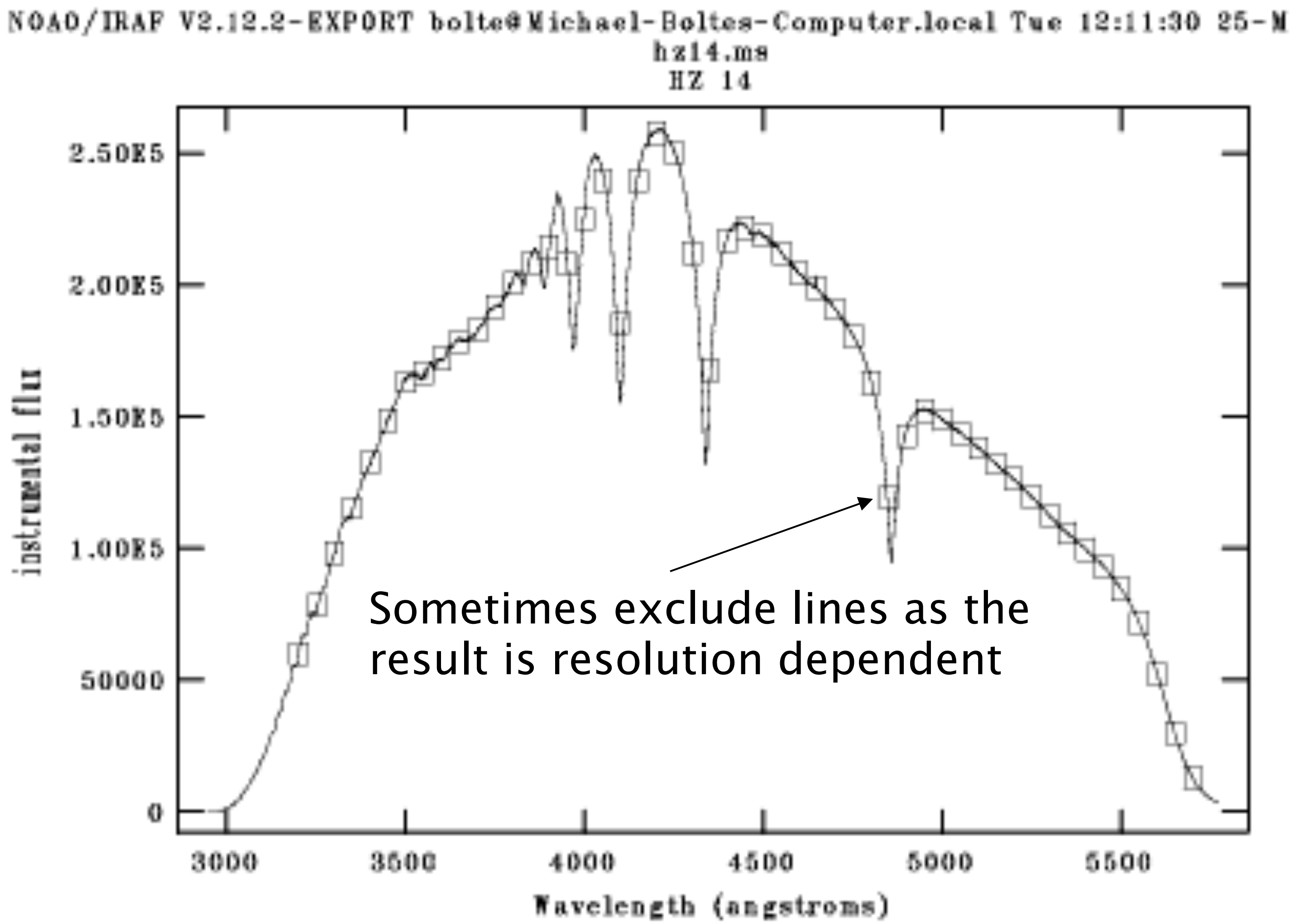
- There are lists of spectrophotometric standard stars:
  - Oke, J. B. 1990, AJ, 99, 1621
  - Stone, R. P. S. 1996, ApJS, 107, 423
  - Massey, P., & Gronwall, C. 1990, ApJ, 358, 344
  - IRAF: onedstds$

Usual zeropoint is based on Vega:

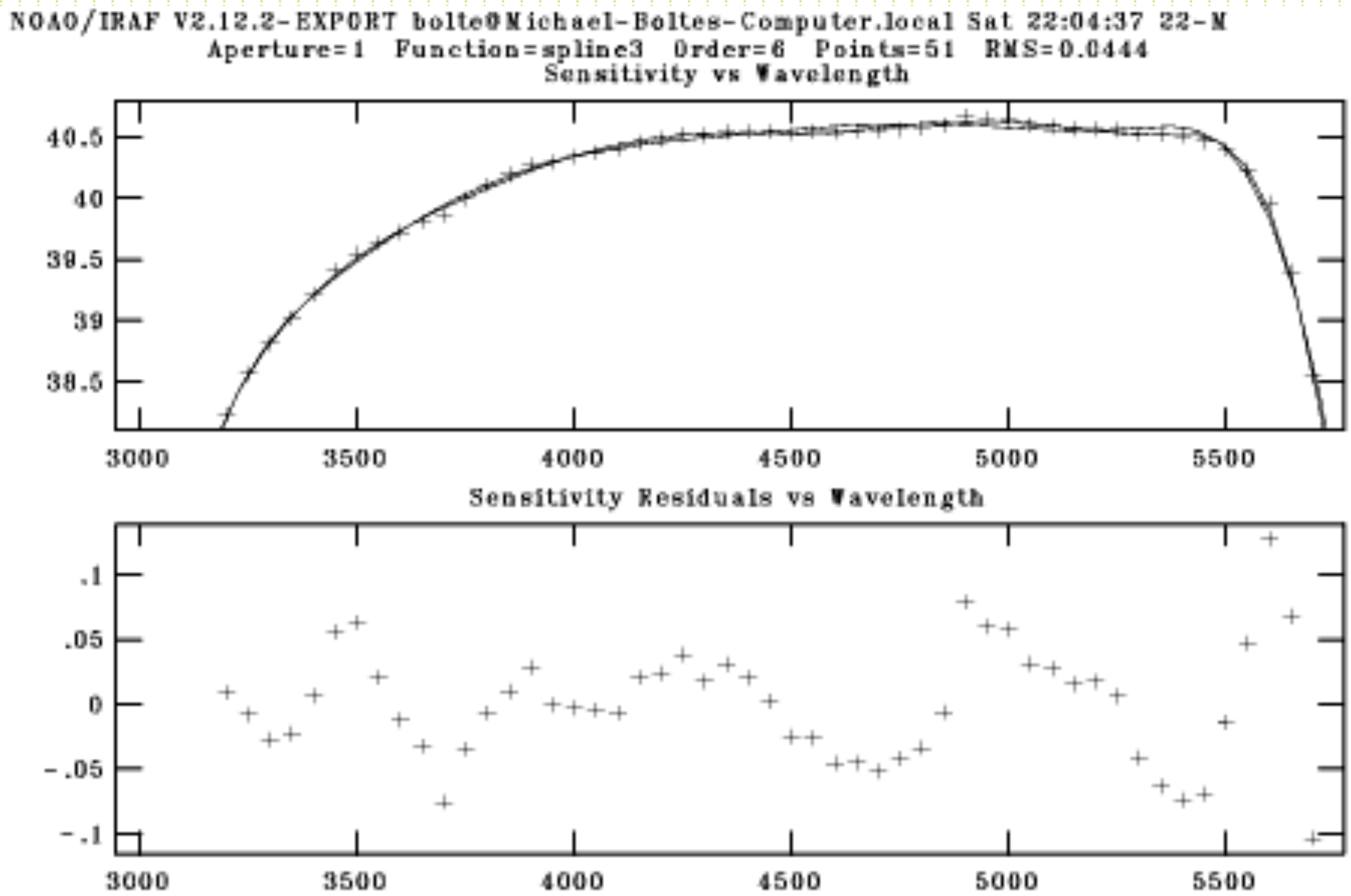
$F_{5556Å}$=3.52 x 10^{-20} erg/cm^2/s/Hz (V=0.048 mag)

Note: In IRAF, you can specify the broadband magnitude of each star to do a rough zeropoint correction for slit losses.

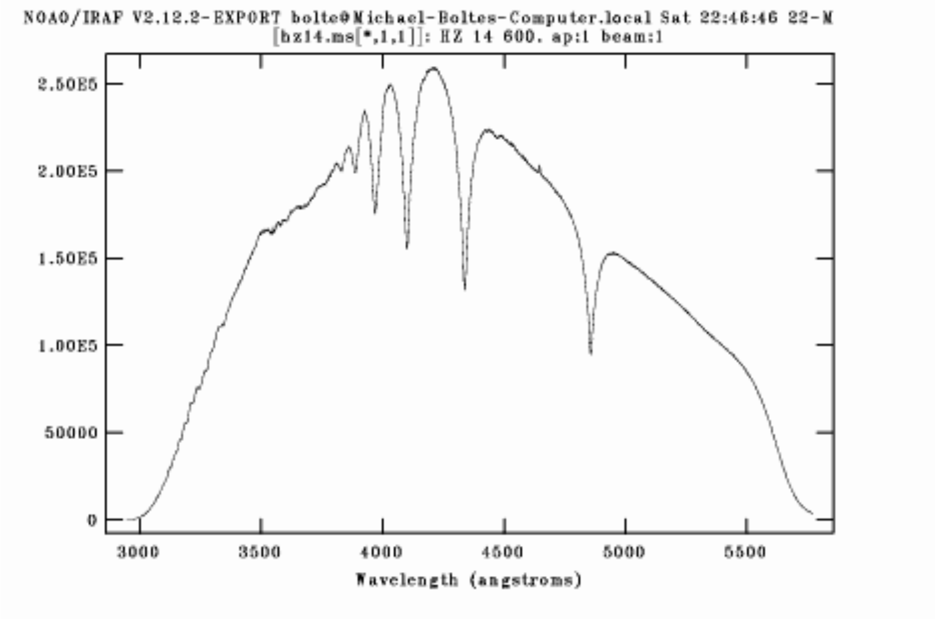
- noao.oned
  - *standard*: identifies standard stars by name, associates an extinction curve, gets airmass exposure time. Output is a file (default name std)
  - *sensfunc*: given extinction function, tabulated standard system flux and your observed spectrum calculate a sensitivity function.
  - *calibrate*: applies the sensitivity function to spectra



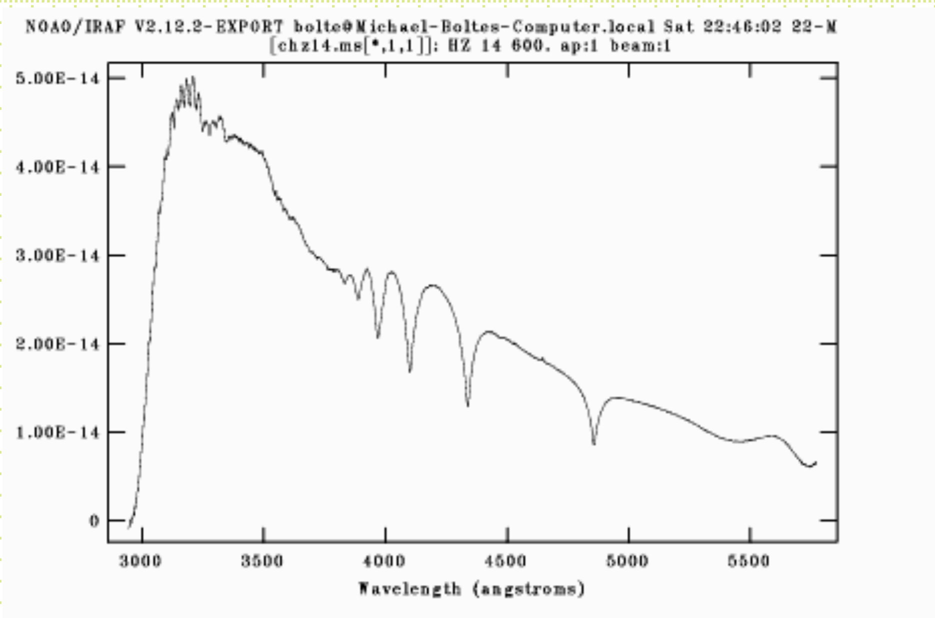
standard interactive graphic



sensfunc interative graphic



Raw extracted Spectrum



Flux calibrated