Reduction of échelle spectroscopy in IRAF

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1. Prerequisites to reduce spectra

- Many alternative ways of echelle spectroscopic reduction exist !!!
- Types of spectra: biases and darks (depends on CCD temperature), object spectra, comparison spectra (e.g. ThAr, FeAr, HeNe), lamp flats (continuous light of tungsten, LED), alternatively chip flats (uniformly illuminated CCD chip without the spectrograph)
- FITS headers should contain: imagetype (flat, dark, object...), object coordinates (RA,DEC), geographical coordinates (longitude, latitude), dispersion axis (DISPAXIS keyword = 1 or 2), gain and read-out noise etc.
- CCD bad pixel mask should be produced with pixels, rows, columns of bad (e.g. hot or insensitive) pixels listed in ASCII file, e.g.

```
# Bad Pixel mask created from file 20161111flat_S_1x1.fits
# 2 bad columns removed
685 686 1038 2048
932 934  730  732
```

A typical FITS header

```
SIMPLE  =                    T
BITPIX  =                   16 /8 unsigned int, 16 & 32 int, -32 & -64 real
NAXIS   =                    2 /number of axes
NAXIS1  =                 1374 /fastest changing axis
NAXIS2  =                 1099 /next to fastest changing axis
BSCALE  =   1.0000000000000000 /physical = BZERO + BSCALE*array_value
BZERO   =   32768.000000000000 /physical = BZERO + BSCALE*array_value
DATE-OBS= '2017-01-29T00:45:32' /YYYY-MM-DDThh:mm:ss observation start, UT
EXPTIME =   900.00000000000000 /Exposure time in seconds
EXPOSURE=   900.00000000000000 /Exposure time in seconds
SET-TEMP=  -20.000000000000000 /CCD temperature setpoint in C
CCD-TEMP=  -20.029999552294612 /CCD temperature at start of exposure in C
XPIXSZ  =   9.0800000000000001 /Pixel Width in microns (after binning)
YPIXSZ  =   9.0800000000000001 /Pixel Height in microns (after binning)
XBINNING=                    2 /Binning factor in width
YBINNING=                    2 /Binning factor in height
XORGSUBF=                    0 /Subframe X position in binned pixels
YORGSUBF=                    0 /Subframe Y position in binned pixels
IMAGETYP= 'LIGHT   ' /           Type of image
SITELAT = '49 09 10' /           Latitude of the imaging location
SITELONG= '20 17 28' /           Longitude of the imaging location
JD      =   2457782.5316203702 /Julian Date at start of exposure
FOCALLEN=   7500.0000000000000 /Focal length of telescope in mm
APTDIA  =   600.00000000000000 /Aperture diameter of telescope in mm
APTAREA =   257296.44548892975 /Aperture area of telescope in mm^2
SWCREATE= 'MaxIm DL Version 5.18 130207 32K52' /Name of software that created
         the image
OBJECT  = 'TX UMa  '
TELESCOP= 'Zeiss 600/7500' /     telescope used to acquire this image
INSTRUME= 'G1_60cm_Eshl' /       instrument or camera used
OBSERVER= 'Hambalek'
NOTES   = 'Pribulla'
DISPAXIS=                    1
RA      = '10 45 20.5'
DEC     = '+45 33 59'
```

2. Photometric reduction

- overscan correction in ccdproc
- making master darks using darkcombine, flatcombine

```
darkcombine input=@dark10.lst output=Dark10.fit combine=median process- scale=none

flatcombine input=@flats.lst output=Flat combine=median reject=crreject process- rdnoise=5.1 gain=0.26
```

- photometric reduction of the object frames, below is dark, flat and and bad-pixel correction done (list of parameters created by mkscript)

```
ccdproc ("raw/"//subor, output=corrsubor, ccdtype="", max_cache=0,
noproc=no, fixpix=yes, overscan=no, trim=no, zerocor=no, darkcor=yes,
flatcor=yes, illumcor=no, fringecor=no, readcor=no, scancor=no,
readaxis="column", fixfile="/scisoft/share/iraf/iraf/local/scripts/bpm-Atik.txt",
biassec="", trimsec="", zero="",
dark=darksubor, flat=flatsubor, illum="", fringe="", minreplace=1.,
scantype="shortscan", nscan=1, interactive=no, function="legendre", order=1,
sample="*", naverage=1, niterate=1, low_reject=3., high_reject=3.,
grow=0., >> "log_34.txt")
```

- removal cosmic hits/spikes (program of V. Pych can be used), alternative is crutil. package in IRAF
- cosmic hits are easily detected and removed when combining multiple spectra

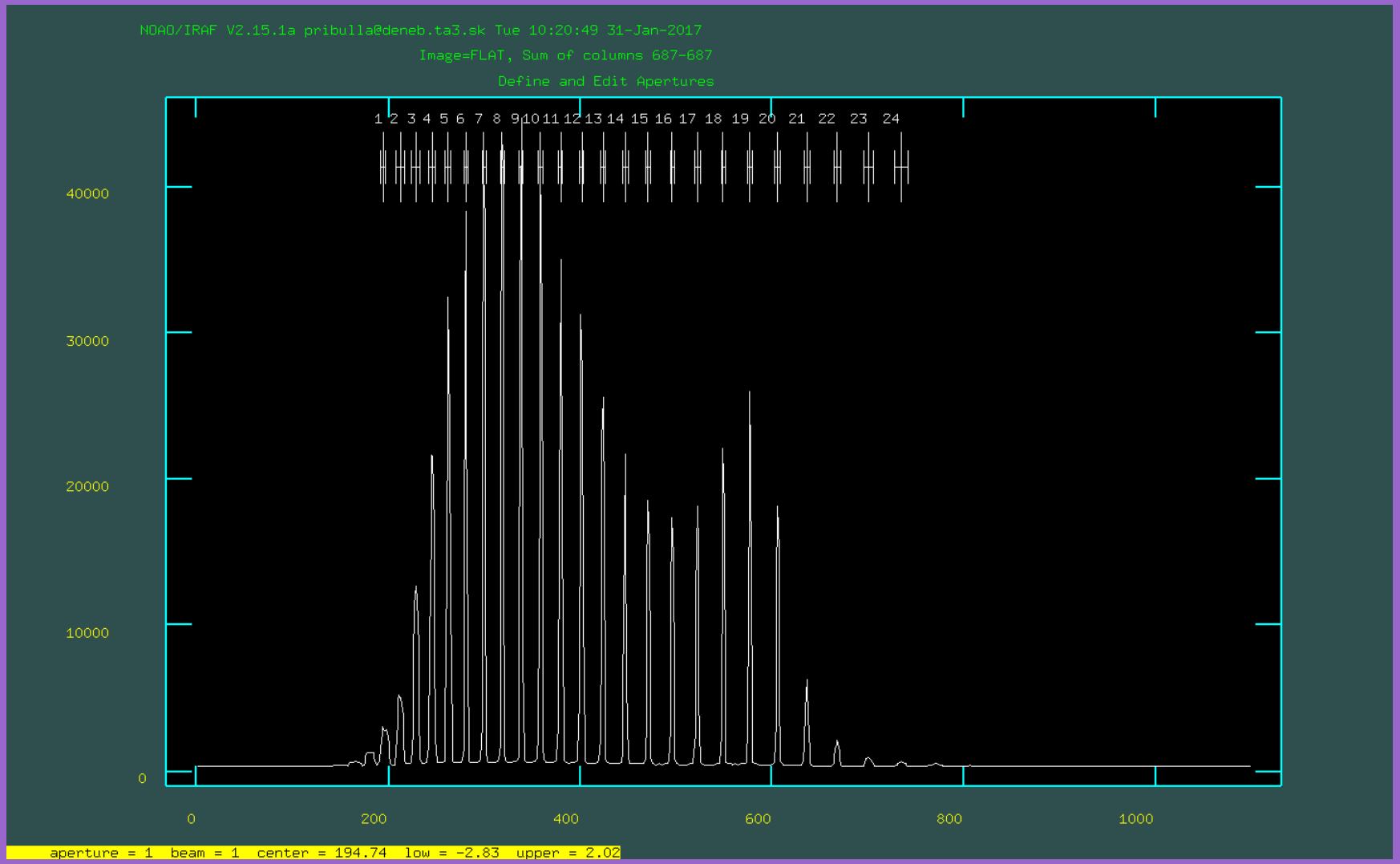
3. Co-adding the frames

- For long-period objects it is practical to co-add the frames to (i) boost SNR (ii) clean cosmic hits
- It is good to define statistical region to weight the frames according to the signal, this can be done by first tracing lamp flats

```
combine ("@"//inplist, outcome, plfile="", sigma="", ccdtype="", subsets=no, delete=no,
clobber=no, combine="average", reject="crreject", project=no, outtype="real",
offsets="none", masktype="none", maskvalue=0., blank=0., scale="median",
zero="none", weight="median", statsec=region, lthreshold=0,
hthreshold=60000., nlow=1, nhigh=1, nkeep=1, mclip=yes, lsigma=3.,
hsigma=3., rdnoise="5.1", gain="0.26", snoise="0.", sigscale=0.1, pclip=-0.5, grow=0)
```

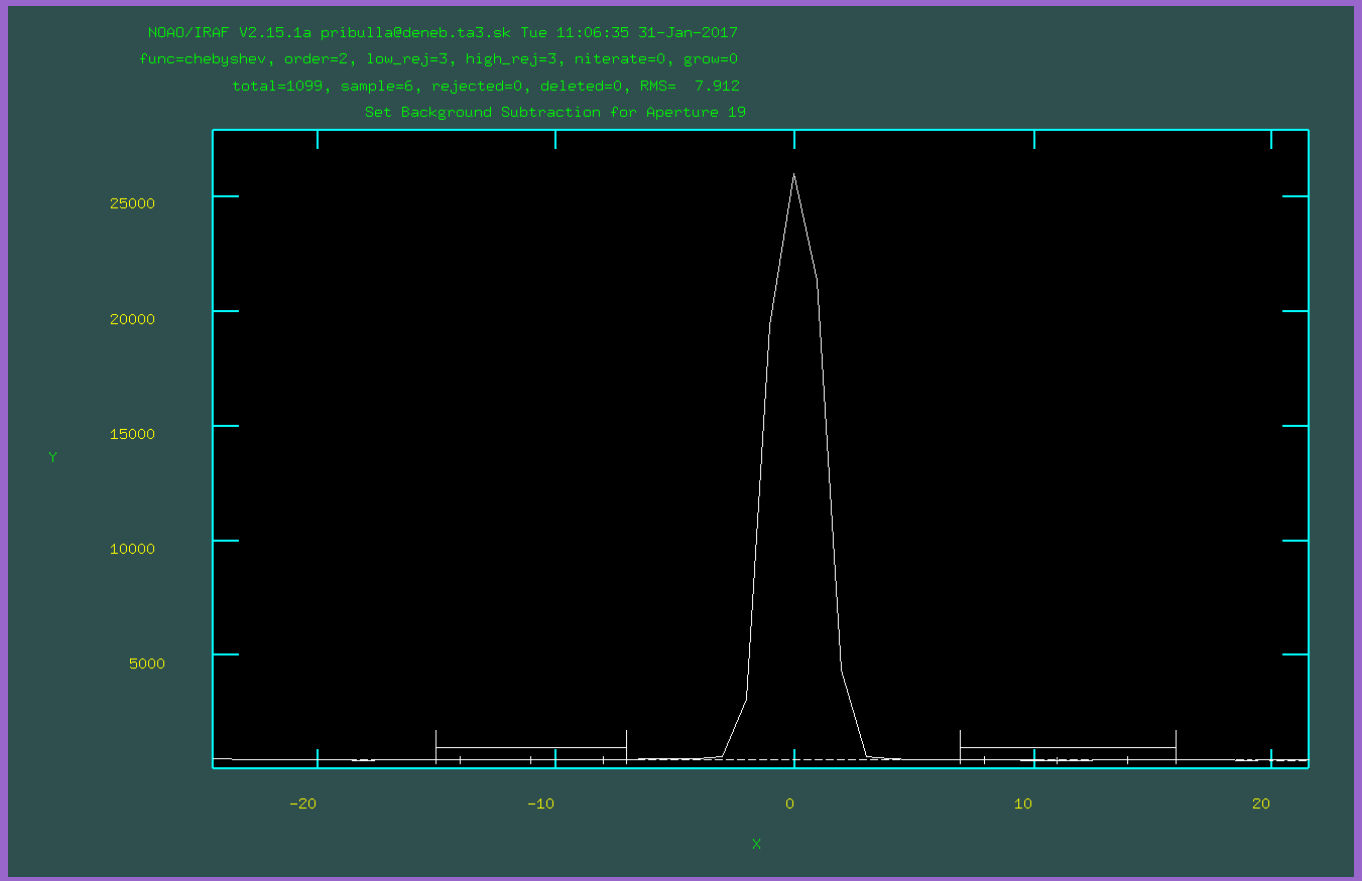
4. Finding the echelle orders

- Now we work in noao.imred.echelle and use task apfind using a spectrum of well-exposed lamp flat or early-type star



5. Defining the apertures and bckgrnd

- Still working in apfind edit the apertures
- Ordering, resizing, deleting, adding of the apertures (=echelle orders)
- Important keys are: . (dot) - selects nearest aperture, l and u - lower and upper range for the aperture, b - set the background, t - initialize, s+s - background range, f - fit the background



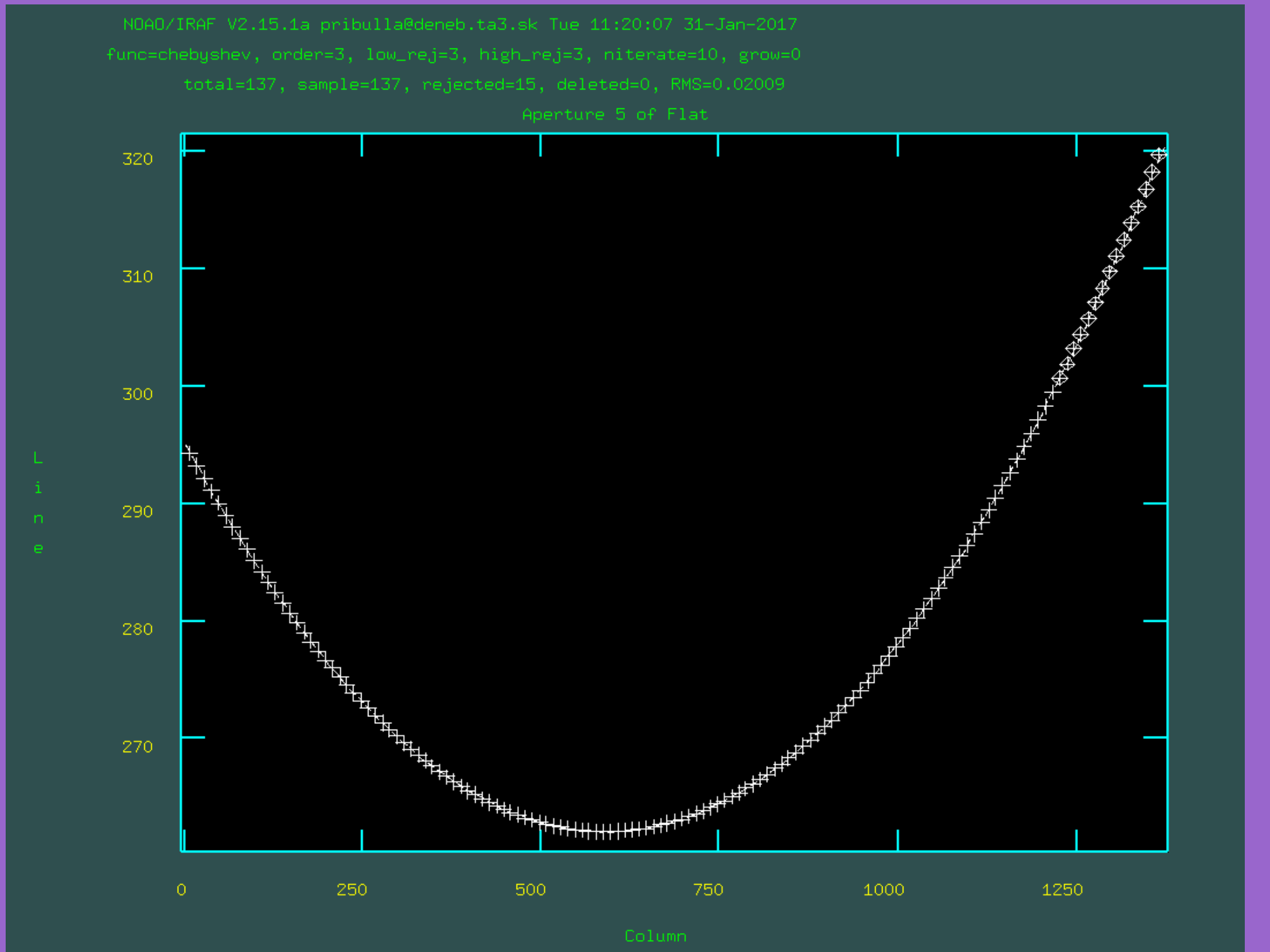
6. Tracing the apertures

- still working with the lamp flat or early-type stellar spectrum use aptrace
- for first order-definition work interactively !

```
cl> aptrace Flat.fits
```

- important keys are: f - fit, d -delete a point, a - add a point, with colon commands one can change e.g. order, polynomial type, number of iterations
- fitted traces are stored in database/ directory and can be used as a reference for future reductions
- when in a script the typical settings look like:

```
aptrace (first, apertures="", references="Trace", interactive=no, find=no, recenter=yes,
resize=no, edit=no, trace=no, fittrace=no, line=INDEF, nsum=10, step=5,
nlost=2, function="chebyshev", order=3, sample="*", naverage=1, niterate=10,
low_reject=2., high_reject=2., grow=0.)
```


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Tue 11:20:07 31-Jan-2017
func=chebyshev, order=3, low_rej=3, high_rej=3, niterate=10, grow=0
total=137, sample=137, rejected=15, deleted=0, RMS=0.02009
Aperture 5 of Flat
320
310
300
290
280
270
Line
0
250
500
750
1000
1250
Column

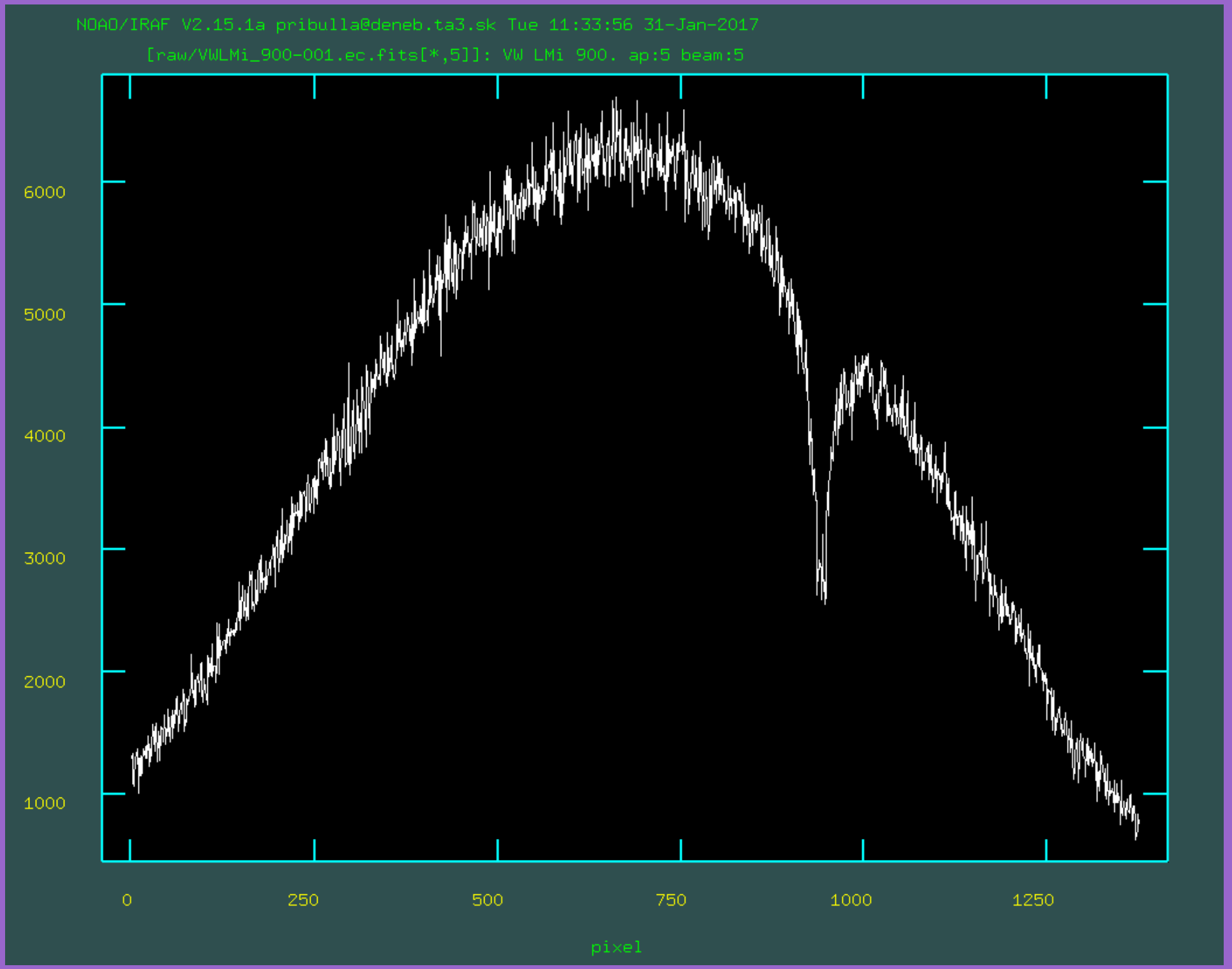
7. Extracting aperture spectra

- Spectra are extracted for object and comparison lamp spectra (ThAr, FeNe...)
- Aperture reference from the traced spectrum is used, apertures are NOT edited or traced now

```
echelle> apsum input=@object.txt format=echelle ref=Flat.fits
echelle> apsum input=@ThAr.txt format=echelle ref=Flat.fits
```

- In scripts more parameters can be used to control e.g. background subtraction, type of the extracted spectrum 2D or 3D (so called extras)

```
apsum ("@compar.txt", output=" ", apertures=" ", format="echelle",
references="FLAT", profiles="", interactive=no, find=no, recenter=no,
resize=no, edit=no, trace=no, fittrace=no, extract=yes,
extras=no, review=no, background="median",
weights="none", pfit="fit1d", clean=no, skybox=1, saturation = INDEF,
readnoise=rdn[ii], gain=gn[ii], lsigma=4., usigma=4., nsubaps=1)
```

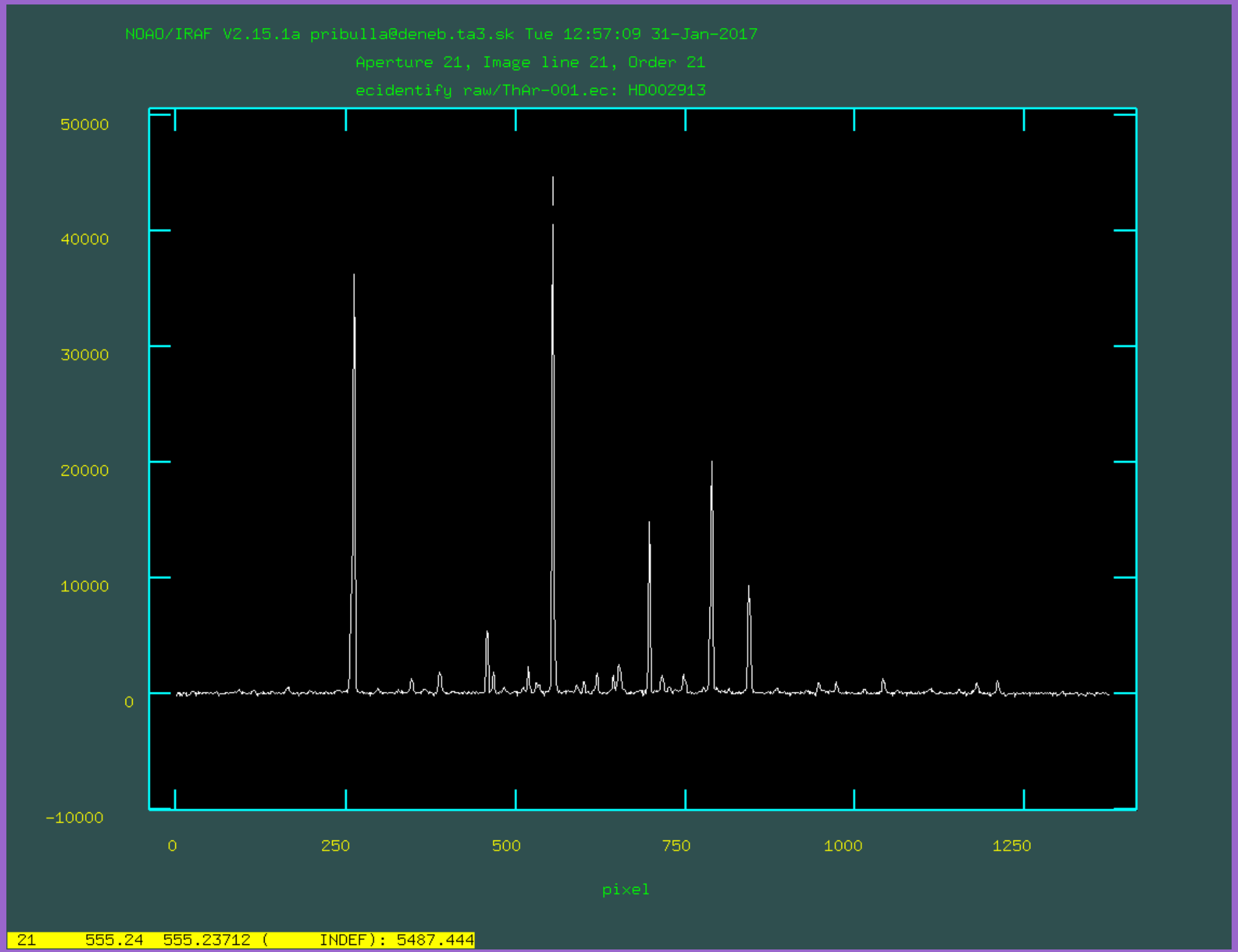

NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Tue 11:33:56 31-Jan-2017
[raw/VWLMi_900-001.ec.fits[*,5]]: VW LMi 900. ap:5 beam:5
6000
5000
4000
3000
2000
1000
0
250
500
750
1000
1250
pixel

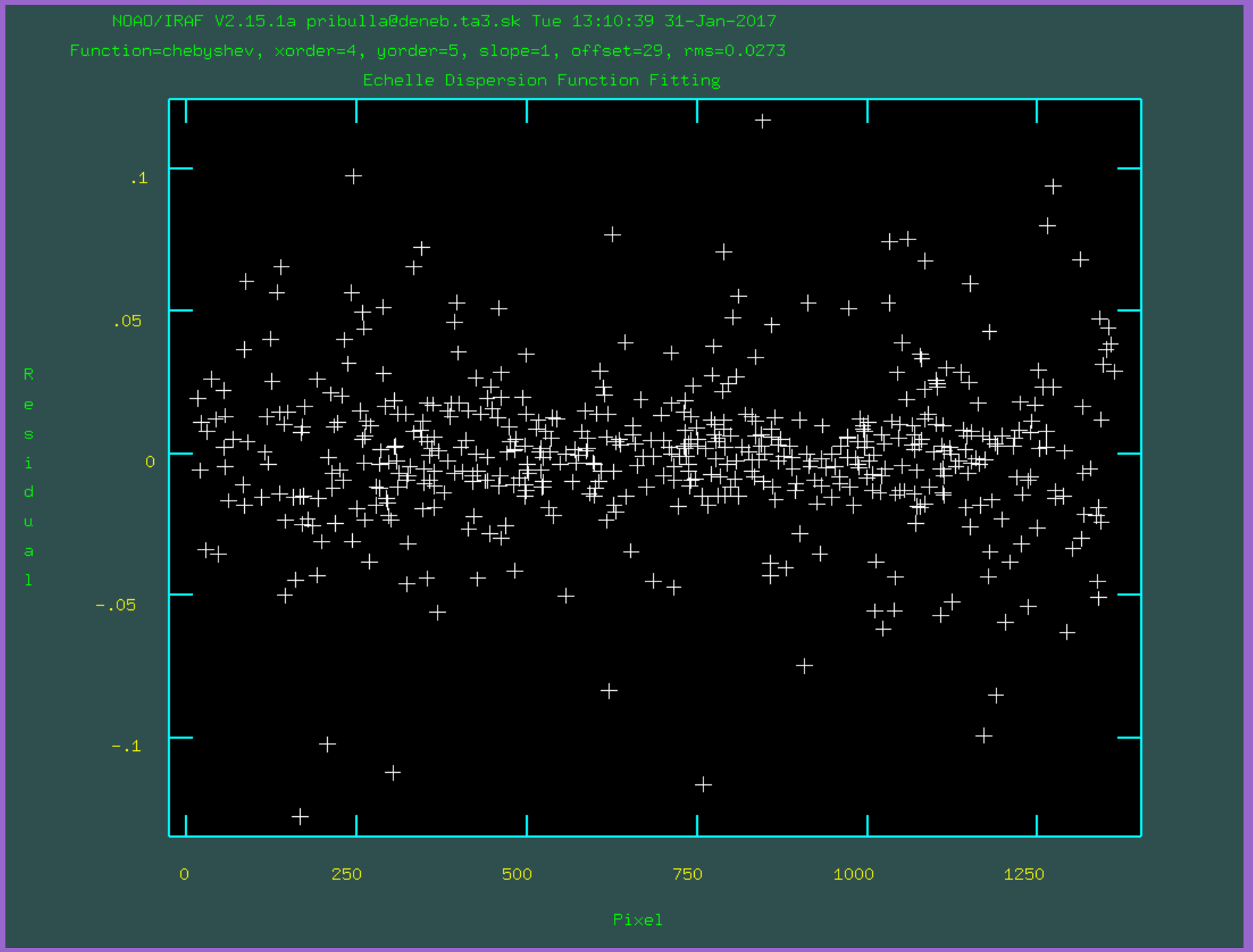
7. Identifying comparison lines

- Well exposed arc/hollow cathod lamp spectrum is needed, e.g. ThAr, FeNe, FeAr.
- The line lists and plots can be found at KPNO, e.g. https://www.noao.edu/kpno/tharatlas/thar/thar.html
- N.B. depending on the calibration source current the lines of different ionization/excitation will change their relative intensity !!!
- ecidentify task is used:

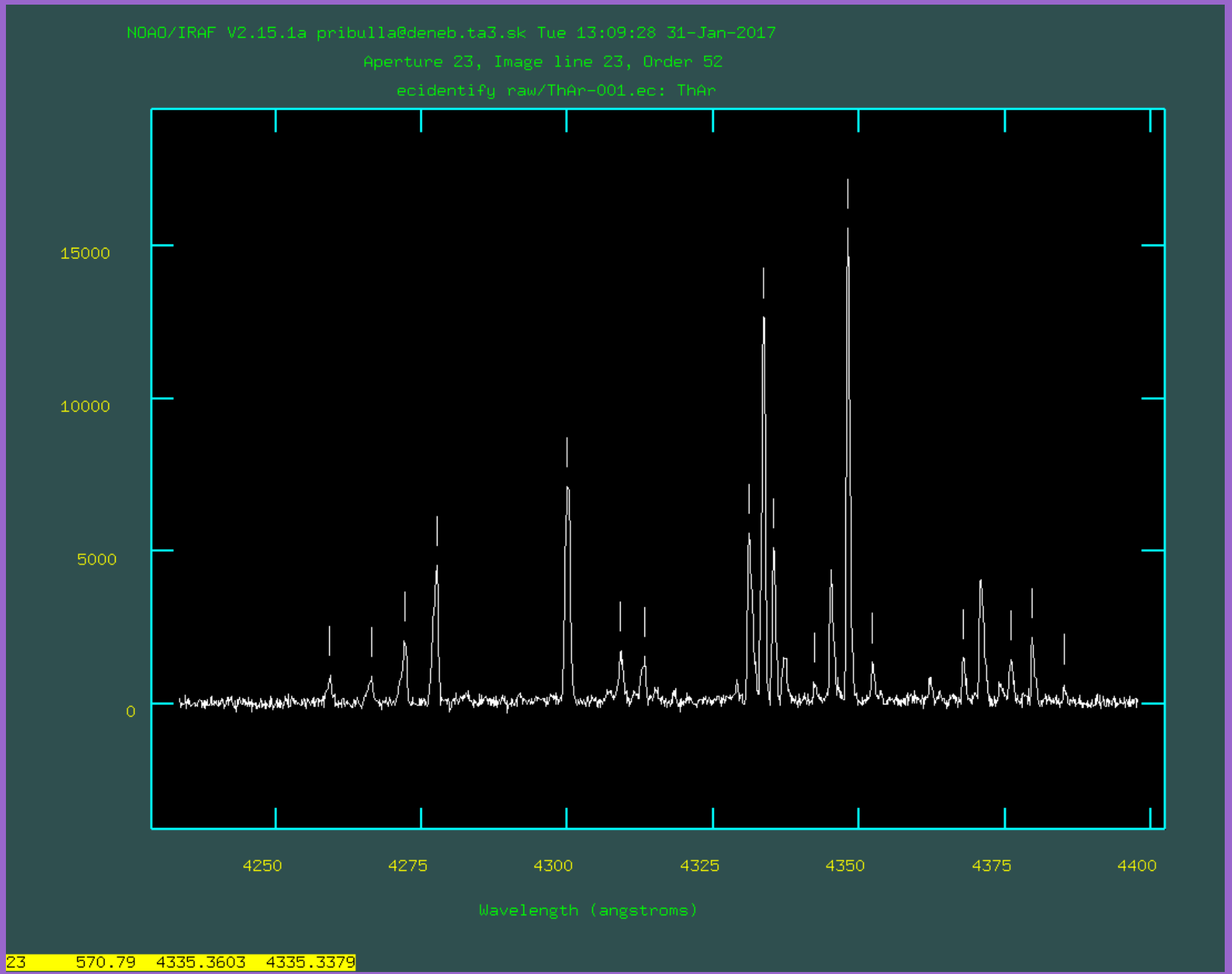
```
echelle> ecidentify raw/ThAr-001.ec.fits
```

- Important key commands: marking a line is done by m + typing catalogue wavelength, to produce a fit press f, orders are changed with j and k
- It is advisable to identify at least 5 lines every other aperture
- after the fit is obtained the x scale changes from pixels to Å
- catalogue wavelength is then suggested after pressing m
- prior to running the command it is practical to set at least the type and order degree of the fitting polynomial in both axes, 4 is appropriate typically


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Tue 12:57:09 31-Jan-2017
Aperture 21, Image line 21, Order 21
ecidentify raw/ThAr-001.ec: HD002913
50000
40000
30000
20000
10000
0
-10000
0
250
500
750
1000
1250
pixel
21 555.24 555.23712 (INDEF): 5487.444


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Tue 13:10:39 31-Jan-2017
Function=chebyshev, xorder=4, yorder=5, slope=1, offset=29, rms=0.0273
Echelle Dispersion Function Fitting
.1
.05
0
-.05
-.1
Residual
0
250
500
750
1000
1250
Pixel

```
# Thu 10:00:44 26-Feb-2015
begin   ecidentify Comp.ec
        id      Comp.ec
        task    ecidentify
        image   Comp.ec
        units   angstroms
        features        532
                  1   30   205.33  7585.82313   7585.7922   4.0  1  1
                  1   30   301.55  7567.81965   7567.7417   4.0  1  1
                  1   30   398.30  7549.33265   7549.3138   4.0  1  1
                  1   30  1000.10  7425.23525   7425.2942   4.0  1  1
                  1   30  1013.87  7422.20399   7422.3118   4.0  1  1
                  1   30  1058.61  7412.29359   7412.3368   4.0  1  1
                  1   30  1144.22  7393.06549   7392.9801   4.0  1  1
                  1   30  1235.56  7372.16243   7372.1184   4.0  1  1
                  1   30  1316.65  7353.26453    7353.293   4.0  1  1
                  1   30  1327.25  7350.77031    7350.814   4.0  1  1
                  2   31    28.97  7372.13632   7372.1184   4.0  1  1
                  2   31   137.43  7353.24425    7353.293   4.0  1  1
                  2   31   151.16  7350.81897    7350.814   4.0  1  1
                  2   31   277.09  7328.21764    7328.285   4.0  1  1
                  2   31   343.56  7316.02634    7316.005   4.0  1  1
                  2   31   366.63  7311.75247   7311.7159   4.0  1  1
                  2   31   628.73  7261.63536       INDEF   4.0  1  1
                  2   31   788.10  7229.73549       INDEF   4.0  1  1
                  2   31   845.32   7218.0145   7218.0542   4.0  1  1
                  2   31  1077.78  7168.91936   7168.8952   4.0  1  1
                  2   31  1107.09  7162.55888   7162.5569   4.0  1  1
                  2   31  1124.06  7158.85866   7158.8387   4.0  1  1
                  2   31  1177.63  7147.09306   7147.0416   4.0  1  1
                  2   31  1272.92  7125.84375     7125.82   4.0  1  1
                  2   31  1353.99  7107.43962   7107.4778   4.0  1  1
                  3   32   123.99  7125.79333     7125.82   4.0  1  1
                  3   32   131.37  7124.53616   7124.5607   4.0  1  1
                  3   32   230.41  7107.45127   7107.4778   4.0  1  1
```


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Tue 13:09:28 31-Jan-2017
Aperture 23, Image line 23, Order 52
ecidentify raw/ThAr-001.ec: ThAr
15000
10000
5000
0
4250
4275
4300
4325
4350
4375
4400
Wavelength (angstroms)
23 570.79 4335.3603 4335.3379

8. Line re-identification

- Automated re-identification of the features and solution of all comparison spectra for a given night:

```
echelle> ecreidentify @thar.lst
```

```
ECREIDENTIFY: NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Wed 18:48:28 01-Feb-2017
Reference image = Comp.ec, Refit = yes
              Image    Found     Fit Pix Shift  User Shift  Z Shift      RMS
    raw/ThAr-001.ec  531/532 531/531     0.159       -1.05  -4.7E-6    0.036
    raw/ThAr-002.ec  529/532 529/529     0.143       -0.95  -4.3E-6    0.042
    raw/ThAr-003.ec  530/532 530/530     0.121      -0.813  -3.7E-6   0.0453
    raw/ThAr-004.ec  532/532 532/532     0.128       -0.85  -3.8E-6   0.0354
    raw/ThAr-005.ec  532/532 532/532     0.124      -0.819  -3.7E-6   0.0344
    raw/ThAr-006.ec  528/532 528/528     0.126      -0.828  -3.7E-6   0.0376
    raw/ThAr-007.ec  530/532 530/530     0.119      -0.798  -3.6E-6   0.0323
    raw/ThAr-008.ec  528/532 528/528     0.108      -0.725  -3.3E-6   0.0295
    raw/ThAr-009.ec  531/532 531/531     0.116      -0.776  -3.5E-6   0.0344
    raw/ThAr-010.ec  526/532 526/526     0.118      -0.785  -3.5E-6   0.0373
    raw/ThAr-011.ec  527/532 527/527     0.122      -0.808  -3.6E-6   0.0356
    raw/ThAr-012.ec  527/532 527/527     0.142      -0.931  -4.2E-6   0.0368
```

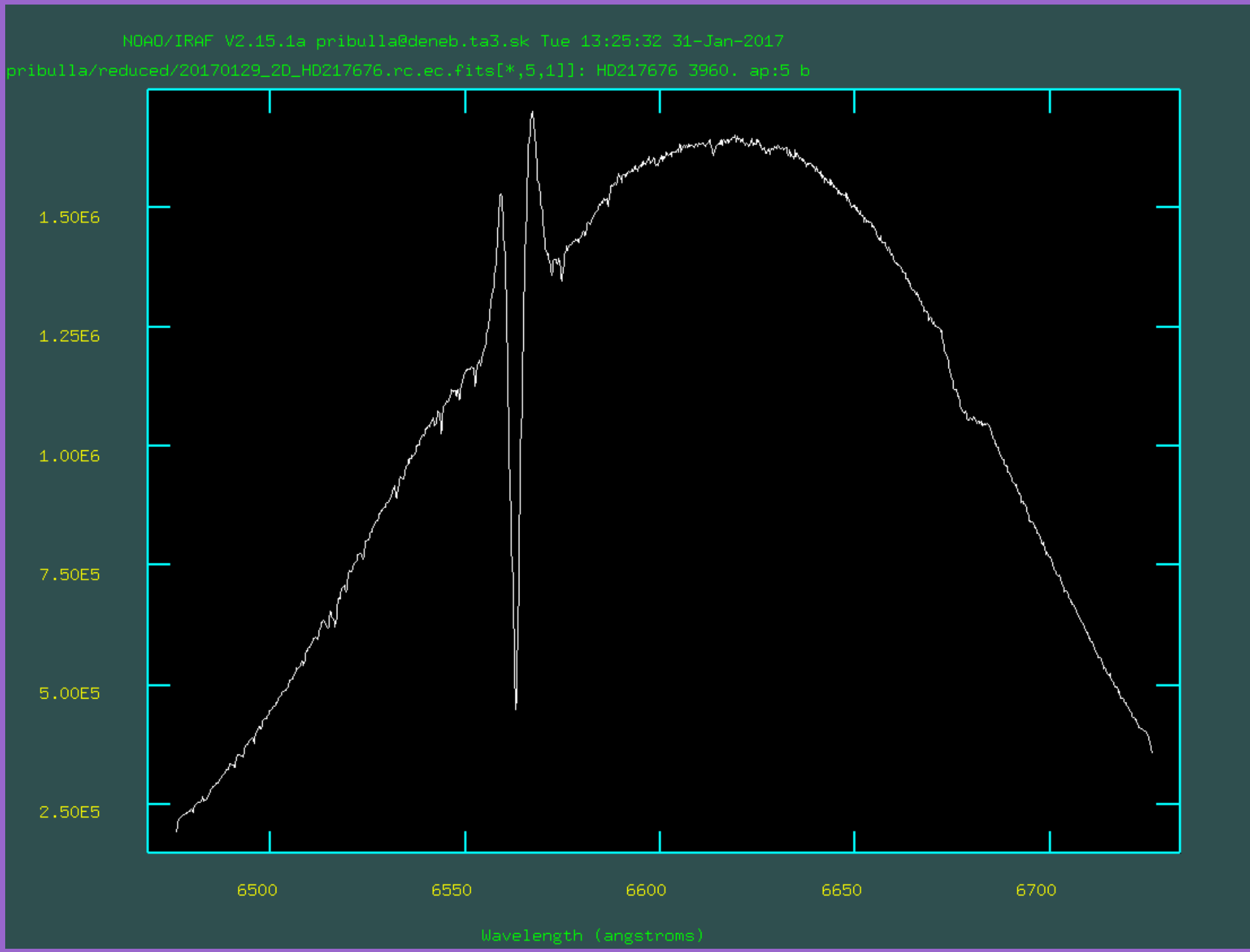
9. References and wavelength sol.

- Assigning the reference comparison spectra for the object spectra.
- Typically the spectra are assigned according to JD. It is ideal to have comparison spectra just before and just after each object spectrum

```
echelle> refspectra @object.lst @ThAr.lst
```

- Dispersion correction of the spectra (using comparisons as references):

```
echelle> dispcor @object.lst
```


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Tue 13:25:32 31-Jan-2017
pribulla/reduced/20170129_2D_HD217676.rc.ec.fits[*,5,1]]: HD217676 3960. ap:5 b
1.50E6
1.25E6
1.00E6
7.50E5
5.00E5
2.50E5
6500
6550
6600
6650
6700
Wavelength (angstroms)

10. 2D to 1D and rectification

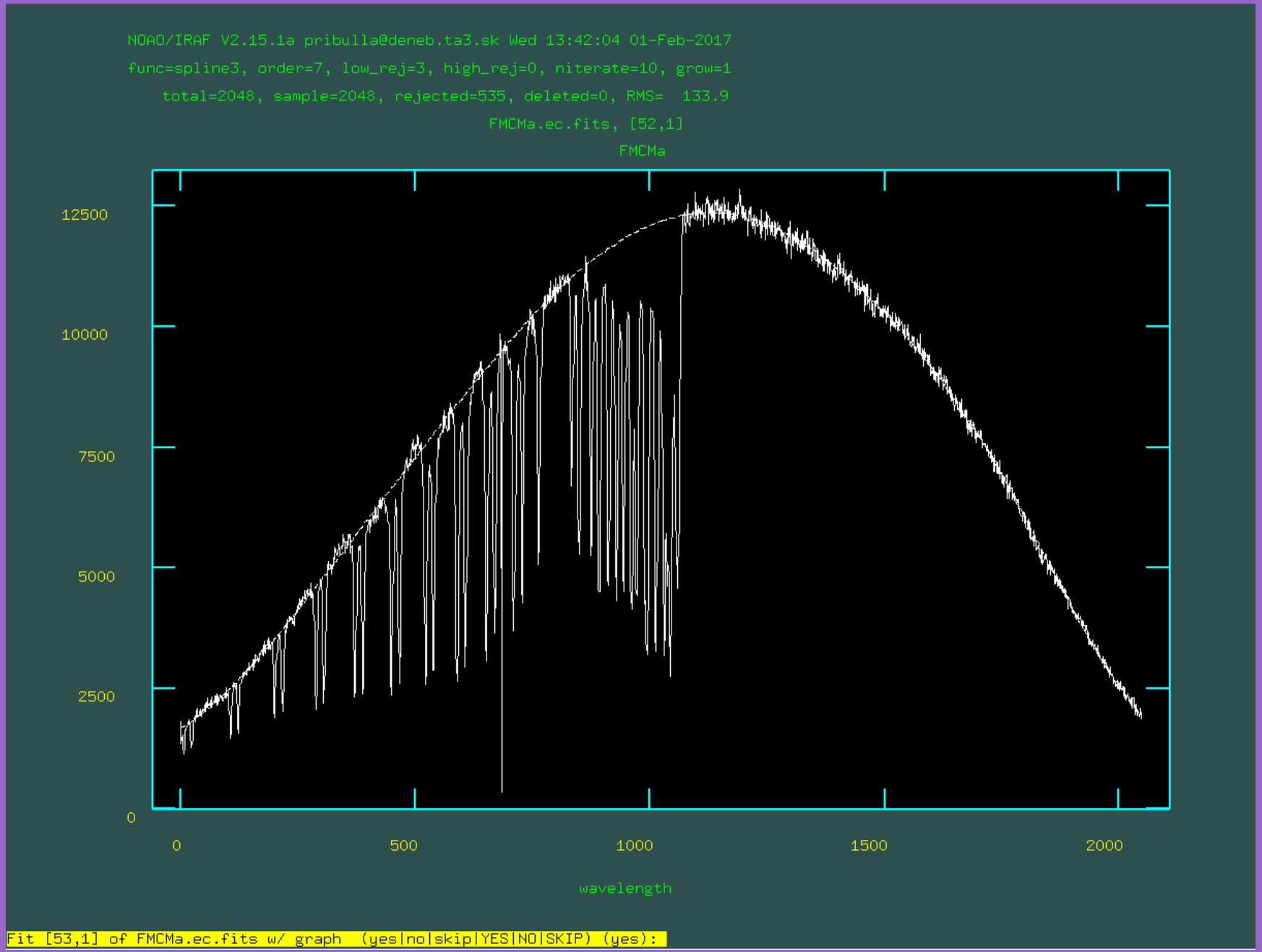
- First, individual orders are rectified to using continuum task and the fits are saved as 2D

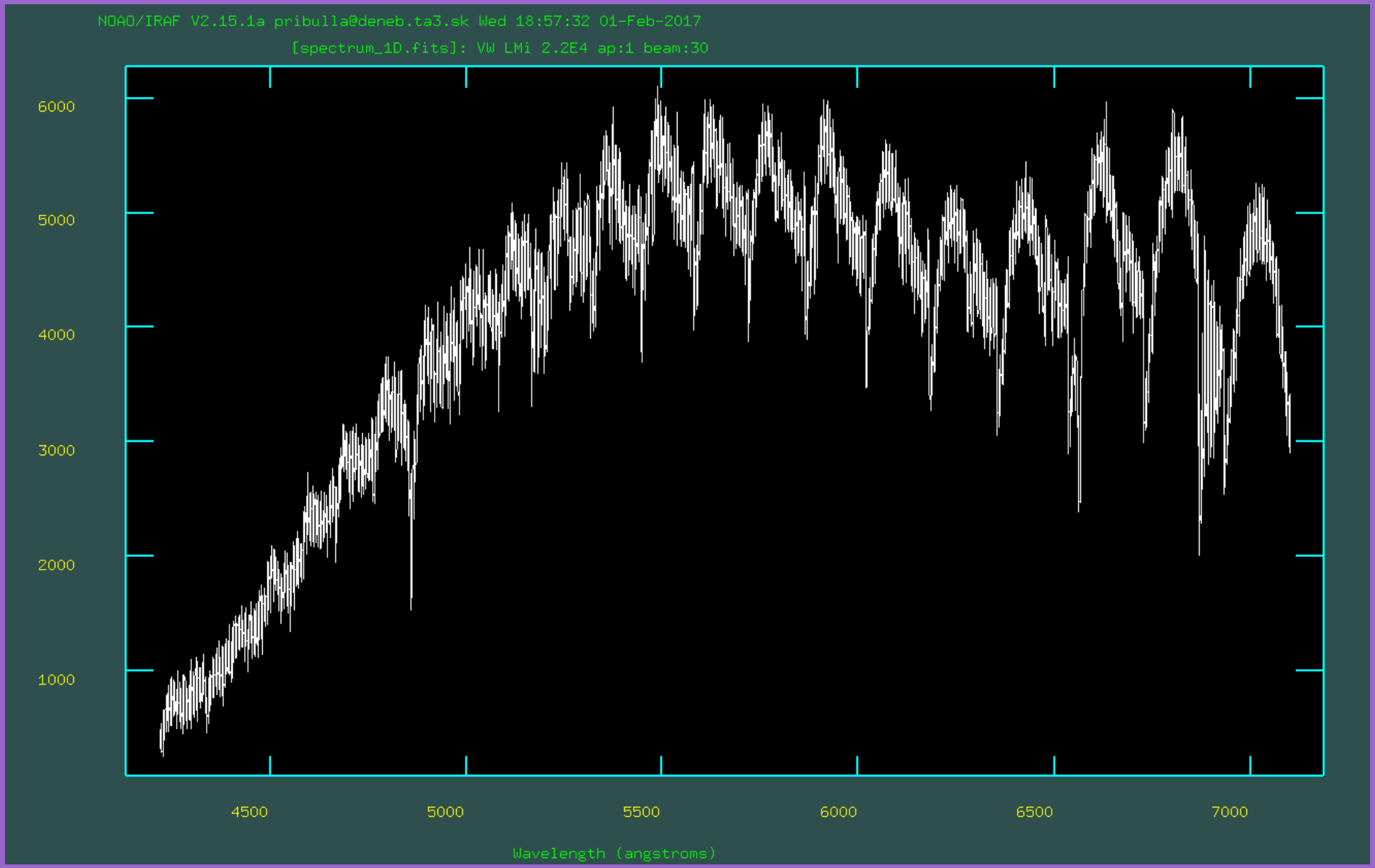
```
echelle> continuum FMCMa.ec.fits FMCMa_fit type=fit
```

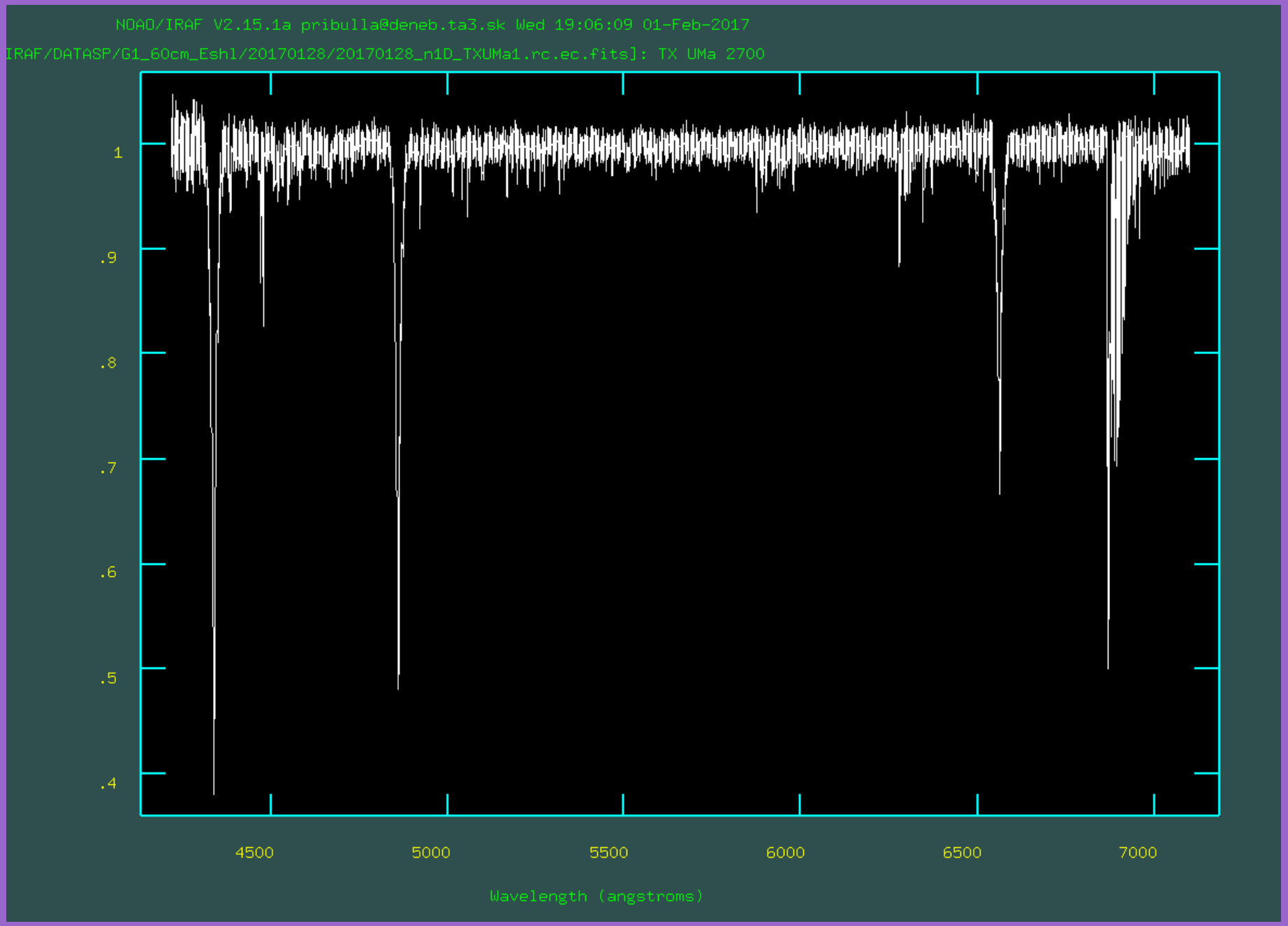
- Then 2D fits to the continuum and 2D spectra are combined to 1D spectra using scombine task:

```
echelle> scombine FMCMa_fit.fits FMCMa_fit_1D.fit group=images combine=sum w1=4220 w2=7300 dw=0.05
```

- Finally, 1D object spectra are divided by 1D continuum fits resulting in 1D combined and rectified object spectra using sarith task

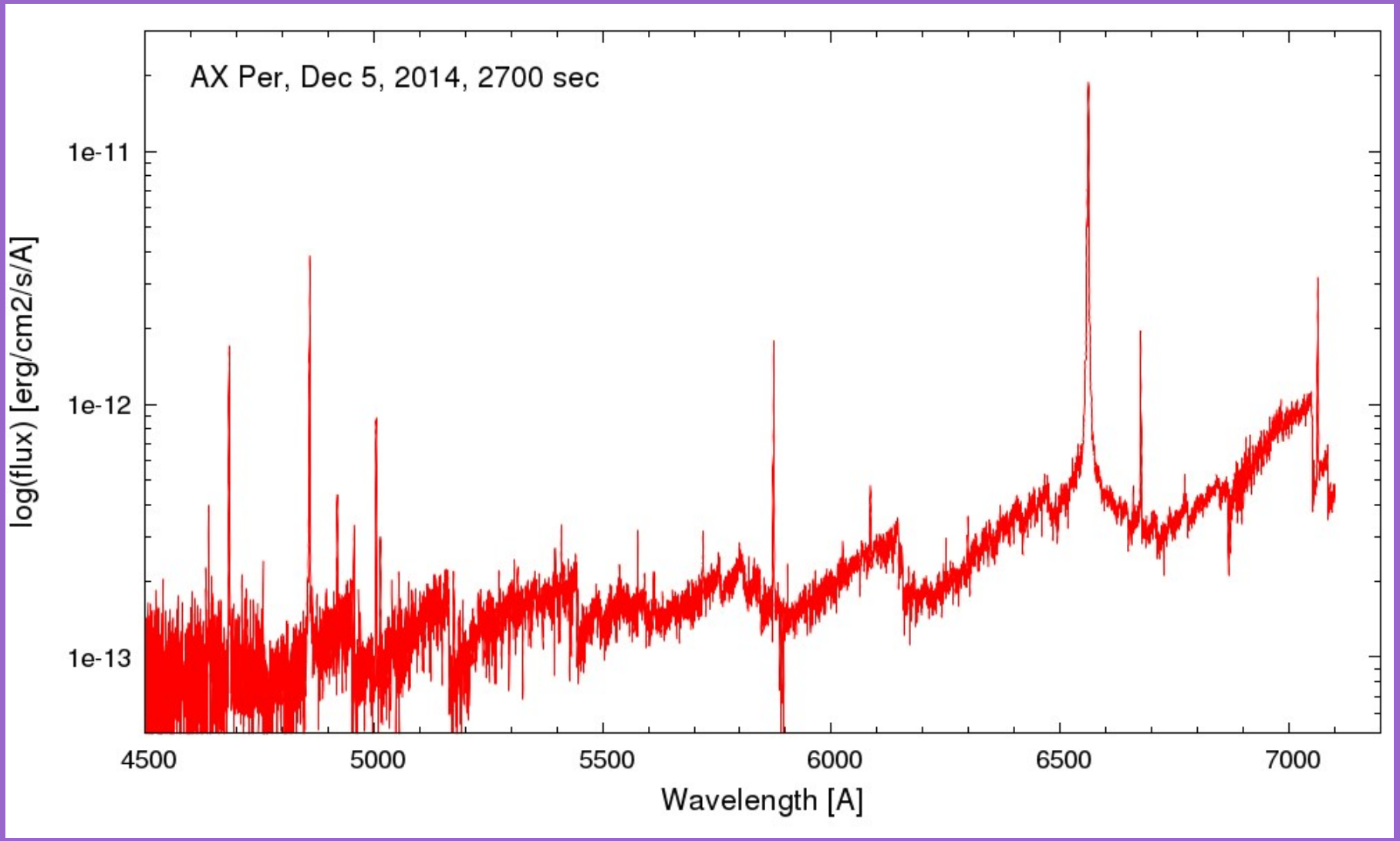

NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Wed 13:42:04 01-Feb-2017
func=spline3, order=7, low_rej=3, high_rej=0, niterate=10, grow=1
total=2048, sample=2048, rejected=535, deleted=0, RMS= 133.9
FMCMa.ec.fits, [52,1]
FMCMa
12500
10000
7500
5000
2500
0
0
500
1000
1500
2000
wavelength
Fit [53,1] of FMCMa.ec.fits w/ graph (yes|no|skip|YES|NO|SKIP) (yes):


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Wed 18:57:32 01-Feb-2017
[spectrum_1D.fits]: VW LMi 2.2E4 ap:1 beam:30
6000
5000
4000
3000
2000
1000
4500
5000
5500
6000
6500
7000
Wavelength (angstroms)


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Wed 19:06:09 01-Feb-2017
IRAF/DATASP/G1_60cm_Esh1/20170128/20170128_n1D_TXUMa1.rc.ec.fits]: TX UMa 2700
1
.9
.8
.7
.6
.5
.4
4500
5000
5500
6000
6500
7000
Wavelength (angstroms)

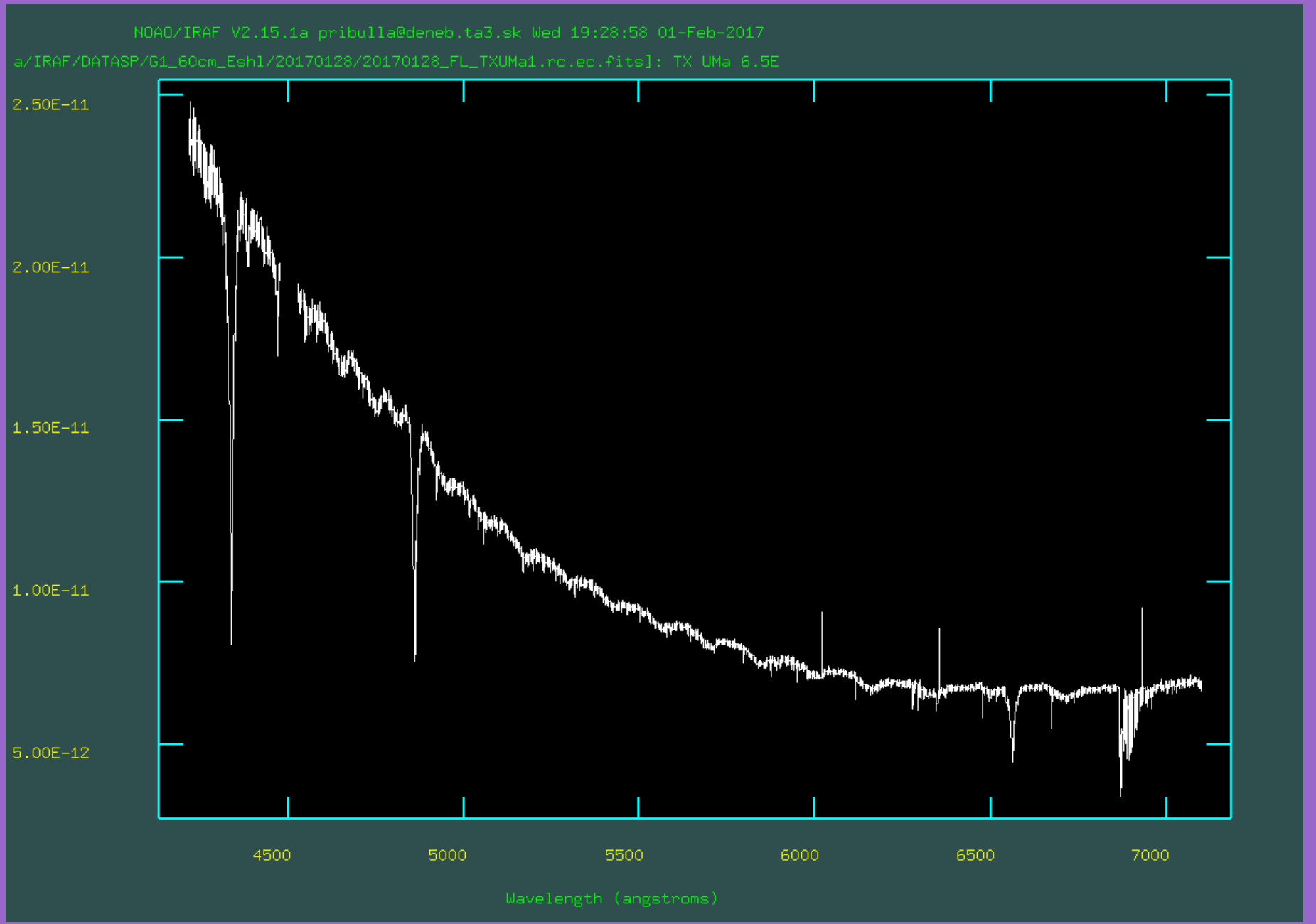
11. Spectrophotometric calibration

- Calibration to fluxes, e.g. erg/s/m^2/Å using spectrophotometric standards
- Complicated by (i) fiber opening/slit loses, (ii) chromatic atm. refraction (for low X), (iii) atmospheric extinction, k = k(λ) (iv) blaze function (v) order overlap



11.Spectrophotometric calibration

- The principal steps are:
  -adding standard star to the sensitivity file using stand task (for a selected spectrophotometric standard)
  -computing sensitivity and extinction function using sensfunc
  -calibrating continuum of the selected standard using calibrate
  -dividing spectrum of the object by the continuum fit of the standard and multiplying the result by the standard calibrating spectrum
- correcting the result for the different exposure times using sarith


NOAO/IRAF V2.15.1a pribulla@deneb.ta3.sk Wed 19:28:58 01-Feb-2017
a/IRAF/DATASP/G1_60cm_Eshl/20170128/20170128_FL_TXUMa1.rc.ec.fits]: TX UMa 6.5E
2.50E-11
2.00E-11
1.50E-11
1.00E-11
5.00E-12
4500
5000
5500
6000
6500
7000
Wavelength (angstroms)

12. Heliocentric and barycentric RVs

- Geocentric wavelength system of the spectrum is transformed to barycentric/heliocentric system using bcvcorr task

```
bcvcorr ("@object.txt", specsky=no, subgrav=no, keyra="RA", keydec="DEC",
keyeqnx="EPOCH", equinox="2000", keydate="DATE-OBS",
keytime=" ", keywhen="start", keyexp="EXPOSURE", keyhjd="HJD", hjd=0., gjd=0.,
obsname=observe[ii], savebcv=yes, savejd=no, verbose=yes, printmode=2, debug=yes)
```

- Heliocentric Julian date is computed by setjd task:

```
setjd (corrsubor, observatory=observe[inst], date="DATE-OBS",
time="TIME-OBS", exposure="EXPTIME", ra="RA", dec="DEC", epoch="EPOCH",
jd="jd", hjd="hjd", ljd="ljd", utdate=yes, uttime=yes, listonly=no, >> "log_34.txt)
```

- Wavelength system of a spectrum is then Doppler corrected:

```
dopcor (output4,output4, "-BCV", isvelocity=yes, add=yes, dispersion=yes, flux=yes, factor=3.,
apertures="*", verbose=yes)
```