

HAT-P-16 OBSERVATIONS

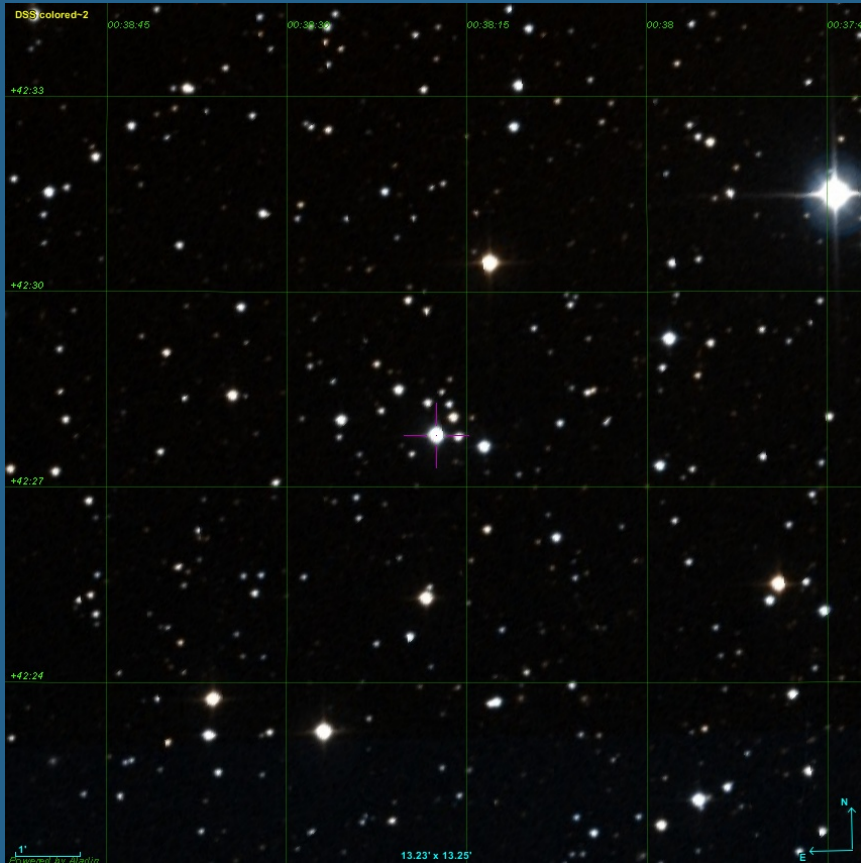
Aperture Photometry & Transit Fitting



Group IV assignment

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HAT-P-16: Host star

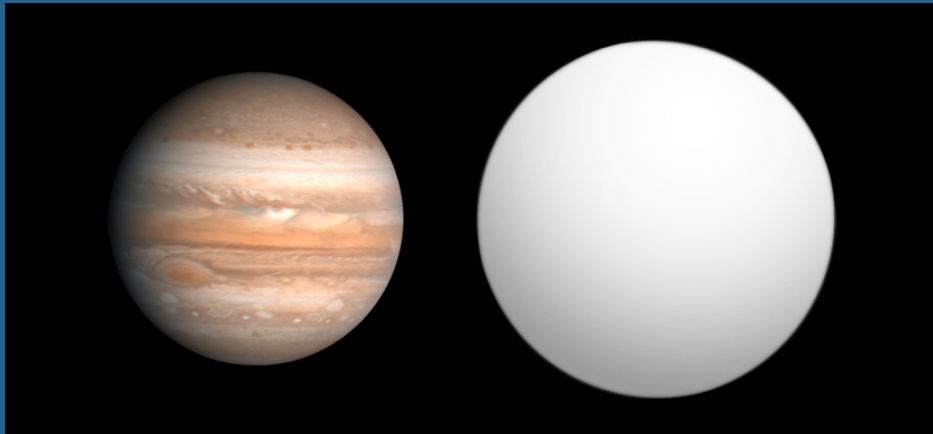


- Name: TYC 2792-1700-1
- RA (2000.0): 00:38:18.0
- DEC (2000.0): +42:27:47
- Magnitude (V): 10.91
- Distance: 232.0 (\pm 10.0) pc
- Spectral type: F8
- Mass: 1.218 (\pm 0.039) M_{sun}
- Age: 2.0 (\pm 0.8) Gyr
- Effective temp: 6158.0 (\pm 80.0) K
- Radius: 1.237 (\pm 0.054) R_{sun}
- Metallicity [Fe/H]: 0.17 (\pm 0.08)

Credit: Aladin sky atlas/DSS2

Sources: Simbad & Exoplanets.eu

HAT-P-16: Transiting planet



Credit: Aldaron

- Discovered: 2010 by HATNet Project
- Mass: $4.193 (\pm 0.094) M_J$
- Semi-Major Axis: $0.0413 (\pm 0.0004) \text{ AU}$
- Orbital Period: $2.77596 (\pm 3e-06) \text{ JD}$
- Eccentricity: $0.036 (\pm 0.004)$
- Radius: $1.289 (\pm 0.066) R_J$
- Inclination: $86.6 (\pm 0.7) \text{ deg}$
- Transit depth: 0.0101 mag

Source: Exoplanets.eu

Observations: 165 cm Telescope at MAO



Basic specifications:

- Ritchey Chretien type
- Primary mirror diameter: 165 cm
- Secondary mirror diameter: 45 cm
- Telescope focal length: 2000 cm
- FOV 8' x 8'
- Mount: Equatorial (Cross-axis)

Source: <http://mao.tfai.vu.lt/mao/>

Credit: Andrius Zigmantas

Observations: CCD Camera



Credit: Optcorp

Basic specifications:

- Chip: E2V CCD47-10
- Array size: 1024 x 1024
- Pixel size: 13 x 13 microns
- Imaging area: 13.3 x 13.3 mm
- Linear full well: 100K electrons

Source: <http://mao.tfai.vu.lt/mao/>

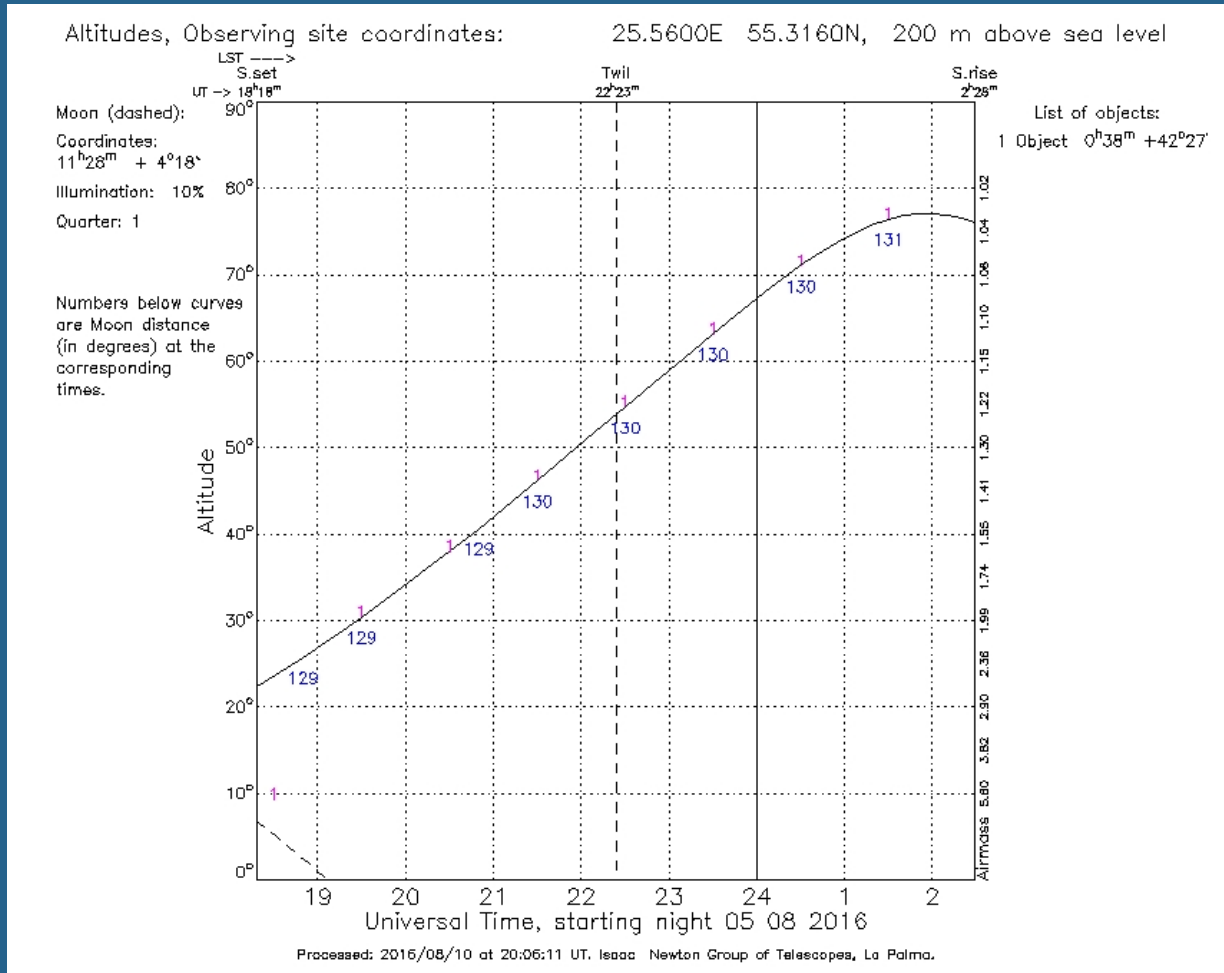
HAT-P-16: Selection

Transits predictions for ELONGITUDE: 25.56320° and LATITUDE: 55.31600°

OBJECT		BEGIN (UT/h,A)	CENTER (DD.MM. UT/h,A)	END (UT/h,A)	D (min)	V (MAG)	DEPTH (MAG)	Elements Coords
WASP-103 b	Her	19:00 34°,S	05.08. 20:18 28°,SW	21:36 19°,SW	155.58	12.1	0.0129	56459.59957+0.925542°E RA: 16 37 15.57 DE: + 07 11 00.07
HAT-P-28 b	And	21:06 37°,E	05.08. 22:43 50°,E	0:19 62°,SE	193.1	13.03	0.0162	55417.59832+3.257215°E RA: 00 52 00.27 DE: +34 43 42.9
WASP-52 b	Peg	21:58 35°,SE	05.08. 22:52 40°,SE	23:47 43°,S	108.58	12	0.0290	55793.68143+1.7497798°E RA: 23 13 58.76 DE: +08 45 40.6
HAT-P-16 b	And	21:30 47°,E	05.08. 23:02 60°,E	0:34 72°,SE	184	10.8	0.0101	55027.59293+2.77596°E RA: 00 38 17.59 DE: +42 27 47.2
Kepler-19 b	Lyr	22:18 66°,SW	05.08. 23:59 53°,W	1:40 39°,W	201.91	11.898	0.0007	54959.70597+9.2869944°E RA: 19 21 41 DE: +37 51 06
KELT-1 b	And	22:53 62°,E	06.08. 0:10 71°,SE	1:27 75°,S	153.245	10.7	0.0066	55909.292797+1.217514°E RA: 00 01 26.92 DE: 39 23 01.7

Transit predictions for 05/08 Aug. Source: ETD - Exoplanet Transit Database

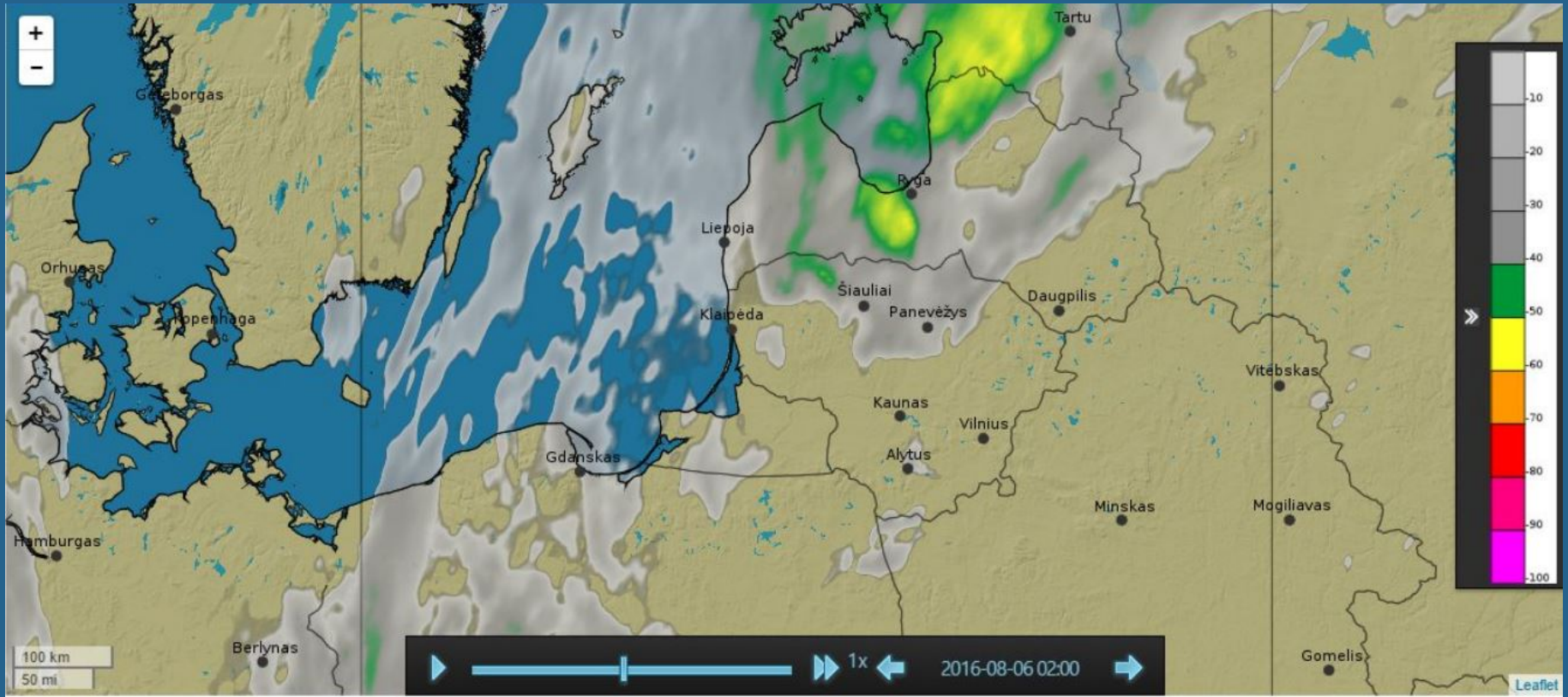
HAT-P-16: Visibility



Observations from 19:00 – 01:30 UTC

Source: <http://catserver.ing.iac.es/staralt/>

Weather conditions on 05/06 August



Cloud cover actual for 05/06 Aug

Data processing with IRAF:

- Calibration of science frames
 - Checking for weird flat features that could ruin photometry
 - Creating master bias
 - Creating master flat
 - Master dark
 - Calibrating science frames
- Finding target star and appropriate reference stars
- Creating coordinate file, and defining aperture(s)
- Performing photometry and extracting relevant info from headers

Data processing with IRAF: Calibration

The screenshot shows the IRAF environment. On the left is a graphical interface with a menu (File, Edit, View, Frame, Bin, Zoom, Scale, Color, Region, WCS) and a control panel. The control panel includes fields for File (Zero.fits), Object (6), Value (159.991), WCS, Physical X and Y, Image X and Y, Frame 2, Zoom (0.335), and Angle (0.000). Below these are buttons for file, edit, view, frame, new, new rgb, and delete.

In the center is a terminal window titled 'mao@mao-VirtualBox: ~' showing the following commands and output:

```
ec1> ls
bias_00877.fits bias_00882.fits bias_00887.fits bias_00892.fits logfile
bias_00878.fits bias_00883.fits bias_00888.fits bias_00893.fits Zero.fits
bias_00879.fits bias_00884.fits bias_00889.fits bias_00894.fits
bias_00880.fits bias_00885.fits bias_00890.fits bias_00895.fits
bias_00881.fits bias_00886.fits bias_00891.fits bias_00896.fits
ec1> displ bias_00877.fits 1
z1=1215, z2=1264,022
ec1> displ Zero.fits 2
z1=1229,105 z2=1240,512
ec1> reset stdimage=imt7
ec1> displ bias_00877.fits 1
z1=1215, z2=1264,022
ec1> displ Zero.fits 2
z1=1229,105 z2=1240,512
ec1> imexa
```

#	SECTION	NPIX	MEAN	MEDIAN	STDDEV	MIN	MAX
[269:273,259:263]	25	1233.	1233.	1,108	1231.	1236.	
[30:34,874:878]	25	1233.	1233.	1,113	1231.	1236.	
[911:915,582:586]	25	1234.	1233.	1,593	1231.	1237.	
[845:849,555:559]	25	1233.	1232.	5,083	1224.	1241.	
[374:378,355:359]	25	1235.	1234.	5,134	1225.	1247.	
[24:28,767:771]	25	1232.	1232.	3,855	1224.	1237.	

On the right is another graphical window showing a zoomed-in image of a region with a green crosshair and X/Y axes. Below the image are buttons for region, wcs, help, previous, next, and last.

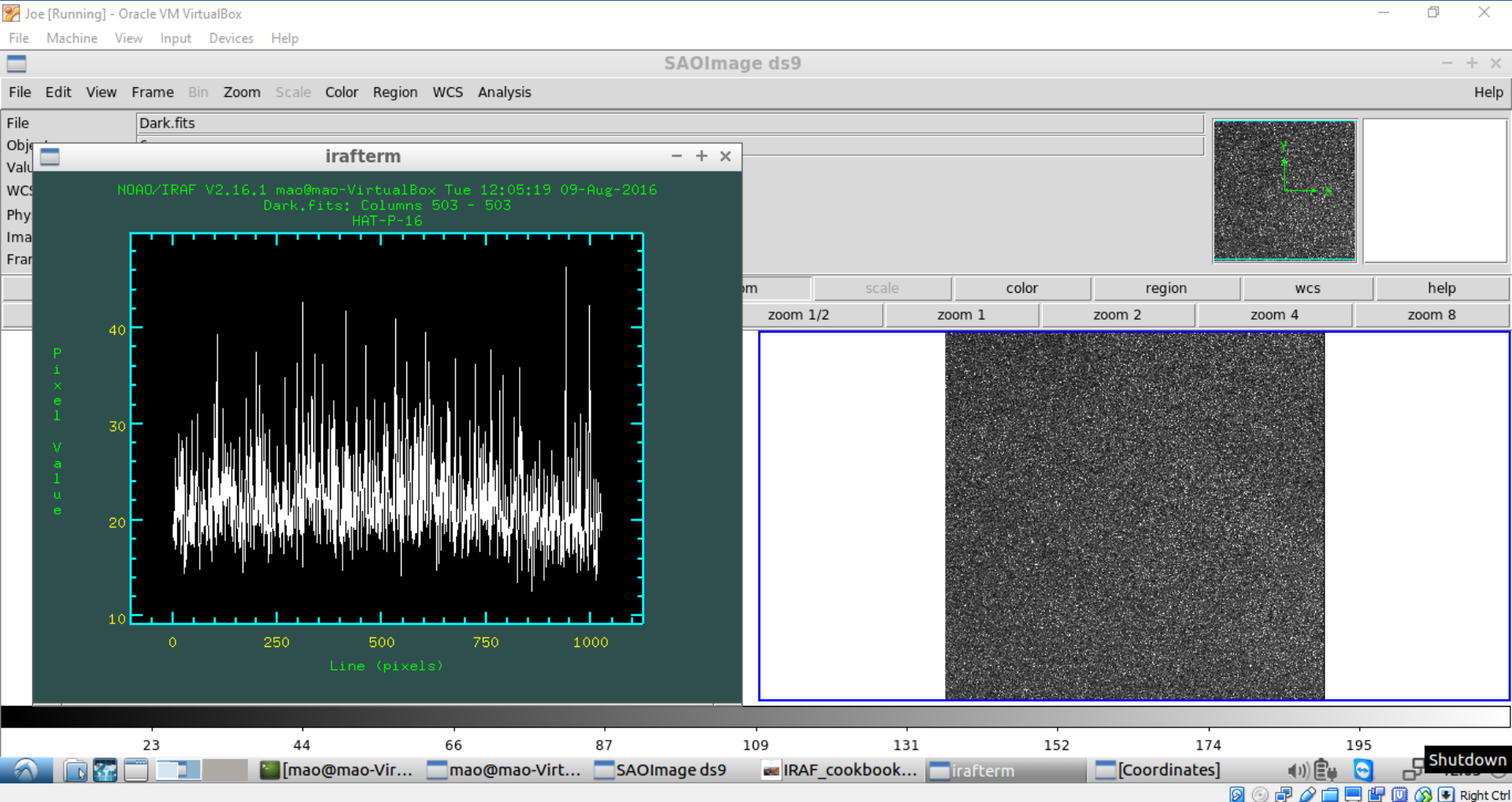
Bias frame and master bias frame → readnoise parameter

Data processing with IRAF: Calibration

The screenshot displays the SAOImage ds9 software interface. The title bar reads "SAOImage ds9". The menu bar includes File, Edit, View, Frame, Bin, Zoom, Scale, Color, Region, WCS, Analysis, and Help. The left sidebar contains a file list with "Flat.fits" selected, and various parameters such as Object (6), Value (173.927), WCS, Physical X and Y, Image X and Y, Frame 2, and Zoom (0.335). The main window shows two side-by-side grayscale images of a star field. The left image is the original data, and the right image is the result of applying the master flat, which exhibits prominent vertical banding artifacts. A small inset window in the top right shows a green crosshair on a dark background. The bottom status bar shows a coordinate scale from 23 to 195 and a taskbar with various system icons and the time 11:23.

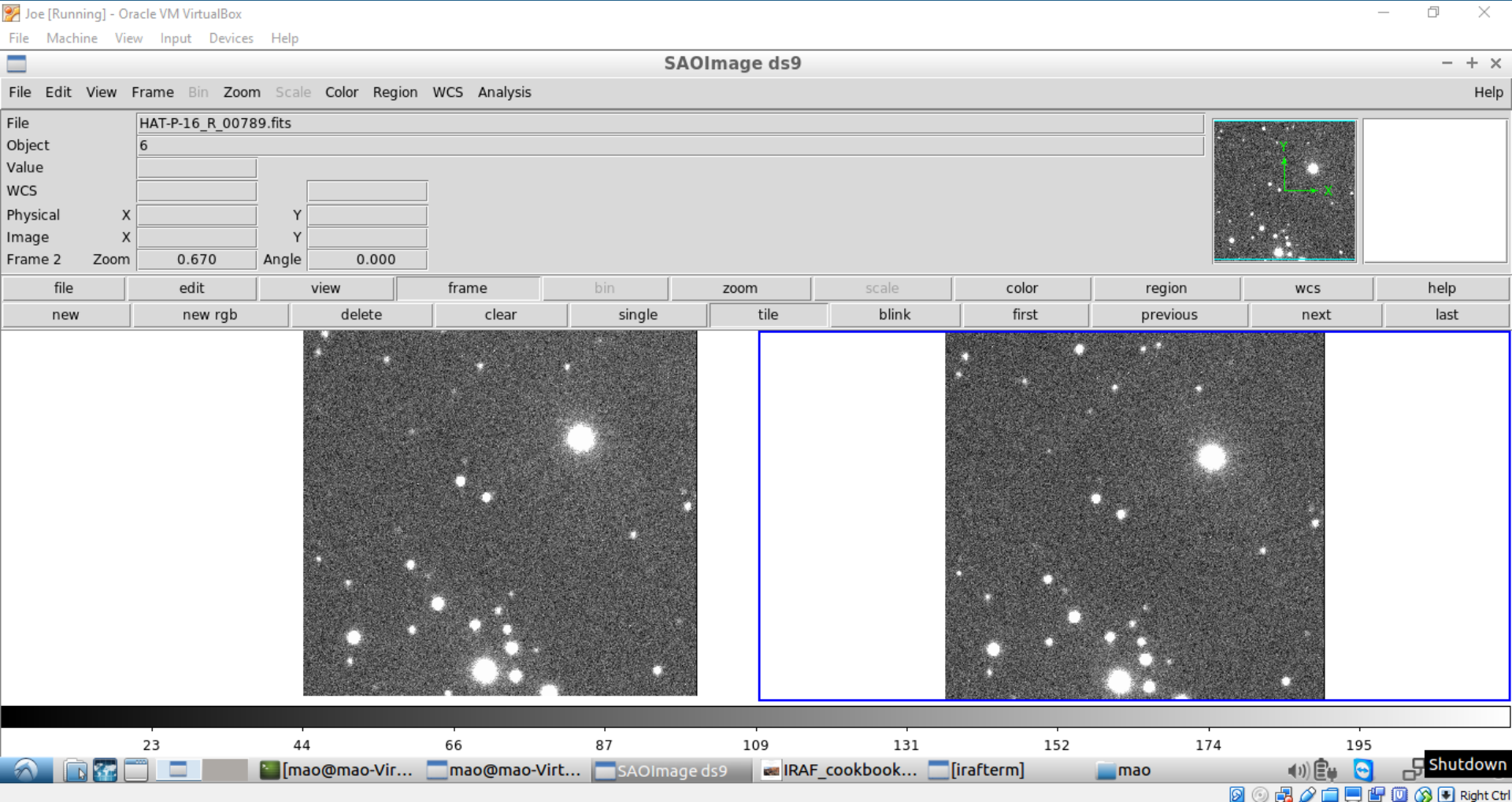
Really really bad master flat....

Data processing with IRAF: Calibration



Master dark not used as exposure was only 3 seconds

Data processing with IRAF: Calibration



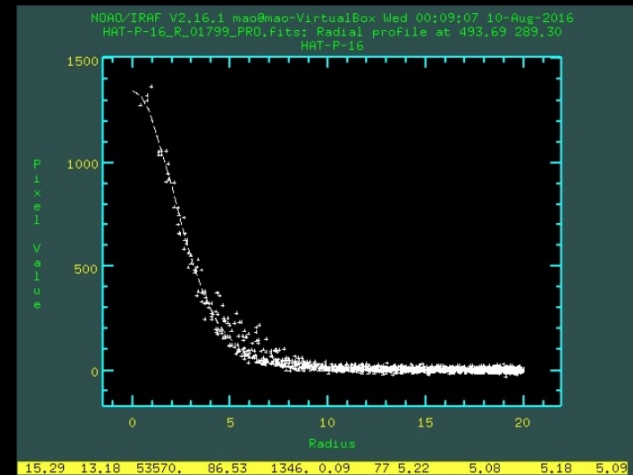
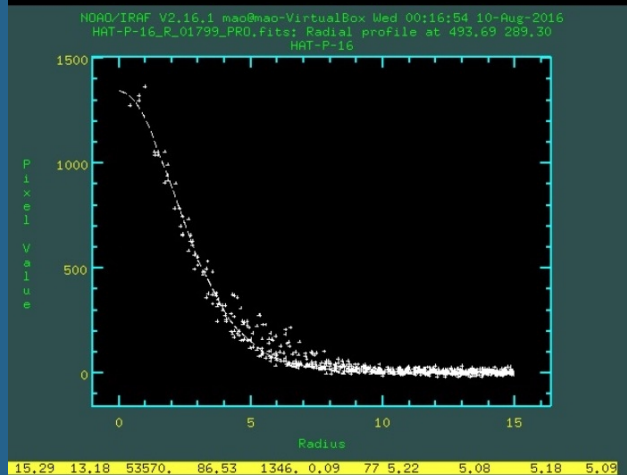
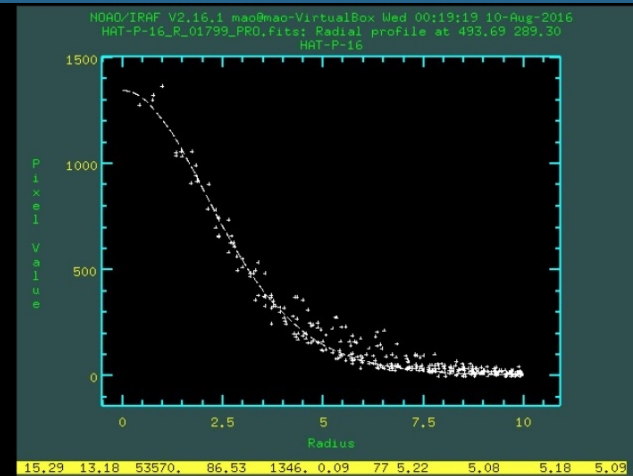
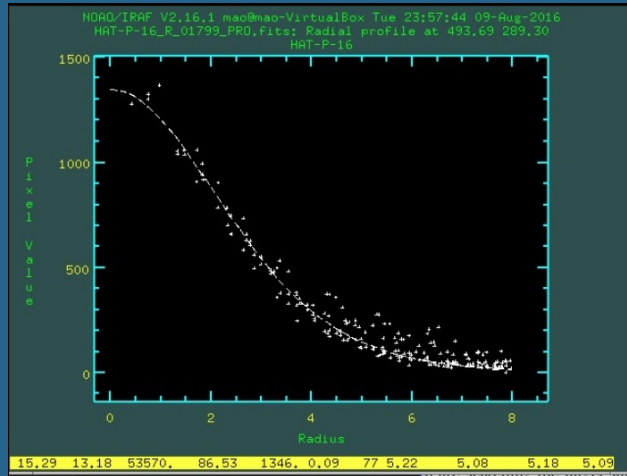
Reduced frame vs original science frame (Spot the difference!)

Data processing with IRAF: Reference stars

The screenshot displays the SAOImage ds9 software interface. The main window shows a grayscale astronomical image of a star field. Five stars are circled in yellow and labeled with numbers 1 through 5. The interface includes a menu bar (File, Edit, View, Frame, Bin, Zoom, Scale, Color, Region, WCS, Analysis) and a toolbar with buttons for file, edit, view, frame, bin, zoom, scale, color, region, wcs, help, about, open, save image, header, page setup, print, and exit. The left panel shows the file name 'HAT-P-16_R_00789_PRO.fits' and various parameters like Object (6), Value, WCS, Physical X and Y, Image X and Y, Frame 1, Zoom (0.694), and Angle (0.000). A small inset window in the top right shows a coordinate system with X and Y axes. The bottom status bar shows the file path and the time 15:56.

Reference stars selection ($0.5 < \text{Intensity}_{\text{Target star}} < 3$)

Data processing with IRAF: Apertures



Radial profiles of the same star with different aperture radii

Data processing with IRAF

Header file missing two parameters:

airmass

- Arbitrarily set to 1.0

rdnoise

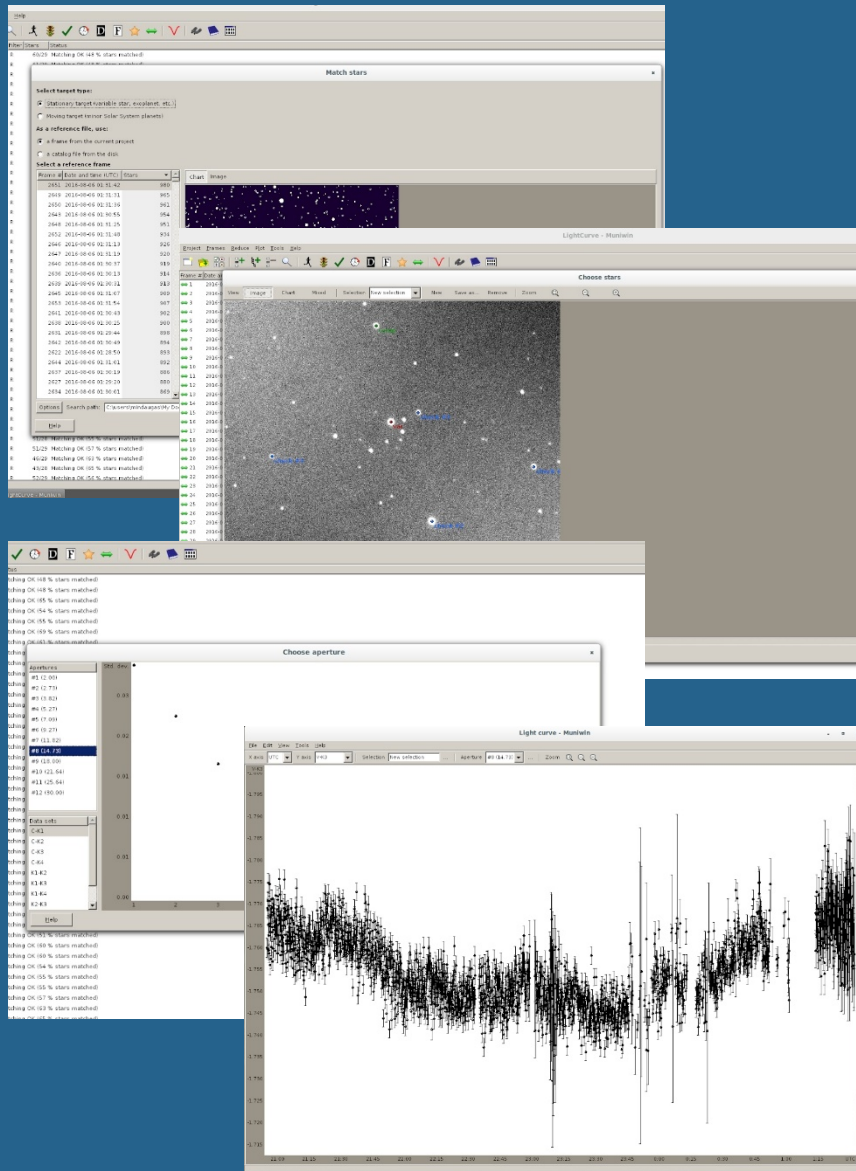
- Obtained from standard deviation of master bias frame.

Files are then ready for aperture photometry.

Script takes flux from each aperture and places in ascii file for later use

```
mao@mao-VirtualBox: ~
DATE = '2016-08-09T11:17:23' / file creation date (YYYY-MM-DDThh:mm:ss UT)
DATE-OBS= '2016-08-06T01:31:51.819' / Date of observation(UTC time)
TIME = 5511.819 / UT in seconds since 00h UT
TEMPERAT= -23.71515 / CCD temperature
TEMPERHS= 27.76177 / Heat sink temperature
READOUT = 0. / Readout time (seconds)
GAIN = 2. / [e-/ADU] CCD gain
CCDBIN1 = 1 / CCD binning factor
CCDBIN2 = 1 / CCD binning factor
OBSERVAT= 'MAO' /
LATITUDE= '55:18:57' /
LONGITUD= '25:33:47' /
ALTITUDE= '200' /
TELESCOP= 'T165' /
INSTRUME= 'CCD4710ALT' / Head type
IMAGETYP= 'OBJECT' / Type of the image
FILTER = 'R' /
OBSERVER= 'E. Pakstiene' /
RA = '00:38:17.59' /
DEC = '+42:27:47.2' /
EQUINOX = '2000.0' /
FOCUS = ' /
STIME = '-1.59046' / Local Sidereal Time
TRA = '4.08505e-34' / telescope RA
TDEC = '-1.52253e-05' / telescope DEC
AIRMASS = ' /
HOST = 'eee.mao.lt' /
HISTORY Written by "Camera V 3.0(2008-2009/05/20)" (R.Janulis jr@nserv.itpa.lt)
NCSDIM = 2
LTM1_1 = 1.
LTM2_2 = 1.
WAT0_001= 'system=physical'
WAT1_001= 'wtype=linear'
WAT2_001= 'wtype=linear'
BI-FLAG = 'Aug 9 14:17 Zero level correction image is ../bias/Zero.fits'
CCDSEC = '[1:1024,1:1024]'
CCDMEAN = 6678.701
CCDMEANT= 1155219443
CCDPROC = 'Aug 9 14:17 CCD processing done'
JD = 2457606.56381157
HJD = 2457606.56514905
LJD = 2457606.
ec1>
```


Data processing with C-Munipack



Simple steps:

- Generation of:
 - master bias,
 - master dark,
 - master flat frames
- Calibration of science frames
- Identification of stars in science frames
- Selection of reference stars
- Photometry
- Light curve
- For comparison with Python

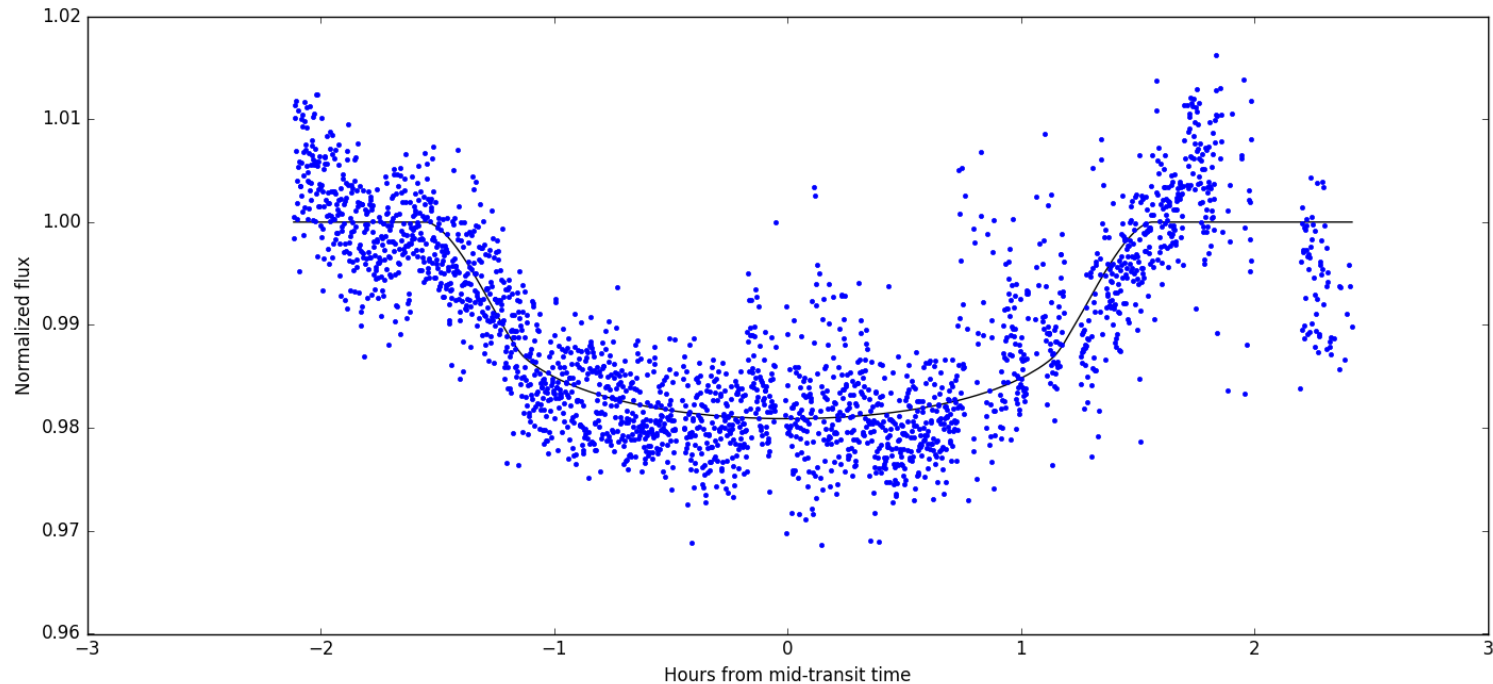
Parameters needed for transit fitting

```
Editor - Canopy
File Edit View Search Run Tools Window Help
TransitFitting_MCMCEdit.py
59 time = time[index]
60 diff_lc = diff_lc[index]
61 err_diff = err_diff[index]
62 #####
63 # Create MandelAgolLC object with circular orbit and quadrat
64 ma = ft.MandelAgolLC(orbit="circular", ld="quad")
65
66 # Set parameters for transit:
67 ma["per"] = 2.77596
68 ma["i"] = 86.6
69 ma["a"] = 7.1544
70 ma["T0"] = 0.
71 ma["p"] = 0.092902
72 ma["linLimb"] = 0.5214#a from vizier database, claret (2000)
73 ma["quadLimb"] = 0.2350
74 ma["b"] = 0.
75
76 ma.thaw(["p", "T0"])
77
78 #####
79 # Create detrending object:
80 df = DetrendFunction1()
81 # Set parameters for detrending:
82 df["off"] = 1.01
83 df["lin"] = -0.01
84 df["qua"] = 0.01
85 df.thaw(["off", "lin", "qua"])
86
```

The diagram illustrates the geometry of a transit. A large circle represents the star with radius R_* . A smaller circle represents the planet with radius R_p . The planet is shown at two positions during the transit, labeled 1 and 2. The impact parameter is given as $bR_p = a \cos i$. The transit is divided into four quadrants labeled 1, 2, 3, and 4. The vertical axis is labeled ΔF .

Used Simbad & Vizier databases to obtain parameters

Results: least square transit light curve



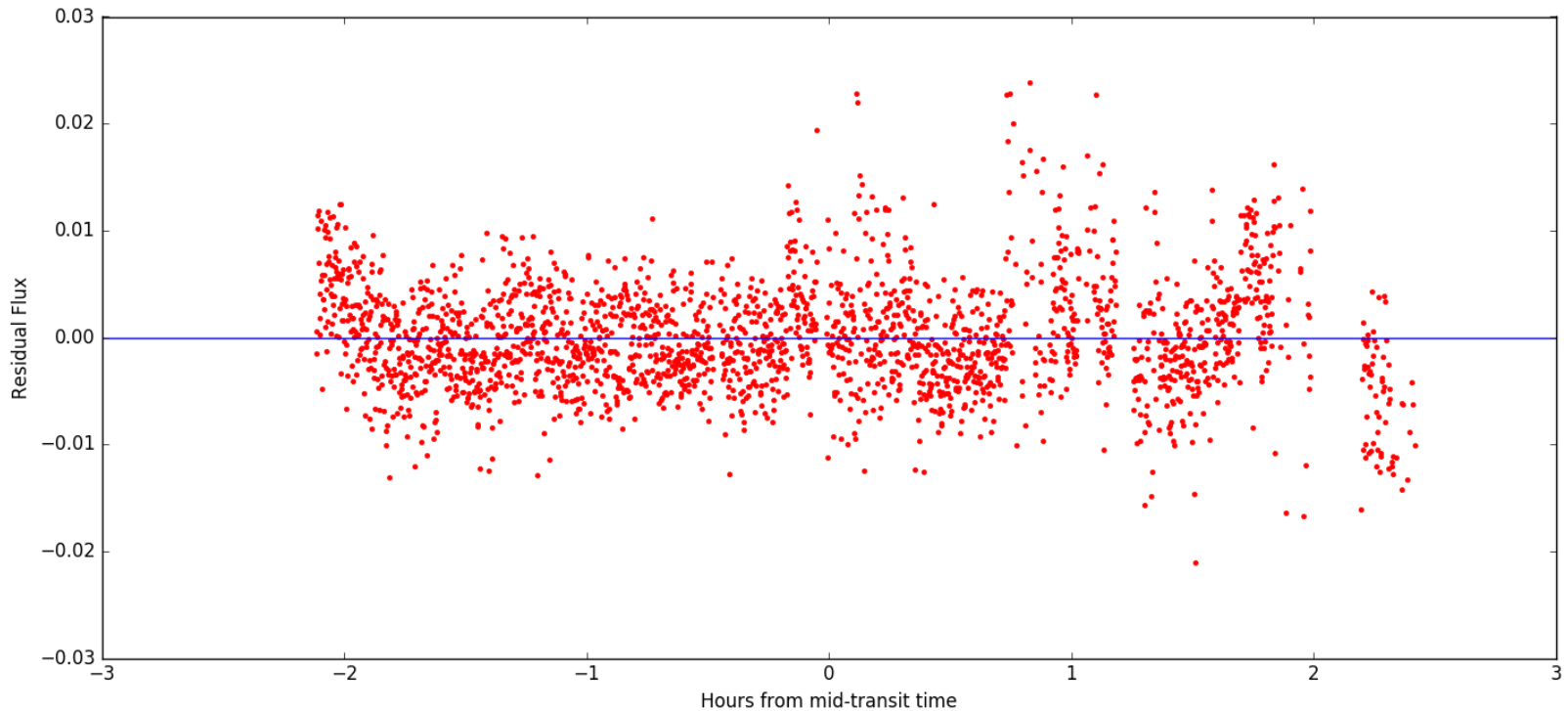
Parameters:

Ratio of Planet/Star Radius (p) = 0.1260947

Epoch of Transit (T_0) = 2457606.459722 + 0.000215498 (JD)

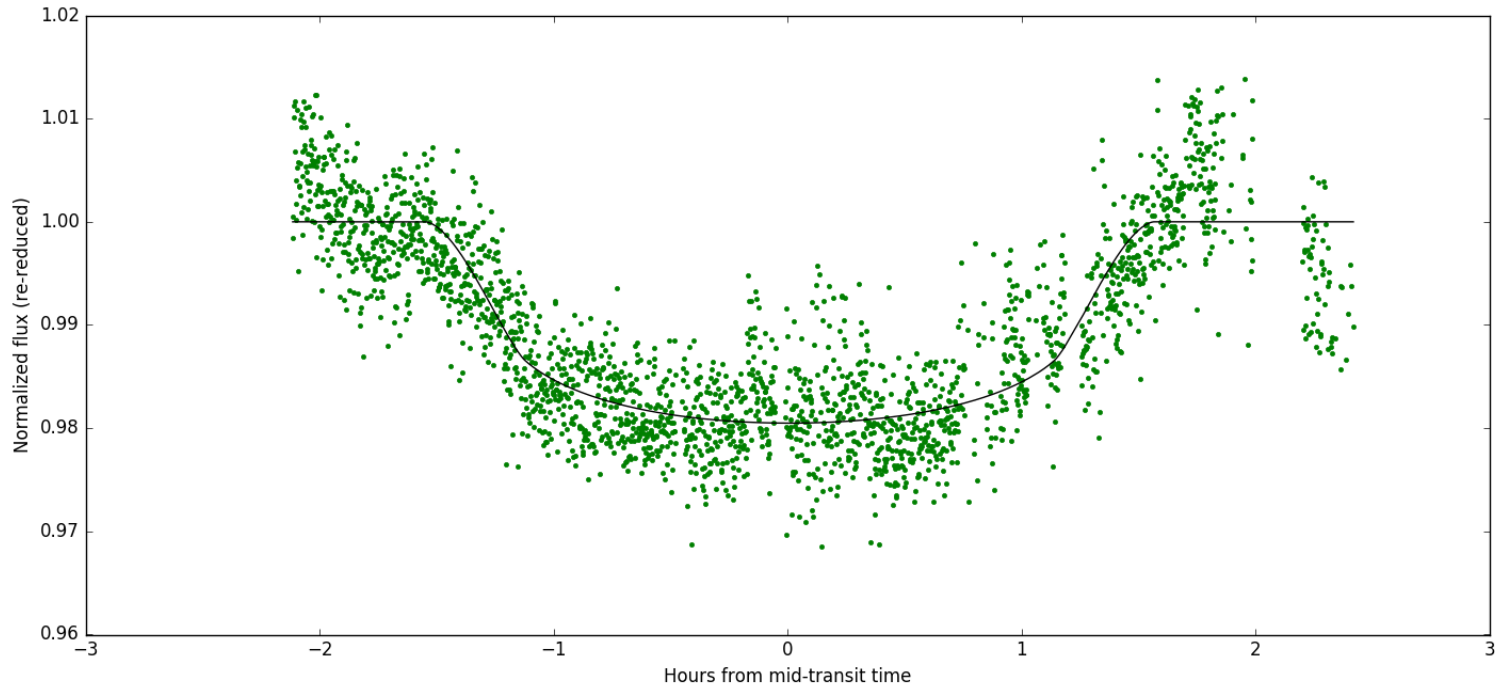
Stdev of Residuals (σ) = 0.0050977

Results: residuals



Cut data points > 3 standard devs from mean
perform fitting algorithm again

Results: re-reduced light curve

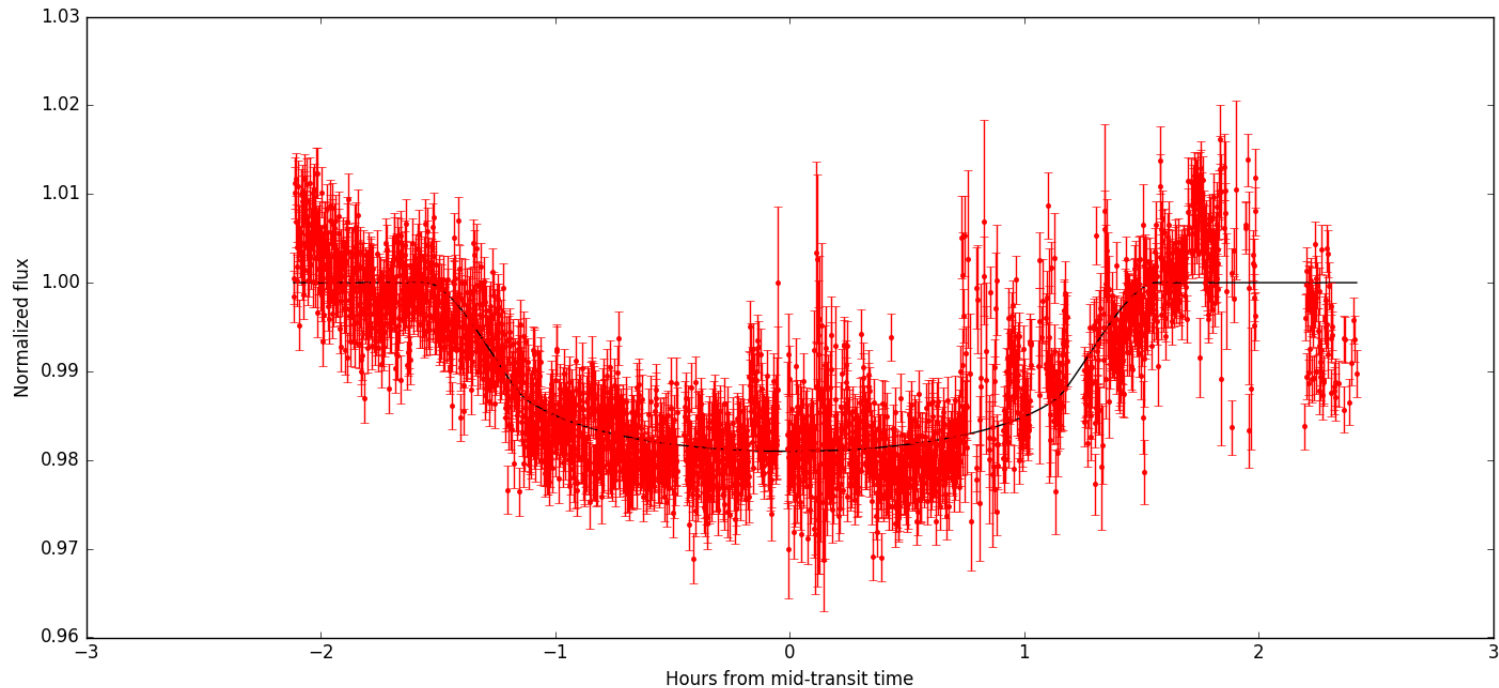


New parameters:

$$p = 0.12742814$$

$$T_0 = 2457606.459722 + 0.0003649 \text{ (JD)}$$

Results: MCMC transit light curve



Perform Markov Chain Monte Carlo (MCMC) method to find parameters (T_0 , p) for transit fit.

$$p = 0.126 \pm 0.002$$

Giving:

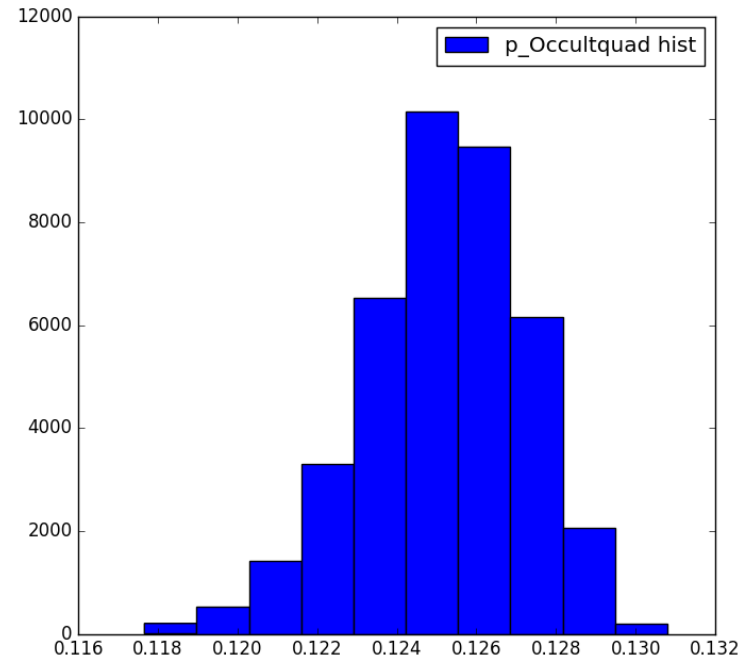
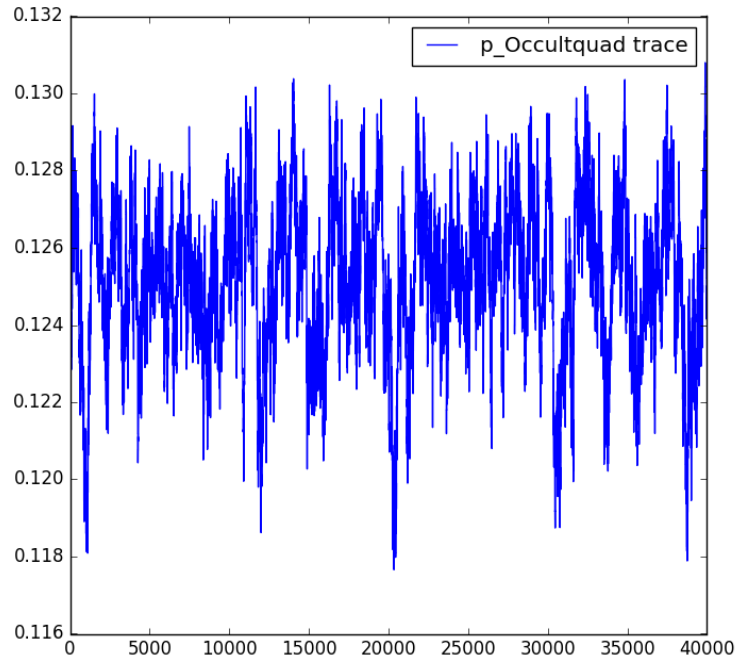
Accepted values:

$$T_0 = 0.0002 \pm 0.0004 \text{ (JD)}$$

$$1.55 \pm 0.03 R_J$$

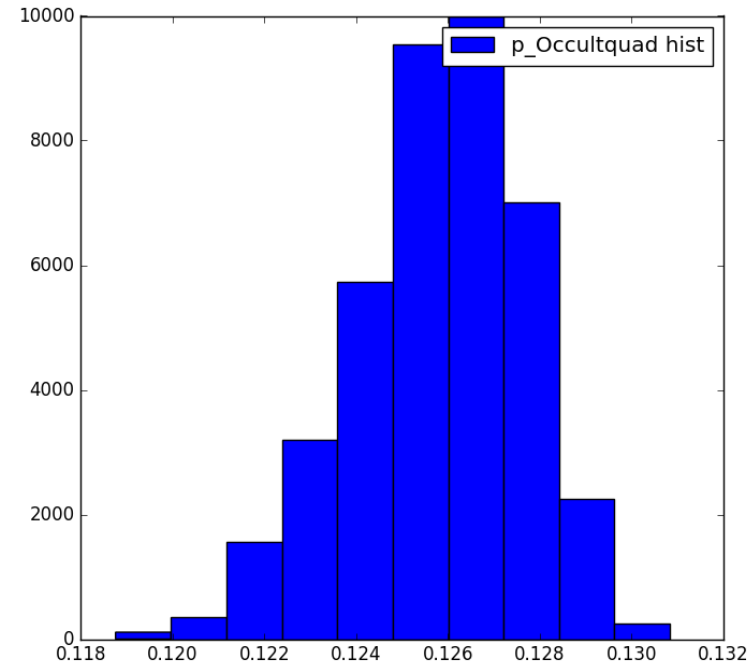
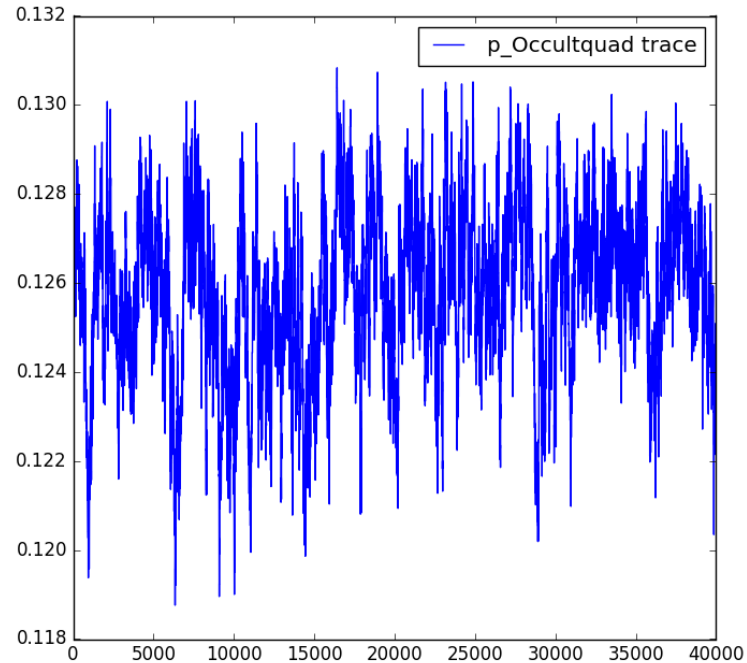
$$1.282 \pm 0.087 R_J$$

Results: Transit parameter chain



Markov chain for parameter p , with no burn (40,000 iterations)

Results: Transit parameter chain with burn

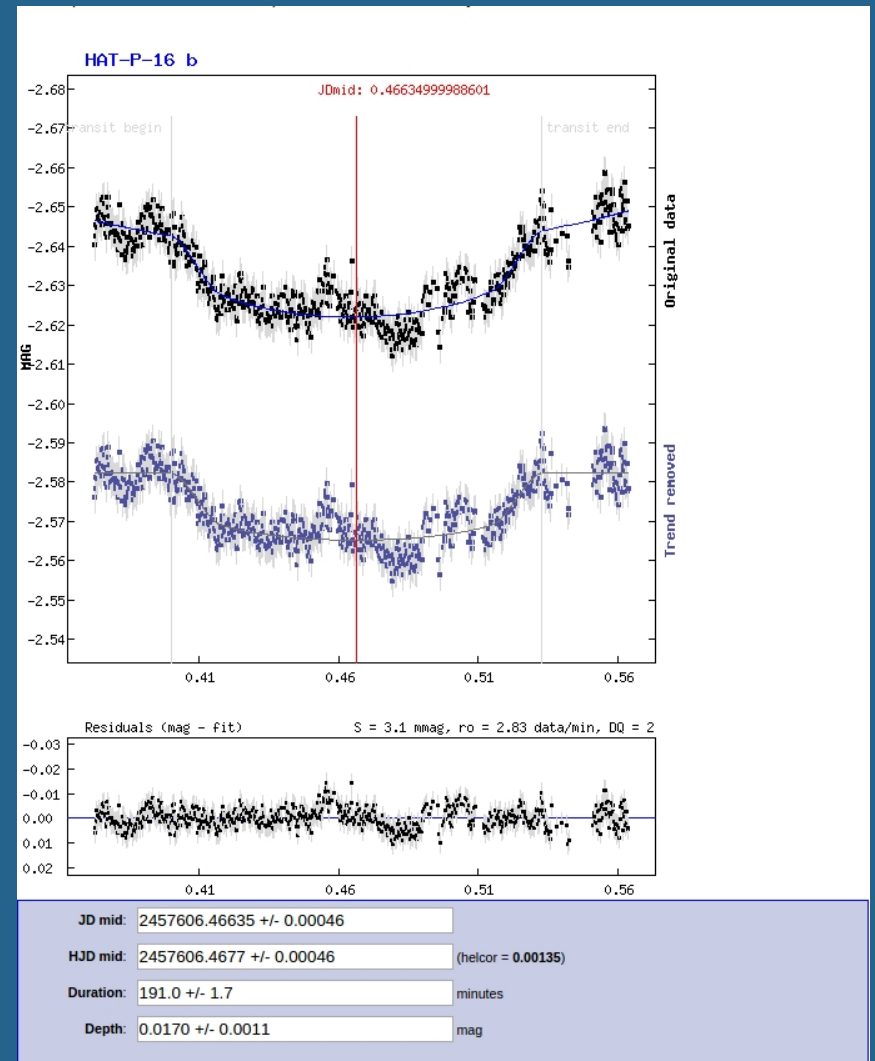


Markov chain for parameter p , with burn (40,000 iterations)

Results: C-Munipack + ETD

Basic results of transit data fitting in ETD (Exoplanet Transit Database)

- Mid-transit time (JD): $2457606.46635 \pm 0.00046$
- Duration: 191.0 ± 0.00046 min.
- Transit depth: 0.0170 ± 0.0011 mag



Conclusions

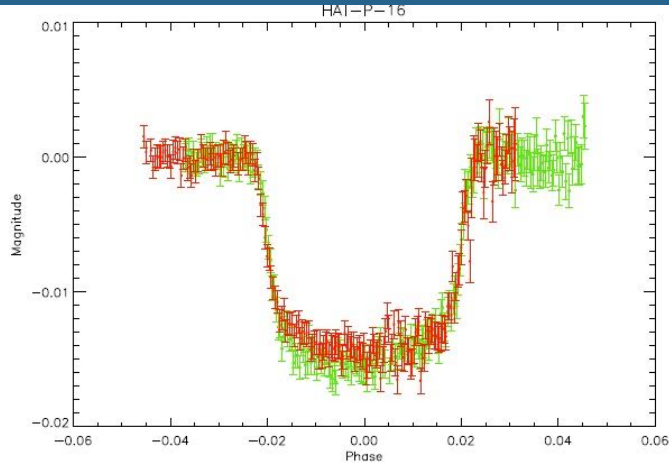
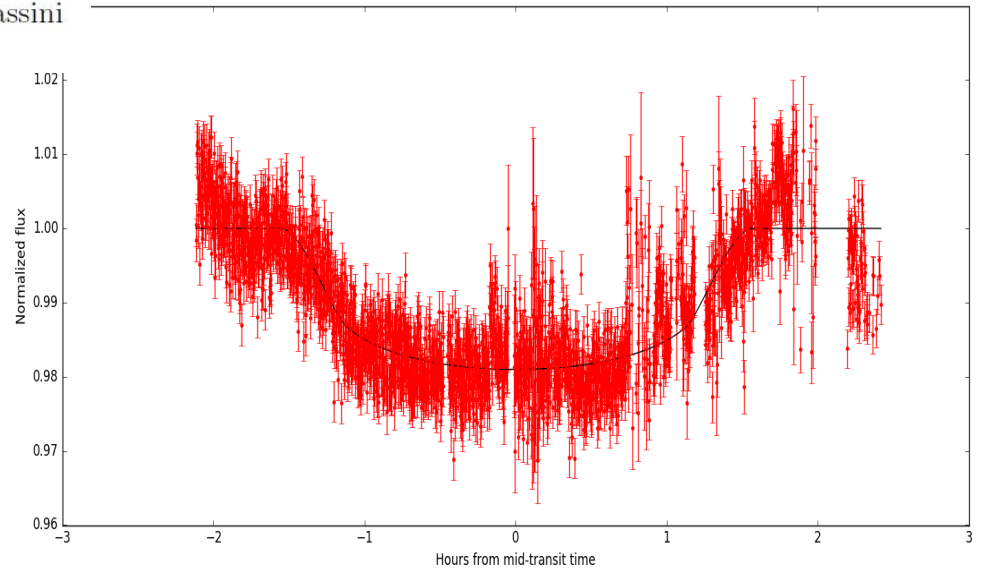


Fig. 1. Observations of the October 2012 transit of HAT-P-16. The green points show the data from the CA 1.23 m telescope, and the red points the data from the Cassini telescope.

Source: Ciceri et al. (2011)



Conclusions

- success in obtaining transit from obtained light curve - goal of summer school achieved!
- IRAF sufficient for
 - gaining transit from data,
 - Introducing students to aperture photometry
- demonstrated simple instrumentation can detect transits of Hot Jupiters (Not so 20 years ago!)
- even smaller exoplanets observable with:
 - better weather
 - improved reduction (flat, dark)
- prospect for more “simple” exoplanet research (e.g. GJ1132) and future summer-schools

Acknowledgements

Many thanks to Carolina & Erika!