The Transit Light Curve of HAT-P-5b

Jashandeep Sohi
Department of Astronomy, University of Washington, Seattle, USA
jashandeep.s.sohi@gmail.com

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Abstract

In this report we produce a transit light curve of the extrasolar planet, HAT-P-5b, as it transits its parent star HAT-P-5. Along the way, we also discuss the procedure used to remove various sources of noise from CCD images, so they can be used for scientifically valid measurements. We discuss a script written in python which can be used to automatically perform aperture photometry on multiple frames, even if the field of view drifts dramatically from frame to frame. From our measured transit light curve, we calcualted the depth magnitude to be 0.0238 ± 0.012.

1 Introduction

A light curve is a simple plot of the light intensity, or magnitude, of some celestial object with respect to time. Using light curves, an astronomer can detect and study extrasolar planets hundreds of light years away. The method is relatively simple: Measure a light curve for some candidate star and look for a slight periodic decrease in its magnitude. A periodic decrease in its magnitude could indicated the presence of an orbiting planet. If a planet orbits some distant star, it would appear to transit in front of the star's disk periodically as seen from earth. During the transit, it would block some of the star's light from reaching earth, and thus, cause a slight decrease in the star's light curve. Such a light curve is called a transit light curve (See Figure 1).

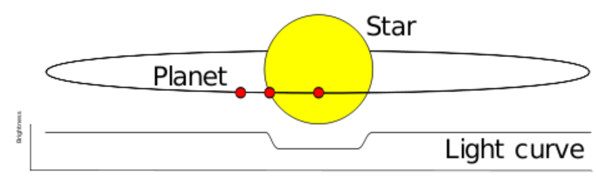

Figure 1: An illustration of a planetary transit. (Wikimedia Foundation, 2012)

However, there are some limitations to this method. Firstly, it is only applicable to planets whose orbits are perfectly aligned with the astronomer's vantage point. Thus, this method can not always answer the question of whether there are any planets orbiting a particular star. Secondly, a periodic decrease in the light curve need not be necessary caused by a transiting planet. Other celestial systems, such as eclipsing binary stars, can also show a periodic decrease in their light curves. Generally, planets discovered through this method require further confirmation using different methods, such as radial velocity measurements. Once the planet is confirmed, its transit light curves can be used to determine some important properties about it and its orbital system, such as the radius of the planet, period of the orbit, orbital speed, and the duration of the transit.

HAT-P-5b is one such transiting extrasolar planet. It was discovered by Bakos et al. on October 9, 2007 using data from the HAT-7 telescope at the Fred Lawrence Whipple Observatory (FLWO) and the HAT-9 telescope at the Submillimeter Array (SMA) site in Mauna Kea, both part of the HATNet project. It was first detected using a transit light curve and later confirmed using radial velocity measurements. The planet is a hot Jupiter with a mass 6% greater than Jupiter and a radius 26% greater than Jupiter. It orbits around a 12th (visual) magnitude star, HAT-P-5, in the constellation Lyra, approximately 1,100 light years away from earth, and has an orbital period of about 2.78 days. Bakos et al. used transit light curves, spectrometry and stellar evolution models to determine the properties of the star and the planet. Table 1 summarizes these properties.

In this report, we produce a transit light curve of the planet, HAT-P-5b, during an expected transit across its parent star, HAT-P-5. However, before doing so, we shall first discuss some details about the observations and then the procedure used to remove various sources of noise from the collected frames. Then, we discuss how these noise corrected frames were processed to produce a transit light curve. And finally, we end with a discussion on the transit light curve produced.

HAT-P-5	
Constellation...	Lyra
Right ascension...	18h 17m 37.299s
Declination...	$+36°37'16.88"$
Distance (pc)...	340 ± 30
Mass ($M\odot$)...	1.160 ± 0.062
Radius ($R\odot$)...	1.167 ± 0.049
$\log(L\star/L\odot)$...	0.187 ± 0.064
$T_{eff}(K)$...	5960 ± 100
Specral type...	G
M_v...	4.32 ± 0.18
m_v...	11.95 ± 0.24
Age (Gyr)...	2.6 ± 1.8
HAT-P-5b	
Transit Duration (days)...	0.1217 ± 0.0012
Period (days)...	2.788491 ± 0.000025
Eccentricity...	0
Semimajor axis (AU)...	0.04075 ± 0.00076
Inclination (deg)...	86.75 ± 0.44
Orbital Speed (km/s)...	159.5
Mass (M_J)...	1.06 ± 0.11
Radius (R_J)...	1.26 ± 0.05
$R_p/R_\star$...	0.1106 ± 0.0006
Density...	0.66 ± 0.11

Table 1: Star and Planet Properites from Bakos et al.

2 Observations

Observations of HAT-P-5 were made at the Astronomy Wing Optical Observatory (AWO), located at the University of Washington in Seattle (GMT +7; +47° 39' 10.08", -122° 18' 40.21"; 30 meters above sea level). Observations were made with a 16 inch Meade LX200ACF telescope, used in conjunction with a ST-10XME CCD camera. The telescope was attached to a German equatorial mount, capable of object tracking. Table 2 lists some of the characteristics of these equipment.

Using the Exoplanet Transit Database from the Czech Astronomical Society, an optimal transit, visible form our telescope location, was determined to occur on May 12, 2012. Ingress was expected at 07:13 GMT and egress at 10:08 GMT. Observations of HAT-P-5 were started about 30 minutes before ingress (06:45 GMT) and stopped about 20 minutes after egress (10:28 GMT).

All together, 96 observations were made of HAT-P-5 in the V (visual) filter with an exposure time of 120 seconds and 2x2 binning. It was estimated that an exposure time of 120 seconds would give us a signal-to-noise ratio of about 200 for most stars. The sky was clear at dusk and there were no signs of any visible low clouds throughout the night. In hindsight, the seeing of our frames ranged from 3 to 5 arcsec.

While observing, a major problem occurred

CCD Camera	
Model...	ST-10XME
Pixel Array...	2184 x 1472 pixels
Pixel Size...	6.8 μm
A/D Gain...	1.3e^-/ADU
Dark Current at 0°C...	0.5e^-/pixel/sec
Read Noise...	8.8e^- RMS
Telescope	
Model...	Meade LX200ACF
Primary Mirror...	16 in (40.64 cm)
Focal Ratio...	f/10
Plate Scale...	0.345 arcsec/pixel (1x1 binning)

Table 2: Characteristics of the Equipment

with the tracking system of our mount. It was not able to track HAT-P-5 with sufficient accuracy, leading to the field of view to drift substantially from frame to frame. Fortunately, this problem was discovered early on and a solution was devised to keep this drift in check. After each exposure, the telescope was manually moved, or jogged, opposite the direction of the drift. These corrections were by no means perfect, but they did stop HAT-P-5 and its neighbouring stars from going out of the field of view. The device was jogged anywhere from 2 to 8 arcsec per frame. For a more detailed account of which frame was jogged and by how much see the observation log (Appendix A.2).

A standard array of calibration frames were also taken. Flat-field frames were produced by taking 5 frames of the twilight sky in the V filter, each with an exposure time of 4 seconds. In between each exposure, the telescope was slightly jogged, so that any stars in the frame could be removed later by averaging all of the flat-field frames. Two sets of dark frames, were also taken; one for the object frames, with an exposure time of 120 seconds, and the other for the flat-field frames, with an exposure time of 4 seconds. See Appendix A.1 for information on how to obtain these files.

3 Reduction

Before using the object frames for science, we had to remove any sources of noise in them due to the characteristics of our CCD. This meant removing the dark noise, the read-out noise and the bias offset, and then, correct for any pixel-to-pixel variations across the CCD. The procedure used is as follows. (See Appendix B, for the software and commands used to perform the following procedure)

3.1 Average the Frames

As mentioned in §2, we took two sets of dark frames containing 5 frames each. One set had an exposure time of 120 seconds and the other 4 seconds. We averaged each set separately to produce two averaged dark frame; one with a 120 second exposure time and the other 4 seconds. We also took 5 flat-field frames with a 4 second exposure time. Similarly, we combined these flat-field frames into one averaged flat-field frame. This averaging process would have removed any stars in the averaged flat-field frame.

3.2 Subtract the Dark Frames

Dark frames contain the dark noise, the read-out noise and the bias offset. To remove these sources of noise from our object frames, we subtracted the 120 second averaged dark frame (§3.1) from all 96 object frames. Similarly, we subtracted the 6 second averaged dark frame (§3.1) from the averaged flat-field frame.

3.3 Divide by the Flat-field Frames

Flat-field frames can be used to correct for the pixel-to-pixel variations across the CCD as well as any non-uniform illumination of the device. We did so by first normalizing the flat-field frame generated in the previous step (§3.2) to the mode value in the frame (By "normalize to the mode value" we simply mean divide each pixel in the frame by the mode value of that frame). Next, we divided all 96 dark-frame-subtracted object frames (§3.2) by the normalized flat-field frame.

After performing this procedure, our object frames had various sources of noise and variations corrected for, and could now be used for performing scientific measurements.

4 Photometry

To produce a transit light curve of HAT-P-5b we needed to compute the magnitudes of HAT-P-5 and a number of comparison stars in all of our object frames. Since, the stars in our images were separated enough, we did not have to use PSF fitting to determine their magnitudes. Instead, we simply performed software aperture photometry on them. The software package, IRAF, and its python scripting extension pyRAF were used to perform the image analysis. The IRAF task, *phot* found in the *noao.digiphot.daophot* package, was used to perform the actual aperture photometry.

Although there exist a number of pre-programmed subroutines within IRAF which are more than capable of automatically performing aperture photometry on a number of object frames, it was decided that scripting our very own python script using pyRAF would offer the most amount of flexibility and control over how the photometry was performed, and how the results were saved. This script can be obtained using the information in Appendix A.3.

The first task in this script, asks the user to pick which stars they would like to perform aperture photometry on. As the instructions in the script mention, the first star picked should be the one with the transiting planet and the rest are to be the comparison stars, in any order. Thus, we picked HAT-P-5 first and 5 other comparison stars. We made sure to pick stars that were not too close to the edge and were sufficiently distant from other stars to avoid erroneous calculations. Once the stars had been chosen, the script displayed them on the display and marked them according to the order in which they were picked. The coordinates were also saved in the file, *map.dat*. Figure 2 shows the stars we picked. Before we can move onto the photometry, there is a problem we must first address.

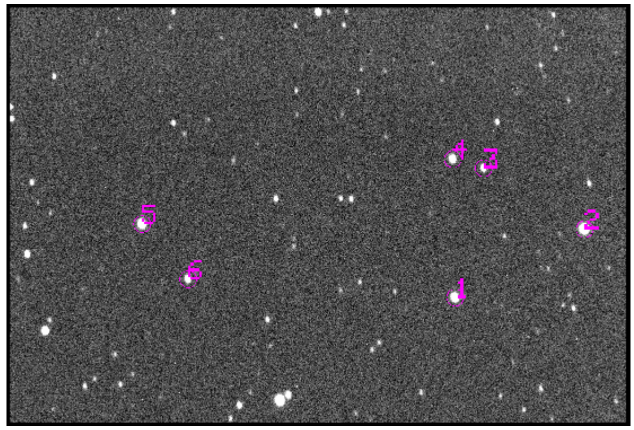

Figure 2: The stars we performed aperture photometry on. *(Star 1 is HAT-P-5)*

As mentioned in the observations section, our mount was not able to track HAT-P-5 accurately which led to the stars in our field of view to shift substantially from frame to frame. Small shifts would not have been a problem, since the IRAF task *phot* uses a centring algorithm which is able to find the centre of stars within a few pixels of a first approximate. If the shift was small enough, we could have simply provided the coordinates of the stars in the first frame, and the *phot* task would have been able to determine their coordinates in the remaining frames automatically. Since this was not the case for our observations, we needed a way to account for this. Instead of using IRAF's in-house tasks to solve this problem, we devised a simple solution in our python script. Once the coordinates of the stars to perform photometry on had been picked, the script then iterated through all the images, and asked the user to pick the location of only the first star in every frame. This location was compared with the one in the *map.dat* file, and the change in the two was saved to a new file, *change.dat*. Once the iteration was complete, this file contained the change in the location of the first star in each frame relative to *mat.dat*. Using this file and the coordinates in *map.dat* we were able to account for the shift in each frame when we performed aperture photometry.

Before running the *phot* task on each frame in our script, a number of parameters had to be determined and set in a number of different tasks in the *noao.digiphot.daophot* package, so that it could perform aperture photometry and error calculations accurately. These parameters and tasks are listed in table 3. As mentioned briefly in section two, the seeing of our observations ranged from about 3 to 5 arcsec over the course of the night. This corresponds to a FWHM (full with at half maximum) of the PSF ranging from about 4 to 7 pixels in our images. Thus, for the *fwhmpsf* parameter in the 'datapars' task we used a value of 5 pixels. The standard deviation of the sky pixels was determined using the task *daoedit* for a few frames and found to have an average of about 37, which was used for the *sigma* parameter in the *datapars* task. The size of the aperture used to perform the photometry was set equal to the FWHM of the PSF. Other parameters were determined using the CCD characteristics or looking at the headers of our frames.

datapars	
fwhmpsf	...5
sigma	...37
readnoise	...8.8
epadu	...1.3
exposure	...EXPTIME
obstime	...DATE-OBS
centerpars	
calgorithm	...centroid
cbox	...10
photpars	
apertures	...5
fitskypars	
annulus	...9
dannulus	...10

Table 3: Tasks and their parameters required by the *phot* task.

Once these parameters were set, the script could proceeded to perform aperture photometry on the 6 stars in each frame. The results of each frame were saved to the file, *phot.dat*. Each line in *phot.dat* corresponds to the calculations of the magnitudes in each frame. The first column is simply the time of the observation, in HH:MM:SS format. Columns 2 and 3 are the magnitude and the error in magnitude for HAT-P-5, respectively. Rest of the columns are the magnitudes and the error in magnitudes for the comparison stars. See Appendix A.4 for obtaining this file.

5 Analysis

After performing photometry on each object frame, we had the data necessary for plotting the light curve of HAT-P-5. However, as the first plot in Figure 3 shows, we can not simply plot it's magnitude with respect to time, and expect to detect the transit. This is due to the effects of the atmosphere as seen from the plots of the comparison stars in Figure 3 and 4. When using a single frame for scientific calculations, the effects of the atmosphere can be ignored since the field of view is small enough that any variations in the atmosphere are minuscule from pixel-to-pixel.[1] However, when using many frames taken over an extended period of time, the effects of the atmosphere can no longer be ignored because the atmosphere imaged by the CCD changes from frame to frame. This can be a major problem when measuring light curves, since the changing atmosphere can introduce its own random variations into the measured magnitude of a star. One solution to correct for the effects of the atmosphere is to use differential photometry. In differential photometry one measures the photometric difference between stars, thus eliminating the effects of the atmosphere.

[1] The effects of the atmosphere must always be accounted for if the intent is to produce absolute measurements or if the field of view is large.

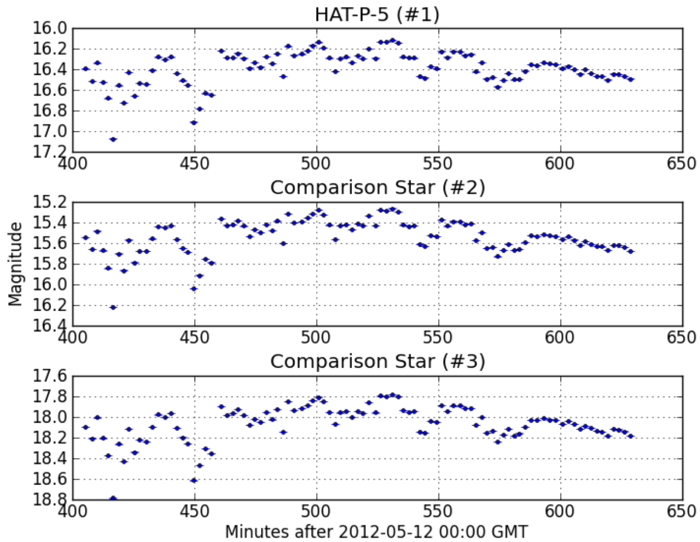

Figure 3

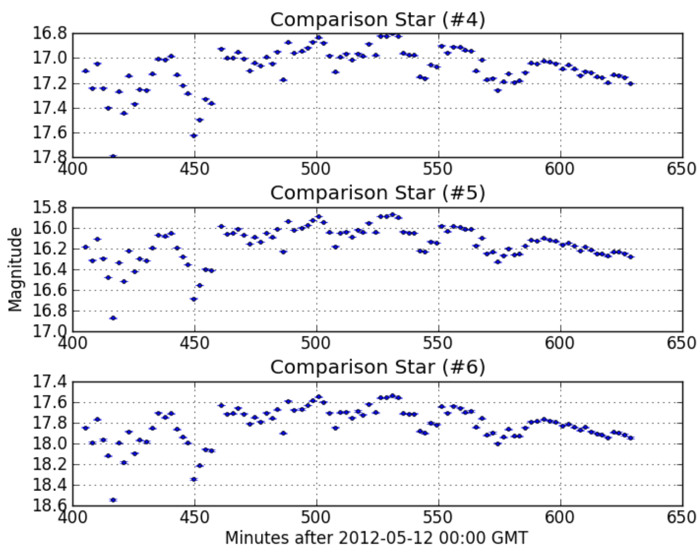

Figure 4

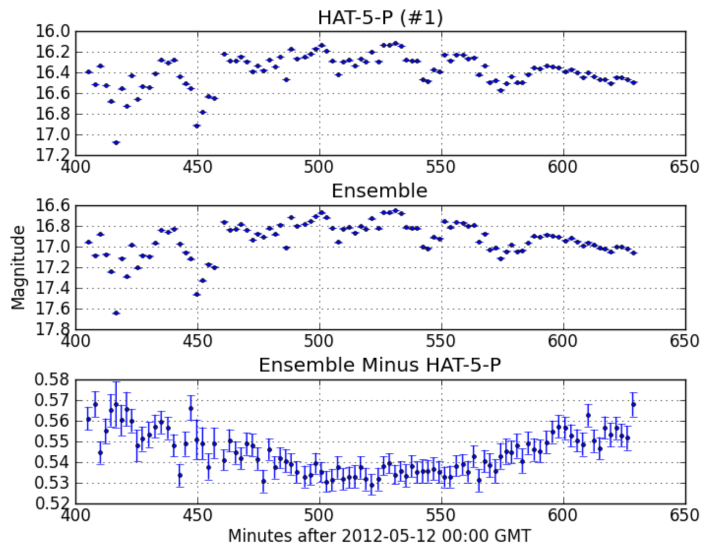

Figure 5

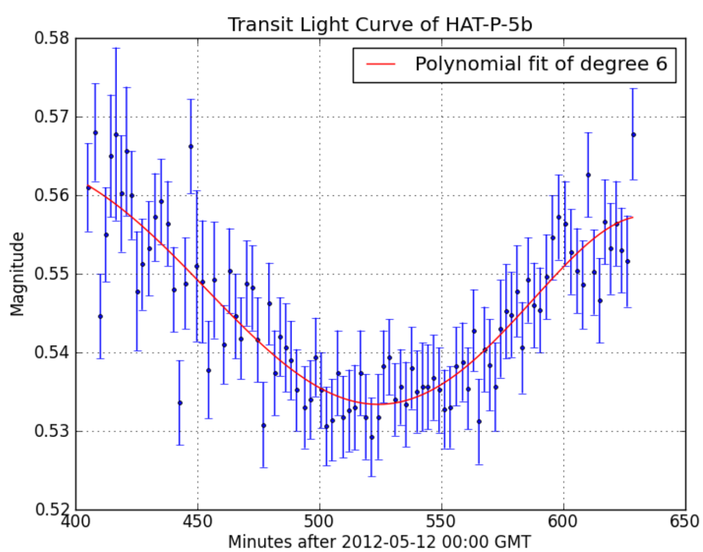

Figure 6

We did just that for the last plot in figure 5. We made an ensemble of stars composed of the comparison stars, added their magnitudes together and divided by 5 to obtain an averaged magnitude of the 5 comparison stars in each frame. Finally, we plotted the difference in the magnitude of the ensemble and HAT-P-5 to obtain a transit light curve of HAT-P-5b. Figure 6 shows a larger plot along with an polynomial fit of degree 6. The error in the magnitude was also calculated and plotted for each point. The average value of the magnitude error was calculated to be 0.006 magnitudes.

The depth magnitude is the difference between the magnitude of a star before ingress or after egress, and when it is half-way through its transit. Using the polynomial fit, the depth of the transit was estimated to be about (0.5571-0.5333) 0.0238 $\pm$ 0.012 magnitudes according to our results. Given the error in our measurements, our depth magnitude could range from 0.0118 to 0.0358 magnitudes. The depth magnitude listed by the Czech Astronomical Society is 0.0142 mag, which is within the error range of our measured values.

6 Conclusion

The goal of this report was to produce a transit light curve of HAT-P-5b. To produce such a light curve, we first had to observe and image its parent star, HAT-P-5, during one of its transits. Next, we had to remove various sources of noise from our observation images so we could perform scientifically valid measurements. And finally, using aperture and differential photometry, we were able to produce a transit light curve (6), and using the light curve, we determined a depth magnitude of 0.0238 $\pm$ 0.012.

A future suggestion for observing the transit of HAT-P-5b, would be to make daily measurments of the planet for a period of at least 10 days. This way, one could obtain multiple measurements (possibly in diffrent filters) of the transit. Having multiple measurements, would also allow one to measure the orbital period of the planet directly from data.

References

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Czech Astronomical Society. Exoplanet Transit Database: HAT-P-5b, May 2012. URL http://var2.astro.cz/ETD/etd.php?STARNAME=HAT-P-5&PLANET=b.

Wikimedia Foundation. File:planetary transit.svg, June 2012. URL http://en.wikipedia.org/wiki/File:Planetary_transit.svg.

Appendices

A Various Files

A.1 Images

All images produced during our observation can be found at the following URL. We include the calibration frames (darks and flats) and the original object images. We also include the reduced object images. `http://ia600300.us.archive.org/18/items/astronomy.observation.hat-p-5b.jashandeep.sohi/observations.20120512-jashandeep.sohi.tgz`

A.2 Log

The observation log can be found at the following URL. Observations were made as part of a larger group observing many differnt objects, so the observations in the first two pages of the log are of no concern to us. `http://ia600300.us.archive.org/18/items/astronomy.observation.hat-p-5b.jashandeep.sohi/log.pdf`

A.3 Photometry Script

The script we used to perfrom the photometry on our scripts can be found at the following URL. `http://ia700300.us.archive.org/18/items/astronomy.observation.hat-p-5b.jashandeep.sohi/photometry.py`

It is also available via the Git protocol at the following url. `https://github.com/jashandeep-sohi/astro-tools.git`

A.4 Photometry Data

The output of our photometry script can be found at the following URL. `http://ia700300.us.archive.org/18/items/astronomy.observation.hat-p-5b.jashandeep.sohi/phot.dat`

B Reduction

The image processing software we used for various tasks was IRAF. Here we show the commands used to reduce our images.

B.1 Average Frames

First, we combine (average) our darks and flat-field frames.

```
ecl> imcombine ./darks/120sec/*.fits ./dark.averaged.120sec.fits
ecl> imcombine ./darks/4sec/*.fits ./dark.averaged.4sec.fits
ecl> imcombine ./flats/4sec/*.fits ./flat.averaged.4sec.fits
```

B.2 Subtract the Dark Frames

Now, we subtract the appropriate dark frames from our images.

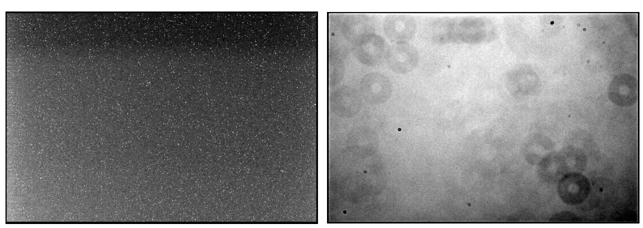
```
ecl> imarith ./objects/@object.list - ./dark.averaged.120sec.fits ./objects/@objects.list
ecl> imarith ./flat.averaged.4sec.fits - ./dark.averaged.6sec.fits ./flat.fits
```

B.3 Divide by the Flat-field Frames

Now, first we normalize our flat-field frame and then, we divide each object image by this frame to remove any pixel-to-pixel variations.

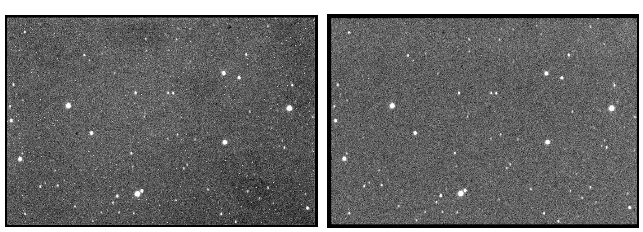
```
ecl> imstat ./flat.fits fields="mode"
#      MODE
         30248.
ecl> imarith ./flat.fits / 30248. ./flat.normalized.fits
ecl> imarith ./objects/@objects.list / ./flat.normalized.fits ./objects/@objects.list
```

B.4 Images



(a) Dark Frame (b) Flat Frame

Figure 7: Calibration Frames



(a) Original (b) Reduced

Figure 8: Object Frames