SURVEY OF TRANSITING EXTRASOLAR PLANETS AT THE UNIVERSITY OF PITTSBURGH

by

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In the past two decades, a wealth of planets and planetary candidates orbiting other stars have been discovered and are awaiting more follow-up study to further characterize them. To pursue such follow-up avenues, I recruited a research team of undergraduate collaborators for a project we named Survey of Transiting Extrasolar Planets at the University of Pittsburgh (STEPUP). Since its inception in August 2009, STEPUP has investigated both known planets and planetary candidates, making use of the Allegheny Observatory's 16" Meade LX-400 ACF telescope. In total we have taken 90 nights' worth of data, observing 17 stars hosting known or suspected substellar companions. We have been able to confirm transits of known gas giant planets such as XO-2b, TrES-2b, and HD80606b. In fact, our observations of HD806060b contributed to an international ground-based effort to collaboratively observe this long transit, a collaboration which demonstrated the success of coordinating observations across geographical distances. Our transit detections indicate our ability to obtain relative photometric precision of roughly 1%. In addition to studying known transiting planets, STEPUP has worked with the SDSS-III MARVELS team to search for transits of planetary candidates, which, if detected could help confirm the planetary nature of those candidates.

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1.0 INTRODUCTION

1.1 OVERVIEW

Are we alone in the universe? This is an age-old question which until recently was traditionally part of the realm of philosophy. As far as we know, the answer to this question relies on whether or not other planets that could support life exist. The origin of the word "planets," in fact, is a misnomer, since it comes from the Greek term for "wandering stars" (Carroll and Ostlie, 2007, p. 2). It wasn't until after the Copernican revolution that we began to understand that planets were not stars at all but actually other worlds which orbited stars. With this paradigm shift came fanciful speculations of life on other planets, such as those presented in Christiaan Huygens' *New Conjectures Concerning the Planetary Worlds, Their Inhabitants and Productions*, c. 1690. The dreamy visions of extraterrestrial life in our own solar system, of course, met their end when the other planets in our solar system were more closely examined in the 20th Century and shown to be largely inhospitable to life. Yet by the time probes had ruled out the likelihood of life on other planets in the solar system, we knew our star was one of only billions in our galaxy. So the fact that life existed on at least one of the planets of our own solar system naturally led to the question of whether or not there could be habitable worlds orbiting other stars.

For most of the 20th Century, planetary formation theories and models seemed to suggest that if planets orbited other stars, though they would likely be somewhat different from the planets of our solar system, their distances from their star would roughly mimic our solar system, with larger planets orbiting farther out and smaller planets orbiting closer in

(Isaacman and Sagan, 1977; Boss, 1993, 1995). Similarly, in the majority of cases, their orbital eccentricities would likely be nearly circular (Isaacman and Sagan, 1977), and we could describe relationships between their mass and radius using arguments of composition and density that were thought to be understood based on our solar system (Hartmann, 2005; Lunine et al., 2008).

Yet, when the first extrasolar planets were found near the turn of this Century, these conventional expectations were challenged. For a detailed account of the history of early extrasolar planet discoveries and the ways in which such discoveries challenged scientific notions at the time, see Chapter 3 of the *Report of the Exoplanet Task Force to the Astronomy and Astrophysics Advisory Committee* (Lunine et al., 2008). Or for a more concise overview, see Section 7.1 in the *Exoplanet Community Report* (Lawson and Unwin, 2009). Here I summarize the details of such accounts:

The astounding announcement in 1995 of the discovery of 51 Pegasi b by Mayor and Queloz was just the first of many Jupiter-sized planets were found not at several AU away from their star, but at fractions of an AU from their star, roasting in an environment we never would have predicted. Many of these "hot Jupiters," as they came to be known, were found to have unexpectedly large radii, and some extrasolar planets were also found to be on highly eccentric orbits. Astronomers quickly learned that nature exhibits great diversity when it comes to planets, and that it is not safe to take much for granted about what we should expect to find.

If there is one lesson we should take away from our tendency towards a human-centric view of the universe, it is that science is about understanding nature as it is, not as we wish it to be. Still, the motivation behind these age-old questions of our place in the universe is a driving force behind our quest.

1.2 CONTEMPORARY UNDERSTANDING OF EXTRASOLAR PLANETS

At the present time, planets ranging in size from several times Jupiter's mass down to a couple times Earth's mass have been found. Many are on close-in orbits, but some orbit far from their star. A few gas giants are near that most precious place, the "habitable zone." At least one rocky planet may just barely be within that zone, though the exact number of planets in this system (Gliese 581) and their potential habitability are still being disputed (Vogt et al., 2010; Tuomi, 2011; von Paris et al., 2011; Wordsworth et al., 2010; von Paris et al., 2010; Wordsworth et al., 2011). But so far, no true Earth-analogs have been definitively discovered and confirmed. This is likely to change in the near future since the launch of the Kepler Mission in March 2009. This NASA mission put a 1.4m telescope into an earth-trailing heliocentric orbit. From this orbit, Kepler will constantly monitor a region of the sky in the constellations of Cygnus and Lyra for the next 3.5 to 6 years searching for earth-sized planets in the habitable zones of stars in this region of the sky [1]. However, even when Kepler finds a candidate Earth analog, it will likely orbit a star far away in Kepler's limited fixed field of view, and follow-up observing from the ground could be challenging. In the meantime, ground-based astronomers have the rest of the sky to explore, and a multitude of worlds to characterize.

Most of the known planets outside our solar system were discovered by a technique that exploits the Doppler shift[2]. This technique is usually referred to as the radial velocity technique, and it involves measuring tiny periodic shifts in the spectra of stars that might indicate a planet gravitationally tugging on the star (Carroll and Ostlie, 2007, pp. 180-198). The advantage of this technique is that, in principle, at some points in the planet's orbit, there should be a component of light that is Doppler-shifted in any planetary system that is not oriented completely face-on to our line of sight (ie. the angle of inclination, conventionally termed i, is zero in a face-on system). In practice however, the technique is most sensitive when that component is large, which means larger angles and/or more

[1]http://kepler.nasa.gov/Mission/QuickGuide/faq/

[2]http://exoplanet.eu

massive planets and/or planets orbiting close to their stars (since gravitational force decreases with increasing distance and so weakens the signal in the spectrum). Also once a planet is discovered, only a lower-limit of its mass can be made with this technique since, assuming the mass of the host star is known, only $M_p \sin i$ can be determined (where M_p is the mass of the planet). Thus there is a degeneracy of solutions with different possible angles corresponding to different exact masses (Mason, 2008).

In addition to the radial velocity technique, there are several other techniques that can be used to detect extrasolar planets, such as direct imaging, astrometry, microlensing, and photometric transit technique. Each technique has advantages and disadvantages, but the most fruitful method by far has been the radial velocity technique, followed by the transit techniques (Mason, 2008).

1.3 MOTIVATION FOR THE CURRENT STUDY

The University of Pittsburgh is fortunate to have the Allegheny Observatory at its disposal for astronomical research. Throughout its long history, much in the way of observational research has taken place here, such as the study of the rings of Saturn, the measurement of the distances to and proper motion of nearby stars via their parallax angles, the obtaining of lightcurves of Cepheid variables and eclipsing binaries, and searches for extrasolar planets (originally using the astrometric method–see Section 2.1)[3].

Currently at the Allegheny Observatory we do not have the capability to use the radial velocity technique to study extrasolar planets; however, we do have the ability to use the transit technique. The transit technique is responsible for the discovery of over a hundred planets to date, and relies on a planetary system being aligned edge-on to our line of sight (ie. the inclination angle, i, is approximately 90°). In such a system, a planet will, from our perspective, cross directly between us and the parent star at some point in its orbit. In so

[3] http://www.pitt.edu/~aobsvtry/history.html

doing, it blocks out a tiny but detectable fraction of light we receive from the star.

Like the radial velocity technique, the transit technique is most sensitive to large planets. This is due to the fact that more starlight is blocked out for such systems since this stellar dimming is directly proportional to the circular area we see; ie. it is proportional to the square of the planet-to-stellar radius ratio: R_p^2/R_*^2 (see Section 2.3.2). Clearly, then, the smaller the star, the smaller the planet can be in order to be easily detectable. In other words, a terrestrial-sized planet blocks out a much smaller portion of the light of a G star like our sun, for example, than would the same planet orbiting a much smaller M star, and so it would be easier to detect an earth-sized planet if it orbits an M star compared to the same planet orbiting a G star. But for any planet detected via the transit technique, there is a multitude of information we can learn about that planet.

By measuring the light of the parent star and quantifying how much it is dimmed as a function of time, we can plot a "lightcurve" of the star, which is characterized by bright measurements followed by an "ingress," which is characterized by dimmer measurements and then an "egress" which is characterized by brighter measurements as the planet completes its transit. Examining the change in flux, or the "transit depth," tells us about the ratio of the planet to stellar radius (see Figure 1.1). Also if we have radial velocity mass estimates, we can break the degeneracy of $M_p \sin i$ by taking $\sin i = 1$, since i must be very close to $90°$ for a transit to occur. Using this mass and the planet to stellar radius ratio, we can determine the density of the planet if the stellar radius is known. In addition, we can determine the orbital speed and period from the duration of the transit and the amount of time between transits. This makes transit follow-up observations useful in characterizing known planets, if we are fortunate enough to find that these planets do indeed transit.

Another use of transit follow-up observations is in helping to understand the nature of a planetary candidate. If we happen to find a transit occur for a system which has previously exhibited a tantalizing periodic radial velocity signal, we can confirm that the signal is genuine and determine the size of the planet. We are unable to rule out the existence of a substellar companion if we do not find a transit, since the system could be aligned too far from $i = 90°$ for a transit to occur; however, nature has nonetheless generously bestowed us with certain planetary systems that happen to be aligned in a most precious edge-on way. Indeed the geometric probability of a planet transiting its star is, in general, a non-negligible one, typically ranging between 1 and 10 % (Mazeh, 2009). For a star of a given radius, R_*, with an orbiting planet of radius R_p and semi-major axis, a, the probability of transit is:

$$Prob(transit) \approx \frac{2(R_* + R_p)}{\pi a} \tag{1.1}$$

This can be seen geometrically in Figure 1.2. Equation 1.1 implies that planets orbiting close to their stars will have an enhanced probability of transiting compared to the same planet orbiting far from its star. This probabilty enhancement combined with the larger transit depth for a larger planet is why planetary transit discoveries, like radial velocity discoveries, tend to be of the "hot Jupiter" variety.

So we can determine the odds that a planetary candidate will transit, and if we are able to find such a transit, we learn important information about the system under study. Thus transit detection is only one piece of the puzzle of learning about extrasolar planets, but it is a very important piece of the puzzle.

1.4 BEGINNINGS OF CURRENT STUDY

My interest in extrasolar planets began while I was still an undergraduate, and I was fortunate to have the opportunity to start research in this field thanks to the Emil Sanielevici Undergraduate Research Scholarship of which I was co-recipient in 2008. At that point I wanted to follow up on observing known transiting planets since this would be the easiest starting point to prove that it was possible to detect transits using the 16" Meade LX-400ACF [4] at the Allegheny Observatory. As presented in my talk in Febrauary 2009, as an

[4] This particular model of Meade was formerly known as the Meade RCX-400, but was re-named the Meade LX-400ACF to reflect that it is not truly a Ritchey-Chretien design: `http://www.meade.com/lx400-acf/index.html`

undergraduate, I successfully detected the ingress of a transit of XO-2b (a known transiting planet) using very rudimentary analysis methods. (Good, 2009) These methods involved using Mira, a GUI software installed on the computers at the Allegheny Observatory, to measure the photometry of XO-2 and two reference stars by hand in each individual image of my data set. Then I took those measurements and, using Mathcad, manually created arrays, calculated the relative magnitudes, and plotted the results (see Figure 1.3). (Good, 2009) While this approach was sucessful it was very tedious and so when I began my graduate research, my first goal was to make the analysis more automated.

Thus I spent the summer of 2009 learning Interactive Data Language (IDL) and developing code to re-analyze the XO-2b transit data I had gathered as an undergraduate. I was successful both in developing an automated way to measure photometry of a set of data and in confirming the ingress of the transit I had detected using my less-sophisticated analysis method. Furthermore, the automated method using IDL yielded less error since it was not prone to the lack of accuracy of "pointing and clicking" on the star when performing photometric measurements. Instead, I used a star catalog to astrometrically align my images and specified the center of the aperture photometry for each star by inputing their RA and Dec. The results of this first IDL analysis can be seen in Figure 1.4.

By the beginning of the fall of 2009, I was working on generalizing the code I had developed in order to allow it to take any star field as input and then output a lightcurve of the relative photometric measurements. Two additional function I included were: 1. proper calibration of the images using a flat, dark, and bias images, and 2. tracking the Julian Date of each image and using Julian Date on the x-axis of my plots instead of the image number to more accurately plot brightness vs. time.

The fall of 2009 also saw the birth of my research team project: Survey of Transiting Extrasolar Planets at University of Pittsburgh (STEPUP). With the support of and under the direction of Prof. Michael Wood-Vasey, several undergraduates were recruited to help in my extrasolar planet research efforts. The original mission statement of STEPUP was to create a group project to focus initially on observing known transiting systems and, as the project grew, to embark upon more ambitious follow-up and discovery research. The five year science objectives were to:

1. Obtain lightcurves of known transiting extrasolar planets using the 16" Meade LX-400ACF and 30" Thaw telescope and search for any anomalies in transit timing.

2. Survey known extrasolar planets not yet known to transit for evidence of transits.

3. Survey additional stars, especially including M stars, for new discoveries using the 30" Thaw telescope and the 16" Meade LX-400ACF.

4. Follow up, as needed, on targets of particular interest, and participate, if possible, in the discovery confirmation process.

5. Educate and train undergraduate students to enhance their observation skills, increase their awareness of current scientific research, and help prepare them to contribute to extrasolar planet or other astronomic research.

I am happy to report that in the first two years, STEPUP has made great strides in most of these science objectives and has begun work on all of them. The main challenges we face are in helping undergraduates find the balance between their research responsibilities and their coursework responsibilities, making ongoing technical improvements at the Allegheny Observatory, understanding our sources of error, and dealing with suboptimal weather and seeing conditions. Despite these challenges, STEPUP has been able to help make hardware improvements, further develop our software and analysis procedure, observe some important science targets and contribute data to two different scientific collaborations. Furthermore, the stage has been set for STEPUP to continue making contributions to the greater scientific community. For a listing of past and present STEPUP members, see table 1.1.

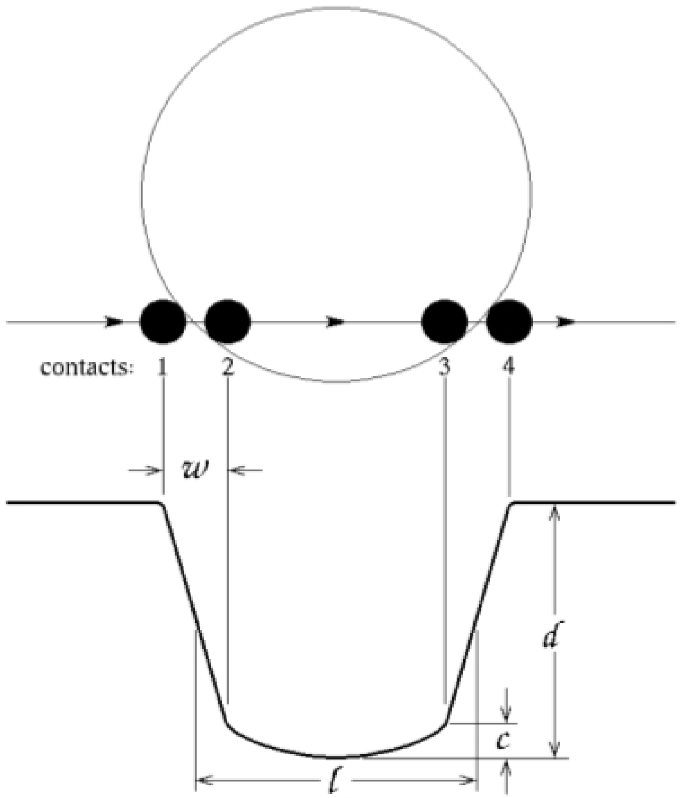

Figure 1.1: Brown et al. (2001) lightcurve Schematic: l is the transit length, w is the duration of the ingress/egress, d is the transit depth, and c is the central curvature of the lightcurve, which can tell us about the degree of limb darkening

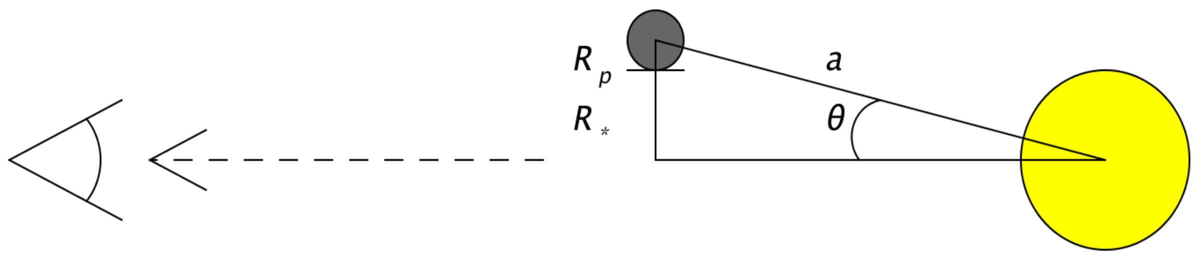

Figure 1.2: Depicted here is the geometry of a grazing planetary transit. This particular θ (which is equal to $\frac{\pi}{2} - i$) corresponds to the minimum angle needed for a transit to take place. From this diagram we can see that $\sin\theta = \frac{R_* + R_p}{a}$. For a small angle $\sin\theta \approx \theta$. To determine the probability that a planet will transit, then, we need only look at the proportion of transiting angles out of all possible angles. That range of angles is 2θ out of π. Thus the probability of a planetary transit is $\frac{2\theta}{\pi} \approx \frac{2(R_* + R_p)}{\pi a}$ which agrees with Equation 1.1.

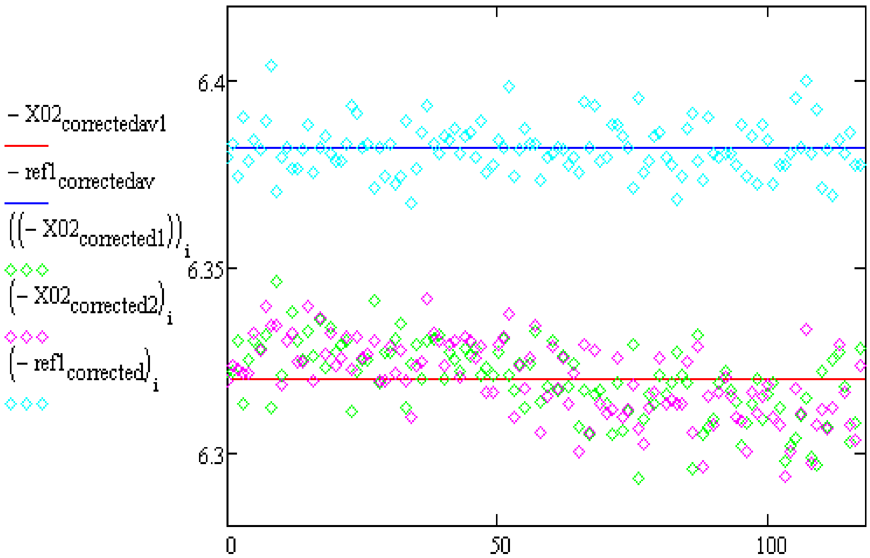

Figure 1.3: Original analysis of an ingress of XO-2b, from February 2009. This plot was made using Mathcad, with the x-axis indicating the image number, and the y-axis indicating the corrected, unnormalized magnitudes of the reference and target. The upper points plot the corrected magnitudes of the reference star in each image (relative to another reference star), with a line overplotted indicating the average relative reference magnitude over this set of images. The lower points plot the corrected magnitudes of the target star in each image, with an average line overplotted.

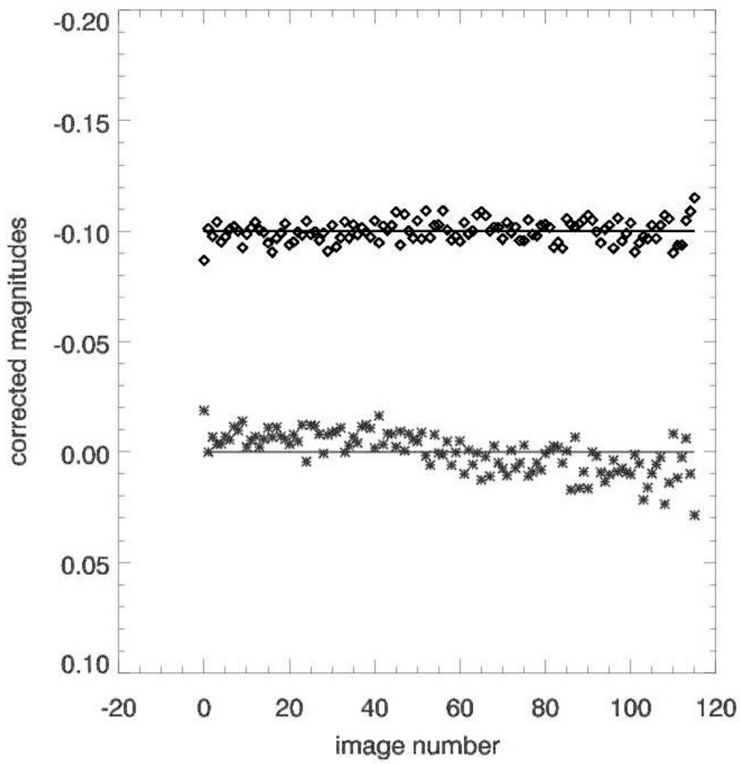

Figure 1.4: Result of IDL re-analysis of an ingress of XO-2b, from February 2009. The x-axis indicates the image number, and the y-axis indicates the corrected, normalized magnitudes of the reference (plus offset) and target. The upper diamonds plot the corrected magnitudes of the reference star in each image (relative to another reference star), with a line overplotted indicating the average relative reference magnitude over this set of images. The lower asterisks plot the corrected magnitudes of the target star in each image, with an average line overplotted.

Table 1.1: STEPUP Membership

Name	Affiliation	Grad. Yr.	Where they are now
Melanie Good	Grad Student	MS 2011	
Dr. Michael Wood-Vasey	Asst. Prof.		
Lou Coban	Observatory Manager		
Maya Hunt	Alumnus	BS 2010	Teaching physics in RI
Eric Roebuck	Alumnus	BS 2011	Grad School at Tufts U.
Chelsea Vincent	Undergrad	2012	
Gary Lander	Alumnus	BS 2011	Grad School at WVU
Korena Costello	Alumnus	BS 2011	L3 Brashear Optics
Gwen Weaver	Alumnus	BS 2010	Teaching physics in OK
Nelson Hua	Undergrad	2013	
Justine Drobitch	Undergrad	2012	
Kaitlyn Yoha	Engin. Undergrad	2012	
Aniket Patel	Undergrad	2014	
Linzi Webster	Undergrad	2014	
Shane Cerutti	Undergrad	2013	

2.0 METHODS

2.1 TELESCOPES/HARDWARE

By the time I was an undergraduate at the University of Pittsburgh, the heyday of active astronomical research at the Allegheny Observatory was largely over. There were a few lingering paid observers, but even these were no longer part of the staff by the time I began my graduate studies. Interestingly, the most recent field of research that had been taking place at the Allegheny Observatory was related to extrasolar planets. Throughout the career of Emeritus Professor George Gatewood, the Thaw telescope was used to astrometrically search nearby stars for signs of planetary companions, which would be evidenced by a periodic astrometric wobble in the position of the nearby star with respect to the "background" stars, which remain relatively fixed over short time spans of a couple decades or less.

In order to employ the transit method to detect extrasolar planets, I used the more modern 16" Meade LX-400ACF Keeler telescope. This telescope had replaced the 30" open-tube Keeler. The 16" is equipped with a Santa Barbara Instruments Group (SBIG) STL-6303E and a Jim's Mobile Incorporated (JMI) zero image shift focuser with a smart focus attachment that allows computer control. As of January 2010, the Keeler telescope could be operated remotely from the astronomy computer lab in Allen Hall on the campus of the University of Pittsburgh. STEPUP members thus no longer need to have independent transportation to the Allegheny Observatory in order to use this instrument. The Keeler telescope is the instrument we have used to gather all of our observational data to date.

2.2 PIPELINE/SOFTWARE

After generalizing the basic IDL code to perform photometry, calculate relative flux, and plot the results, STEPUP members and I collaborated to transform the code into modular procedures, each of which could, in principle, be run independently if needed/desired. Thus we parceled off different tasks to independent procedures which were called from the main procedure shell. We also added several capabilities to our pipeline, including additional outputs of data files, in addition to the visual output of the lightcurve plot. These data files included two initial data files (one in fluxes of target and reference start and one in magnitudes of the same), two corresponding cut data files which had outliers cut from them, and two corresponding corrected data files (one in relative fluxes and one in relative magnitudes). The final result of our pipeline can be summarized in a flowchart of modules (see Figure 2.1)

The basic shell of the pipeline is called generaltransit.pro. From it, we first call up the master bias, master dark, and master flat procedures which take our calibration images and make masters of each type of calibration. After these masters are made, the shell calls up a procedure which takes the masters and performs image calibration and outputs these images to the directory */home/depot/STEPUP/workspace* on the department's network of astronomy computers such as *diu* or *ra*. That procedure, in turn, calls up a procedure to determine the saturation level of the calibrated image and another procedure to take the calibrated images and perform astrometry on them, putting the wcs information into the header of the image file. The astrometry is accomplished with *imwcs*, part of the wcs tools developed by Doug Mink at the Harvard-Smithsonian Center for Astrophysics and publicly available on the wcstools website[1]. *imwcs* can take an input catalog of stars and compare them to another catalog of stars to find an astrometric solution. In our case, we use star catalogs downloaded from Simbad[2] and compare them to the catalog of stars consisting of

[1]http://tdc-www.harvard.edu/wcstools/

[2]http://simbad.u-strasbg.fr/simbad/

stars found by the *find* command in IDL[3], which is executed prior to using *imwcs* in this module.

After the astrometry has been performed, the shell calls up a procedure to read the date from the image header (in Universal Time, UT[4] and convert it to Geocentric Julian Date, GJD[5]. The next procedure the shell calls performs all the photometry on the target and two reference stars, outputting arrays of target and reference fluxes as well as errors for the target and reference fluxes. A simple procedure called from the shell then converts these fluxes to magnitudes, and then the shell outputs two initial data files, one which uses the flux arrays and the other which uses the magnitude arrays. The columns in these files are: GJD, target magnitude or flux, reference 1 magnitude or flux, reference 2 magnitude or flux, error of the target (in magnitude or flux), WCSSEP (a measure of the quality of the astrometric solution), WCSmatch (a measure of how many stars were matched in making the astrometric solution), WCSnref (the number of reference stars used in making the astrometric solution), error of reference 1 (in magnitude or flux), and error of reference 2 (in magnitude or flux).

Next, the shell calls up a procedure which performs differential photometry, calling it once for magnitudes and once for fluxes. This procedure, gtcorrection.pro then calls up a procedure that cuts any nonsensical data (such as a value of 99 for magnitude), and then outputs two sets of a cut data file and a corrected data file (one in magnitudes, the other in fluxes). These files contain the same basic columns as the initial data files, except that they are in normalized, relative fluxes or magnitudes.

Finally the shell calls up its final procedure, plotlc.pro, which outputs two sets of plots, one in relative magnitude of the target vs. GJD and the other in relative flux of the target vs. GJD. In addition, this procedure also outputs zoomed-in versions of each of these plots.

The pipeline can also be started at several different points so that we can bypass com-

[3] http://idlastro.gsfc.nasa.gov/ftp/pro/idlphot/find.pro

[4] Universal Time is measured from 0 hours at midnight in Greenwich, England, and is based on the mean solar day (http://tycho.usno.navy.mil/systime.html).

[5] Geocentric Julian Date, also known simply as Julian Date refers to the time elapsed since noon on January 1, 4713 B.C. as specified by the Julian calendar. This time acts as a zero point from which other times are measured, with 1.0 equal to one day (Carroll and Ostlie, 2007, pp. 13-14).

plete re-analysis if desired. For example, if we would like to begin with the calibrated images instead of re-doing the image calibration, we can begin at that point in the flowchart. In addition most modules can be used independently. A convenient application of the independent use of an individual module is that if we already have initial photometry on a data set and would like to calculate relative photometry and output this information in a data file. In that case, we can simply run gtcorrection.pro by itself, inputting the initial photometry file.

This modular nature has allowed our pipeline to be both comprehensive and flexible. Such comprehensiveness has generally given us the ability to analyze data efficently, and such flexibility has proven to be very valuable when encountering issues that need troubleshooting, as well as very utilitarian when we wish to focus on a particular aspect of pipeline improvement.

All the code we have written is stored on the astronomy's network of computers in the directory */home/depot/STEPUP/code*. Our raw data is stored both on the Allegheny Observatory computer, and on the department network of computers. At first we stored the raw data in */home/diu-data/STEPUP/raw* and when we exhausted the space there we stored subsequent raw data in the directory */home/depot/STEPUP/raw*. Our code automatically searches for raw data in the former of these two directories and if it does not find the specified target and date there, it searches in the other directory. This allows us to leave the old raw data in place and no matter which directory a set of data is stored in, our code can find it. We also check our code into an svn repository[6]:

/home/bruno/users/mlg52/repository/myrepository.

Svn is a version control software that allows us to keep track of changes made to our code. Utilizing svn for version control allows us not only to log changes we make to the code, but to revert to previous versions of the code if warranted. With multiple members of STEPUP revising the code, this helps us better track our changes and improvements. Svn acts somewhat like a library wherein you can "check out" a set of code from the repository

[6] http://subversion.apache.org/

and check it back in by "committing" the revised file, along with a log message describing the changes made. If in the meantime, someone else has committed a change to the current version, the conflict will be shown and will need to be resolved in order to commit. This prevents one person from undoing a revision another person made. Furthermore, once you initially check out the project, you need only "update" your code files to the current version. From any of the astro network of computers in the department, one can check out the current version of the code by typing from the command line:

```
$ svn checkout file:///home/bruno1/users/mlg52/repository/myrepository/code
```

2.3 PHOTOMETRY

2.3.1 STEPUP Aperture Photometry

The 16" Keeler telescope is equipped with a Johnson-Cousins UBVRI filter system, and typically our data is taken using the R band filter. STEPUP members follow a checklist protocol for collecting data which specifies this filter. Also on the checklist is the procedure for selecting exposure times. This procedure is simply based upon optimizing our signal to noise ratio by selecting an exposure time which results in the number of counts received by our target star being between 50 and 60 percent of the saturation value. For the majority of our targets, this exposure time is usually between 30 and 60 seconds.

Within the photometry module of our pipeline we perform aperture photometry in IDL with the *aper* command[7]. This command allows us to specify the radius of the star aperture, as well as the radii of the inner and outer sky annuli, and, using these radii, it measures the brightness of the star compared to the surrounding sky. These radii are currently set at 10, 15, and 35 pixels respectively, as we have found that these radii work well for the majority of our targets. Originally the star radius had been set at 7 pixels since this seemed to work

[7] http://idlastro.gsfc.nasa.gov/ftp/pro/idlphot/aper.pro

for our first data set, the February 6, 2009 transit of XO-2b. However, due to some out-of-focus data in our HD80606b campaign, the sky radius was increased to 10 pixels. I later examined what star radius would yield optimal signal-to-noise for both a single image taken from both a night of good seeing (when the point spread function, psf, was fairly sharply defined) and a night of poor seeing (when the psf was more broadly defined). For the first case the maximal signal-to-noise is achieved with a 5 pixel star radius and for the second case with an 8 pixel star radius. However, for several sets of data, we found that using a star radius smaller than 10 pixels, while sometimes yielding lower individual errors, resulted in more of a photometric spread in our output files. The exact reason for this is currently being investigated by STEPUP members. (See Appendix B) Additionally, one of our next goals will be to calculate the maximum signal-to-noise aperture radius within our pipeline so that the radii are chosen to be optimal for the set of data being analyzed.

2.3.2 Theoretical Flux Received During Planetary Transit

The flux we receive on Earth from a star located at a distance d from us is equal to that star's luminosity divided by the area of a huge imaginary sphere of radius d upon whose edge we are sitting:

$$F_* = \frac{L}{4\pi d^2} \tag{2.1}$$

If we think of the star as a circular disk of area πR_*^2, the Stefan-Boltzman Equation allows us to replace the luminosity with $L = \pi R_*^2 \sigma T^4$ where R_* is the radius of the star and T is the surface temperature of the star. Thus the flux of the star can be expressed as

$$F_* = \frac{R_*^2 \sigma T^4}{4d^2} \tag{2.2}$$

When a planet is blocking the light coming from the star, and if we make the approximation that the distance from earth to the star is the same as the distance from earth to the planet orbiting the star, we can then think of the light radiating out from the partially-blocked star as a circular disk being blocked by a smaller circular disk. Subtracting this smaller circular disk from the larger one, the Stefan-Boltzman Equation becomes: $L = (\pi R_*^2 - \pi R_p^2)\sigma T^4$. Of course to be precise, the planet has some surface brightness of its own, so it is not entirely taking all of the brightness to zero in the small portion of the star that it is "blocking." However, since, in general, planets have a much lower temperature than the stars they orbit, a planet's surface brightness (especially in visible wavelengths) is much much smaller than that of the star, making the preceeding a good approximation. This means that during a transit (ie. when the planet is blocking some flux from the star), the flux we receive from the star is well approximated by:

$$F_{*p} = \frac{(R_*^2 - R_p^2)\sigma T^4}{4d^2} \tag{2.3}$$

We can then define a quantity, $\Delta F = F_* - F_{*p}$. Now we can express the ratio of ΔF to F_* as:

$$\frac{\Delta F}{F_*} = \frac{(R_*^2 - R_*^2 + R_p^2)\sigma T^4}{4d^2}\frac{4d^2}{R_*^2\sigma T^4} = \frac{R_p^2}{R_*^2} \tag{2.4}$$

So the "depth" of a planetary transit (ie. how much the star dims compared to its out-of-transit brightness) tells us about the ratio of the planet radius to the star radius. Given Equation 2.4, we can ask ourselves what transit depth we would expect like for an Earth-analog planet, and using Equation 1.1 we can determine the transit probability for such an object. Plugging in values for the radii of the Earth and of the Sun into Equation 2.4 we conclude that a transit depth due to an Earthlike planet transiting a Sunlike star would be: $\frac{\Delta F}{F_{\text{sun}}} \approx 0.0084\%$. Taking $R_{\text{sun}} + R_{\text{earth}} \approx R_{\text{sun}}$, and using Equation 1.1, an Earthlike planet orbiting a Sunlike star at 1AU would have a probability of transiting of $\sim 0.3\%$. These numbers help explain why a planet as small as the Earth and orbiting at a similar semi-major axis as the Earth has not yet been found.

Nevertheless, as discussed in Section 1.2, the NASA Kepler mission has the ability to detect an Earth-analog. Indeed, Kepler is capable of detecting a transit depth as shallow as 0.003% (Jenkins et al., 2010). And to overcome the low probability of transit, Kepler is targeting 100,000 main sequence stars (Jenkins et al., 2010). Thus just based on the sheer number of targets, Kepler expects to find a handful of Earthlike planets by the completion of its mission.

2.3.3 Corrected Photometry

The detection of extrasolar planets by the transit method relies upon calculating relative photometry. What this means is that we look for any changes in brightness of our target star *relative* to other, reference stars in the image. This allows us to dismiss any changes in brightness which occur both to target and reference stars as being due to changes in observing conditions or similar such effects, and instead identify changes in brightness that are unique to the target star itself.

As we know from the previous section, the ratio of flux during a transit to that out of a transit is simply related to the square of the ratio of the planetary radius to the stellar radius (Eq. 2.4).

In reality though, not all the flux emitted from the star reaches our detector perfectly due to the atmosphere of earth, instrumental instabilities, inconsistent CCD response, dark current noise, etc. If we assume the flux we actually observe from our target star, F_{to} has been reduced by some factor, η due to all of these sources of noise, we can write that $F_{to} = F_{t*}\eta$ where η is a number less than one and F_{t*} is the true flux received by the target (ie. what we would measure if there were no sources of noise). Here is the beauty of relative photometry: If we don't care about knowing the absolute brightness of the star, and if we assume that the unspecified sources of noise affect all stars in the image the same way, we can cancel η out by looking instead at the flux of our target relative to the flux of a reference star or or the average flux of many reference stars, F_r. Thus the relavant quantity is:

$$\frac{F_{to}}{F_{ro}} = \frac{F_{t*}\eta}{F_{r*}\eta} = \frac{F_{t*}}{F_{r*}} \tag{2.5}$$

Whatever quantity this gives us should, in principle, remain constant in time if no other effects besides η cause any stars to change brightness. Thus if we notice a periodic dip in brightness followed by an increase in brightness to the original value, this could be taken as a sign that something unseen, such as a planet, crossed in front of the star and blocked out a portion of its light for a brief time. While this is not the only possible explanation for periodic changes in brightness, such a detection is very powerful evidence of a planetary companion orbiting the star if other explanations for the brightness change can be ruled out.

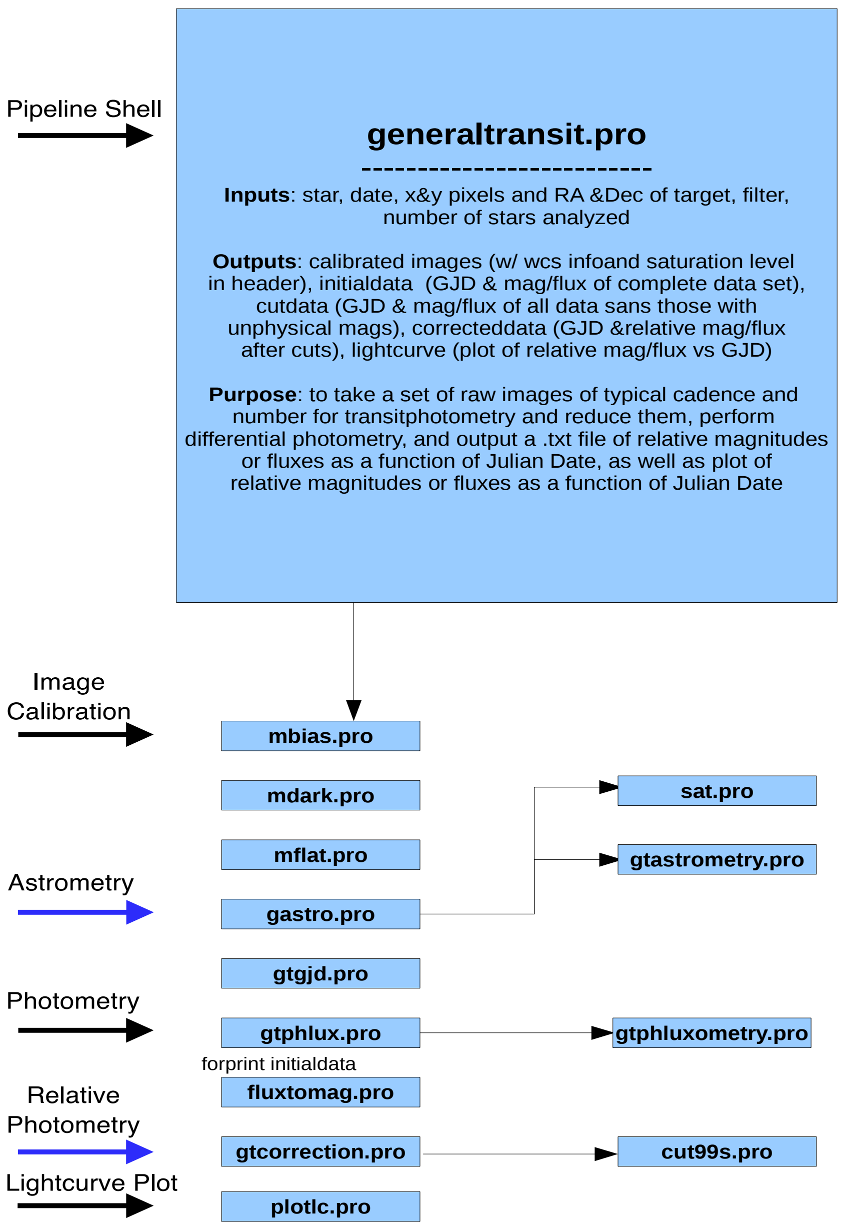

Figure 2.1: Pipeline Flowchart. The arrows indicate the functions performed at various points in the pipeline. “Astrometry” and “Relative Photometry” are indicated in blue arrows, since these are alternate entry points into the pipeline. If we already have good image calibration, for example, we can begin our analysis at the astrometry entry point. Or if we already have a good initial data file, we can enter the pipeline at the relative photometry calculation.

3.0 KNOWN TRANSITING PLANETS

3.1 PLANNING FOLLOW-UP OBSERVATIONS

One way STEPUP contributes to extrasolar planet research is through follow-up observations of known transiting planets. The convenient aspect of observing known transiting planets is that we can strategize a timeframe of when to observe them since the times that they are expected to transit are, in general, known. Indeed, expected transit times are made publicly available through resources such as Transitsearch[1] and the Exoplanet Transit Database, ETD[2](Poddaný et al., 2010). (See Appendix A for details on our strategy for utilizing Transitsearch and ETD in planning our follow-up observations of known extrasolar planets). Both of these tools have advantages and disadvantages.

Transitsearch is a website run by Prof. Gregory Laughlin at University of California Santa Cruz. Included on this website are the coordinates of each target, the depth of the transit and when a transit is expected to take place (in Universal Time and Heliocentric Julian Date). This site includes many known extrasolar planets, not all of which are known to transit. Those that are not yet known to transit are planets that were discovered via radial velocity, and these particular planets are listed along with their geometrical probability of transiting on Transitsearch. The inclusion of these planets and their expected possible transit times allows observers to strategize when to search for signs of a transit. If a transit is found it allows for the breaking of the $M_p \sin i$ degeneracy and allows us to take i to be fairly close

[1]www.transitsearch.org
[2]http://var2.astro.cz/ETD/index.php

to 90° and make the accurate approximation that $\sin i = 1$ and thus that $M_p \sin i = M_p$. In this case, by combining this with the planet to star radius ratio found from the depth of transit (Eq. 2.4) all we need is the radius of the star to determine the radius of the planet and thus determine the density of the planet by using $M_p \sin i = M_p$ for the mass of the planet.

Consequently, Transitsearch is a useful tool for photometrically following up on planets not yet known to transit. Furthermore observers can prioritize their targets based on their probability of transiting and the depth of the expected transit. The main disadvantage of Transitsearch is that, while it lists the coordinates of the target, users must find an image of the star field from another source in order to pinpoint more exactly which star is the target in their field of view.

On the other hand Exoplanet Transit Database (ETD) does include field images of each target star with the target clearly marked, in order to aid in identifying it. Like Transitsearch, ETD includes the expected transit time (in Universal Time), coordinates of each target and depth of the transit. However, ETD only includes targets that are known to transit, so it is not helpful in providing information to follow up on searching for transits of planets that are not yet known to transit. Still if our objective is to provide follow-up data for known transiting systems ETD is a very useful tool for planning our observing (Poddaný et al., 2010).

In addition to these websites STEPUP has also planned follow-up transit observing based on information from collaborators. For example, for the HD80606b campaign, the collaboration organizer, Josh Winn, had predicted the mid-transit time for the night our collaboration was to observe (Shporer et al., 2010; Winn et al., 2009). Another example is our SDSS-III MARVELS targets. The identity of these targets is confidential, since they are planetary candidates awaiting confirmation. Thus for MARVELS targets, Transitsearch and ETD will not help us in planning observing. Occassionally we are given some information from the MARVELS team about expected transit times, but since the targets are generally on short-period orbits of a couple of days, there is not much to gain by planning out exact observing runs over simply observing a priority target all night each clear night.

Once we have planned our observing and taken our data, we run it through our analysis pipeline and look for signs of a transit. In addition to simply plotting our corrected brightness vs. time, for known transiting planets, we can use ETD to upload our corrected data files for more exact fitting (see Section 3.3). Even if the planet is not yet known to transit, if we know certain predicted parameters about the planet and star, we can use the Transit Analysis Package[3] to further search for signs of a transit. In addition, a couple STEPUP members have more recently been working to develop a simple procedure to perform a chi-square test which will flag data sets that potentially include a transit.

Finally, we submit our data to various scientific entities. If it is a known transiting planet we can submit our data to be publicly available on ETD. Or, if it is a collaboration such as the HD80606b campaign or the SDSS-III MARVELS targets, we submit our data for use with the collaborative observing effort. This has resulted in STEPUP contributing to one paper thus far (Shporer et al., 2010) with another paper (regarding a MARVELS target) currently in the making. The MARVELS paper will discuss a target dubbed "MC002" for "MARVELS Candidate 2," since its identity is currently confidential. The paper will report on the radial velocity findings of the MARVELS observations, and include the photometric findings that STEPUP has contributed to the study of this target.

3.2 BRIEF DESCRIPTION OF OBSERVED TARGETS

The targets STEPUP has observed, including basic information about them and problems we encountered can be summarized as follows:

[3] http://ifa.hawaii.edu/users/zgazak/IfA/TAP.html

3.2.1 HAT-P-1b

HAT-P-1b is a 0.524 Jupiter-Mass, 1.217 Jupiter-Radius planet orbiting a G0V star 139 pc away at RA: 22:57:47 Dec:+38:40:30. The star is in a close binary system. HAT-P-1b orbits at a semi-major axis of 0.05535 AU, with an eccentricity < 0.067 and an orbital period of 4.4652934 days.[4] STEPUP has observed this target once in December 2009. This data set might include a partial transit. GJD=2455167.67, which appears to look like a possible mid-transit time, closely coincides with the predicted mid-transit time for HAT-P-1b, being off by only about 8 min. However, this data set suffers from poor tracking and our limited ability to obtain accurate brightness measurements for such a close binary star system using aperture photometry, so it is unclear if we can make any statement about having captured a transit in this data set. The lightcurve can be seen in Figure E1.

3.2.2 HAT-P-9b

HAT-P-9b is a 0.67 Jupiter-Mass, 1.4 Jupiter-Radius planet orbiting an F star 480 pc away at RA: 07:20:40 Dec:+37:08:26. HAT-P-9b orbits at a semi-major axis of 0.053 AU, with an approximately zero eccentricity and an orbital period of 3.922814 days.[5] STEPUP has observed this target once in November 2009. Unfortunately, the FWHM for this data set was 10.219, the largest of any of our data sets, making accurate aperture photometry difficult to obtain, and resulting in very poor RMS. See table 3.2.

3.2.3 HAT-P-13b,c

HAT-P-13b is a 0.85 Jupiter-Mass, 1.28 Jupiter-Radius planet orbiting a GIV star 214 pc away at RA: 08:39:32 Dec:+47:21:07. HAT-P-13b orbits at a semi-ma jor axis of 0.0426 AU, with an eccentricity of 0.0142 and an orbital period of 2.916243 days. HAT-P-13c is a 14.5 Jupiter-Mass planet orbiting the same star. HAT-P-13c orbits at a semi-major axis of 1.186

[4] http://exoplanet.eu/planet.php?p1=HAT-P-1&p2=b

[5] http://exoplanet.eu/planet.php?p1=HAT-P-9&p2=b

AU, with an eccentricity of 0.666 and an orbital period of 448.2 days.[6]

STEPUP has observed this target eleven times in March and April 2010. At the time, STEPUP was searching for signs of a transit of HAT-P-13c, which had been discovered by Bakos et al. (2009) but not yet known to transit. Thus our lightcurves were not necessarily expected to coincide with a transit of HAT-P-13b. Nevertheless, given its short orbital period and the frequency with which we were observing this target, there was definite potential for us to find a transit of HAT-P-13b in our data. Had we found such a transit, we could have explored any signs of transit timing variations which might have been due to the presence of HAT-P-13c.

Unfortunately, tracking, guiding, and focussing issues consistently plague most of these data sets as is summarized in table 3.2. In addition, on many nights, the telescope was left taking images after observers retired for the night. The rationale behind this practice is to maximize the amount of data one observer can collect. This can yield reasonable results provided conditions do not significantly worsen, and focus and guiding are maintained; however, one or more of these criteria were typically not met, resulting in significant scatter towards the end of many data sets, in addition to the previously mentioned factors that contributed to large FWHM, and poor RMS in general. Three nights of data have not been successfully analyzed through our pipeline due to these sorts of problems. Our best lightcurve is Figure E6 and consistent with constant flux, showing no signs of transit of either planet.

3.2.4 HD80606b

HD80606b is a 3.94 Jupiter-Mass, 0.921 Jupiter-Radius planet orbiting a GV star 58.4 pc away at RA: 09:22:37 Dec:+50:36:13. HD80606b orbits at a semi-major axis of 0.449 AU, with an eccentricity of 0.93366 and an orbital period of 111.43637 days.[7] STEPUP has observed this target three times in September 2009, January 2010 and April 2010. This

[6] http://exoplanet.eu/planet.php?p1=HAT-P-13&p2=b
[7] http://exoplanet.eu/planet.php?p1=HD+80606&p2=b

target will be discussed at length in Chapter 4.

3.2.5 TrES-2

TrES-2 is a 1.253 Jupiter-Mass, 1.169 Jupiter-Radius planet orbiting a G0V star 220 pc away at RA: 19:07:14 Dec:+49:18:59. TrES-2 orbits at a semi-major axis of 0.03556 AU, with an approximately zero eccentricity and an orbital period of 2.470614 days.[8] I observed this target when it was out-of-transit, as an undergraduate in October 2008, and STEPUP has observed this target once in August 2010. See Figures E14 and E15.

3.2.6 WASP-2b

WASP-2b is a 0.847 Jupiter-Mass, 1.079 Jupiter-Radius planet orbiting a KIV star 144 pc away at RA: 20:30:54 Dec:+06:25:46. WASP-2b orbits at a semi-major axis of 0.03138 AU, with an approximately zero eccentricity and an orbital period of 2.470614 days.[9] STEPUP has observed this target once in October 2010.

3.2.7 WASP-3b

WASP-3b is a 2.06 Jupiter-Mass, 1.454 Jupiter-Radius planet orbiting a F7V star 223 pc away at RA: 18:34:32 Dec:+35:39:42. WASP-3b orbits at a semi-major axis of 0.0313 AU, with an approximately zero eccentricity and an orbital period of 1.8468372 days.[10] STEPUP has observed this target once in May 2011.

3.2.8 XO-2b

XO-2b is a 0.57 Jupiter-Mass, 0.973 Jupiter-Radius planet orbiting a K0V star 149 pc away at RA: 07:48:07 Dec:+50:13:33. XO-2b orbits at a semi-major axis of 0.0369 AU, with an

[8] http://exoplanet.eu/planet.php?p1=TrES-2&p2=

[9] http://exoplanet.eu/planet.php?p1=WASP-2&p2=b

[10] http://exoplanet.eu/planet.php?p1=WASP-3&p2=b

approximately zero eccentricity and an orbital period of 2.615838 days.[11] I observed this target once as an undergraduate, in February 2009.

3.3 KNOWN TRANSIT ANALYSIS

Our earliest analysis was done on known transiting planets, and our analysis at this time consisted of plotting the relative brightness vs. time of our target compared to two reference stars. (For examples, see Figure 3.1). Though we generated output data files listing the points on the plots as columns, we did not employ any sort of fitting on our own. However, we did submit some of our data to the Exoplanet Transit Database, ETD[12] which performed more sophisticated analysis and fit of our data. For example Figure 3.2, Figure 3.3, Figure 3.4, and Figure 3.5 summarize the results of ETD analysis of our observations of TrES-2b taken on August 18, 2010. As can be seen from Figure 3.5 the geometric values implied by our data are within the errors of the catalogue data. Most other analysis results also agree well with existing data. In Figures 3.6,3.7, and 3.8 our data point is seen in blue. It not only agrees well with other data points plotted, but ETD's "data quality indicator" suggests it is good quality data: a 2 on a scale of 1 to 5 with 1 being the best, as is seen on the insets of Figuress 3.6,3.7, and 3.8.

When we strategically planned our observing of known transiting planets to coincide with predicted transit windows, we generally knew there would be a transit somewhere in the data sets. Moreover we knew about what time to expect the transit to take place. Thus these observations of known transiting planets served to help us confirm the success of our basic analysis procedures if we were able to reproduce a lightcurve of the right depth and at the right time. More recently a STEPUP member has taken on the challenge of working to develop a box fitting algorithm for more sophisticating fitting of our data. Furthermore, obtaining out-of-transit data has served to verify that our photometry measurements indeed

[11] http://exoplanet.eu/planet.php?p1=XO-2&p2=b

[12] http://var2.astro.cz/ETD/index.php

yield a constant relative flux, as well as to begin to investigate possible additional transiting planets in the target system, such as HAT-P-13c.

In addition, our contributions to the Exoplanet Transit Database served the scientific community in adding to the publicly available follow-up data on transiting extrasolar planets. Indeed, the Exoplanet Transit Database has been used by scientists searching for phenomena such as transit timing variation (Maciejewski et al., 2010; Christiansen et al., 2011). Finally, one case study in particular allowed us to contribute important data to a collaborateive effort to observe the transit of a known planet, namely HD80606b. The HD80606b analysis was more rigorously treated by the collaboration at large, and is detailed in Chapter 4: HD80606b Campaign and in the paper that resulted from the collaborative observing effort (Shporer et al., 2010).

3.4 CONCLUSIONS ON KNOWN TRANSITING PLANETS

Much can be learned from our observations of known transiting planets. First, targeting these systems helps us confirm our techniques and analysis. For the systems we have studied, we have obtained results that agree with predictions for values such as transit depth and timing. This is especially useful for new members of STEPUP who are just learning the principles of the transit technique. Understanding what we are aiming for then helps STEPUP members both in maintaining quality observational results and in developing software improvements. Indeed our August observations of TrES-2 have become our benchmark for a quality lightcurve and for testing new improvements made to our analysis procedures. Also, in developing fitting procedures of our own, our TrES-2 observations give us a quality test case to run such procedures on, since we have a clear, comprehensive transit and we can directly compare the results of any fitting procedure we develop to the fit done using ETD (Poddaný et al., 2010).

Second, we can contribute to various collaborations and scientific entities. For example, looking for long-term patterns in transit timing or duration becomes more useful with tools like ETD which allow for using archived data such as ours. Or when observing on long-period transits, it is often useful to collaborate with other observatories to maximize coverage of the transit, as we did for the case of HD 80606b.

Finally, our observations of known transiting planets give us the opportunity to move forward in understanding our sources of errors and to optimize our results. One STEPUP member used known transiting planet data to investigate the gain we use to better pinpoint this contribution to our error budget. Moreover, Appendix B illustrates how we improved the spread of our data in our TrES-2 lightcurve by changing the choice of inner and outer sky radii in our aper command.

These are some of the highlights of the many practical and scientific applications for our observations of known transiting planets. Follow-up observations are a very important aspect of the study of extrasolar planets, both to confirm what we know and to search for clues that might point towards what we do not yet know. Therefore, observing such known systems will continue to be an ongoing endeavor for STEPUP research.

For a summary of all known transiting targets observed and number of data sets analyzed for each target see table 3.1. For a summary of number of images, FWHM, and RMS of each data set, see table 3.2. For example images of all transiting targets observed, see Appendix C. Finally lightcurves of these targets can be found in Appendix E, and data files of the photometry for these data sets can be found in Appendix F.

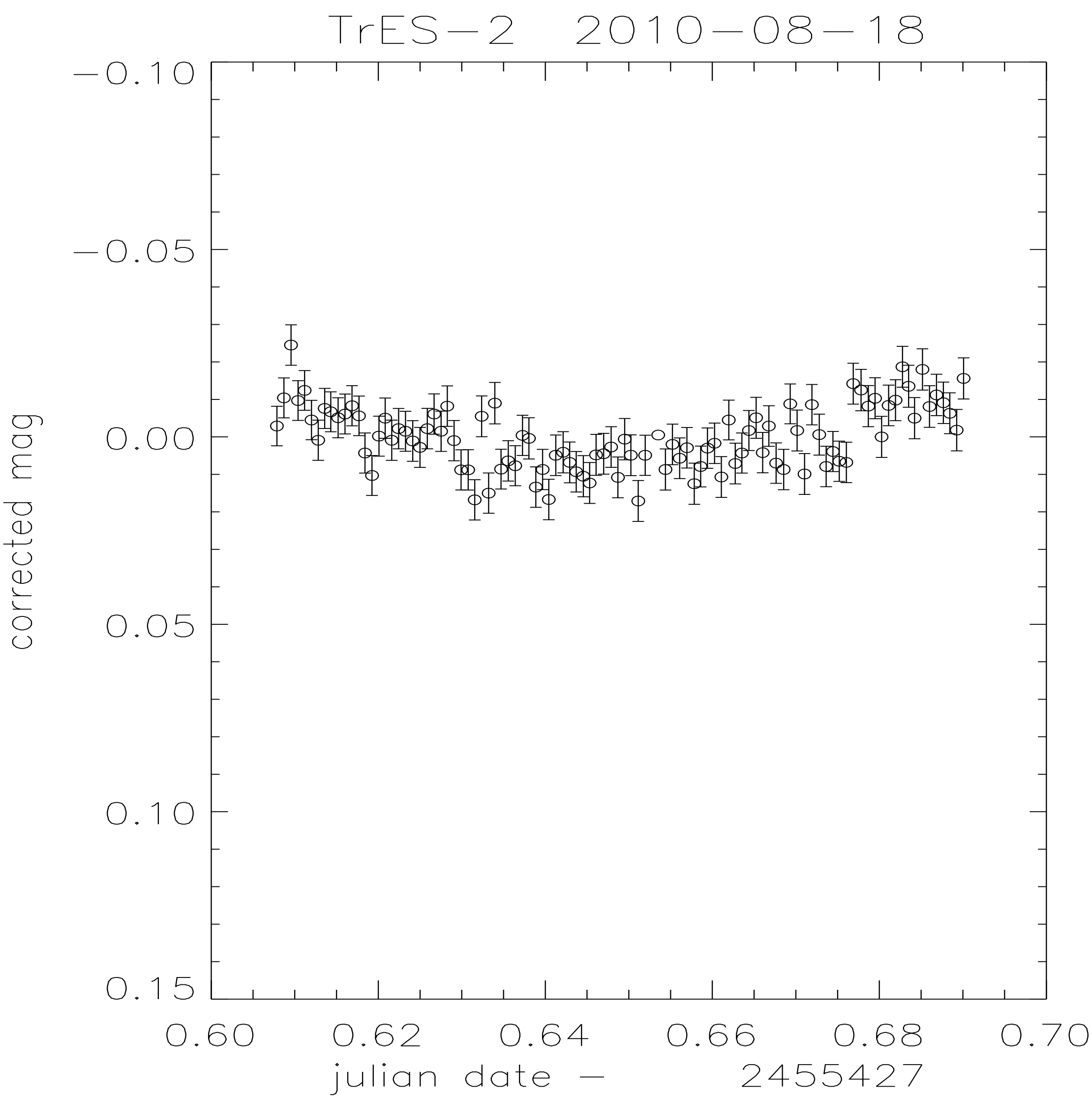

Figure 3.1: STEPUP Plot of relative brightness vs. Julian date for transit of TrES-2b from August 18, 2010

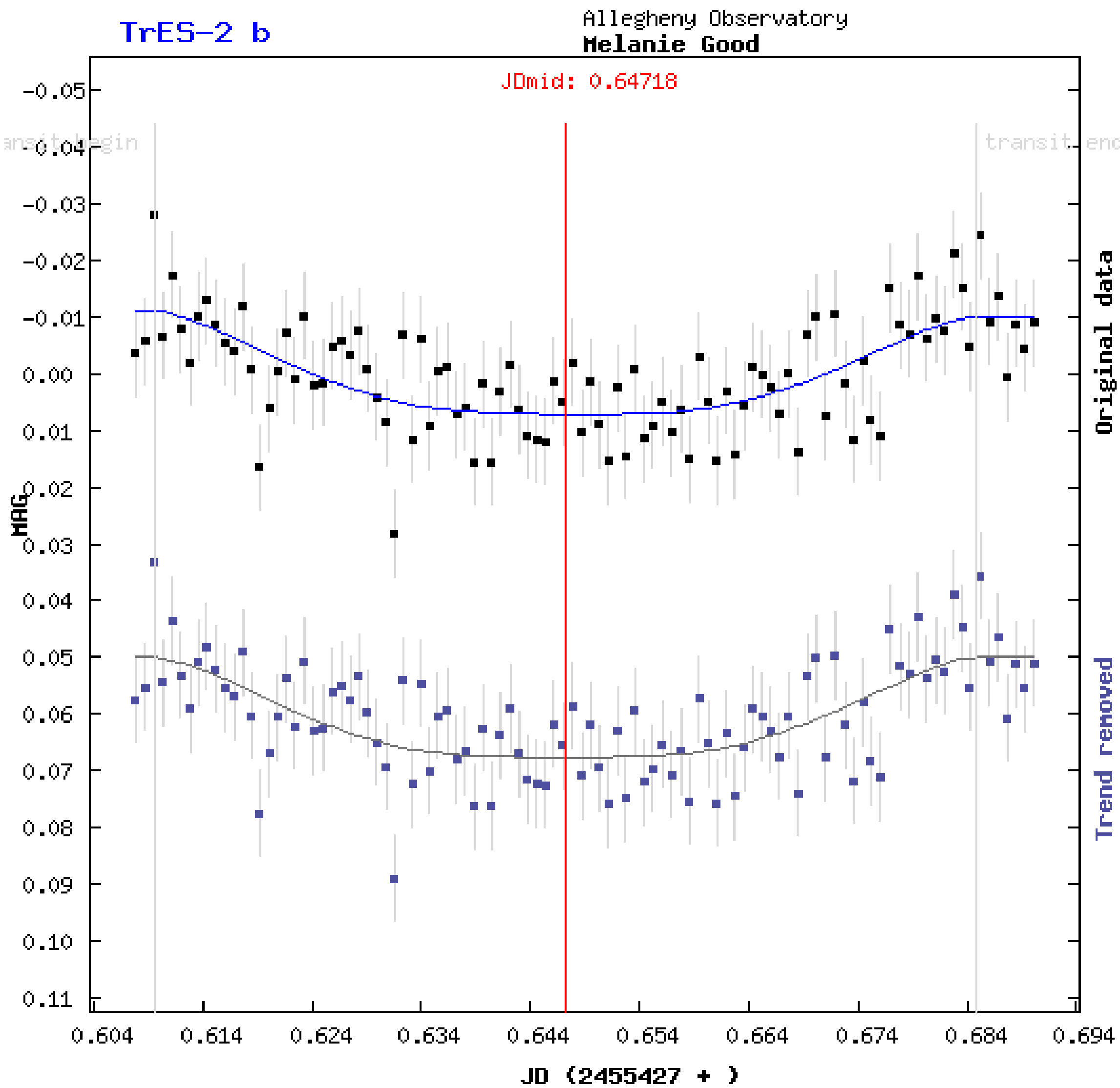

Figure 3.2: Transit of TrES-2b from August 18, 2010, as fitted by ETD, http://var2.astro.cz/ETD/index.php The lower "trend removed" lightcurve appears on all fitted lightcurves submitted to ETD. This lightcurve corrects for systematic errors (Poddaný et al., 2010).

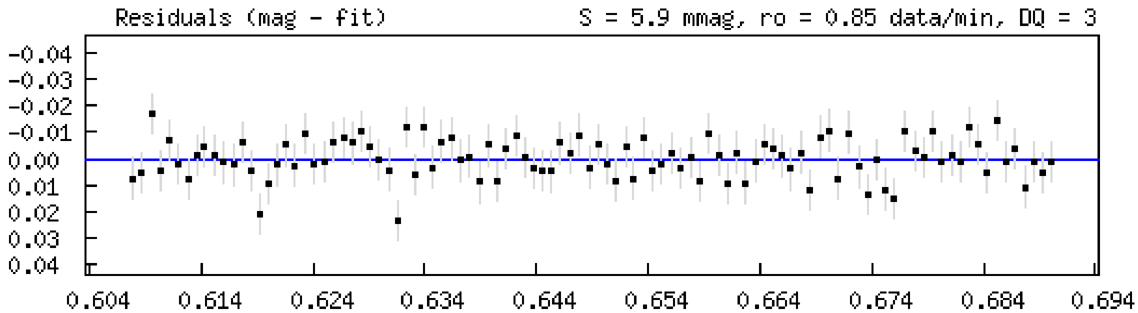

Figure 3.3: Residuals of August 2010 TrES-2b transit as calculated by ETD (Poddaný et al., 2010).

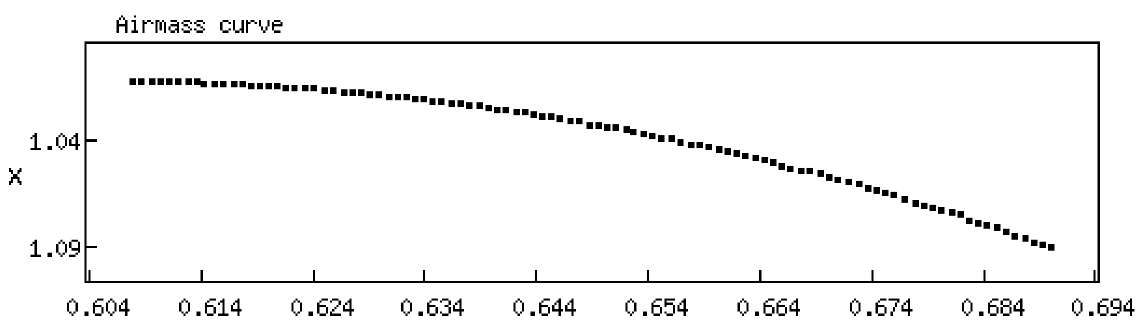

Figure 3.4: Airmass calculated by ETD for August 2010 TrES-2b transit (Poddaný et al., 2010).

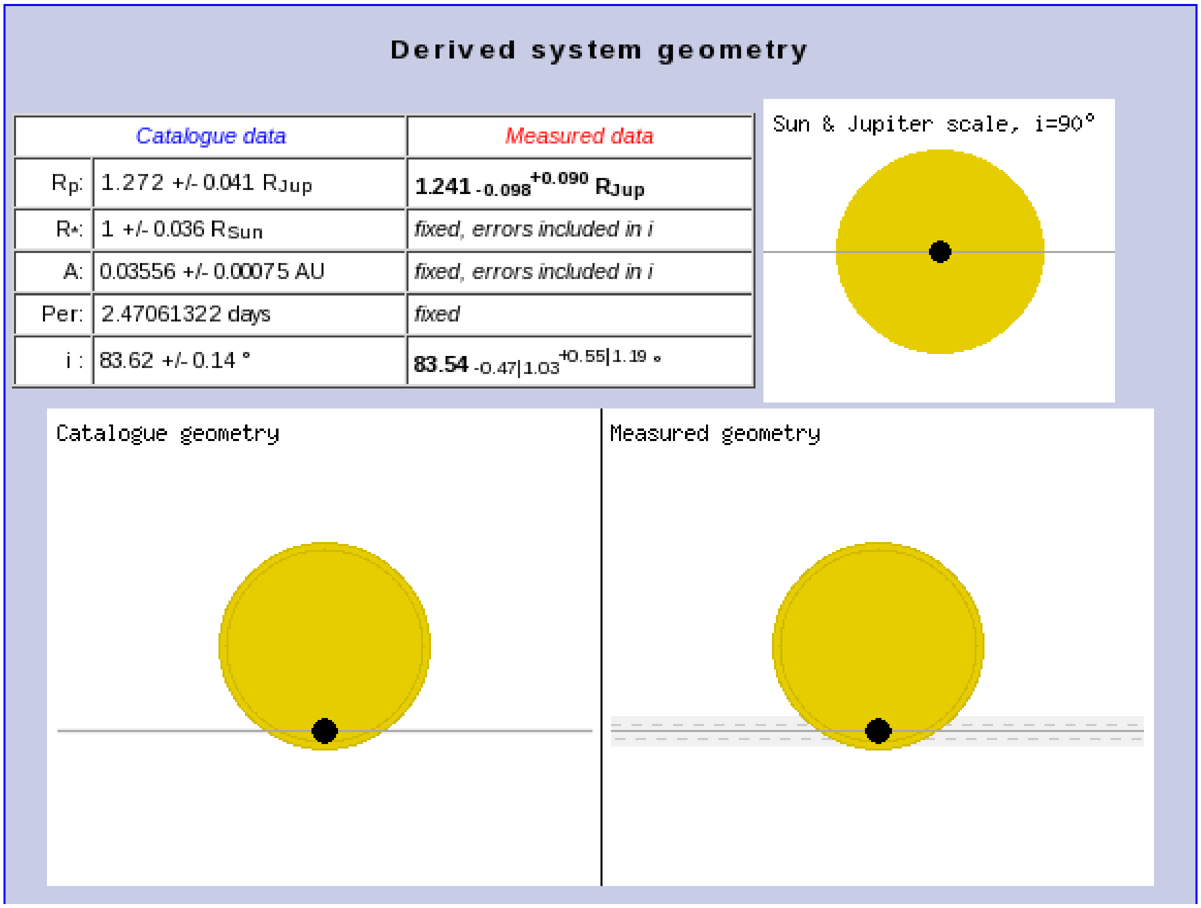

Figure 3.5: ETD-derived geometry for TrES-2 system using STEPUP August 2010 data (Poddaný et al., 2010).

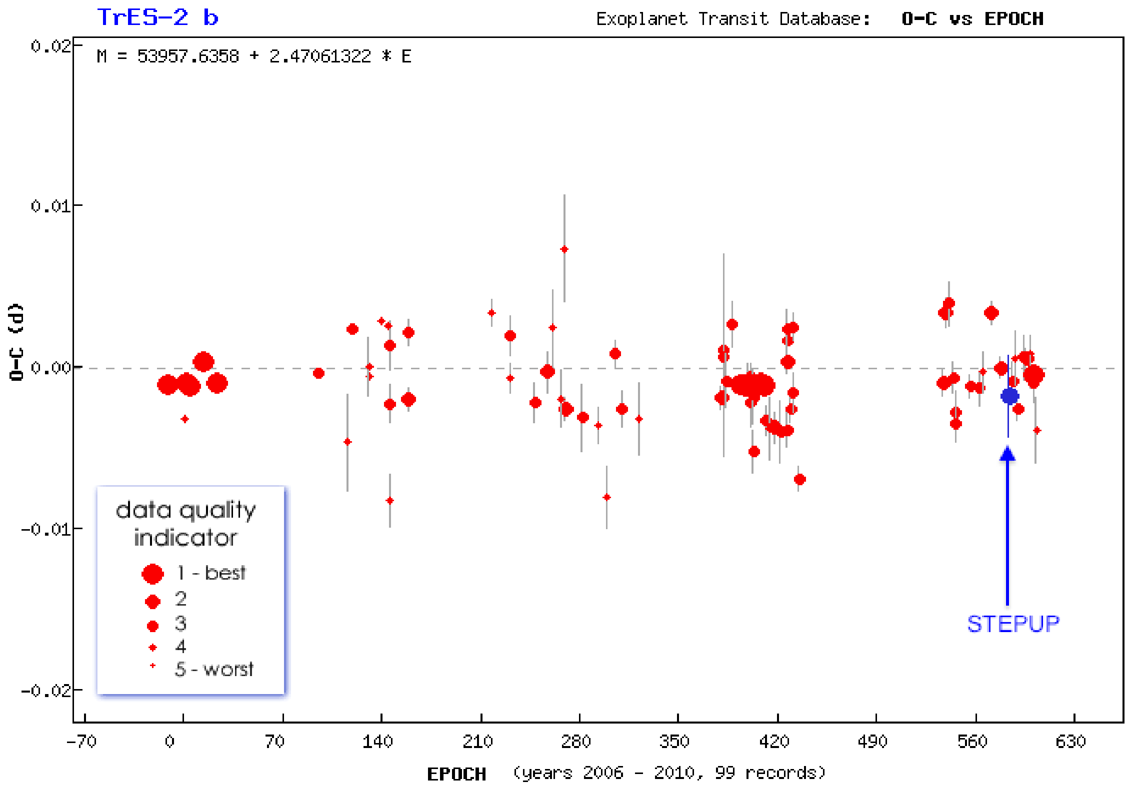

Figure 3.6: ETD O-C plot of TrES-2b with submitted observations from various observatories. STEPUP data point is labeled and appears in blue with error bars. The size of the data point represents its quality as judged by ETD and explained on the inserted box. STEPUP data is a 2 on a scale of 1 to 5, with 1 being the best. The vertical axis represents the "observed minus calculated" value for the mid-transit time, with zero indicating that the mid-transit time occured at the same time as was calculated. A dashed horizontal line at O-C = 0 is overplotted. A discrepancy from this line in the data could indicate a transit-timing variation, which has implications for the nature of the system in question, such as possibly indicating the presence of additional planets not yet detected (Poddaný et al., 2010).

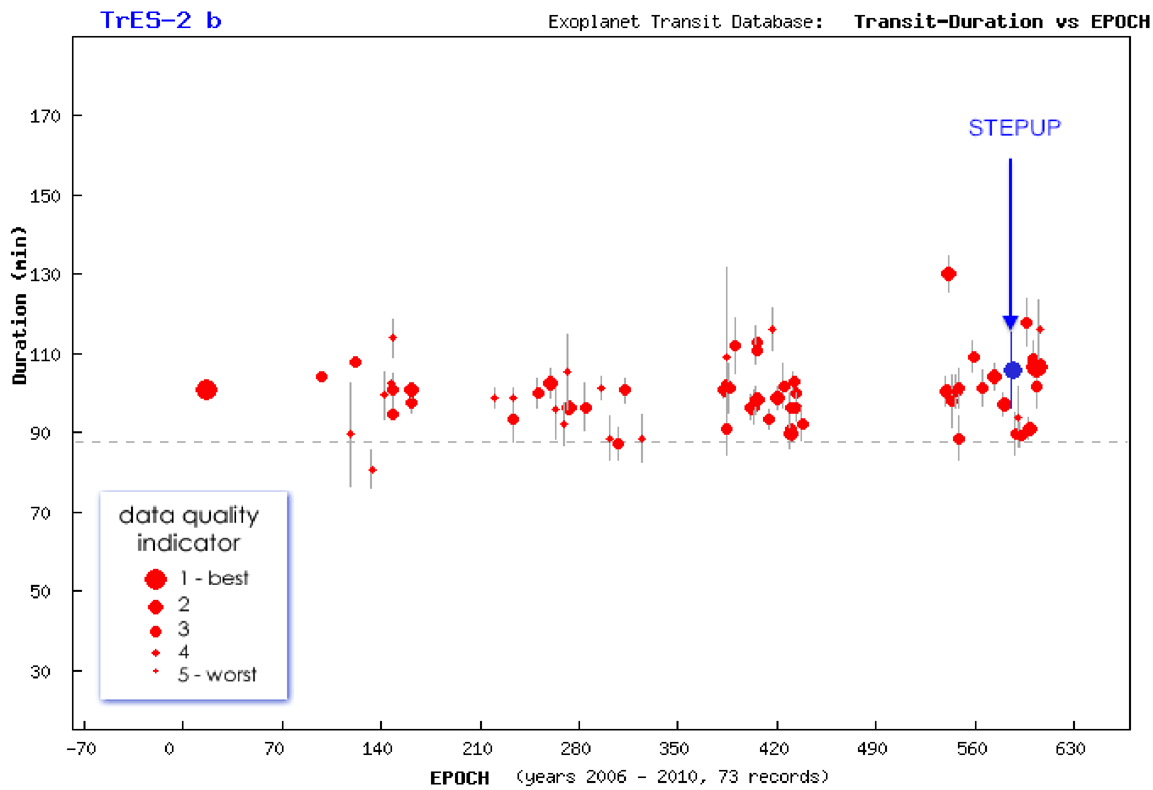

Figure 3.7: ETD transit duration plot of TrES-2b with submitted observations from various observatories. STEPUP data point is labeled and appears in blue with error bars. The dashed horizontal line indicates the calculated transit duration (Poddaný et al., 2010). Many observations seem to imply a longer duration than expected. Transit-duration variation might indicate that the accepted orbital parameters are not yet precisely correct or even something as exotic as the presence of an exomoon, though this is not likely to be the case for TrES-2b, since it was studied in detail by Kepler and not shown to exhibit signs of an exomoon (`http://www.homepages.ucl.ac.uk/~ucapdki/tres2.html`)

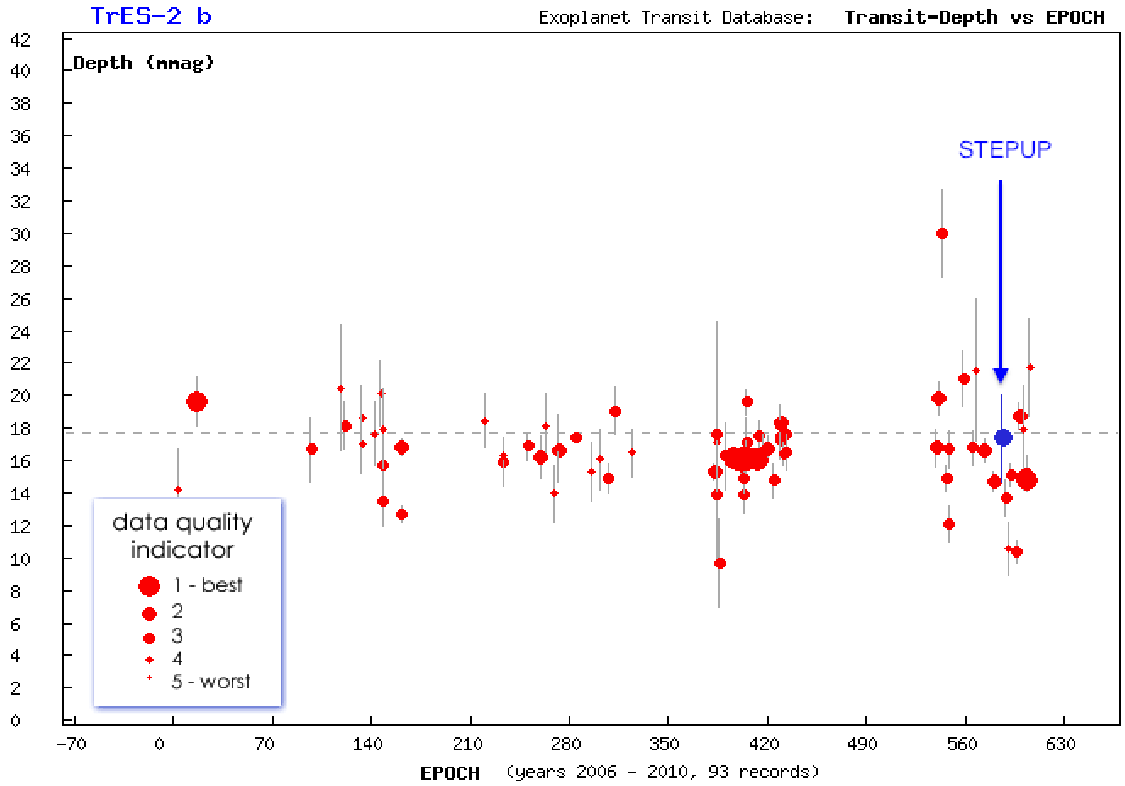

Figure 3.8: ETD transit depth plot of TrES-2b with submitted observations from various observatories. STEPUP data point is labeled and appears in blue with error bars. The dashed horizontal line indicated the expected transit depth (Poddaný et al., 2010).

Table 3.1: Summary of Known Transiting Targets Observed

Target	No. Data Sets	Beginning	Ending	Stellar Mag	Spectral Type
HAT-P-1	1	2009-12-01	2009-12-01	10.4	G0V
HAT-P-9	1	2009-11-03	2010-04-26	11.27	F
HAT-P-13	11	2010-03-31	2010-04-27	10.62	GIV
HD80606b	3	2009-09-23	2010-04-29	8.93	GV
TrES-2	2	2008-10-31	2010-08-18	11.41	G0V
WASP-2	1	2009-10-05	2009-10-05	11.98	KIV
WASP-3	1	2011-05-31	2011-05-31	10.64	F7V
XO-2	1	2009-02-06	2009-02-06	11.18	K0V

Table 3.2: Summary of Statistics of Known Target Data Sets

Target	Date	No. Images	FWHM (pixels)	RMS (%)	Note
HAT-P-1	2009-12-01	85	6.411	1.06	possible transit?
HAT-P-9	2009-11-03	150	10.219	9.09	large FWHM
HAT-P-13	2010-03-31	102	6.952	1.73	poor focus
HAT-P-13	2010-04-06	129	8.977	0.77	low counts; poor focus
HAT-P-13	2010-04-07	150	5.697	0.59	poor focus/guiding
HAT-P-13	2010-04-13	155	5.477	0.39	
HAT-P-13	2010-04-14	426	4.966	6.55	re-focus; left running
HAT-P-13	2010-04-18	190	7.456	40.57	low counts; poor guiding
HAT-P-13	2010-04-22	268	5.131	7.57	re-focus; left running
HAT-P-13	2010-04-26	124	7.215	1.48	poor guiding
HD80606b	2009-09-23	43	5.191	21.0	
HD80606b	2010-01-13	358	5.584	0.43	partial transit
HD80606b	2010-04-29	168	4.193	0.33	
TrES-2	2008-10-31	23	4.572	0.45	
TrES-2	2010-08-18	101	4.038	0.71	full transit
WASP-2	2009-10-05	110	6.397	4.82	
WASP-3	2011-05-31	61	5.902	0.67	
XO-2	2009-02-06	117	6.997	0.36	partial transit

4.0 HD80606b

4.1 OVERVIEW OF PLANET-STAR SYSTEM

HD80606b is one of the most unusual extrasolar planets discovered so far. It orbits the GV star HD80606 which itself is in a visual binary system, its stellar companion HD806067 located about 2000AU away from HD80606 (Naef et al., 2001) (See Figure 4.1 for a STEPUP image of the star field). HD80606b is almost four times the mass of Jupiter, and it takes 111.4 days to orbit its star[1]. None of these facts are very remarkable, until you learn that HD80606b is on an orbit which takes it from 0.034AU to 0.905AU (Naef et al., 2001) with an eccentricity of 0.93366 [1] and a spin-orbit misalignment of $\lambda \approx 50^\circ$ (Pont et al., 2009) ($\lambda = 0$ for a perfectly aligned system).

HD80606b was originally discovered in 2001 via radial velocity (Naef et al., 2001), and only later was it discovered that the planet transited its star. In fact the primary transit was not the first transit to be detected. Instead, in November 2007, Greg Laughlin and collaborators found a secondary eclipse in their 30-hour long Spitzer observations (Laughlin et al., 2009). A secondary eclipse occurs when a planet passes directly behind a star to our line of vision. This results in the star blocking some of the brightness of the planet. Since planets are much dimmer than stars, only a very small drop in overall brightness occurs during a secondary eclipse. So it is generally easier to see at longer wavelengths where the planet has more surface brightness relative to the star, and for planets with a higher surface temperature. Still, this is a very tiny effect, so because secondary eclipses generally have

[1] http://exoplanet.eu/planet.php?p1=HD+80606&p2=b

such a shallow depth in the lightcurve, they are often detected *after* a primary transit has already been discovered, if they are detectable at all. However in the case of HD80606b the secondary eclipse was discovered first. The detection of a secondary eclipse was aided not only by the fact that the Spitzer observations were taken at a wavelength of $8\mu m$ but also by the fact that the geometry of the orbit is such that the secondary eclipse occurs when the planet is fairly close to periastron and reaching a surface temperature of approximately 800 K during the secondary eclipse (Laughlin et al., 2009). These two factors resulted in an observed dip of

$$\frac{\Delta F}{F_*} = 0.001 \pm 0.0002 \tag{4.1}$$

(Laughlin et al., 2009)

The existence of a secondary eclipse indicated that the system must be very close to $i = 90°$ and thus increased the odds that a primary transit would occur. Based on this increased probability of transit, Greg Laughlin used his blog, http://oklo.org, to encourage observers across the world to look for a primary transit to occur. He predicted that the transit would last about 16 hours on the night of February 13, 2009 [2], and that the odds of the transit occurring were about 15% (as compared to 11% a-priori geometric probability before the secondary eclipse had been discovered)[3]. Sure enough, a primary transit was discovered that night by Fossey et al. (2009).

4.2 COLLABORATIVE NATURE OF GROUND-BASED OBSERVATIONS

As the Fossey et al. (2009) paper reveals, only a partial transit could be obtained at one geographic location due to the long duration of the planetary transit. Traditionally, most transiting extrasolar planets thus observed have had a fairly short period and, as such,

[2]It is now known that the duration of the transit of HD80606b is actually 11.88 hours, http://var2.astro.cz/ETD/etd.php?STARNAME=HD80606&PLANET=b

[3]http://oklo.org/2009/02/12/ready-set/

complete a transit in no more than a few hours. This means an entire transit can easily be obtained in a single night at a single observatory. But for a longer-period planet, a transit could potentially last longer than the number of hours of darkness at any one ground-based location. Or even if the transit is not strictly longer than the number of hours of darkness, the odds of an entire transit fitting withing observable nighttime hours at one particular location decrease significantly for transits whose duration is more than a few hours. For ground-based observing, then, this opens up the need for collaborative observing efforts if an entire transit is to be obtained.

This was a motivating factor behind Greg Laughlin's promoting the idea of many observers in various locations all searching for the February 2009 transit. Once a transit was discovered, this inspired a more organized collaborative effort to observe the next transit. I was fortunate enough to speak with Greg Laughlin about this opportunity when visiting the University of California, Santa Cruz in the spring of 2009. He encouraged me to contact Josh Winn at MIT and join the collaborative effort, dubbed the HD80606b Campaign[4]. Though I was unprepared to participate in the upcoming June 2009 transit (since I was just beginning my graduate studies and re-vamping my analysis procedures), I did contact Josh Winn about participating in the September 2009 transit, and the Allegheny Observatory was added to the list of observatories collaborating on the HD80606b Campaign. The collaborative effort proved successful in covering most of the June 2009 transit (Winn et al., 2009) (with just a small amount of the transit right at the beginning of the ingress not covered by the collective data), and I was eager to contribute to the goal of full coverage of the September 2009 transit. With our fledgling STEPUP team set to gather data that September 23, 2009, it unfortunately turned out to be a night of terrible weather conditions in Pittsburgh, and we were unable to obtain useable data. We were not alone in our misfortune. Indeed, the September 23, 2009 transit collaborative effort was largely unsuccessful, as only three observatories (Rosemary Hill Observatory in Florida, Fred Lawrence Whipple Observatory in Arizona, and Mount Laguna Observatory in California) were able to obtain good data

[4]http://oklo.org/2009/09/21/campaign-mode/

that night, and the collective data only spanned a small portion of the beginning of the transit.(Shporer et al., 2010)

Not dissuaded, the HD80606b Campaign members set our sights on the following transit, which was to take place on January 13, 2010. This time, luck would be on our side, as we joined 8 other observatories to obtain a full lightcurve of this transit event.

4.3 JANUARY 13, 2010

The observatories that contributed data to the January 13, 2010 collaborative lightcurve were the following: Wise Observatory in Israel; Gran Telescopio Canarias, La Palma, Canary Islands; Observatoire de Haute Provence, France; Allegheny Observatory, Pittsburgh, Pennsylvania, USA; Rosemary Hill Observatory, Bronson, Florida, USA; Fred Lawrence Whipple Observatory, Mt. Hopkins, Arizona, USA; Table Mountain Observatory, Wrightwood, California, USA; George R. Wallace Jr. Astrophysical Observatory, Westford, Massachusetts, USA; Faulkes Telescope North, Mt. Haleakala, Maui, Hawaii, USA. (Shporer et al., 2010) Each observatory was subject to local weather conditions and as such different amounts of data were contributed by different observatories. At Allegheny Observatory, we were fortunate to be able to contribute more hours' worth of data than any other observatory, though our most important contribution occurred during the transit egress. (Shporer et al., 2010)

Our contribution was not without painstaking struggles with some subpar data. As a team STEPUP members divided the night into shifts to decrease risk of human error due to sleep deprivation. Nevertheless, some students remained for the entire night. Others had only recently completed training on our observing procedures. Due to early morning obligations, I was only able to be present personally for the beginning few hours to help the team get set up.

When analyzing the data, it was clear that just before the egress, some of the data must not have been sensible. In troubleshooting, we were able to ascertain that some of the problem had been due to out-of-focus data prior to a refocus that was performed about halfway through the night. Thankfully this data was salvaged by increasing the star radius in our aperture photometry from 7 pixels to 10 pixels. Other data after the refocus had actually saturated. Checking for saturation was something that had been discussed and included in the opening checklist but not emphasized as something to continually monitor.

Fortunately, most of our data was useable after the aperature radius increase was implemented and the saturated data were cut from the data set. What resulted was coverage of the transit from just after the ingress ended to after the egress was completed. No other observatory in the collaboration was able to get enough data to establish the baseline bottom of the lightcurve and include the egress and out-of-transit data as well. This made the STEPUP contribution unique in helping quantify both the transit duration and the depth of transit. In Figure 4.2 you can see each observatory's individual data contributions. Allegheny Observatory is indicated by the label "AO." Once the entire collaboration's data was put together, what resulted was a very comprehensive lightcurve of the entire January 13, 2010 transit, which can be seen in Figure 4.3.

4.4 COLLABORATION ANALYSIS

Once we cut out all our un-usable data, we re-ran it through our IDL pipeline. This analysis resulted in a file containing the Julian Date and fluxes of HD80606 and HD80607 for comparison. We then generated a similar file for a night when a transit of HD80606b was not taking place.

These files were then forwarded to Josh Winn at MIT, who coordinated the collaboration. The task then remained of incorporating each set of data into the colloaborative set of data points. It is difficult to combine measurements taken at different locations experiencing different weather conditions and using different instruments with different sensitivities and bandpasses. The flux ratios for each observatory must be carefully rescaled to a common scaling. Avi Shporer at UC Santa Barbara set about doing this by assigning a normalization factor to each data set using out-of-transit data given by each observatory whenever possible (which was the case for 6 observatories). There were four observatories, however, for which there were no or negligible amounts of out-of-transit data, and, for those, the normalization factor was a free parameter in the fitting process.(Shporer et al., 2010)

For the overall lightcurve shape itself, the following Hébrard et al. (2010) parameters were adopted as constraints, since these were derived based on high-quality Spitzer data: orbital period: P, planet-to-star radius ratio: $r = R_p/R_s$, orbital semimajor axis in units of stellar radius: a/R_s, orbital eccentricity: e, inclination angle : i, and values related to the argument of periastron: $e\cos\omega$ and $e\sin\omega$ where ω is the argument of periastron. (Shporer et al., 2010)

The 8 limb-darkening coefficients were estimated and held fixed in the fitting process using grids from Claret (2004) and Claret (2000) for a star of $T_{\text{eff}} = 5645K$, $\log g = 4.5$, and $[Fe/H] = 0.43$ (Naef et al., 2001; Shporer et al., 2010).

Thus in the fitting model, there were 34 parameters. 8 of these were held fixed, 12 were controlled mainly by Gaussian priors (the Hébrard et al. (2010) parameters and the 6 normalization factors), and 14 were free parameters. These free parameters included the normalizations of the 4 observatories with insufficient out-of-transit data, and an individual periastron passage time for each observatory, which was later converted to a mid-transit time. (Shporer et al., 2010)

After an intial fit, cutting of outliers $> 4\sigma$, and weighting of each observatory's data based on the size of its errors, a final fit was performed using a Monte Carlow Markov Chain (MCMC) algorithm (Shporer et al., 2010). The end result for the January 2010 transit had $\chi^2/N_{\text{dof}} = 442/429$ (Shporer et al., 2010). This fit is overplotted with the data points in Figure 4.2 and Figure 4.3.

4.5 RESULTS OF COLLABORATIVE EFFORT AND STEPUP CONTRIBUTION

The collaboration analysis resulted in 10 mid-transit time estimates, one for each observatory. Of these 10 estimates, 3 had large uncertainties, and these corresponded to observatories with less than 5 hours of transit data, and no out-of-transit data. These were eliminated before averaging the remining 7 to determine a collaborative mid-transit time estimate. (Shporer et al., 2010) The average was unweighted in order to average out possible correlated noise in the individual estimates. If a weighted average is used, the mid-transit time changes by $< 0.25\sigma$. The unweighted average yields an HJD mid-transit time of $T_c = 2455210.6502$ with an rms uncertainty of 0.0064 days (Shporer et al., 2010). This mid-transit time is in between the mid-transit time derived from the Hébrard et al. (2010) Spitzer observations, and the mid-transit time predicted by Winn et al. (2009). Specifically, this mid-transit time is 1.3σ later than the Hébrard et al. (2010) mid-transit time, and 1.1σ earlier than the Winn et al. (2009) predicted mid-transit time, which does not confirm or refute the Hébrard et al. (2010) result (Shporer et al., 2010). Thanks to our ability to get many hours' worth of data (including out-of-transit data) STEPUP was one of the 7 contributers to this estimate of the collaborative mid-transit time.

One other aspect of the Hébrard et al. (2010) Spitzer observations that was neither confirmed nor refuted by the ground-based collaboration was the "bump" in the Spitzer lightcurve. This "bump" amounted to an hour-long increase in flux of $\sim 0.1\%$ just before the mid-transit which could be explained by the possible presence of a star spot (Hébrard et al., 2010). The ground-based effort did not have the sensitivity to identify such a small flux variation; however, the collaboration data implies that it is unlikely that there was a flux increase of 0.2% (Shporer et al., 2010). The STEPUP data included the time period during which the Spitzer "bump" was observed and as such helped constrain the size of the possible flux increase as likely being $< 0.2\%$.

Considering the amount of data STEPUP obtained, and the advantageous timeframe during which our data contributions took place, we were able to contribute in a useful way to a collaborative ground-based effort to observe a transit of HD80606b. This effort has served to show that complete and accurate lightcurves can be obtained for longer-period planets by working together from the ground. Such efforts will no doubt become an affordable way to complement space-based observations as more longer-period planets are discovered.

For example, if we want to follow-up on any planets discovered in the habitable zone of a Sun-like star, this would involve a long transit duration. Consider the Earth orbiting the Sun. The duration of the Earth transiting the Sun can be calculated by considering the portion of Earth's orbit during which the Earth would be transiting to a distant observer. The geometry would look very similar to that in Figure 1.2, only imagining that instead of the orbital plane being perpendicular to the page, it is parallel to the page. In that case, the transit duration will last from the time the planet is in the position depicted until the planet is 2θ from where it is currently depicted. For clarity, we can call that angle α, and, using the small angle approximation again, $\alpha \approx \frac{2(R_* + R_p)}{a}$. For the case of the Earth and the Sun, $R_{\rm sun} \gg R_{\rm earth}$, so we can approximate this as $\alpha \approx \frac{2R_{\rm sun}}{a}$. This is the angular portion of the Earth's orbit during which the transit takes place, so the fraction of this angular portion to the whole orbit would simply be $\frac{\alpha}{2\pi}$. To determine what this fraction of the orbit is in time, we need only multiply by the period of the orbit: in this case, one year. Plugging in 1AU for a and the radius of the Sun for $R_{\rm sun}$, we find this transit duration to be $\sim$13 hours, very similar to that of HD80606b. This means that potentially-habitable worlds will likely require collaborative observing efforts like the HD80606b Campaign, for ground-based follow-up to capture an entire transit.

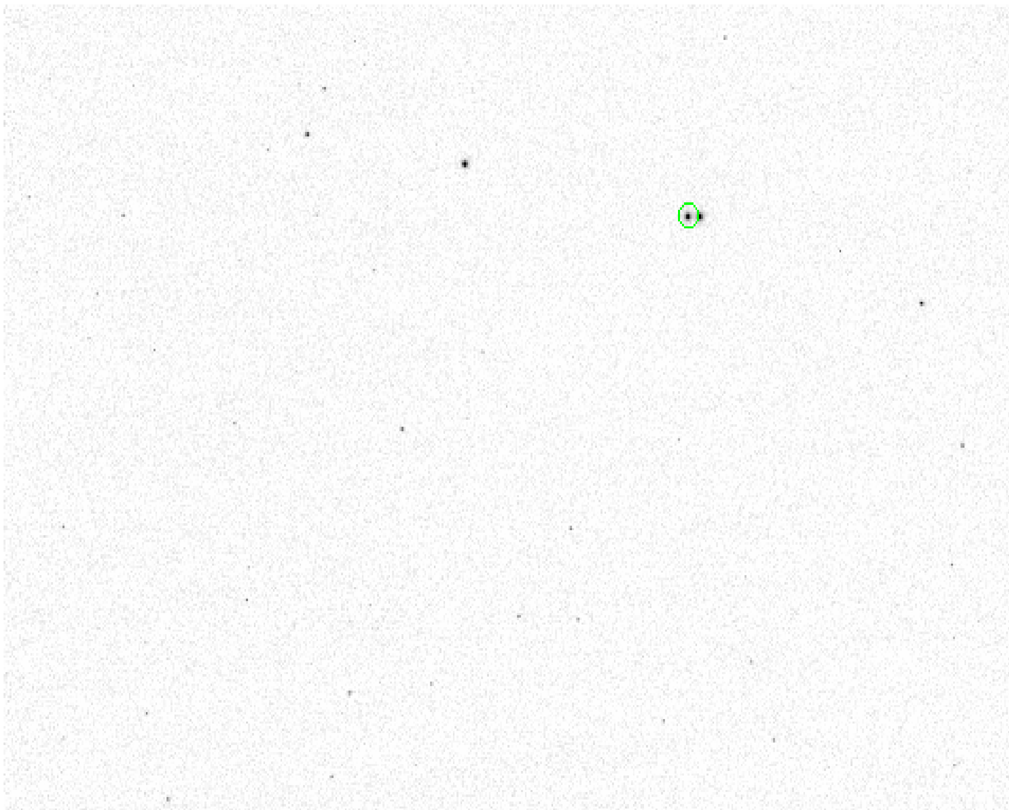

Figure 4.1: Image from STEPUP data of HD80606 starfield. The visual binary system of HD80606 and HD80607 is clearly visible near the upper part of the image. HD80607 is the left of the two stars and HD80606 is the right of the two stars.

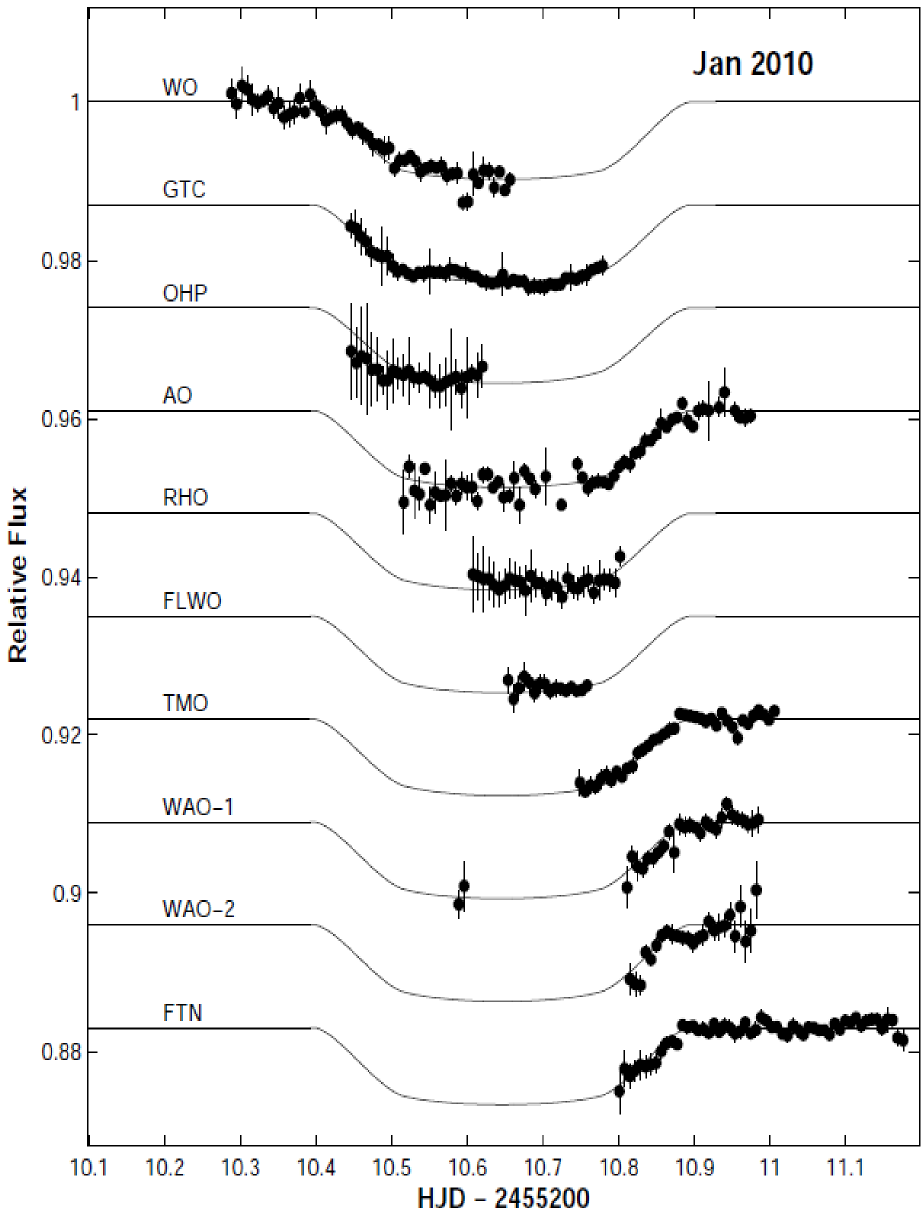

Figure 4.2: (Shporer et al., 2010, Fig. 1),Individual HD80606b transit data from 10 observatories with best-fitting model overplotted. Allegheny Observatory is indicated as AO. Note that the lightcurves are separated by an arbitrary vertical offset so that they can be seen individually.

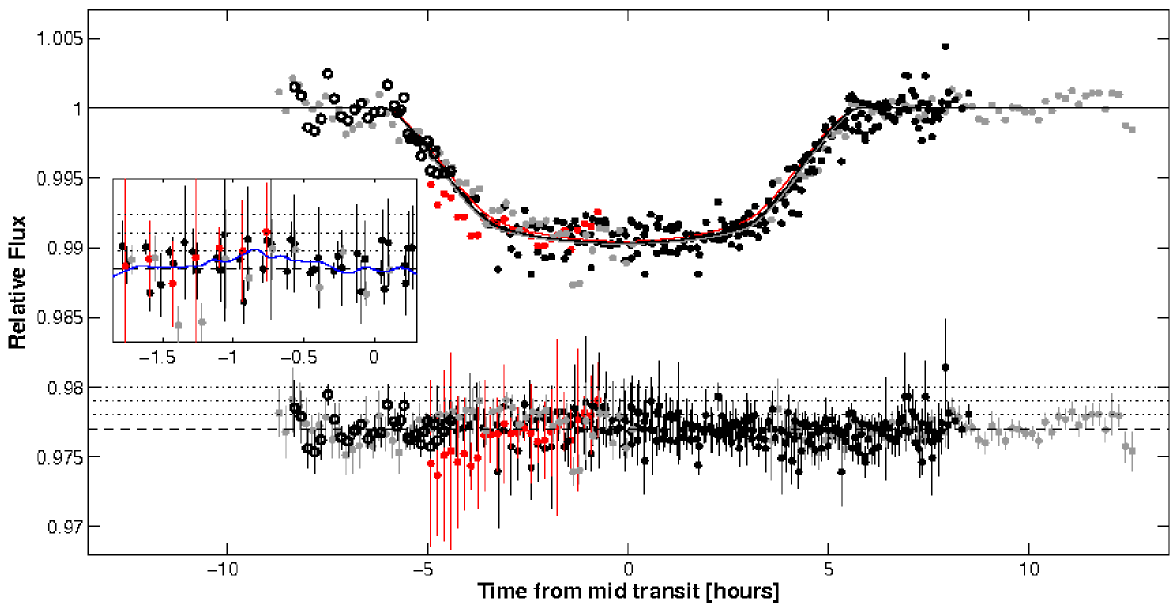

Figure 4.3: (Shporer et al., 2010, Fig. 2),HD80606 Collaborative Lightcurve. Z-band data are in gray, i and I data in black and r data in red. September 2009 data are indicated by open circles; whereas, filled circles are the January 2010 data. Plotted below the lightcurve are the residuals, with error bars. The inset shows a zoomed-in view of the residuals when a “rebrightening”or“bump”was observed with Spitzer, a feature which is overplotted in blue Hébrard et al. (2010). The collaboration data neither confirm nor refute the existence of the bump Shporer et al. (2010).

5.0 SDSS-III MARVELS

5.1 MARVELS PROJECT DESCRIPTION

The Multi-object APO Radial-Velocity Exoplanet Large-Area Survey (MARVELS) is part of the Sloan Digital Sky Survey-III. MARVELS simultaneously observes multiple targets, which it achieves by using a multi-fiber instrument that combines a spectrograph with a Michelson-type interferometer. The advantage of measuring multiple objects at once is that it is more efficient in discovering many planets than single-object surveys; thus this technique more quickly amasses a large sample. MARVELS will monitor 8,400 stars in total (Eisenstein et al., 2011), most of which are main sequence stars in spectral classes F, G and K and a small portion of which are giant stars for roughly 5 years. The magnitude of the stars being monitored is $8 < V < 12$. By monitoring stars that meet these criteria, MARVELS targets will be a well-controlled sample, and, having large amounts of data gathered by the same instrument, any systematics will be consistent across the sample. The main goal is to provide a large, statistically significant, controlled sample of gas giant planets of $M > 0.2M_J$ that can be used for testing detailed models of planet formation, migration and dynamical evolution. It is expected that MARVELS will detect between 150 and 200 planets around main sequence stars. Of those planets that MARVELS finds, it is expected that about 10 of them should be transiting systems, which is more than double the number of transiting systems found in previous radial velocity surveys (Eisenstein et al., 2011; Ge and Eisenstein, 2009).[1]

[1] http://www.sdss3.org/collaboration/description.pdf

5.2 PHOTOMETRIC FOLLOW-UP OF PLANETARY CANDIDATES

Once a periodic RV signal is found on a particular MARVELS target, photometric follow-up of this individual star can be undertaken. Identity, coordinates and other pertinent information is only shared with MARVELS collaborators; this is where STEPUP enters the picture. Through our collaborative relationship with MARVELS, we are given proprietary information on the target star. That information includes such things as the coordinates of the star, its magnitude, and an image of the star field. This allows us to find the star and observe it for any possible signs of transit.

More specifically, the STEPUP team chooses the specific MARVELS target(s) to monitor based on the observability of the target at a particular time of year. Then this target takes priority and on any clear night we take a continuous set of images of the target throughout the night, choosing the exposure time based on the flux we receive from the star (see Section 2.3.1). Since MARVELS targets tend to host massive sub-stellar companions on short periods of a few days or less, this observational strategy gives us some assurance that over several weeks' time, we ought to have a good chance of stumbling upon a transit should the system be aligned close to $i = 90°$.

On the other hand, observing constant flux is is also important information because it can contribute towards ruling out a transiting geometry. This would imply that the mass estimate $M_p \approx M_p \sin i$ is only a lower limit for the true mass of the orbiting object. Thus far, none of our observed MARVELS targets have exhibited any inconsistency with a constant flux which might indicate a possible transit.

Given the expected yield of transiting planets and our photometric sensitivity, we can determine what size planets we are capable of detecting should they transit and see how well that aligns with the expected types of planets MARVELS should discover. Since MARVELS expects to detect massive planets of $M > 0.2M_J$ and since extrasolar planets are often found to have radii at least as large, if not larger than theoretical predictions (Laughlin et al., 2005; Kuchner and Seager, 2007), it is reasonable to expect the planets MARVELS discovers to be

$R \geq 0.5R_J$ (Kuchner and Seager, 2007). Table 5.1 summarizes what size planet STEPUP is sensitive to for a give magnitude (listed in the first column). The second column lists typical RMS values from STEPUP data taken during optimal conditions. The third column gives what the square of the planet-to-stellar radius ratio would be that corresponds to a 3σ detection, given our typical RMS. The final two columns give a size of planet that this implies would be detectable for a star twice the size of the sun and a solar-sized star. These two values were chosen as examples, since MARVELS is not targeting very many stars more massive than spectral class F, and for stars smaller than the sun, the size of planet STEPUP can detect is $\sim 0.2R_J$ which is even smaller than the typical size planets MARVELS is expected to discover. Indeed this size planet corresponds to an object with $R_p \sim 2.24R_{\rm earth}$.

Even for a solar-sized star of 10th magnitude, STEPUP can detect a planet of $R_p \sim 0.34R_J \approx 3.8R_{\rm earth}$, which is still well below the Jupiter-sized objects MARVELS expects to find. This means that STEPUP is sensitive to planets MARVELS is not. This gives STEPUP a unique parameter space to explore and enhances our likelihood of discovering a new transiting planet. In particular, since the MARVELS targets given to us are already suspected to host substellar companions, these stars are more likely to host other, smaller companions that could be detectable by STEPUP. This provides a more focussed search than simply observing a random sample of stars which may or may not host planetary companions. For example if half the stars that host one planet also host more than one planet, there is a roughly 50% chance that one of the MARVELS targets might host additional orbiting objects.

Furthermore, if a transit of a MARVELS candidate is discovered, then any additional orbiting bodies have an increased probability to also transit. If we assume relatively small inclinations of the orbital planes of the orbiting objects (a reasonable assumption based on planetary formation models), then if one of them transits, another almost always will (Borucki et al., 1996). Even for larger inclinations of the orbital plane (an angle we will call ϕ), there is still a greater likelihood that the additional object will transit. According to Borucki et al. (1996) (Eq. 2), for $\phi \geq \dfrac{2R_*}{a}$ the probability that a second planet will transit,

Table 5.1: Size of Planets Detectable to STEPUP

Mag	RMS	R_p^2/R_*^2 for 3σ detection	R_p for $R_* = R_{\rm sun}$	R_p for $R_* = 2R_{\rm sun}$
10	0.39%	0.0012	$0.34R_J$	$0.68R_J$
11	0.71%	0.0021	$0.46R_J$	$0.92R_J$

given that the first planet transits is given by:

$$P_2 = \frac{1}{\pi} \arcsin \frac{\sin(2R_*/a)}{\sin \phi} \tag{5.1}$$

According to this equation, then, even if the second planet was inclined as much as 7° to the first (as is the case with Mercury, the planet exhibiting the largest inclination in our solar system to the ecliptic), a planet orbiting a Sun-sized star at 1AU would have a $\sim 2.4\%$ probability to transit, which is much higher than the $\sim 0.3\%$ transit probability of the Earth around a Sun-sized star, as derived in Section 2.3.2 using Equation 1.1. Although a planet as small as the Earth is not detectable by STEPUP, the use of Equation 1.1 for a planet which could be detected (eg. $R_p \approx 3.8R_{\rm earth}$ as mentioned above), would yield a very similar transit probability to that of Earth (assuming $a = 1$AU), since it would still be true that $R_{\rm sun} + R_p \approx R_{\rm sun}$. Thus we enhance our likelihood of discovering additional, smaller objects by selecting MARVELS candidates over stars not yet known to host any substellar companions, and this enhancement is even greater if the MARVELS candidate is found to transit.

5.3 ANALYSIS OF MARVELS TARGETS

5.3.1 Problems Encountered

The first MARVELS target we observed was located in a very dark portion of the sky, and finding a suitable tracking star proved to be a challenge. What resulted in terms of raw data were sets of images with the target near the edge of the field of view, some images in which the stars were badly streaked. Moreover, in an attempt to expose the target long enough, some data sets had exposure times that saturated some of the other, potential reference, stars in the images. This made analysis of the Fall 2010 semester of data difficult.

Some other problems encountered were the discovery that refocussing during an observing run does not seem to affect all stars' psf the same way, especially when they appear far from the center of the field of view. Upon analyzing such data sets, trends appear in the data just at the time(s) of re-focus. For examples of this, see Figures D21, D23, and D49 in Appendix D.

Finally there were a couple evenings in which star flux was lost through the night, sometimes disappearing altogether by the end of a data set. This would sometimes happen when the telescope was left to run after active observers had left for the night. The resultant lightcurves seem to exhibit an "ingress" just as flux was being lost. It is more likely that this "ingress" is related to this loss of flux than to a true planetary transit ingress. For examples of this, see Figures D27 and D43 in Appendix D.

5.3.2 Troubleshooting and Re-Analysis

Starting in January 2010, careful troubleshooting was undertaken to uncover and correct some of the problems mentioned above, such as cutting some data, and using different reference stars if they were saturated in some data sets. Re-analysis proved largely successful in salvaging most data sets, and we can say with greater confidence that no signs of transits have yet been discovered in our observations of MARVELS targets.

For an example of this sort of null finding, see Figure 5.1. This particular example was well-studied by STEPUP from the months of May 2010 through September 2010. In addition to visually seeing from examples such as this that the flux appears to remain constant, our data was also compiled over this four month interval and run through a software package called Transit Analysis Package, TAP (Gazak et al., 2011)[2], to search for signs of a transit. This software package was designed at the University of Hawaii and is publicly downloadable. TAP takes the analytic model presented in the seminal Mandel and Agol paper on analytic light curve parameters (Mandel and Agol, 2002) and uses Markov Chain Monte Carlo (MCMC) techniques to fit lightcurves using this model, in the process parameterizing correlated and uncorrelated noise (Carter and Winn, 2009; Eastman et al., 2011). Using TAP no correlated variation in flux was found for the predicted period. However, this does not yet rule out the possibility that this planet could transit, since this particular example has a somewhat longer expected orbit of roughly 50 days. So despite our extensive observations, our data still only cover a fraction of the entire orbit. Nevertheless our findings contribute towards further understanding this planetary candidate.

For more examples of findings consistent with a constant transit, see Appendix D for a compilation of STEPUP lightcurves of MARVELS targets.

5.4 CONCLUSIONS

As mentioned in Section 3.1, the STEPUP photometric findings for MC002 will be used in an upcoming paper about this particular target. Our findings thus far are consistent with a constant flux and show no signs of a transit. However, with such a long period planetary candidate, the possibility of transit is not ruled out. Since STEPUP involvement with MARVELS is relatively recent, further observations of MC002 and/or other MARVELS targets may continue to be consistent with constant flux or may reveal signs of a transit.

[2] http://ifa.hawaii.edu/users/zgazak/IfA/TAP.html

Thus STEPUP will continue to observe MARVELS targets to search for signs of transits. A summary of the MARVELS targets observed, dates and number of data sets can be found in table 5.2. STEPUP is sensitive to detecting planets as small as $\sim 0.4R_J$ for a 10th-11th magnitude solar size star which is around the minimal size planets MARVELS is expected to discover. For stars twice as large as the sun, STEPUP is sensitive to planets between $\sim 0.8R_J$ and $\sim 0.9R_J$ for a 10th-11th magnitude star. Finding a transit from a MARVELS target will help confirm the size and planetary nature of the candidate, and STEPUP will thus contribute important information to the process of planetary discovery.

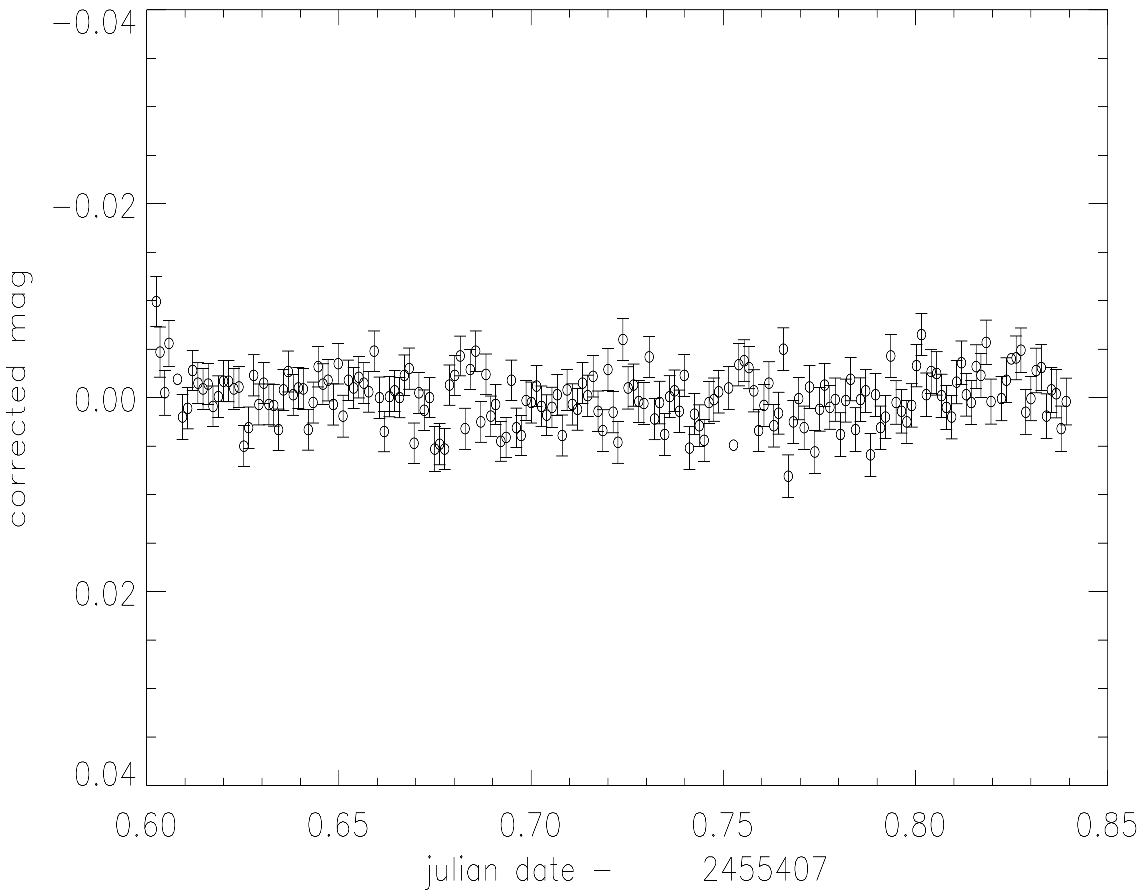

Figure 5.1: Photometry of a MARVELS Target from July 29, 2010

Table 5.2: Summary of MARVELS Targets Observed

Target	Number of Data Sets	Beginning	Ending
MC000	1	2010-03-04	2010-03-04
MC001	6	2011-02-03	2011-03-02
MC002	21	2010-05-25	2011-06-30
MC004	1	2010-11-09	2010-11-09
MC006	9	2011-02-03	2011-03-27
MC007	5	2011-04-05	2011-05-11
MC009	7	2010-05-03	2010-05-27
MC010	4	2011-02-23	2011-03-19
MC024	6	2011-04-05	2011-06-01

6.0 FUTURE DIRECTIONS AND CONCLUSIONS

6.1 FUTURE DIRECTIONS

6.1.1 Hardware Improvements

As of the beginning of January 2010, it was possible to securely log into the Allegheny Observatory Keeler computer from elsewhere. With this ability, one can operate the telescope, move the dome, switch the lights inside the dome on or off, take images, etc. This gave STEPUP the freedom to observe from Allen Hall on campus without the need for independent transportation to the Allegheny Observatory. This freedom was a huge boon for the undergraduate researchers who often did not have access to their own vehicles.

Even with this freedom, however, we have had to coordinate observation runs with Lou Coban at the observatory, since we have no way of removing or replacing the telescope cover. In the summer 2011, Kaitlyn Yoha, a student from the School of Engineering is designing and building a telescope cover for the 16" Keeler that can be operated remotely. This project will complete the process of making the Keeler fully remotely operable. This final piece of the puzzle should be complete by the end of August 2011 with the implementation of the remotely-operable Keeler cover. Once this improvement is in place, STEPUP members will be able to remotely observe at any time, even if no one is physically present at the observatory.

Additional recent and ongoing hardware improvements involve the upgrading of the Thaw telescope. The Thaw is an historic telescope. It was built in 1912 with a 30" lens, making it the third largest refracting telescope in the country.[1] The Thaw is fitted with a Finger Lakes Instruments FLI-4240 CCD camera. The chip on the camera is a thinned backside illuminated CCD chip with a 2048 x 2048 array of 13.5 micron pixels. Unfortunately the telescope wiring which had historically been advantageous in the past severely constrained the use of the Thaw for extrasolar planet transit observations, as it fed the wiring through an external bridge that limited the mobility of the Thaw and restricted it to the western side of the pier.

Thus, STEPUP members Gary Lander and Korena Costello have, over the past two years, made improvements to the Thaw telescope to get it ready for future use with STEPUP research. The first project was to re-wire the Thaw to give it full mobility to slew wherever we wanted it to. This was a long and tedious process, but was completed by the winter of 2011. On February 11, 2011, the success of the re-wiring was tested when the telescope was moved to the eastern side of the pier for the first time in roughly 40 years.

In addition new software was installed and the CCD camera is currently set to be repaired. Also, the RA and Dec limit switches are being revamped. By the end of 2011, STEPUP hopes to be able to use the Thaw telescope for extrasolar planet research in addition to the 16" telescope. A detailed account of all the work done on the Thaw by STEPUP can be found in a write-up by undergraduate member Gary Lander. From any of the astro computers the file can be found here:

`/home/giga/ugrads/grl5/Thaw_Writeup/Thaw_Writeup.pdf`

6.1.2 Analysis/Pipeline Improvements

Some STEPUP members are working on a way of stacking our images to find asteroids whose position could be used to calibrate the timing of data sets taken at different locations. This project is useful for any collaborative observing effort such as the HD80606b Campaign, since it will allow the relative timing of data sets from different locations to be known with respect

[1] http://www.pitt.edu/~aobsvtry/index.html

to any asteroids that are also in the field of view. This sort of analysis is being developed in a separate pipeline:

`/home/depot/STEPUP/code/asteroids`

The most ambitious improvement to the STEPUP pipeline is also underway. STEPUP member Justine Drobitch is undertaking the task of improving our photometry by performing relative photometric measurements of every star in the field of view and calculating the relative photometry of the target compared to all other stars. This requires a more efficient way of storing the measured brightnesses than in a columned data file. Most of the new code for this improvement has been written and is in the process of being tested. The hope is that this approach will ultimately decrease our errors.

6.1.3 Additional Projects

In addition to the analysis improvements using photometry on all stars, future analysis goals will be to continue developing a more sophisticated fitting algorithm, to find a better way to optimize the aperture radii chosen for each target, and to explore and understand better the source of our errors.

Finally, in terms of hardware improvements, the work on the Thaw telescope is likely to be an ongoing effort through the end of 2011. As mentioned above, things that still need to be upgraded include replacing the camera, being sure the RA and Dec limit switches are working properly, and troubleshooting any bugs that are encountered as the Thaw is tested for use as an active observing telescope.

6.2 SUMMARY OF STEPUP WORK

The Survey of Transiting Extrasolar Planets at the University of Pittsburgh has been a project which has conducted follow-up observations of unconfirmed substellar companions as well as of known planets. To these ends, STEPUP has contributed in an important way to a new collaborative approach to ground-based observations of HD80606b. This collaborative effort has demonstrated the success of coordinating observations across geographical distances in order to achieve full coverage of a long planetary transit. This lays the groundwork for future follow-up collaborative efforts as more long-period transiting planets are anticipated to be discovered. In addition, STEPUP has submitted interesting follow-up data to public scientific entities, such as the Exoplanet Transit Database (Poddaný et al., 2010). In particular, STEPUP data for observations of known planets such as TrES-2b may be of use to astronomers looking to explore the possibility of transit timing variation and/or transit duration variation. Finally, STEPUP has provided photometric observations for the SDSS-III MARVELS planetary candidates. This photometric information is helpful in the planetary confirmation process. Moreover, if a transit is discovered for a MARVELS candidate, STEPUP will have helped determine crucial parameters of the candidate, such as a reliable mass and radius, from which other characteristics can be derived.

All of these efforts have contributed to scientific understanding of extrasolar planets. With the pace of planetary discovery rapidly increasing, follow-up observations will become increasingly more crucial. Hence, small observatory follow-up contributions to larger scientific collaborations are a thorough and cost-effective way of increasing knowledge of extrasolar planets.(Seagroves et al., 2003) The current era in extrasolar planetary science is one in which we are building up empirical information and in the process, we are uncovering startlingly unique worlds. Understanding the nature of the plethora of planets that exist requires not only discovering them, but also carefully studying them in more detail. And through the information we gain in such careful follow-up study, we shed light on the nature of planetary formation, migration, and other such theoretical matters.

In conclusion, providing useful observational study of extrasolar planets and planetary candidates will continue to be the goal of STEPUP. These observational efforts are not done in isolation but connect intimately to the greater scientific community and help to develop collaborative efforts to understand the diversity of worlds in the cosmos.

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APPENDIX A

HOW TO PLAN OBSERVING

Below is the STEPUP detailed strategy for planning observing of known extrasolar planets.

How To Plan Known Transit Observations

Melanie Good

2011 May

1. Strategy

One of the STEPUP objectives is to gather follow-up data on know planetary systems. We can strategically plan our observing in order to meet this objective by using some online resources. For planets that are known to transit, the reccommended website is called Exoplanet Transit Database. For planets that were discovered by other techniques and are not yet known to transit, the reccommended website is called Transitsearch. Each of these two sites has its advantages and disadvantages which makes them more useful for the particular application of either known or unknown transiting systems. Either way, the general strategy you want to follow is this:

1. Choose a target then plan a night to observe or alernatively, choose the night you can observe and find the best target for that night.Considerations for choice of target:

a. Since one of our other objectives is to get images that might also contain asteroids, try to choose a target of low ecliptic coordinates. You will likely have to convert Ra and Dec to ecliptic coordinates using skycalc.

b. Try to find a transit that is predicted to have a transit depth of at least 0.5%

c. The duration of the transit should easily fit within your observing timeframe.

2. Use the website recommended to plan when that night to observe. You want to get some data both before the transit begins and after the transit ends.

3. Obtain an image of the star field with the target marked so that you can identify it when you observe and keep it as close to the center of the field of view as possible. Many of these should be in the binder in Allen 416 along with any notes about tracking stars that have been used in the past. If not, star field images are automatically available on Exoplanet Transit Database or can be found using Simbad. If STEPUP has not previously observed the target, you might be also able to pick out a few stars that could serve as a tracking star if you find an image of roughly the same size as our field of view. If you are unable to find a tracking star before observing, be sure to take careful note of the tracking star in your observing report so that it can be used for future observations.

2. Exoplanet Transit Database for Known Transiting Planets

Here are the basic steps to follow to use Exoplanet Transit Database (ETD):

1. Go to http://var2.astro.cz/ETD/

2. Click on "Transit Predictions" near top

3. Input our latitude and longitude. Note that it is *East* Longitude!! For our purposes, it's good enough to input 280 degrees ELongitude and 40 degrees Latitude. Press the "submit" button.

4. You will see a chart of predicted transits, along with the duration of the transit, magnitude of the target star, depth of magnitude, and coordinates. Above that are several upcoming dates you can click on to change the chart to a different night's predictions so you can plan your next observing night accordingly."Begin" is approximately when you can expect the transit to start. "center" is the approximate mid-transit time, and "end" should be when the transit is done. Times are in UT, which for summer is 4 hours later than our local time. After we set our clocks back in the fall this will become 5 hours later than our local time. So to find the mid-transit time in local time, subtract the appropriate number of hours from the time listed in these columns.

5. Once you choose your target (keeping in mind our strategy for target choices), you can click on the object name and you will see an image of what the star field looks like and which star is the target. Below that is a year's worth of predicted transits, complete with colors to indicate observability at our location. Grey times indicate the star is not rising above 20 degrees above the horizon, yellow times indicate the transit is taking place during the day, and black times indicate the star is above 20 degrees and the transit takes place at night in our location. This is helpful in planning future observations.

3. Planets Not Yet Known To Transit with Transitsearch

Following up on planets not yet known to transit is a secondary objective. Should you choose such observations, the planning processs is less user-friendly. Transitsearch used to have a similar functionality to ETD where you would input your local latitude and longitdue and it would give you some predictions. However, it now only consists of charts that you must wade through to plan your observing, and there are a few bugs that remain with it. This should not dissuade you because Transitsearch is still a useful tool if you want to prioritize which targets to look for a transit for based on their probability of transiting (which is included in the charts).

Here are the basic steps to follow to use Transitsearch:

1. Go to http://www.transitsearch.org/

2. Click on "Candidates" to make an interactive table appear

3. Understand each column to help plan which target to observe when:

-First three columns are pretty self-explanatory; they identify the target by name and tell you its orbital period

-Fourth column tells you the probability that the planet transits. 100% means it is a known transiting planet. Other percentages are based on the geometric probability that a system that has not yet been shown to transit actually does transit.

-Columns five and six give you the coordinates of the target

-Column seven tells you the depth the transit ought to have (as a percentage). We know we can detect a 1% transit depth and possibly a little less but if this number is less than 0.5%, it's unlikely we could detect it.

-Column eight tells you the predicted mid-transit time for the soonest transit from now. This time is in UT, which for now is 4 hours later than our local time. After we set our clocks back in the fall this will become 5 hours later than our local time. So to find the mid-transit time in local time, subtract the appropriate number of hours from the time listed in this column.

-Column nine tells you if the transit is taking place during the day or night. "In" means it is taking place at night; "out" means it is taking place during the day. But be careful because I have found marginal cases that would actually be observable even though they are labeled "out," as I think these designations are based on the west coast (since Greg Laughlin, who maintains the site, is located at UC Santa Cruz). So don't rule out a possible target just based on this column–take a more careful look at column eight.

-The tenth column is probably one of the most useful columns. By clicking on this column you will be given a detailed chart of the timing of each transit (ie. an "ephemeris") from about a year ago to about a year from now. In addition to HJD the dates and times are listed, again all in UT so you must subtract hours if you want to know them in local time. The "begin transit window" is approximately when you can expect the transit to start. "Predicted central transit" is the approximate mid-transit time, and "end transit window" should be when the transit is done. Ideally you'd like to get some data before the beginning of the transit and after the end of it. The transit duration is listed at the top. Also be careful with these ephemeris pages. I have recently clicked on a few where, instead of the times following the three columns they should, it appears that the left-hand column starts at one date chronologically until it fills that column and then the second column is a continuation of the bottom of the first column. Instead of telling you the whole transit window, all you are given is the mid-transit time for that particular date. If you encounter one of these faulty ephemeris pages, you can get a rough idea of when the beginning of the transit is by looking at the transit duration and assuming that subtracting half the total duration off the mid-transit time ought to give you the beginning of the transit, and adding half the total duration to the mid-transit time should give you the end of the transit window. Please email the list when you encounter such pages, as we may want to alert Greg Laughlin of these bugs.

4. Once you are familiar with these columns you can see that you can use them to either look for a particular night you are observing and see what might be a good target, or choose a target and then look for the next predicted transiting evening, and plan your future observing accordingly.

APPENDIX B

APERTURE RADII CHOSEN

Below is the write-up detailing our choice of aperature radii used in the aper command of our photometry module.

Aperture Radii Chosen for *aper* in gtphluxometry.pro Module

Melanie Good

2011 May

1. History of Radii Used in *aper*

From the early days of our analysis, aperture photometry was performed using the *aper* command in IDL. The radii were chosen to suit our only set of data at that time, XO-2/2009-02-06. Originally they were set to be 7 pixels for the star radius, and [15,20] for the inner and outer sky radii. This gave us reasonable results for this original set of data. It is worth noting that, using these radii, the ingress for this particular transit was quite clear in the original analysis without the use of any astrometric tweaking with the *gcntrd* command. Once the *gcntrd* command was implemented in the photometry, this gave even better results with a smaller standard deviation. Based on the success of this particular analysis, *gcntrd* was thereafter used in the photometry module, and the radii in *aper* were set to the values listed above, so that we had the following sequence of commands after reading in the reference catalog:

```
ad2xy, ra, dec, astr, x, y
gcntrd imagw, x, y, xcen, ycen, 5
aper, imagw, xcen, ycen, mag, errap, sky, skyerr, 1.48, [7],  [15,20], [0,0], /NAN
```

During the HD80606b campaign in January, 2010, it was decided that a bigger star aperature would give us better results after our initial analysis attempts revealed some out-of-focus data. (There were other problems with our data, such as some saturated data that had to be cut, but that was a separate issue). The change to a 10-pixel star radius was implemented and gave us good results for our HD80606b/2010-01-13 data that ultimately earned STEPUP our first published work.

For unclear reasons (likely due to simply forgetting that this change to a larger star radius had been made), the 10-pixel star radius remained in the *aper* command for over a year until other troubleshooting efforts in teasing out the best results we could from our MC002 data revealed that the star radius in the *aper* command was never changed back to 7 pixels.

2. Calculating Optimal Signal-to-Noise

In April, 2011, an effort was made to calculate what star radius would yield optimal signal-to-noise for most of our data sets. This was done both to quantitatively justify our choice and to investigate whether we would do better to revert to the smaller radius used in the past. The following email was sent to the group 2011-04-22 at 12:28:44 PM EDT summarizing the results of this investigation:

"I have added the signal-to-noise calculation to

"/home/depot/STEPUP/code/TransitErrors/radwatv.pro

"and had it print out the S/N for various aper radii. I then ran this module on two different nights of data.

"The first was a night of poor seeing: 2011-03-02/MC001 where the seeing in the observing report was listed as 1/5 and FWHM was 4.45 pixels. The resultant output file I generated is /home/depot/STEPUP/code/TransitErrors/signaltonoise.txt You will see that the S/N is best at 8 pixels for this night; however this is only $\tilde{2}$ % better S/N than the S/N for the radius the code currently has aper set at (10 pixels).

"The second night of data was decent seeing: 2010-08-18/TrES-2 where the seeing in the observing report was listed as 3/5 and FWHM was 2.98 pixels. The resultant output file is /home/depot/STEPUP/code/TransitErrors/signaltonoise2.txt Comparing this to the first night I ran, we see that the S/N is best at 5 pixels for this night, AND this is a significant improvement over the 10 pixels radius: we get $\tilde{15}$ % better S/N by decreasing the radius to 5 pixels.

"My conclusions are the following:

"1. Even for poor seeing nights, 10 pixels does not appear to be the optimal radius. Certain weird circumstances might cause us to go this big (like the HD80606b campaign) but I don't think it's warranted in the vast majority of cases.

"2. That said, changing it from 10 pixels to a smaller radius may not make that big of a difference for poor seeing nights, but might make a big difference for nights of good seeing. Thus it might be worth including this S/N calculation near the beginning of generaltransit to calculate the best radius to use and then feeding this optimized radius to aper."

Based on these results, the star radius in the *aper* command was restored to 7 pixels.

3. TrES-2 Re-Analysis

With the implementation of this change back to a 7 pixel star radius, TrES-2/2010-08-18, our useful test case of a clear and complete transit, was re-analyzed on 2011-05-03 using this radius.

Unfortunately, though the individual errors appeared smaller in the .dat output file, the overall spread was *worse*, not better, than before. See Figure 1 and Figure 2 for a visual comparison of the lightcurves that resulted.

At first it was unclear if it was only the aperture radius change that resulted in this much poorer lightcurve, but a quick re-analysis with the aperture radius changed back to 10 pixels reproduced the original, better lightcurve. Due to TrES-2 giving us obviously better results with at 10-pixel star radius, the star radius in the *aper* command was changed back to 10 pixels on 2011-05-19.

The exact reason for the better results with a 10 pixel radius is not entirely clear, since the calculated signal-to-noise is much better with a smaller radius, and this is also shown by the individual errors improving with a smaller radius. Thus reason likely has something to do with the image-to-image variation using this smaller radius, and this leads to the possibility that perhaps imperfect astrometry is to blame. If this is the case, then it could be that with a smaller star aperture, some of the light of the star is being cut off in some images that are not as well-centered as others. Further investigation is warranted.

On 2011-05-20 the sky annulus was changed from [15,20] to [15,35] to help us better characterize the background noise above which we are attempting to measure the stellar brightness. TrES-2/2010-08-18 was then re-run again and found to have less of a photometric spread in the lightcurve. See Figure 3. A more careful investigation of the optimal sky annulus is also warranted.

4. Future Investigations

As mentioned above, it will be important in the future to get to the root of the problem with a smaller radius. In the meantime STEPUP may have to accept the larger individual errors in favor of a larger radius to yield better overall results. However, this underscores the fact that there is certainly room for improvement. If astrometry is revealed to be the issue, then if we can do a better astrometric job of centering our apertures, then we can use a smaller star radius that would be closer to our optimal signal-to-noise and thus obtain better results.

In addition, the sky annulus needs to be optimized. At the time of this writing, it is under loose investigation and will be increased to see if better results can be obtained, but a systematic and thorough investigation of this would be an important near-term goal. Better characterization of our sky will allow us to better characterize how bright our stars are in comparison to the background noise, which will in turn give us better photometric measurements.

5. Conclusions

At the present time the aper command looks like this:

```
aper, imagw, xcen, ycen, mag, errap, sky, skyerr, 1.48,  [10], [15, 35], [0,saturation], /FLUX
```

It is recommended that the star radius of 10 pixels remain as is until such time as it can be shown what the reason is for such a large radius giving us better results, and that reason can be addressed. In addition, further investigation of the optimal sky annulus is also recommended.

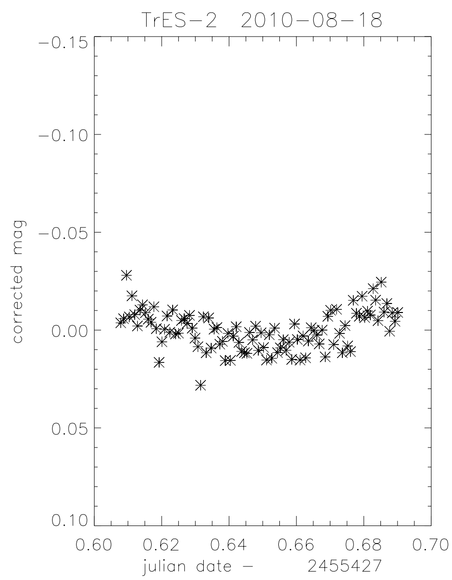


Fig. 1.— TrES-2/2010-08-18 Lightcurve with a 10-Pixel Star Radius

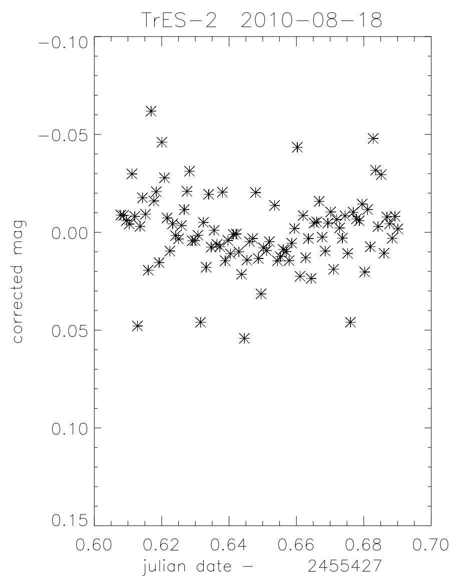


Fig. 2.— TrES-2/2010-08-18 Lightcurve with a 7-Pixel Star Radius

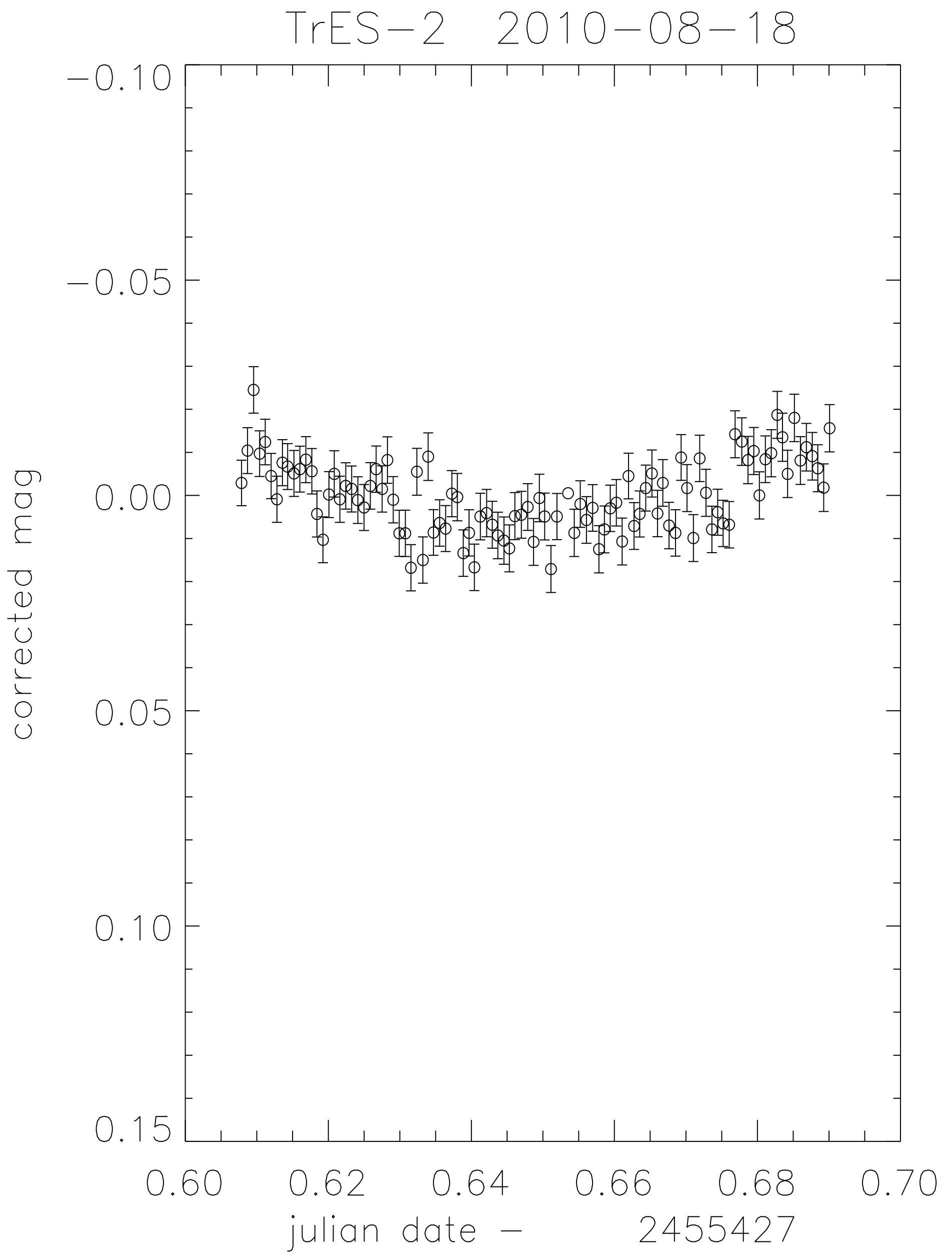


Fig. 3.— TrES-2/2010-08-18 Lightcurve with a 10 pixel star radius, and a 15 and 35 pixel inner and outer sky radius respectively

APPENDIX C

STAR FIELD IMAGES

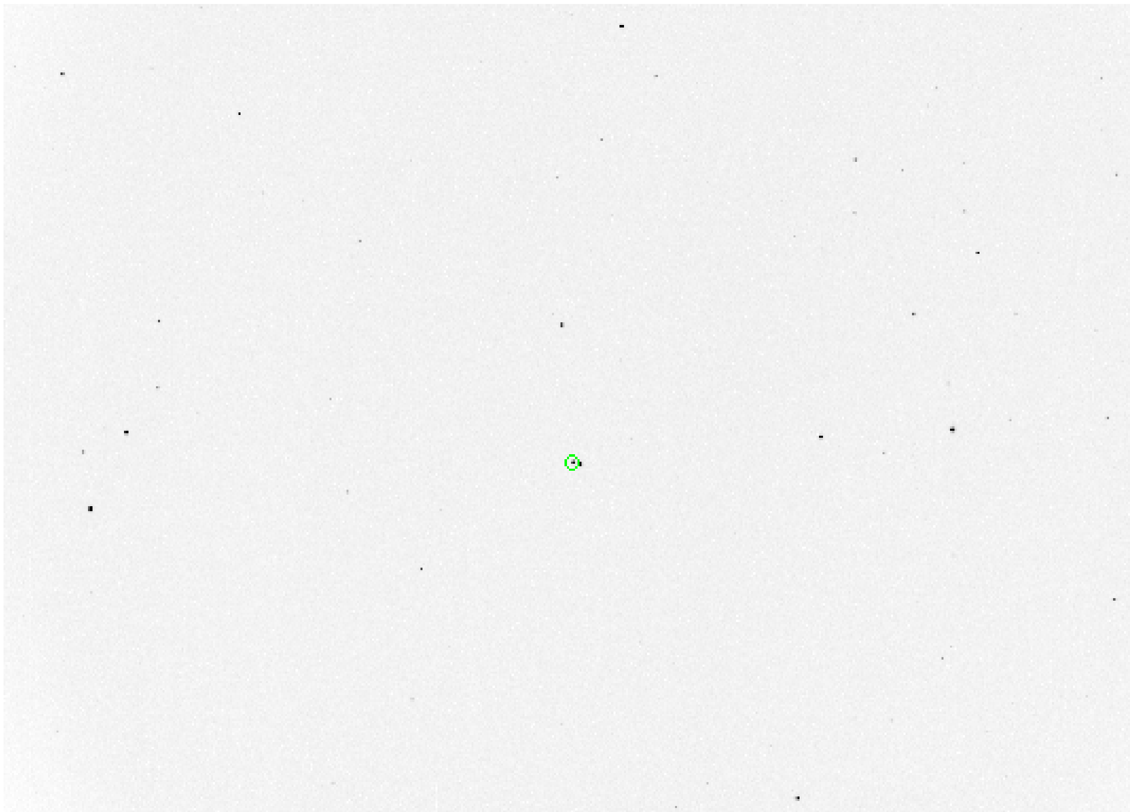


Figure C1: A STEPUP image of HAT-P-1. HAT-P-1b is a 0.524 Jupiter-Mass, 1.217 Jupiter-Radius planet orbiting a GV star 139 pc away at RA: 22:57:47 Dec:+38:40:30. HAT-P-1b orbits at a semi-major axis of 0.05535 AU, with an eccentricity < 0.067 and an orbital period of 4.4652934 days (http://exoplanet.eu/planet.php?p1=HAT-P-1&p2=b) STEPUP has observed this target once in December 2009.

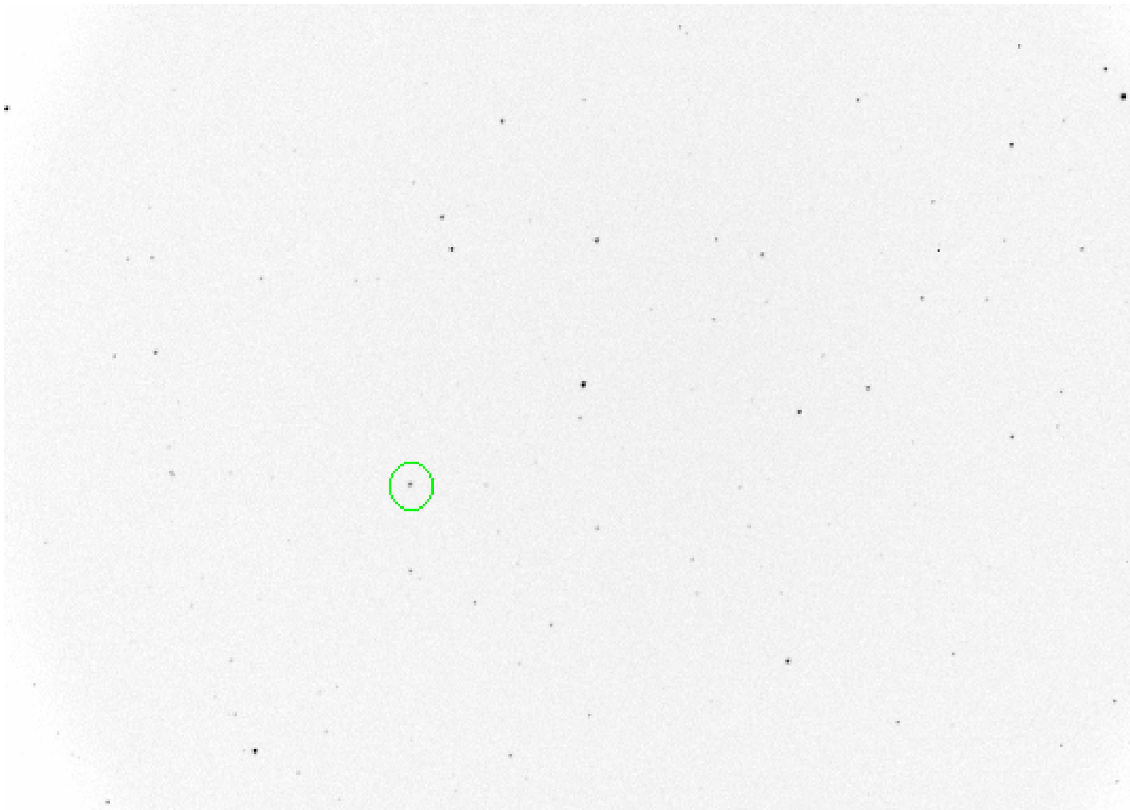


Figure C2: A STEPUP image of HAT-P-9. HAT-P-9b is a 0.67 Jupiter-Mass, 1.4 Jupiter-Radius planet orbiting an F star 480 pc away at RA: 07:20:40 Dec:+37:08:26. HAT-P-9b orbits at a semi-major axis of 0.053 AU, with an approximately zero eccentricity and an orbital period of 3.922814 days (http://exoplanet.eu/planet.php?p1=HAT-P-9&p2=b) STEPUP has observed this target once in November 2009.

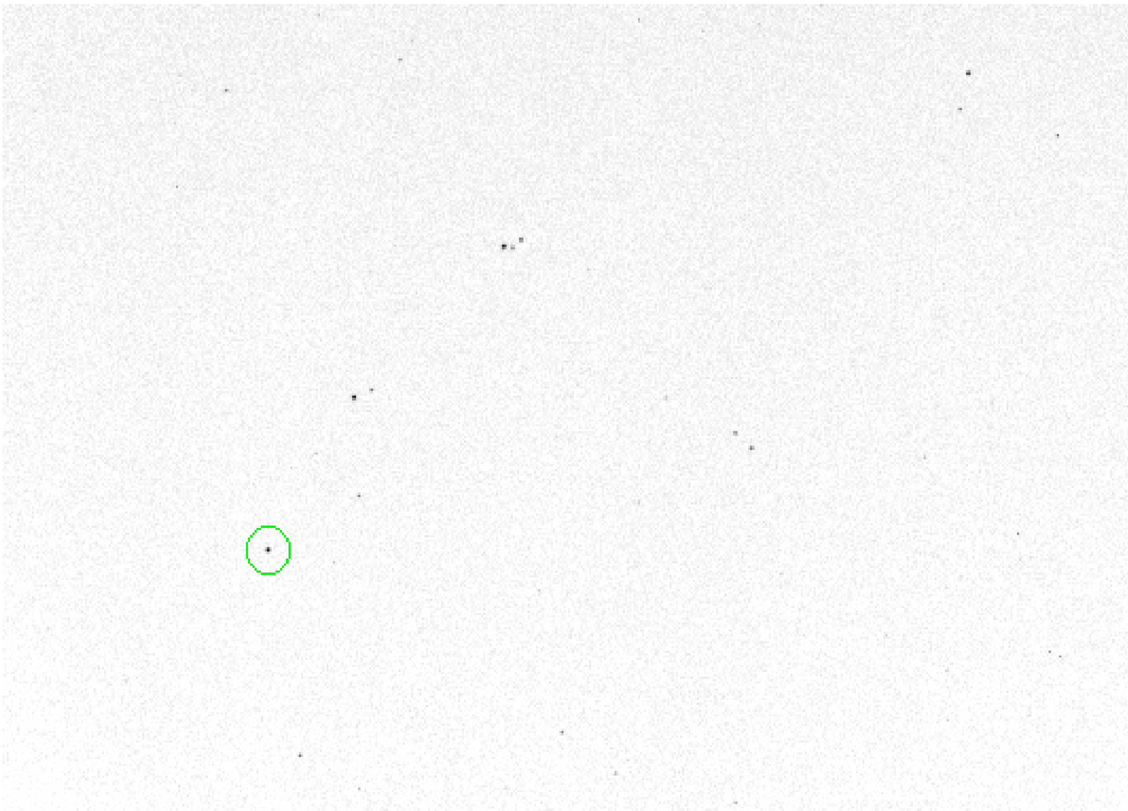


Figure C3: A STEPUP image of HAT-P-13. HAT-P-13b is a 0.85 Jupiter-Mass, 1.28 Jupiter-Radius planet orbiting a GIV star 214 pc away at RA: 08:39:32 Dec:+47:21:07. HAT-P-13b orbits at a semi-major axis of 0.0426 AU, with an eccentricity of 0.0142 and an orbital period of 2.916243 days (http://exoplanet.eu/planet.php?p1=HAT-P-13&p2=b) STEPUP has observed this target twelve times in March and April 2010.

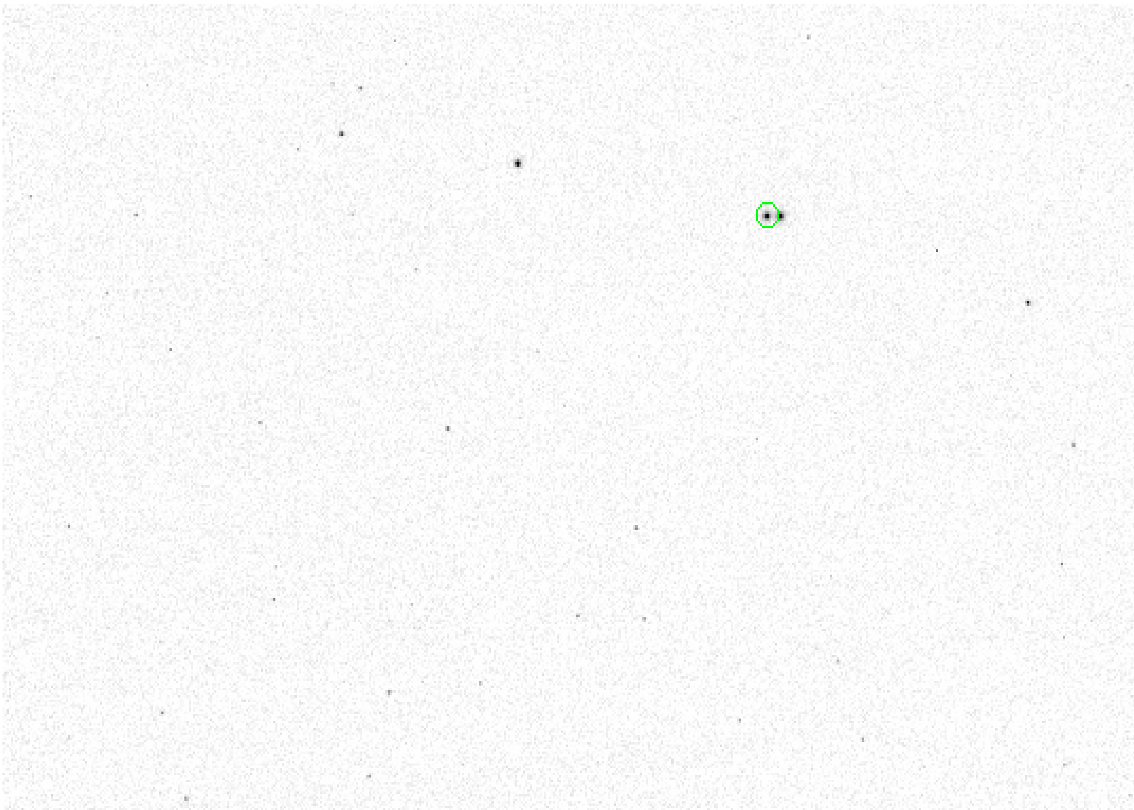


Figure C4: A STEPUP image of HD80606b. HD80606b is a 3.94 Jupiter-Mass, 0.921 Jupiter-Radius planet orbiting a GV star 58.4 pc away at RA: 09:22:37 Dec:+50:36:13. HD80606b orbits at a semi-major axis of 0.449 AU, with an eccentricity of 0.93366 and an orbital period of 111.43637 days (http://exoplanet.eu/planet.php?p1=HD+80606&p2=b) STEPUP has observed this target five times in September 2009, January 2010 and April 2010.

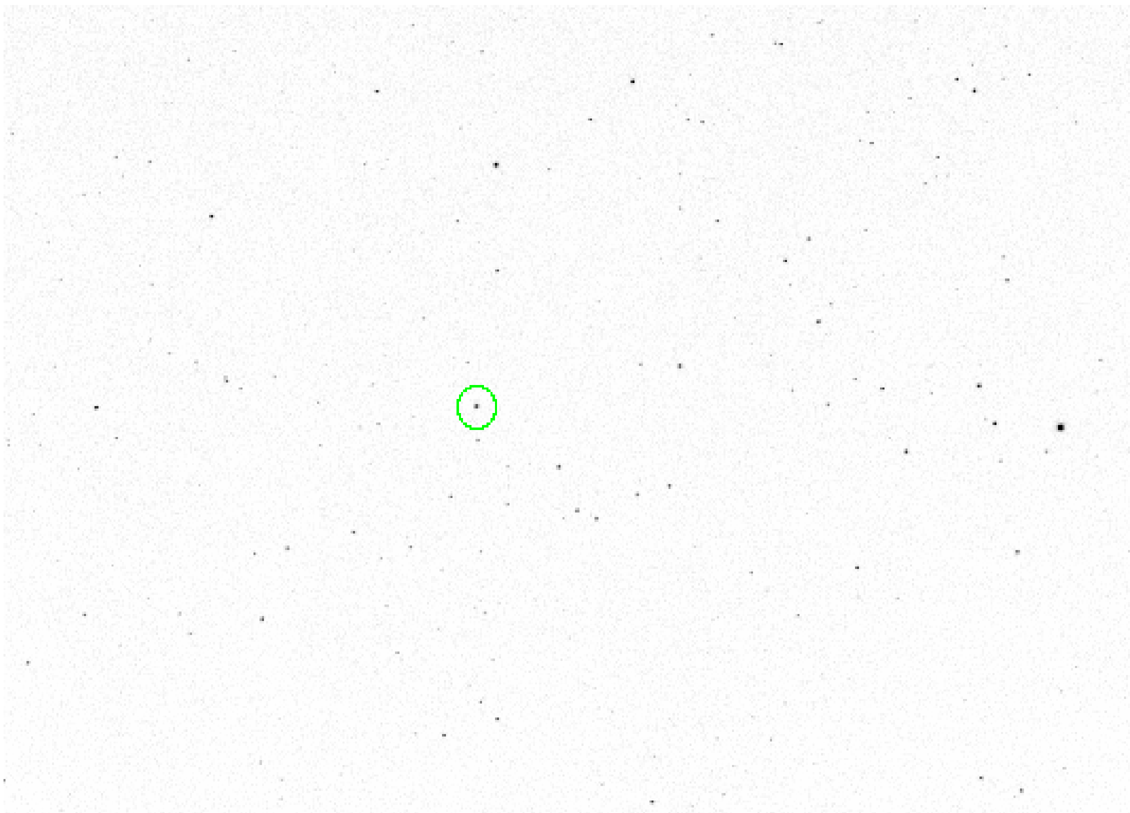


Figure C5: A STEPUP image of TrES-2. TrES-2b is a 1.253 Jupiter-Mass, 1.169 Jupiter-Radius planet orbiting a GV star 220 pc away at RA: 19:07:14 Dec:+49:18:59. TrES-2 orbits at a semi-major axis of 0.03556 AU, with an approximately zero eccentricity and an orbital period of 2.470614 days (http://exoplanet.eu/planet.php?p1=TrES-2&p2=) STEPUP has observed this target twice, once in August 2010 and once in October 2010.

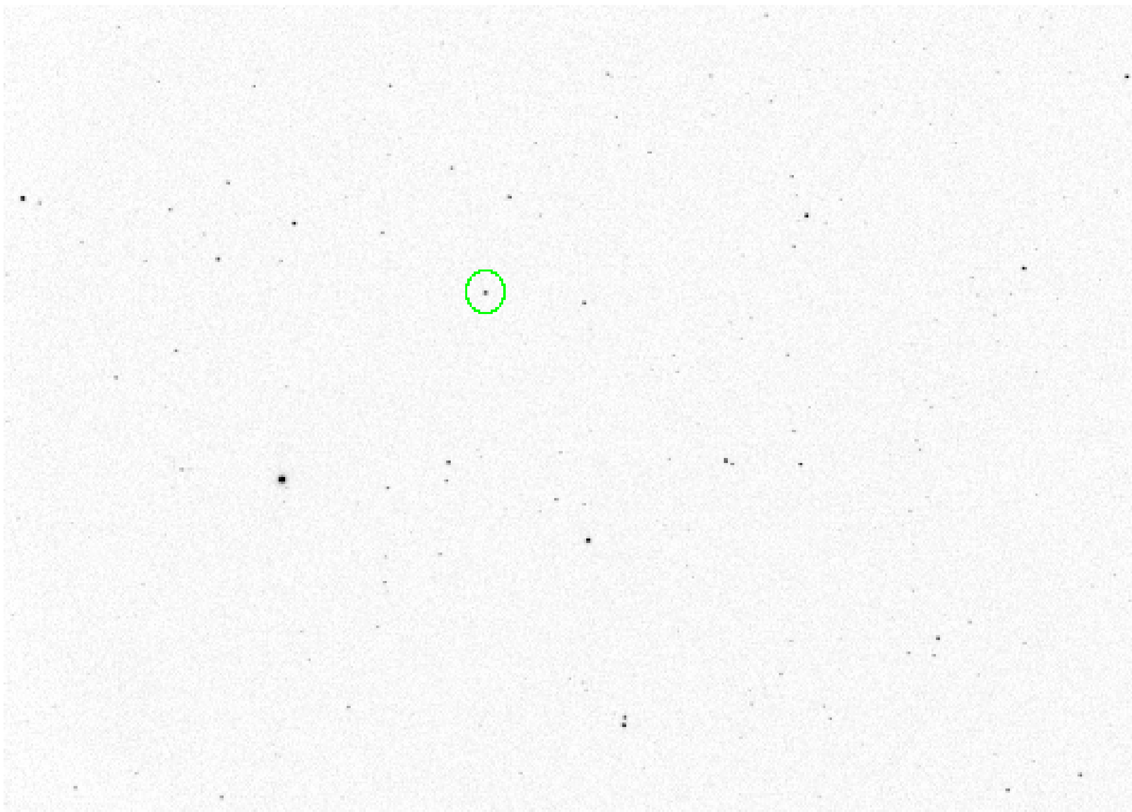


Figure C6: A STEPUP image of WASP-2. WASP-2b is a 0.847 Jupiter-Mass, 1.079 Jupiter-Radius planet orbiting a KIV star 144 pc away at RA: 20:30:54 Dec:+06:25:46. WASP-2b orbits at a semi-major axis of 0.03138 AU, with an approximately zero eccentricity and an orbital period of 2.470614 days (http://exoplanet.eu/planet.php?p1=WASP-2&p2=b) STEPUP has observed this target once in October 2010.

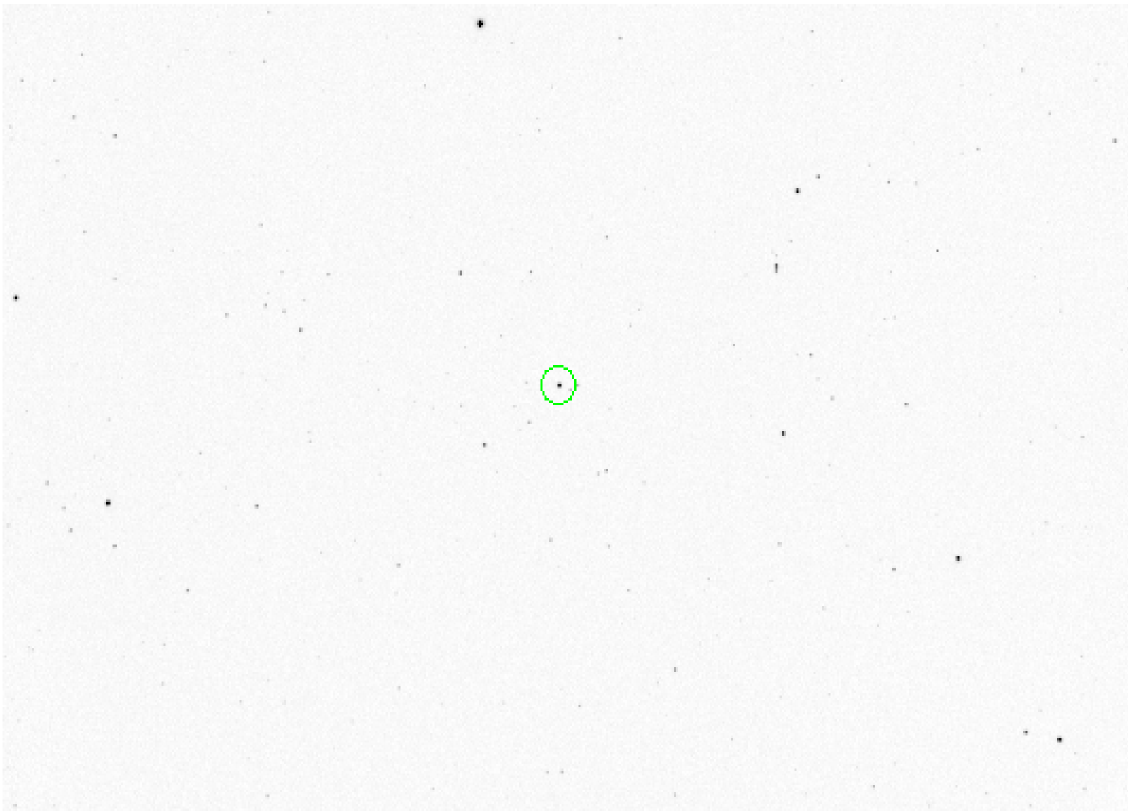


Figure C7: A STEPUP image of WASP-3b. WASP-3b is a 2.06 Jupiter-Mass, 1.454 Jupiter-Radius planet orbiting a F7V star 223 pc away at RA: 18:34:32 Dec:+35:39:42. WASP-3b orbits at a semi-major axis of 0.0313 AU, with an approximately zero eccentricity and an orbital period of 1.8468372 days (http://exoplanet.eu/planet.php?p1=WASP-3&p2=b) STEPUP has observed this target once in May 2011.

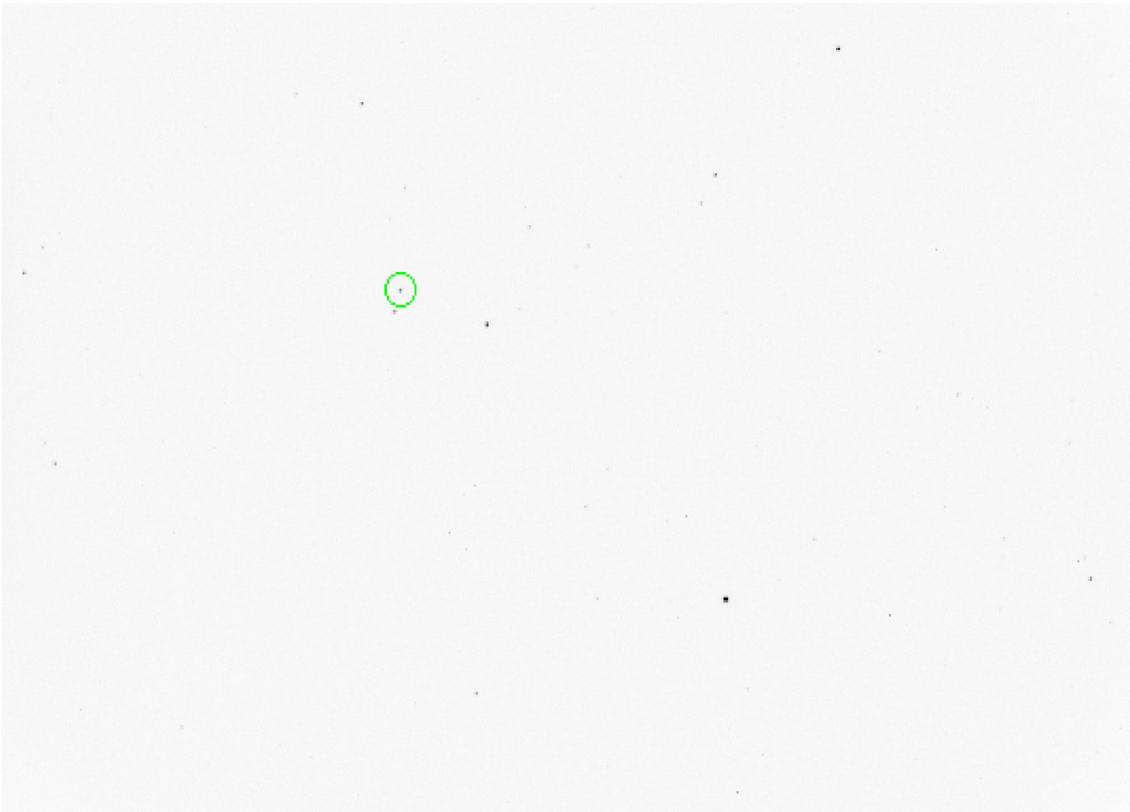


Figure C8: An image from my data of XO-2b. XO-2b is a 0.57 Jupiter-Mass, 0.973 Jupiter-Radius planet orbiting a KV star 149 pc away at RA: 07:48:07 Dec:+50:13:33. XO-2b orbits at a semi-major axis of 0.0369 AU, with an approximately zero eccentricity and an orbital period of 2.615838 days (http://exoplanet.eu/planet.php?p1=XO-2&p2=b) I observed this target once prior to the creation of STEPUP, in February 2009.

APPENDIX D

LIGHTCURVES OF MARVELS TARGETS

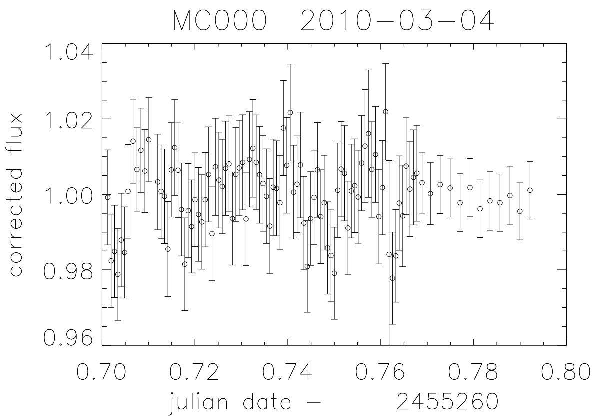


Figure D1: A STEPUP Lightcurve of a MC000 from March 4, 2010.

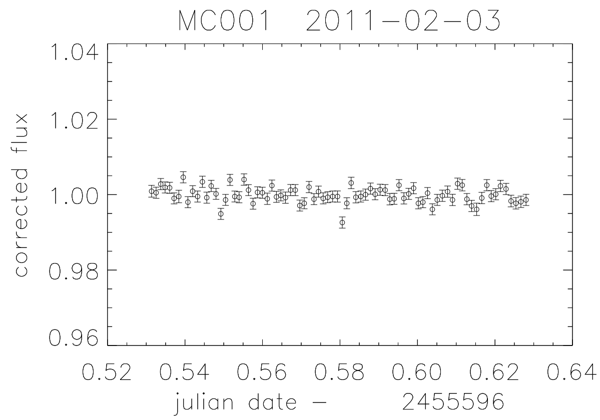


Figure D2: A STEPUP Lightcurve of a MC001 from February 3, 2011.

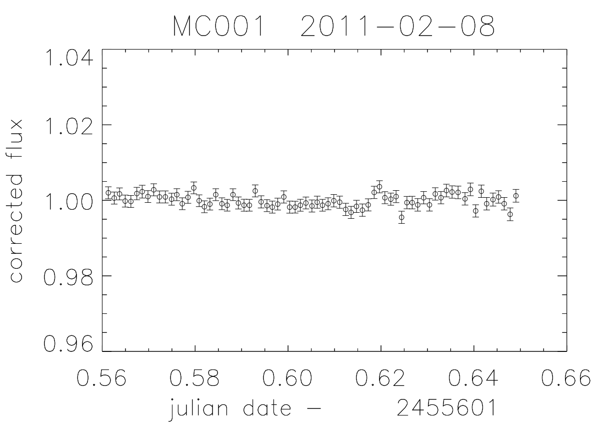


Figure D3: A STEPUP Lightcurve of a MC001 from February 8, 2011.

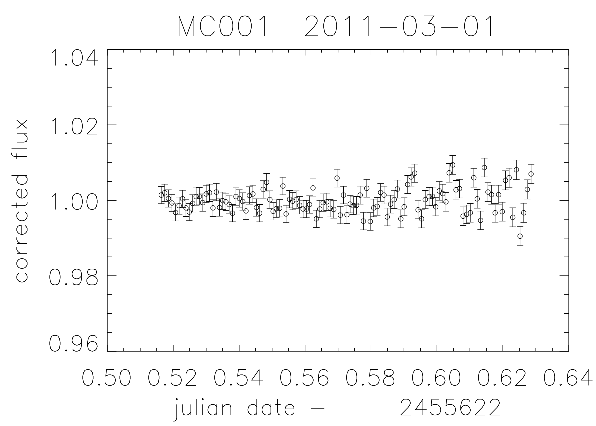
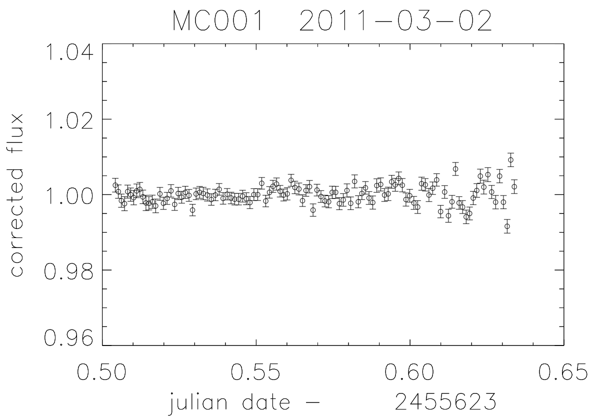


Figure D4: A STEPUP Lightcurve of a MC001 from March 1, 2011.



t

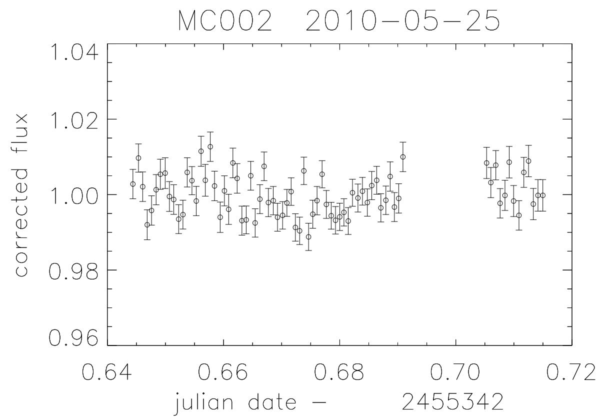
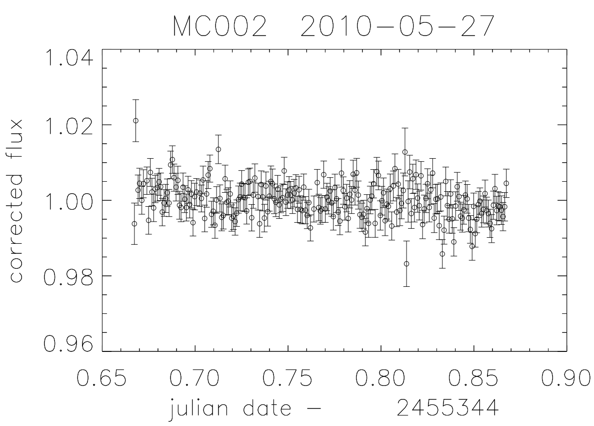


Figure D5: A STEPUP Lightcurve of a MC001 from March 2, 2011.

Figure D6: A STEPUP Lightcurve of a MC002 from May 25, 2010.



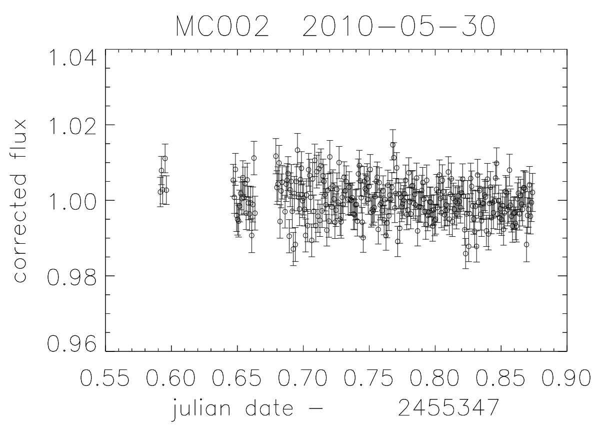
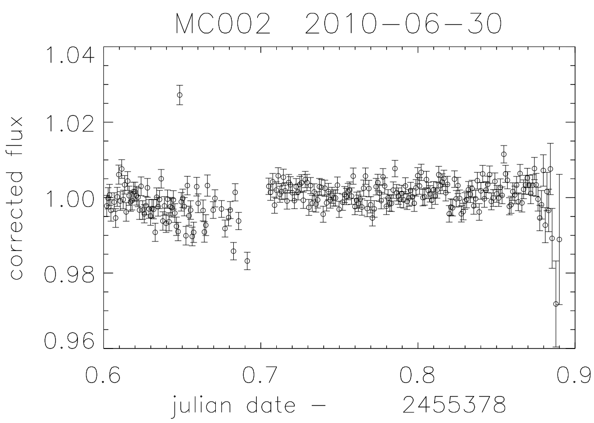


Figure D7: A STEPUP Lightcurve of a MC002 from May 27, 2010.

Figure D8: A STEPUP Lightcurve of a MC002 from May 30, 2010.



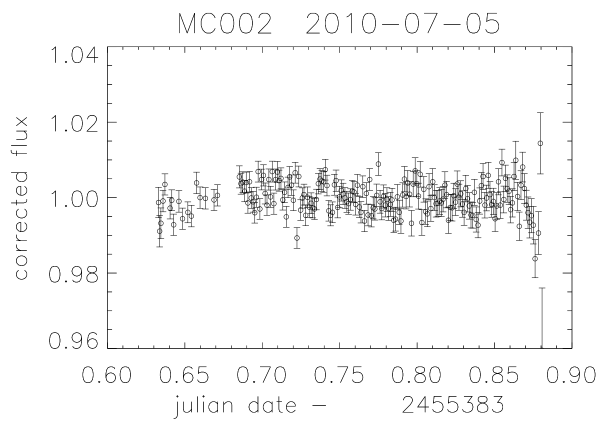
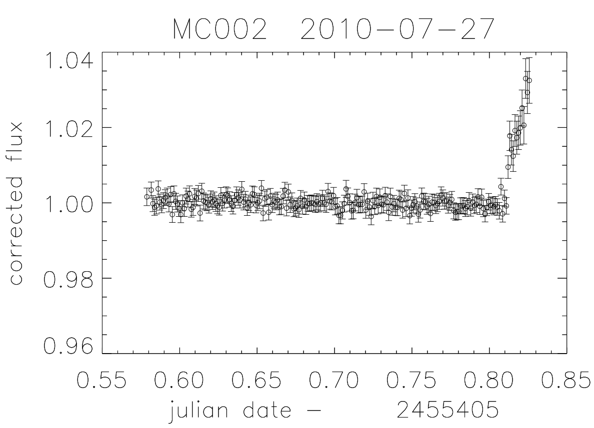


Figure D9: A STEPUP Lightcurve of a MC002 from June 30, 2010.

Figure D10: A STEPUP Lightcurve of a MC002 from July 5, 2010.



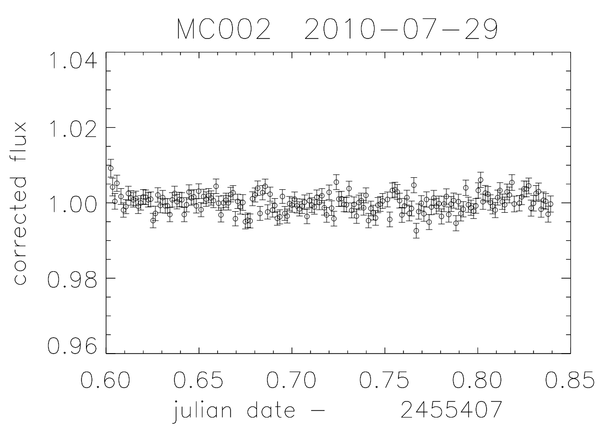


Figure D11: A STEPUP Lightcurve of a MC002 from July 27, 2010.

Figure D12: A STEPUP Lightcurve of a MC002 from July 29, 2010.

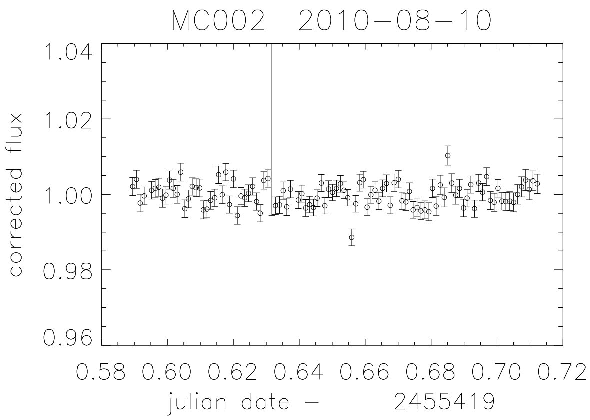


Figure D13: A STEPUP Lightcurve of a MC002 from August 10, 2010.

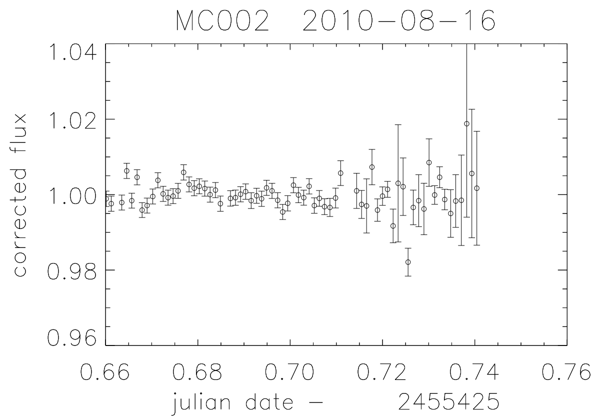


Figure D14: A STEPUP Lightcurve of a MC002 target from August 16, 2010.

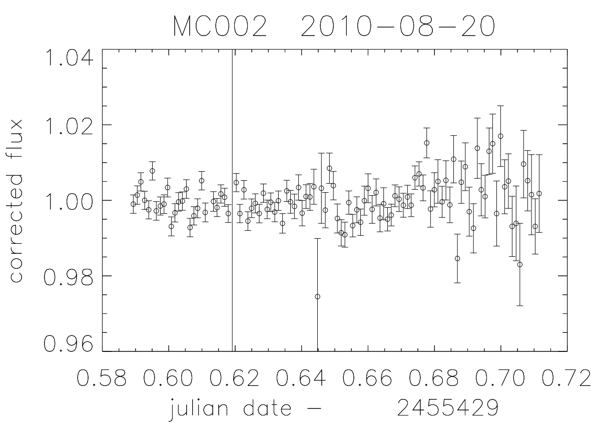


Figure D15: A STEPUP Lightcurve of a MC002 from August 20, 2010.

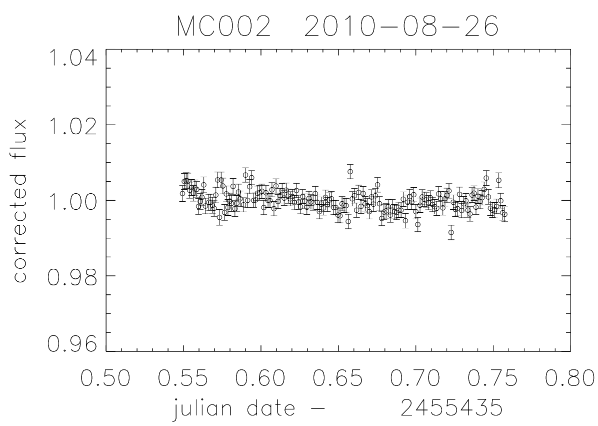


Figure D16: A STEPUP Lightcurve of a MC002 from August 26, 2010.

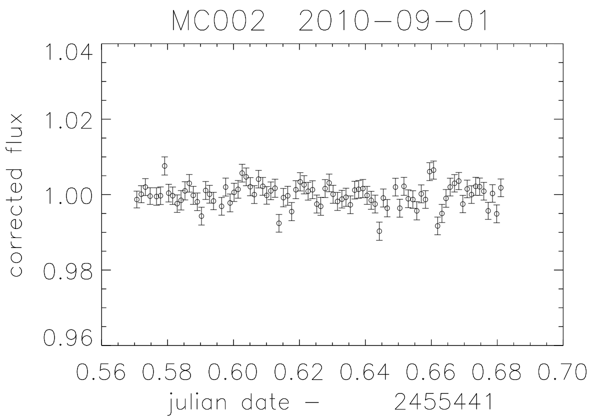


Figure D17: A STEPUP Lightcurve of a MC002 from September 1, 2010.

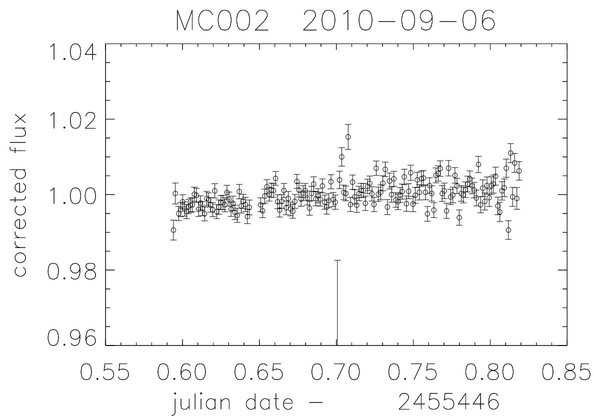


Figure D18: A STEPUP Lightcurve of a MC002 from September 6, 2010.

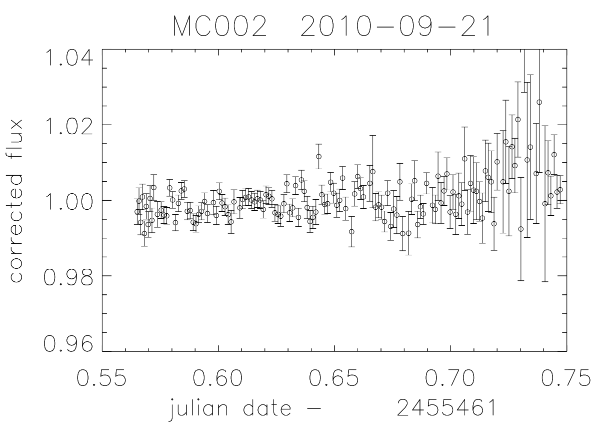


Figure D19: A STEPUP Lightcurve of a MC002 from September 21, 2010.

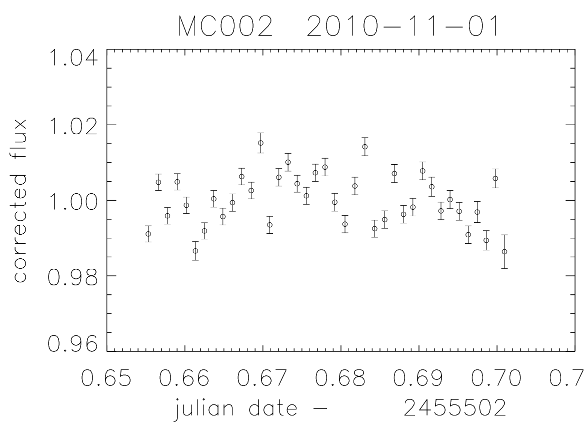


Figure D20: A STEPUP Lightcurve of a MC002 from November 1, 2010.

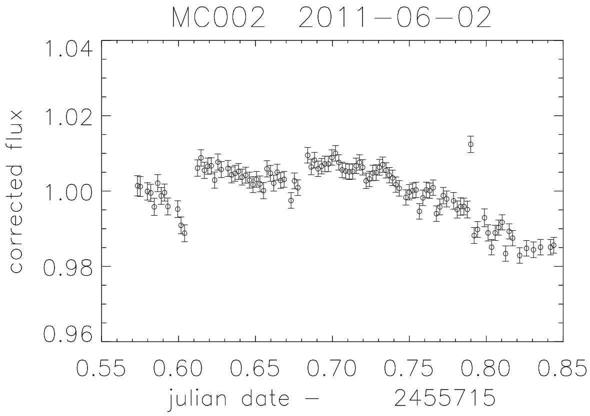


Figure D21: A STEPUP Lightcurve of a MC002 from June 2, 2011. The trends in this lightcurve are artifacts of refocussing, a matter which is currently under investigation.

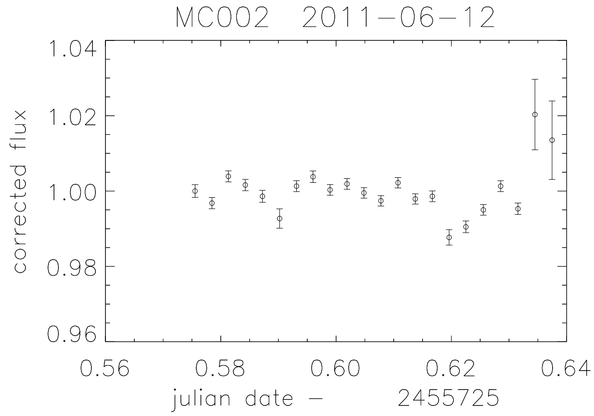


Figure D22: A STEPUP Lightcurve of a MC002 from June 12, 2011.

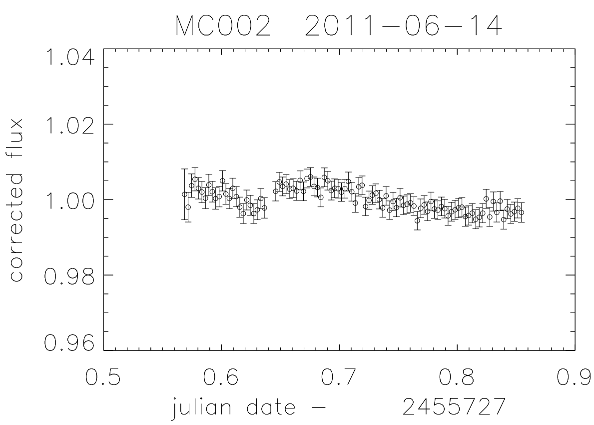


Figure D23: A STEPUP Lightcurve of a MC002 from June 14, 2011. The trends in this lightcurve are artifacts of refocussing, a matter which is currently under investigation.

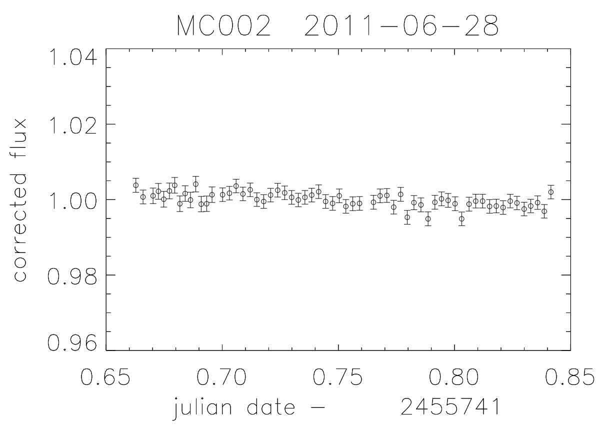


Figure D24: A STEPUP Lightcurve of a MC002 from June 28, 2011.

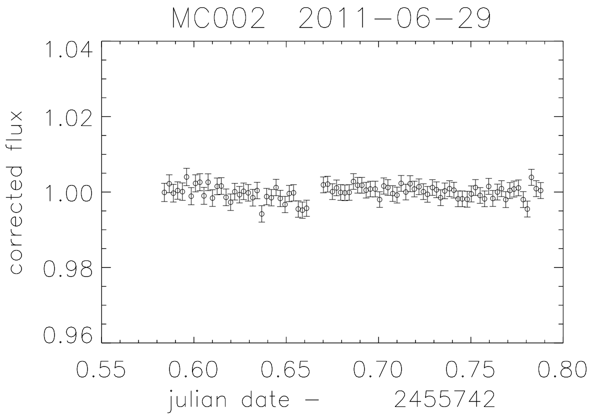


Figure D25: A STEPUP Lightcurve of a MC002 from June 29, 2011.

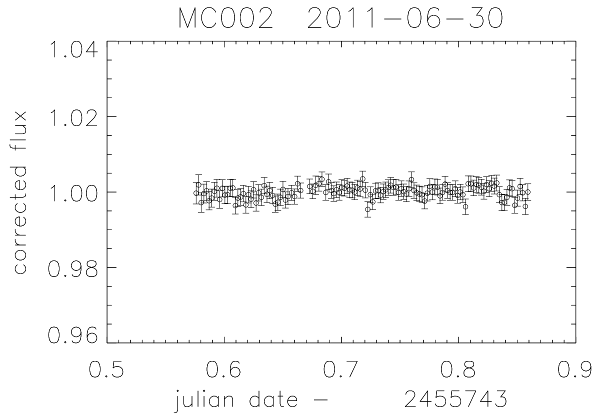


Figure D26: A STEPUP Lightcurve of a MC002 from June 30, 2011.

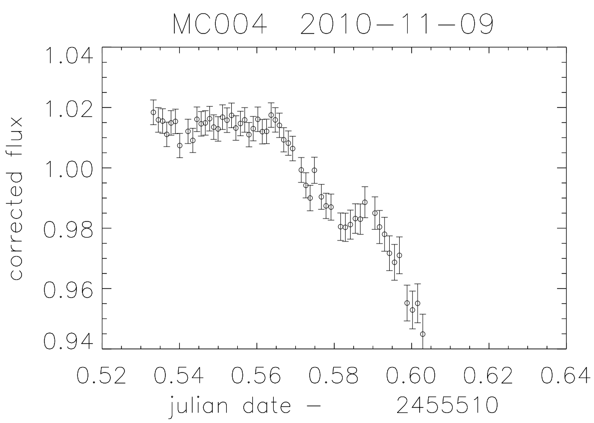


Figure D27: A STEPUP Lightcurve of a MC004 from November 9, 2010. This is an example of data that exhibit an "ingress" just as the images reveal that the flux of the stars disappears. In other words, this is not a true planetary transit ingress.

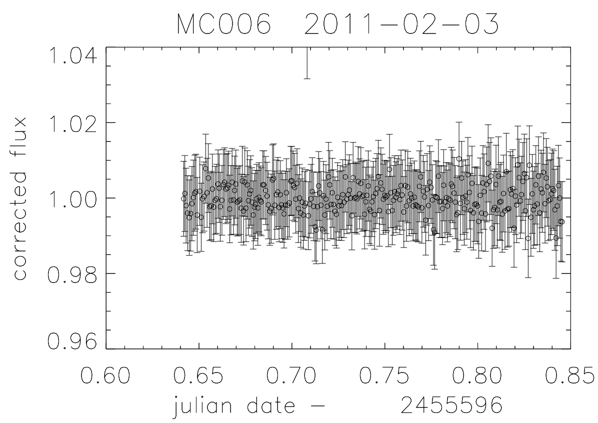


Figure D28: A STEPUP Lightcurve of a MC006 from February 3, 2011.

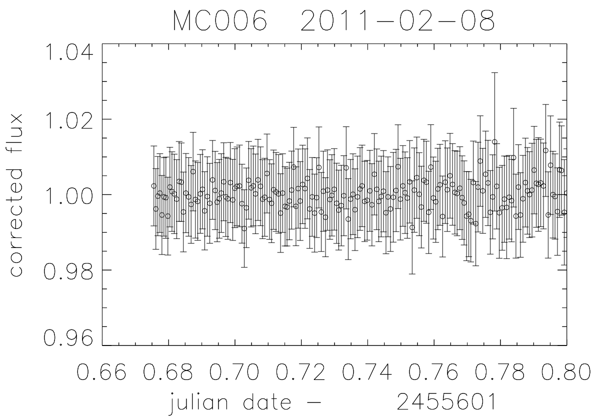


Figure D29: A STEPUP Lightcurve of a MC006 from February 8, 2011.

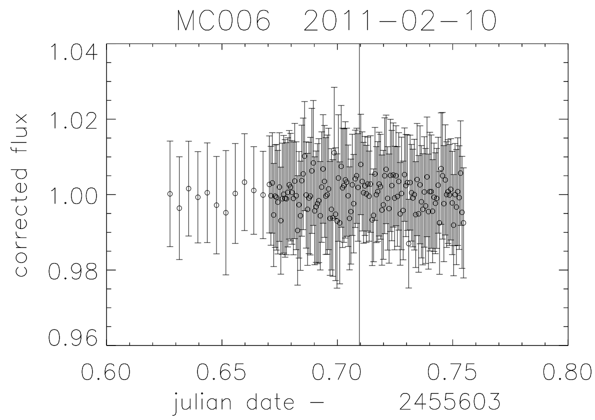


Figure D30: A STEPUP Lightcurve of a MC006 from February 10, 2011.

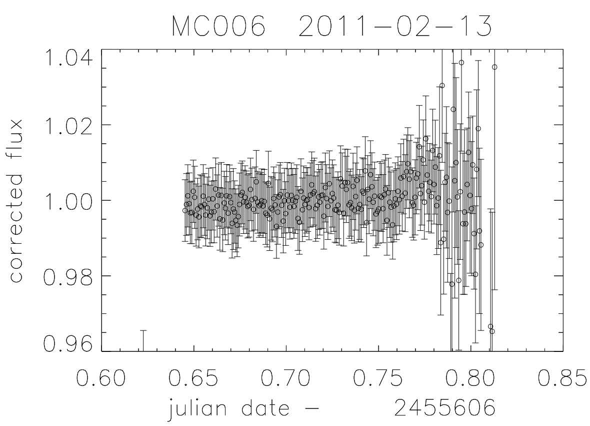


Figure D31: A STEPUP Lightcurve of a MC006 from February 13, 2011.

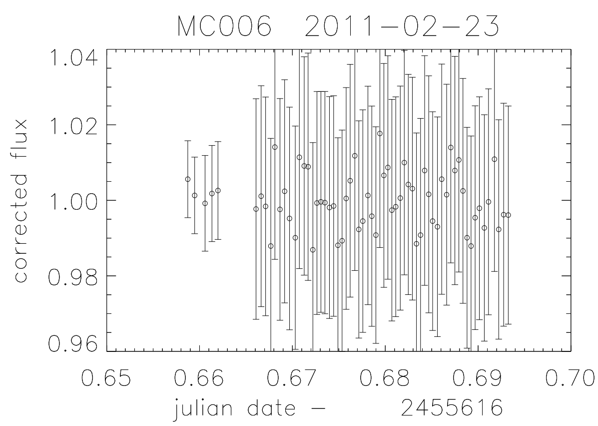
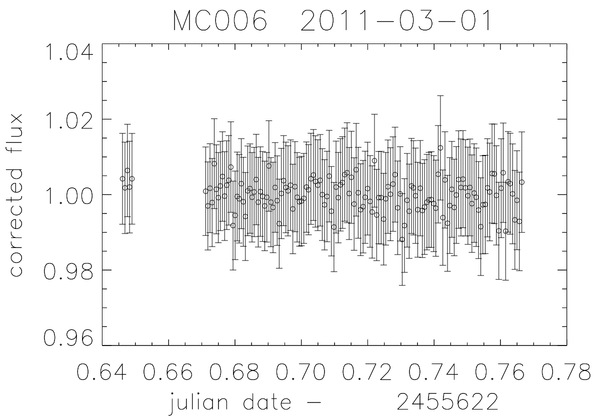


Figure D32: A STEPUP Lightcurve of a MC006 from February 23, 2011.



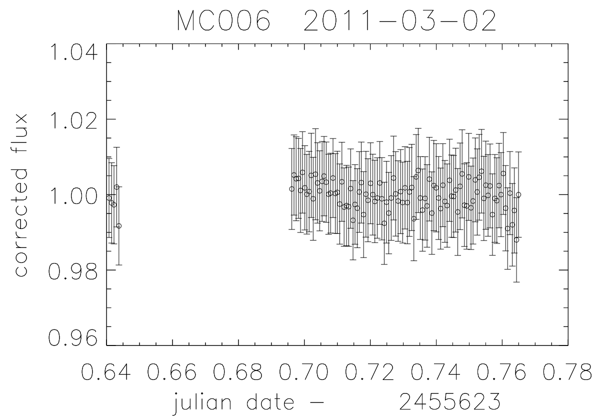
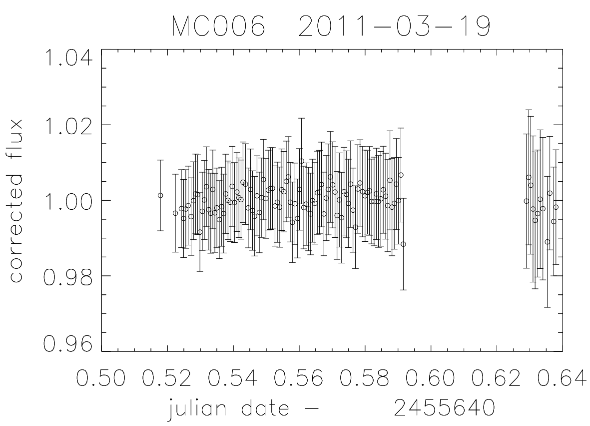


Figure D33: A STEPUP Lightcurve of a MC006 from March 1, 2011.

Figure D34: A STEPUP Lightcurve of a MC006 from March 2, 2011.



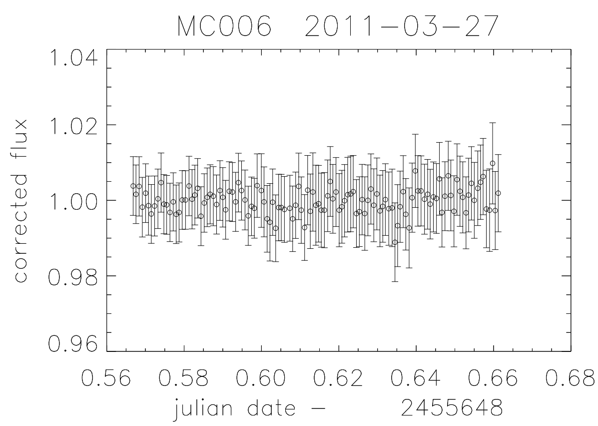


Figure D35: A STEPUP Lightcurve of a MC006 from March 19, 2011.

Figure D36: A STEPUP Lightcurve of a MC006 from March 27, 2011.

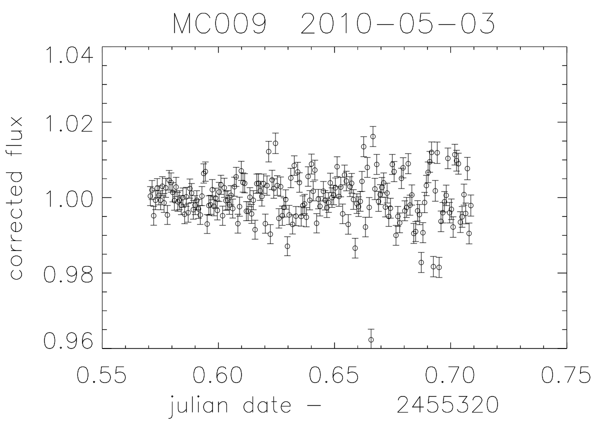


Figure D37: A STEPUP Lightcurve of a MC009 from May 3, 2010.

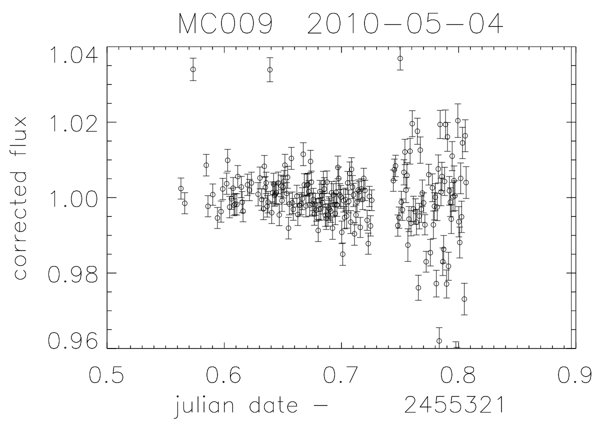


Figure D38: A STEPUP Lightcurve of a MC009 from May 4, 2010.

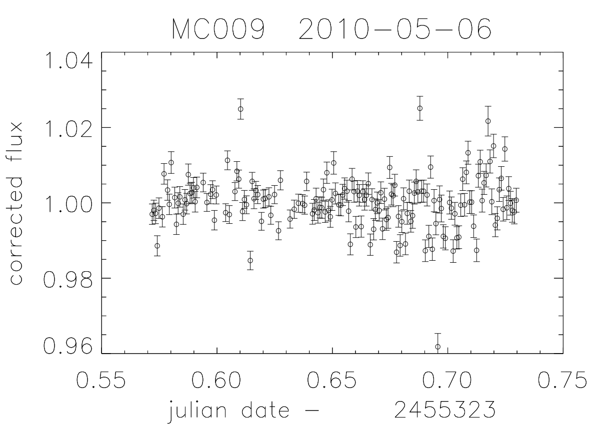


Figure D39: A STEPUP Lightcurve of a MC009 from May 6, 2010.

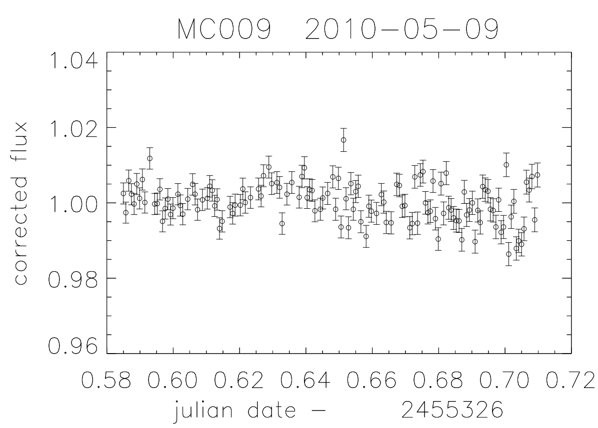


Figure D40: A STEPUP Lightcurve of a MC009 from May 9, 2010.

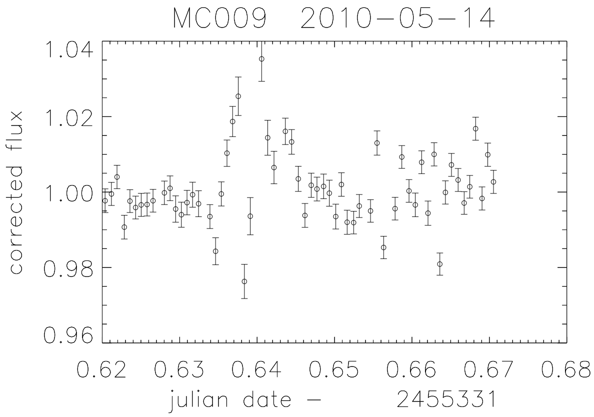


Figure D41: A STEPUP Lightcurve of a MC009 from May 14, 2010.

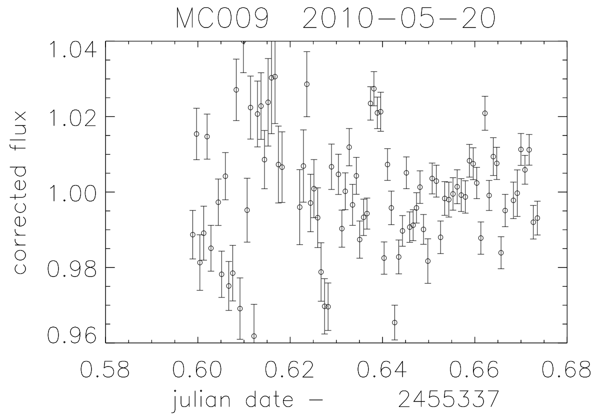


Figure D42: A STEPUP Lightcurve of a MC009 from May 20, 2010.

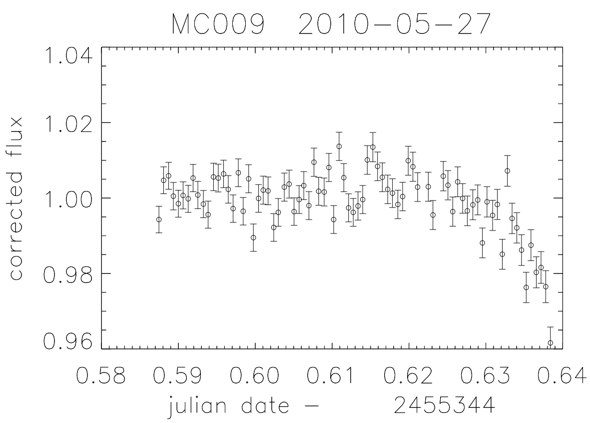


Figure D43: A STEPUP Lightcurve of a MC009 from May 27, 2010. This is an example of data that exhibit an "ingress" just as the images reveal that the flux of the stars disappears. In other words, this is not a true planetary transit ingress.

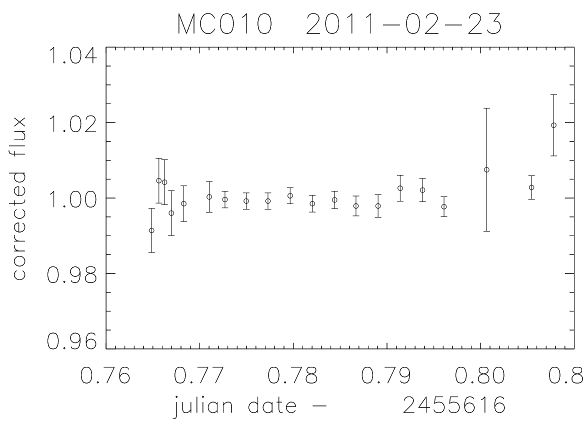


Figure D44: A STEPUP Lightcurve of a MC010 from February 23, 2011.

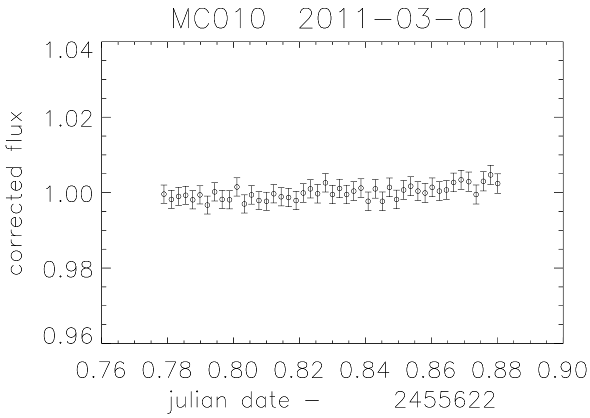


Figure D45: A STEPUP Lightcurve of a MC010 from March 1, 2011.

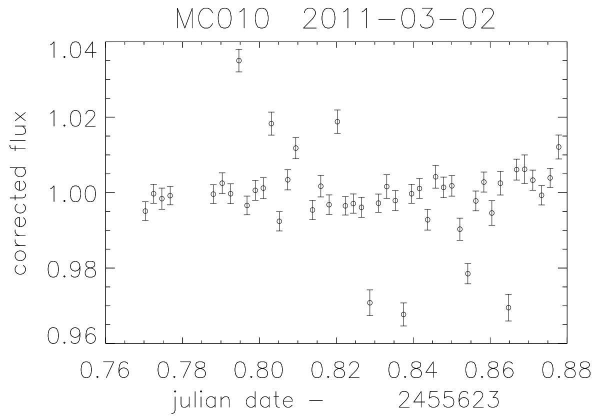


Figure D46: A STEPUP Lightcurve of a MC010 from March 2, 2011.

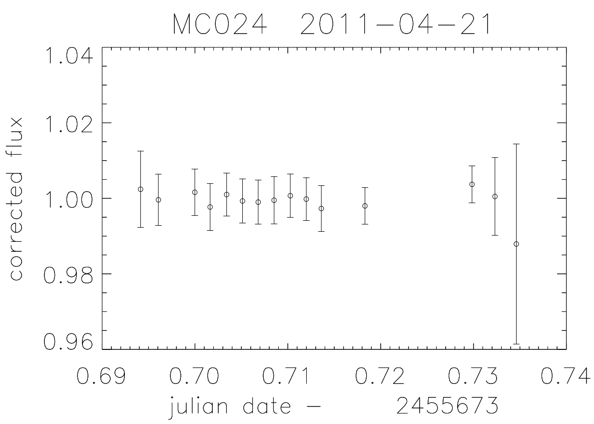


Figure D47: A STEPUP Lightcurve of a MC024 from April 21, 2011.

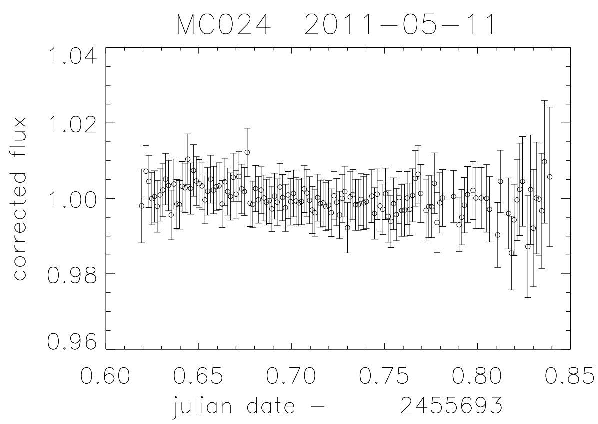


Figure D48: A STEPUP Lightcurve of a MC024 from May 11, 2011.

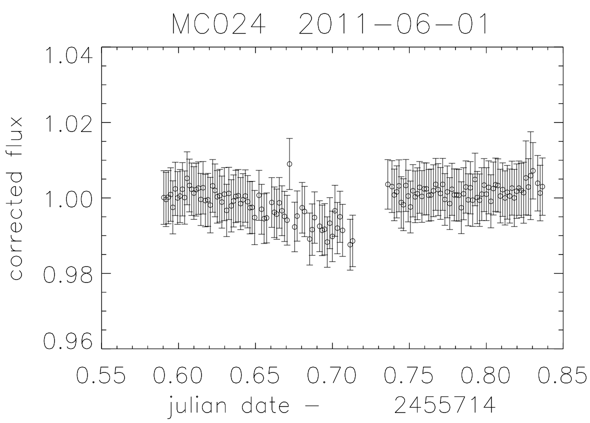


Figure D49: A STEPUP Lightcurve of a MC024 from June 1, 2011. The trends in this lightcurve are artifacts of refocussing, a matter which is currently under investigation.

APPENDIX E

LIGHTCURVES OF KNOWN TARGETS

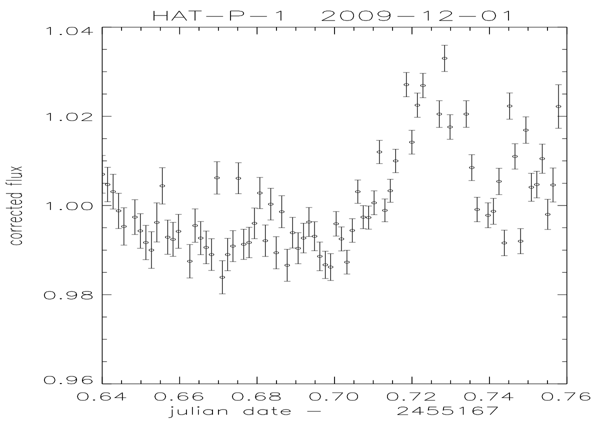


Figure E1: A STEPUP Lightcurve of HAT-P-1 from December 1, 2009. This data set might include a partial transit. GJD=2455167.67 closely coincides with the predicted mid-transit time for HAT-P-1b, being off by only about 8 min. However, this data set suffers from poor tracking and our limited ability to obtain accurate brightness measurements for such a close binary star system using aperture photometry, so it is unclear if we can make any statement about having captured a transit in this data set.

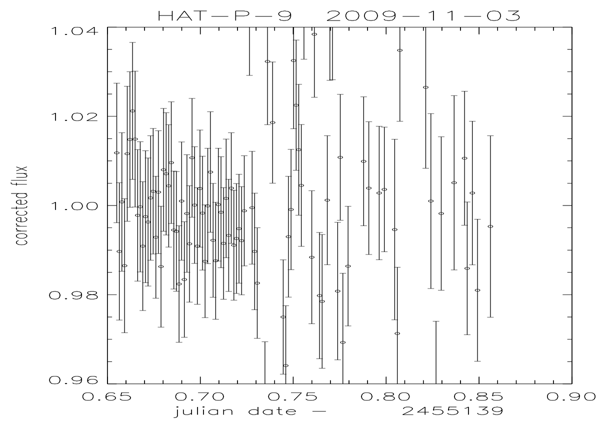


Figure E2: A STEPUP Lightcurve of HAT-P-9 from November 3, 2009. FWHM for this data set was 10.219, the largest of any of our data sets.

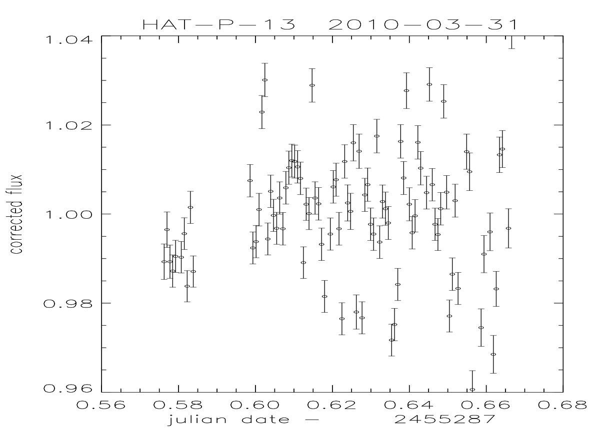


Figure E3: A STEPUP Lightcurve of HAT-P-13 from March 31, 2010. This data set suffered from very poor focus.

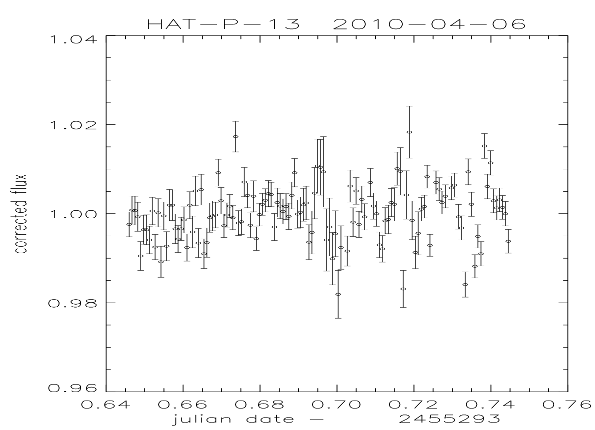


Figure E4: A STEPUP Lightcurve of HAT-P-13 from April 6, 2010.

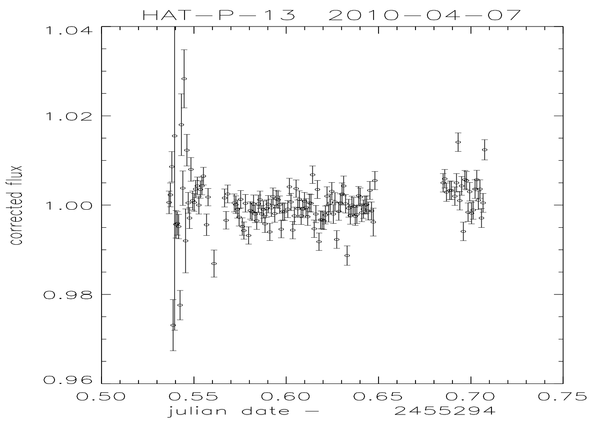


Figure E5: A STEPUP Lightcurve of HAT-P-13 from April 7, 2010. This data set suffered from poor guiding, with elongated and doubled stars in the images. A refocus was done partway through the data set and later the guide star was lost.

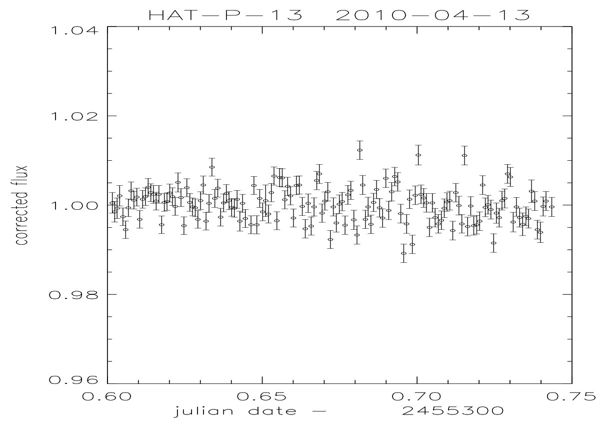


Figure E6: A STEPUP Lightcurve of HAT-P-13 from April 13, 2010.

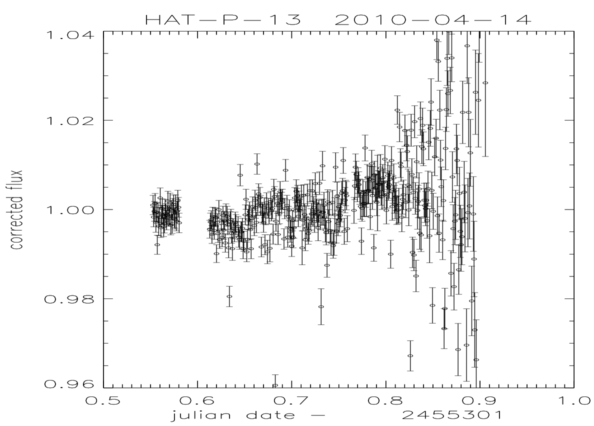


Figure E7: A STEPUP Lightcurve of HAT-P-13 from April 14, 2010. A refocus was done partway through the data set. Then image-taking was left running without supervision.

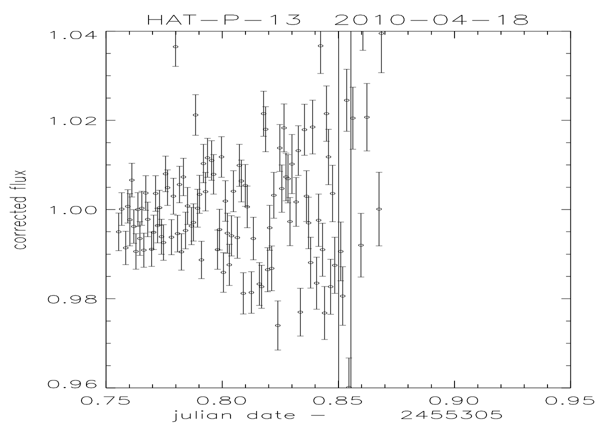


Figure E8: A STEPUP Lightcurve of HAT-P-13 from April 18, 2010. This data set suffered from poor guiding and image-taking was left running without supervision. During that time, flux was gradually lost until stars all but disappeared near the end of the data set.

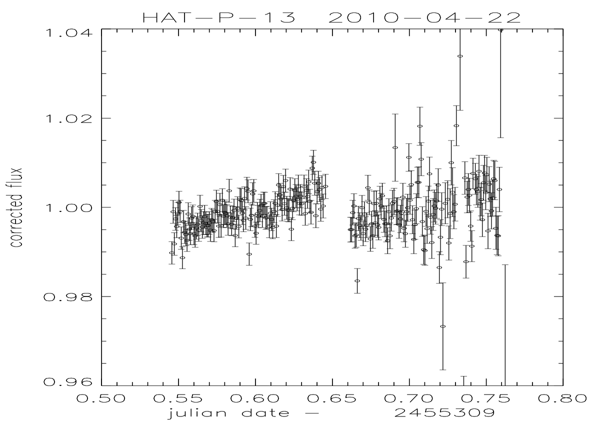


Figure E9: A STEPUP Lightcurve of HAT-P-13 from April 22, 2010. A refocus was done partway through the data set. Then image-taking was left running without supervision.

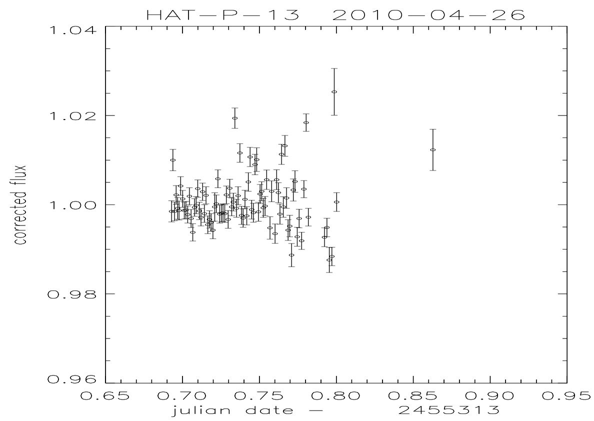


Figure E10: A STEPUP Lightcurve of HAT-P-13 from April 26, 2010. The observing report from this night mentions that weather conditions worsened and guide star was lost about half-way through the data set.

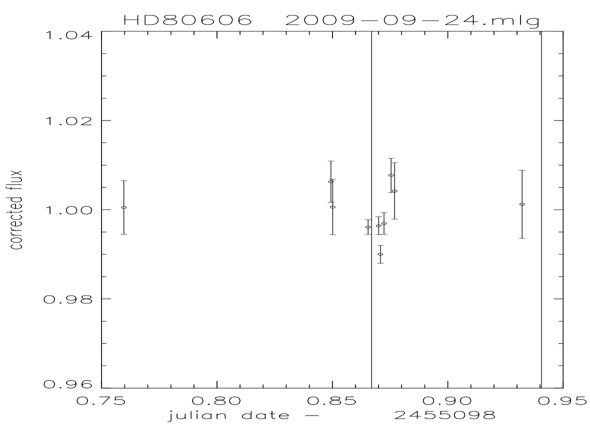


Figure E11: A STEPUP lightcurve of HD80606 from our attempt at the September 23, 2009 collaborative observing effort. Weather conditions were not at all conducive to observing and very little data was salvagable.

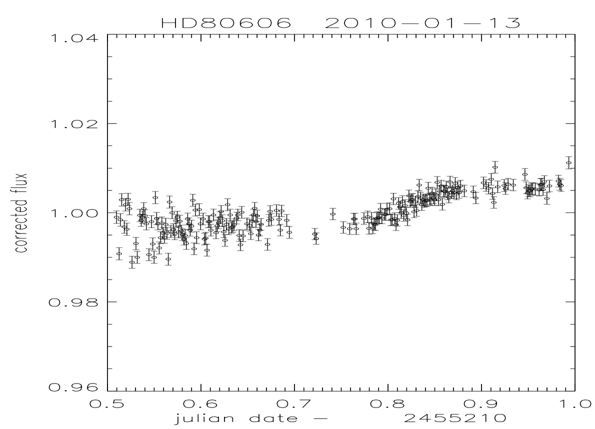


Figure E12: A STEPUP lightcurve of HD80606 from the January 13, 2010 collaborative observing effort. This lightcurve shows a partial transit of HD80606b from that night and is a result of our individual analysis, and does not reflect the fitting done by the collaboration.

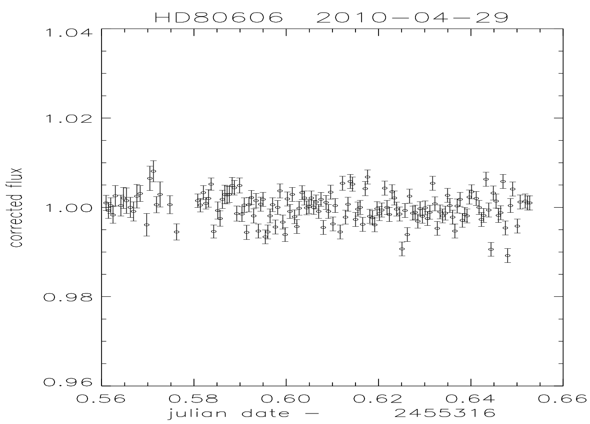


Figure E13: A STEPUP lightcurve of HD80606 from April 29, 2010. This data was purposely taken during an out-of-transit phase of the system to serve as a baseline for the collaborative observing effort.

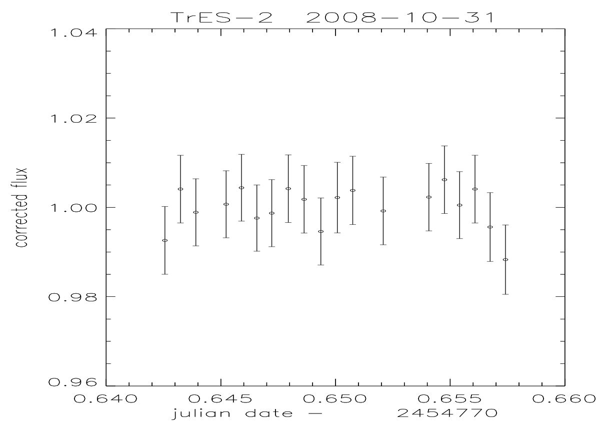


Figure E14: A recent lightcurve from the data I obtained as an undergrad of TrES-2 from October 31, 2008.

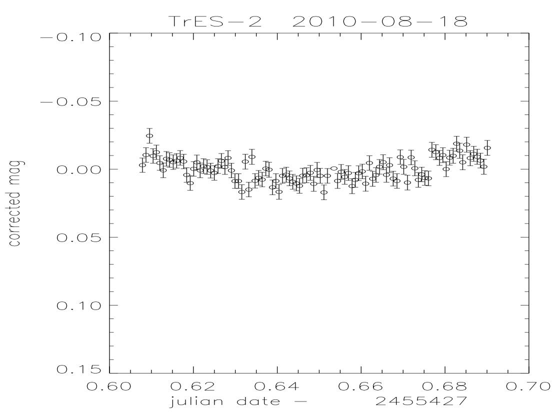


Figure E15: A STEPUP lightcurve of a TrES-2 from August 18, 2010, containing a full transit of the planet TrES-2b.

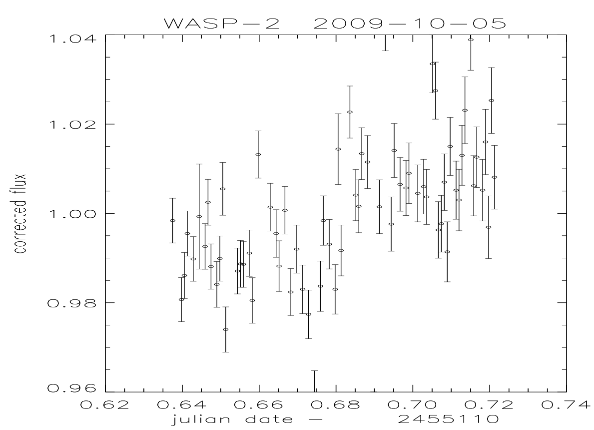


Figure E16: A STEPUP Lightcurve of a WASP-2 from October 5, 2009.

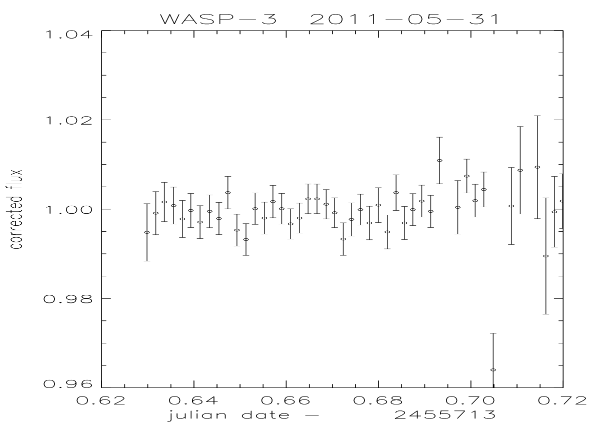


Figure E17: A STEPUP Lightcurve of a WASP-3 from May 31, 2011.

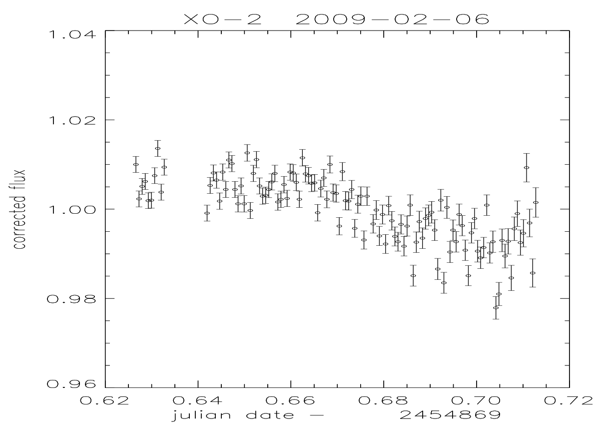


Figure E18: Most recent lightcurve of the XO-2b partial transit I obtained as an undergraduate on February 6, 2009.

APPENDIX F

DATA FILES OF KNOWN TARGETS

HAT-P-1_2009-12-01_initial.flux.abridged.dat

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2455167.6442200001 94246.0781 59679.3750 117380.9766 285.67749023 231.22926331 305.75265503
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2455167.6512699998 96667.5312 60990.8320 121923.5312 285.06912231 232.86973572 309.06597900
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2455167.6710199998	101750.0625	64222.5078	129838.8672	294.49227905	239.27299500	319.59259033
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2455293.6564799999	334118.3125	245556.7031	245556.7031	652.07507324	595.78295898	595.78295898
2455293.6572199999	345774.1562	254130.0156	254130.0156	654.32794189	592.46575928	592.46575928
2455293.6579499999	358109.7188	264576.1250	264576.1250	662.57928467	598.21484375	598.21484375
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2455293.6713899998	471247.1562	347102.0312	347102.0312	714.32574463	642.11700439	642.11700439
2455293.6721399999	500504.3438	367905.9062	367905.9062	716.97558594	646.65026855	646.65026855
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2455293.6828800002	462920.2188	339399.4062	339399.4062	700.14013672	634.19598389	634.19598389
2455293.6837300002	402010.7188	296909.4688	296909.4688	670.87683105	622.58764648	622.58764648
2455293.6844700002	373160.4688	274073.7500	274073.7500	664.82232666	607.25640869	607.25640869
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2455301.6991599998	474367.5938	355327.1562	355327.1562	635.46319580	567.88244629	567.88244629
2455301.6999900001	476095.9062	358002.3438	358002.3438	639.39349365	570.02636719	570.02636719
2455301.7008600002	489246.8125	365789.8750	365789.8750	644.38299561	572.57598877	572.57598877

2455301.7015900002	485037.0938	364044.1875	364044.1875	640.72125244	573.46307373	573.46307373
2455301.7023399998	484890.6562	363147.5000	363147.5000	642.39923096	576.06127930	576.06127930
2455301.7031700001	488918.6875	363700.6875	363700.6875	645.93713379	576.06762695	576.06762695
2455301.7039600001	486812.6250	363182.3750	363182.3750	647.28424072	575.46435547	575.46435547
2455301.7047999999	418570.5938	310900.9688	310900.9688	609.63623047	551.87304688	551.87304688
2455301.7055400000	486486.1875	361949.4062	361949.4062	644.90380859	572.40020752	572.40020752
2455301.7062800000	487895.9375	362751.1562	362751.1562	647.26495361	574.31274414	574.31274414
2455301.7070100000	483491.8750	361135.2812	361135.2812	645.76391602	577.80554199	577.80554199
2455301.7077400000	483806.0938	360196.5938	360196.5938	644.00762939	573.20495605	573.20495605
2455301.7084800000	481866.4062	359419.1250	359419.1250	642.95098877	574.25604248	574.25604248
2455301.7093600002	483046.0938	360160.2812	360160.2812	643.46575928	576.74725342	576.74725342
2455301.7102100002	483806.0938	359715.4375	359715.4375	645.00073242	572.56951904	572.56951904
2455301.7110799998	235434.7656	177112.6094	177112.6094	506.33599854	470.19876099	470.19876099
2455301.7119399998	480651.3750	359329.6875	359329.6875	642.01013184	575.79016113	575.79016113
2455301.7127800002	481061.6250	357646.7812	357646.7812	642.97277832	577.41876221	577.41876221
2455301.7136200001	473843.5625	353793.2188	353793.2188	642.57977295	575.71234131	575.71234131
2455301.7144300002	458313.6250	344166.8750	344166.8750	636.16644287	573.29351807	573.29351807
2455301.7152399998	474312.4375	354368.3750	354368.3750	643.09765625	572.95019531	572.95019531
2455301.7159699998	474734.7812	355543.0938	355543.0938	640.54785156	575.17834473	575.17834473
2455301.7167099998	463440.8125	344512.6875	344512.6875	637.50036621	566.87103271	566.87103271
2455301.7175799999	464674.0938	348457.4688	348457.4688	636.97454834	568.65020752	568.65020752
2455301.7184500000	463331.0625	347184.5000	347184.5000	636.84326172	568.32897949	568.32897949
2455301.7193300002	465001.4062	345342.0938	345342.0938	641.75592041	569.53784180	569.53784180
2455301.7201999999	469278.5938	350765.6250	350765.6250	640.12188721	573.45989990	573.45989990
2455301.7210800000	468600.5000	349850.2812	349850.2812	641.55859375	568.60113525	568.60113525
2455301.7218700000	456349.0938	338932.4688	338932.4688	633.18927002	572.85510254	572.85510254
2455301.7226300002	365545.4375	272884.5625	272884.5625	588.40539551	528.41009521	528.41009521
2455301.7233600002	459269.1875	342374.7188	342374.7188	635.69799805	566.37841797	566.37841797
2455301.7242500000	459597.5000	343693.9688	343693.9688	637.48419189	573.14483643	573.14483643
2455301.7249799999	457691.0938	339390.4062	339390.4062	632.44018555	566.63287354	566.63287354
2455301.7257099999	455994.6875	339604.8125	339604.8125	636.22644043	571.07501221	571.07501221
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2455301.7271900000	426360.1250	318356.5625	318356.5625	618.23107910	558.85211182	558.85211182
2455301.7280799998	358166.5312	268220.6562	268220.6562	587.94689941	532.13842773	532.13842773

2455301.7288199998	446640.0938	333241.6562	333241.6562	630.45361328	565.28991699	565.28991699
2455301.7295499998	436543.6562	323661.8750	323661.8750	623.86425781	563.36035156	563.36035156
2455301.7303599999	360129.5625	269057.4375	269057.4375	581.09014893	529.12750244	529.12750244
2455301.7312300000	216100.0938	164760.9375	164760.9375	503.43167114	466.56170654	466.56170654
2455301.7319899998	363853.0312	271520.8438	271520.8438	587.71392822	533.52740479	533.52740479
2455301.7327200002	308846.1250	228106.3750	228106.3750	558.53118896	507.61871338	507.61871338
2455301.7334599998	349268.9688	260646.3125	260646.3125	581.04064941	532.36132812	532.36132812
2455301.7342599998	368684.0625	274698.1562	274698.1562	596.98779297	539.39263916	539.39263916
2455301.7350300001	444872.3750	332347.1562	332347.1562	634.87707520	568.85162354	568.85162354
2455301.7357500000	400210.3438	299876.7500	299876.7500	609.13427734	549.77398682	549.77398682
2455301.7366300002	386668.1562	289903.8438	289903.8438	604.38800049	546.03906250	546.03906250
2455301.7374900002	392987.0312	296815.3125	296815.3125	605.23712158	543.87799072	543.87799072
2455301.7382299998	388428.4062	289208.4375	289208.4375	600.91162109	540.88598633	540.88598633
2455301.7391800000	400718.6562	299667.0000	299667.0000	612.56268311	553.05078125	553.05078125
2455301.7400300000	404314.0312	301160.7500	301160.7500	613.65716553	549.20776367	549.20776367
2455301.7408799999	387082.6875	290061.4062	290061.4062	603.06726074	545.11352539	545.11352539
2455301.7417600001	363486.3438	273113.2500	273113.2500	589.11199951	534.86181641	534.86181641
2455301.7426000000	NaN	NaN	NaN	NaN	NaN	NaN
2455301.7433300000	391810.6562	291752.3438	291752.3438	604.52825928	549.58673096	549.58673096
2455301.7440700000	370908.3438	278897.8125	278897.8125	596.47631836	536.76141357	536.76141357
2455301.7450000001	380140.5625	285672.3438	285672.3438	602.71832275	545.52307129	545.52307129
2455301.7457599998	238725.4844	178262.8750	178262.8750	520.27508545	476.17419434	476.17419434
2455301.7466300000	315438.6875	233043.7188	233043.7188	567.82916260	519.75341797	519.75341797
2455301.7474400001	393202.8438	294666.1875	294666.1875	608.12506104	545.89367676	545.89367676
2455301.7482799999	330860.4062	246030.0938	246030.0938	580.68664551	528.83258057	528.83258057
2455301.7491400000	388446.2188	290614.1875	290614.1875	607.36090088	550.62402344	550.62402344
2455301.7499699998	390763.6562	291255.9375	291255.9375	607.58410645	547.41284180	547.41284180
2455301.7508200002	374549.5000	279995.7188	279995.7188	604.92987061	541.78546143	541.78546143
2455301.7516200002	425295.5312	317615.1562	317615.1562	626.88824463	562.67913818	562.67913818
2455301.7523699999	429109.8750	320097.7812	320097.7812	627.79187012	565.54974365	565.54974365
2455301.7532299999	414574.5312	308055.2812	308055.2812	619.30792236	561.96063232	561.96063232
2455301.7539900001	385998.8750	286697.4688	286697.4688	603.89416504	550.10046387	550.10046387
2455301.7547300002	368140.5312	271575.2188	271575.2188	593.26239014	540.86840820	540.86840820
2455301.7557999999	358352.6562	268574.6562	268574.6562	591.51434326	543.38934326	543.38934326

2455301.7566100000	373083.9688	277672.6250	277672.6250	599.85589600	543.32415771	543.32415771
2455301.7573699998	374427.2812	278231.6562	278231.6562	602.75238037	544.72003174	544.72003174
2455301.7582200002	325719.4375	242182.7812	242182.7812	584.35339355	527.56848145	527.56848145
2455301.7590600001	357661.9375	267903.4688	267903.4688	594.38964844	538.22784424	538.22784424
2455301.7661700002	364759.1562	272095.6250	272095.6250	601.38543701	544.06390381	544.06390381
2455301.7669099998	343973.2188	255200.4375	255200.4375	591.80377197	534.76800537	534.76800537
2455301.7677400000	357110.0312	263825.9062	263825.9062	591.78027344	532.47235107	532.47235107
2455301.7685400001	358903.2812	265571.6875	265571.6875	592.79718018	536.32293701	536.32293701
2455301.7696900000	357221.5625	265183.5625	265183.5625	599.48394775	537.66198730	537.66198730
2455301.7705600001	370806.3438	274773.1250	274773.1250	598.70745850	542.84765625	542.84765625
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2455301.7723800000	380718.6562	282827.5000	282827.5000	609.73382568	550.48181152	550.48181152
2455301.7731699999	371097.0312	276585.1250	276585.1250	604.40045166	548.78076172	548.78076172
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2455301.7747800001	369830.5312	275749.4062	275749.4062	608.30169678	548.91558838	548.91558838
2455301.7756500002	375140.5938	278716.5312	278716.5312	607.59094238	552.41949463	552.41949463
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2455301.7771899998	377289.8750	281034.0938	281034.0938	611.15747070	559.52398682	559.52398682
2455301.7779299999	380709.2500	280068.2500	280068.2500	615.50073242	554.90399170	554.90399170
2455301.7786500002	379506.2812	282077.0625	282077.0625	614.78356934	554.09326172	554.09326172
2455301.7793899998	361075.3750	268909.7188	268909.7188	600.58593750	552.26275635	552.26275635
2455301.7802200001	377300.5938	279386.0938	279386.0938	612.84948730	555.83587646	555.83587646
2455301.7809400000	378981.3438	281467.6562	281467.6562	614.41168213	554.14044189	554.14044189
2455301.7817099998	380471.5000	282554.9062	282554.9062	617.40686035	553.90802002	553.90802002
2455301.7825900000	356792.5625	264311.0625	264311.0625	605.67633057	544.99243164	544.99243164
2455301.7834100001	375552.5625	280540.4062	280540.4062	611.92315674	560.73583984	560.73583984
2455301.7842399999	374177.3125	277176.0000	277176.0000	613.65856934	559.86206055	559.86206055
2455301.7849800000	367515.7188	271295.5000	271295.5000	611.52606201	553.74407959	553.74407959
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2455301.7864600001	341291.3438	252898.1250	252898.1250	594.07348633	542.60943604	542.60943604
2455301.7872100002	351190.0312	264188.3438	264188.3438	601.76898193	552.96032715	552.96032715
2455301.7879300001	353553.7188	261636.5625	261636.5625	601.67712402	547.56909180	547.56909180
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2455301.7895599999	364111.7188	270231.6562	270231.6562	607.29614258	549.59985352	549.59985352

2455301.7904200000	360798.7500	268652.0625	268652.0625	607.15435791	553.60839844	553.60839844
2455301.7911600000	96726.0703	71873.2031	71873.2031	448.51538086	434.53231812	434.53231812
2455301.7919399999	366746.6875	271991.6562	271991.6562	613.63476562	551.95739746	551.95739746
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2455301.7942499998	357682.3750	264300.6250	264300.6250	605.67517090	552.19769287	552.19769287
2455301.7950200001	358769.4062	266524.1250	266524.1250	606.07873535	553.97979736	553.97979736
2455301.7958800001	363636.3438	270387.3125	270387.3125	608.66217041	557.68359375	557.68359375
2455301.7967200000	363150.6250	268937.0000	268937.0000	612.05792236	548.84643555	548.84643555
2455301.7974500000	364632.0312	270313.4688	270313.4688	611.23217773	556.93267822	556.93267822
2455301.7982100002	363270.0625	270051.1250	270051.1250	608.38055420	553.32849121	553.32849121
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2455301.8013300002	351853.6562	261535.2812	261535.2812	604.26049805	550.69598389	550.69598389
2455301.8020600001	354157.2188	262159.6562	262159.6562	610.08978271	544.55383301	544.55383301
2455301.8027900001	353718.3438	262462.6875	262462.6875	606.55426025	549.50482178	549.50482178
2455301.8035200001	352940.5312	261757.0469	261757.0469	601.56127930	553.06292725	553.06292725
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2455301.8051700001	333049.3125	250899.5469	250899.5469	598.79156494	545.65393066	545.65393066
2455301.8060300001	347190.7500	256136.0938	256136.0938	601.84991455	548.48278809	548.48278809
2455301.8068100000	343476.2188	256002.8906	256002.8906	599.96875000	551.36517334	551.36517334
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2455301.8091199999	345844.6562	257339.0469	257339.0469	600.20916748	552.29290771	552.29290771
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2455301.8107300000	339395.0938	252403.7031	252403.7031	597.14678955	545.00848389	545.00848389
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2455301.8121900000	340148.3750	248149.0938	248149.0938	593.24963379	541.78515625	541.78515625
2455301.8129599998	336596.8125	251063.6719	251063.6719	592.90710449	543.29968262	543.29968262
2455301.8137699999	259325.2500	193237.2812	193237.2812	556.76281738	523.07379150	523.07379150
2455301.8145900001	331485.6875	242736.2500	242736.2500	600.64953613	547.07617188	547.07617188
2455301.8153900001	332616.8438	245524.5312	245524.5312	595.64575195	544.33441162	544.33441162
2455301.8161999998	325159.8125	240194.1875	240194.1875	594.47448730	543.20599365	543.20599365

2455301.8169700000	318871.0625	238218.3281	238218.3281	591.58874512	543.36694336	543.36694336
2455301.8177899998	318798.6875	237214.2812	237214.2812	595.67315674	541.94647217	541.94647217
2455301.8186100000	316761.7812	235481.4375	235481.4375	590.56866455	538.72241211	538.72241211
2455301.8194599999	99.0000	99.0000	99.0000	590.56866455	538.72241211	538.72241211
2455301.8202900002	298615.1250	218834.6562	218834.6562	574.19824219	523.91223145	523.91223145
2455301.8211699999	301373.1250	224419.6875	224419.6875	582.10046387	532.52728271	532.52728271
2455301.8219699999	301612.2500	221749.2969	221749.2969	585.81121826	527.96118164	527.96118164
2455301.8227800000	292501.1875	215353.3750	215353.3750	575.69061279	522.35229492	522.35229492
2455301.8236099998	288801.3750	214211.4219	214211.4219	574.35821533	533.88378906	533.88378906
2455301.8243300002	289700.1250	216096.3281	216096.3281	571.27990723	534.70196533	534.70196533
2455301.8251600000	293173.8750	217549.4531	217549.4531	577.32763672	532.05053711	532.05053711
2455301.8260300001	285522.3750	220180.9062	220180.9062	570.34008789	531.08264160	531.08264160
2455301.8268599999	294210.6562	215588.2969	215588.2969	577.43688965	533.36108398	533.36108398
2455301.8276000000	299490.0625	221608.7500	221608.7500	587.18890381	529.44000244	529.44000244
2455301.8283699998	298768.5625	224988.2656	224988.2656	583.41235352	534.46710205	534.46710205
2455301.8291000002	291390.3125	216495.3438	216495.3438	575.91430664	528.39392090	528.39392090
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2455301.8305799998	292945.5625	214267.0781	214267.0781	575.85870361	530.07659912	530.07659912
2455301.8313300000	289406.0625	215317.4375	215317.4375	574.92053223	530.04638672	530.04638672
2455301.8320599999	284647.1250	215512.1094	215512.1094	574.48736572	533.77832031	533.77832031
2455301.8328000000	287552.2812	212195.2969	212195.2969	574.14923096	530.57128906	530.57128906
2455301.8336100001	235875.8750	175958.9531	175958.9531	562.30224609	504.32125854	504.32125854
2455301.8344100001	279277.9688	207917.0312	207917.0312	569.00488281	524.58013916	524.58013916
2455301.8352700002	284077.8438	210909.5938	210909.5938	575.66516113	529.76196289	529.76196289
2455301.8359800000	278665.0625	208942.0938	208942.0938	571.77172852	527.99536133	527.99536133
2455301.8367400002	281620.1250	205847.3281	205847.3281	575.97570801	523.01599121	523.01599121
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2455309.6028800001	447692.8125	332457.8125	332457.8125	637.72113037	568.13464355	568.13464355
2455309.6036299998	446387.5312	331123.7500	331123.7500	633.16809082	571.99871826	571.99871826
2455309.6044700001	445399.7500	331186.6875	331186.6875	636.56750488	567.71148682	567.71148682
2455309.6052299999	446215.8438	330836.6562	330836.6562	637.40283203	565.25701904	565.25701904
2455309.6059800000	449122.0938	332993.2500	332993.2500	633.76135254	565.63305664	565.63305664
2455309.6067400002	446680.0938	332267.6250	332267.6250	634.11773682	573.03546143	573.03546143
2455309.6074999999	443697.4688	330019.2812	330019.2812	628.98815918	568.58978271	568.58978271
2455309.6082500000	−31.6003	−98.4452	−98.4452	309.86914062	352.03240967	352.03240967
2455309.6089800000	439456.7812	327514.7500	327514.7500	635.14758301	563.59509277	563.59509277
2455309.6097499998	439493.3438	326545.7188	326545.7188	632.70477295	571.52697754	571.52697754
2455309.6105000000	441811.9688	328742.5000	328742.5000	631.09515381	566.79565430	566.79565430
2455309.6112299999	440579.9688	328408.9688	328408.9688	631.86859131	568.62670898	568.62670898
2455309.6120799999	431775.1875	320706.6562	320706.6562	630.82739258	564.10467529	564.10467529
2455309.6128500002	433272.5625	321243.4688	321243.4688	628.89404297	564.30987549	564.30987549
2455309.6135900002	431523.4375	321564.1875	321564.1875	629.87152100	564.17785645	564.17785645
2455309.6143399999	440261.0000	326553.0938	326553.0938	634.67309570	567.54669189	567.54669189
2455309.6151000001	439411.5312	324456.8125	324456.8125	632.33996582	566.85235596	566.85235596
2455309.6158599998	439646.1250	325350.4688	325350.4688	633.61712646	572.77136230	572.77136230
2455309.6165999998	437785.4375	324240.0000	324240.0000	633.36560059	566.96960449	566.96960449
2455309.6173500000	436699.4062	324219.4375	324219.4375	630.96771240	565.37048340	565.37048340
2455309.6181100002	439454.0312	324623.3750	324623.3750	631.87145996	568.72064209	568.72064209
2455309.6188500002	438373.8750	325027.0000	325027.0000	634.56488037	569.13177490	569.13177490
2455309.6195700001	438494.5000	323463.2500	323463.2500	633.46362305	567.54522705	567.54522705
2455309.6203399999	436221.0000	323727.0938	323727.0938	632.80133057	567.45831299	567.45831299
2455309.6210900000	435898.9062	323663.1562	323663.1562	634.63916016	569.53729248	569.53729248
2455309.6218200000	436609.4062	324211.2188	324211.2188	633.99578857	565.14093018	565.14093018
2455309.6225600000	435605.0625	321923.8438	321923.8438	629.20562744	562.57165527	562.57165527
2455309.6233199998	433474.5625	323253.7812	323253.7812	631.88623047	565.15844727	565.15844727
2455309.6240699999	435258.9688	323046.5000	323046.5000	629.73913574	570.21923828	570.21923828
2455309.6247899998	432652.7188	320552.6562	320552.6562	632.03057861	564.70739746	564.70739746
2455309.6255600001	432509.7188	319726.4375	319726.4375	631.10437012	568.65039062	568.65039062
2455309.6263299999	429810.4375	318152.6250	318152.6250	631.02233887	565.93231201	565.93231201
2455309.6270900001	429311.2500	317995.6250	317995.6250	627.34887695	564.46801758	564.46801758

2455309.6278499998	425861.9375	314579.1250	314579.1250	629.35443115	564.44903564	564.44903564
2455309.6285899999	429869.0938	318695.7500	318695.7500	630.99407959	565.24176025	565.24176025
2455309.6293400000	429331.8125	317795.2500	317795.2500	633.98297119	567.70214844	567.70214844
2455309.6300900001	427088.7500	316670.3438	316670.3438	631.28680420	563.50671387	563.50671387
2455309.6308400002	186975.7031	NaN	NaN	497.62069702	NaN	NaN
2455309.6316000000	425065.6562	313977.6875	313977.6875	630.58117676	563.31353760	563.31353760
2455309.6323699998	425571.1562	316240.5625	316240.5625	626.88085938	565.95629883	565.95629883
2455309.6331300000	428142.5625	316511.4688	316511.4688	630.62188721	563.19519043	563.19519043
2455309.6338800001	426176.2812	315495.1250	315495.1250	632.15899658	566.36932373	566.36932373
2455309.6345899999	424899.0625	313506.0625	313506.0625	632.14685059	568.04754639	568.04754639
2455309.6353900000	422019.6562	312722.9688	312722.9688	628.93670654	563.95800781	563.95800781
2455309.6361099998	421715.9688	313272.8750	313272.8750	630.04663086	565.08691406	565.08691406
2455309.6369300000	420736.7188	309496.3438	309496.3438	628.65960693	567.03973389	567.03973389
2455309.6376899998	417810.9375	306956.0000	306956.0000	630.95965576	564.13592529	564.13592529
2455309.6385400002	420354.3125	310259.9375	310259.9375	627.49542236	565.54241943	565.54241943
2455309.6392700002	416004.1250	309276.4375	309276.4375	625.54431152	564.04754639	564.04754639
2455309.6400700002	416305.5625	307851.2188	307851.2188	633.08526611	564.37945557	564.37945557
2455309.6408799998	411961.3438	304070.2188	304070.2188	625.82531738	564.81616211	564.81616211
2455309.6416600002	411911.2188	304438.0312	304438.0312	627.48327637	558.46270752	558.46270752
2455309.6424400001	410182.7500	304507.9688	304507.9688	624.13818359	565.18481445	565.18481445
2455309.6432099999	412033.6875	304404.6562	304404.6562	626.45257568	563.41302490	563.41302490
2455309.6439800002	414579.6250	307558.0938	307558.0938	628.44158936	564.23718262	564.23718262
2455309.6447700001	386868.6250	263720.0312	263720.0312	610.72766113	540.90887451	540.90887451
2455309.6455299999	412085.4688	304360.1875	304360.1875	629.94824219	566.86053467	566.86053467
2455309.6617700001	398733.3438	297375.2812	297375.2812	627.92059326	565.05957031	565.05957031
2455309.6625100002	398521.9062	297204.7188	297204.7188	619.46789551	561.64495850	561.64495850
2455309.6632400001	402827.6562	299293.7812	299293.7812	623.23162842	571.49462891	571.49462891
2455309.6639999999	404032.2188	299715.3125	299715.3125	625.56610107	562.76696777	562.76696777
2455309.6647299998	399676.5312	298501.7812	298501.7812	626.43542480	562.04748535	562.04748535
2455309.6654599998	402623.9688	300630.8750	300630.8750	621.54913330	562.32830811	562.32830811
2455309.6661899998	386863.0625	291899.2500	291899.2500	619.21154785	561.13763428	561.13763428
2455309.6669299998	403381.2812	300101.0938	300101.0938	624.49420166	559.26202393	559.26202393
2455309.6677799998	393048.4688	292852.9688	292852.9688	621.02581787	560.05834961	560.05834961
2455309.6685199998	400502.3125	298586.9062	298586.9062	627.39306641	563.60162354	563.60162354

2455309.6692700000	400751.5938	297408.3438	297408.3438	621.72265625	565.18292236	565.18292236
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2455309.6715699998	398345.5312	297065.5625	297065.5625	627.40173340	564.22955322	564.22955322
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2455309.6739599998	394997.5312	292805.8438	292805.8438	621.30120850	560.44177246	560.44177246
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2455309.6755400002	396262.0938	295140.0000	295140.0000	626.56707764	564.64056396	564.64056396
2455309.6762700002	396749.7500	296315.8125	296315.8125	626.14111328	560.88891602	560.88891602
2455309.6770600001	399316.5938	296078.0312	296078.0312	629.36096191	567.89727783	567.89727783
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2455309.6785800001	399628.3438	296294.7500	296294.7500	630.14501953	564.25134277	564.25134277
2455309.6793300002	387161.4688	288431.7500	288431.7500	620.91558838	555.87036133	555.87036133
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2455309.6808900000	393054.1562	291119.1562	291119.1562	621.04162598	564.97052002	564.97052002
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2455309.6842200002	384354.0312	286263.3125	286263.3125	627.83319092	560.44848633	560.44848633
2455309.6851700000	243459.1094	181332.8594	181332.8594	555.63800049	509.13034058	509.13034058
2455309.6858999999	379560.9375	283782.8125	283782.8125	626.40893555	569.08197021	569.08197021
2455309.6867100000	379147.0312	281624.8750	281624.8750	623.98992920	562.00335693	562.00335693
2455309.6874400000	380160.0312	283923.2188	283923.2188	618.68426514	567.40863037	567.40863037
2455309.6883100001	378631.2500	281644.3438	281644.3438	622.48333740	565.38909912	565.38909912
2455309.6890699998	379410.1562	281285.5000	281285.5000	622.60443115	566.04919434	566.04919434
2455309.6900700000	376096.0000	278727.5625	278727.5625	626.78607178	565.33190918	565.33190918
2455309.6908200001	117078.7734	85728.1016	85728.1016	481.51309204	444.74682617	444.74682617
2455309.6916100001	369588.0000	274502.0000	274502.0000	616.04132080	566.38677979	566.38677979
2455309.6923400001	368865.0312	273928.6875	273928.6875	617.77069092	565.91741943	565.91741943
2455309.6933400002	362612.6875	270132.1562	270132.1562	622.83514404	565.17840576	565.17840576
2455309.6942199999	362018.6875	269331.4375	269331.4375	622.79217529	572.29779053	572.29779053
2455309.6949499999	361918.8438	268919.1562	268919.1562	618.52258301	559.74584961	559.74584961
2455309.6958099999	362236.6250	268192.1875	268192.1875	625.54418945	566.32971191	566.32971191

2455309.6965500000	361568.9688	269583.5000	269583.5000	618.60479736	567.68139648	567.68139648
2455309.6974399998	361110.5312	269545.8125	269545.8125	618.71618652	568.18707275	568.18707275
2455309.6982200001	362987.9375	269619.5312	269619.5312	626.66021729	562.73651123	562.73651123
2455309.6989600002	362666.7188	269153.5312	269153.5312	623.76275635	565.97802734	565.97802734
2455309.6997000002	365697.7188	268368.5938	268368.5938	624.01824951	568.52337646	568.52337646
2455309.7004300002	358995.4375	265986.1562	265986.1562	629.23614502	571.95465088	571.95465088
2455309.7012499999	358871.0625	264964.9062	264964.9062	623.96325684	570.65808105	570.65808105
2455309.7020600000	350929.2500	261153.9844	261153.9844	619.71228027	566.61962891	566.61962891
2455309.7029100000	344895.8125	257792.2500	257792.2500	618.43634033	567.81176758	567.81176758
2455309.7036600001	334603.5312	249275.6094	249275.6094	615.44537354	567.84100342	567.84100342
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2455309.7052799999	328867.7188	242675.2656	242675.2656	619.80401611	574.67663574	574.67663574
2455309.7061500000	319402.4375	235703.6406	235703.6406	613.10424805	565.15393066	565.15393066
2455309.7068800000	259735.2188	189294.9531	189294.9531	601.28033447	558.92242432	558.92242432
2455309.7077100002	296147.9375	217415.5625	217415.5625	606.24536133	552.16876221	552.16876221
2455309.7084599999	329007.7500	244936.0000	244936.0000	618.29931641	560.71978760	560.71978760
2455309.7093600002	330169.5312	247346.2656	247346.2656	614.86743164	566.30438232	566.30438232
2455309.7101300000	330157.9688	247406.9844	247406.9844	620.38836670	564.51190186	564.51190186
2455309.7108600000	331550.0625	246242.9062	246242.9062	617.31970215	562.89831543	562.89831543
2455309.7115699998	331764.1562	247377.7344	247377.7344	615.26629639	566.31665039	566.31665039
2455309.7124000001	330076.0000	244604.9844	244604.9844	621.56054688	567.84887695	567.84887695
2455309.7131400001	292383.5625	215354.0312	215354.0312	605.32250977	564.67071533	564.67071533
2455309.7138700001	284552.0000	211619.8125	211619.8125	604.58416748	559.14904785	559.14904785
2455309.7145900000	305236.4375	228320.2656	228320.2656	612.11853027	569.03948975	569.03948975
2455309.7154999999	308747.1875	229477.8750	229477.8750	620.70666504	564.63684082	564.63684082
2455309.7162299999	306768.1875	227566.0625	227566.0625	608.48229980	572.08770752	572.08770752
2455309.7170699998	309853.1250	229983.9219	229983.9219	614.75012207	566.23229980	566.23229980
2455309.7178400001	280422.2188	207807.7188	207807.7188	607.83831787	557.85162354	557.85162354
2455309.7187700002	305264.0312	225401.0312	225401.0312	611.75408936	570.31658936	570.31658936
2455309.7195100002	301578.1250	226856.1875	226856.1875	606.72442627	568.31738281	568.31738281
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2455309.7210599999	299091.5312	222038.5625	222038.5625	614.38476562	567.26696777	567.26696777
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2455309.7233600002	233642.7969	173223.5938	173223.5938	590.94140625	561.03735352	561.03735352
2455309.7240900001	29397.7363	23757.6895	23757.6895	578.41625977	571.55462646	571.55462646
2455309.7249300000	260491.3750	192962.6094	192962.6094	598.20825195	562.44171143	562.44171143
2455309.7256900002	282388.0312	211242.3906	211242.3906	606.35479736	562.99542236	562.99542236
2455309.7265300001	189798.5312	141044.3438	141044.3438	584.49322510	558.99707031	558.99707031
2455309.7272600001	218880.6250	160811.2812	160811.2812	596.90582275	555.82354736	555.82354736
2455309.7280799998	193741.8281	143278.8438	143278.8438	583.86157227	549.92956543	549.92956543
2455309.7289499999	290068.0312	215466.1094	215466.1094	613.50860596	580.00250244	580.00250244
2455309.7297100001	292867.7500	217173.3906	217173.3906	614.10821533	567.10754395	567.10754395
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2455309.7314399998	199900.3750	141638.3906	141638.3906	580.44183350	543.10552979	543.10552979
2455309.7321799998	65954.6484	46033.3594	46033.3594	554.93743896	538.49841309	538.49841309
2455309.7330200002	90091.3281	64659.0703	64659.0703	570.54071045	548.53515625	548.53515625
2455309.7337600002	NaN	−1073.1212	−1073.1212	NaN	731.82720947	731.82720947
2455309.7346199998	99.0000	99.0000	99.0000	NaN	731.82720947	731.82720947
2455309.7353500002	174158.7500	135104.2812	135104.2812	562.01812744	541.25250244	541.25250244
2455309.7361099999	310500.1250	228899.9844	228899.9844	625.00158691	576.52618408	576.52618408
2455309.7368500000	296734.1875	222916.7188	222916.7188	614.68334961	569.92974854	569.92974854
2455309.7376000001	313204.1562	231880.6094	231880.6094	616.31231689	570.31646729	570.31646729
2455309.7383599998	309759.8438	228940.8594	228940.8594	611.91583252	570.69506836	570.69506836
2455309.7391400002	282769.0938	209276.0469	209276.0469	599.66137695	550.71081543	550.71081543
2455309.7398799998	321503.7500	239595.0312	239595.0312	610.35485840	565.13531494	565.13531494
2455309.7406400000	315256.8438	235986.4531	235986.4531	618.14697266	571.58032227	571.58032227
2455309.7413800000	322531.1250	237545.6094	237545.6094	608.17218018	564.42272949	564.42272949
2455309.7421200001	205215.2656	NaN	NaN	560.83355713	NaN	NaN
2455309.7428799998	320676.7812	236455.6094	236455.6094	613.62835693	564.50769043	564.50769043
2455309.7436099998	319096.2812	235852.3281	235852.3281	612.62188721	560.67956543	560.67956543
2455309.7445399999	315674.1250	233443.9375	233443.9375	616.92559814	564.54681396	564.54681396
2455309.7452699998	308981.7500	227438.5156	227438.5156	611.08917236	564.82391357	564.82391357
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HAT-P-13_2010-04-26_initial.flux.abridged.dat

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2455316.6008000001	598388.1875	531479.8750	531479.8750	664.58160400	627.69372559	627.69372559
2455316.6013099998	604756.2500	535054.4375	535054.4375	665.43762207	628.21228027	628.21228027
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2455316.6028000000	603569.6250	535660.7500	535660.7500	664.38665771	629.76531982	629.76531982
2455316.6034400002	606118.6875	536062.3125	536062.3125	665.85485840	629.90490723	629.90490723
2455316.6039399998	607010.0000	537505.8750	537505.8750	665.27618408	630.80993652	630.80993652
2455316.6044299998	606663.0000	538379.0625	538379.0625	665.77642822	631.61877441	631.61877441
2455316.6049299999	605313.6875	537036.9375	537036.9375	664.81066895	629.15887451	629.15887451
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2455316.6059500002	603240.7500	535299.2500	535299.2500	666.86499023	629.67633057	629.67633057
2455316.6064499998	603858.5625	535187.6875	535187.6875	664.50244141	629.18463135	629.18463135
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2455316.6121899998	598571.3125	528265.8125	528265.8125	662.69122314	626.09960938	626.09960938
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TrES-2_2008-10-31_initial.flux.abridged.dat

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2454770.6514200000 720857.1875 310818.7188 NaN 830.48455811 628.91809082 NaN
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TrES-2_2010-08-18_initial.flux.abridged.dat

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