

Detecting Extrasolar Planets

Julia Kamenetzky
Cornell College PHY312, February 2008, Professor Derin Sherman
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I. Introduction

An "extrasolar planet" (or exoplanet) is a planet orbiting a star other than our own. With a moderately sized telescope and commercially available CCD camera, it is possible to detect the periodic 1% drop in a star's brightness caused by a planet crossing in front of its star within our line of sight. I began my project intending to observe such a transit and roughly model some of the planet's size and orbital parameters. I worked with the [Cedar Amateur Astronomers](#) at the [Palisades-Dows Observatory](#), just south of Mount Vernon, IA. On Saturday, February 23rd, I attempted the first observing run for the transit of XO-3.

II. Extrasolar Planet Transits

There are many different methods that can be used to detect extrasolar planets; some work better than others, depending on the particular star system. The transit method is only applicable when the planet's orbital plane is aligned with our line of sight, so we can see the planet crossing in front of the star. The planet thus blocks some of the star's light, and a measurement of light output vs. time shows a noticeable "dip" during the transit. The moment the planet begins to cross the star is known as ingress, and the moment it finishes crossing the star is egress.

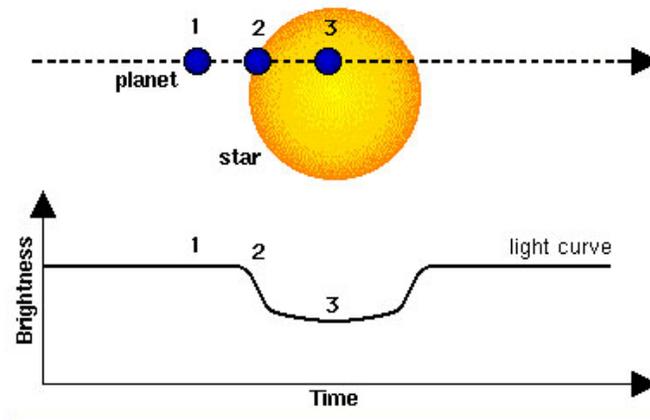


Figure 1 - Exoplanet Transit Diagram
Centre National d'Études Spatiales (CNES)

The key is that these transits occur regularly, at intervals equal to the period of the planet's orbit. Clearly, this type of method is most applicable to very large planets with very small orbits. Irregularities in the timing may indicate the gravitational influence of another planet; see the [recently released alert from the AAVSO](#) regarding one such transit known as GJ 436.

The "brightness" axis on the above chart is measured in units of magnitude. The Greek astronomer Hipparchus originally catalogued stars from 1 to 6, with 1 being the brightest and 6 being the faintest. Astronomers have continued to use this system, though by quantifiably defining the magnitude differences and expanding the range to include the faint objects now visible with telescopes. Magnitude is logarithmic, not linear: a magnitude 1 star is about 2.5 times brighter than one of magnitude 2, which is 2.5 times brighter than one of magnitude 3, and so on. Many of the so-called "bright transiting exoplanets" have magnitudes from about 8 to 12. Again, lower magnitudes indicate brighter objects, so on light curves that show a dip in brightness like the one above, the values on the magnitude axis appear reversed.

III. Preparing to Observe a Transit

A. Select a Transit

I have used the [BTE_Ephem.xls spreadsheet](#) created by Bruce Gary, author of [Exoplanet Observing for Amateurs](#). After inputting my observing coordinates (approximately 42 degrees North, 91.5 degrees West), and the year and month in which I would like to observe, the other spreadsheet pages automatically calculated the predicted transit times for over 20 bright known transiting exoplanets. The times show up for transits which meet a minimum elevation criterion for the

observing site (generally, 20 degrees for mid-transit).

	A	B	C	D	E	F	G	H	I	J	
1	XO-2	Transit Times					57.30	6.2571	6.0		
2		Tc [HJD]	4147.74902	day				2008	6.3		
3		P	2.615857	hr				0.3	UT (darkness)		
4		L	2.7	hr				12.2	UT (darkness)		
5		RA	7.80	deg			383	18	1.6	Season	
6		Dec	50.2	desired JD				DOY		20	
7			4495				UT	UT	UT	EL	
8	Try	132	HJD mid	Year	Mo	Day	ing	mid	egr	mid	
9											
10	XO-2	132	4493.042	2008	1	27.542				19	
11	XO-2	133	4495.6580	2008	1	30.158	2.330	3.680	5.030	72	
12	XO-2	134	4498.2739	2008	2	1.774				4	
13	XO-2	135	4500.890	2008	2	4.390	7.90	9.25	10.60	45	
14	XO-2	136	4503.506	2008	2	7.006				43	
15	XO-2	137	4506.121	2008	2	9.621				5	
16	XO-2	138	4508.737	2008	2	12.237	4.25	5.60	6.95	75	
17	XO-2	139	4511.353	2008	2	14.853				17	
18	XO-2	140	4513.969	2008	2	17.469	9.81	11.16	12.51	22	

Figure 2 - Example of BTE_Ephem Spreadsheet

Transit times are displayed in Universal Time (also known as Greenwich Mean Time). Central Standard Time is UT – 6. Close attention needs to be paid to the actual date of the transit. For example, the transit boxed in red above appears to be on February 12th. However, the UT time for ingress is 4.25, which in central time (and converted to hours:minutes) is 10:15PM, which would actually make it on the night of February 11th. I found it useful to take note of the different transits available for the month, and then write them in a calendar, in Central Time, to make planning easier.

B. Check the Weather

For weather conditions, I used the [NOAA Graphical Forecast](#), which displays predicted conditions for temperature, weather, precipitation, wind, sky cover, and more. Of course, predictions do change frequently and they may not be right anyway.

C. Predict Air Mass

Air Mass is a measure of “how much” atmosphere is being looked through when observing a star. This varies as approximately $\sec(z)$, where “z” is the angle as measured from the zenith (straight up). At zenith, air mass = 1. At 60°, air mass = 2, and at 70°, air mass = 3. The higher the target in the sky, the lower the air mass, and the better the results.

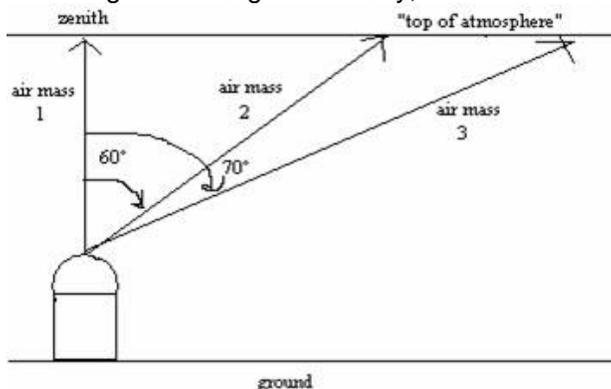


Figure 3 - Air Mass Diagram (not to scale)

I use the [Hourly Airmass Table](#) by Brian Casey to estimate air mass for a target at each hour of the night. This is helpful if there are multiple transit options for an evening; it is generally best to go for the one with air masses closest to 1.

D. Orient yourself with a planetarium program

I used the open source planetarium software [Stellarium](#) to determine roughly where my target star will be as the night progresses. This is also useful to find nearby constellations and bright stars which will be used to set the coordinates of the telescope.

E. Print Finder Charts

A finder chart is literally a chart which is used to find the target object. It is one thing to point the telescope at the predicted

coordinates; it is another to determine which of the stars in the field of view is the target. The [AAVSO Variable Star Plotter](#) is a good resource. This plotter also contains photometric information on comparison stars in some parts of the night sky; however, such data was unavailable for the particular targets that I had researched.

IV. Equipment

A. Equipment Summary

Table 1 - Equipment

Telescope	Meade 16" LX200
Focal Ratio	f/5 (used focal reducer)
Aperture	16" = 406.4 mm
Focal length	Approx. 2032 mm
CCD Camera	SBIG ST-9E
Pixel size	20x20 microns
Array size	512x512 pixels
Field of View	Approx. 17x17 arcmin
Software	MaxIm DL, free trial
Computer	HP Pavilion zv5160us

There are two pieces of equipment that would be ideal for this project, but that were not included in my setup. The first is a set of filters; without them, I could only observe unfiltered light, making transits that are prominent at specific wavelengths hard to detect. Also, different wavelengths are affected differently by increasing air mass, so stars of different colors are hard to use as comparisons without filtering. The second is an auto-guider for the CCD, which would keep the target stars stationary in the field of view of the camera. Upon further research, it seems that the ST-9E does in fact have guiding capabilities, but I had not been introduced to this ability at the time. Relying only on the telescope's tracking introduced some error, as explained in the next section.

B. Observing Procedure

The procedure described below applies specifically to my work at Palisades-Dows; other setups likely have slightly different procedures. An evening of observing starts before sundown by setting up the equipment, including: powering up the dome, telescope, CCD camera, and laptop, connecting the CCD to the laptop and beginning its cool down. The CCD needs to be cooled in order to reduce thermal noise; on my observing night, I set the CCD to -25.0° C.

Right around sunset, "twilight flats" need to be made for later image calibration. A "flat field" is just a CCD exposure of a uniformly illuminated field; such a field is roughly approximated by the twilight sky. The scope should be positioned approximately 13° from the zenith, pointing east (opposite the sunset). The timeframe for quality flats is incredibly short, as there are two major considerations: full well capacity and exposure time. Full well capacity refers to the maximum number of counts (65,535) one pixel can contain (2.8 electrons = 1 count for the ST-9E). Near saturation, the relationship between electrons and counts is no longer linear (it is possible to measure the linearity of a particular CCD camera to determine how high a pixel can be filled). However, if the count is too low, the field has a low signal/noise ratio. Exposure time is also a consideration, because the times need to be long enough such that the time it takes the shutter to move across the image does not impact the total exposure time. The right type of sky is only available for a few minutes, making twilight flats quite an art. We found that at the right time of twilight, the CCD camera was already able to detect some stars. By turning off the telescope's tracking, the stars would quickly move out of the picture. Median combining many different flat frames removes the various stars that appear.

Once it's dark, the next step is to set the telescope's coordinates using a known, bright star. From there, it's possible to use the electronic control pad to slew the telescope to your target location. Note: due to precession, coordinates change over time. Many coordinates are given in terms of the year 2000, but this particular telescope system used updated coordinates for the current epoch (for this project, 2008.15). I had to be sure to [convert coordinates](#) ahead of time. After using the finder charts to locate which of the stars in the camera's field of view, I centered the image so that the target and any particularly relevant comparison stars were included.

The proper exposure time for the camera is mainly limited by the brightest star in the field of view. The exposure time needs to be short enough that the brightest star does not saturate the pixels, but long enough to achieve a high signal to noise ratio. After determining the proper exposure time, I set up a sequence in MaxIm DL specifying the exposure time, delay between exposures, and number of exposures to take. I also had to take into account the download time of each image, which was about 10 seconds using a parallel port connection (newer USB connections take much less time, maybe

about 2 seconds). Then I went inside to warm up!

My particular setup required checking the equipment every once in a while, for a few reasons. First, the dome is not automated, so I had to move it to catch up with the telescope. Second, during our first run of the equipment we found that the tracking of the telescope (with no auto-guiding) was not particularly accurate, and so the telescope needed to be manually readjusted to avoid losing the target and comparison stars. [Click here for an animation](#) showing the tracking issues over approximately a 2-hour timeframe. The telescope also began to lose focus, as can somewhat be seen in the animation as well.

At some point in the night, dark and bias frames should also be taken for later image calibration. "Dark" frames measure the amount of thermal noise collected throughout the exposure time, therefore they must be taken at the same temperature as the images, and also for the same time – the only difference is that the shutter remains closed. Bias frames measure the pre-charge bias, or number of counts, that remain on the camera as measured by the shortest exposure time possible. Like twilight frames, it's best to take multiple bias and darks and median combine them. Median combining is less effective at reducing noise than averaging, but is preferable to remove irregularities like cosmic rays or, in the case of flat fields, unintended stars.

V. Photometry

A. Image Calibration

The number of counts in each pixel is determined by the following:

$$\text{Measured Intensity} = \text{Pre-charge Bias} + \text{Dark thermal noise} + (\text{Actual Intensity})(\text{Response Factor of Pixel})$$

To mathematically extract out the actual object's intensity...

$$\text{Actual Intensity} = [\text{Measured Intensity} - \{\text{Pre-charge Bias} + \text{Dark thermal noise}\}] / (\text{Response Factor of Pixel})$$

Therefore, the raw images collected from the CCD camera need to be calibrated, hence the need for bias, dark, and flat frames described in the observing procedure. Generally, multiple calibration frames are collected and combined to make master frames. MaxIm DL makes this calibration fairly simple. The image below illustrates the mathematical equation above with real images (note: the pre-charge bias is included in the dark frame, hence why it does not explicitly appear in the numerator of the fraction).

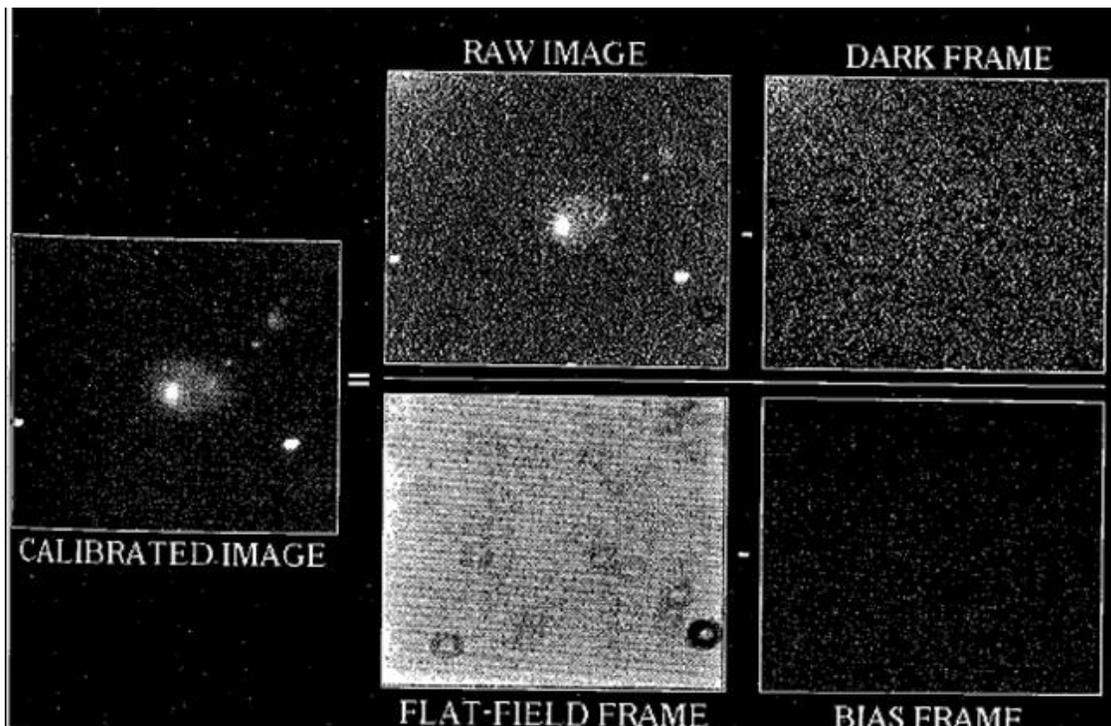


Figure 4 - Image Calibration

Martinez, A Practical Guide to CCD Astronomy

B. Light Curve

Photometry with MaxIm DL is fairly straightforward. After calibration, it's best to have MaxIm automatically align all of the

images from the night, and then begin photometry by marking the object and check stars with the cursor. I also included a false “reference star” (superimposed on the top left corner of the image) to check the stability of my other check stars. MaxIm outputs the magnitude of each star (by adding up the counts for all pixels included in the small aperture) reported relative to the reference star.

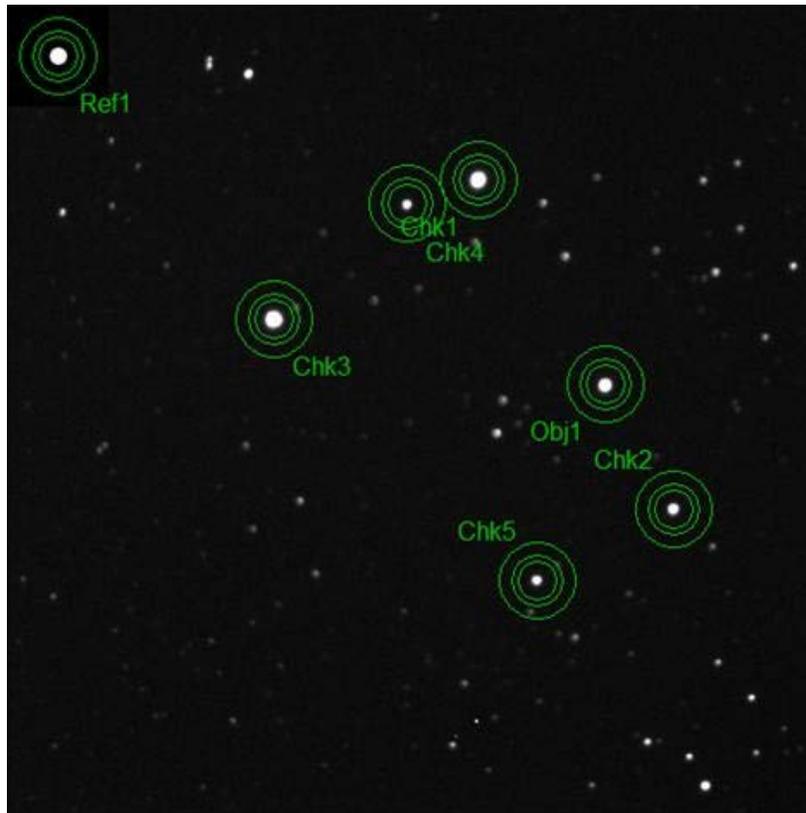


Figure 5 - Photometry in MaxIm DL

The aperture size for photometry is customizable. Too small of an aperture won't collect all of the flux, and too large of an aperture introduces additional noise. A size about 3 times the full-width half maximum of the intended stars is a good starting point. The apertures above appear a bit large, in order to accommodate for the less focused images that occurred later.

From there, the process to convert MaxIm's data to produce a meaningful light curve is fairly intensive. I made a spreadsheet largely based on [Bruce Gary's LCx Template](#), with mostly aesthetic changes. Key steps in the process include: calculating air mass, determining the extent of and correcting for atmospheric extinction, analyzing check stars for problems, quantifying other losses due to clouds or other sources, removing outlying data, and calculating running averages and group medians. It is also possible to model the resulting plot, which can provide estimates of the planet's size. Below is an excellent example light curve from the [Amateur Exoplanet Archive](#).

XO-2, 2008.02.01, C-band, Bart Staels (Belgium, 11-inch)

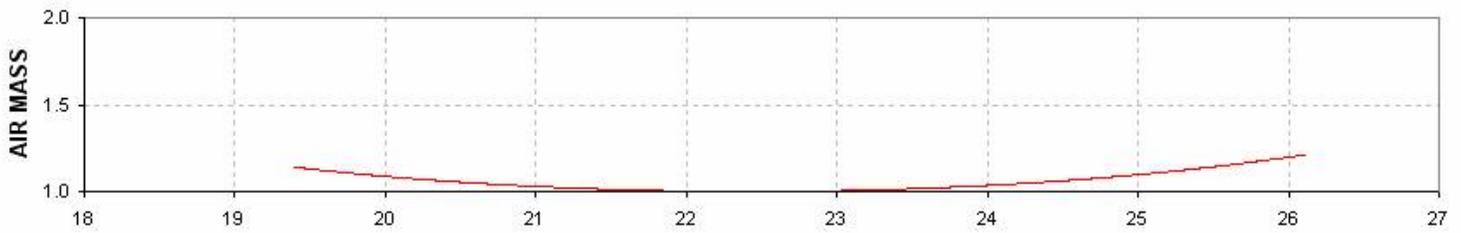
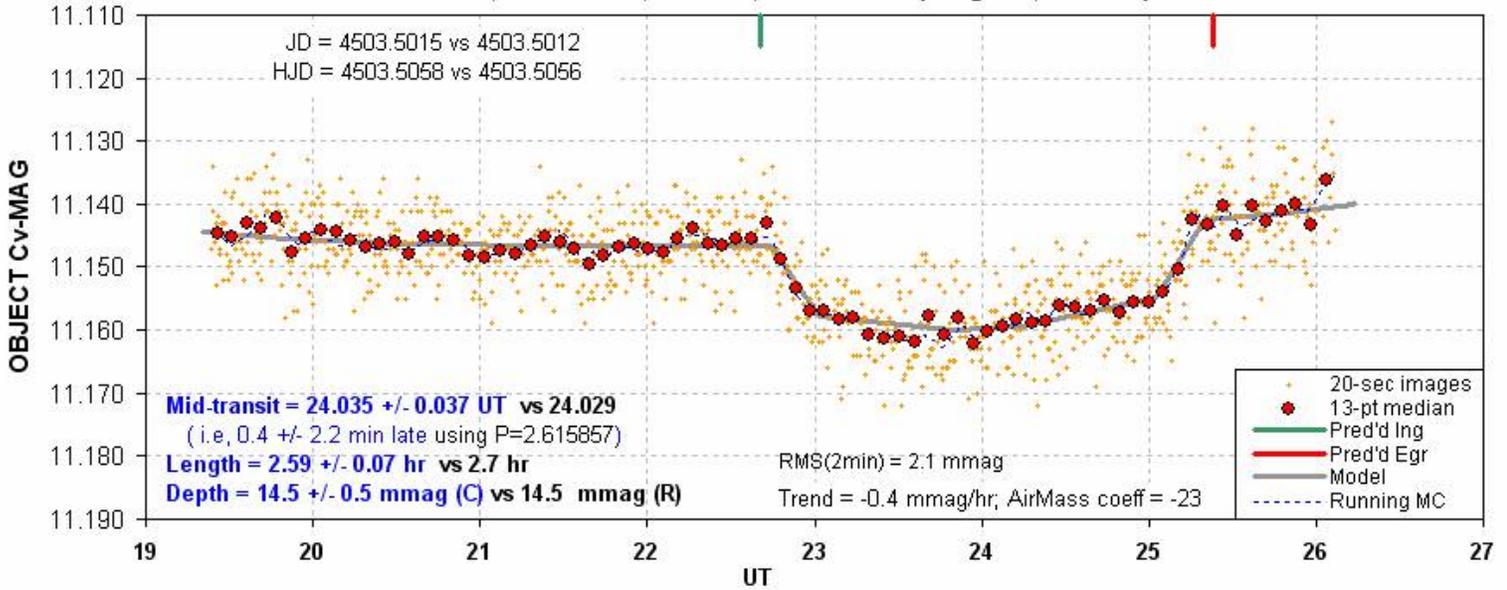


Figure 6 - Light Curve Example

VI. Results

I unfortunately only had one chance this block to observe a transit, that of XO-3 on Saturday, February 23rd. Because this was the first run, I was unsure what I would encounter and how to best adapt. Bad tracking caused error by continually changing which pixels were measuring which stars (only a theoretically perfect flat frame could fix such a problem). As a result of some manual changes' effects on saturation, I changed the exposure time midway through the observations, and then had to change it back again. This prompted me to have to analyze three different sets of data and then try to reconcile them as best as possible. Because of these and other mistakes, I would take the following plot with a grain of salt. This was merely a first attempt, and a great learning experience, but not a definitively successful observation of a transit.

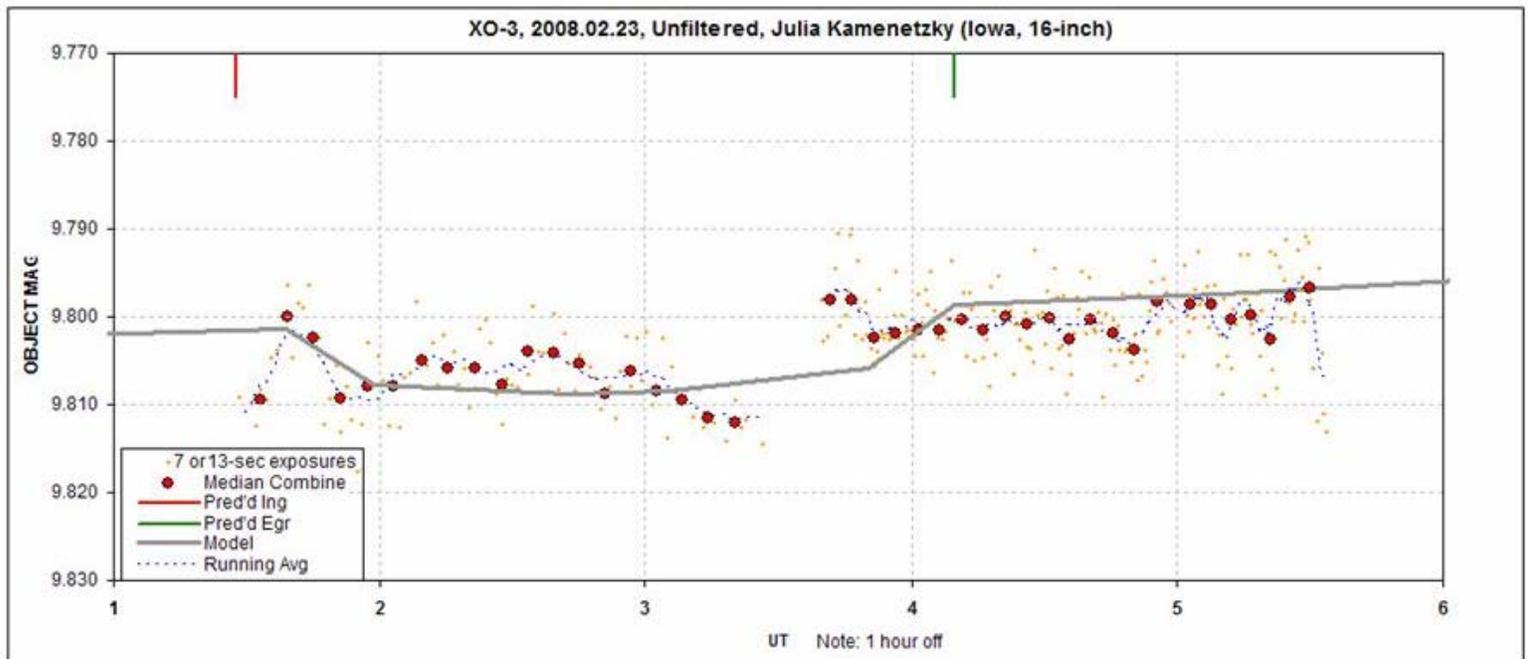


Figure 7 - First Attempt at a Light Curve

The already existing equipment problems were compounded by the incredibly shallow transit of XO-3 (8.5 mmag in the R-band, and I was observing unfiltered). Some transits are as deep as 25 mmag, and would probably be easier to detect with this setup.

VII. Future Plans

Although I was unable to successfully observe an exoplanet transit this February, I plan on continuing this project over the next couple of months. First, I hope to conduct more observations at Pal-Dows in April, when the weather is a bit milder and I am not enrolled in any other course. I hope to investigate the auto-guiding capabilities of the ST-9E, take more frequent exposures, achieve better focus, and hopefully observe with filters. Also, Professor Mutel at the University of Iowa has expressed interest in my project, opening the possibility of using the Rigel robotic telescope, located in Arizona, for the detection of exoplanet transits. The telescope is currently joining the [Skynet](#) array of telescopes, and once the transition is complete, it will be capable of the milli-magnitude precision required for this type of project.

VIII. Radial Velocities and Systemic

In addition to the study of transiting extrasolar planets, I also did a bit of work with radial velocity data as part of the [Systemic](#) project. Radial velocity focuses on the component of a star's velocity either towards or away from us, measurable by the Doppler Effect. Changes in radial velocity indicate the movement of a star as influenced by the gravity of surrounding planets; such data is useful for confirming the discoveries made by the transit method, for example.

In this online project, any participant can download the Systemic console, fit orbital parameters of planets to radial velocity data (either real data collected over time, or simulated data), and upload their fit to the project backend to share with other users. For each planet (and multiple ones may be selected), users can change the orbital period, mass, eccentricity, and location of periastron. A few of my fits are uploaded under the username jkamen (an account with the Systemic backend is required to view these files). This project is quite accessible to anyone with a computer, and I recommend viewing the tutorials for using the console.

IX. Resources

A. Extrasolar Planets and CCD Techniques

- Exoplanet Observing for Amateurs (free book): http://brucegary.net/book_EOA/x.htm
- Martinez, Patrick and Klotz, Alain. A Practical Guide to CCD Astronomy. Cambridge University Press, 1998.
- Transitsearch, keeps a list of "candidate" transits to investigate: <http://www.transitsearch.org/>
- The Extrasolar Planet Encyclopedia: <http://exoplanet.eu/>
- Amateur Exoplanet Archive: <http://brucegary.net/AXA/x.htm>
- Systemic, radial velocity fitting collaboration: <http://www.oklo.org>

- CCD Photometry, by E. Norman Walker: http://www.britastro.org/vss/ccd_photometry.htm

A. Helpful Astronomy Links

- Cedar Amateur Astronomers: <http://www.cedar-astronomers.org/>
- MaxIm DL Software: http://www.cyanogen.com/products/maxim_main.htm
- NASA HEASARC Coordinate Converter: <http://heasarc.nasa.gov/cgi-bin/Tools/convcoord/convcoord.pl>
- NASA LAMBDA Coordinate Epoch Converter: http://lambda.gsfc.nasa.gov/toolbox/tb_coordconv.cfm
- Stellarium, free open source planetarium software: <http://www.stellarium.org/>
- Hourly Airmass Table: <http://www.briancasey.org/artifacts/astro/airmass.cgi>
- AAVSO Variable Star Plotter (finder charts): <http://www.aavso.org/observing/charts/vsp/>

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