# Search for Transiting Planets in Open Clusters Using Millimagnitude Photometry

**Matt Dahl**
University of Denver – Department of Physics and Astronomy
Undergraduate Student

Advisor: Dr. Robert E. Stencel
University of Denver – Department of Physics and Astronomy
Associate Professor and Director of Observatories
&
Steven Howell, WIYN Telescope & National Optical Astronomy Observatories

## Abstract

In the summer of 2005, we began a search for transiting planets in open clusters, specifically NGC 6791. Using a 0.7 m telescope, we took data on nights during the several months of 2005 on this particular cluster along with NGC 6822. This paper will present the results of those observations regarding the planetary transits, as well as some other data that resulted from these observations.

## 1. Introduction

As the number of known extra-solar planets increases [see http://exoplanets.org ], so does the expectation that some planets should occasionally eclipse their parent stars in a "transit" event. Modern digital detectors used on astronomical telescopes have sufficient precision to measure these events [ http://www.transitsearch.org and see Figure 1], even if only milli-magnitudes in eclipse depth (Howell et al. 1999). A magnitude is an astronomical unit representing factors of 2.5 change in brightness. A millimagnitude, therefore, represents a tenth of a percent of that change in brightness, just as a millimeter would be a tenth of a percent in the full length on a meterstick. The suggestion for this project was presented to us by Dr. Steve Howell of Kitt Peak National Observatory in 2005 April. A similar project, PISCES [Planets in Stellar Clusters Exensive Search] was started by Mochejska, et al. (2002 and later papers).

Although over one hundred planets are detected around nearby stars using spectroscopic means, very few are oriented to exhibit transits. By observing clusters, one can monitor large numbers of stars in search of elusive transit events, depending on the likelihood of planets being present in systems with the characteristics of open star clusters. Adopting their methods of data reduction and analysis, in the summer of 2005, we began a search for transiting planets in open clusters, specifically NGC 6791, and to a lesser extent in NGC 6822. As described in Mochejska, et al., NGC 6791 is "a very old, populous, metal-rich cluster", making it an ideal target to search for transiting planets, even if it lies 3,750 parsecs distant. We direct the reader to paper number one by Mochejska, et al. [2002] for detailed reasoning behind and methodology for searching in metal-rich clusters. Along with the planetary transit search, we were able to confirm variability in two variables, V5 and V6 mentioned in the list of variables discovered by Mochejska, et al. [2002]. For this paper, section 2 describes the observations, section 3 discusses the planetary transit requirements, section 4 explains the data reduction methods used, section 5 discusses the variables analyzed, and section 6 is conclusions and acknowledgements.

**2. Observations**

Over the course of several nights during 2005 summer, NGC 6791 was observed using DU's Meyer-Womble twin 28.5 inch (0.7 m) f/21 telescopes [Stencel 1999]. Two additional nights include data from this cluster, but the cluster is not placed correctly, so the data were not used. Typically, an equal number of images were taken in Bessel [confirm] R-Band as were in V-Band. The images were obtained with an ST-7

CCD camera cooled to -30C.  Because of the nature of the telescope and the camera, even with a 3x focal reducer, the field of view was still only 3 x 5 arcminutes [confirm]. Because of this, we were unable to fit the entire cluster in the field of view.  Therefore, we felt it necessary to make sure the images taken each night were of the same area in the cluster, so we identified that all images would be taken on the Northern edge of the cluster, as identified in figure 2.0.

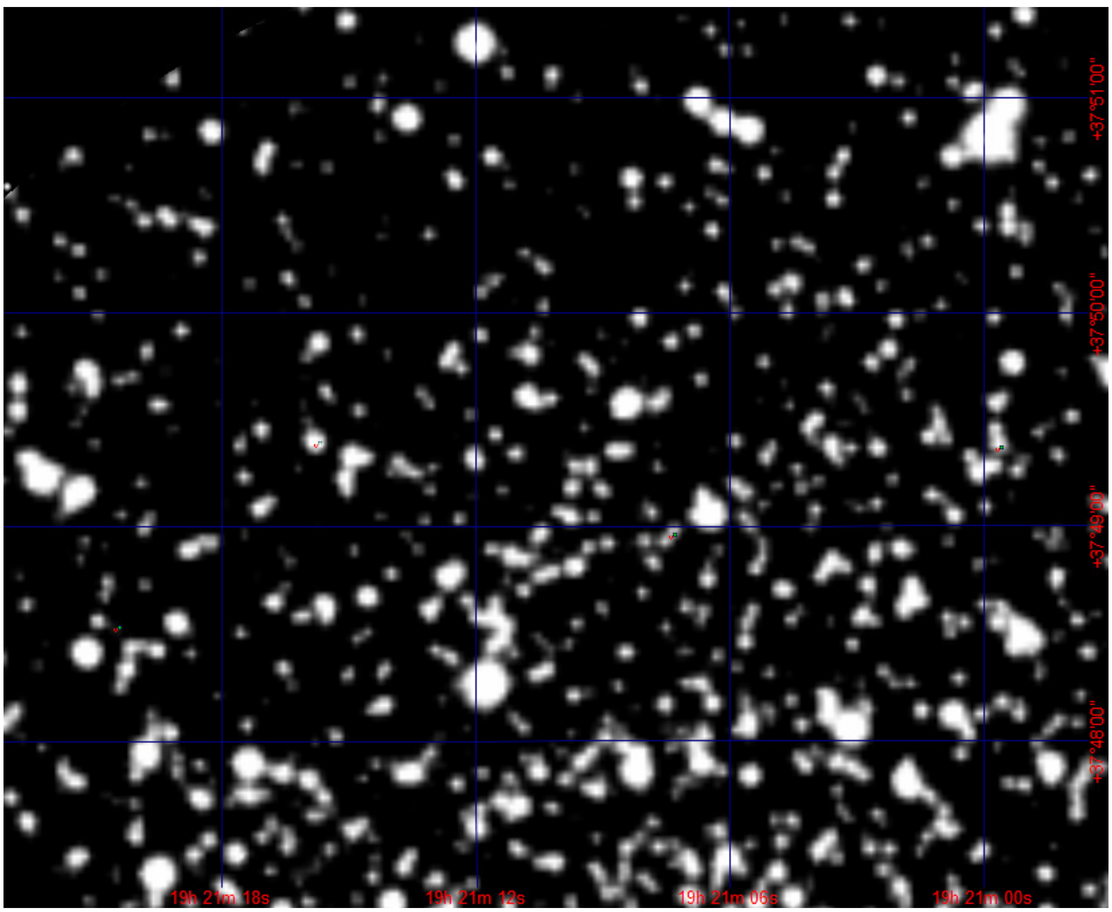



Figure 2.0: The approximate field of view of the Meyer-Womble scope combined with the ST-7 CCD.  The characteristic "butterfly" pattern in the lower right was used as a mark to make sure the images were all of the same area in the cluster.  This frame is centered at RA 19h 21m 07s DEC +37d 49' 20".  Courtesy: <u>theSky6</u> by Software Bisque.

All together, there were 232 R-band images and 225 V-Band images, for a total for 457 images. Most of these images were 60 seconds in exposure length. Table 2.1 displays a list of the images taken over the course of the observing sessions.

Table 2.1: This table displays the list of data taken during the course of this study. Note that there is no account for data that portrayed the wrong area of the cluster, thus rendering it unusable in this study. Also note that the date displayed here is in local (MDT) time.

| Date | Object | Exposure Length | Frame Number | Filter |
|---|---|---|---|---|
| 6/8/2005 | ngc 6791 | 60 sec | 2…18 | r-band |
| 6/8/2005 | ngc 6791 | 60 sec | 19…33 | v-band |
| 6/8/2005 | ngc 6811 | 60 sec | 1…6 | v-band |
| 6/8/2005 | ngc 6811 | 60 sec | 7…11 | r-band |
| 6/15/2005 | ngc 6791 | 60 sec | 0…11 | r-band |
| 6/15/2005 | ngc 6791 | 60 sec | 13…24 | v-band |
| 6/21/2005 | ngc 6791 | 30 sec | 1…11 | r-band |
| 6/21/2005 | ngc 6791 | 30 sec | 12…24 | v-band |
| 6/28/2005 | ngc 6791 | 60 sec | 16…36 | r-band |
| 6/28/2005 | ngc 6791 | 60 sec | 37…57 | v-band |
| 6/28/2005 | ngc 6811 | 60 sec | 58…62 | v-band |
| 6/28/2005 | ngc 6811 | 60 sec | 63…66 | r-band |
| 6/29/2005 | ngc 6791 | 60 sec | 68…79 | r-band |
| 6/29/2005 | ngc 6791 | 60 sec | 80…91 | v-band |
| 7/28/2005 | ngc 6791 | 60 sec | 84…94 | r-band |
| 7/28/2005 | ngc 6791 | 60 sec | 95…104 | v-band |
| 7/28/2005 | ngc 6791 | 60 sec | 105…114 | r-band |
| 7/28/2005 | ngc 6791 | 60 sec | 115…124 | v-band |
| 7/28/2005 | ngc 6791 | 60 sec | 180…191 | r-band |
| 7/28/2005 | ngc 6791 | 60 sec | 192…201 | v-band |
| 8/2/2005 | ngc 6791 | 60 sec | 1…1 | r-band |
| 8/23/2005 | ngc 6791 | 60 sec | 44…54 | r-band |
| 8/23/2005 | ngc 6791 | 60 sec | 55…65 | v-band |
| 8/24/2005 | ngc 6791 | 60 sec | 2…11 & 71…82 | r-band |
| 8/24/2005 | ngc 6791 | 60 sec | 12…23 & 83…92 | v-band |
| 8/29/2005 | ngc 6791 | 60 sec | 11…22 & 58…70 & 110…115 | r-band |
| 8/29/2005 | ngc 6791 | 60 sec | 1…10 & 71…83 & 118...123 | v-band |
| 8/30/2005 | ngc 6791 | 60 sec | 6,8…21 & 35…47 & 100…104 | r-band |
| 8/30/2005 | ngc 6791 | 60 sec | 22…34 & 48…60 & 90…99 | v-band |
| 8/31/2005 | ngc 6791 | 60 sec | 2…11 & 22…31 | r-band |
| 8/31/2005 | ngc 6791 | 60 sec | 12…17 & 32…38 & 42, 43 | v-band |

### 3. How to Detect Transiting Planets

In any experiment, it is important to precisely define what is being measured, and why. In our case, it was necessary to determine how much of a magnitude change we could expect to see in the event we caught a transit event. This is determined by a simple calculation, using the relationship between magnitude and brightness:

$$\Delta m = -2.5\log(\frac{B_1}{B_2})$$

Where $\Delta m =$ change in magnitude and $(\frac{B_1}{B_2}) =$ the brightness ratio of the parent star, representing eclipsed brightness to standard brightness. Brightness can easily be expressed as

$$B = \text{Luminosity} = \text{Watts} = \text{Joules/sec}$$

And since brightness can be expressed as luminosity, the variable B can be related to the variable L, which has an equation we can use, with spherical approximation:

$$L = 4\pi r^2 \sigma T^4$$

Where $\sigma =$ Stephan/Boltzmann constant and T = temperature of the object, in this case, the star. Therefore, if we wanted to detect a planet that was at least Jupiter-sized (Jupiter is ~10% of the radius of the sun, making it ~1% of the area of the sun, so we would be observing a 1% coverage of the parent star for stars similar in size to the sun), we would expect the change in magnitude to look like this

$$\Delta m = -2.5\log(\frac{(.99)4\pi r^2 \sigma T^4}{4\pi r^2 \sigma T^4})$$

which means

$$\Delta m = -2.5\log(.99) = .011$$

So to detect a Jupiter-sized planet transiting a Sun-sized star, the expected change in magnitude of the star would be .011 magnitude, or 11 milli-mags. It is also possible to reverse this equation and determine the size of the planet in relation to its parent star from already known transits, such as the one in figure 3.0.

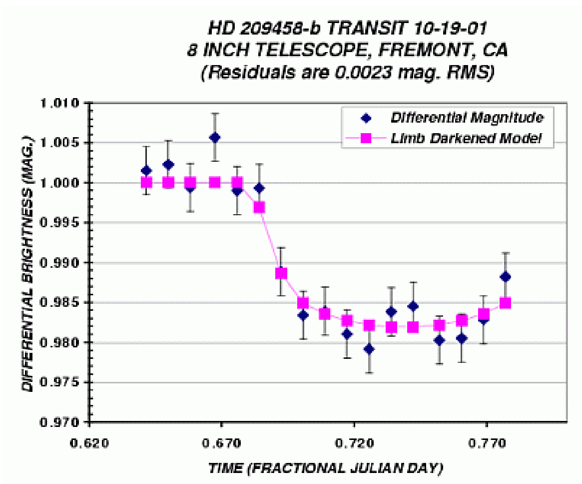



Figure 3.0: A record of the known transit around star HD 209458-b. Courtesy: www.transitsearch.org [confirm]

In this instance, there is an 18 millimag drop during the course of the transit event of star HD 209458-b. That being the case, we reverse the above equation and solve for the variable "x" to determine how much of the planet is eclipsed.

Applying these numbers, yields

$$.018 = -2.5\log\left(\frac{(x)4\pi r^2\sigma T^4}{4\pi r^2\sigma T^4}\right)$$

Therefore

$$-.0072 = \log(x)$$

So, $x = .984$ meaning slightly more than 98 % of the star's surface remains visible, which yields a ~2% coverage. Therefore, the planet that is eclipsing star HD 209458 is ~2% the area of its parent star.

## 3.1 Timescales of Transit Events

An important fact to keep in mind while looking for these transit events is that they do not occur in a matter of seconds, but rather in a matter of hours. Keeping this in mind, we had to spread our observations over a course of several hours during the night if we were going to be able to catch a transit event and recognize it as such.

Mathematically, we can address this issue and get a vague idea of the time it takes for a planet at "infinite" distance to transit its parent star. If we assume that the planet resides at a distance similar to that of Mercury, and therefore has a similar period, we can measure the time of transit using the following equation:

$$V = \frac{2\pi a}{P}$$

Where $a$ is equal to the semi-major axis of the orbit and $P$ is equal to the period of the planet's orbit. Therefore, $V$ is equal to:

$$V = \frac{2\pi(50000000km)}{2073600s}$$

$$V \approx 151km/s$$

Therefore, taking the average surface area of a sun-like star, and dividing by the velocity calculated above, we can determine the approximate time scale:

$$T = \frac{700000km}{151km/s} \approx 4635s \approx 1.28hrs$$

3.2 Challenges to achieving millimag precision

As seen above, in order to detect the transiting planets, it is important to be very precise with our measurements if we are to detect a distant planetary transit. It is important to note, however, that what we are searching for is photometric *precision*, not *accuracy*. This means that we are only concerned with the "internal uncertainties in the light curve . . . and not the absolute calibration to a standard photometric system" (Howell et al 1999). In order to achieve this millimag precision, there are a few things one must be aware of. One of the most important is the condition of the CCD detector being used for measurement. The noisier the device, the more difficult it will be to achieve an accurate measurement of the characteristics of the stars. It is also necessary to take into account the Earth's atmosphere, certain color issues, and any other light "extinction" problems one may encounter (Howell 75). For example, i.e. clouds, low angle viewing, etc. can produce a frame that shows drops in star brightness when there really is no brightness change at all.

3.3 Kinds of stars present in the frame

An interesting point to consider when searching for possible transit events is to consider what kind of stars one is observing in the frame. The kind of stars present tells us something about where in the frame a transit is most likely (i.e. it is more probable to find planets around metal-rich K, G, and F main-sequence stars, like the sun, as opposed to M-dwarfs(Sozzetti 2005)).

To understand the stars we are observing, we must use an equation known as the Distance Modulus. This is an easily derived equation that relates distance with the brightness of the star. To derive this Distance Modulus, we must return to our magnitude equation that was used above and we must also understand that the brightness of the star is related to the inverse of the distance squared. Therefore, recall that

$$\Delta m \propto -2.5\log(B)$$
$$and$$
$$B = 1/d^2$$

More specifically for the magnitude equation, we should write it as

$$M - m = -2.5\log\left(\frac{B(d)}{B(10pc)}\right)$$

Where B(10pc) refers to the absolute brightness of the star at 10 parsecs. Understanding that the relationship between B(d) and B(10pc), when using the brightness-distance relationship given above is equal to the following

$$\frac{B(d)}{B(10pc)} = \frac{10pc^2}{d^2}$$

Therefore, we can say that

$$m(d) - M(10) = -2.5\log\left(\frac{10pc^2}{d^2}\right)$$
$$= -5\log\left(\frac{10}{d}\right)$$
$$= -5\log(10) + 5\log d$$
$$m(d) - M(10pc) = 5\log d - 5$$

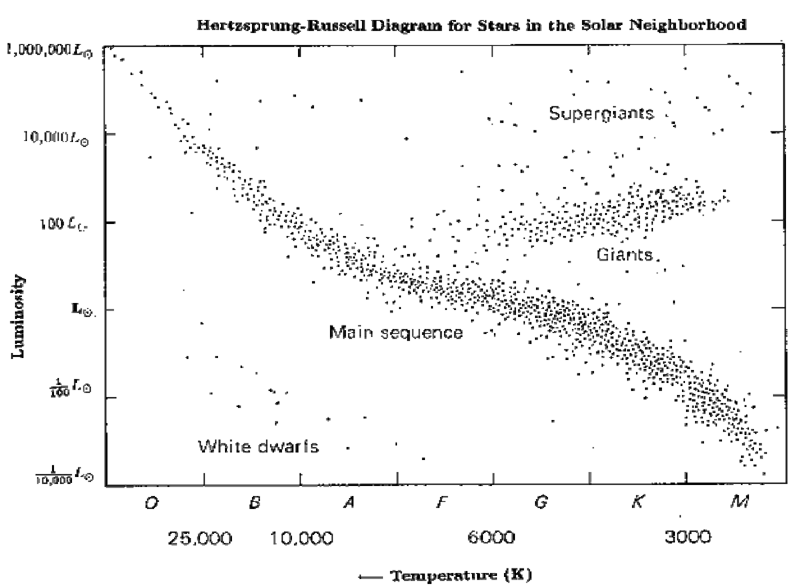
From the known distance of the observed cluster and the average magnitude of the brighter stars, we can calculate the absolute magnitude of the stars in the frame at a baseline of 10 parsecs,

$$
\begin{aligned}
12.5 - M(10pc) &= 5\log(3750pc) - 5 \\
12.5 - M(10pc) &= 5(3.574) - 5 \\
12.5 - M(10pc) &= 17.870 - 5 \\
12.5 - M(10pc) &= 12.87 \\
M(10pc) &= -.37
\end{aligned}
$$

And for our sun (for comparison)

$$
\begin{aligned}
-27 - M(10pc) &= 5\log(4.85 * 10^{-6} pc) - 5 \\
-27 - M(10pc) &= 5(-5.314) - 5 \\
-27 - M(10pc) &= -26.57 - 5 \\
-27 - M(10pc) &= -31.57 \\
M(10pc) &= 4.57
\end{aligned}
$$

So, the absolute magnitude at a baseline distance of 10 parsecs is -.37 for the stars in the frame and is 4.57 for the sun at that same distance. Comparing on a Hertzsprung-Russel diagram, we can determine that the brightest stars in the frame are main-sequence K stars and K giants.




H-R diagram representing luminosity versus temperature. Courtesy http://cassfos02.ucsd.edu/public/tutorial/HR.html.

## 4. Data Reduction

In order to find the transiting planets in this cluster, if any, we must reduce our data and analyze it. We attempted several methods to try and flag large changes in the stars' magnitudes in the field. The two main methods attempted were to 1) use Source Extractor and Excel and 2) program IDL to flag large changes in star magnitudes as reported by IDL.

### 4.1 Data Reduction

Before either program could be run, the data had to be reduced from its raw frame. This simple process involved taking the raw frame and subtracting a dark frame. From that a flat-field frame was also divided out after being dark subtracted. This produced a final reduced image. This CCD equation, can also be described by "Final Reduced Object Frame = (Raw Object Frame – Bias/Dark Frame)/(Flat-Field Frame – Dark Frame)" (Howell, 60).

### 4.2 Source Extractor/Excel method

In this method, we used the Source Extractor program to pull instrumental magnitudes from the frames and place them in an SRC file that could be read by Excel. Then the SRC files were each arranged by ascending magnitude and compared side by side. An average and a sigma (standard deviation) were created for each set of instrumental magnitudes. We discovered after careful inspection, however, that Source Extractor was unable to put the same stars in the same pixel values every time, even with the autoguider running during exposures. This meant that as each frame was analyzed, some stars that had comparable instrumental magnitudes may be switched in pixel value alignment, hence making our comparisons inaccurate. After a few days of trying to work this problem unsuccessfully, we decided to scrap it and move on with a different approach.

## 4.3 IDL Program Method

Using the program IDL (Interactive Data Language) courtesy of Research Systems, Incorporated we attempted to write a program that would read the SRC files from Source Extractor, then line up the pixel x,y values and then stack multiple frames together and compare instrumental magnitudes. Without much difficulty, we were able to create a program to read the SRC files. Creating a program that would create a data cube of the multiple data frames proved more difficult and is still in creation at the time of this publication. It is believed that once this part of the program is mastered, we will be able to say whether or not any of the observations included a transit event.

## 4.4 Stack and Compare Method

Perhaps the most successful of our data reduction thus far, the "stack and compare" method allowed for us to make the comparisons we needed. This method involved brute force in data reduction and was incredibly tedious, but it got the job done. Before any reduction took place, the correct analyzing aperture size (in pixels) was determined through trial and error. Once determined for a particular group of stars (i.e. brightest, middle-range, or dimmest), we took the frames from each night and made groups of 10 (note that the data did occasionally overlap, but that did not matter). These groups of 10 were then aligned and added together. After all the nights had been combined this way, the combination frames were aligned with each other and Source Extractor was run on them. The resulting SRC files were then used to compare various stars of the appropriate brightness.

## 5. Variables

To confirm that the measurements being taken were providing values that would allow for planetary transits to be detected, we decided to confirm that we could measure the variables that were in our field of view. Mochejska et al describe in their paper the "47 new low-amplitude variables" they discovered. As it turned out, two of these variables were in our FOV, designated as V5 and V6. These stars, also known as GCVS V0518 Lyr and GCVS V0522 Lyr, respectively, showed promise for determining the precision of our hardware. Table 5.0 depicts the necessary information for these two variables as provided by Mochejska et al.

| ID | R.A. | Dec | P (days) | R max | V max | A r | A v |
|---|---|---|---|---|---|---|---|
| V5 | 19 20 46 | 37 48 47 | 0.3126 | 16.689 | 17.152 | 0.052 | 0.054 |
| V6 | 19 21 02 | 37 48 48 | 0.279 | 15.008 | 15.406 | 0.088 | 0.09 |

Table 5.0: Eclipsing Binaries in FOV of the Meyer-Womble Observatory with the SBIG ST-7 CCD Camera

### 5.1 Data Analysis of Variables

These two variables were analyzed in one of two ways, depending on the functionality of the software for the frames in question. If and whenever possible, CCDSoft by Software Bisque was used to generate the light curve data for two reference stars and the variable in question. If CCDSoft failed to identify the field, as it does occasionally, then the SRC file was manually read for two reference stars and the variable in question. From these two processes, figures 5.1-5.4 were created. Figures 5.5 and 5.6 provide a reference for what is known about these binaries.

Figure 5.1: Light curve for GCVS V0518 Lyr in the R-Band

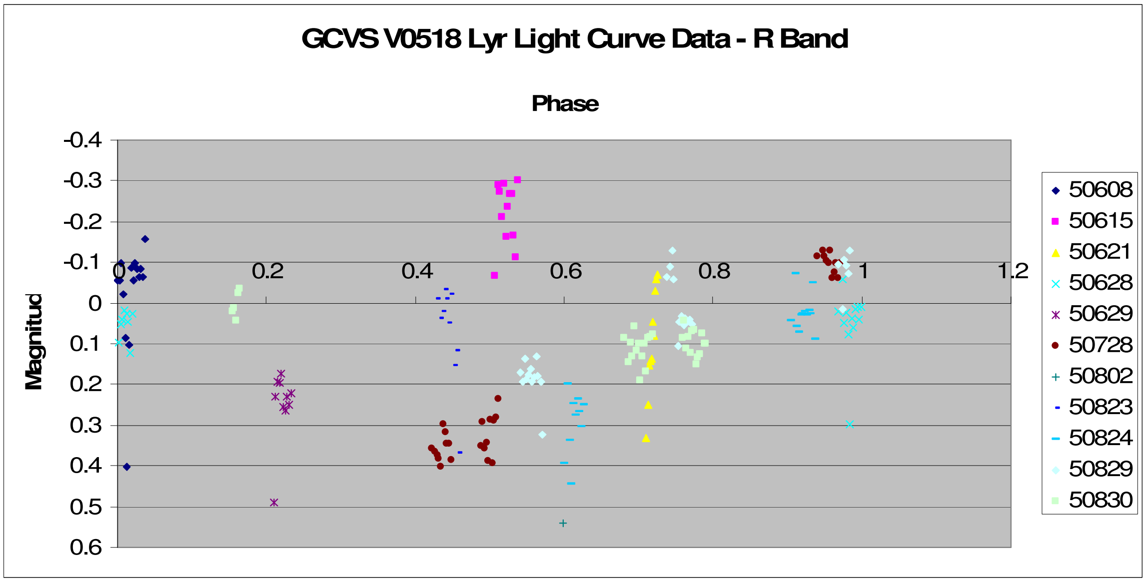



Figure 5.2: Light Curve for GCVS V0518 Lyr in the V-Band

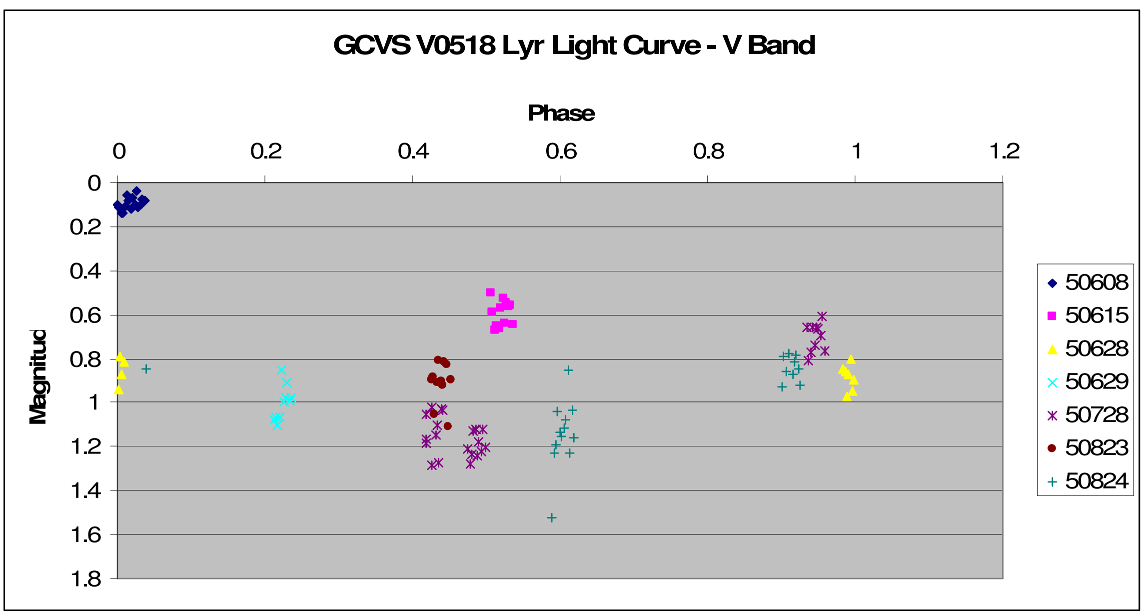


Figure 5.3: Light Curve for GCVS V0522 Lyr in the R-Band

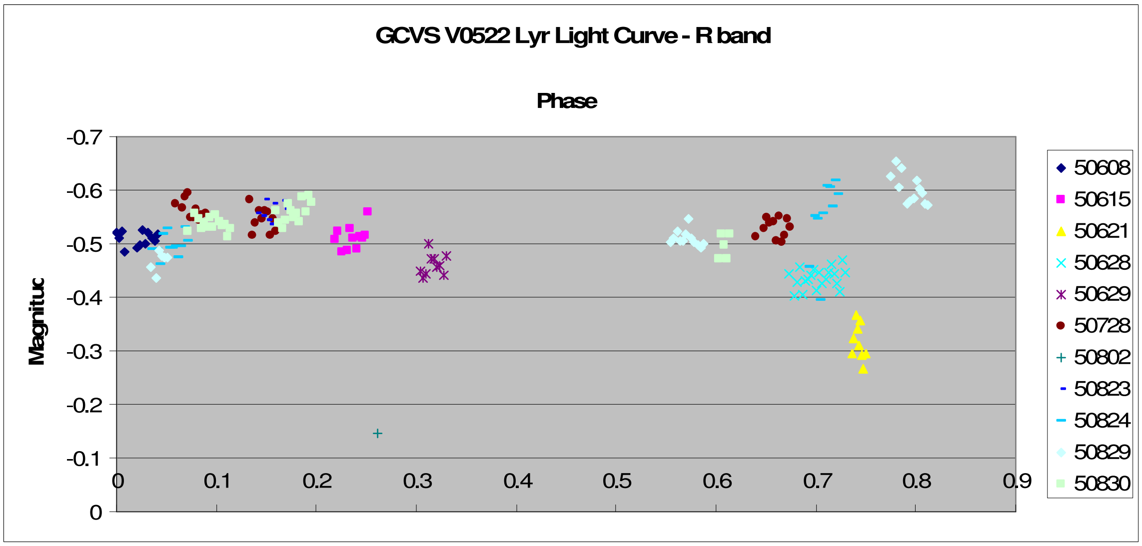



Figure 5.4: Light Curve for GCVS V0522 Lyr in the V-Band

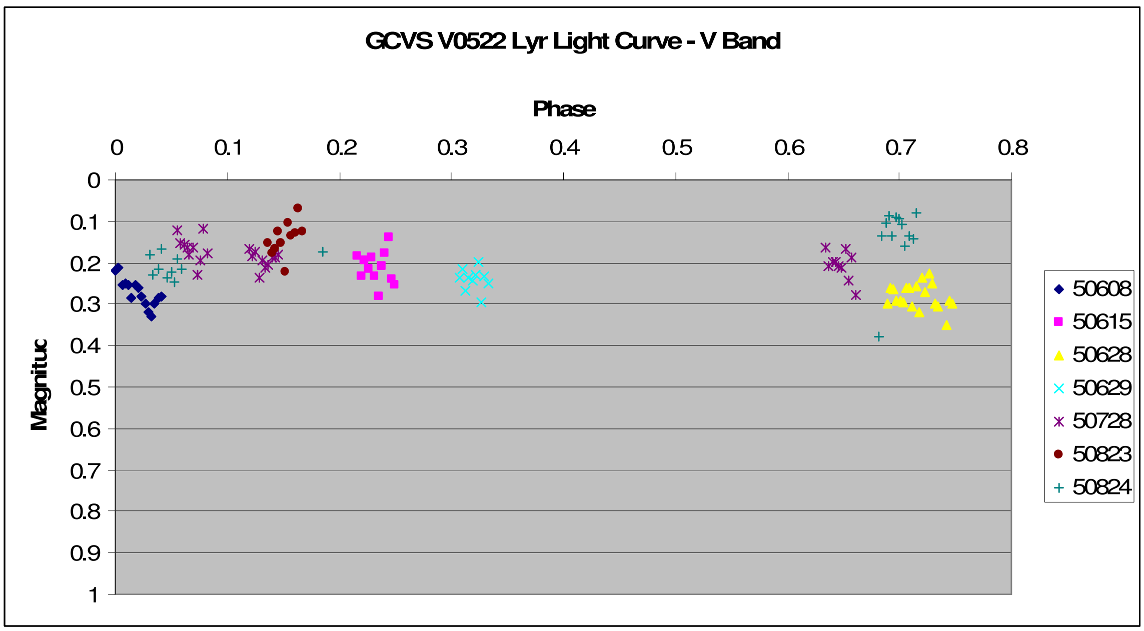


Figure 5.5: Reference for GCVS V0522 Lyr, R and V-Bands, courtesy: VizieR

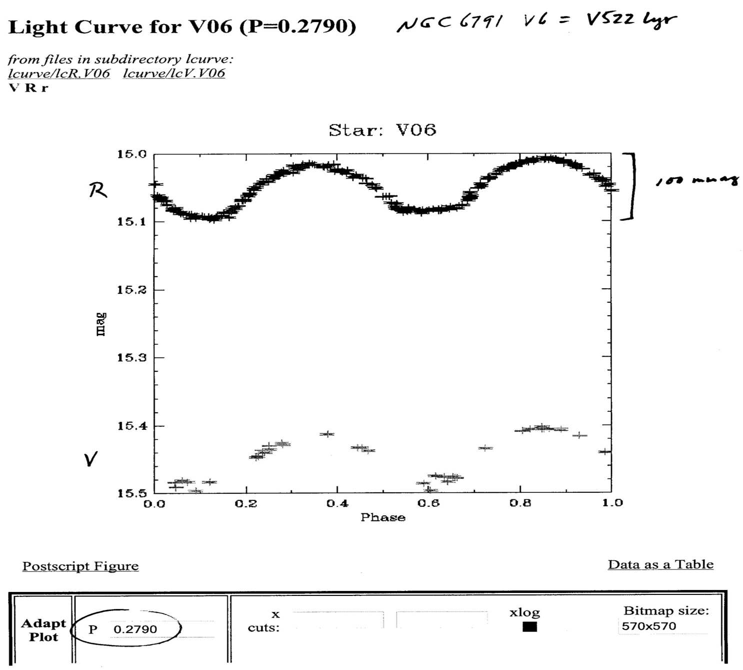
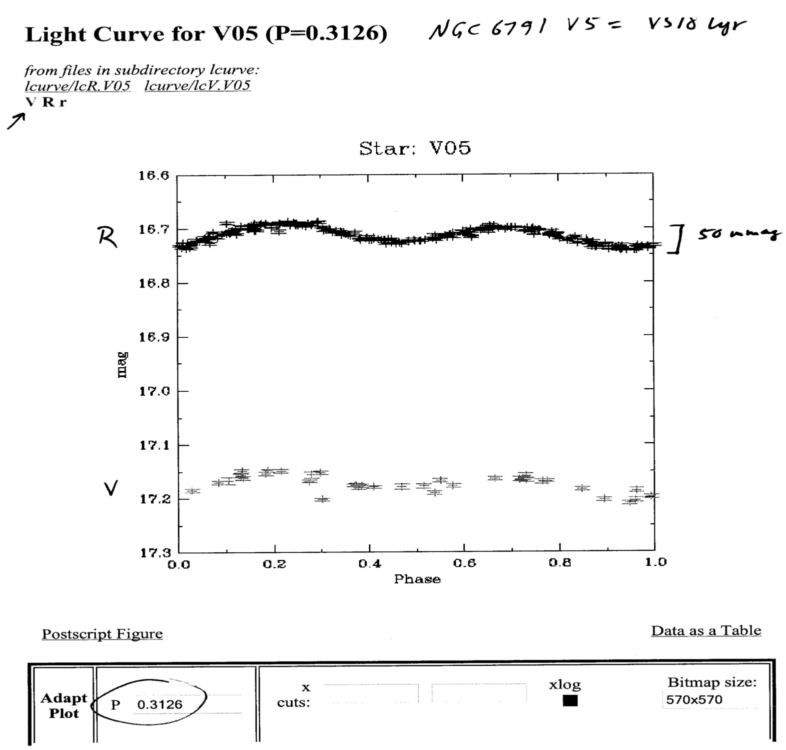



Figure 5.6: Reference for GCVS V0518 Lyr, R and V-Bands, courtesy: VizieR



For these observations, it was average to see the reference stars have a standard deviation of about 20 millimags. On one occasion, however, we did see a 4 millimag sigma from the reference star, indicating that our measurements, at least on that night, were very precise.

## 6. Conclusions and Acknowledgements

Despite the fact that our programs are still in the works and we did not find and transiting planets thus far, we find that this experiment was a success. From this, we learned that with our sub-meter telescope and fairly noisy camera, we are capable of millimag photometry. This is encouraging, as it shows that we are capable of detecting planetary transits from the Meyer-Womble Observatory. We will continue to process data and work on programs for analyzing the data. Eventually, we will be able to say whether we detected a planetary transit or not with a fair amount of certainty. This project will continue to be a focus for us here at DU. Hopefully, as our technology advances, we will be able to make our measurements even more precise and eventually discover an exosolar planet in this cluster.

There are many people to whom I owe my deepest gratitude, for without them, I would not have been able to work on this project. The first is my advisor and mentor, Dr. Robert E. Stencel. His allowing me to use the Meyer-Womble Telescope and his help with the data analysis for this project was essential. This opportunity brought additional knowledge that cannot be gained in a classroom or through a textbook. The people at Research Systems, Incorporated for providing the IDL program that, once complete, will help greatly in the data analysis. Also, the people at Software Bisque, who make the taking of these measurements so much easier through their programs. Furthermore, I am indebted to Dr. Steve Howell of the NOAO for presenting us with this idea and to the Meyer foundation for making this research possible. Also, I thank Rachel Matson and Anu Bhartia for their help with IRAF setup and instruction.

**References**

Howell, S.B. Handbook of CCD Astronomy. Cambridge University Press 2000.

Howell, S. B., Everett, M. E., Esquerdo, G., Davis, D. R., Weidenschilling, S., van Lew, T. 1999 Precision CCD Photometry, ASP Conference Series, Vol. 189: 170, "Photometric Search for Extra-Solar Planets."

<http://exoplanets.org>

Hartman, J.D., Stanek, K.Z., Gaudi, B.S., Holman, M.J., and McLeod, B.A. 2005 Astron. Journal 130: 2241, "Pushing the Limits of Ground-based Photometric Precision: Submillimagnitude Time-Series Photometry of the Open Cluster NGC 6791."

Laughlin, Gregory. "Transitsearch.org." 21 April 2005. July 2005 <http://www.transitsearch.org/>.

Mochjeska, B.J, Stanek, K.Z., and Kaluzny, J. 2003 Astron. Journal 125: 3175, "Long-Term Variability Survey of the Old Open Cluster NGC 6791."

Mochjeska, B.J., Stanek, K.Z., Sasselov, D.D. and Szentgyorgyi, A.H. 2002 Astron. Journal 123: 3460, "Planets in Stellar Clusters Extensive Search. I" [see also paper III, 2005 AJ 129: 2856].

Smith, H. E. 21 April 1999. University of California, San Diego Center for Astrophysics & Space Sciences. 20 October 2005. <http://cassfos02.ucsd.edu/public/tutorial/HR.html>

Sozzetti, Alessandro. 2005 Publications of the Astronomical Society of the Pacific 117: 1023, "Astrometric Methods and Instrumentation to Identify and Characterize Extrasolar Planets: A Review."

Stencel, Robert E. 1999 The Journal of the American Association of Variable Star Observers, 27: 61, "First Light at the New Mt. Evans Observatory."

"VizieR Service." CDS. 5 July 2005. Centre de Données astronomiques de Strasbourg, France. 20 July 2005. <http://vizier.cfa.harvard.edu/viz-bin/VizieR>.