USING REMOTE TELESCOPES FOR EXOPLANET SEARCHES

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ABSTRACT

The Small Telescope Extrasolar Transit Search (STExTS) project involves undergraduates in research using ground-based small aperture, wide-angle telescopes to search for transiting exoplanets of stars down to 13th magnitude. The observational campaigns in 2015 and 2016 used the Monroe Observatory of the University of North Texas with a f/1.5 152 mm astrograph installed for remote observing and in 2017 twin f/1.25 152 mm astrographs were remotely accessed at the Dark Sky Observatory Collective (DSOC) near Ft. Davis, TX. Hardware and the use of commercial software for remote operation of the telescope and camera were installed and coordinated by the team. Observational campaigns usually run 25 to 35 nights, capturing 5000+ stars per image, 250 image per night of the same region of the sky. A software processing pipeline and SQL database were created for the searches. The pipeline examines the images, calibrates them, extracts the stars, and matches each star with an astronomical catalog of stars for identification. Finally a complex photometric analysis is performed to measure the light curve of every star, the results of which are stored in the project SQL database hosted by the University of Dallas. PERANSO and VARTOOLs are used to analyze the light curve and to identify stars of interest. The STExTS team has found six candidates for exoplanets, as well as discovering numerous new RR Lyrae variable stars and W UMa binaries. The process of converting the astrograph to remote use, the development of the data pipeline, the role of student researchers, and a new exoplanet candidate, GSC 2087-1126, are presented.

Keywords: techniques: photometric — methods: data analysis — planets and satellites: detection

1. INTRODUCTION

Exoplanets with large magnitude depths often transit bright host stars, allowing ground-based, photometric measurements of flux over time to be acquired with differential photometry on even modest astronomical equipment. Since the first transiting exoplanet discovery by Charbonneau (Charbonneau et al. 1999) in 1999 several ground based small telescope search projects have succeeded to find numerous exoplanets, most notably WASP (Cameron et al. 2007) and KELT (Pepper et al. 2007), through the transit method.

The transit depth scales as

$$\left(\frac{\Delta F}{F}\right) \approx 0.01 \left(\frac{r}{R_J}\right)^2 \left(\frac{R}{R_{Sun}}\right)^{-2}, \quad (1)$$

where r and R are the planet and star radii, respectively. For Jupiter transiting the Sun, taking Jupiter's radius as $R_J \approx 0.1 R_{Sun}$, the transit depth is $\sim 1\%$. For an edge-on orbit, the transit time is given by

$$\Delta t \approx \frac{PR}{\pi a} \approx 3 \left(\frac{P}{4}\right)^{1/3} \left(\frac{R}{R_{Sun}}\right) \left(\frac{M}{M_{Sun}}\right)^{-1/3} \quad (2)$$

where M is the star's mass and P is the orbital period in days. Therefore, for hot Jupiters transiting sun-like stars, a 1% decrease in flux and a transit length of 3 hours is expected and is easy to detect with modern CCD detectors. Since transits occur only when the orbit is close to edge-on, that is, for orbital inclinations $i < 90°$, the transits become shallower and narrower and vanish when $cos(i) < (R+r)/a$. Consequently, for random orientations of orbits, the probability of seeing a transit is (Haswell 2010)

$$Prob = \frac{R+r}{a} \approx 0.1 \left(\frac{P}{4}\right)^{-2/3} \left(\frac{R}{R_{Sun}}\right) \left(\frac{M}{M_{Sun}}\right)^{-1/3} \quad (3)$$

For a hot Jupiter, $P \approx 4$ d, $a \approx 0.05$ AU, so the transit probability is a $\sim 10\%$. By comparison, for an Earth-size planet ($P = 1$ yr, $a = 1$ AU), the transit probability is only 0.5%.

The Small Telescope Extrasolar Transit Search (STExTS) project is a ground-based small aperture, wide-angle telescope project involving undergraduates in research using remote observatories to search for transiting exoplanets of stars down to 13th magnitude. Section 2 describes the remote observatories, astrographs, and software used for operation. Section 3 describes the nightly routine used by undergraduates, the software processing pipeline and SQL database that were created for the searches. Section 4 describes the methods and software used in analyses. In Section 5 we present the results of observations and analysis of a new exoplanet candidate, GSC 2087-1126, and discuss its physical parameters. In Section 6 we summarize the methods and results of the project.

Figure 1. Castor and Pollux, twin 152 mm f/1.25 astrographs on a Paramount MEII mount are shown at the Dark Sky Observatory Collaborative near Ft. Davis, TX.

2. EXPERIMENTAL DESIGN

The Small Telescope Exoplanet Transit Search (STExTS) project at the University of Dallas has been in operation since 2012. For approximately 35 nights each summer, the team observes the same single patch of sky through wide-angle astrographs, in order to gather data on a large number of stars over an extended period. Time-resolved CCD photometry was conducted with a f/1.5 152 mm astrograph with a 2° field of view and a f/1.25 152 mm astrograph with a 0.8^0 FOV, SBIG ST-10 CCD cameras and Paramount MEII mount. Target regions were in Hercules, Vulpecula, and Cygnus – all outside of WASP and Kepler target areas.

In 2012 - 2014 the STExTS telescopes were set up in an area with very low light pollution at a 9200 foot (2800 m) elevation in Pitkin, Colorado. In the 2014, observations were done on the shore of a small lake in the Ottawa National Forest in the Upper Peninsula, Michigan. Since 2015 the project has configured the telescopes for remote observing at the University of North Texas Monroe Observatory outside

Figure 2. The 3-degree field of view of the astrograph Fatboy centered on SAO 85344. The blooming of the central star can be seen; however no data was taken on that star. As described in the text, approximately 5000 stars can be extracted from each image.

Gainesville, TX and the Dark Sky Observatory Collaborative (DSOC) near Ft. Davis, TX.

Two scopes were originally used to collect data, christened "Fat Boy" and "Serena" by students to differentiate them. Fatboy is a 6-in (152 mm) astrograph constructed in-house from a professional-grade television camera lens and Serena is 6-in (152 mm) astrograph constructed from components. In 2017 the project moved to using two identical Serena-type telescopes, Castor and Pollux, that were constructed in house. These two telescopes are mounted slightly off axis to each other on a platform on the MEII mount, as seen in Fig.1.

Undergraduate student researchers learn how to control the telescopes and to take data remotely. In addition, they take data for two months, weather permitting, and reduce images into photometric data. They also learn how to use various software packages for analyses (PERANSO, VARTOOLS, etc.). Students are also required to write a 35-page thesis on their work with portions ready for incorporation in publications.

3. OBSERVATIONS

Typical observation sessions last six hours during which images are taken with a 60-second integration time. The images are centered on a bright star for each campaign, which is used for image identification. Figure 2 shows the field of view from our 2014 campaign in which SAO 85344 was used for identification. Tracking is accomplished with the internal CCD guide chip in the ST-10 camera. Sixteen bias and sixteen dark frames for calibration are collected each night. Sixteen flat fields are taken on alternate nights. Dark and bias frames are taken at same temperature as data frames. Raw images, flats, bias, and darks are acquired with Maxim DL. All image frames are calibrated using AIP4Win (Berry & Burnell 2000), utilizing dark frames for removing CCD thermal noise, bias frames for removing digitizing and read-out noise, and flat fields for removing CCD pixel sensitivity variances. Figure 3 shows the nightly routine followed by the undergraduate researchers. Access to the remote observatory is achieved with Teamviewer and The SkyX is used to interface with the telescopes.

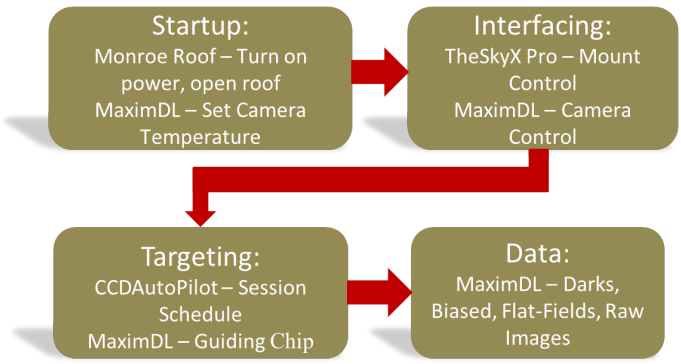

Figure 3. The nightly routine followed by undergraduates taking data indicating the software components utilized by them.

Each image is passed to PinPoint Astrometric Engine (Denny 2006) software for Photo-metric and Astrometric processing. Given approximate coordinates from the FITS header file and input from the GSC 1.1 star catalog, PinPoint obtains an Astrometric solution for the plate. PinPoint is configured to then load Source Extractor (SExtractor) (Bertin & Arnouts 1996). SExtractor is a program that builds a catalog of objects from an astronomical image. Although it is particularly oriented towards reduction of large scale galaxy-survey data, with thresholds and nets adjusted, it performs reasonably well on moderately crowded star fields. SExtractor extracts the x, y position of each star and passes this, along with its measured magnitude, back to PinPoint. Given the right ascension and declination, a locally generated catalog (of just the field area) is accessed to identify each star. The locally generated catalog is necessary because PinPoint does not provide the name of all of extracted stars. We use the VizieR Catalog Service to download and create a subset catalog based on the centers of our plates and their field of view of about 3 degrees. A raw data SQL file is created that contains data on each processed image and a raw data file that contains data on each star identified. If a star cannot be identified, it is given a unique name based on its coordinates.

For each unique star in the raw data file, each night of data, for that star, is processed. Each star in each night of data is analyzed for number of observations and consistency of magnitudes. A modified Z score is calculated, based on the median absolute deviation (MAD), for each data point during the night. If the Z score is greater than 3.5 the data point is considered an outlier and discarded. If, during a night of observation, a given star is missing for for more than 25%

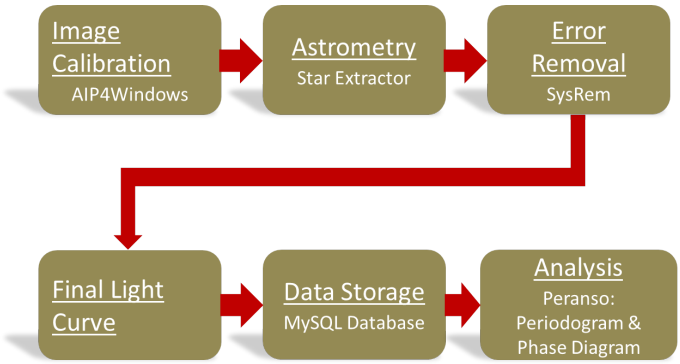

Figure 4. The flowchart shows the steps taken from observations to data storage and transit search.

of the images, all data points for the star, for that night, are flagged as suspect. Finally, each data point for the night is compared to its nearest four neighbors and if it deviates by more than 2σ it is flagged in the database.

The final step in the main processing pipeline is performed by another custom program written that performs systematic error reduction using the SYSREM algorithm (Tamuz et al. 2005). The new calculated magnitudes are placed in another field of the SQL database.

3.1. *Observational Errors*

The presence of systematic (red) noise limits the detection efficiency of searches for transiting exoplanets (Pont et al. 2006). Consequently our surveys were limited by systematic noise and most significantly by random or stochastic noise in the data. We find that because we are interested primarily on the shape of a light curve, and are implementing differential photometry, systematic noise is of little consequence because it is, in general, applicable to all stars and images.

The greatest source of noise in the Stexts project is stochastic noise, and in particular, Poisson noise, aperture pixel noise, scintillation noise and seeing noise. We believe that of these, seeing noise is by far the most significant.

A detailed measurement and analysis of a typical single image of our data indicates that, for example, the star GSC 2087- 0364 (mag = 10.88) has a SNR of 171 and a standard error of 0.006 mag. This value comports with a theoretical calculation based on equipment used. We find the measured noise of the entire dataset for the star is 0.012 Mag for a single night. We attribute this difference in error to sky conditions, mainly high clouds. We find, however, the measured noise of the entire dataset for the star is 0.026 Mag. The preceding error analysis is performed before a SYSREM (systematic error removal) algorithm is applied and we find that the SYSREM algorithm reduces standard error $\sim 20\%$ in certain cases/campaigns but does not completely remove the red and white (pink) noise.

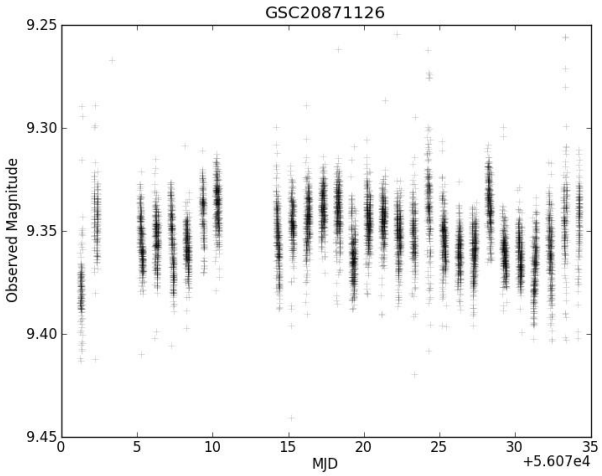

Figure 5. Observational light curve of GSC 2087-1126 for 35 nights of observations. The vertical axis gives the R-band magnitude and the horizontal axis the modified Julian date.

Our Astrometric analysis error as reported by PinPoint ranges from 0.5 to 1.5 arc-secs. The Astrometric error has proven to not be a problem in the overall project goals.

4. DATA ANALYSIS

The light curves of all stars in the SQL database are initially visually examined to see if there is any indication of a periodic trend (Aumen et al. 2015). Often, one must zoom in on a single night's data in order get a good idea of whether there is a trend in the light curve since the typical detectable transit lasts only a few hours. A visual scan of a single light curve in PERANSO (Vanmunster 2007) only takes a few seconds, but there are thousands of stars to analyze, even if we limit our analysis to stars between magnitude 9 and 13. The database also accommodates performing differential photometry on stars of interest.

Periodograms are then calculated for detrended data for the candidates of interest using the Lomb-Scargle method in PERANSO. The Lomb-Scargle periodogram (Lomb 1976) (Scargle 1982) decomposes the data into a series of sine and cosine functions and is similar to least-squares 'statistical' methods, which minimize the differences between observed and modeled data. In PERANSO the Lomb-Scargle algorithm is optimized using the Horne and Baliunas method (Horne & Baliunas 1986), which scales the periodogram by the total variance of the data, yielding a better estimation of the frequency of the periodic signal.

For the light curves of interest that might contain transits we use an EEBLS (Edge Enhanced Box-fitting Least Squares) algorithm (Heuser 2013) in PERANSO to determine the period and produce a phase diagram. The box-fitting least squares (BLS) algorithm finds periodic alternation between levels. EEBLS augments the BLS by account-

ing for edge effects during transits. PERANSO displays the fit of the EEBLS method and calculates the epoch of mid-transit events, the transit depth, and duration. Figure 6 shows the phase diagram for GSC 2087-1126 when the BLS algorithm in PERANSO found a possible transit with a period 0.79380 day, which is shown in red.

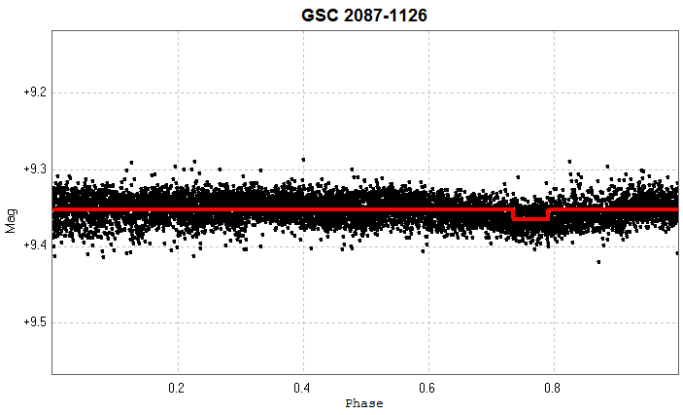

Figure 6. PERANSO phase diagram for GSC 2087-1126 produced by the BLS algorithm with a period of 0.79380 day.

Once we identify a light curve to have a possible transit, VARTOOLS (Hartman & Bakos 2016) is used to run an EEBLS on the candidate light curve. VARTOOLS light curve analysis program is a free resource available for download that was developed by Joel Hartman of Princeton for manipulating large batches of light curves; the Windows-executable version was created in-house by one of our team members (A. Sweeney). The BLS algorithm outputs an assortment of useful information about the light curve found for a transit. A specified number of transit periods are calculated in listed in order of probability. The analysis yields the orbital period P, which for GSC 2087-1126 is 0.7933028(7) day, comparable to the period found using PERANSO software of 0.79380 day. The additional parameters from the model (synthetic) light curve produced by the algorithm are the transit duration after ingress (Q_{tran}) as a fraction of the period, the ingress duration ($Q_{ingress}$) as a fraction of the transit duration, and the depth of the transit in millimags ($\sqrt{\Delta F}$). Twice the ingress duration added to the transit duration yields the total transit duration (t_T).

We use the Mandel-Agol algorithm Mandel & Agol (2002) in VARTOOLS to fit a model curve with limb-darkening to the phase curve. Limb-darkening refers to the phenomenon where a star appears brighter in the center than around its edges. This is because of decrease in temperature in the outer atmosphere of the star. Therefore, since the outer edges of the star are less dim, less light from the star will be blocked by a planetary disk that is in front of the rim of stellar disk than a planet that is in front of the center of the stellar disk. This phenomenon leads to a light curve that is more of a gradual curve in the ingress and egress phases, as one can see in Fig.7. This model fits the data better than the standard BLS model, since the data shows this gradual curvature as well. The transit parameters for calculation of the physical parameters, given in Table 1 are taken from the VARTOOLS Mandel-Agol model of GSC 2087-1126. The modeling analysis also indicates that 16 transits were observed over the the campaign. We specifically observe the same area of the sky night after night to increase the chance of observing multiple transits and, therefore, increase the signal-to-noise ratio.

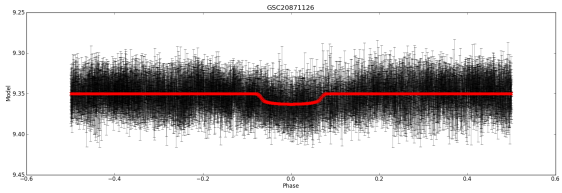

Figure 7. Phase plot for GSC 2087-1126 with the Mandel-Algol model curve shown in red. The vertical axis gives the relative magnitude to the average in the R band.

The five physical parameters–the radius of the star R_*,the mass of the star M_*, the inclination of the orbit i,the semi-major axis of the orbit a, and the radius of the planet R_P–can be derived from the four measured parameters of the transit, P,t_F,$t_T$and ΔF along with the stellar mass-radius relation $\rho/\rho_{Sun} = (\rho_*/\rho_{Sun})^{1/(1-3x)}$. For Main Sequence stars $x \approx 0.8$. The relationships for the five physical parameters (Seager & Mallen-Ornelas 2003) and the measured transit characteristics are shown in Fig.8.

Students also write a Python script to implement the exoplanet diagnostic of Tingley (Tingley & Sackett 2005), which indicates the probability that a transit is due to a planet not a binary. We usually find main sequence spectral types F through late K, whose radii can vary by a factor of three or so, while the typical planetary radius that can produce a transit observable by ground-based search varies by about a factor of two. The Tingley diagnostic η_p takes the radius of the planet to be constant and is given by

$$\eta_p = \frac{D_{obs}}{2Z(1+\sqrt{1.3/d})}\left(\frac{2\pi G M_{Sun}}{P}\right)^{1/3} R_p^{-7/12} R_{Sun}^{-5/12}\left(\frac{1.3}{d}\right)^{5/24} \quad (4)$$

where D_{obs} is the measured duration of the transit, d is the fractional depth of the transit, and P is the orbital period. For an exoplanet event, $\eta_p \leq 1$ whereas $\eta_p \geq 1$ usually designates blending of stars, grazing binaries, or similar events.

5. RESULTS AND DISCUSSION

Using the output of VARTOOLS BLS, students wrote a Python script to calculate the physical parameters of the star-

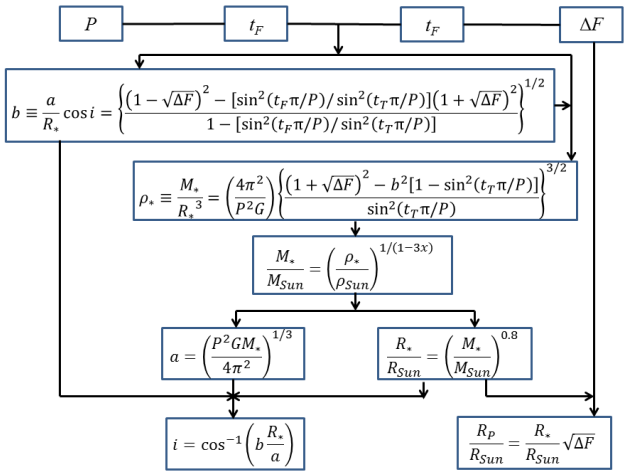

Figure 8. Th five physical parameters–the radius of the star R_*,the mass of the star M_*, the inclination of the orbit i,the semimajor axis of the orbit a, and the radius of the planet R_P–can be determined from four measured characteristics of the model transit light curve.

planet system from the equations shown in Fig.8. As summarized in Tables 1, and 2 GSC 2087-1126 is very similar to the Sun, having a temperature of 5867 K, a mass slightly greater than the Sun, at 1.48 M_{Sun} and a radius 1.37 times that of the Sun. The average density of 1318 kg/m^3 is also similar to that of the Sun. The UCAC4 catalog Zacharias et al. (2013) reports GSC 2087-1126 as a spectral type *F0* main sequence star; the calculated mass, radius, and average density are less than that of a F0 main sequence star. However, since the calculated physical parameters are sensitive to the measured parameters, it is not unexpected that the values would not be exact. Table 1 also indicates that 12 transits were observed and the average transit depth was 12 mmag and the total transit duration of 0.15261 day with a period of 0.79330(3) day.

Measured	Value
Period P [d]	0.79330(3)
Q_{tran}	0.14713
Q_{in}	0.15375
ΔF [mag]	0.01223
N_{tran}	12
B	12.34
V	11.74
Temp [K]	5867
Epoch [MJD]	56071.84204(4)

Table 1: Transit parameters measured from modeling and stellar characteristics of GSC 2087-1126.

Table 2 shows that the planet is 1.5 Jupiter diameters and orbits very close to a star at 0.019 AU which is approximately $1/20^{th}$ of the orbital radius of Mercury about the Sun. The angle of inclination of the system falls in the range $80°-90°$, which is what one would expect from a detectable transit. The Tingley diagnostic is 0.76, which indicates the candidate is more likely a planetary transit than a binary and that it is worthy of subsequent follow-up studies for verification.

In order to conduct follow-up studies, we need to know when a transit would occur in the future. The ephemeris of a transit refers to a time in the future when the object is predicted to enter into transit again and it is calculated by taking the epoch of the transit–the Julian date of the first transit–and adding to it the period multiplied by the number of cycles desired, that is,

$$JD = E_0 + P \times E, \tag{5}$$

We find the ephemeris for the transit ingress for GSC 2087-1126 to be given by

$$JD = 2456071.84204(4) + 0.79330(3) \times E \tag{6}$$

where E is the cycle number and P is the period in days. This ephemeris allows for subsequent follow-up on the candidate.

Parameter	Value
b	0.594
ρ [kg/m^3]	1318
$M*/M_{Sun}$	1.4799
a [AU]	0.019
$R*/R_{Sun}$	1.3683
$inc(^0)$	82.16
R_p/R_J	1.5072
η_p	0.76

Table 2: Summary of characteristics of GSC 2087-1126 and the exoplanet candidate GSC 2087-1126 b.

6. SUMMARY

Students from the University successfully use robotic telescopes at sites in west Texas (DSOC) and the TX-OK border (Monroe) to conduct transit searches. The students learn/participate in all phases of research: data acquisition, data reduction, data analysis, and modeling of candidate transits. Students gain valuable experience working as team members and learn that persistence, responsibility, and reliability are necessary in science. They also experience the thrill of discovery. The project has to date produced thirteen undergraduate theses accompanied by student presentations at American Physical Society meetings.

The core experimental tactic–taking approximately 30 nights of data on the same starfield–improves the signal-to-noise ratio by recording multiple transits and is shown to be a viable, successful approach to transit searches conducted through small colleges. Ground-based transits are finding hot Jupiters in 1 out of 30,000-50,000 stars. Our results are consistent with this statistic. Furthermore, realistic, physical results for the new transit candidate GSC 2087-1126 b have been obtained. Follow-up studies, both photometric and radial velocity, would confirm or not support a new exoplanet.

The support of the Donald A. Cowan Institute and the Joe Oscar Neuhoff Fund at the University of Dallas is gratefully acknowledged. Access to the Monroe Observatory through the University of North Texas is greatly appreciated. Use of the Deep Sky Observatory Collaborative has made this work possible.

Software: Python, Numpy, The SkyX, Maxim DL, Pinpoint, SExtractor, AIP4Win, PERANSO, VARTOOLS

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