High Precision Photometry of Transiting Exoplanets

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In order to increase the rate of finding, confirming, and characterizing Earth-like exoplanets, the MINiature Exoplanet Radial Velocity Array (MINERVA) was recently built with the purpose of obtaining the spectroscopic and photometric precision necessary for these tasks. Achieving the satisfactory photometric precision is the primary focus of this work. This is done with the four telescopes of MINERVA and the defocusing technique. The satisfactory photometric precision derives from the defocusing technique. The use of MINERVA's four telescopes benefits the relative photometry that must be conducted. Typically, it is difficult to find satisfactory comparison stars within a telescope's field of view when the primary target is very bright. This issue is resolved by using one of MINERVA's telescopes to observe the primary bright star while the other telescopes observe a distinct field of view that contains satisfactory bright comparison stars. In order to maintain time-efficiency throughout MINERVA's survey of many bright stars, the relative photometry, analysis of defocused images and the production of light curves have been automated via software recently constructed.

I.   Introduction

Within the past two decades, the search for planets around stars other than our Sun, also known as exoplanets, and the characterization of their physical properties have given astronomers a plethora of new questions about planetary astronomy. The study of exoplanets is a relatively new field of research. Although great scientists like Benjamin Banneker contemplated the topic even in the 18th century, the astronomy community has only recently confirmed that exoplanets exist. In 1995, Mayor and Queloz' announced their discovery of the first known exoplanet [9]. In 1999, current Harvard professor David Charbonneau led the team that found the first transiting exoplanet [2].

In order to confirm the detection of an exoplanet, photometry and spectroscopy are used. Photometry is the measurement of light/electromagnetic radiation/photons and spectroscopy is the study of how matter reacts to electromagnetic radiation. Photometry helps astronomers

produce graphs known as light curves. Spectroscopy allows astronomers to determine how fast an object is moving toward or away from the observer and helps to produce radial velocity (RV) plots. Both light curves and RV plots are used to detect, confirm and analyze exoplanets. These plots become even more fascinating when the star being observed by an astronomer is also being transited by its revolving exoplanet.
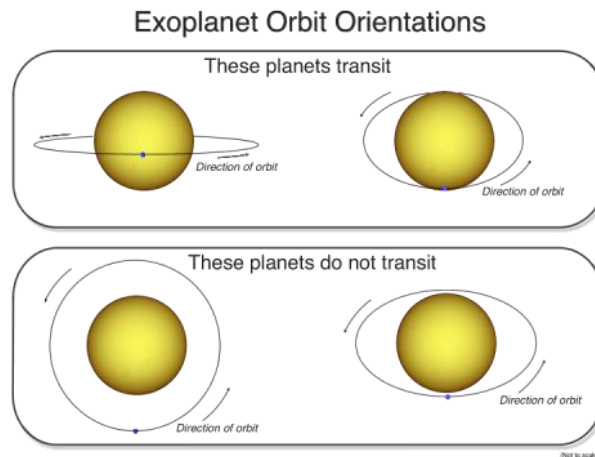
Exoplanet Orbit Orientations

Figure 1: Distinct views of a star-exoplanet system can be taken with respect to an observer on Earth. A planet transits its host star when it blocks some of the star's light from reaching the observer [8].

With modern technology and current methods utilized in this field of research, much more information can be extracted and extrapolated from the data of a transiting exoplanet than data from exoplanets that do not transit their host star. Observations of transiting exoplanets have revealed the physical properties of many exoplanets with a radius near the size of Jupiter and Saturn. The Kepler Mission was responsible for finding more than 400 of these exoplanets in 2009 [1]. This was confirmed by the RV surveys where the stellar spectra conveyed Doppler shifts that were induced by their companion planets. These discoveries have revealed that there are many planets within the Galaxy and that they have a large range of masses, radii, and internal structures [7]. The NASA/UC η_{earth} and HARPS surveys have agreed that 23% of Sun-like stars should have an Earth-mass planetary companion [6]. There are more planets less than 4 Earth-radii than there

are larger planets in the Galaxy [5]. Determining the physical properties of these low-mass exoplanets found by the Kepler mission can advance the search for life on planets outside of the Solar System but within the Solar Neighborhood.

MINERVA

Discovering many of these nearby planets is not feasible by mere photometry because the orbital inclination would have to be extremely aligned with Earth to detect. RV surveys are less sensitive to orbital inclination and thus have a higher probability for detections. Detecting planets near the size of Earth requires high precision photometry because modern instruments cannot achieve the necessary velocity precision for their RVs and/or cannot achieve the high cadence and phase coverage needed to densely sample a planet's full orbit and a range of stellar noise sources [3, 4]. Consequently, only after the RV measurements confirm/detect a transit should time be spent on gathering the high precision photometry of the low-mass planet. Although this RV-then-photometry method has been successful in the past, there is a need for an observatory capable of achieving high precision RV as well as high precision photometry to advance the search for planets within the Solar Neighborhood. This is the basis for why the MINiature Exoplanet Radial Velocity Array (MINERVA) was recently constructed.

The primary science goal of MINERVA is to detect super-Earths (2-5 Earth-radii) within the Habitable Zones of nearby stars, as well as terrestrial-mass planets in close-in orbits. It is an array of four telescopes located on Mt. Hopkins in Arizona. Each telescope has a diameter of 0.7 meters. This observatory was built to consistently achieve a Doppler shift precision of 0.8 meters per second for the spectroscopy as well as a photometric precision of less than 1 millimagnitude.

The work discussed in this paper focuses on overcoming the obstacles that hinder achieving the photometric precision.

II. Methodology

The spectroscopy of a star-planet system is considered first. To meet the Doppler shift precision mentioned previously, the spectra of bright stars are taken as a way of simplifying the work. Bright stars, as opposed to faint stars, radiate a greater flux that yields a greater signal-to-noise ratio, where the signal is the data derived from the star and the noise is unwanted data from other sources measured by the instrument. This ratio is directly related to the accuracy of the spectroscopic measurements gathered by spectrographs. Although these measurements provide a plethora of information regarding the orbital mechanics of the star-planet system, spectra and Doppler shifts alone fail to reveal the mass and radius of the exoplanet. The inclination of the exoplanet's orbit must be known to deduce these physical properties. The photometry of the system provides that inclination angle and much more. This is why another instrument—the charged coupled device (CCD)—is used to observe the same bright stars.

Attempting to analyze and gather photometry on bright stars leads to two serious issues. These issues can be seen in Figure 2 and are explained in the following two sections.
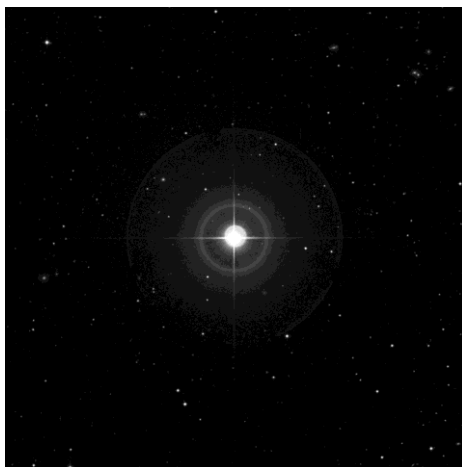
Figure 2: Image of the star Tau Bootes provides an excellent example of why bright star photometry can be difficult. Tau Bootes has an exoplanet orbiting it that periodically transits. This image reinforces the need for techniques like defocusing and an observatory capable of observing bright primary and comparison stars simultaneously [11].

Bright Star Relative Photometry

In order to analyze the photometry properly, the fluctuations in the Earth's atmosphere must be accounted for. As the light from stars propagate toward Earth and the MINERVA telescopes, this light is significantly affected by many atmospheric effects such as the wind, pressure variations and subtle atmospheric turbulence. Such effects alter the stellar measurements gathered by the telescope. To counteract such an interference, relative photometry is performed. This effectively distinguishes the astrophysical information of the star-planet system from the measurements affected by the Earth's atmosphere. To do this, relative photometry requires the observation of several other stars that are similar in brightness and color to the primary target of interest—i.e. a star with a transiting exoplanet orbiting it. Furthermore, these stars must not be variable stars. Such variable stars include eclipsing binaries, Cepheid variables, other stars with transiting planets, etc. Stars meeting these criteria are satisfactory comparison stars. The observation of these comparison stars must be performed simultaneously with the observation of the star-planet system. Finding satisfactory comparison stars to observe with the primary target is

frequently a problem specifically when the primary target is a bright star. This is due to the difficulty of finding multiple bright stars that lie within a telescope's field of view. As Figure 2 demonstrates, there are no stars that are as bright as Tau Bootes within that image. For most ground-based telescopes that must endure the effects of the Earth's atmosphere, performing relative photometry for this star-planet system is not feasible. However, with MINERVA one telescope can observe the primary target while the other 3 telescopes observe satisfactory comparison stars in different patches of the sky. Being able to observe multiple fields of view makes conducting relative photometry feasible with MINERVA.

Defocusing Technique

The other issue noticed within the image of Figure 2 is the saturation of the CCD caused by the bright Tau Bootes star. A CCD has hundreds of pixels that each has a maximum limit for the amount of photons it can detect within one time interval of camera exposure. When this maximum limit is reached over time, the subsequent photons hitting that pixel will not be read by the detector. Furthermore, this subsequent impact of photons will alter the measurements of other pixels near it. Therefore, CCD saturation causes the data collected by those pixels to be misleading. The measurements of the star from those pixels are no longer trustworthy. In Figure 2, the features around the bright star conspicuously imply that the CCD observing Tau Bootes became saturated during the exposure time interval. Saturation can occur even within a 1-second exposure time when observing bright stars. Throughout an observation run, having an extremely short exposure time to avoid saturation can significantly reduce the duty cycle, or ratio of time spent gathering data to time spent closing the shutter, reading out data, and performing all other time-consuming obligations. A high duty cycle significantly enhances the precision of the

photometry and thus yields small error bars for the light curve that is later produced. One strategy that allows for a substantial increase in exposure time when observing bright stars is the defocusing technique.

The defocusing technique has already proven to be beneficial in the past [10]. Employing this technique means that the camera is defocused during the observation of the primary and comparison stars. The point spread function of the defocused star is calculated ahead of time. The optimal point spread function will allow the star's photons to hit more pixels than when the star is in focus, while simultaneously avoiding the convergence of photons from two close stars or objects. By dispersing the photons over more pixels, there are now more pixels that share in detecting the load of the star's photons. Distributing this load naturally reduces the likelihood of a pixel becoming saturated. Therefore, the exposure time can be increased because it will take longer for a pixel to reach its maximum limit. This technique leads to a significant decrease in flat-fielding errors and thus yields the high photometric precision desired for the data collected by MINERVA.

Automation of Observations and Analysis

Soon, a survey of ~80 bright stars will be taken using MINERVA. In order to remain efficient with time, the observation preparation, telescope observations and analysis for such a large set of stars and data must be automated. Software has now been created to easily search the SIMBAD database for satisfactory comparison stars [12]. Once the primary and comparison stars are determined, the user of this software can produce target files that can be read by the MINERVA computers. These computers then control the telescope autonomously and observe the stars listed

in the target file. This target file also contains information such as the exposure time, the filter,

the amount of defocusing and the number of images desired.

After the observations, this software can conduct the analysis of the star-planet systems

and produce light curves of the results. This analysis includes relative and aperture photometry.

Aperture photometry is necessary to distinguish the star's flux from the flux of the sky background.

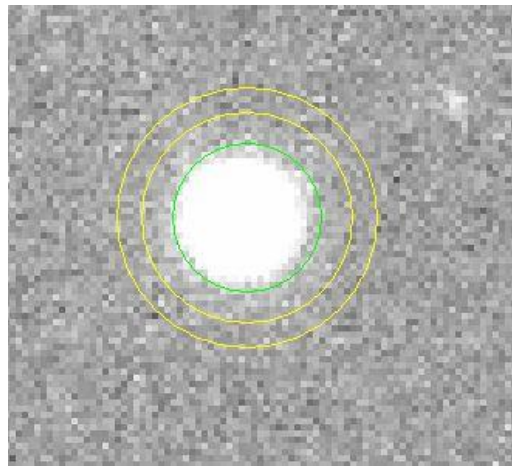Figure 3 illustrates how the software does this.

Figure 3: Raw image of bright star (in focus) observed by one of the MINERVA telescopes. The region within the green circle indicates the pixels where the flux from the star and sky background was measured. The space within the yellow annulus signifies merely where the sky background was measured. The software uses the yellow annulus to calculate the average sky background flux. This sky background is then subtracted from the measurements within the green circle. Consequently, the region within the green circle only contains the flux from the star-planet system. The measurements within the green circle are then extracted for further examination.

After the aperture photometry, the relative photometry is performed and a light curve is produced

by the software. Results of the aperture and relative photometry will be discussed in the

following section.

III.   Results and Discussion

One data set gathered by the MINERVA telescopes was for the star WASP 52. Three

comparison stars were used for the relative photometry. Light curves for all four stars are
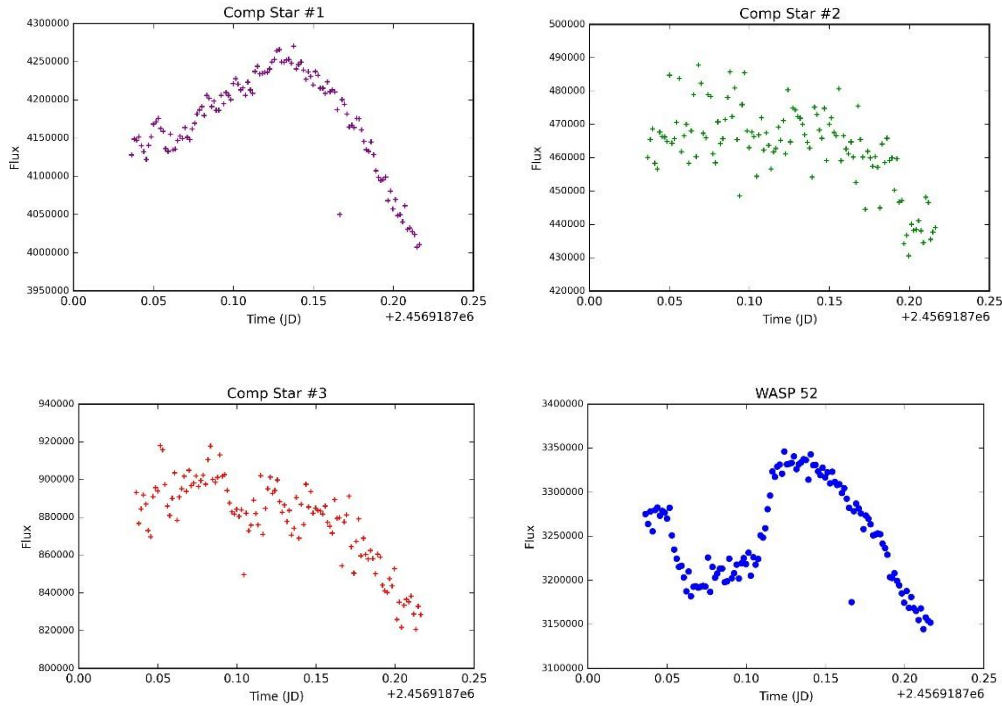
presented in Figure 4.

Figure 4: Light curves for three comparison stars and one primary star (WASP 52).

Each light curve in Figure 4 illustrates the data gathered by distinct MINERVA telescopes observing distinct patches of the sky. However, their fields of view were not far from each other. The software mentioned previously has a criterion for choosing comparison stars that is proximity. Therefore, the closest comparison stars to the primary target are chosen as the most satisfactory comparison stars. The light curves for the comparison stars reveal the effects due to Earth's atmosphere. This is true because the comparison stars are not variable and thus, any variation in the flux of their light curves indicate that such variation is due to the Earth's atmosphere. For the light curve of WASP 52 (a star-planet system), the significance of the atmospheric effects on the data is not known. This is where relative photometry is needed. The flux measurements of the three comparison stars are first averaged together. Subsequently, the flux data in the primary target's light curve is divided by this average flux. The result is illustrated in Figure 5.
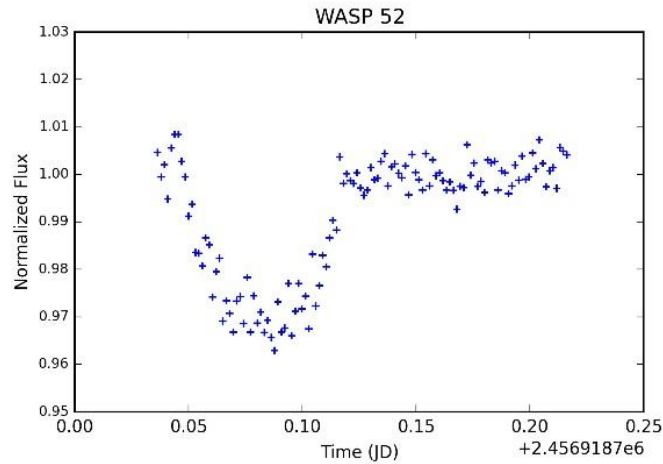
Figure 5: Resultant light curve after relative photometry isolates the astrophysical information from the measurements due to Earth's atmosphere. The y-axis represents the flux of the star relative to the star's quiescent flux.

The light curve of Figure 5 reveals the astrophysical information that is necessary to deduce the physical properties of the exoplanet. Only the flux from the star is seen in this light curve. There is a "dip" in the light curve that is due to the transit of the exoplanet that orbits WASP 52. At one point in time, the exoplanet blocked ~4% of the star's light. The data to the right of the dip remains constant because there is no longer anything blocking that star's full light. The analysis of this data set proves that MINERVA's unique capability of conducting relative photometry with four telescopes can be successful—as expected. This ability will greatly benefit the survey of bright stars when it begins.

Another set of data was for the double star system 16 Cygnus. With one of MINERVA telescopes, this system was observed while utilizing the defocusing technique. The light curves for both stars are illustrated in Figure 6.
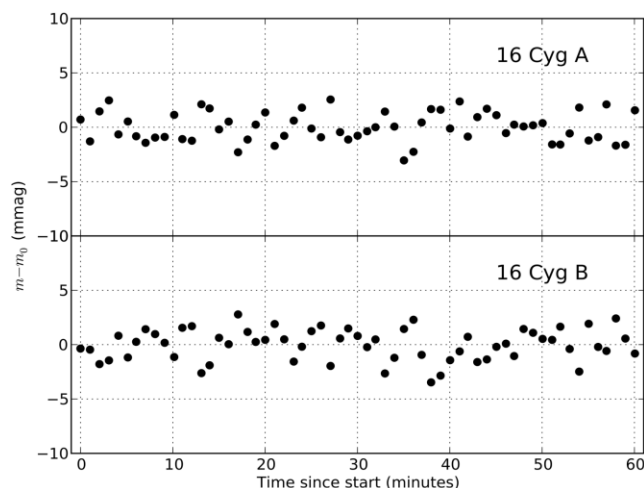
Figure 6: Light curves for the double star system 16 Cygnus. The y-axis represents the brightness of the star relative to a reference brightness measured. The variation from this reference is very small and thus required that the y-axis units be in millimagnitude.

The light curves of Figure 6 do not exhibit much flux variation because the data was taken during a time period when no transit or eclipse was occurring. These light curves result in a photometric precision of 2.7 millimagnitude. Such precision is excellent to achieve, especially when considering that 16 Cyg A is 5.95 magnitudes bright in the V-filter and 16 Cyg B is 6.25 magnitudes in the V-filter. However, this data set proves that a photometric precision of less than 1 millimagnitude was also achieved. This was done by creating a new light curve with optimal binning of the data.
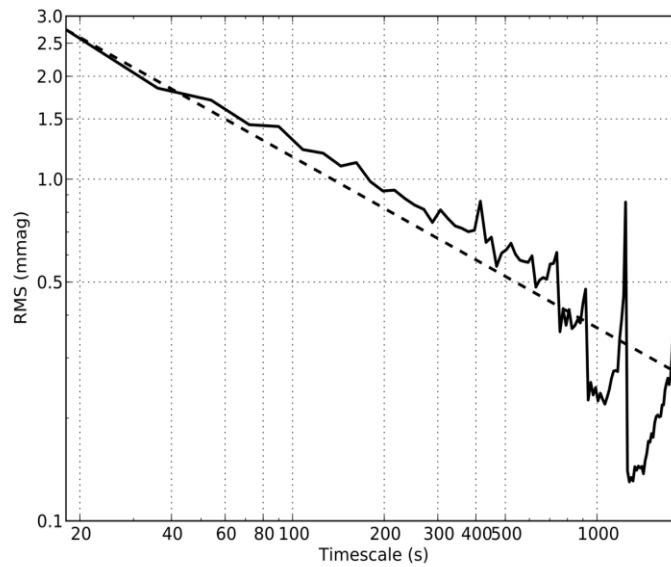
Figure 7: Plot illustrating the precision of various 16 Cygnus light curves with distinct binning. The y-axis represents the root-mean-square, or precision, of the light curve. When the data is binned at timescales of ~200 seconds (or 3 minutes), the precision bins down to below 1 millimagnitude.

This data set proves that the defocusing technique works well with the instrumentation of MINERVA. The goal of achieving less than 1 millimagnitude of photometric precision is complete. However, the more important goal is to remain consistent in achieving this precision while having code that can swiftly analyze the data of defocused stars and produce light curves. Before the MINERVA survey begins, such goals for precision and speed must prove to be feasible. Each component of the MINERVA bright star observation and analysis has proven to be feasible, but it is not yet verified that all of these components can be done simultaneously and swiftly. In other words, the defocusing technique must be utilized with the multiple-telescope relative photometry so that the subsequent data can be analyzed by the software. These three aspects of this project have not complemented each other in such a way yet. Consequently, this is ongoing research with the intentions of preparing for the bright star survey. All of the components of this project are ready to complement each other on a test run. However, this has yet to happen due to monsoon season in Arizona which has immensely delayed the ability of conducting any

observations with the MINERVA telescopes. Once this season is over, such a test run will be conducted and more results will be presented afterwards.

IV.   Acknowledgments

V. References

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