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Photometric Techniques Using Small College Research Instruments for Study of the Extrasolar Planetary Transits of HD 209458

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Abstract: We present the results of a program to develop techniques that enable high-resolution photometric measurements using modest research instruments available to small colleges, and then demonstrate those techniques in a pilot photometric project.

Using a 25 cm Schmidt–Cassegrain telescope and SBIG ST7E CCD camera, we develop techniques that enabled milli-magnitude photometric resolution. The pilot project studied five transits of the recently discovered gas giant planet orbiting HD 209458. We measured a flux drop of $1.46 \pm 0.17\%$ during the transit which corresponds to a planetary diameter of 1.39 ± 0.14 R_{Jup}, a transit period of 2^{h} $48^{min} \pm 21^{min}$, and planet orbital inclination of $87.6 \pm 1.3°$. We determined the orbital period as 3.5234 ± 0.0026 days. These results agree well with other studies which used professional grade research instruments. We suggest a number of other challenging photometric research areas suitable for graduate and undergraduate investigation using equipment common to many small colleges.

Keywords: teaching astronomy — techniques: photometric — binaries: eclipsing — planetary systems — stars: individual (HD 209458)

1 Introduction

With inexpensive but high quality computer-controlled telescopes and CCD cameras now common tools available to college students and even advanced amateurs, we have reached 'a golden age' of possibilities in astronomy education (Baruch 2000). Dedicated students or amateurs with only modest equipment can participate in useful and fascinating scientific research that would have been difficult to imagine just a few years ago. Small colleges with even modest equipment can participate in original research projects for students and teach key elements of observational research including instrument calibration and careful understanding of error bars.

To this end, we undertook development of a student research project that utilises advanced amateur level equipment to study the recently discovered planetary transits of a gas giant planet orbiting star HD 209458. This is the first (and so far only) extrasolar planet found to transit the disk of its star (Gonzalez 1999; Henry et al. 1999, 2000; Charbonneau et al. 2000). Earlier, analysis of doppler data (Latham et al. 1999) indicated a companion of $M_p \sin i = 0.69 \pm 0.05\, M_{Jup}$, at a distance of only $a = 0.0468$ AU. They suggested that the extreme closeness of the planet indicated a relatively high probability that the planet might actually transit the disk of the star. This was subsequently found by Charbonneau et al. (2000), who observed a dimming of less than 2% in the stellar flux at intervals that agreed with the orbital period of 3.524 days as predicted by Henry et al. (2000). However, Castellano et al. (2000) used the *Hipparcos* satellite photometric data and found an orbital period of 3.524736 days with an uncertainty of just 3.9 s.

With the wide publication of these revolutionary results, we began developing a method to detect and measure the planetary transits of HD 209458 using modest small-college research equipment. Our goal was to develop observational and data analysis techniques in order to acquire reliable milli-magnitude differential photometry — and apply it to this pilot project of the planetary transits of HD 209458.

2 Method

The research instrument consists of a 25 cm Meade LX200 Schmidt–Cassegrain telescope and unfiltered SBIG ST7E CCD camera. The study was done from a heavily light-polluted urban environment, as common to most college campuses. An observing and data collection schedule was developed from predictions by Charbonneau et al. (2000) and constrained by considerable obstruction from nearby buildings and trees. A maximum airmass of 2.9 was allowed. Despite these practical limitations, we were able to collect data over five complete or partial planetary transits. Almost 1500 images of HD 209458 were taken and photometrically measured in this study.

One of our first efforts in the project was to determine a criterion for minimum data accuracy. Previous studies (Charbonneau et al. 2000; Henry et al. 2000) measured the dimming of HD 209458 during the planetary transit as 1.5–2%, or approximately 0.02 magnitude. To achieve modest detection of the ingress and egress points, we

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adopted from the beginning a target of 0.005 (v) magnitude precision as possible for this equipment assuming the development of a careful photometric technique.

Some obstacles that were anticipated in achieving the necessary photometric precision included the following: small scale variations in seeing and extinction; instrument instabilities; software limitation in number of comparisons stars used; and Poisson noise for dim comparison stars.

A single measurement 'error' of 0.01 magnitude established in previous extrasolar planet detections is a realistic goal even using our modest instruments. Therefore, in order to reach our target resolution of 0.005 magnitude, some form of statistical sampling was required. Following equipment calibration and the development of a photometric process as described below (also see Section 5), we observed five transits of HD 209458 between July and October 2001. Three of the five transits resulted in useful data sets with one-sigma errors of from 0.003 to 0.007 magnitude.

In general, we began exposing the CCD images at least 1 h prior to the start of ingress and extending 1 h after egress. Typically 200–350 images were taken of each transit event. Various precautions (as further discussed in Section 5) were taken before the start of each observing run to reduce instrumental variables. These included stabilising the camera at 0°C, and implementing a focusing and exposure test procedure to assure consistent results. The time of exposure for each image (typically eight seconds) was recorded from radio timing signals broadcast by the (US) National Institute of Standards and Technology in Fort Collins, Colorado.

We used the technique of differential photometry to quantify only slight changes in the stellar flux rather than an absolute measure of magnitude. In this approach, CCD images are taken of the target star (conventionally called the V star; Figure 1), and two additional reference stars in the same field. These reference stars are referred to as the 'comparison star' (C; Figure 1) and the 'check star' (K; Figure 1). The principal measurement is the V–C differential magnitude, with the K–C magnitude used to verify linearity and stability of the observation measurement.

The selection of these reference stars was shown to be very important to minimise photometric measurement errors. Figure 1 presents an actual data image of the target field, with the various stars labelled. The primary star HD 209458 is described (Høg et al. 2000; Mazeh et al. 2000) as spectral type F8V–G0V and $m_v = 7.65$. The selected reference stars are C = TYC 1688-1766-1 with $m_v = 10.13$, and K = GSC 1688-1716, $m_v = 11.62$.

Data reduction of all images was done using the readily available AIP4Win software (Berry & Burnell 2000). We used the differential photometry mode and a circular measurement aperture to extract the data. The current version of AIP4Win only allows only a single comparison and one check star. We used a star measurement annulus of 8 pixels radius and subtracted a background annulus of 16 pixels radius.

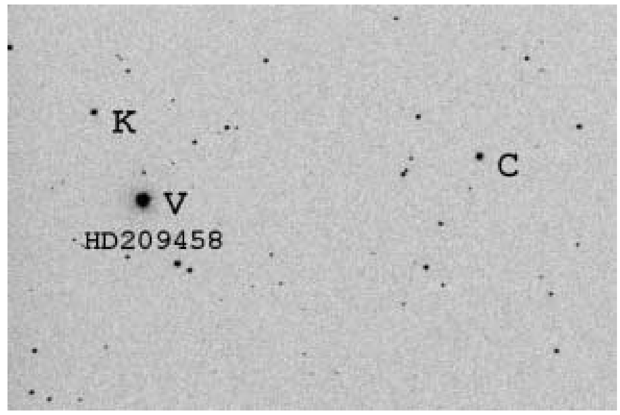

Figure 1 Sample data image of the field around HD 209458 (V; $m_v = 7.65$) showing the comparison star (C = TYC 1688-1766-1; $m_v = 10.13$) and check star (K = GSC 1688-1716; $m_v = 11.62$) which are typically used in differential photometry to assure data quality.

The AIP4Win software was initially calibrated for our telescope/camera setup on the target star HD 209458 to minimise measurement errors. The camera was operated with the standard CCDOPS software provided by the manufacturer (Santa Barbara Instruments Group).

All images were dark framed in the conventional manner, and then flat fielded from a master generated from ten twilight-sky flats. These flats were carefully selected to eliminate any with cosmic ray hits or stars. Flats were exposed to about one-half the full well capacity.

After photometric reduction with the AIP4Win software, all data were collected on MS Excel spreadsheets. Statistical analysis and graphing was also done using Excel software.

3 Transit Observations

Between July and October 2001 we observed five transits of the planet orbiting HD 209458. Two of these were partial transits (21 August and 21 September) that produced very high quality data with one sigma errors of only 0.003 magnitude. The transit of 7 August 2001 produced data with errors of 0.007 magnitude which was slightly higher than our target errors. However, being a complete transit, it contained especially valuable data concerning transit time. We therefore report the results of this observed transit here.

Figures 2–4 present the light curves of three planetary transits of HD 209458 observed in this study. Based on these three events, we measure the on-transit flux drop as $1.46 \pm 0.17\%$. From the complete transit of 7 August 2001, we measure the transit time from first to fourth contact as $2^{h}\ 48^{min} \pm 21^{min}$. This agrees well with previous results as shown in Table 1.

4 Analysis of Transit Observations

4.1 Planet Size

To estimate the planet's radius we modelled the light curve as an opaque sphere of radius R_p occulting a star

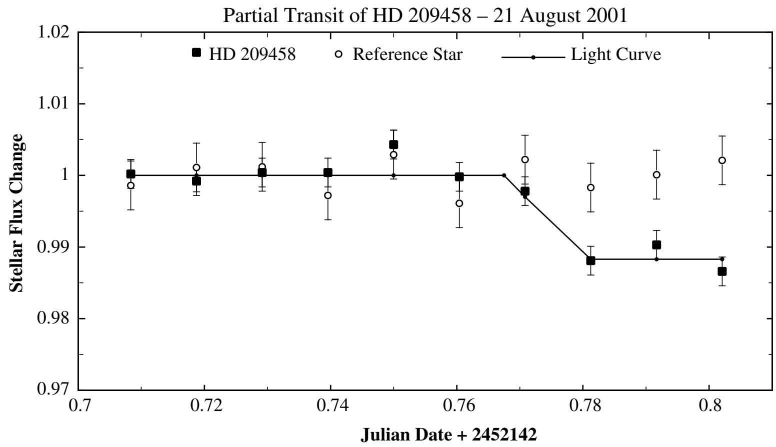

Figure 2 The egress of the planetary transit on 21 August 2001.

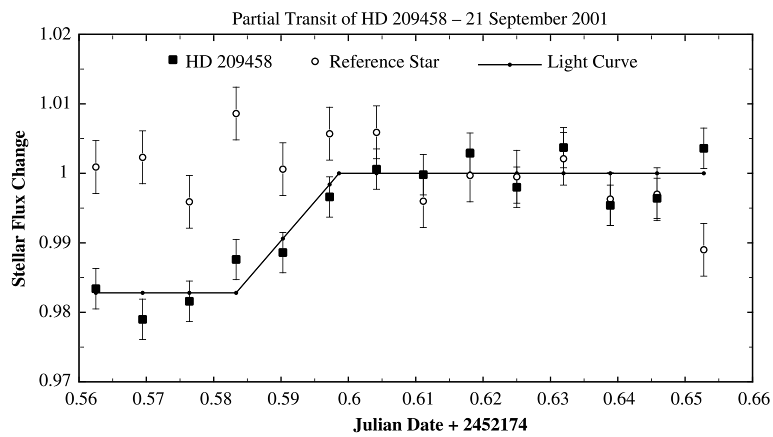

Figure 3 The ingress of the planetary transit of 21 September 2001.

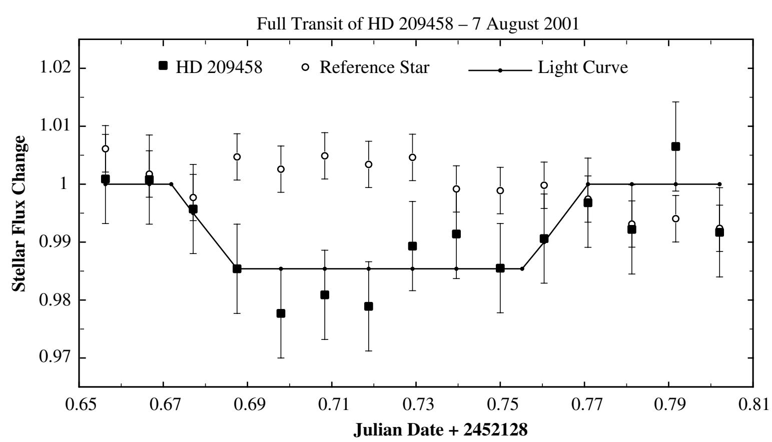

Figure 4 A complete transit of the planet orbiting HD 209458 observed on 7 August 2001. The slope of the light curve at ingress and egress was outside the resolution of direct detection, but was calculated from the planet diameter determined by this study. The consistently larger error of the target star versus the check star in this particular transit is unexplained.

of spectral type F8V–G0V with radius $1.146 \pm 0.050\,R_{\odot}$ in an inclined circular orbit (Brown et al. 2001). The model excluded limb darkening effects as they are below the errors of our measurements.

The on-transit flux drop was calculated at 0.0146 ± 0.0017 based on data from three transits. Our planetary model revealed a radius of 96,380 km. Converting the planet radius to Jupiter units the R_p estimate is 1.39 ± 0.14

Table 1. Comparison of our results with previous findings

Parameter	This Study	Brown et al. (2000)	Charbonneau et al. (2000)	Mazeh et al. (2000)	Jha et al. (2000)
Planet size (R_{Jup})	1.39 ± 0.14	1.347 ± 0.060	1.27 ± 0.02	1.54	1.555 ± 0.1
Planet transit time	$2^h48^m \pm 21^m$	3^h4^m	2^h57^m	–	–
Planet orbital period (days)	3.5234 ± 0.0026	3.5248 ± 0.0004	3.5250 ± 0.003	–	3.5249 ± 0.0003
Planet inclination (degrees)	87.6 ± 1.3	86.6 ± 0.14	87.1 ± 0.2	85.2	85.9 ± 0.5
Flux drop during transit (%)	1.46 ± 0.17	1.6	1.4	–	–

R_{Jup}. The overall error included the addition of uncertainties from observational measurements and the errors in the theoretical model. This figure agrees with other work as shown in Table 1.

4.2 *Planet Orbital Period*

The orbital period of the planet is calculated using the observed ingress times from two transits and the approximate orbital period of 3.5 days from Doppler data. Using the ingress times from the transits of 7 August 2001 and 21 August 2001, the 'best fit' is four (4) complete orbits yielding an orbital period of 3.5234 ± 0.0026 days. The maximum error of light travel time due to changing Earth orbital position between the transits is 0.0003 days which is negligible.

4.3 *Planet Orbital Inclination*

From the observed orbital period and assumed mass of HD 209458 ($1.1\,M_\odot$), we applied Newton's form of Kepler's third law to derive the dimension of the semi-major axis as $a = 0.0468$ AU. Based on doppler data and previous observations of 'hot Jupiter' extrasolar planets we assume the orbit is essentially circular. This yields an orbital speed of 5.201×10^5 km h^{-1}.

Based on the observed transit time and calculated orbital speed, we estimate the transit chord across the stellar disk as 1.46×10^6 km $\pm$ 13%. If this chord is applied to an assumed stellar disk of 1.595×10^6 km, it requires an off-set from the centre of the star of 32 560 km $\pm$ 13%. At the calculated orbital distance of 0.046 AU, this corresponds to an orbital inclination of $87.3 \pm 1.3°$. This agrees with previous work as shown in Table 1.

5 Discussion of Observing Techniques

The initial tests showed that the AIP4Win software was able to make very repeatable measurements of the V–C and K–C values for any one image. That error was a very small 0.0095 magnitude and therefore was disregarded in later tests. Our initial tests of the entire system on HD 209458 revealed, however, an alarming error of 0.04 magnitudes. Clearly, substantial changes and improvements would be required in our photometric technique in order to achieve the resolution needed to describe the transit light curve.

Over the course of the study, through helpful suggestions and trial-and-error experiment, the following changes were introduced into the photometric process.

- Statistical sampling of data: In order to reach the criterion of 0.005 magnitude, it was necessary to obtain more than a single measurement at each time increment. We used the automatic exposure feature of the CCDOPS camera software to take a rapid burst of CCD images centered on each 10 or 15 min time increment. Data reduced from these images formed a statistical sample that greatly reduced instrumental errors. We began the study taking 20 image samples, but later improved our technique to the point that we could reduce each time-series data point to a sample of 10 images.
- Focus: We found that very sharply focused stars actually increased measurement error — presumably because a changing proportion of the Airy disk falls on the CCD chip gate array structure. By 'softening' the image diameter of HD 209458 from four (4) pixels to eight (8) pixels, increasing exposure, and using a larger measurement aperture of 16 pixels, we improved the measured accuracy by a factor of two.
- Selection of reference stars: Best results are obtained if the stars are all within one (1) magnitude. However, we found this advantage to be lost in the case of our ST7E camera where bright reference stars were at the extreme edge of the chip. We eventually adopted reference stars that had a three (3) magnitude flux difference, but were located close to the target star on the chip.
- Exposure: To maximise the S/N ratio while operating the Kodak KAF-1602E detector over its linear range, we found best results with about 40% of the full well capacity, i.e., about 25,000 analog-to-digital units. The ST7E operates at about 2.5 electrons/ADU, yielding about 62,500 electrons per pixel for the target star and only 6000 electrons for the fainter comparison star. The relative faintness of the comparison star made the milli-magnitude measurements more difficult. Longer exposures that were still within the advertised linear range of the chip did not improve results as expected, but actually increased errors somewhat. Careful experiment with exposure is required to minimise errors.
- Number of comparison stars: The existing version of AIP4Win software limited the differential photometry to a single comparison star. This certainly increased the difficulty of reaching our single frame magnitude precision of 0.01 magnitude. Substantial improvements in measurement precision would be achieved by using multiple comparison stars to form a mean (Frandsen et al. 1996). This would also relieve the problem

encountered in this study in which all the field stars were substantially fainter than the target star. Future versions of the AIP4Win software are planned that allow multiple comparison stars.

- Miscellaneous instrumental errors:
  (1) We found that slow movement of star images across the chip over the course of the transit resulted in increased error. Presumably this is due to small imperfections in the flat field. We marked the target star image on the CCD monitor and made slight corrections to the telescope drive over the several hours of data collection to keep the star images within a consistent area of the chip.
  (2) We found that the mirror in the SC telescope will shift and slowly settle changing the telescope focus and introducing measurement inconsistencies. We found it necessary to allow the mirror focus to stabilise for 1 h and then perform the slight defocus adjustment before starting data collection.
  (3) We found slight changes in camera sensitivity during the first 30 min of cooling and operation. As a result, to reduce this instability, we started imaging at least 30 min before actual data were required.
  (4) To assure quality data, we established criteria that any data in which the target star image exceeded 8 pixels in diameter would be rejected from the sample. Due to drive errors this occurred about 5% of the time.

These changes enabled us to achieve a final error resolution of 0.003 magnitudes for the last two transits.

6 Future Work

This successful study, of an extrasolar planet using a modest instrument found in many small colleges, demonstrates the challenging and educational photometric studies now possible for both graduate and undergraduate research. Modest telescopes and amateur-grade CCD cameras can be employed by students along with careful photometric technique as described here — to enable differential photometry measurements with errors of only 0.003 magnitude.

Milli-magnitude photometric precision enables a variety of challenging student projects. Some suggested projects, roughly in order of difficulty, include the following:

- small amplitude red variables;
- asteroid rotation curves;
- short period and eclipsing dwarf novae (e.g., SU Ursae Majoris stars);
- RS Canum Venaticorum stars (starspots);
- near-IR variability of pre-main sequence stars in molecular clouds (e.g. Orion);
- short period pulsations of ZZ Ceti white dwarfs.

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