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Author(s): Mercedes López-Morales
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Millimagnitude-Precision Photometry of Bright Stars with a 1 m Telescope and a Standard CCD

Mercedes López-Morales[1]

Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC, 20015; mercedes@dtm.ciw.edu

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ABSTRACT. This paper summarizes a three-night observing campaign aimed at achieving millimagnitude-precision photometry of bright stars ($V < 9.0$ mag) with the 1 m Swope Telescope at Las Campanas Observatory. The test targets were the main-sequence stars HD 205739 and HD 135446. The results show that by placing a concentric diaphragm in front of the aperture of the telescope, it is possible to avoid saturation and achieve a photometric precision of 0.0008–0.0010 mag per data point, with a cadence of less than 4 minutes. It is also possible to reach an overall precision of less that 0.0015 mag for time series of 6 hr or more. The photometric precision of this setup is only limited by scintillation. Scintillation could be reduced, and therefore the photometric precision further improved, by using a neutral-density filter instead of the aperture stop. Given the expected median depth of about 0.01 mag for extrasolar-planet transits, plus their typical duration of several hours, the results of this paper show that 1 m telescopes equipped with standard CCDs can be used to detect planet transits as shallow as 0.002 mag around bright stars.

1. INTRODUCTION

High-precision photometry of bright stars is becoming a subject of increasing interest in extrasolar planet studies. Precision photometry complements Doppler observations by establishing whether the observed radial velocity variations are caused by the reflex motion induced by a planetary companion or by stellar magnetic activity (e.g., Henry et al. 2000a; Queloz et al. 2001; and Paulson et al. 2004). Precision photometry can also determine the presence or absence of transits for stars with known planets. The presence of a transit provides additional information about the planet by allowing the determination of its radius and its absolute mass (e.g., Charbonneau et al. 2000; Henry et al. 2000b; Sato et al. 2005; and Charbonneau et al. 2006), and also provides more precise orbital parameters of the system.

Photometric precision of a few millimagnitudes is routinely achieved using ground-based telescopes and standard CCDs for stars fainter than $V = 9.0$–10.0 mag. Gilliland et al. (1991) showed that by using a 1 m telescope and a standard CCD, it is possible to achieve a precision of 0.0008 mag for 13th magnitude stars in time series of about 9 hr with a 2 minute candence. Everett & Howell (2001) have more recently demonstrated that it is possible to reach precisions of 0.00019 mag in a 4.5 hr time series for $V = 14.0$ stars with a 0.9 m telescope and a mosaic CCD. However, for stars with $V = 9.0$ mag or brighter, millimagnitude-precision photometry basically remains in the realm of photomultiplier tubes.[2] A typical CCD immediately becomes saturated when we place it in a 1 m class telescope and try to image a bright star. Saturation can be avoided by using a smaller telescope, but in that case atmospheric scintillation limits the photometric precision to 3–5 mmag.

Efforts to reach millimagnitude-precision photometry of bright stars with CCDs on ground-based 1 m class telescopes are now beginning to produce results that are comparable to those of photomultipliers tubes. For example, Bouchy et al. (2005) recently published the detection of an extrasolar-planet transit around HD 189733 with the 1.2 m telescope at the Haute-Provence Observatory in France, using a 1024 × 1024 SITe back-illuminated CCD. The depth of this transit is 0.03 mag, and their photometric precision per data point varies between 0.002 and 0.003 mag. Similarly, Charbonneau et al. (2006) have confirmed the 0.003 mag deep transit of HD 149026b (Sato et al. 2005) using a two-chip 2048 × 4608 CCD installed at the 48 inch (1.2 m) telescope of the F. L. Whipple Observatory at Mount Hopkins, Arizona. Most efforts have been focused on the Northern Hemisphere, where small telescopes are more numerous. However, at least half of the sample of stars currently being searched for planets lie at southern latitudes. In this paper,

[1] Carnegie Fellow.

[2] The most successful ground-based experiment using photomultipliers is the automatic photometric telescopes (APTs) at Fairborn Observatory (Henry 1995a, 1995b, 1999; Strassmmeier et al. 1997; Eaton et al. 2003). The APTs routinely achieve photometric precision of 0.001 mag for single observations of stars brighter than $V = 8.5$. They are also the only instruments that have maintained that precision for more than 10 years—it is what makes them a superb tool.

I present the results of tests performed with the 40 inch (1 m) telescope at the Las Campanas Observatory in Chile. The tests were intended to achieve millimagnitude-precision photometry of bright southern stars that are currently being searched for planets by radial velocity surveys. The selected targets were HD 205739 ($V = 8.5$) and HD 135446 ($V = 8.2$). Section 2 describes the instrumental setup and the observations. Section 3 summarizes the data analysis and presents the resulting light curves. Section 4 compares our results to the three currently known exoplanet transits around bright stars. Finally, the summary of this work and future plans are given in § 5.

2. INSTRUMENT SETUP AND OBSERVATIONS

2.1. Instrument Setup

The data were collected at the Henrietta Swope Telescope, located at the Las Campanas Observatory in Chile. The Swope is a 40 inch (1 m) reflector with an f/7 Ritchey-Chrétien optical design. It is currently equipped with a 2048 × 3150, 15 μm pixel SITe CCD that provides an unvignetted field of view of 14′.8 × 22′.8. The dynamic range of the CCD is 32,727 ADU (analog-to-digital converter units), and it converts electrons into ADUs at a fixed gain of 2.5 e^{-} ADU^{-1}. The readout time of the CCD on its 1 × 1 unbinned configuration is 128 s. In addition, there is a minimum exposure time of 5 s, to ensure that the CCD shutter has moved completely out of the way.

With that setup, stars brighter than $V = 8.5$ will unavoidably saturate in the 5 s minimum exposure time. Saturation occurs even if we try to distribute the photons over a larger number of pixels by defocusing the telescope.

One way to prevent saturation is to use a neutral-density filter to block a fraction of the photons arriving from the stars. Unfortunately, a neutral-density filter is not currently available at Swope. Another way to reduce the number of photons impacting the CCD is to employ an aperture stop to reduce the photon-collecting area of the telescope.

With the help of Las Campanas Observatory personnel, I built a stop to reduce the effective aperture of the telescope from 0.589 to 0.146 m^2. The stop, a 1 m diameter piece of plywood painted black, with a central aperture diameter of 0.67 m, was placed in front of the aperture of the telescope, as shown in Figure 1. Objects appear 2.0 mag fainter with that setup, making it possible to image stars as bright as $V = 6.5$ without saturation.

To partially reduce the duty cycle of the observations, the readout of the CCD was limited to an area of 2048 × 2048 pixels (14′.8 × 14′.8). The area is still large enough to simultaneously image the target star and at least one nearby comparison star of similar magnitude, but it reduces the readout time to 90 s, instead of the 128 s that it takes to read out the full CCD.

2.2. Observations

The test targets for this work were the two southern stars HD 205739 ($V = 8.57$, $B - V = 0.50$, spectral type F7 V) and HD 135446 ($V = 8.20$, $B - V = 0.57$, spectral type G1.5 V). Both stars have no previous record of any kind of intrinsic variability and are being searched for planets by radial velocity surveys. HD 205739 was observed during three nights, on UT 2005 August 3–4, 8–9, and 9–10. HD 135446 was observed on the nights of UT 2005 August 8–9 and 9–10. A log of the observations is presented in Table 1. HD 135446 was monitored over the first 3 hr of each night. HD 205739 was monitored over the second half of the nights (about 6 hr per night). The observations were all collected under photometric conditions, spanning air masses between 1.01 and 1.63.

The comparison star used for HD 205739 was HD 205860, a slightly brighter star than HD 205739 and of the same spectral type ($V = 8.27$, $B - V = 0.50$, spectral type F7 V). This last point is very fortunate, since it eliminates from the differential photometry the second-order extinction effects introduced by color differences between the comparison and the target stars. The separation between the two stars is $\Delta\alpha = 46^{s}.32$ and $\Delta\delta = -10'.31$. In the case of HD 135446, the comparison star was HD 135342 ($V = 9.27$, $B - V = 0.51$, spectral type F6 V). The separation between the target and comparison star is $\Delta\alpha = -25^{s}.04$ and $\Delta\delta = 1'.87$. Both stars also have similar colors in this case, but the comparison star is 1.1 mag fainter than the target.

The telescope was defocused so that the count level per pixel in both the target and comparison stars remained within the linearity limit of the CCD (<25,000 ADU). The FWHM of the stars during the observations ranged between 15 and 19.5 pixels (6″.5–8″.5) in the images of HD 205739 and between 19 and 23.5 pixels (8″.2–10″.2) in the images of HD 135446. While keeping the count levels below 25,000 ADU, the exposure times also had to be long enough to (1) ensure that enough photons were collected for both the target and comparison stars to keep the Poisson noise level below one part in a thousand, and (2) reduce the errors introduced by scintillation. Typical exposure times were 20–22 s for HD 205739 and 30–32 s for HD 135446, respectively.

Pixel-to-pixel sensitivity differences is one of the main precision-limiting factors in CCD photometry. To minimize this contribution to the noise, the stars were placed over the same pixels each night and then monitored with careful telescope guiding to ensure that the center of the stars were always located within the same $\pm$1–2 pixels. All the images were taken using a standard Johnson V-band filter.

Finally, several hundred bias and flat frames were collected each night to ensure an overall count level of over 10^6 photoelectrons per pixel in the final calibration frames. In this manner, one can avoid introducing additional random noise in the calibrated images beyond the intended photometric precision of 1/1000.

3. ANALYSIS AND RESULTS

All the images were bias-substracted and flat-fielded using the same combined bias and combined flat frames. Those

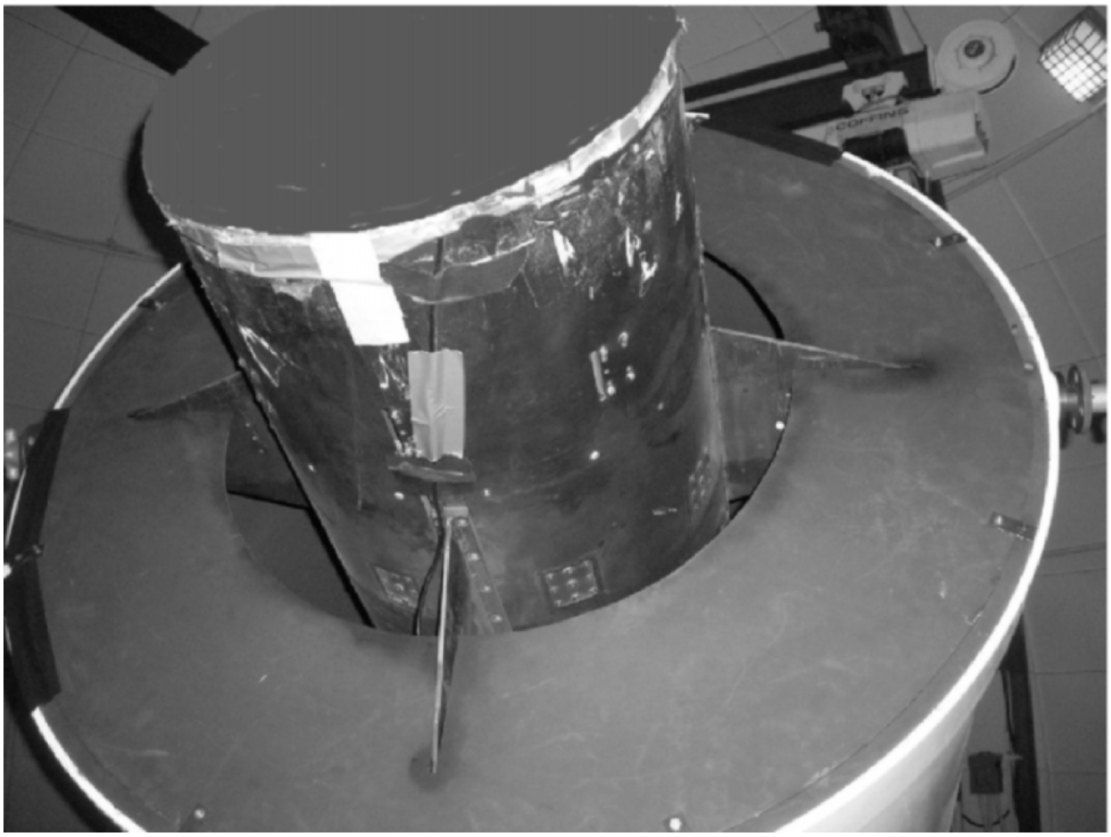

FIG. 1.—Aperture stop constructed to reduce the effective aperture of the Swope Telescope from 0.589 to 0.146 m^2. The stop is a 1 m diameter piece of plywood with a central aperture diameter of 0.67 m. The stop reduces the brightness of the stars by 2 mag so that it is possible to image stars as bright as $V = 6.5$ without saturation.

frames were generated by combining all the biases and flats collected in different nights so that each of the final two calibration frames had an overall count level of at least 10^6 photons. That level of counts ensures that the random noise introduced during the calibration of the images, assumed to be Poisson noise, does not exceed 0.001 mag.

The next step of the reduction processs consisted of performing aperture photometry of each target and their comparison star on the calibrated images. In order to optimize the results of the aperture photometry, I performed the photometry over a series of apertures with radii varying between 12 and 35 pixels. The area used to compute the sky background around each star was always the same (an annulus of 15 pixels at a radius of 60 pixels centered on the stars). The size and location of the sky-background annulus does not affect the results of the aperture photometry as long as that annulus is located at a radius from the center of the stars that is large enough to avoid including a significant number of counts from the objects. The area covered by the annulus has to contain enough pixels to provide good statistics. In addition, one should avoid areas of the CCD that are contaminated by other objects or by bad pixels. In those cases, a σ-clipping algorithm should be applied when computing the sky background.

TABLE 1
LOG OF OBSERVATIONS OF THE TEST TARGET STARS HD 205739 AND HD 135446

Date (UT)	Object	Time (HJD −2,453,500)	Air Mass
2005 Aug 3–4	HD 205739	86.62829–86.86426	1.18–1.42
2005 Aug 8–9	HD 135446	91.46557–91.60766	1.01–1.63
	HD 205739	91.63257–91.85669	1.11–1.51
2005 Aug 9–10	HD 135446	92.46533–92.58154	1.01–1.59
	HD 205739	92.62891–92.87488	1.12–1.58

Differential photometry light curves were generated iteratively for all the possible combinations of apertures of the target and the comparison star. The best light curve was then selected as the one resulting from the combination of apertures that gave the smallest value of the standard deviation σ_{f_t/f_c}, where f_t and f_c are respectively the instrumental flux counts of the target and the comparison star. The subscript f_t/f_c corresponds to the ratio of those fluxes. First, a prelimimary minimum of σ_{f_t/f_c} is sought by assigning aperture increments of 1 pixel per iteration. Once an approximate value of the minimum of σ_{f_t/f_c} is found, one runs a second pass around that minimum to

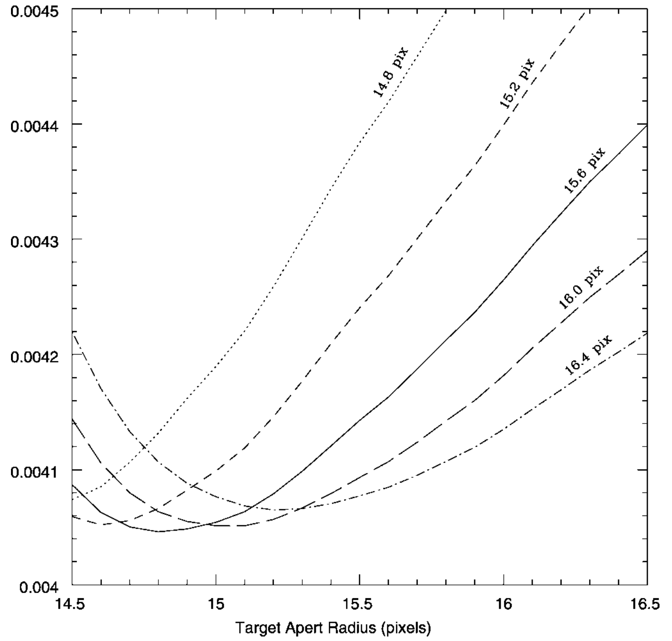

FIG. 2.—Example of the σ_{f_t/f_c} vs. aperture plots used to determine the best combination of photometric apertures for the target and comparison stars, as described in § 3. The plot shows the values of σ_{f_t/f_c} (*y*-axis) for different apertures around the target HD 205739 (*x*-axis). Each line corresponds to a different aperture for the comparison star. The best photometry in this case is obtained when using an aperture of 14.8 pixels for the target and 15.6 pixels for the comparison star. The values of σ_{f_t/f_c} in this plot include outliers (points that deviate by more than 5 σ from the mean of the light curve). These outliers were removed from the final light curves.

optimize the solution. In that second pass, the aperture increments are 0.1 pixels instead of the 1.0 pixel in the first pass. The optimum apertures found were different for each target and each night. An example of the aperture versus σ_{f_t/f_c} plots generated to determine the best combination of apertures is illustrated in Figure 2, where I show the results of the aperture photometry of HD 205739 for the data collected on August 3–4. The optimum apertures in that case were 14.8 pixels for the target

TABLE 2
OPTIMUM PHOTOMETRIC APERTURES FOR EACH TARGET IN EACH NIGHT

Target	Date (UT)	Optimum Aperture of Target (pixels)	Optimum Aperture of Comparison (pixels)	σ_{f_t/f_c} [a]
HD 135446	2005 Aug 8–9	18.6	18.8	0.00506
	2005 Aug 9–10	23.1	22.1	0.00501
HD 205738	2005 Aug 3–4	14.8	15.6	0.00405
	2005 Aug 8–9	19.2	18.9	0.00452
	2005 Aug 9–10	18.8	18.4	0.00235

[a] The values of σ_{f_t/f_c} in this table include outliers (points that deviate by more than 5 σ from the mean value of the light curve). These outlayers were removed from the final light curves.

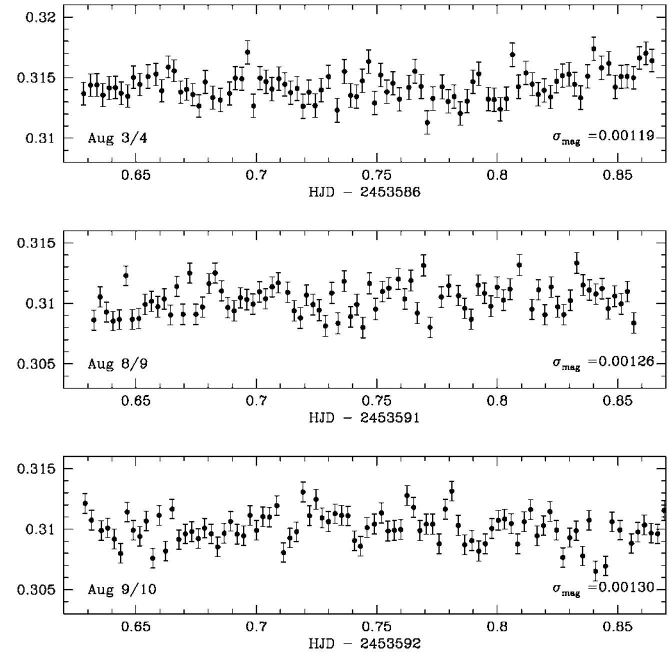

FIG. 3.—Plot of 16.95 hr of photometric coverage of HD 205739 over three nights. Light curves correspond to the data collected on UT 2005 August 3–4 (*top*), 8–9 (*middle*), and 9–10 (*bottom*). The average rms of the individual points ranges between 0.0008 and 0.0010 mag. The standard deviations of the nightly light curves are, from top to bottom, 0.00119, 0.00126, and 0.00130 mag. The data have been binned into two-point bins, resulting in a cadence time of 3.5 minutes.

and 15.6 pixels for the comparison star. The optimum apertures for each target in all the other nights are listed in Table 2.

The final light curves are presented in Figures 3 and 4. Fig-

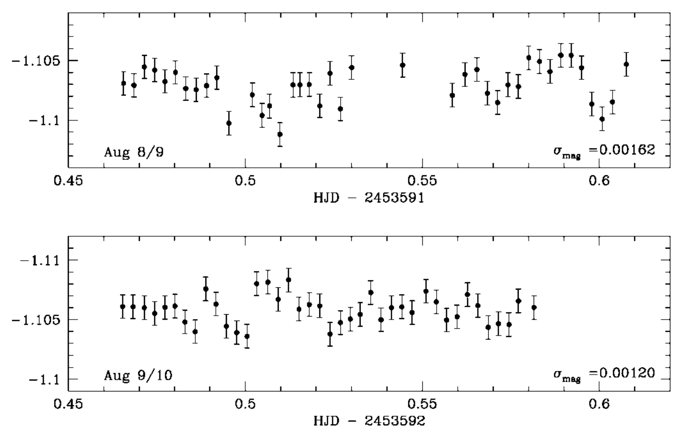

FIG. 4.—Plot of 6.2 hr photometric coverage of HD 135446 over two nights, August 8–9 (*top*) and 9–10 (*bottom*). The average rms of the individual points ranges between 0.0008 and 0.0010 mag. The standard deviations of the nightly light curves are respectively 0.00162 (*top*) and 0.00120 mag (*bottom*). The data have been binned into two-point bins, resulting in a cadence time of 4.0 minutes.

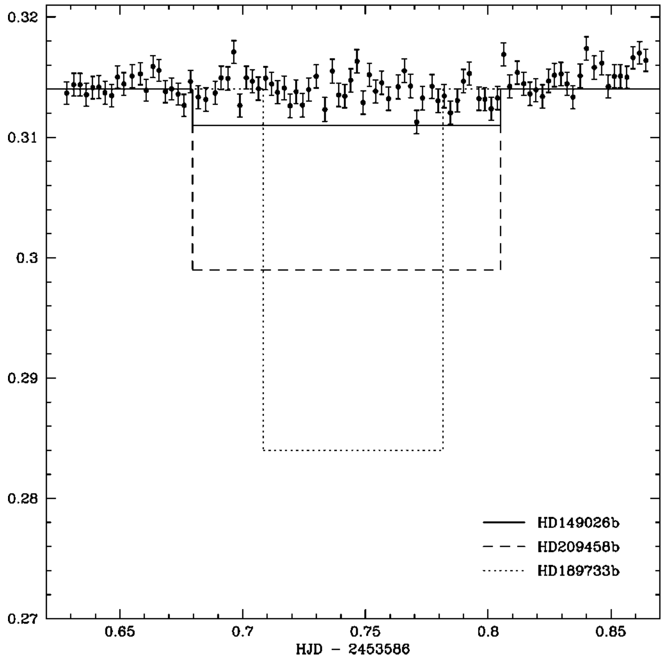

FIG. 5.—Schematic representation of how the three known transits of extrasolar planets around bright stars ($V < 9.0$ mag) would look when superposed on one of our light curves. The solid line represents the transit of HD 149026b (Sato et al. 2005), and the dashed and dotted lines represent the transits of HD 209458b (Charbonneau et al. 2000) and HD 189733b (Bouchy et al. 2005), respectively. The values of Δt and Δmag for each transit are summarized in Table 3.

ure 3 shows 16.95 hr of photometric coverage of HD 205739 over the three nights that this star was observed (August 3–4, 8–9, and 9–10). Figure 4 shows the 6.2 hr of coverage of HD 135446 during August 8–9 and 9–10. The data in both figures have been averaged into two-point bins, resulting in a time of cadence of 3.5 minutes for HD 205739 and 4.0 minutes in the case of HD 135446.

The average rms of the individual points range between 0.0008 and 0.0010 mag, depending on the night. The average standard deviation of the nightly light curves range between 0.00119 and 0.00130 mag for HD 205739 and 0.00120 and 0.00162 mag for HD 135446, indicating that both targets and their comparison stars were photometrically stable to at least those levels of precision during the nights that they were observed.

The similarity in the brightness and color of the targets to their comparison stars minimizes the appearance of differential extinction effects. These extinction effects are also reduced by limiting the photometric follow-up to air masses smaller than 1.65. None of the light curves present differential extinction trends. I believe that the slight 0.003 mag slope between times 0.80 and 0.87 (HJD − 2,453,586) in the top light curve in Figure 3 is real, after discarding extinction and background brightness gradient effects in the frames. Unfortunately, there are no follow-up observations to further investigate the cause of that slope.

TABLE 3
DURATION AND DEPTH OF TRANSITS OF HD 149026b, 209458b, AND 189733b

Planet	Δt (hr)	Δmag (mag)
HD 149026b ……	∼3.0	0.003
HD 209458b ……	∼3.0	0.015
HD 189733b ……	∼1.76	0.030

Scintillation is the limiting factor to the photometric precision of this setup. Equation (10) from Dravis et al. (1998) yields a scintillation photometric variation[3] of 0.0012 mag for the average of two 25 s exposures at an intermediate air mass of 1.3. That value is in agreement with the standard deviation of the light curves in Figures 3 and 4.

4. APPLICATION TO EXTRASOLAR-PLANET TRANSITS

The expected median transit depth of giant close-in planets is 0.01 mag and the duration of those transits is typically several hours. By comparing these numbers to the results presented in the previous section, one can conclude that a typical extrasolar-planet transit would be easily detected around bright stars with the telescope setup and the observational plus data reduction strategies used at Swope.

To reinforce this statement, I provide in Figure 5 an schematic representation of how the three known transits of extrasolar planets around bright stars ($V < 9$) would appear when superimposed on one of the light curves obtained in this work. The solid line simulates the transit of HD 149026b (Sato et al. 2005), the dashed line simulates the transit of HD 209458b (Charbonneau et al. 2000), and the dotted line simulates the transit of HD 189733b (Bouchy et al. 2005). The transits have been represented by boxcar functions instead of using a model that is closer to their real shape, to emphasize their duration Δt and their depth Δmag as compared to the observed light curves, represented by the filled dots. The values of Δt and Δmag have been estimated from the original papers and are summarized in Table 3.

The main conclusion from Figure 5 is that the three extrasolar-planet transits would have beeing easily detected by the setup that we are using at Swope.

5. SUMMARY AND CONCLUSIONS

This paper shows the results of a three-day test campaign aimed at achieving millimagnitude-precision photometry of bright southern stars ($V < 9.0$ mag) with a 1 m telescope and a standard CCD. The targets for these tests were HD 205739

[3] Assuming a telescope aperture diameter of 66 cm, an observatory height of 2100 m, and an atmospheric scale height of 8000 m.

and HD 135446, two 8th magnitude stars with no previous record of photometric variability.

Stars that bright would inevitably saturate, given the collecting area of the telescope and the minimum exposure time of 5 s imposed by the displacement rate of the CCD shutter. In the absence of neutral-density filters at Swope, saturation can be avoided by implementing an aperture stop to reduce the aperture of the telescope, dimming the stars by 2 mag, and making it possible to image objects as bright as $V = 6.5$ without saturation.

The observations consisted of follow-up photometry of HD 205739 over three nights, for a total of 16.95 hr. HD 135446 was also monitored over two nights, for a total of 6.2 hr. Special care was taken to keep all sources of noise below the photometric precision goal of 0.001 mag. The total number of counts in both the targets and the comparison stars was at least 10^6 photoelectrons. The level of counts per pixel never exceeded the linearity limit of the CCD. The level of counts in the combined bias and master flat-field calibration frames was also at least 10^6 photoelectrons. The stars were monitored only at air masses under 1.65 to reduce differential extinction effects. The stars were also placed and kept over the same pixels each night to minimize errors caused by the pixel-to-pixel sensitivity variation of the CCD. Finally, to minimize the effects of extinction, we chose as comparison stars nearby objects with magnitudes and colors that were similar to the targets.

The aperture photometry was performed by iteratively generating differential photometry light curves for different combinations of apertures of the target and the comparison star. The light curves selected were those that resulted from aperture combinations that gave the smallest standard deviations.

The resulting light curves show that it is possible to achieve precisions between 0.0008 and 0.0010 mag in individual points with a cadence of less than 4 minutes. The results also show that it is possible to keep the level of precision of the light curves below 0.0013–0.0015 mag for extended periods of time (at least 6 hr).

The precision of the light curves is limited by atmospheric scintillation, which, with the telescope aperture diaphragm and the current exposure times (20–30 s), introduces an average photometric variation of 0.0012 mag. Scintillation depends heavily on the diameter of the telescope. Its effect can therefore be reduced to 0.0008 mag if we replace the aperture stop with an inexpensive neutral-density filter. The neutral-density filter will have the same advantage of dimming the stars by 2 mag as the aperture stop, but will not have the inconvenience of the loss in telescope aperture that enhances the effect of atmospheric scintillation.

These tests demonstrate that a 1 m telescope equipped with a standard CCD can be used to obtain high-precision photometry of bright stars by applying very small alterations to its current setup. In particular these telescopes can be used to detect transits of close-in giant planets around bright planet-hosting stars. For example, Swope would have easily detected the transits of the planets HD 189733b, with a depth of 0.030 mag, HD 209458b, with a depth of 0.015 mag, and even the merely 0.003 mag deep transit of HD 149026b.

There are currently no facilities in the Southern Hemisphere pursuing targeted planet transit searches among known planet-bearing bright stars. The Swope Telescope at Las Campanas Observatory will hopefully become the first of those facilities.

Future plans include the replacement of the aperture stop by neutral-density filters, in addition to the extension of these tests to other wavelengths, mainly *UBVRI* Johnson filter passbands. Another technical goal is to try to improve the duty cycle of the observations. In addition, we are starting a targeted search for transits around southern stars with known planets that have not yet been monitored.

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