Observing Exoplanet Transits with Digital SLR Cameras

Colin Littlefield
Department of Physics, University of Notre Dame, Notre Dame, IN 46556; clittlef@nd.edu

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Abstract Using a digital single lens reflex (DSLR) camera, I observed a transit of exoplanet HD 189733 in order to determine the feasibility of using these types of cameras for high-precision photometry. The results were scientifically useful, showing that even though the camera is not explicitly designed for scientific applications, it can nevertheless produce high-quality differential photometry.

1. Introduction

DSLR cameras have revolutionized amateur astroimaging, but they are not optimized for photometry and present a variety of obstacles for obtaining useful data. First, DSLRs generally have a maximum bit depth of just 12 bits, which increases the risk of quantization errors caused by having relatively few steps with which to represent the dynamic range of an image. These errors can prevent the detection of subtle variations in the flux of a star. Second, the sensors in these cameras are overlaid with a matrix of color filters. This is particularly problematic because even though DSLRs have sensors with millions of pixels, only a fraction of those pixels will be covered by a particular color filter. In most cameras, half of the sensor's pixels are overlaid with green filters, one quarter with red filters, and the remaining quarter with blue filters. Thus, there are non-negligible gaps between pixels of a given color, which can create spurious features in light curves as star images drift over different-colored pixels. Third, DSLRs have low quantum efficiency, making them ill-suited for faint objects, and anti-blooming sensors, which can compromise the linearity of the camera's response.

This paper assesses the photometric capabilities of DSLRs by presenting the results of an observation of an exoplanet transit with a DSLR. I first verify that my DSLR's response curve is sufficiently linear for photometry before I describe the procedures that I used to successfully observe an exoplanet transit.

2. Overcoming DSLR limitations

As serious as the aforementioned limitations are, they do not prevent DSLRs from realizing a high level of photometric precision. The camera must be set to record images in its RAW mode, which, as its name implies, saves the raw image data without applying any form of processing. Consequently, it preserves the full 12-bit data from each pixel without compromising the data's photometric quality.

To lessen quantization error, the camera's gain can be decreased by increasing the ISO setting, which reduces the dynamic range and, therefore, the number of electrons which correspond to a single analog-to-digital unit (ADU). Meanwhile, the deleterious effects of the color filter matrix can be largely overcome by defocusing the image so that each star image covers hundreds of pixels. As an added benefit, defocusing the image allows for longer exposure times without the risk of saturation.

3. Linearity

One of the greatest photometric strengths of CCD cameras is their linear response to light, without which a camera would be nearly useless for photometry. Thus, characterizing a DSLR's response curve is of the utmost importance for photometry, a task which can be easily accomplished in an indoor setting. I tested the linearity of my Canon EOS 20Da DSLR by pointing it at an unvarying, indoor light source and taking a series of images, changing only the exposure time of each image. The camera was set to record the images using its 12-bit RAW mode, and to reduce the risk of quantization error inherent to 12-bit cameras, I used a relatively high ISO value of 1600. According to the analysis of planetary scientist and imaging expert Roger Clark, the ISO setting which best corresponds to the 20Da's unity gain—the ISO setting at which one electron is converted into one ADU—is ISO 1600 (Clark 2010; Clark finds that unity gain for the 20Da would occur at ISO 1200, but this setting is not available on the 20Da. Instead, I selected the next-highest setting, ISO 1600). Increasing the camera's ISO setting beyond unity gain merely decreases dynamic range without increasing the camera's ability to record a fainter signal.

The test data were analyzed in Iris, a free-but-powerful program developed by Christian Buil (2008) for processing astronomical images. Iris contains many useful features for processing DSLR data, including the ability to extract each of the four color channels—two green, one red, and one blue—from a RAW image. I split each image into its channels and measured the average intensity value of the same region in each image. A plot of average intensity against exposure time, which is reproduced in Figure 1, showed a linear response up to nearly 4,000 ADUs (the maximum value is 4,096 ADUs). These findings imply that the sensor's linearity is sufficient to provide useful photometry at ISO 1600 as long as the maximum ADU count is kept below approximately 4,000.

4. Transit of exoplanet HD 189733b

On September 19, 2009, exoplanet HD 189733b transited its star. With a *V*-magnitude of 7.67, a transit depth of 0.028 magnitude, and a number of suitable reference stars, HD 198733 is an ideal test object for detecting exoplanet transits. I detected and measured this transit of HD 189733b with the 20Da DSLR and a polar-aligned Celestron CPC 800 telescope, an eight-inch Schmidt-Cassegrain. I used a piggybacked guidescope for autoguiding. The telescope was also heavily defocused, so that each star image was approximately 35 pixels in diameter. I obtained one hundred, ninety-second exposures at ISO 1600 of the transit before dew and fog forced an early shutdown.

I used Iris for reduction, image alignment, and photometry. I applied flat fields and dark frames to the images before splitting them into their red, green, and blue components. I then performed aperture photometry on each channel, using four nearby bright stars as references. To decrease noise, I averaged the two green channels. Additionally, an outlier identification algorithm rejected individual data points if they varied too far from the median value of nearby data points. This caused two green data points, one blue data point, and ten red data points to be removed from analysis.

Light curves from the green, red, and blue channels are shown in Figures 2, 3, and 4, respectively. To create these light curves and to perform a chi-square analysis of the data, I used a spreadsheet created by Bruce Gary (2010b), a retired professional astronomer who operates the Amateur Exoplanet Archive (AXA). A detailed description of the light curve fitting routine employed in Gary's spreadsheet (NASA 2009) can be found at:

http://nsted.ipac.caltech.edu/NStED/docs/datasethelp/AXA/html

Table 1 compares the observed data for each channel with accepted values found on the AXA. The green and blue channels showed comparable timing anomalies, but the red channel, which had the lowest signal-to-noise ratio, did not.

Depth is consistent in each band, but the measured length of the transit in the green band is longer than it is in the blue and red channels. Also, while the timing anomalies of the blue and green channels suggest that the transit was late, the red channel timing anomaly indicates that it came early. These differences between the three channels are probably attributable to systematic errors caused by image rotation across an imperfect flat field and differences in color between HD 189733 and the reference stars. Because there are relatively little out-of-transit data to provide a baseline, it is difficult to determine the effect of these systematic errors with a high degree of confidence.

5. Discussion

Defocusing and using a high ISO setting—that is, a low gain—were probably the two most important factors in the high quality of the photometry. Photometry of star images spread across hundreds of pixels is unlikely to be substantially impacted by image drift and changes in stars' point spread functions, even with measurable gaps between pixels, and the high ISO setting assures that quantization errors should be relatively minimal.

The transit light curve for the green channel showed the highest signal-to-noise ratio. The red channel had the worst signal-to-noise ratio, although it was still useable. This is not surprising, as most off-the-shelf DSLRs contain built-in infrared blocking filters to improve color balance for daylight photography. These filters also curtail the red response in DSLRs, and the 20Da's red sensitivity plummets after the hydrogen-alpha wavelength of 656 nm. In addition, since a RAW image contains two distinct green channels, both green channels can be averaged together to reduce noise. The relatively low scatter in the light curve of the combined green channels demonstrates that for moderately bright stars, very high-precision photometry is feasible with a DSLR camera. Even the red and blue channels, while noisier than the green channels, were still quite useable.

Much of the observed scatter in the light curves is likely attributable to electronic noise. Since DSLRs have peak sensitivities in the green part of the spectrum, the signal-to-noise ratios of the blue and red channels will tend to be worse than that of the green channel. Additionally, an examination of the 20Da's dark frames from the evening showed that the blue and red channels had standard deviations of 19.5 ADUs and 17.5 ADUs, respectively, whereas the corresponding figure for the averaged green channel was just 13.5 ADUs. Clearly, the green data is less noisy than the data from the other channels. Since sensors in DSLRs are not cooled, they will perform better on cooler nights than on warm ones.

6. Conclusion

Other people have demonstrated that DSLRs can provide precision, cost-effective photometry. For example, Buil (2009) has detected exoplanet transits with a DSLR, as have AXA contributors Nicolaj Haarup (2009) and Gregor Srdoc (Gary 2010a). In addition, DSLRs can provide very accurate photometry of bright variable stars with only a standard camera lens and tripod, and many AAVSO observers have obtained excellent DSLR photometry of the ongoing eclipse of Epsilon Aurigae. DSLRs offer wider fields of view than CCD cameras of comparable cost and can be run without either a computer or an external power supply. Although they have lower quantum efficiencies than CCD cameras and lack cooling, internal guiding, and true photometric color filters, they are eminently capable of the precision necessary to observe exoplanet transits.

Finally, I originally submitted photometry of this particular transit to the AXA within days of the event. However, I subsequently reprocessed the data with different photometric apertures, which resulted in better photometry. Consequently, the data presented here are slightly different from the earlier version that I sent to the AXA.

7. Acknowledgements

I wish to express my gratitude to the Physics Department of the University of Notre Dame, which provided some of the equipment necessary to perform the observations described in this paper. In particular, Professors Peter Garnavich and Terrence Rettig provided invaluable guidance. Lastly, the resources made available by Bruce Gary through the AXA greatly facilitated these observations and the subsequent analysis.

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Table 1. HD 189733 transit parameters derived from blue, green, and red channels.

	Depth (mmag)	*Length (hrs)*	*Timing Anomaly (min)*
Blue Channel	28.5 ± 1.0	1.71 ± 0.05	3.0 ± 1.6
Green Channel	28.5 ± 0.9	1.79 ± 0.04	4.6 ± 1.3
Red Channel	28.8 ± 1.2	1.67 ± 0.05	–3.2 ± 1.5
Accepted Values	29.0 ± 0.4	1.70 ± 0.03	—

A chi-square analysis of the data was performed using Bruce Gary's Light Curve Creation Spreadsheet (Gary 2010b). The timing anomaly estimates assume an orbital period of 2.2185733 days and a transit epoch of HJD 2453988.80336. Both figures were obtained from the Exoplanet Transit Database of the Czech Astronomical Society (Poddany et al.*; http://var2.astro.cz/ETD/index.php).*

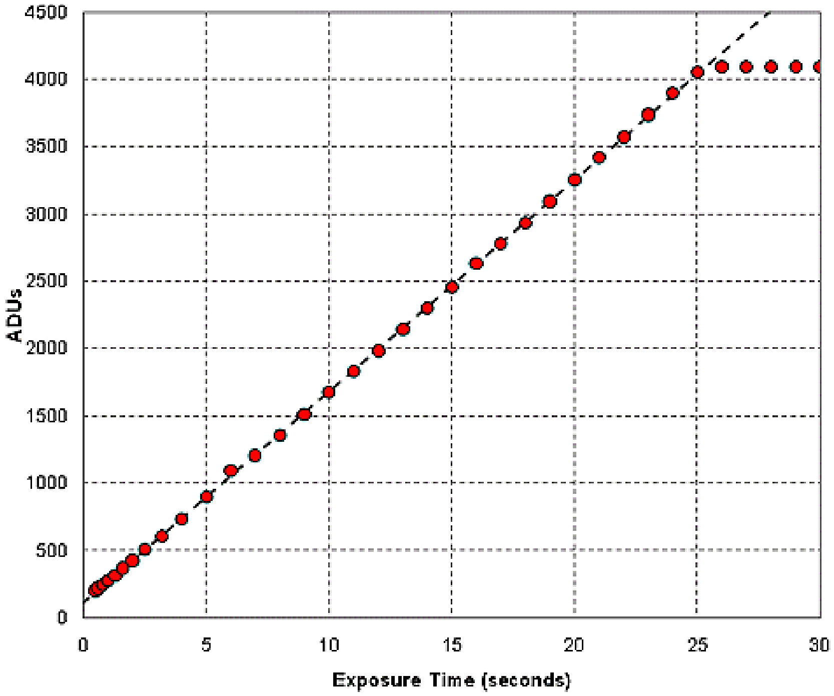

Figure 1. Linearity of the Canon 20Da. I tested the linearity of the Canon 20Da by pointing it at a constant light source and increasing exposure time in successive images. This graph plots average intensity of the same region in each image as a function of exposure time. The relationship between intensity and exposure time is linear to approximately 4,000 ADUs at ISO 1600, which is very close to the limit of 4,096 ADUs of the 12-bit camera.

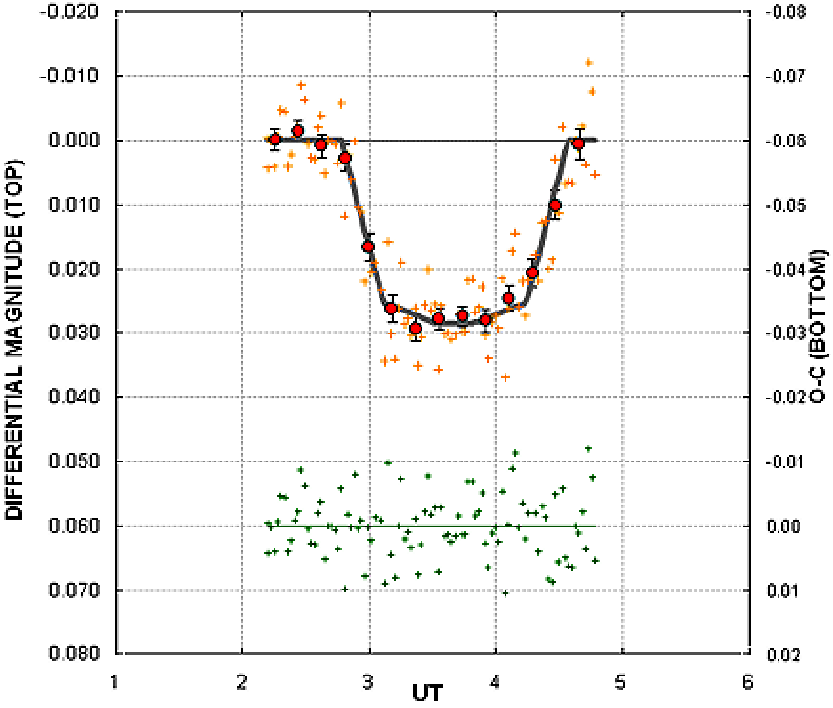

Figure 2. HD 189733b Transit, DSLR Green Channel. I measured the flux of HD 189733 and compared it to the sum of the fluxes of four nearby reference stars to produce this light curve of the differential magnitude of the transit of HD 189733b. The small crosses represent individual images, which were 90 seconds long at ISO 1600 with the telescope significantly defocused. Larger circles with error bars denote five-image, non-overlapping averages, and the plot below the light curve shows the residuals from the transit model. Finally, systematic errors, such as air mass curvature caused by differences in star colors, have been removed. All three light curves were created with Bruce Gary's Light Curve Creation Spreadsheet, version 9908 (Gary 2010b).

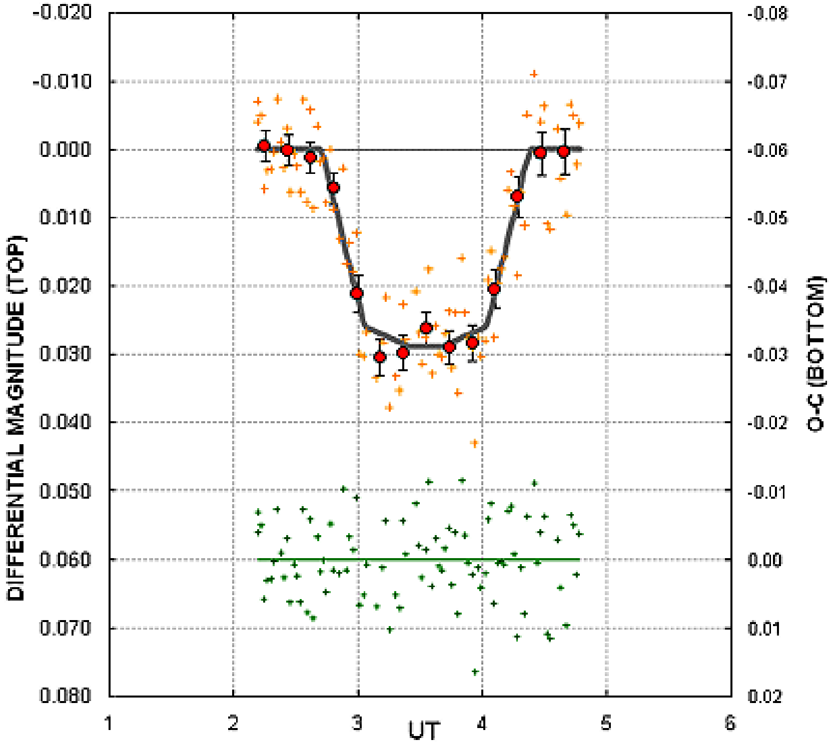

Figure 3. HD 189733b Transit, DSLR Red Channel. Individual images are 90 seconds long, and the bins combine five non-overlapping images. Residuals are shown beneath the light curve.

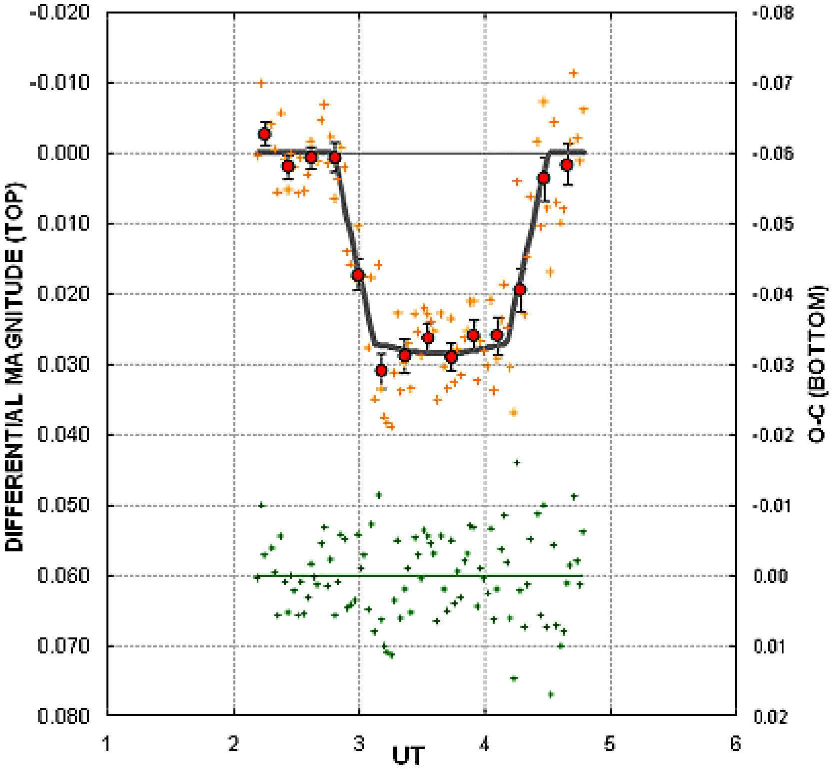

Figure 4. HD 189733b Transit, DSLR Blue Channel. Individual images are 90 seconds long, and the bins combine five non-overlapping images. Residuals are shown beneath the light curve.