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Exoplanet Observing Tips

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Abstract

Exoplanet transit lightcurves with depths less than ~25 mmag require observing practices that challenge the amateur and professional alike. The gold standard of 2 mmag precision per minute during a 6-hour observing session is possible, but difficult – especially using amateur hardware. Pitfalls are present in almost every aspect of observing and image analysis, but perhaps the most important, which is too often neglected, is the use of same-color reference stars. Different-color reference stars affect transit depth, shape and timing. Transit observations are used to illustrate these effects and a simple procedure for selecting same-color reference stars is presented.

1. Introduction

Procedures commonly used for observing and processing images of variable stars may be inadequate for exoplanet transits. When variations of 10 to 25 milli-magnitude (mmag) are to be measured during a 6-hour observing session subtle effects that can be regarded as “second order” for cataclysmic variable stars, undergoing >100 mmag changes during the same period, become “first-order” effects for the exoplanet transit lightcurve (XLC).

This article describes a few “good practices” for the XLC observing phase. A more extensive treatment is given for one aspect of the image analysis phase: the need to select reference stars having the same color as the target star.

2. Observing Phase Precautions

Flat fields are sometimes taken without subtracting dark frames with the same exposure. This can lead to a master flat frame sprinkled with hot and cold pixels that would have been removed had darks been used. The magnitude of these defects can be especially large for old CCDs. During a 6-hour XLC observation the target star and reference stars will move across the CCD pixel field and any defects along these paths will produce systematic errors in the XLC. Always use dark frame calibrations when acquiring flat frames.

A master dark frame should be free of systematic defects and have a low level of stochastic noise. Systematic defects can be produced by assuming that the master dark frame can be created when the CCD is cooled to one temperature and then used for XLC observations taken at another temperature. It is a

good observing practice to set the CCD cooler to a coldest possible temperature prior to XLC observations, and acquire a dozen or more dark frames before and after the XLC observations. If an insufficient number of dark frames are taken, or if they are made at a different temperature than the XLC observations, any deviations from perfect will lead to slowly changing systematic variations in the final XLC.

Auto-guiding during the entire XLC observing session will reduce movement of the star field across the CCD pixel field, and this will reduce systematic effects related to imperfect flat fields and imperfect master dark frames. However, even if the auto-guiding is perfect the star field will move. The amount of movement will be proportional to the polar axis alignment error. The auto-guider star may stay fixed to the same pixel location on the auto-guider chip but the location on the sky for the auto-guider star will be a center of rotation for the image on the main CCD chip. A polar axis alignment error of only 1/2 degree can lead to an image rotation of 30 'arc (depending on source declination), or 10 pixels for my telescope system. Therefore, it is important to achieve a polar alignment accuracy of ~0.1 degree.

Differential photometry requires the presence in the same image as the target star at least one bright and unsaturated star for use as reference. Several reference stars will reduce scintillation noise, and if they surround the target star it's reasonable to expect that the additional stars will reduce systematic effects related to an imperfect flat field. Thus, a large field-of-view (FOV) is desirable, and this means there's an incentive to use a focal reducer (or “telecompressor”) lens. The farther the focal reducer lens is placed from the CCD chip, the larger the FOV. However, it is also

true that the farther the focal reducer is placed from the CCD chip (than intended in its design), the greater are the optical degradations, such as coma. The size of these degradations will increase with distance from the optical “center” on the CCD image (which hopefully is somewhere near the center of the FOV). If during a 6 or 8-hour observing session the focus changes and is not corrected the point-spread-function (PSF) will become different near the FOV corners and edges compared with near the FOV center. This will cause the percentage of the PSF that’s inside a photometry aperture to vary with image location. This, in turn, will produce a systematic error related to how the focus changed. Therefore, if a focal reducer is used it is important to place it at the designed distance from the CCD chip.

Plate scale, the number of “arc per pixel, should be matched to the observing site’s “atmospheric seeing” and it must also meet the spatial sampling criterion for precision photometry of at least 3 pixels per full-width half-maximum (FWHM) of the sharpest image’s PSF. For example, if the best FWHM is 2.5 “arc, the plate scale should be <0.8 “arc/pixel. This requirement places a constraint on how much FOV increase can be produced using a focal reducer.

These are a few precautions that should be considered before an observing session. In my opinion, however, the most important precaution for achieving accurate XLCs occurs after the observing session, during the image analysis phase. It has to do with choosing the best star, or stars, for use as reference. This is the subject of the rest of this article.

3. Atmospheric Extinction Spectrum

Because amateurs observe exoplanet transits through an atmosphere it is not sufficient to choose a reference star that is brighter than the target star, unsaturated and non-varying. This is because each star’s flux changes with air mass at a rate that depends on the star’s color. Blue stars fade with increasing air mass faster than red stars. To understand why this occurs let’s review what causes star light to fade with increasing air mass.

There are three sources for atmospheric extinction, listed here in the order of their importance: 1) Rayleigh scattering by molecules, 2) Mie scattering by atmospheric aerosols (dust), and 3) resonant absorption by three atmospheric molecules (oxygen, ozone and water vapor). Figure 1 is a plot of the spectrum of Rayleigh scattering for the CCD response wavelength region.

Figure 2 plots aerosol scattering for four site altitudes. Figure 3 shows the sum of these two scattering

components compared with measured zenith extinction at a 4600-foot altitude site.

Notice in these figures that atmospheric extinction increases with decreasing wavelength. The effect is greatest for the B-band filter.

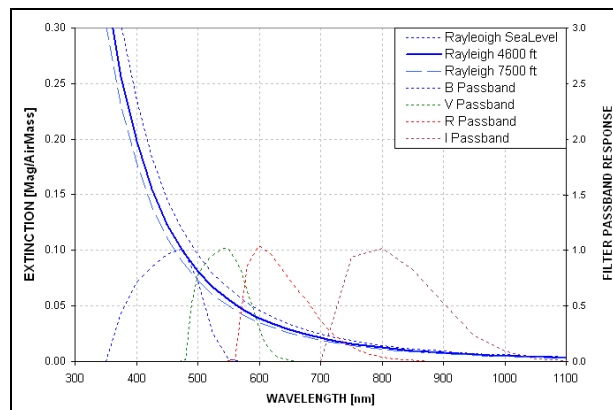


Figure 1. Rayleigh scattering spectrum for 3 observing site altitudes. Typical spectral response curves are shown for B, V, Rc and Ic filters.

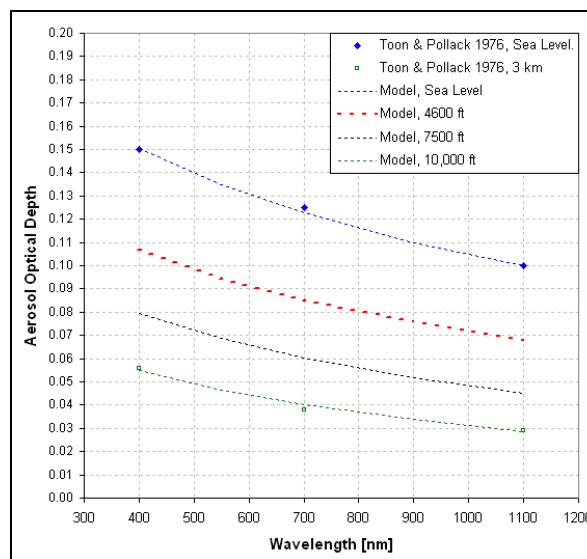


Figure 2. Aerosol scattering spectrum for 4 observing site altitudes.

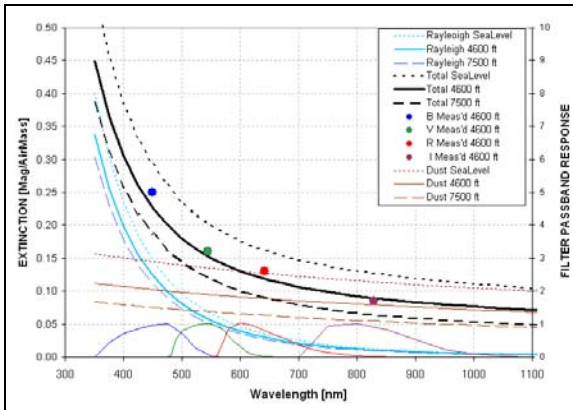


Figure 3. Sum of Rayleigh and aerosol scattering compared with measurements at a 4600-foot site.

4. Star Color Affects Zenith Extinction

Stars radiate with a blackbody spectrum, as a first approximation. The next figure shows blue and red star blackbody spectra in relation to a B-band response function.

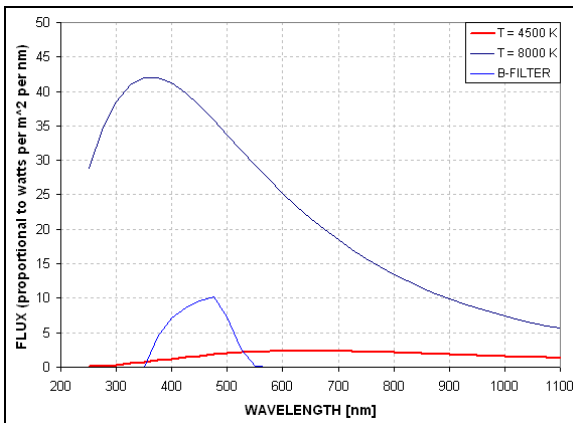


Figure 4. Blackbody spectra for blue and red stars in relation to B-band response function.

Throughout the B-filter passband the red star has increasing flux with increasing wavelength, whereas the opposite is true for the blue star. The flux-weighted wavelength for the blue and red stars is 445 nm and 467 nm, respectively. The flux-weighted extinction coefficients are 0.244 and 0.228 magnitude/air mass. In other words, a blue star fades with increasing air mass faster than a red star.

Consider the case of a target star (the one undergoing an exoplanet transit) with red and blue stars nearby that are otherwise suitable for use as a reference star. Figure 5 shows what can be expected for a lightcurve when either star is used for differential photometry reference.

Clearly, for B-band it is important to choose reference stars that are approximately the same color as the target star. Although use of R-band or I-band filters will have smaller effects than the 10 mmag systematic error shown in this figure, effects correlated with air mass have been seen using these filters.

Unfiltered observations are also subject to reference star and target star color mismatches. The next figures illustrate this. Figure 6 is a lightcurve of an exoplanet using a properly-matched reference star. The out-of-transit (OOT) baseline level is “flat.”

Figure 7, however, was produced using blue stars for reference. Although the plot is less noisy, because more reference stars were used, the OOT baselines are curved. The curvature is in the way that is expected, with symmetry about transit (~5 UT).

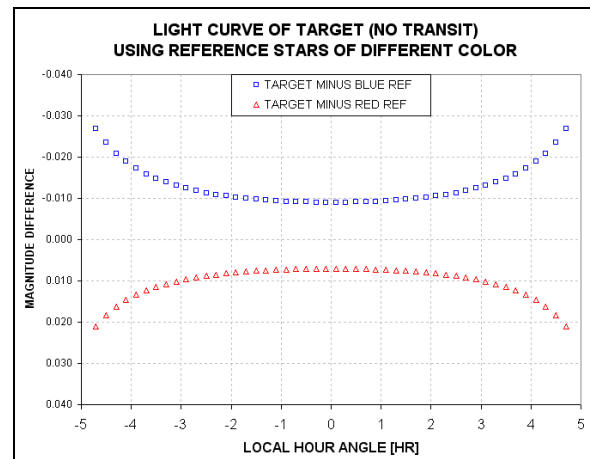


Figure 5. Model lightcurves for observations of a typical color star with a B-filter using nearby blue and red stars for reference.

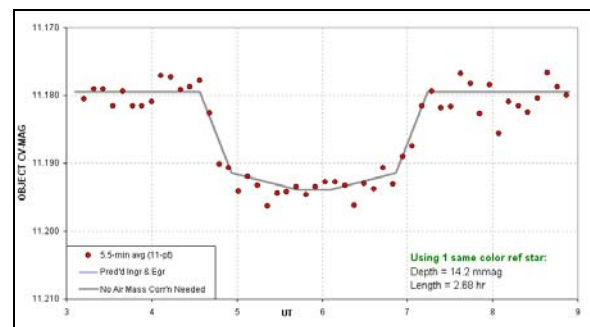


Figure 6. Measured exoplanet lightcurve using a same-color reference star.

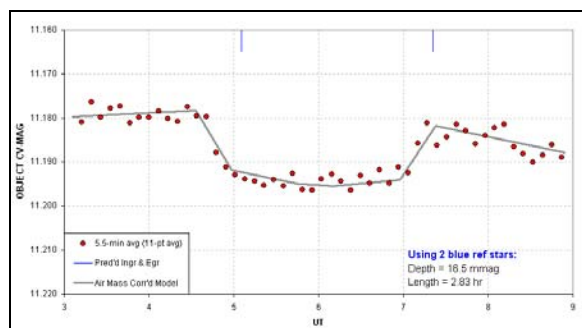


Figure 7. Measured exoplanet lightcurve using two blue reference stars.

The same XLT measurements were processed using a red star (not shown), and the curvature is opposite that for the blue reference stars. Readings of the three lightcurves show a systematic change of measured transit depth, length and mid-transit timing. The depth readings are 13.5, 14.4 and 16.0 mmag for use of blue, same-color and red reference stars, respectively. The transit length readings are 2.71, 2.68 and 2.74 hours, for use of blue, same-color and red reference stars. The mid-transit times are 5:56.7, 5:54.2 and 5:52.2 UT for use of blue, same-color and red reference stars, respectively. Thus, systematic effects are present at the level of 1 mmag for depth, 0.04 hour for length and 2 minutes for mid-transit times.

It therefore makes a difference whether same-color or different-color reference stars are used for processing exoplanet lightcurves.

5. Finding Same-Color Stars

Figure 8 shows typical passband shapes for BVRcIc and JHK filters. It has been shown that J-K star colors are highly correlated with B-V, V-R and R-I star colors (Caldwell et al, 1993, Warner, 2007). The correlations break-down for very red stars, but it is rare that very red stars will be sought for use as reference. Since J and K magnitudes exist for almost all stars brighter than 18th magnitude (V-band), and since J and K magnitudes are conveniently available in most star map programs (such as TheSky6 and Canopus), it is feasible, and convenient, to find same-color reference stars using only the J and K magnitudes.

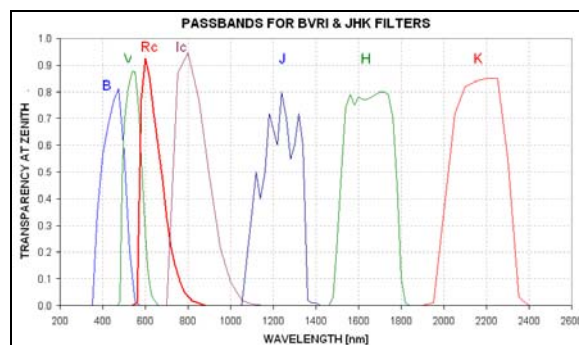


Figure 8. Passbands for BVRcIc and JHK filters, scaled to show typical zenith transparency.

6. Conclusion

One of the most-overlooked yet important requirements for achieving high quality exoplanet transit lightcurves is the use of same-color reference stars.

7. Acknowledgements

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8. References

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