Chapter 7
Filter Choices

You are probably wondering why an entire chapter is devoted to the matter of which filter to use for a specific observing session. Until recently the most common filter choices were B, V, Rc and Ic, whose transmission functions are shown in the top panel of the following figure.

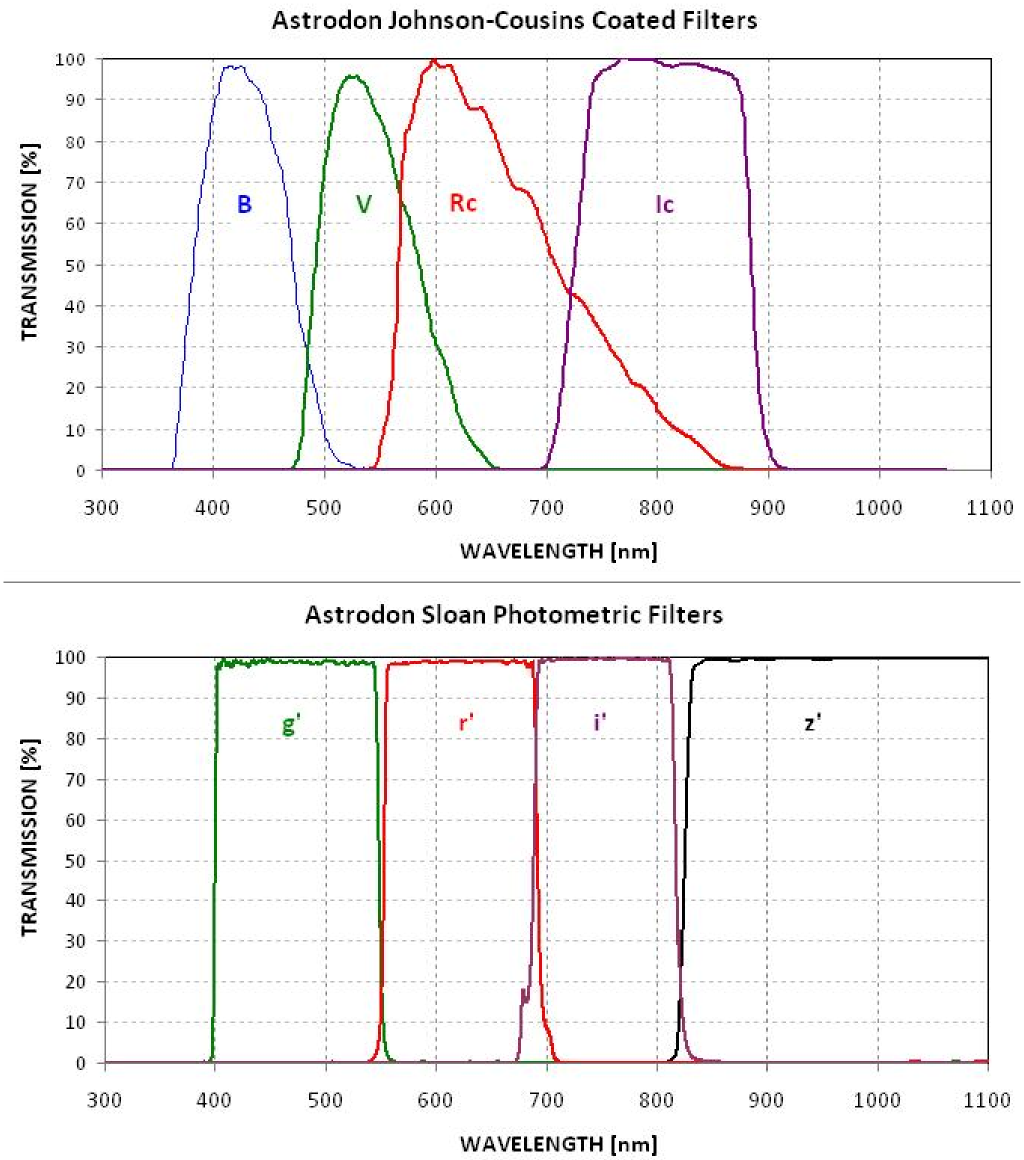

Figure 7.01. *Filter transmission for the two main filter set choices (transmission functions were kindly provided by Don. S. Goldman, PhD, Astrodon Imaging, Orangevale,CA).*

Most amateur observers now use an R-band filter for all their exoplanet transits, and they produce good quality light curves. So what's wrong with just adopting R-band for all exoplanet observing? The simple answer is that "it's not optimum for most situations."

Now we have the additional filter choices of g', r', i' and z'. This is the so-called SDSS filter set because they were designed on behalf of the Sloan Digital Sky Survey. Passband responses for the SDSS filter set are shown in the lower panel of Fig. 7.01.

Two more filters should be considered for exoplanet observing: CBB and NIR. The spectral transmission shapes for these filters is shown in Fig. 7.02. (The CBB filter is manufactured and sold by Custom Scientific; a CBB is also manufactured by Astrodon and sold by Adirondack Astronomy with a product name XOP-BB, www.astrovid.com). The CBB filter is similar to a clear filter because it passes about 93% of a typical star's light, but it has a "turn-on" wavelength of about 480 nm, the same as a V-band turn-on. The NIR filter (Near Infra-Red Luminance, manufactured by Astrodon) is similar, as it passes wavelengths longer than ~710 nm, but only about 32% of a typical star's light is at these long wavelengths. Both CBB and NIR are useful for two main reasons: 1) they block blue light, thus reducing sky background levels when the moon is up, and 2) the light they pass has smaller atmospheric extinction than a clear filter, thus enabling an observing period to be extended to times when elevations are very low.

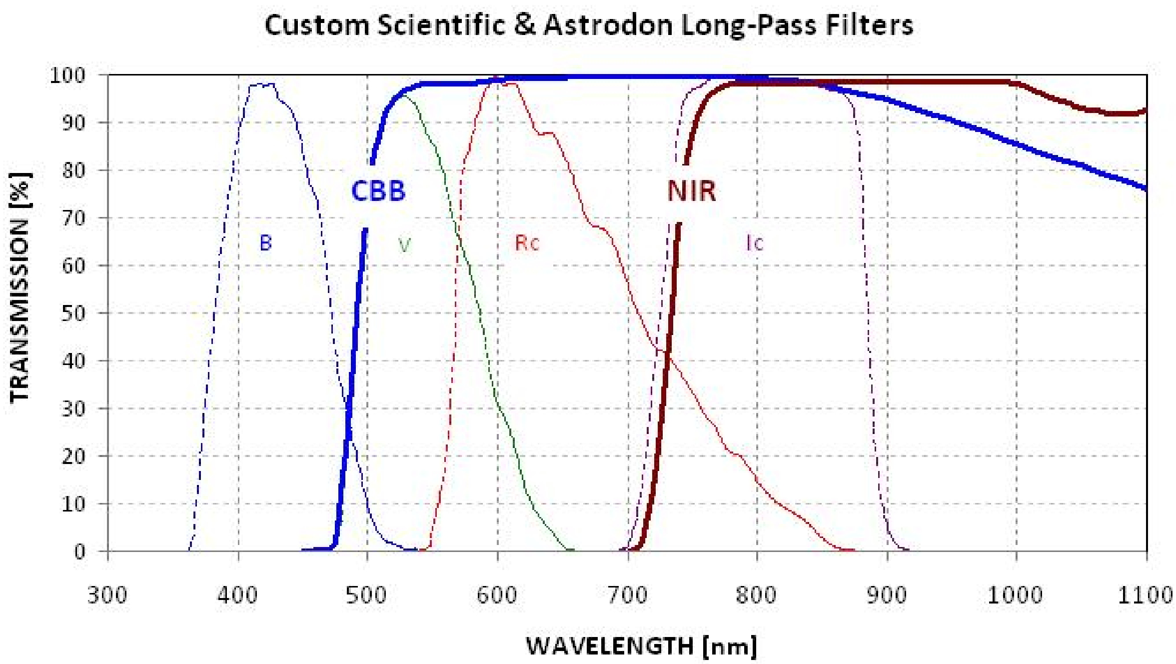

Figure 7.02 *Long pass filter transmission functions. The Custom Scientific CBB passes longward of ~480 nm and the Astrodon "NIR Luminance" filter passes longward of ~ 710 nm.*

My first exoplanet transit observation was made with a V-band filter because that's what a professional astronomer recommended. I didn't give much thought to the matter, until maybe a year later when I noticed that R-band produced light curves with better SNR. R-band then became my default filter choice. I had a "clear" filter (parfocal with the others), but I only used it for the faintest

BTEs. My thinking at the time was that R-band had fewer systematic effects than the clear filter but for very faint BTEs systematic effects were less important than the need to simply "detect" the transit.

Two years ago, when I wrote the First Edition of this book, I included (in Chapter 14 of that edition) a demonstration of the effect of using reference stars that were redder or bluer than the target star for images made with a clear filter. In one case the light curve was "bowed" upward, symmetric about transit, and in the other case the bowing was downward. The measured "air mass curvature" effect was consistent with the explanation that without a filter the effective wavelength of a star could shift enough to cause blue stars to exhibit larger atmospheric extinction than red stars. I concluded that it was "dangerous" to observe exoplanet transits unfiltered (or with a clear filter).

Calculations (described in the First Edition) showed that a filter that blocked blue light should have significantly smaller "air mass curvature" since most of the blue star's greater extinction was due to just the blue component of its light. I therefore recommended use of a blue-blocking filter, or CBB filter, which "turned on" at the same wavelength as a V-band filter (~ 480 nm) and never "turned off" at longer wavelengths. By not filtering out long wavelength light the CCD's reduced response at longer wavelengths determined the spectral response function of the filter/CCD combination. CBB-band, as I refer to it, removed only about 7% of a typical star's light, yet my calculations showed that it should reduce systematic effects by about a factor of 7.

At the time I wrote the First Edition I hadn't verified with observations the merits of using a CBB filter, and I mistakenly allowed the impression to exist that the R-band filter should be the default choice for exoplanet observing. During the last two years I have seen the merits of observing with a CBB filter (and also unfiltered, when I was "forced" into a backend optical configuration that couldn't accommodate a CFW) and this caused me to revive interest in the CBB-band option, as well as NIR as a new option. I am now able to make the following statement:

A "clear with blue-blocking" filter (CBB)
should be an amateur's default choice for exoplanets.

And I will expand on this by also stating that:

A "near infra-red" filter (NIR)
should be used when observations at low elevations are necessary
or when a nearly full moon is above the horizon.

The CBB filter has most of the high SNR advantages associated with unfiltered observing, yet it has most of the reduced systematics advantages associated with V-band and R-band observing. For most BTEs (those fainter than 10^{th} magnitude), and for most telescopes (smaller in aperture than ~ 16 inches), I recommend that CBB-band be the first filter that you consider using. The most important exceptions are when a complete transit requires observing at low elevations or when a nearly full moon is causing bright sky backgrounds, for which the NIR filter is to be preferred.

So why would a professional astronomer recommend observing exoplanets with a V-band filter (or I-band, or even the longer wavelength of z-band)? It's because they use large aperture telescopes that afford plenty of photons, and even with a narrow band filter their SNR is large. For the professionals, therefore, the SNR loss associated with a filter as narrow as V-band is a small penalty that's worth the benefit of reduced systematics. I am frequently reminded that professional astronomers take for granted the large collecting area that their large aperture telescopes afford, and they forget the plight of us amateurs trying to work with maybe 5% of their photon plenitude.

When the question of what filter to use is addressed by observers experienced with AAVSO type observations it is natural for them to think in terms of which filter affords the best possibility for inter-comparison between observers, as if two or more observers will be needed to create an exoplanet transit light curve. I know of only one case where this has been a valid concern in the past: the 2009.02.13 transit of HD 80606, which lasted ~ 12.6 hours and therefore required more than one observer's data for piecing together a transit light curve. With a standard filter, such as V-band, adjustments can be made for telescope system star color systematics (i.e., CCD transformations) so that each observer can present their portion of the transit light curve using a standard magnitude system to facilitate comparison with data from other observers.

Before you conclude that using V-band (or R- or I-band) filters are a good idea because it allows many observers to combine their portions of a light curve, consider the following. This BTE has a period of 111 days, the longest for any known transiting exoplanet. No other exoplanet has such a long transit (with so few opportunities for characterizing transit properties), so this is a rare example of when special attention should be paid to the use of standard filters. Note that among the 5300 transits that occur during a typical year, only 3 of them (0.06%) are by HD 80606. Of the 46 known BTEs all except HD 80606 have transit lengths less than 4.6 hours. The median transit length of the presently known 46 BTEs is 2.91 hours, and the median interval between transits is 3.08 days. Single observing sessions can produce data for a complete transit on many occasions each year for 98% of the known BTEs. The AXA has very few transit events tat were observed simultaneously by two or more observers at significantly different longitudes. The need for inter-comparing data from many observers is essentially non-existent, so the argument for using standard filters (BVRcIc) that can be "CCD transformed" to standard magnitudes has negligible validity for observers of exoplanet transits.

Another argument that has been presented for using one of the standard filters instead of a broad bandpass filter (such as clear or CBB or NIR) is that the broad bandpass filters have large "throughputs" (lots of photons), and this requires short exposures, which in turn mean that each short exposure image will suffer from large scintillation noise. This complaint is baffling since the effect of scintillation on the average of 10 short exposures is the same as the scintillation of one exposure 10 times as long. The scintillation argument is frequently misunderstood, as it is also used to argue for the benefits of defocusing – which I will address in a later chapter (it's a false argument). Scintillation needs to be considered in terms of its effect on a "per observing session unit of time" basis, not its effect on single exposures, so whenever you hear about the need for something on the basis of scintillation, pause and ask yourself if the argument makes sense.

Another argument for sticking with V-band is that R-band filters, as well as CBB and clear, include H-alpha emission from stars, which has been found to vary for some stars. Recall that H-alpha emission occurs at 656 nm, and its ~ 0.1 nm wide (i.e., it constitutes 0.05% of the R-band width, and < 0.02 % of the CBB and clear filter width).

A statistical analysis of the Amateur Exoplanet Archive, which now has over 640 entries by amateurs, shows a preponderant preference for the R-band filter. 53% of the AXA data submissions employed an R-band filter, and 26% use a clear filter (or CBB filter, or are unfiltered). In other words, 83% of observers chose either an R-band or clear type filter (all of which include the H-alpha emission line), while only 11% chose a V-band filter. (Ironically, the V-band observations at AXA have the greatest percentage of poor quality light curves.) V-band filters may serve the professionals well, but amateurs have shown a preference for using R-band as a first choice (and C or CBB for second choice), and there can be little doubt that these choices have produced a wealth of useable exoplanet transit light curves.

Not every observing situation is best served by using the CBB and NIR broadband filters that I recommend as default choices. These exceptions will call for use of one of the standard filters (BVRcIc) or even a SDSS i' or z' filter. Here's my list of those exceptional situations:

1) One is when the BTE is very bright, such as V-mag ~ 7.7 (HD 209458 and HD 189733). These stars are so bright that SNR is actually "too high" for apertures greater than ~ 4 inches, requiring very short exposures, which cause poor duty cycles (described later). For these bright stars amateurs should consider using one of the standard filters, such as V, Ic or z'. Among these alternatives my favorite is the z' filter. An alternative to changing filters is to observe defocused, which is discussed in Chapter 9.

2) Another situation for not using a CBB filter is when the BTE is very red, or very blue, leading to the probable situation that reference stars can't be found that have a star color similar to the BTE. The reddest BTE is GJ 436 (B-V = +1.52), and the bluest is HAT-P-6 (B-V = +0.34). These would be BTEs for which the CBB filter may not be as good as one of the following (provided the star is sufficiently bright): NIR, V, R or Ic-band, or g', r' and i'.

3) The third situation for using a different filter from CBB (or clear) has already been mentioned: when a nearly full moon is above the horizon causing the sky background to appear to be bright. Notice that I used the word "appear." At night we can't notice that a bright full moon sky is actually blue, just like the daytime sky (only less bright). Using a long wavelength filter, such as Ic, i' or NIR, should be considered for all nights when a nearly full moon is above the horizon, and especially when it is near the target.

4) High air mass observing should be done with one of the long wavelength filters: Ic, i', z' or NIR. Atmospheric extinction is lowest at z'-band, and even quite low at NIR-band. If the target star is faint then CBB may still be preferred because of its greater "throughput" (flux).

5) As stated above, HD 80606 has transits longer than any single observing session, which means that data from two or more observers have to be combined to characterize a full transit. For this one BTE it is recommended that one of the standard filters be used, so that CCD Transformations Equation corrections can be applied to produce magnitudes on a standard scale. These are rare events, occurring no more often than three times per year.

I will mention a couple rare situations that are best handled by using a filter other than the CBB filter. Shortly after discovery of an exoplanet there is value in knowing whether or not transit depth decreases or increases with wavelength. This information provides a constraint on the geometry of the transit chord with respect to the star's disk. When the transit chord has a closest approach to the star center that is less than ~ 0.7 times the star's radius (which is the case for most exoplanets) transit depth will decrease with wavelength. When the chord is farther from star center, such as for a grazing transit, transit depth will increase with wavelength. This pattern is due to limb darkening being greater at shorter wavelengths. For this case transit depth should be measured using a wide spacing of wavelengths, such as B and Ic, or g' and i'.

The other situation calling for a filter other than CBB or unfiltered is when the goal is to monitor transit timing variations, TTV. The purpose for producing high-quality TTV might be to search for anomalies produced by another planet in a resonant orbit, or to search for an exomoon of the known exoplanet. TTV can be done best when there are sharp transitions from OOT (out-of-transit) to ingress and from egress to OOT. Referring to the light curve on the cover of this book, the desire for "sharp" transitions means we want the brightness change at contact 2 and 3 to be as deep as possible, thus causing the slopes to be steeper. This occurs when limb darkening is small (when the star's brightness is almost as great near the limb as at the center). And for a typical star this is the situation at long wavelengths. Therefore, the "sharpest" ingress/egress transitions are observed with such filters as (listed in order of improved sharpness): I-band, i'-band, NIR-band or (best of all) z'-band.

In support of item 4, above, I once observed an exoplanet transit with an I-band filter until it abruptly set behind a nearby mountain at an elevation angle of 7 degrees (air mass = 8). The light curve showed no evidence of distortion due to this rare observing condition. Using z'-band would be even better when the need calls for high air mass observing, especially when the observing site is near sea level.

For all other situations it is possible to achieve good quality light curves using CBB or NIR filters, or even a clear filter. The light curve on the cover of this book was obtained unfiltered, and the reason for its success is that the target was high in the sky for the entire observing session. The light curve is for the exoplanet system WASP-10. This star is somewhat fainter than the median for BTEs (V-mag = 12.7, versus 11.20 median), it is somewhat redder (B-V ~ +1.1, versus +0.63 typical). The median color for stars that can be used for reference, based on the 1259 stars in the Landolt list, is B-V = +0.64. Thus, observing WASP-10 unfiltered might seem risky since few nearby stars are likely to have the same redness as the target star. In a later chapter I'll describe a procedure that I use for dealing with this situation. For now let the cover light curve stand for the notion that although unfiltered observations may produce light curve systematics there are data analysis ways for dealing with them (described in Chapter 18). The payoff for this approach is that clear filter observing provides the highest SNR, which for amateurs is almost always very important.

Probably few observers factor-in the need for a bright autoguider star when they choose a filter for a specific observing session. To minimize systematic errors it is important to keep the star field fixed with respect to the pixel field (to minimize systematics related to an imperfect flat field), and it's therefore important to have a sufficiently bright autoguider star to assure quality autoguiding. When all autoguider star candidates are faint it may be better to use a CBB filter than any of the others, merely to permit good autoguiding.

Occasionally a very faint star is to be observed using a small aperture telescope. This situation forces the use of a CBB (or clear) filter. If systematics are present using such a broad bandpass they probably won't be noticed since the light curve will be too noisy for the defects to show.

If you're fortunate to own a large aperture telescope (e.g., larger than 16 inches), observations can be made alternating between filters. One accomplished observing team, using a 24-inch aperture (Jerry and Cindy Foote), routinely make 3-color light curves of medium bright exoplanets. Deciding which filter will be optimum is an easier task when you have sufficient SNR to alternate between several filters. Large aperture observers will rarely need to use the CBB or NIR filters since they pass too much light; the larger the aperture the greater is the payoff for using such narrow-band filters as V-band and z'-band.

Occasionally I am surprised about something unusual done by an advanced amateur that turns out "better than it should." One of the most interesting was an observation submitted to the AXA by Colin Littlefield, of Indiana. He observed HD 189733 with an ordinary DSLR camera attached to an 8-inch telescope. He processed the 3-color images by first separating the R, G and B images from each RGB image, then producing a light curve for each color. All 3 light curves are good quality and scientifically useful. One of them is shown here.

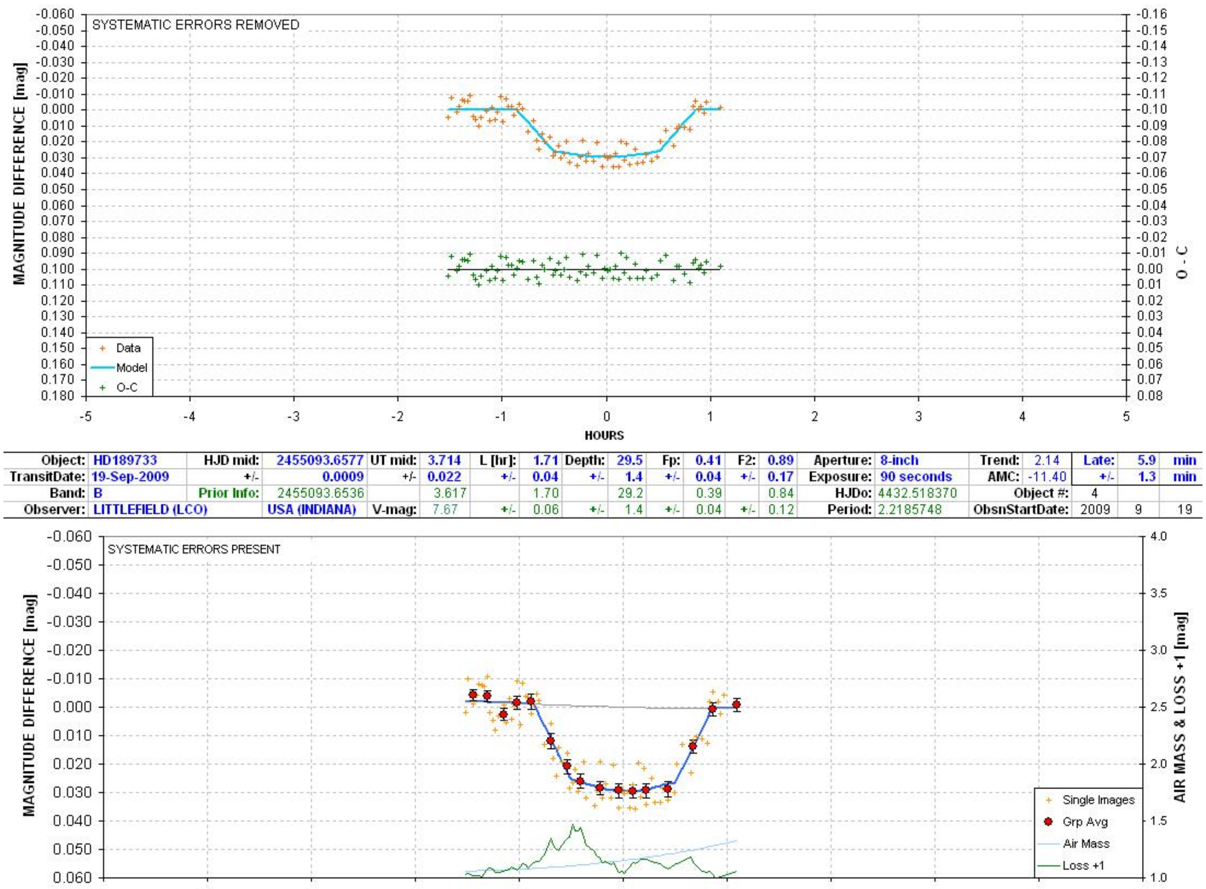

Figure 7.03. *Light curve by Colin Littlefield using a regular DSLR camera. B-images were extracted from RGB images to produce this blue band light curve. Other light curves of similar quality for green and red bands were also produced from the same set of RGB images.*

Finally, the question often arises "What are the differences between observing unfiltered, using a clear filter and using a luminance filter?" Unfiltered is what it says, and photons of all wavelengths that the telescope optics pass make it to the CCD. "Pretty picture amateurs" may want to brighten the final color image by adding a less filtered image (that shows fainter stars). If this is to be done unfiltered, when the color filter wheel rotates to the unfiltered position the focus setting will have to be adjusted (since filters change focus plane location). If a clear filter is used, however, and providing it is "parfocal" with the other filters (same focus setting for all filters), then a focus change would not be needed. A "luminance" filter blocks UV and infra red (IR), passing essentially B, V and R. Removing UV and IR can lead to a sharper image since the optics ahead of the filter wheel (focal reducer and corrector plate) are designed to produce the sharpest images in the BVR region, which means the optical designer may decide to sacrifice image quality at UV and I bands in order to be best for B, V and R bands. A similar situation may arise for an exoplanet observer, such as when a "bright" image is needed to see if background stars are present at locations that could produce problems with precision photometry using a standard filter.

It's possible to construct a decision "flow chart" for choosing a filter. I have not yet done so for my personal use, but the day I feel compelled to optimize observing to the highest level I may rely upon a formalized decision flow chart. It's better for you, dear reader, to think about the material in this chapter and devise your own filter choosing procedure. It will be intuitive at first, and with experience it may become rigorously defined. Exceptions to any rules that apply in most situations will always exist (e.g., XO-2 has an equally bright companion nearby, with the same color, so some of the above guidelines don't apply). So many factors can influence the choice of filter that my advice is to try out various "filter philosophies," evaluate the results and use the one that you like – even if it is V-band!

For those who want "data based evidence" that the CBB and NIR filters are good choices for a typical exoplanet, I have included in Appendix H the results of an observational project to evaluate 5 filter choices by observing with all of them in alternation. I found that the best performing filters for the exoplanet chosen for this case study (CoRoT-3) were CBB, NIR, R, i' and V – in that order!

The question we ended Chapter 5 with can now be answered: what filter should be used for an observation of XO-1 on the night of June 18, 2010. Recall that ingress, mid-transit and egress occur near midnight at elevations within the range 47 to 84 degrees! One hour before ingress the moon will be at an elevation of 81 degrees, and one hour after egress it will be at 35 degrees. This is an unusually favorable observing situation, so we can relax in considering atmospheric extinction. There is no need for the NIR filter's small atmospheric extinction feature. The CBB filter will afford a greater SNR than the NIR filter without any penalties related to extinction. But where's the moon during transit? According to TheSky/Six the first-quarter moon is at 14 degrees elevation, and setting, at ingress. It will be 70 degrees from XO-1. The sky background will therefore only be slightly brighter than without a moon, so the CBB filter is still a good choice.

What a lot of work just to decide on using the CBB filter for the observations of XO-1 on June 18, 2010! Before we can take a break for dinner we need to answer one more question: "When should flat fields begin?"

APPENDIX H – Filter Playoff Observations

Summary of Results

Observations were made of CoRoT-3 on 2009.09.14 using filters CBB, NIR, V, Rc and i' rotated into place in alternation. Exposure times were set in a way that led to similar total flux (and SNR) for the target for each filter. A standard procedure was used for image processing and spreadsheet light curve optimization for each filter. Since for this 5-hour observing session there was no transit the data were fitted using a simple model with three free parameters (offset, slope and air mass curvature). RMS departure from the best model fit was used to assess measurement quality. Since exposure times ranged from 5 seconds to 32 seconds a "figure of merit" was calculated that endeavors to predict the RMS quality of what would have been measured if each filter were used exclusively during the observing session. The figure of merit is proportional to "information rate" (proportional to the inverse square-root of the predicted RMS off a model light curve) using exposure times of 48 seconds and download and settle times totaling 12 seconds (which are typical observing settings for amateur telescopes observing typical exoplanet stars). Such a figure of merit can be described as the speed with which a specific precision can be achieved. The results of these calculations show the following "speed for reaching a precision goal", presented in order of the fastest (and normalized to the slowest filter): CBB (6.3), Rc (2.9), NIR (1.7), i' (1.3) and V (1.0). For this observing situation the CBB filter was about 6 times better than the V-band filter. Since CoRoT-3 is fainter than the typical exoplanet star the same set of 500 images was re-processed with a brighter star assigned to the role of exoplanet. For a "make believe" exoplanet star with V = 11.7 (similar to the median for the list of 46 BTEs) the following figure of merits were determined: CBB (8.1), NIR (5.4), Rc (5.1), I' (4.6) and V (1.0). When an even brighter star was assigned the exoplanet star role (V = 10.2) the results were essentially the same: i' (8.1), NIR (6.8), CBB (6.2), Rc (5.4) and V (1.0).

Introduction

The observations reported here were designed to determine which filter produces the best quality light curves for typical exoplanet observing conditions using amateur hardware and software. I use my Celestron 11-inch (CPC 1100) telescope with a focal reducer placed in front of the CFW/CCD. The CCD is a SBIG ST-8XE (KAF 1602E chip). Autoguiding is performed using the second CCD chip. The CFW contains the following filters, all of which are used in this evaluation: CBB, NIR, V, Rc and i' (where CBB is a clear filter with blue blocking at ~ 480 nm, NIR is a long pass filter with turn-on at 710 nm, V is Johnson V-band, Rc is a Cousins R-band and i' is SDSS i-band). Although additional observing sessions may be used to verify the results reported here the following description of the first observing session, on 2009.09.14, shall serve to illustrate the protocol and analysis procedures for all of them.

Observation Protocol

The observing session was 4 hours long (after which the dome's low-elevation opening obstructed observations). Observations started at air mass 1.2 and data for air mass > 4.5 were not used. CoRoT-3 was observed under out-of-transit conditions. This enabled the measured magnitudes to be fitted using a simple light curve (LC) model with only three free parameters (offset, slope and air mass curvature). It was decided to employ exposure times that produced approximately the same flux for the target star (CoROT-3) for each filter (Arne's suggestion). This led to greatly different exposure times due to the large range of filter throughputs. Filter throughputs for all the filters I use are listed in the following table, and the exposure times used for this "filter playoff" observing session. For the chosen exposure times the star fluxes for the target were approximately the same and so were the SNR's (although SNRs should differ slightly because sky background levels differ with wavelength).

Filter Throughput (at airmass 1.2) and Exposure Times

CLR	100%	
CBB	92%	5 sec
NIR	37%	16 sec
B	6%	
V	19%	32 sec
R	36%	14 sec
I	22%	
g′	26%	
r′	48%	
i′	37%	16 sec
z′	9%	

Images were made in the following sequence: NIR, V, Rc, i' and CBB. Exactly 100 cycles of this sequence were made (prior to the dome obstruction problem), so there are 100 images with each of these 5 filters. Autoguiding was used to maintain the star field fixed to the CCD pixel field (although some wander did occur). Master flats were made on the same night of these observations for each filter using the twilight sky (and a diffuser over the telescope aperture). A master dark frame was made at the end of the target observations (at the same CCD temperature as the target observations). A bias frame was used from a previous observing session. Focus settings were automatically adjusted to compensate for telescope tube temperature changes. Measures were taken so that all images had the same sharpness (FWHM typically 4.5 pixels). All observing was controlled by MaxIm DL (MDL).

MDL was also used for image calibration and measurement. Calibration consisted of bias, dark and flat field corrections. Hot pixels were removed from each image (25% was determined to be "safe" because it didn't change a star's maximum count for many tests of sharp images). Star alignment was made for all images for a filter group. MDL was then used to perform photometric measurements of the target star (CoRoT-3), the artificial star (flux the same for all images) and 27 nearby bright (unsaturated) stars. CSV files were recorded for measurements made with a selection of photometry aperture radii. It is well known that the optimum aperture size depends on SNR. Faint asteroids provide the best rotation LCs for a photometry aperture radius, r, of about 1.4 x FWHM. Bright stars produce the best LCs for r about 3 x FWHM. CoRoT-3 is of intermediate brightness for the present choice of exposure times (SNR ~ 40) so the range of photometry apertures employed was from ~1.8 to 3 x FWHM.

A spreadsheet was used for the rest of the analysis. Star magnitudes were converted to flux, and these were added for all 27 non-target stars in order to solve for atmospheric extinction. It was found that extinction ranged from 0.065 mag/airmass (NIR) to 0.160 mag/airmass (V-band). A search was made for which subset of the 27 stars provided the lowest RMS noise for the target. This RMS noise was calculated by comparing each target star magnitude with the median of its 8 closest neighbors, and a standard deviation of all such differences (with a small correction for the fact that 8 isn't infinity) was used to establish an RMS for the filter of interest and for the entire observing session. The next step was to model-fit the target magnitudes using as a criterion the lowest RMS deviation from the model, called RMSmodel. When a good model fit was found a search was made of reference star sub-sets that produced the lowest RMS deviation from the model. This step usually did not lead to many changes in reference star selection (a change would occur if systematic effects differed among the 27 candidate reference stars). If a large improvement in fitting the model was achieved by changing the reference star sub-set then another iteration was performed: model fit for minimum RMSmodel, search for a better reference star subset (that reduces RMSmodel). It is rare to have to iterate like this more than once. I view the final model and reference star subset to be a "global minimum" solution.

Observational Results

The next figure is a "solution" for CBB.

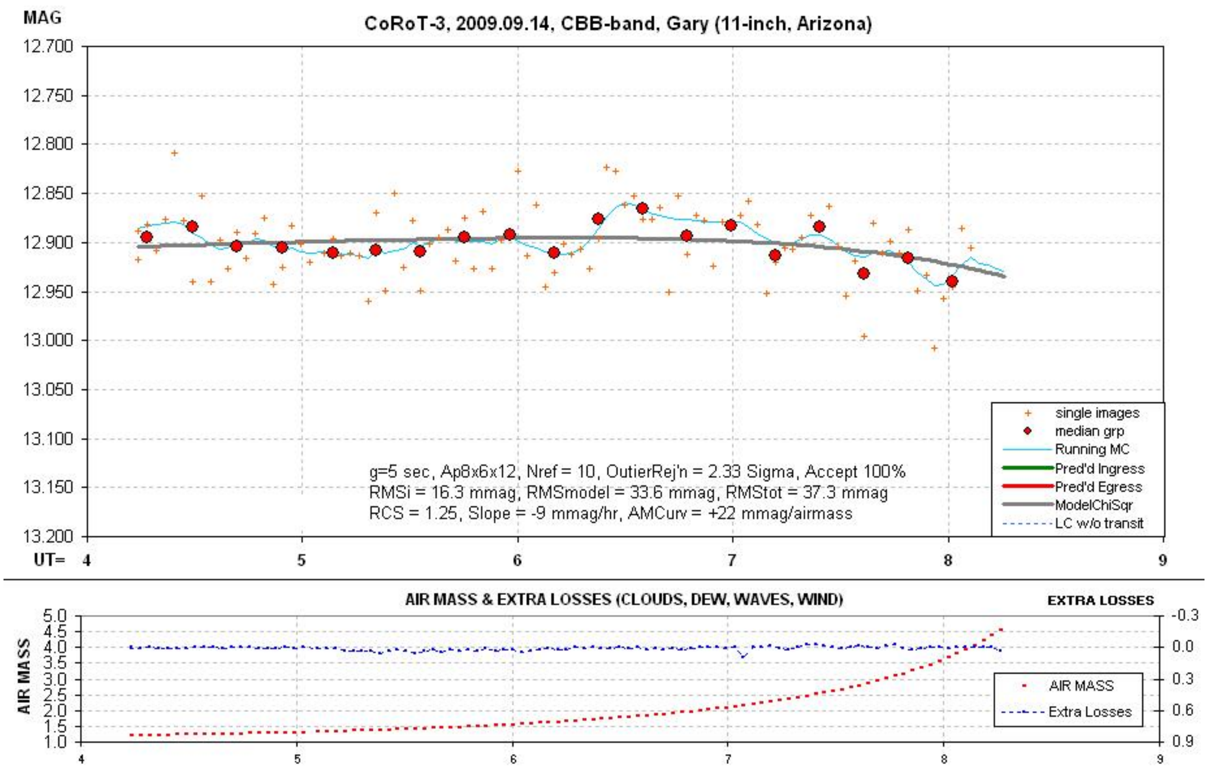

Figure H.01. *Example of a LC solution. The filter is CBB and exposures were 5 seconds.*

The other filters produced similar looking light curves. The target is bluer than average (B-V = +0.91), so most of the references stars must be redder. Notice that air mass exceeds 3.0 during the last 40 minutes, and this, combined with the difference in color of the target and references stars, must cause the model fit to require an "air mass curvature" component.

The next table summarizes the measurements for each filter image set. The first row (below filter names) is "throughput" – or percentage of light from a typical star that reaches the CCD when a filter that is in the optical path compared to the amount of light reaching the CCD when no filter is in place. The second row is the median FWHM of the images. The third row shows the photometry aperture radius that produced the best result. By best result is meant the smallest RMS departure from the LC model fit (where all of the following parameters were optimized: sub-set of candidate reference stars used for reference, model offset, slope and airmass curvature). The next row shows atmospheric extinction. The next row shows RMSi, which is the RMS of measurements with respect to the median of the 8 nearest neighbors. This noise is for a short timescale, and if systematics vary slowly they will not affect RMSi. Next is RMSmodel, which is the RMS deviation of differences with the best fitting model LC. This RMS can be thought of as the orthogonal sum of RMSi and RMSsys (systematics). Therefore, by orthogonally subtracting RMSi from RMSmodel we arrive at RMSsys, shown in the next row. Exposure time, g, is shown in the next row. Info/image is "information per image", calculated from the inverse square of RMSmodel. The next row converts RMSmodel and exposure time to "Precision per minute of observing time" under the assumption that one exposure is made each minute with an exposure time of 48 seconds (which allows 8 seconds for download and 4 seconds for autoguider re-acquisition). This row is calculated by multiplying RMSmodel by the square-root of g/48. Finally, a Figure of Merit is calculated by multiplying a constant by the inverse square of the previous row. The constant is chosen so that the V-band filter has a Figure of Merit equal to one. This Figure of Merit can be viewed as the speed with which a specific precision can be achieved. For example, if a precision of 27.6 mmag per minute of observing time is chosen as the goal, then using the V-band filter this level of precision can be achieved in 1 minute. If the Rc-band filter were used this level of precision could be achieved 2.93 times faster (or 20 seconds, neglecting for now that short exposure times incur a duty cycle penalty). When the CBB filter is used specific level of precision can be achieved 6.3 times faster than if the V-band filter were used.

Star V = 13.3	CBB	NIR	VIS	RED	i'	Data of 20090914
Throughput	92	37	19	36	37	%
FWHM	3.8	4.3	4.4	5.1	4.3	pixels
PhotApRadius	8	8	10	8	10	pixels
K'	90	65	160	115	75	mmag/airmass
RMSi	16.7	19.5	17.6	15.2	21.7	mmag per image
RMSmodel	34.1	36.9	33.8	29.8	42.5	mmag per image
RMSsys	29.7	31.3	28.9	25.6	36.5	mmag per image
g	5	16	32	14	16	sec
Info/image	1.13	1.02	1.20	1.52	0.75	Arbitrary units
Precision/Minute	11.0	21.3	27.6	16.1	24.5	mmag (per minute)
Figure of Merit	6.27	1.67	1.00	2.93	1.26	Speed reaching a goal

Figure H.02. *Summary of filter playoff results for the CoRoT-3 (V = 13.3).*

There are some instructive things to notice about this table. The values of RMSi should decrease with increasing exposure time, according to 1/sqrt(g), if we're in the "faint star" domain – where stochastic noise (thermal, sky background, etc) is dominant. The values for RMSsys, however, should not change with exposure time since they are a component of systematics that presumably varies slowly with time (as the star field slowly moves over the CCD field, for example) and some components of systematics will be approximately the same for each filter.

RMSi consists of two major components: Poisson noise and scintillation noise. It is always interesting to keep track of the importance of scintillation noise in order to know how to fine-tune observing strategy. Although the level of scintillation can change greatly from night to night, or even on hour timescales, it's worth asking what a typical scintillation level should be for the observing conditions of this case study. According to Dravins et al (1998):

$$\sigma \approx 0.09 \times D^{-2/3} \times \sec(Z)^{1.75} \times \exp(-h/ho)/(2g)^{1/2}$$

where sigma is RMS fluctuation (fractional intensity), D is telescope diameter (cm), sec(Z) is air mass, h is observing site altitude (meters) and g is exposure time (seconds). All observations reported here have the same D and h, so this equation becomes:

Sigma [mmag] = 5.8 * AirMass^1.75 / sqrt(g)

The highest scintillation level is predicted for CBB-band near the end of the observing session; during the last 40 minutes the scintillation level is predicted to be ~ 23 mmag. Inspection of the RMSi(t) plot shows an increase at this time, being ~38 mmag (instead of 32 mmag before then). These two RMSi values are consistent with the predicted scintillation increase. For the other filters and exposure times predicted scintillation was never significant.

It is interesting to note the relation between “Precision per Minute” and filter throughput.

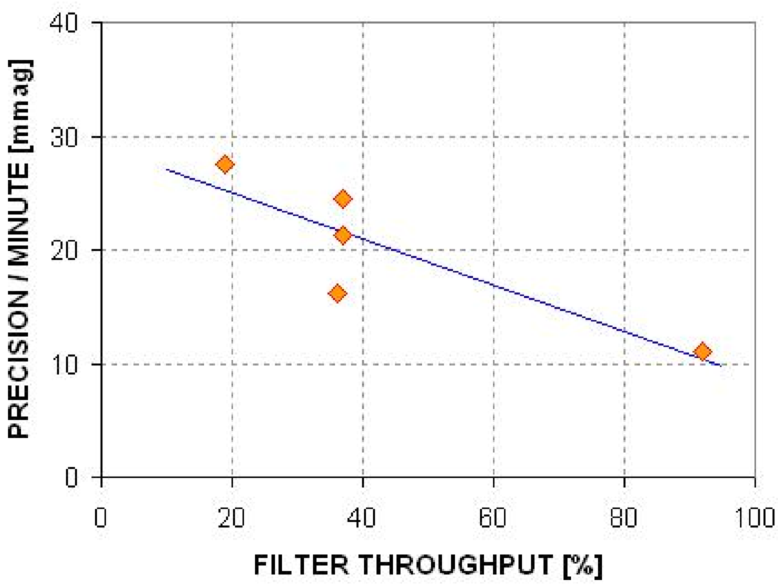

Figure H.03. *Precision/Minute versus filter throughput (13.3 magnitude star and 11-inch aperture).*

The message of this plot is “The greater the filter throughput the better the precision!” This may simply be a consequence of observing a faint target (SNR ~ 40 for all filters). This result suggests that optimum filter choice may depend on target brightness, and the results so far are what we can expect for the faint regime. It is therefore not surprising that for this example the Figure of Merit is correlated with filter throughput. Just because the CBB filter is optimum for faint exoplanet stars doesn’t mean it will be optimum for bright exoplanet stars.

Fortunately, the set of images used in the analysis so far can be used to evaluate Figure of Merit for a brighter star. This can be done by simply selecting a brighter star for treatment as the "target." That's the goal of the next section of this appendix.

Average BTE Brightness Target Star Analysis

The following figure shows two other stars that can serve as surrogate exoplanet stars in OOT mode available for use to evaluate Figure of Merit versus star brightness.

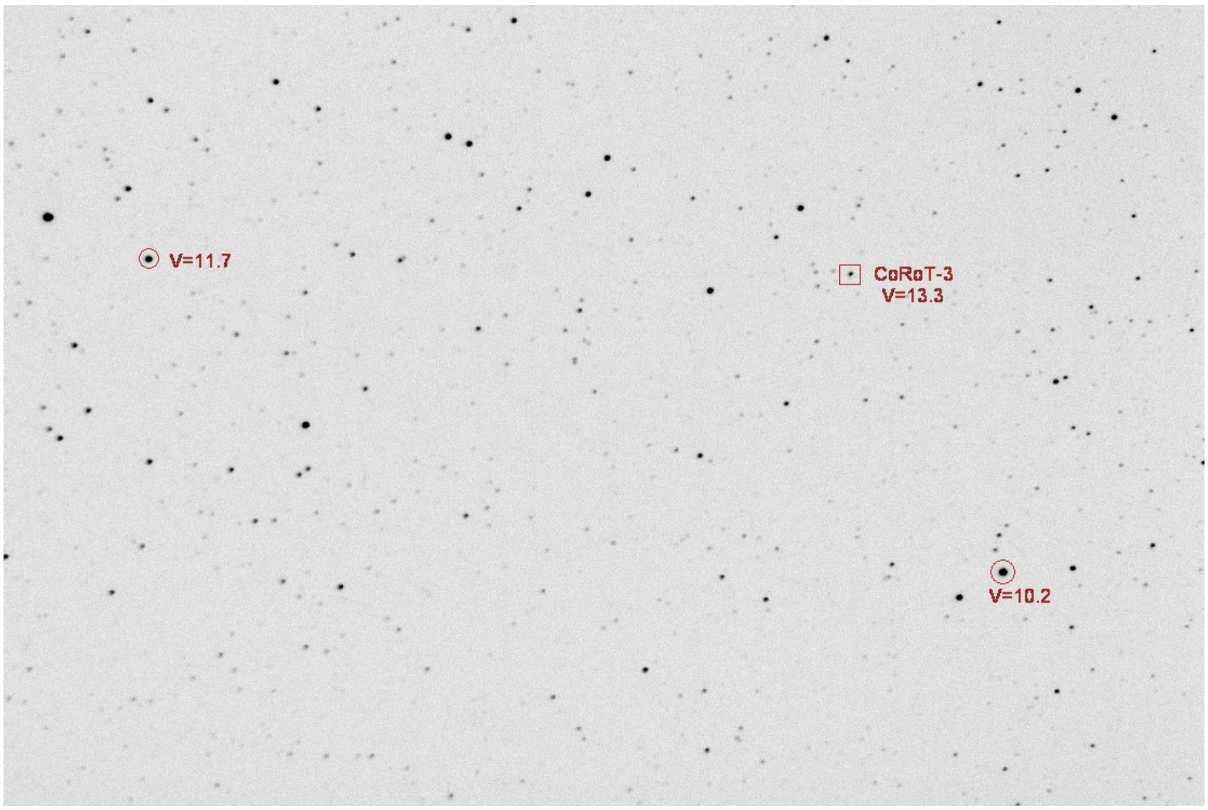

Figure H.04. *CoRoT-3 FOV, 22x14 'arc, showing two stars brighter than CoRoT-3.*

The star labeled V=11.7 is 1.6 magnitudes brighter than CoROT-3 and is also close to the median brightness of the list of 46 known BTEs. It will be used to determine filter performance in a way analogous to what was done in the previous section.

The same procedure used for CoRoT-3 was used with the V-mag = 11.7 star. As expected the LC quality for this brighter star is better than for the 13.3 magnitude exoplanet star. The next figure is the LC using the NIR filter.

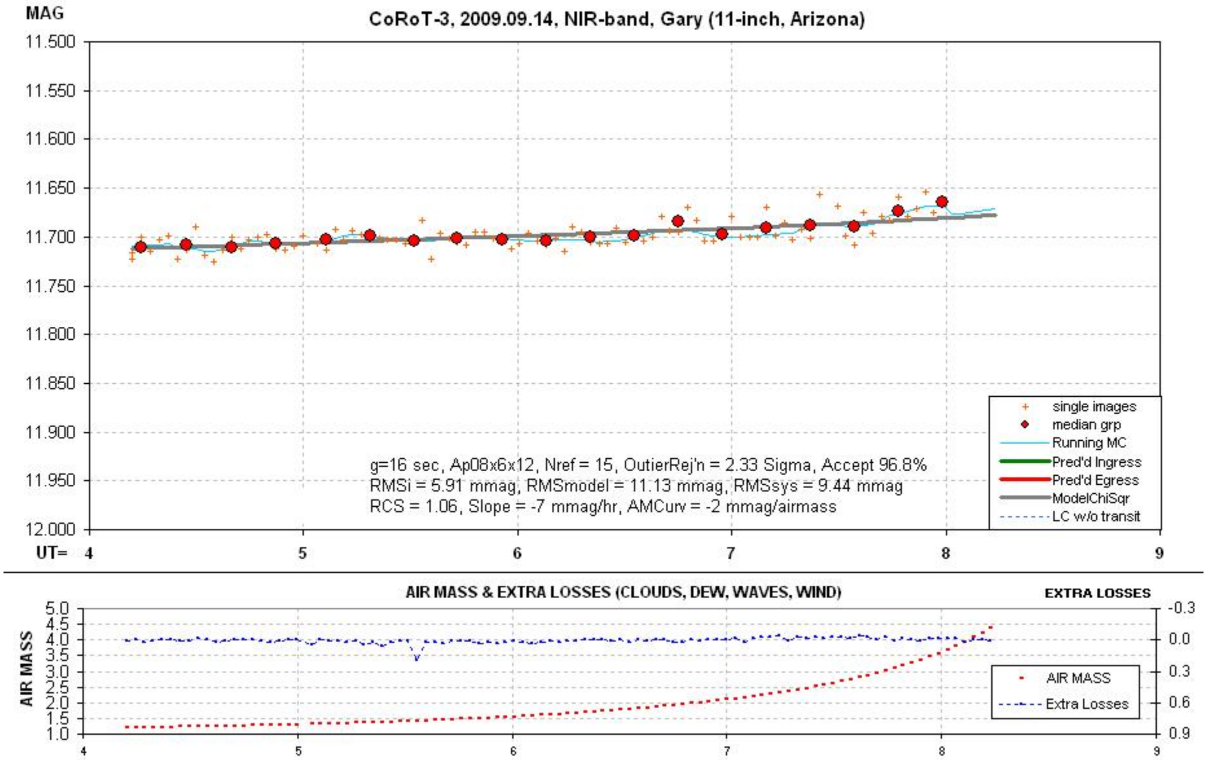

Figure H.05. *NIR filter LC for the V-mag 11.7 star.*

The following figure summarizes results for this star for the 5 filters.

Star V = 11.7	CBB	NIR	VIS	RED	i'	Data of 20090914
Throughput	92	37	19	36	37	%
FWHM	3.8	4.3	4.4	5.1	4.3	pixels
PhotApRadius	8	8	10	8	10	pixels
K'	90	65	160	115	75	mmag/airmass
RMSi	8.15	5.91	14.7	5.86	5.86	mmag per image
RMSmodel	16.33	11.13	18.4	12.3	12.05	mmag per image
RMSsys	14.2	9.4	11.1	10.8	10.5	mmag per image
g	5	16	32	14	16	sec
Info/image	3.75	8.07	2.95	6.61	6.89	Arbitrary units
Precision/Minute	5.3	6.4	15.0	6.6	7.0	mmag (per minute)
Figure of Merit	8.10	5.45	1.00	5.10	4.65	Speed reaching a goal

Figure H.06. *Summary of observations of a star with V = 11.7, similar to typical BTE.*

The highest Figure of Merit is obtained using the CBB filter, but the NIR, Rc and i' filters are all a close second. The V-band filter is the slowest choice for achieving useable LCs.

Precision per Minute is not as strongly correlated with filter throughput as it is for the fainter star, as the next figure shows.

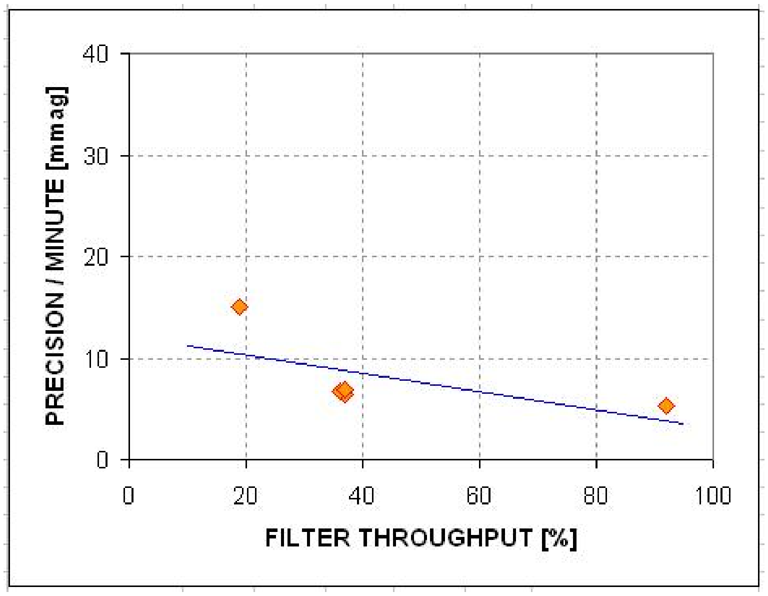

Figure H.07. *Precision performance versus filter throughput for the V = 11.7 star.*

Scintillation is predicted to be more important for the brighter star simply because other stochastic noise levels are lower (whereas scintillation level is the same for all stars, regardless of their brightness.) The scintillation levels for each filter will be the same as calculated above, for fainter CORoT-3. As stated above, the highest scintillation is expected for the CBB images, with a low of 3.6 mmag for the first few hours and an average of ~23 mmag during the last 40 minutes. A plot of RMSi(t) shows a rise from ~12 mmag during the first few hours to ~25 mmag near the end of the observing session. This could be explained if scintillation near the end was ~22 mmag, which is close to what is expected from the Dravins et al (1998) scintillation model. Scintillation levels for V-band ranged from 1.4 mmag to 9.2 mmag, and these are small enough to have only small effects on the observing session averages.

For given levels of noise and scintillation, if we ignore the effect of duty cycle on exposure time, longer exposure times don't reduce the effect of scintillation when considering "information rate" – or Precision per Minute of observing time. In other words, the average of 10 short exposures will have the same level of scintillation noise as one exposure 10 times as long. This concept is commonly understood for other stochastic noise levels (such as thermal noise, sky background noise, etc), but when the issue is scintillation there is a tendency to forget the concept and mistakenly recommend long exposures to reduce scintillation.

Brighter Than Average BTE Target Star Analysis

Finally, let's consider a star brighter than most exoplanets to see if CBB continues to outperform the other filters. The V = 10.2 star, shown in Fig. A.04, has been processed using the same procedure used for the two fainter stars. The LC performances for the i' and V filters are shown in the next two figures.

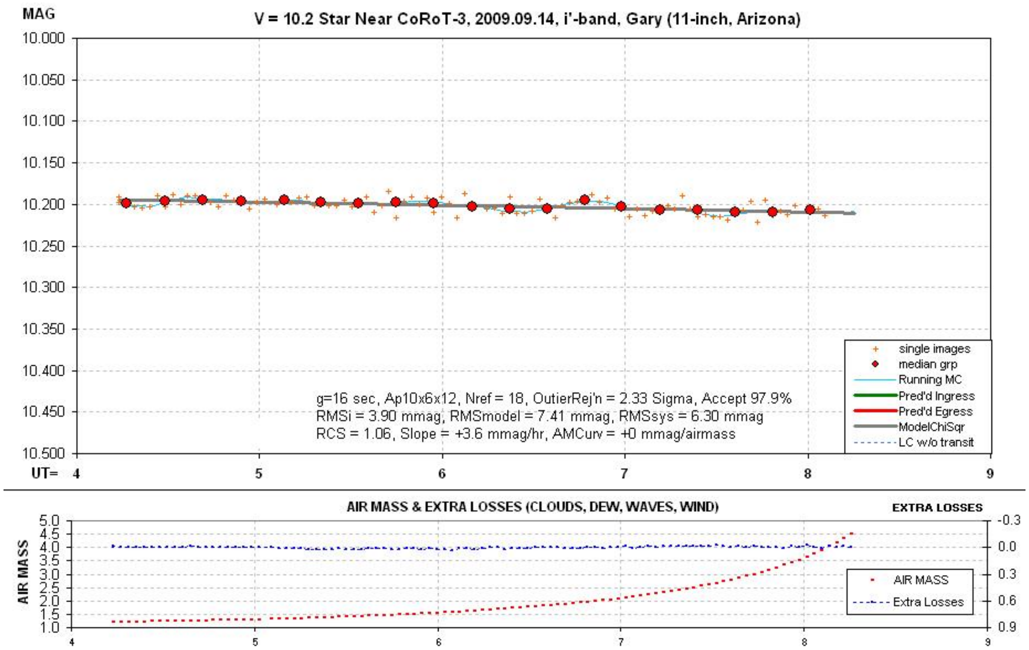

Figure H.08. *i'-band light curve for the V = 10.2 star.*

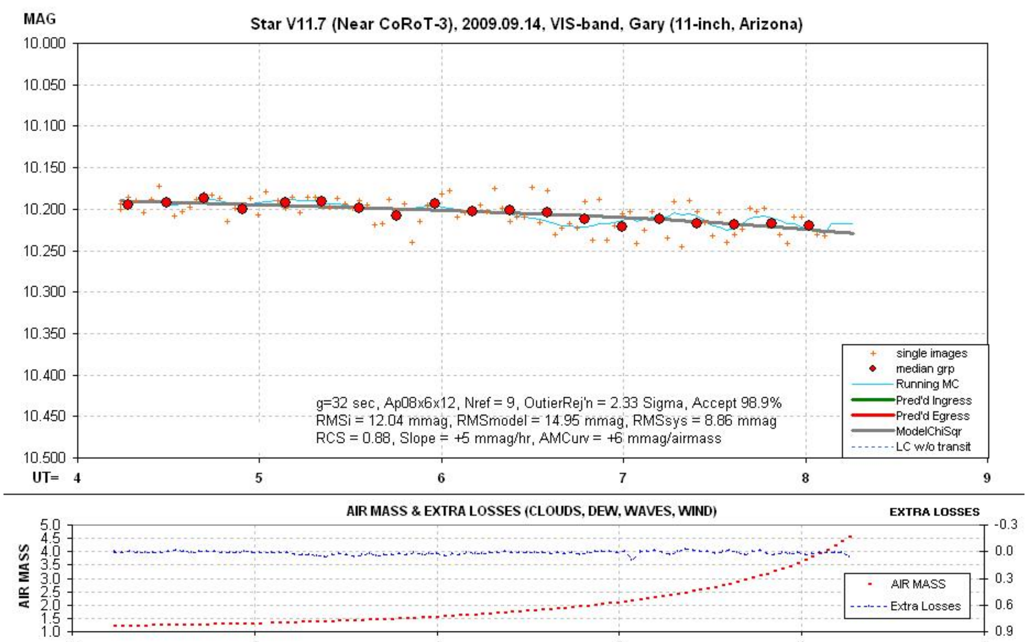

Figure H.08. *V-band light curve for the V = 10.2 star.*

It's apparent from visual inspection that the i'-band light curve is a better quality one than the V-band light curve. This is also borne out by the quantitative measurements, shown in Fig. A.09.

Star V = 10.2	CBB	NIR	VIS	RED	i'	Data of 20090914
Throughput	92	37	19	36	37	%
FWHM	3.8	4.3	4.4	5.1	4.3	pixels
PhotApRadius	8	8	10	8	10	pixels
K'	90	65	160	115	75	mmag/airmass
RMSi	8.43	3.68	12.04	5.08	3.9	mmag per image
RMSmodel	15.24	8.09	14.95	9.75	7.41	mmag per image
RMSsys	12.7	7.2	8.9	8.3	6.3	mmag per image
g	5	16	32	14	16	sec
Info/image	4.31	15.28	4.47	10.52	18.21	Arbitrary units
Precision/Minute	4.9	4.7	12.2	5.3	4.3	mmag (per minute)
Figure of Merit	6.16	6.83	1.00	5.37	8.14	Speed reaching a goal

Figure H.09. *Summary of observations of a star with V = 10.2, brighter than a typical BTE star.*

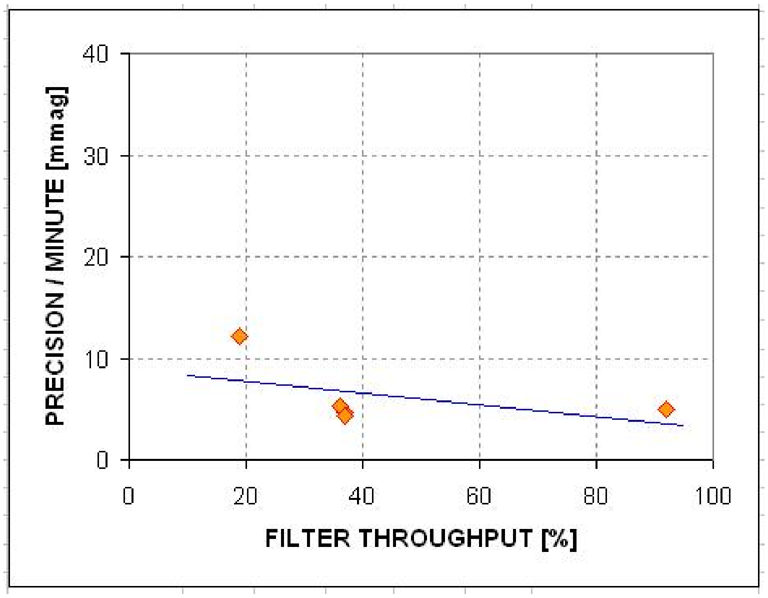

Figure H.10. *Precision performance versus filter throughput for the V = 10.2 star.*

For stars near the bright end of those in the BTE list the best filter for light curves is the i'-band filter. It is 8 times faster than the V-band filter in achieving a specific RMS level of precision. The NIR filter is almost as good, and the CBB and RED filters are close behind.

Concluding Remarks

The results reported here suggest that the best overall filter choice for exoplanet light curve observing is the CBB filter. Brighter exoplanet stars might be observed with greater precision using an i'-band filter, or maybe the NIR filter. For star ranging in brightness from brighter than typical to the faintest, the worst-performing filter was found to be V-band.

Most of the superior performance of the CBB filter can be attributed to its large throughput. That being the case, why not use a clear filter? As explained in the Chapter about "Star Colors" (Chapter

19), a clear filter should be avoided for exoplanet light curve observations because it has different effective atmospheric extinction values for red and blue stars (0.132 and 0.191 mmag/airmass), whereas with a CBB filter the two extinction coefficients are almost the same (0.116 and 0.124 mmag/airmass). In other words, the extinction difference between red and blue stars is 59 mmag/airmass for a clear filter and only 8 mmag/airmass for a CBB filter. That's a 7-fold improvement, which means there should be a 7-fold reduction in the size of the "air mass curvature" systematic error component when using a CBB filter instead of a clear filter. For a typical star the CBB filter passes ~92% of the light passed by the clear filter. This 8% loss is a small penalty for a 7-fold reduction in the "air mass curvature" component of systematic error.

To my knowledge this is the first report of results from an observing session designed specifically to identify optimum filter choices for exoplanet light curve observing. There may be flaws in my procedure, and I am open to comments on an improved observing protocol or an improved image analysis protocol. I welcome others to conduct their own "filter playoff" observations, and share them with the community of amateur exoplanet observers. Until others confirm what I have found it is fair to characterize my results as merely "suggestive." The suggestion, to be explicit, is that the overall best filter choice is CBB-band.