HIGH PRECISION STELLAR PHOTOMETRY WITH CCDs. II.

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ABSTRACT: CCD photometry is capable of high internal precision, however there are several important requirements necessary to attain high precision in standardized photometry. Firstly, the CCD passbands must match as closely as possible the standard passbands; secondly, new faint standards must be set up in several declination zones and thirdly, for convenience a sufficient number of standards covering a good range in color should be obtained on a single CCD frame so that several different frames should suffice for standardization. Landolt has taken the first steps in defining several such fields. The small systematic differences between different UBVRI systems have been examined and transformations can be applied to the photometry of Landolt and Bessell to place it on the Cape - SAAO system.

1. INTRODUCTION

Modern broad-band photoelectric photometry such as the UBVRI system established by Cousins at the Cape and extended by his colleagues at Sutherland (e.g. Cousins 1980, Menzies et al. 1991) and Landolt's equatorial version of the UBV and the Cape RI system (Landolt 1983, 1992) and the Washington system CMT_1T_2 (e.g. Geisler 1990) have been shown to be of high precision and capable of tackling a wide range of astrophysical problems. However, just as widespread adoption of the Cousins system for photoelectric photometry is achieved, photometry is increasingly being done with CCDs and we are now faced with the task of ensuring that the internally precise CCD photometry can be precisely transformed onto the standard system. In this paper I would like to discuss the steps that must be taken to attain this end.

2. SCARCITY OF SUITABLE CCD STANDARDS

The first problem is the scarcity of standards relevant for CCD work. Most of the E-region standards (Menzies et al. 1989) and many of the equatorial standards (Menzies et al. 1991) are too bright for CCD work with 1 - 3-m class telescopes and the faintest stars in these e-regions (48 stars fainter than tenth mag) cover only a small range in color. Just as importantly, we need to make many standards per frame. Single star observations with a CCD are very limiting because few CCD observers are prepared to observe as many individual standard stars as normally observed by photoelectric observers for adequate standardization. It is very wasteful of both observing time (large CCDs can take several minutes to read out a complete frame) and reduction time to have only a single standard in a frame.

Landolt (1992) has recently provided excellent UBVRI standards in several convenient CCD-sized fields. This photometry is based on the equatorial standards of Landolt (1973, 1983)

A. G. Davis Philip et al. (eds.), New Developments in Array Technology and Applications, 175–185.

which have been carefully compared with the Cousins system by Menzies et al. (1991). Some systematic differences are evident and probable reasons for the differences in the UBV colors have been discussed by Menzies et al. (1991), Menzies (1993) and Bessell (1990b). That comparison was essentially for stars bluer than (V-I) = 2.0 (earlier than spectral type M1). For the redder stars, larger systematic differences in (V-R) and (V-I) of up to 0.05 mags between the photometry of Landolt, Bessell and Weis exist. Such differences are not unexpected given that there were few stars in Cousins lists as red as (V-I) = 2.0 and none redder than (V-I) = 2.7 (the latest M dwarfs have (V-I) = 4.4). However, careful intercomparisons between the various data sets enables good transformations to be made onto the Cousins (Cape-SAAO) system.

3. TRANSFORMATION OF LANDOLT UBVRI TO THE CAPE SYSTEM

Laing (1989) has published UBVRI photometry for about 400 faint nearby stars. From the 260 stars common to Bessell (1990a) it has been possible to correct Bessell's photometry for stars with (V-I) ≥ 1.50 and place it on the Cape system. Then by combining Bessell's corrected photometry for about 20 M dwarfs common to Landolt with the Menzies et al. (1989. 1991) data for the bluer stars it has been possible to derive polynomial fits to the differences (Cape - Landolt) and so transform Landolt's photometry onto the standard Cape system (Bessell 1995). The coefficients of the polynomials are given in Table 1. These functions permit transformations to within 0.01 mag for most stars [0.02 for (U-B)] and can be used for standard colors in Landolt's CCD-sized fields until direct CCD measurements within the Cape system are available. The transformed Landolt (1992) data is available by anonymous ftp from pub/bessell at MERLIN@ANU.EDU.AU.

TABLE 1

Coefficients of polynomials to correct Landolt colors to Cape colors.

	A0	A1	A2	A3	A4	A5
(B-V)	-0.005155883	-0.000743423	-0.069862929	-0.055528320	-0.004085570	-0.001869369
(U-B)	-0.013029154	-0.010560242	-0.018461003	-0.022517123	-0.0032750981	
(V-R)	-0.000595208	-0.006163583	-0.027564391	-0.038906376	-0.008676337	
(R-I)	-0.000548123	-0.002518544				
(V-I)	-0.001104410	-0.012484664	-0.005182837			

$$X_{Cape} = XL_{Landolt} + A0 + A1*X_L + A2*X_L^2 + A3*X_L^3 + A4*X_L^4 + A5*X_L^5$$

Bessell and Weis (1989) derived precise transformations between the supposed Cousins system colors of Bessell (1990a) and Kron system colors of Weis (1984, 1986, 1987). With the readjustments to Bessell (1990a) colors, transformations between the Weis Kron system and the standard Cape system have also been rederived (Bessell 1995). Landolt's equatorial fields are an excellent start for CCD standards but it will be advantageous to derive more standard stars within these fields and within additional fields containing some of the very red stars. CCD-sized standard fields need also to be set up in the E-regions, the F-regions and near the Magellanic Clouds in the southern hemisphere and in other declination zones in the north.

Graham (1982) has provided some valuable faint standards in E-region fields. However, these stars have a very restricted color range (there are no very blue stars) limiting their usefulness. Comparison between Menzies et al. (1989) and Graham indicate systematic differences for red stars in all colors. Graham and Landolt used the same B filter that appears to have introduced systematic differences in the (B-V) and also the (U-B) colors. Walker (1991) has examined the (U-B) differences in detail and recommends the following transformations be applied to Graham's (U-B) colors:

$$(U\text{-}B) = (U\text{-}B)_G - 0.130(B\text{-}V) + 0.015, \text{ for } 0.0 < (B\text{-}V) < 0.2$$
$$(U\text{-}B) = (U\text{-}B)_G + 0.046(B\text{-}V) - 0.020, \text{ for } 0.2 < (B\text{-}V) < 1.0$$
$$(U\text{-}B) = (U\text{-}B)_G - 0.060(B\text{-}V) + 0.086, \text{ for } 1.0 < (B\text{-}V) < 1.7.$$

Graham's fields are again a good start for E-region standards; however, they also need to be supplemented with more stars per field and with some bluer and redder stars.

It must be emphasized that all the standards we discussed above are from photoelectric photometry and have therefore been observed through large apertures of at least 14 arcsec. As inspection of deep CCD frames of many of the stars indicates that there are often faint companions within such an aperture; the published magnitudes must include the contribution of these companions. Therefore when using the photoelectric standards as CCD standards, the CCD derived magnitude for that standard must be evaluated for a 14 arcsec aperture (or whatever aperture size was used) and not for a small aperture of from profile fitting. For this and other reasons it would be preferable to use CCD photometry instead of photoelectric photometry when setting up CCD standards. But before attempting that, we must ensure that the passbands used for CCD photometry are as close as practicable to those of the standard photoelectric system or at least understand the systematic differences that will result from mismatched passbands.

4. THE PASSBANDS OF CCD PHOTOMETRIC SYSTEMS

Bessell (1990b) has devised passbands that represent the standard UBVRI system. Guided by these passbands one can compute CCD passbands by convolving the transmissions of glass filter combinations and the sensitivity functions of CCDs until they match as closely as possible the standard passbands. Synthetic photometry can then be made by folding the CCD passbands with the data in spectrophotometric atlases, such as the Vilnius spectra (Straižys and Sviderskiene 1972) or the Gunn-Stryker spectra (Gunn and Stryker 1983; corrections given by Rufener and Nicolet 1988). Some CCD passbands were discussed in Bessell (1990b) as were differences in photoelectric systems due to mismatched passbands.

One of the additional complications we now face is that there is much diversity in the wavelength response of CCDs. Originally, most CCDs comprised thick Si photoreceptors which provide high R and I response, lower B and V response and little U response, but through a variety of techniques, such as thinning the Si, electrically treating the backsurface, UV flooding or the application of lumogen or dyelaser coatings, it is now possible to obtain a wide variety of response curves. The U and B responses and to a lesser extent the V response show the most variation. Fig. 1 shows the dramatic differences in CCD sensitivities. All the responses differ from that of the GaAs photocathode with which the standard photoelectric observations were made. This response was basically flat between 300 nm and 850 nm and had a rapid cutoff below 870 nm.

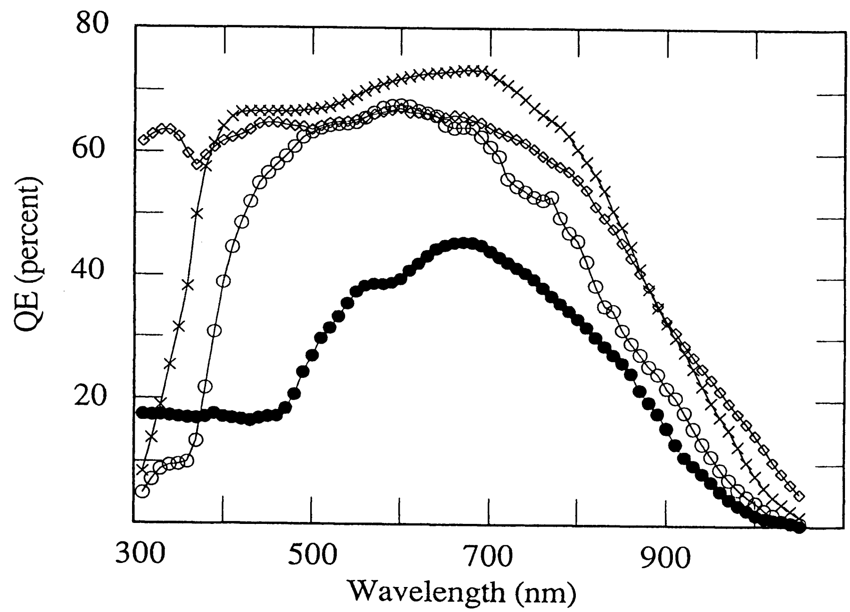

Fig. 1. Sensitivity curves for selected CCDs.

Because of the significantly different responses of some CCDs it has been found for some passbands that it is best to use different glass filter recipes for different CCDs. Walker (1992) shows examples of UBVRI transformations with different CCDs and different filter recipes. Some recipes have been made for total thicknesses of four mm but a thickness of five mm permits more flexibility in recipes and better finetuning of the passbands. In addition, because 1 mm thicknesses of some glasses are difficult to work optically in the large sizes needed for some applications, they need to be replaced by a thicker piece of an alternate glass. Each of the UBVRI CCD passbands will now be discussed in turn.

4.1 The U passband

As pointed out in Bessell (1990b) the photoelectric U band has been quite well defined by most observers and some of the problems in (U-B) systems seem to have arisen from the B band and much from the transformation techniques used; regressions against (U-B) or (B-V) for example. One of the main problems in U photometry with a CCD is the red leak of the UV glasses. The other problem is the low and steeply varying sensitivity of the CCDs across the U band and its variation between CCDs. The coated CCDs and the UV flooded CCDs offer a flat response, so the normal 1 mm UG1 or 3 mm UG5 will define the red cutoff adequately. With the thinned CCDs, the restricted and rapid drop off to shorter wavelengths in some CCDs response necessitates a thicker piece of UV glass to keep the long wavelength side of the band sufficiently blue. The problem with the red leak remains. It was possible with the GaAs photoelectric filter to use liquid or solid copper sulphate to eliminate the red leak. That is still possible, but the larger sizes of some filters and the good imaging quality required of the filters in some optical systems has forced the consideration of alternatives. The Schott BG39 and BG40 glasses with their improved UV transmissions are very useful in this context although they do restrict quite severely the flux shortward of 340 nm; however, the new glass S8612 available from Schott Glass Technologies, Inc., Duryea, Pennsylvania has the same red cutoff as the BG39 glass but has much better UV transmission and seems to offer good transformation possibilities. (I am grateful to Alistair Walker for pointing out this glass to me.) Some interference filter manufacturers offer a coating that appears to eliminate the red leak; however, the reduction in far-red transmission is inadequate for UV observations of red stars with CCDs. The high red sensitivity of some CCDs compared to their UV sensitivity and the low UV flux of some stars (K giants in particular) compared to their red flux can mean that a red leak of a fraction of a percent can still dominate the observation. It is important therefore that the red leak be extremely low for UV work on red objects while for hot objects it is not as important. However, it is best to try for a very low red transmission to avoid later unforseen problems. The 1 mm BG39 recommended in Bessell (1990b) for use with UG1 still has a small red leak for the reddest stars; 3 mm BG40 has negligible leak as does 1.5mm of S8612. The left hand side of Fig. 2 shows the UV transmittance of 1 mm UG, 1 mm BG39 and 1 mm S8612. On the right hand side is shown the far-red transmittances for the same glasses (RH scale); the lowest curve shows the product of 1 mm UG1 and 1 mm S8612, the red-leak. An additional 0.5mm of S8612 or BG39 would apparently reduce the red-leak by a factor of about ten.

Using BG39, 40 or S8612 to stop the red leak causes an unavoidable loss in UV sensitivity and a cutoff in the blue side of the response, but the resultant photometry appears to be transformable, although there is a large non-linearity for the bluest stars. In Fig. 3 are shown the magnitude differences between instrumental u (measured with a UV flashed Tek CCD and glass filter) and standard U. Fig. 4 shows the magnitude differences between the glass and CuSO4 cutoff U filters. Ugl is for the filter comprising 1 mm UG1 + 2 mm S8612, uCu for 1 mm UG1 + 5 mm CuSO4. Individual stars of Menzies et al. (1991) were observed.

Possible combinations for U are:

1 mm UG1 + 5 mm liquid CuSO4 (for thinned, UV flooded or coated CCDs) or
1 mm UG1 + 2 (or 1.5 mm) S8612 (for UV flooded or coated CCDs)

1 mm UG1 + 1 mm BG39 + one mm BG40 (for UV flooded or coated CCDs) or
2 mm UG1 + 3 mm BG40 (for thinned CCDs).

4.2 The B passband

The B passband has continued to cause some difficulties. The variation in the sensitivity of some CCDs across the B band is high and differs a lot between CCDs. This causes quite a large shift in the effective wavelength of BCCD if the same filters are used. As briefly touched on above and discussed in more detail in Bessell (1990b) the B band used by Landolt and Graham in their photoelectric observations introduced systematic differences into their (B-V) and (U-B) colors compared to the standard Cousins system colors for some stars. The glass filter combinations for B of most CCD observers has been closer to those used by the Cape-Sutherland observers than to that of Landolt and Graham, consequently more linear relations are measured after transforming the Landolt and Graham standards. Nevertheless, the reasonable mix of 1 mm GG385 + 1 mm BG12 + 2 mm BG39 (the BG39 is to stop the

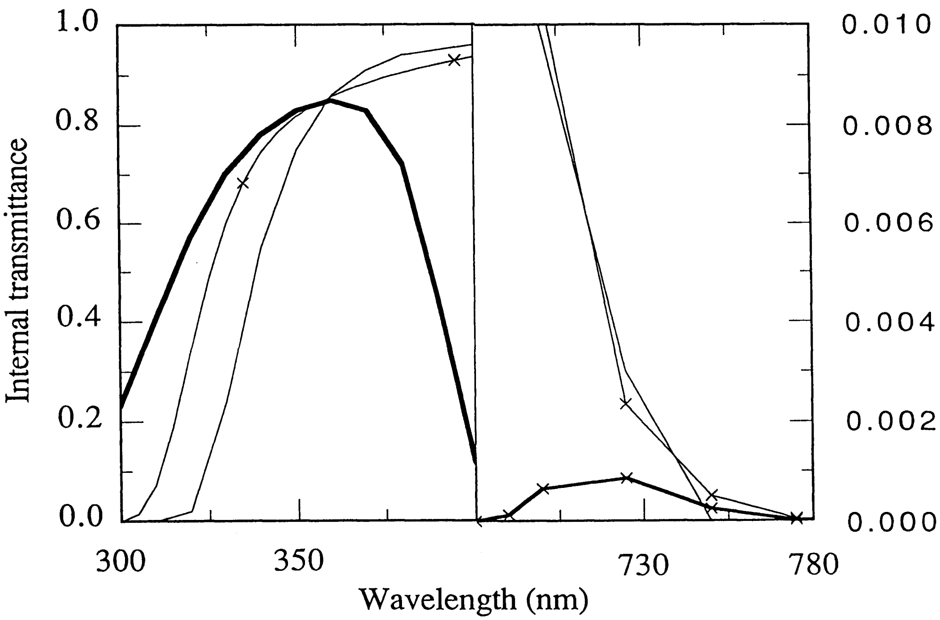

Fig. 2. Transmittance of UG1, BG31 and S8612 glass.

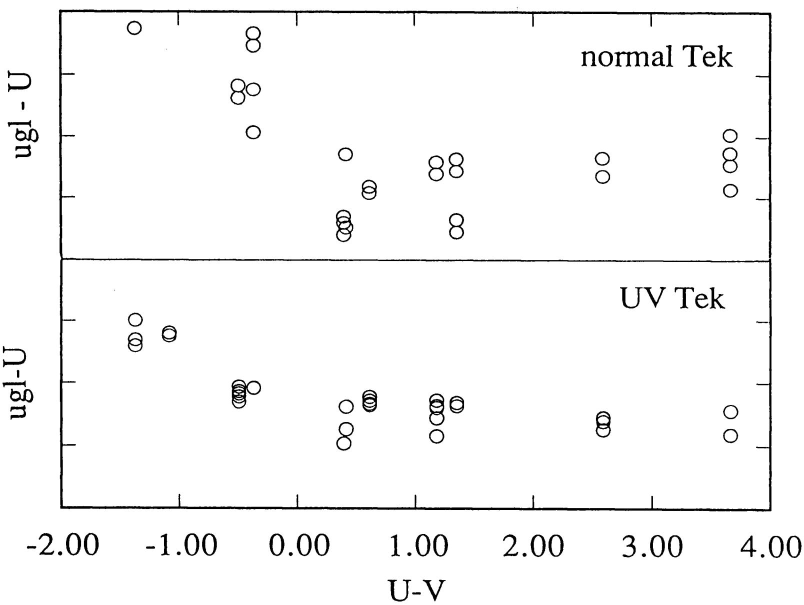

Fig. 3. Differences between natural and standard U magnitudes. Y axis ticks are 0.1 mag.

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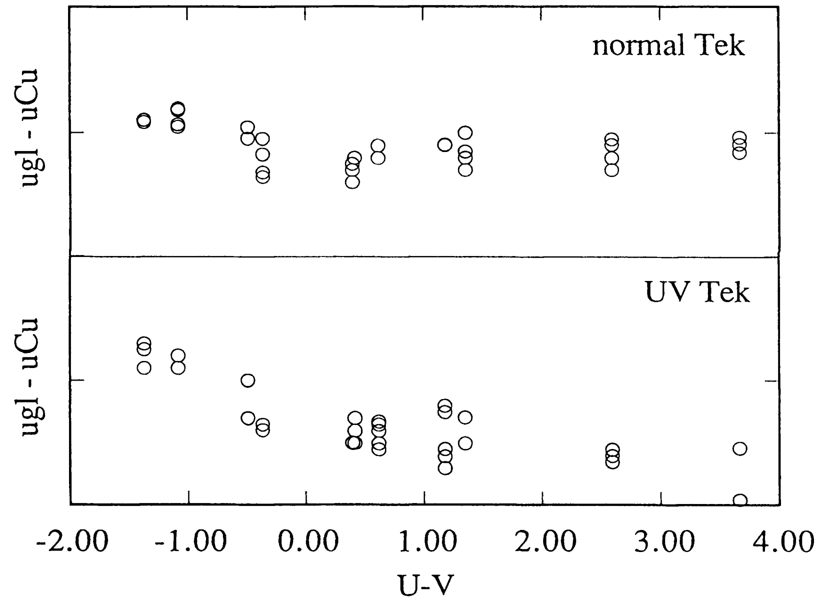

Fig. 4. Differences between glass and CuSO4 blocked responses. Y axis ticks are 0.1 mag.

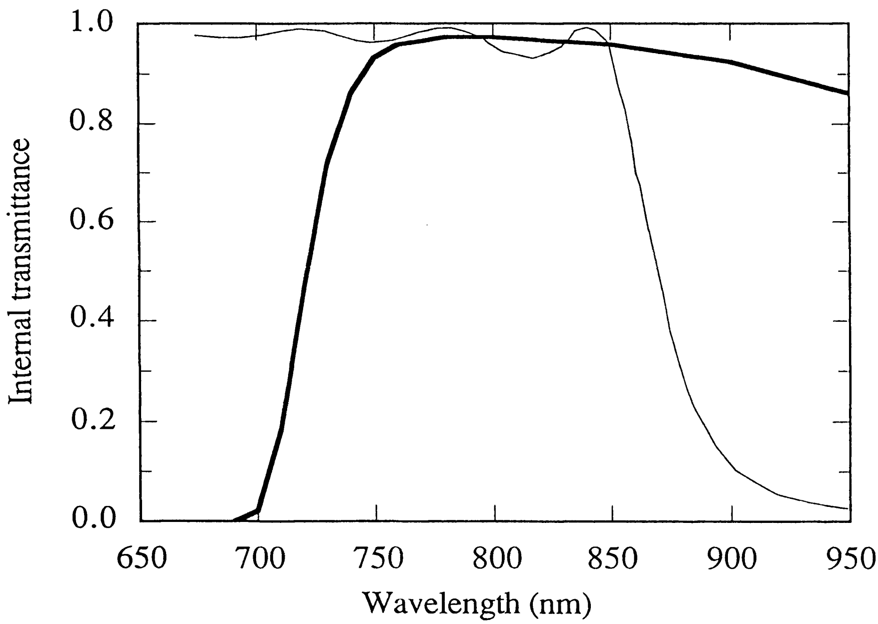

Fig. 5. Transmittance of RG9 glass and interference far-red cutoff filter.

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red leak of the BG12) produces a too red response for most CCDs. Walker (1992) notes that with a thinned Tek CCD this filter has a color correction of 0.18(B-V) compared to 0.05(B-V) with a UV flooded TI CCD and 0.07(B-V) with a coated Thomson CCD. Replacing 1 mm BG12 with 2 mm BG1 for the thinned Tek gave 0.07(B-V). We have found that 3 mm BG37 in place of the 1 mm BG12 virtually eliminated the color term in B for our Tek thinned CCD.

When choosing filter combinations one is invariably faced with deciding between a better matched bandpass or higher throughput. Compromises in favor of throughput are usually made and in many cases these do not degrade the standardized photometry. But it is important to examine the residuals of the standard star photometry and the residuals of the synthetic photometry (especially at the moment when there are not enough CCD standard stars of all spectral types) to see in what color range or range of spectral-types, non-linearities will occur. For instance, pushing the blue edge of the B response further to the UV to counter the effective wavelength shifting to the red is not a good idea because it introduces more light near the confluence of the Balmer lines which will introduce systematically different magnitudes for the A and F stars. Possible combinations for B are:

1 mm GG385 + 2 mm BG1 + 2 mm BG39 (thinned CCDs) or
1 mm BG395 + 3 mm BG37 + 1 mm BG39 (thinned CCDs) or
2 mm GG385 + 1 mm BG12 + 2 mm BG39 (coated CCDs).

4.3 The V passband

The different slopes of the responses of different CCDs across the V passband produces small shifts in the effective wavelength of the V band. These shifts can be easily removed by varying the thickness and/or the type of the glass defining the red side of the passband. There are four glasses that can be used, BG18 and BG38 or the newer glasses BG39 and BG40. Their responses are subtly different but quite similar in shape. The older glasses are cheaper.

An important reason for trying hard to get as good a match as possible for the V band is that different colors, (B-V) or (V-I) [V-R] are used when deriving the color term in the transformation equation, and this can lead to systematically different V magnitudes for the reddest stars. For example, if V photometry of standard stars between spectral-type AO [(B-V), (V-I) = 0] and KO [(B-V) = 0.98, (V-I) = 1.0) fits a color term of 0.05(B-V) or 0.05(V-I), which may appear acceptably small, then using those relations for an M7 dwarf [(B-V) = 2.0, (V-I) = 4.0) yields a difference of 0.1 mag in the transformed V magnitude. It is clear that differences amounting to more than 0.1 mag do exist in the published V magnitudes of late M stars and the y probably arise in such a way. Calculations using synthetic spectra indicate that the correction based on the (B-V) color and not the red colors is correct. As much CCD photometry of red stars ignores B and observes only VRI, making the color term as small as possible ensures that large systematic errors are avoided. Possible combinations for V are:

2 mm GG495 + 3 mm BG40 (thinned CCD) or
2 mm GG495 + 3 mm BG39 (coated CCD).

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4.4 The R Passband

The two glasses OG570 and KG3 of the photoelectric filter can be used but the thickness of KG3 can be altered to match the standard band better. Because of the asymmetric red tail of the Stan2optdard R response and the variation between batches of KG3 glass it was virtually impossible to match the standard R over the full color range using a GaAs tube; that is, all natural photoelectric R systems needed two straight lines to transform to the standard system. It is even more difficult with CCDs, nevertheless, a good match can be made for most stars and the nonlinear effect restricted to the reddest stars as with the photoelectric systems. Possible combinations for R are:

3 mm OG570 + 2 mm KG3
2 mm OG570 + 3 mm KG3.

4.5 The I Passband

Most CCDs appear to have very similar responses from 700 nm to their cutoff near 1000 nm although in practice, because the red tail is sensitive to temperature and the operating temperatures of CCDs differ appreciably, they may not be so similar. However, as the red cutoff in the standard I band was defined by the rapid cutoff in the sensitivity of the GaAs photocathode near 870 nm and the CCD sensitivity extends at least 100 nm further to the red, most I CCD bands have this extended red response.

Synthetic photometry indicates that the main difference caused by the extended sensitivity in the I band is the inclusion of light above the Paschen discontinuity in early-type stars and the inclusion of additional emission lines in emission lines objects. Additional problems arise due to the night-sky emission that is brighter at longer wavelengths and which lowers the S/N for faint stars by increasing the background relative to the star and by increasing the fringing in thinned CCDs. The fringing in I from the night sky will also be different from that of the twilight sky often used for flat fielding further degrading the S/N. Special multilayer coatings can be made to approximate the cutoff of the GaAs tube and eliminate the reddest sky emission. One such commonly available filter is sold by the Rolyn Optics Company as a hot mirror (#60.5050) and we have successfully used this filter in conjunction with 2 mm RG9 to produce an I CCD passband quite similar to the standard I band. More recently we have taken delivery of several I filters with a 13 layer coating of non-quarter-wave multilayer-optimized stack centered near 870 nm. The coatings were done by the National Measurement Laboratory in Sydney. In Fig. 5 the transmittance of two mm RG9 and the multilayer coating is shown.

However, with an I passband whose red side is defined by the CCD cutoff, excellent transformations for sources with stellar-like fluxes are still possible provided the non-linearities of the transformation are followed by taking care to observe standards covering the spectral types of interest. High precision is also maintained provided the fringing is not a problem. Possible combinations for I are:

2 mm RG9 + 3 mm fill glass (GG385) or
2 mm RG9 + 1 mm Rolyn 60.5050 (or equivalent) + 2 mm fill.

4.6 The Z Band

The extended red response of CCDs compared with GaAs and S20R photocathodes raises the possibility of a passband beyond 1000 nm which would provide some wavelength over lap with the In Sb and Mercatel IR arrays. We have used 2 mm RG1000 to define a far-red band that was quite useful in isolating extremely red stars, such as miras, near the Galactic center but it had a much lower sensitivity compared to the I band.

4.7 The C Band

The C band of the Washington system has proved very useful for measuring line blanketing in faint red giants. It is more sensitive than B for such work. The red leak of the three glass was still a problem with two mm of BG40 (Bessell 1990b) as a blocker, consequently it is better to use 2 mm BG39, 2 mm S8612 or 3 mm BG40.

5. SUMMARY

Faint standards, many to a CCD frame and with a good range in color are required in several declination zones to enable good standardization of CCD photometry. The equatorial CCD-sized fields of Landolt represent a good start to this endeavor. The Landolt standards have systematic differences from the Cousins system but good transformations are possible for most stars. Graham's E-region standards are also useful but again transformation to the Cousins system is necessary and stars with a wider color range need to be included.

Glass filter combinations can be quite readily devised to closely match the standard UBVRI system but some of these filters should be made for specific CCDs, especially for U and B. Systematically different V magnitudes can result for late-M stars if the color correction to V is large; it is therefore worth matching V as closely as possible. There are also advantages in faint object photometry from rejecting the light redward of 870 nm from the I band using a multilayer stack. The red leak of glass U filters remains a problem; it can be eliminated by using thick enough pieces of BG39/40 or much better, S8610 glass. This lowers the throughput somewhat and leads to non-linearities for the hottest stars but should not cause too severe transformation problems.

General comments on making the glass filters. We use a spectrally transparent two-component epoxy "EPO-TEK 301" (Epoxy Technology Inc) to glue the glasses of each filter mix together. This epoxy, which bonds to most glasses, metals, ceramics and plastics is transparent between 300 nm and 2.6 microns, has a refractive index of 1.54 (the same as crown glasses) and cures overnight at room temperature. Trial mixes of filter glasses can be oiled or greased together temporarily. When used in a converging or telecentric beam, the optical quality of the standard rough-polished filter glasses from Schott are adequate without further polishing, but in the collimated beam of a reimaging camera we have found it necessary to polish the glasses to a few fringes. We have not antireflection coated the filters but tilt them if reflections are a problem.

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DISCUSSION

YOUNG: You remarked on the use of either (U-B) or (B-V) as regression variables in the color transformation. Peter Harmanec suggested the use of two color indices in the regression, and I commend his suggestion to you. This option is available in the PEPSYS package distributed with MIDAS.

BESSELL: This is important. Most data reduction packages have not included such a capability.

FLORENTIN-NIELSEN: The newest thinned TK 1024 have a more flat response in U, with about 30% QE at 3000 Å.

BESSELL: That is good news. The flatter the UV repsonse the better the transformation to the standard system.