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UBVRI PASSBANDS

M. S. BESSELL

Mount Stromlo and Siding Spring Observatories, Institute of Advanced Studies,
The Australian National University, Private Bag, Weston Creek Post Office, ACT 2611, Australia

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ABSTRACT

Good representations of the passbands for the Johnson-Cousins *UBVRI* system have been devised by comparing synthetic photometry with actual observations and with standard system magnitudes. Small adjustments have been made to previously published passbands. Users are urged to match these passbands so that better photometry and calibration are ensured. Mismatched *B* bands are shown to be a major source of recent $(U-B)$ transformation problems. The nature of systematic differences between the natural colors of the most widely used sets of standard star photometry is investigated and suggested CCD filter combinations are discussed.

Key words: photometry–standard star systems

1. Introduction

Knowledge of the passbands of photometric systems is essential for two related reasons: to enable color indices to be calibrated theoretically and to enable observations by different observers using different equipment to be made and compared with precision. Astronomical photometry is best considered as low-resolution spectroscopy. When the brightness of a star (or galaxy) is measured through different filters and detectors one is actually isolating sections of the spectrum of the object, and as much care should be taken in determining what wavelengths the filter transmits and how the detector responds to different wavelengths as in setting up a spectrograph. The high precision available in many photometric systems, such as the broad-band Cousins *UBVRI* or the intermediate-band Strömgren *uvby* systems, can only be utilized when the passbands used (filter transmission times detector response) match those of the standard systems. That is, the same part of the spectrum needs to be observed, with much the same relative sensitivity.

Unfortunately, passband differences are not necessarily evident from the photometry made for the standard stars. Observations made for these stars may transform to the standard values with high precision, even though the passbands do not match as indicated by the slope of the regression not being close to 1.0. This is because most standard stars comprise a *one parameter* restricted set of temperatures, gravities, abundances, and reddening (AFG dwarfs and KM giants of low reddening in the solar neighborhood). If, however, one observes stars bluer or redder than the standards, stars with different gravities to the standards (such as BA giants and supergiants, KM dwarfs or white dwarfs), or, in fact, observes any stars not well represented in the standard lists (such as emission-line stars, metal-deficient stars, highly reddened stars, carbon stars, or galaxies), then one will see systematic magnitude differences between observers *because they are not observing the same spectral regions*. That is, two observers using different passbands may achieve well-defined and precise transformations for the standard stars but will find large differences for their program objects which have spectra dissimilar to the standards. For that reason, observers are advised to ensure that their standards include stars covering the spectral type and luminosity class of their program stars, but the most important advice is to first ensure that their passbands closely match those of the standard systems in width and effective wavelength.

The passbands of many standard systems, however, are not known with certainty. This may result from the bands being incorrectly specified due to lack of measuring facilities or to a lack of attention to such details by the originators but, more to the point, many of the systems have undergone much development or refinement in recent times using passbands which were not identical to those of the original system, although the observed colors would have been "transformed" onto some representation of the original system. In other words, the current "best set of standards" defining a standard system may have been observed with passbands differing from those of the originator, and some linear or nonlinear transformations have been applied to the data to make it *appear* as though they were observed with the same effective wavelengths as the original passbands.

It is possible, however, to recover optimum passbands for most systems. If one has absolute spectrophotometry for stars with known "standard magnitudes", one can devise a variety of passbands and then compute synthetic magnitudes by convolving the passbands and the spectra, and compare these synthetic and standard magnitudes. The passband which produces the best match to the standard magnitudes can be considered the passband of the standard system, in particular when supported by justification for its central wavelength, bandwidth, and shape from calculations of measured filter transmission and detector responses. We must be aware, however, that, because of the usually unpublished "corrections" made to transform from the natural colors of the secondary standard system to that of the primary system, it may not be possible to deduce a fictitious band that exactly reproduces over the complete color range the published "standard" colors. We, by necessity, must settle for a band that reproduces the colors for most stars and be aware of differences that can exist for objects with very red or very blue colors due to such inconsistencies.

If one has access to a range of colored glass filters of different thicknesses, rather than calculating responses one can experimentally match passbands by modifying the blue or red edges of the "standard filter" passbands and then observe a range of standard stars and try and eliminate color terms in the magnitude relations—that is, observe stars with a range of color (luminosity class and reddening), plot the difference, $\Delta m = (m_{obs} - m_{true})$ against a color such as $(V-I)$, $(U-V)$, etc. If the *center* of the band matches the standard band then there should be no slope to the regression or no "color term" in the tranformation. If the *width* or *shape* of the observed band differs significantly from the standard band, then the effective wavelength of the observed and standard band will alter differently as the stellar energy distribution changes (as the $(V-I)$ color changes) and the regression should curve. Examination of the magnitude residuals with color for each filter therefore clearly indicates the nature of the passband mismatches. Magnitude residuals such as ΔB or ΔV are more informative than color residuals such as $\Delta(B-V)$, because nonlinear deviations will arise from both B and V mismatches. Similar comparisons can be made theoretically using a collection of standard star spectrophotometry. The results of such analyses will be presented in this paper.

Previous analyses of some of the passbands of the *UBVRI* system have been made by Melbourne (1960) (cited by Matthews and Sandage 1963, hereafter MS), Young (1963), Azusiensis and Straizys (1966*a*,*b*, 1969, herafter AS), Hayes (1975), Cousins and Jones (1974, 1976), Buser (1978), Bessell (1979, 1983, 1986*a*,*b*), Cousins (1981), and Taylor (1986). The analyses of Cousins (1981) and Cousins and Jones (1974, 1976) are of particular importance. Comparisons will be made between the bands devised by some of these authors.

The photometric catalogs which define the "best" representations of the *UBV* and *VRI* (Cousins) systems are Johnson *et al.* (1966), Cousins (1971, 1973, 1980, 1983), Menzies *et al.* (1989), Laing (1989), Landolt (1973, 1983), Graham (1982), and Bessell (1990). The Johnson *UBV* system is nominally defined by the photometry of Johnson and Harris (1954), although there are no systematic differences between that and the photometry of Johnson *et al.* (1966). Cousins *UBV* photometry is defined by the E-region stars (Cousins 1973, 1983; Menzies *et al.* 1989) and other southern or equatorial stars (Cousins 1971, 1984). Cousins V and $(B-V)$ are on the Johnson system and $(U-B)$ can be transformed to an average of it, although the mean air mass of the Johnson "system" $(U-B)$ is uncertain. The precision and internal consistencies of the more modern Cousins photometry are much higher than those evidenced by the Johnson lists. Landolt (1973, 1983) has published very useful *UBV* and *UBVRI* photometry for intermediate-brightness equatorial stars. Landolt (1983) used Cousins E-region standards and the natural system of Graham (1982) for the *UBVRI* photometry but transformed the *UBV* values to his 1973 system. Landolt's *UBV* photometry is nominally on the Johnson system and the *VRI* photometry on the Cousins system, although Cousins (1984) and Bessell (1990) note some systematic differences. This photometry, together with that of Graham (1982), is now commonly used to standardize CCD photometry. There are, however, significant differences between the natural systems used to observe these photometry lists. The different bands which have been used by the different observers have led to systematic differences between colors for particular stars.

2. Natural System Variations

For historical reasons, photometry has generally been in terms of a single absolute flux measurement, such as the V magnitude, and flux ratios or magnitude differences, such as $(U-B)$ and $(B-V)$. Observations were reduced in such terms. Johnson and Morgan (1951) used Corning glass filters (*U:* C9863, *B:* 2-mm GG13 + C5030, *V:* C3384) and an uncooled 1P21 tube in setting up the *UBV* system. Corrections were made for atmospheric extinction, using mean extinction coefficients derived from observations made between air masses of 1.0 and about 1.75. A color term was used in the $(B-V)$ extinction, to account for the different effective wavelengths of the filters (mainly B) for blue and red stars. Because the Balmer discontinuity introduced a nonmonotonic variation in the $(U-B)$ extinction coefficient with color, an average $(U-B)$ extinction coefficient with no color term was used to simplify reductions. This normally does not cause observational problems when observations are made over restricted zenith distances. It does mean, however, that one thereby implicitly includes a certain air mass in the natural passband. Unfortunately, Johnson chose to make the *UBV* system formally extraatmospheric by correcting to an air mass of zero rather than to an air mass of 1.0 or 1.3. The zero point of the $(U-B)$ system is therefore formally extraatmospheric but, in effect, includes some average air-mass extinction. This inconsistency has led to confusion (Cousins and Jones (1976) discuss the effects of extinction on the *UBV* bands.)

For a variety of reasons the passbands of the original system have not been carefully matched. Johnson himself began the move away when after one season he used a dry-ice-cooled tube and an improved photometer with more transparent optics, but he appears to have transformed these later data onto the original system. The Corning glasses were usually sold as unpolished rough sheets of about 5 mm in thickness and Johnson simply listed "standard" thickness in his specifications. The glasses were not the best optical quality, in particular the UV glass which also had a significant "red leak". Many users were therefore more attracted to the Schott optical quality filters and Johnson (1955) listed Schott options for the specified filters, although he did stress that Corning filters were necessary for the best match. Hardie (1962) discussed the variety of color terms caused by mismatches of passbands by using a variety of filters with cooled 1P21 detectors but did not spell out the systematic differences that mismatches could create. Johnson also erred in suggesting 2-mm UG2 as a substitute for C9863 (1-mm UG2 was the correct substitute) resulting in gross nonlinearities for A stars (e.g., Cathey 1974). Argue (1963, 1966) discusses red-leak corrections and systematic deviations from linearity caused by mismatched passbands.

The advent of red-sensitive detectors, such as S20 and GaAs photomultipliers and CCDs, has enabled an even greater variety of bands to be used for *UBV* photometry. Some of these bands (e.g., Bessell 1979) are an excellent match to the original *UBV* passbands, while others are closer to the bluest of the 1P21 bands (e.g., Graham 1982); the effect on photometry of these different passbands will be discussed in detail below.

It is very important that there be general acceptance of some standard *UBV* passbands so that users with detectors of different wavelength sensitivity can design glass filter mixes to duplicate these standard responses and thus prevent the proliferation of different natural systems which can only diminish the precision of broad-band photometry. Hopefully, the passbands analyzed in this paper will serve as the standards.

3. Observational Data

Many recent analyses of passbands have been made using the spectrophotometry set of about 50 averaged spectra (Straizys and Sviderskiene 1972; referred to as the Vilnius spectra) representing different spectral and luminosity types. For this paper additional sources of spectrophotometry have been used: CCD spectra from 310 nm to 660 nm obtained for some 20 bright Cousins standards and Reticon spectra from 350 nm to 950 nm of 213 bright stars measured by Petford *et al.* (1985), which will be referred to as the Oxford spectra. I am very grateful to the authors for providing a tape of the Oxford spectra for use in this analysis. Of the 213 Oxford stars, 57 had Cousins *BVRI* measurements, all had *BV* measurements in the Blanco *et al.* (1970) USNO Photoelectric Catalogue, and 204 had measures in the Johnson 13-color 53 and 80 bands (Johnson and Mitchell 1975).

The slitless CCD spectra comprised single spectra at 15 Å resolution (6 Å pixels) obtained with a coated GEC CCD and calibrated using standards from Taylor (1984). These spectra were from 305 nm to 660 nm and well covered the region of the Balmer discontinuity and the higher Balmer lines, regions a little suspect in the Vilnius and Oxford spectra because of difficulties in calibration at these wavelengths.

In an attempt to better understand the effects of different glass filters and the spectral response of modern cooled 1P21's on the passbands of the *UBV* system, observations of Cousins stars were also made through several different glass filters with the 24-inch (60-cm) telescope at Siding Spring Observatory on four occasions between 1987 and 1989. The transmission of the filters was measured and combined with 1P21 response functions to produce theoretical passbands which were convolved with the various spectrophotometric data to produce synthetic magnitudes. These were then compared with the observed (corrected for extinction) and standard magnitudes.

In the following sections we will discuss each of the *UBVRI* bands in turn, commencing with the *V* band with which most magnitudes are compared to derive colors.

4. The *V* Passband

Following recommendations by Johnson (1955) the blue edge of the *V* passband has usually been defined by either 2-mm Schott GG14 (now GG495) or the similar Corning filter CG3384. The red edge was defined by the sensitivity falloff of the 1P21's S4 photocathode. Johnson initially used an uncooled 1P21 which produced a redder passband than did a cooled 1P21, and although his later work used a dry-ice-cooled 1P21 the *V* magnitudes were reduced to the initial effective wavelength scale. Modern 1P21's (or their equivalent from other manufacturers) selected for low noise appear to have less red response than did some of the old 1P21's, while bialkali cathodes with their enhanced blue response also produced bluer *V* passbands with the same yellow glass filter. As a consequence, most users of the *UBV* system have always had significant color terms to correct their *V* photometry to the original system if they used the Johnson recommended yellow glasses (Hardie 1962); alternatively, they used a "redder" yellow filter (Cousins 1963) to shift the passband. Either way, secondary standards will have been observed using *V* passbands different from the original system.

Extended red sensitive detectors such as S20, GaAs, CCD, etc. need to have the red edge of the V-band filter defined and this is commonly done with one of the Schott bell-shaped blue filters from the BG18/38 or BG39/40 families (e.g., Bessell 1976, 1979). The gradient of the wavelength cutoff of these blue filters is such that by choosing specific thicknesses one can tailor the blue cutoff of the V response to mimic the response falloff of a 1P21 or bialkali tube. In order to maximize the response of systems, observers usually use the widest possible passbands and so the V passband with red-sensitive detectors has tended to be as red as possible, giving a closer match to the "standard V" passband but being a different passband to many of the 1P21 V responses. This will result in systematically different V magnitudes being measured for red stars, as will be shown in computations discussed below. In fact, for all the bands, we must be aware that it may not be possible to derive from the spectrophotometry a band that has the appropriate central wavelength, bandwidth, and band shape of the standard system and which gives no residuals in the comparison between synthetic magnitudes and secondary standard magnitudes.

The V passbands detailed by Matthews and Sandage (1963) (V_{MS}) and Azusienis and Straizys (1969) (V_{AS}) are well justified in terms of filter transmission and detector response and have been used by many workers. The analysis presented below suggests that the V_{AS} passband needs a slight shift redward to better represent the observations. Figure 1 shows these passbands.

Cousins and Jones (1974, 1976, hereafter CJ) have used Cousins natural V passband and the observed transformation to derive a standard V_J magnitude from the Vilnius spectra and compare it with the magnitude derived using the V_{AS} response. The result was $V_J - V_{AS} \approx -0.01(B-V)$, suggesting a redward shift for V_{AS}. Using the absolute fluxes and the observed V magnitudes of the Oxford spectra one independently derives $V - V_{AS} = -0.01(B-V)$. V_{MS} is, in fact, redder than V_{AS} ($V_{MS} - V_{AS} = -0.03(B-V)$), but comparisons between photoelectric V magnitudes measured with different filters discussed below suggests that even a redward shift as large as $0.01(B-V)$ is unlikely. As the blue side of the band was filter defined and the red side defined by the detector response, it is more likely for the red side to be incorrect. From our analysis the red side of the V_{AS} response was shifted to longer wavelengths to remove a color term of $-0.007(B-V)$. The adopted response is V_{90}.

Our photoelectric observations were made of Cousins standard stars (from -0.11 to 1.5 in $(B-V)$; no M dwarfs or giants) using two different 1P21 tubes and three different yellow filters. The yellow filters were 2-mm GG495 (GG14), 2-mm OG515, and 2-mm OG530. The observations were corrected for extinction to zero air mass and the differences from the standard V magnitudes were regressed against the $(B-V)$ colors to derive the color term. The OG515 and OG530 filters produced passbands blueward and redward, respectively, of standard V (the GG495 filter is, of course, blueward of OG515). The transmission of the filters was measured with a Carey monochromator and multiplied by the cold 1P21 response given by Young to give a measured passband for the RCA tube. The passbands were normalized and convolved against the spectrophotometry. The OG515 and OG530 passbands used are shown in Figure 2.

The observed color terms of the V transformations are given in Table 1, together with the computationally derived coefficients. The computed and observed regressions are the same within the errors of the fits which were $\pm\ 0.004(B-V)$. Because the Hamamatsu response was bluer, it was necessary to modify the red tail of the RCA 1P21 response for that tube. The computed color difference between the hot and cold 1P21 responses of Young

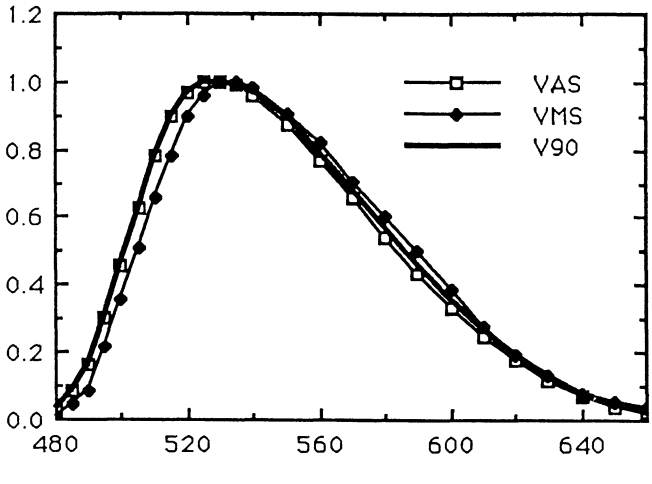

FIG. 1–The V passbands of Azusienis and Straizys (AS), Matthews and Sandage (MS), and this paper.

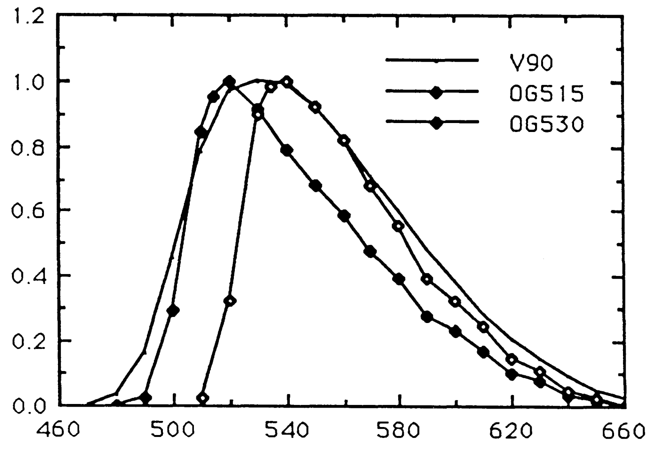

FIG. 2–The observed passbands for OG530 and OG5150 filters with a Hamamatsu 1P21.

TABLE 1

B-V COEFFICIENTS IN THE V TRANSFORMATIONS

$v_{obs} - V = \varepsilon(B-V)$, $v_{com} - V_{90} = \varepsilon'(B-V)$

Tube	Filter	ε	ε'
RCA	GG495	0.082	0.084
Ham	GG495	0.115	0.117
Ham	OG515	0.065	0.069
Ham	OG530	-0.059	-0.055

(1963) were $-0.033(B-V)$, the same as the difference between the RCA and Hamamatsu 1P21's; consequently, the cold 1P21 response was modified by a similar amount to the difference between the hot and cold responses. This bluer response was used to derive the OG515 and OG530 based passbands.

Figure 3a shows the observed regression for the two filters. Figure 3b shows the calculated regression from the CCD spectra. As pointed out in Bessell (1986*b*) cubic rather than linear regressions are the better descriptions of the differences between passbands, and small nonlinear deviations are seen in the observed and computed differences shown. The Vilnius spectra showed an additional difference, namely, the larger scatter shown in the *V* magnitudes of the M stars. The *V* magnitude of these stars whose continua are heavily depressed by molecular bands will clearly be affected by differences in the position and width of the *V* passbands. In particular, as noted above, most of the *V* photometry done with 1P21 based systems used a bluer *V* band than those of the GaAs, S20, and CCD based systems; one can therefore expect differences in the *V* magnitudes for M stars although the magnitudes for the hotter stars may agree.

Another systematic difference in *V* photometry will arise from how the color term in the *V* transformation is applied. In *UBV* photometry the color term used has always involved $(B-V)$; however, often only *VRI* photometry is obtained for faint red stars and $(V-R)$ must be used as the color term. But, as is well known, the $(B-V)$ color is not a smooth function of temperature or continuum color and it reaches a plateau of around 1.5 in early-M stars; therefore, the use of $(B-V)$ will produce an almost constant *V* correction for M stars, while using $(V-R)$ or $(V-I)$ up to a two-times greater correction would be applied for the coolest stars if extrapolated from the correction for stars with colors between A and K. (A0 to K5 covers from 0 to 1.8 in $(V-I)$ while M0 to M6 covers from 1.8 to over 4.0.) Synthetic photometry with mismatched *V* bands actually indicates that corrections for the M stars should be almost constant as imposed by the

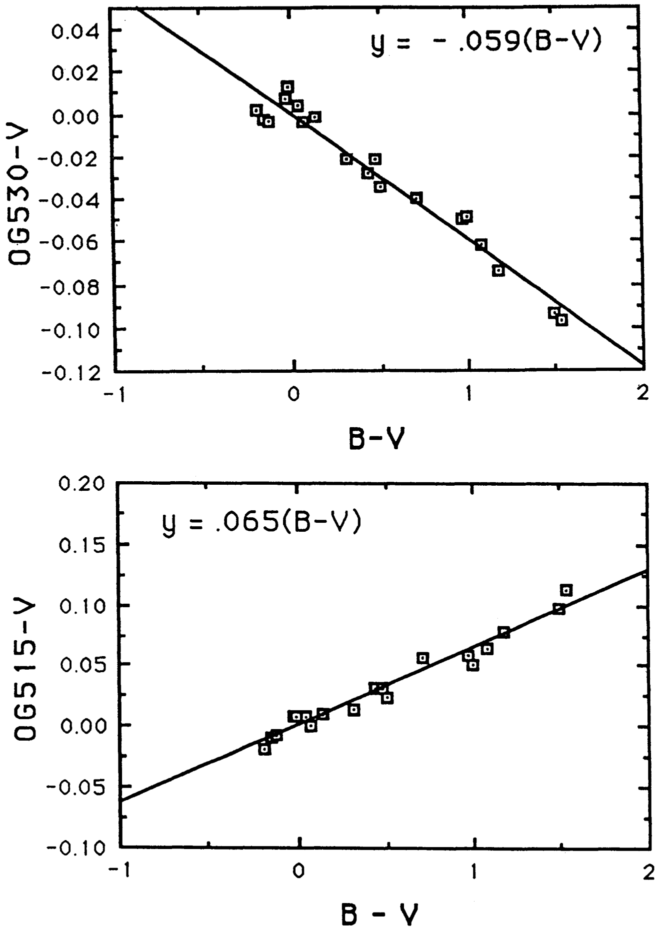

FIG. 3a–The observed differences for the OG530 and OG515 filters.

$(B-V)$ color term. This must result from the fact that the *V* band sits in the middle of the strongest TiO absorption bands and the effective wavelength of *V* does not continue to move redward for later spectral types. Systematic differences can also arise between KM giants and dwarfs because of the different spectral features that they possess, namely MgH and CaH bands in dwarfs, as well as different strength TiO bands at the same continuum colors. It is important for observers to detail their passbands and to publish their transformation equations so that one can assess likely systematic differences that could occur in their photometry.

With regard to such possible systematic differences, in Figure 4 are shown the passbands of Cousins (1963), *V*18t; Cousins (1980), *V*1; Graham (1982), V_{GR}; Bessell (1990), V_B; and V_{90}. Cousins blue *V*18t had a similar effective wavelength to *V* but was a narrower band than the standard. Cousins found *V*18t (blue tube) and *V*1 (GaAs) to have effective wavelengths slightly redder and bluer, respectively, than standard *V* as seen in the regressions $V_{18t} - V = -0.01(B-V)$ and $V_1 - V = 0.03(V-I)$. Bessell (1990) (2-mm GG495 + 1-mm BG18 + 1-mm BG38) closely matched standard *V* both in effective wave-

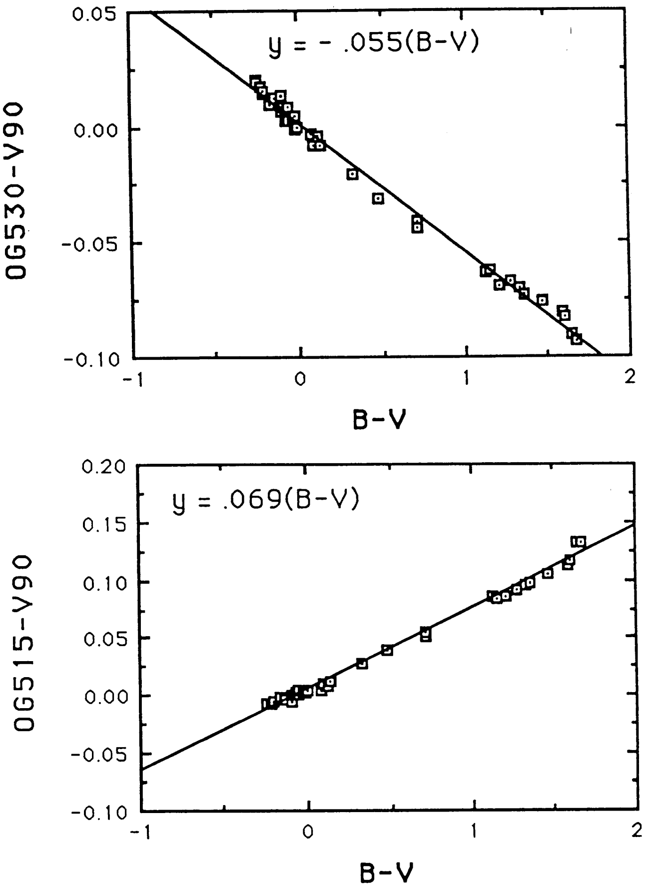

FIG. 3b–The calculated differences for the OG530 and OG515 filters using CCD spectra.

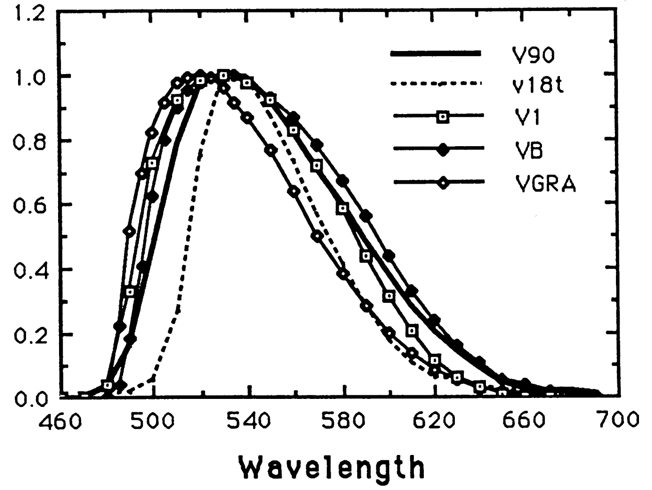

FIG. 4–Natural V passbands for different observers (see text for details).

length and in bandwidth and measured $V_B - V = 0.01(V-R)$. Graham (1982) devised a bluer V_{GR} similar to many 1P21 systems and one can estimate $V_{GR} - V = +0.08(B-V)$.

In summary, the V_{90}, passband (a slightly redshifted V_{AS}) is a good representation to standard V and can be well matched by combinations of GG495 and BG39/40 or BG18/38 with red-sensitive photomultipliers and CCDs (see Section 10). However, because of a diversity of observational V passbands and methods of transforming from instrumental to standard magnitudes, the V magnitudes of stars of some spectral types, mainly type M, will likely differ between catalogs. More consistent photometry can be achieved by transforming from instrumental to standard V via cubic regressions on $(B-V)$ or $(V-I)$ and by ensuring that large corrections are not applied for late-M stars.

5. The *B* Passbands

The B response functions of MS and AS (Fig. 5) have been most often used for the standard response. AS list two response functions, one containing the effects of atmospheric extinction for use with U in the computation of $(U-B)$, and B_{AS} for use with V. This is a good approach to use and we will follow it in this paper. There is evidence that B_{AS} is quite a good match to standard B but should be shifted slightly blueward. B_{MS} is redder than B_{AS} by $\sim 0.03(B-V)$.

Although the blue Corning filter 5030 was used by Johnson, many users since have used the Schott BG12 filter which at 1-mm thickness is less red than the Corning glass (0.75-mm BG12 or 1-mm BG28 would have been a better match). Some users, such as Graham (1982) (2 mm BG12), have devised even bluer responses. Cousins (1973) used additional GG13 glass with BG12 to shift the effective wavelength closer to that of Johnson, but again produced a narrower passband than the standard response. Altering the position and width of the B band is, for the majority of stars, more significant than similar changes in the V band. V-band changes cause significant changes only for M stars but, as the B band is situated near the confluence of the Balmer lines, small shifts will greatly affect the colors of A and F stars and introduce

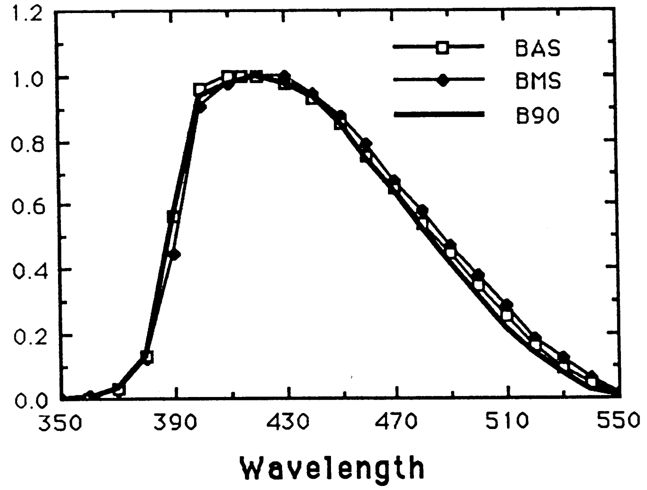

FIG. 5–The B passbands of Azusienis and Straizys (AS), Matthews and Sandage (MS), and this paper.

significant nonlinearities into transformations. For these reasons it is clear that *many of the problems in* $(U-B)$ *tranformations arise from the B band and not from the U band.* Most observers have used very similar U filters but a wide range of B filters and passbands. We will examine the effects that different B passbands can have on the observed colors and magnitudes below. If the B response is too blue it is best to introduce more GG385 or GG395.

Evidence for shifting the B_{AS} passband comes from several sources. From the Vilnius spectra CJ suggest a difference between observed and computed B of $0.014(B-V)$, implying that B_{AS} is too far to the red. From observations made with Johnson's B filter at the Cape, CJ derived a smaller difference of $0.006(B-V)$. Having shifted V_{AS} a little to the red we computed $(B-V) = -0.015 + 1.009(B_{AS}-V_{90})$ from the Vilnius spectra and $(B-V) = 0.014 + 1.004(B_{AS}-V_{90})$ from the Oxford spectra. Although it is difficult to assess the reliability of the different spectrophotometry and assigned colors, it seems clear from these comparisons that B_{AS} does need shifting to the blue.

To obtain additional evidence concerning the B band, observations were made of Cousins standard stars with 1P21's and different blue filters. The addition of an extra 2GG13 to the 1BG12+2GG13 filter resulted in a color correction of $+0.03(B-V)$, although the relation was nonlinear. A regression against $(U-B)$ was more linear as one might expect, the difference in response coming from the UV side of the band. The color term in this case was $+0.023(U-B)$.

An important comparison was also made between a 1BG12 + 2GG13 filter (BBG) and a 2.5(mm)CG5030 + 2GG13 filter (BCG) (Johnson may have used ~5-mm CG5030). These passbands are shown in Figure 6. In Figure 7a are shown the observational results for the two filters. With the blue Hamamatsu tube the BBG band gave a large color term of $0.124(B-V)$, and a cubic regression was clearly more suitable. The BCG band was closer to the standard B in effective wavelength but the regression was also nonlinear; the effective wavelength was too blue for blue stars and too red for red stars. Many users in the past have also used 2-mm CG5030 which must have resulted in even larger nonlinearities than those shown here.

The nature of the observed relations was seen in the synthetic colors, but the computed differences using the B_{AS} response were slightly smaller than the observations. The good agreement between computed and measured differences for the very blue stars suggests that the violet side of B_{AS} is nearly correct, but for the red stars the BCJ − B regression suggested that the red side of B_{AS} needs to be slightly lowered. When this was done it made the BBG − B regression slightly poorer, but, as the computed and observed differences between BCG − BBG already indicated some inconsistency, it was not considered significant. The slight change made a blueshift of $0.013(B-V)$ and did not alter the blue cutoff in the B_{AS} response. In Figure 7b are shown the computed residuals from the CCD spectra using the BBG and BCG passbands and the modified B_{AS} response B_{90}.

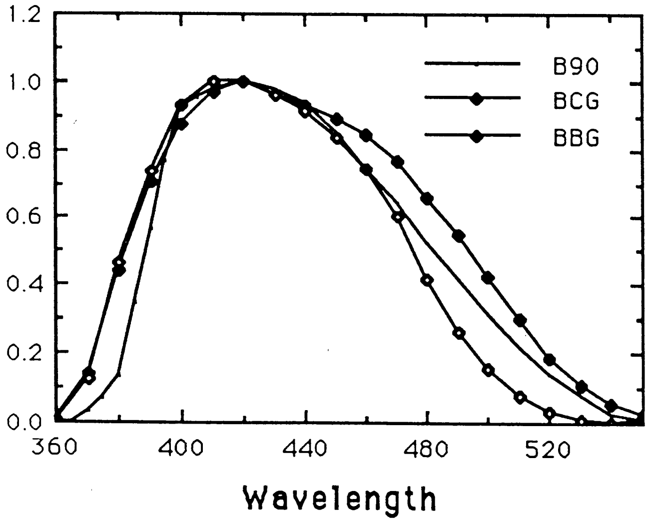

FIG. 6–The observed passbands for two B filters used with a 1P21 tube.

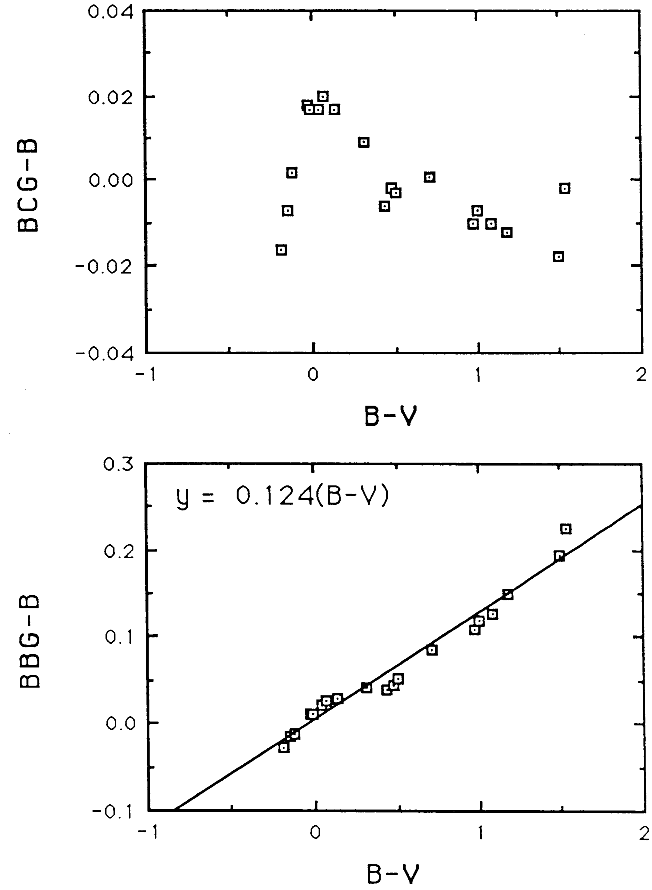

FIG. 7a–The observed differences for the BCG and BBG filters.

With regard to systematic differences between natural systems we show in Figure 8 several of the natural system B responses. Cousins (1973) used 3 mm of GG13 for his B filter to make its effective wavelength redder with an S13 photocathode. The illustrated B 18t response has had the effect of extinction removed; the illustrated B_{GR} response of Graham (1982) has been multiplied by that of a typical GaAs tube. Bessell's (1990) GaAs B_B response is for the filter mix (2GG385 + 1BG12 + 1BG18) specified in Bessell (1976, 1979). The natural passbands of Cousins and Bessell are close to the standard B producing small color terms of 0.01 or $0.02(B-V)$. Graham's (and Landolt's 1983) B response produces a much larger color term. In Figures 9a and 9b are shown the calculated B_{GR} regression together with the residuals from the calculated linear $(B-V)_{GR}$ regression. Cousins (1984) shows the difference between his $(B-V)$ and that of Landolt (1983) and it is significant that this shows almost identical deviations to those predicted in Figure 9. The discrepancy is removed by subtracting the following differences from Landolt's $(B-V)$: $\Delta(B-V) = 0.01 + 0.014(B-V) - 0.087(B-V)^2 + 0.0486(B-V)^3$.

6. The *U* Passband

The $(U-B)$ color seems to be the most difficult to standardize. The reasons for this are involved and do not really reflect difficulties in making observations in the UV or in correcting them for extinction. In fact, it is not much more difficult to make accurate UV observations than it is

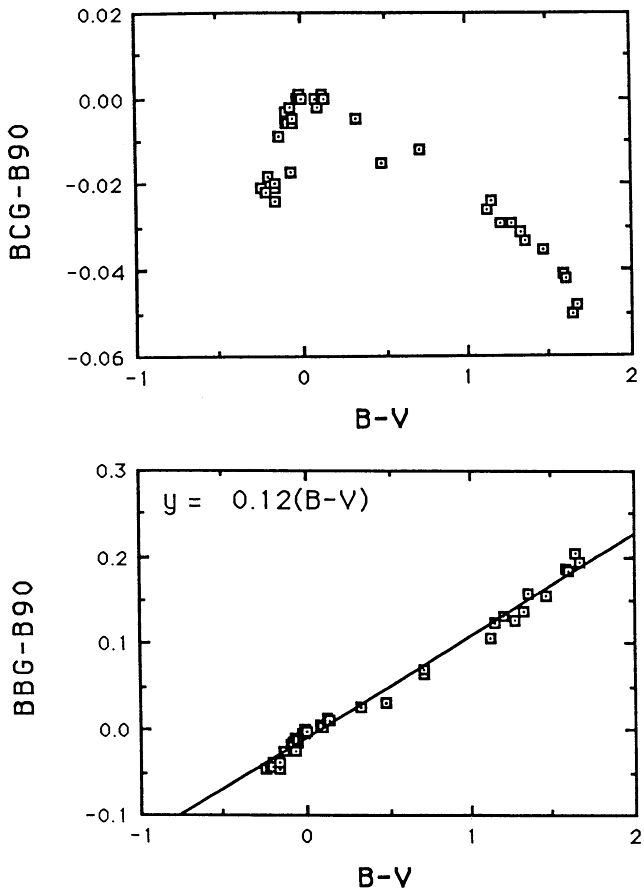

FIG. 7b–The calculated differences for the BCG and BBG filters using CCD spectra.

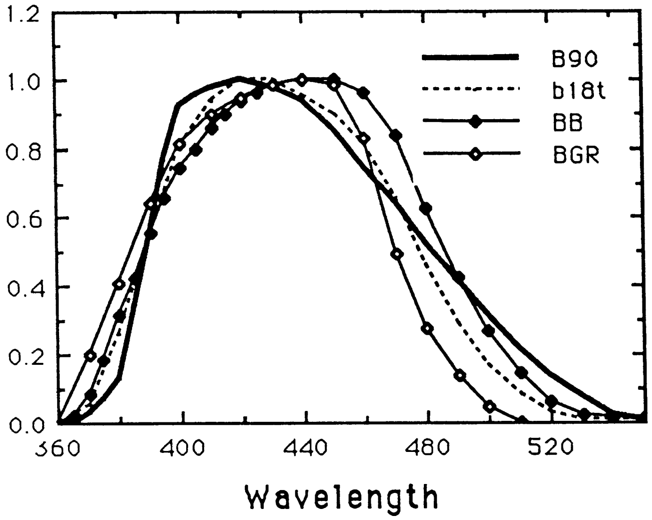

FIG. 8–Natural B passbands for different observers (see text for details).

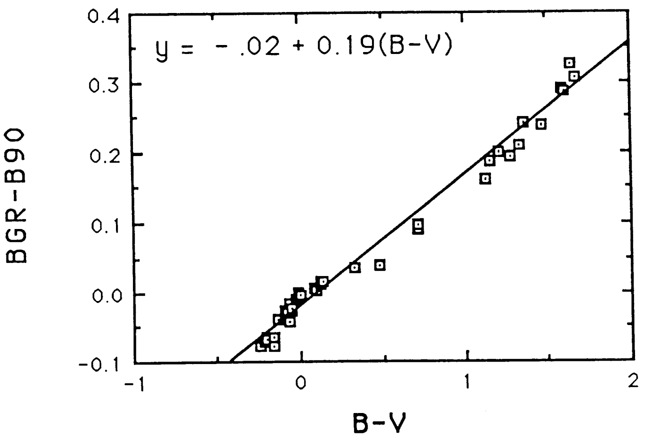

FIG. 9a–Calculated differences between the natural B system of Graham and standard B.

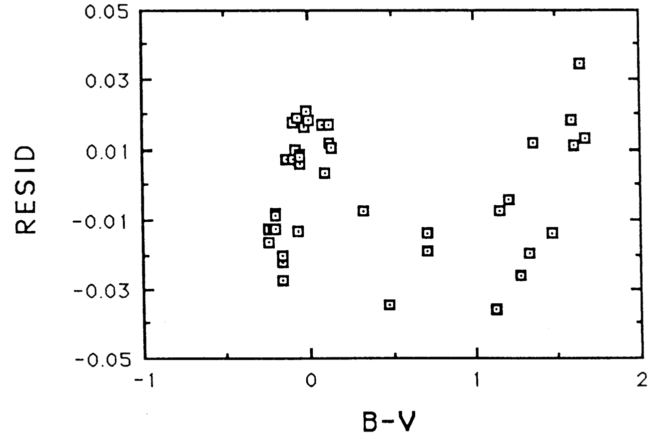

FIG. 9b–Calculated residuals from a linear regression for the natural $(B-V)$ system of Graham.

to do other colors. Although Bessell (1986*b*) discussed some of the issues involving $(U-B)$ photometry it is useful to reexamine them again here. Mismatches in both U and particularly B affect the color significantly and transformation procedures involving regressions on $(B-V)$ as well as $(U-B)$ have added layers of complications. As a result of these various effects, there now exist several $(U-B)$ systems.

Cousins (1984) discussed comparisons between his E-region $(U-B)$ system and that of Johnson and Harris (1954) (the primary $(U-B)$ system source), Johnson *et al.* (1966), Crawford, Golson, and Landolt (1971) and Landolt (1983). He also discussed the effect of $(U-B)$ extinction corrections. These comparisons of $(U-B)$ values in common are particularly instructive. The $(U-B)$ systems show much greater divergences than do the V and $(B-V)$ systems; the differences are greatest for B stars and for the KM stars. The $(U-B)$ of Johnson and Harris (1954, hereafter JH) and Johnson *et al.* (1966, hereafter JMIW) may be slightly different, and the imprecision of the early Johnson $(U-B)$ colors and the lack of red standards also led to standardization problems. Cousins (1984) showed that the addition of $0.015(B-V)$ to the E-region $(U-B)$ colors brought them into line with the mean of the Johnson *et al.* (1966) $(U-B)$ system colors, but differences with other sets of standards are more complicated. The Landolt $(U-B)$ values show large deviations—in particular, deviations much larger than one would expect from the internal standard errors. Landolt (1983) observed with a natural U and B system significantly different from those of Johnson or Cousins, used Cousins E-region standards and then transformed back to the Landolt (1973) equatorial system. Amalgamation of the 1973 and 1983 photometry may be responsible for some of the large deviations between the common equatorial star photometry of Cousins and Landolt, but the different natural systems undoubtedly also contribute.

As Cousins suggests, it is best to try and work within a single system of standards and convert the resultant photometry to another system for comparison if and when necessary. The differences evident in Cousins differential regressions can be expressed by the following polynomials in $(B-V)$. The corrections are to be subtracted from the specified authors' $(U-B)$ values.

Johnson *et al.* (1966): $0.004 + 0.040\,(B-V) - 0.024\,(B-V)^2$.

Crawford *et al.* (1971): $0.016 + 0.069\,(B-V) - 0.118\,(B-V)^2 + 0.040\,(B-V)^3$.

Landolt (1983): $0.007 + 0.095\,(B-V) - 0.158\,(B-V)^2 + 0.074\,(B-V)^3$.

Ryan (1989, page 1697) compared some Graham (1982) and Menzies *et al.* (1989) $(U-B)$ photometry and found Graham's stars to be on the average -0.02 bluer, except for the late-A and early-F stars. Graham's and Landolt's photometry reflects the kind of differences that can creep into standard photometry when grossly nonlinear transformations are induced by mismatched passbands.

Let us now examine problems associated with $(U-B)$ photometry in some detail. The original U band used by Johnson was defined by a Corning 9863 glass filter used with a 1P21 phototube and glass optics at over 7000-ft altitude. Different filters, phototubes, optics, observing heights, and observing and reduction procedures all contribute to different natural systems. Observational problems associated with $(U-B)$ measurements comprise three distinct effects: red-leak problems for late-type stars, problems associated with the Balmer jump and Balmer lines in intermediate A–F stars and supergiants, and too much UV light measured in early-type OB stars. All the glass U filters have "red leaks", transmitting red light beyond about 680 nm, but the red leak of the CG9863 and UG5 glasses commences about 300 nm blueward of the red leak of UG2 and UG1 glass. This is shown in Figure 10a. The amount of red-light contamination in U photometry with blue detectors (S4 and S11) depends, therefore, on the kind of U filter used, the sensitivity of the red tail of the photocathodes, and the spectral type of the star. The red leak is mainly evident for stars redder than K0 and is worse for M giants than M dwarfs. Argue (1963) illustrates some red-leak measurements which can be duplicated by computation with the Vilnius spectra. Inadequate red-leak corrections for late-type stars undoubtedly resulted in early problems of standardizing $(U-B)$ colors for very red stars, but with UG2 or UG1 glass (even the recommended 1 mm thickness) the red leak is less than 1/4 that of the 9863 or 3UG5 glass with the same S4 or S11 cathode and can almost be ignored. When

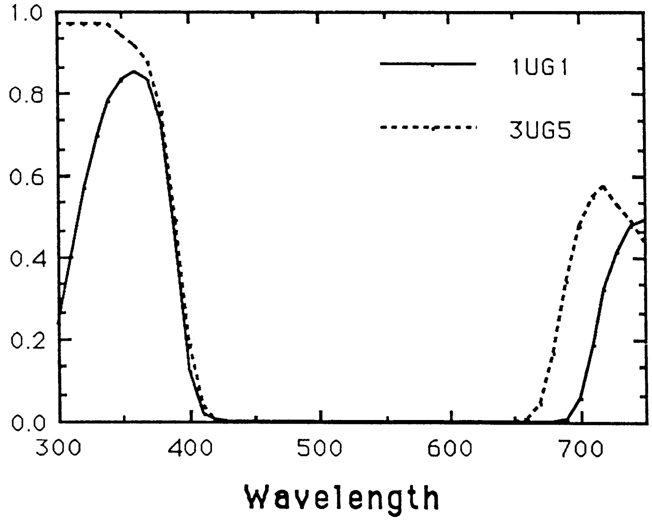

FIG. 10a–The transmission of 1UG1 and 3UG5 filters showing the "red leak".

used with red-sensitive detectors the red leak is blocked, usually with a $CuSO_4$ filter; consequently, red-leak contamination is unlikely to be a serious problem with recent photometry.

Systematic deviations that occur in natural $(U-B)$ colors for mainly A and F stars result from different amounts of light being measured from wavelengths near the confluence of the Balmer lines. When 2-mm UG2 glass was used as suggested by Johnson (1955), nonlinear deviations of up to 0.1 mag were evident in $(U-B)$ regressions for A–F stars (see, e.g., Cathey 1974); the long-wavelength edge of the U passband had clearly shifted too far toward the UV. However, the long-wavelength cutoffs of 3-mm CG9863 glass, 3UG5 and 1UG1 and 1UG2 are almost identical (Bessell 1986*b*) and should not be responsible for Balmer line/jump associated deviations. On the other hand, as discussed above, the B passbands often have very different UV cutoffs which will result in $(U-B)$ deviations related to the Balmer jump. Such deviations can be seen in a comparison of $(U-B)$ photometry of Graham (1982) and Menzies *et al.* (1989), shown by Ryan (1989). (In retrospect, it would have been much better had $(U-V)$ rather than $(U-B)$ been used by Johnson in his establishment of the *UBV* system.)

The short-wavelength cutoff of the U band can also introduce systematic deviations, which are significant mainly for B stars but show some luminosity dependence in supergiants. The Corning 9863 and Schott UG5 glasses transmit UV light well below the atmospheric limit near 300 nm, while the UG2 and UG1 glass cuts off near 290 nm. These filter differences result in only small $(U-B)$ differences when used with the RCA 1P21 because the tube has a lime-soda glass envelope with a more severe UV cutoff than do the filters; however, other S11 tubes have more UV-transparent glass and quartz windows. The EMI6094 used by Cousins (Cousins and Stoy 1963) had a borosilicate glass window but he had glass optics in the photometer. The blue response was rather like that of the Hamamatsu 1P21. GaAs and S20 tubes generally have quartz windows which transmit to below 2000 Å; hence, large differences in $(U-B)$ result when using the same glass filters as with the RCA 1P21. The relative response of these tubes is shown in Figure 10b. Landolt (1983) shows large deviations of 0.1 mag that occurred when a 9863 filter and a GaAs tube were used. Smaller deviations occur for the UG1 glass. When photometry is done with higher UV sensitivity detectors than the 1P21, best results are achieved when some glass, such as 2-mm WG320, is inserted into the filter.

Cousins used an EMI6256 quartz windowed S11-tube, a 0.9-mm glass window, and 1-mm UG2 filter for his E-region stars (Cousins 1973, 1983). He transformed the natural $(u-b)$ colors to standard $(U-B)$ with a small $(B-V)$ color term (Cousins 1973) but no $(U-B)$ term. Cousins (1963) also gives details of the nonlinear corrections that were applied to $(B-V)$, nonlinearities that must have arisen primarily from the B passband mismatch. Such complicated transformations and involvement of B-band mismatches make it virtually impossible to reconstruct the standard U-system passband directly from Cousins data and probable natural-system response, but it does mean that the Cousins natural system has a long-wavelength cutoff defined by 1-mm UG2 and a short-wavelength cutoff defined by the same glass envelope as Johnson's tube, plus sea-level extinction and the UG2 glass.

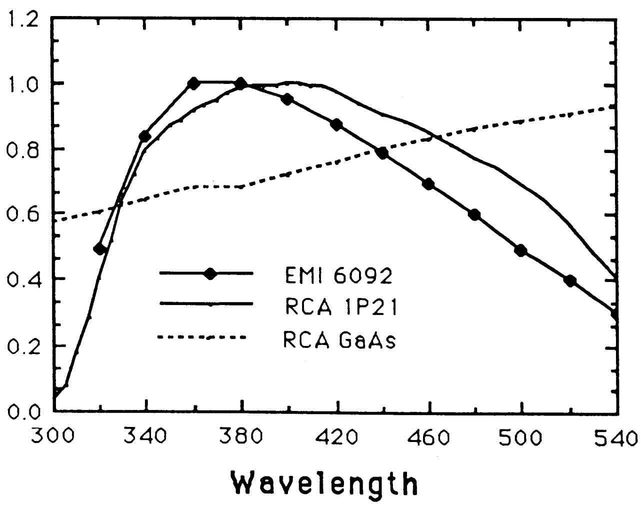

FIG. 10b–The relative ultraviolet sensitivity of 1P21, S11, and GaAs phototubes. The 6092 should read 6094.

Several attempts have been made to devise the Johnson system U passband. MS adopted a U passband based on what Johnson published of his natural system and on estimates of the atmospheric transmission. AS followed similar reasoning but modified the UV cutoff to provide a better effective wavelength. Bessell (1986*a*) showed that a U response function based on the 3-mm UG5 filter (similar to CG9863, but significantly different from what Johnson published) was superior to those of MS and AS and had a very similar long-wavelength cutoff to that devised by Buser (1978). Figure 11 shows these responses. We have since investigated that claim more fully using additional spectrophotometry and additional U photoelectric photometry with 1P21 tubes.

The atmospheric extinction corrections that we have employed for the synthetic photometry are based on the formulae of Hayes and Latham (1975). The extinction comprises empirical fits to the optical and UV ozone and to Rayleigh scattering from molecules and an aerosol component. The formulae were as follows, wavelength λ in microns, observing height H in km.

Ozone: $1.11*0.25*2.5*\{1210*\exp[-131(\lambda-0.26)] + 0.055*\exp[-188(\lambda-0.59)^2]\}$

Rayleigh: $0.0095*\exp(-H/8)*(1/\lambda)^4*\{0.23465$

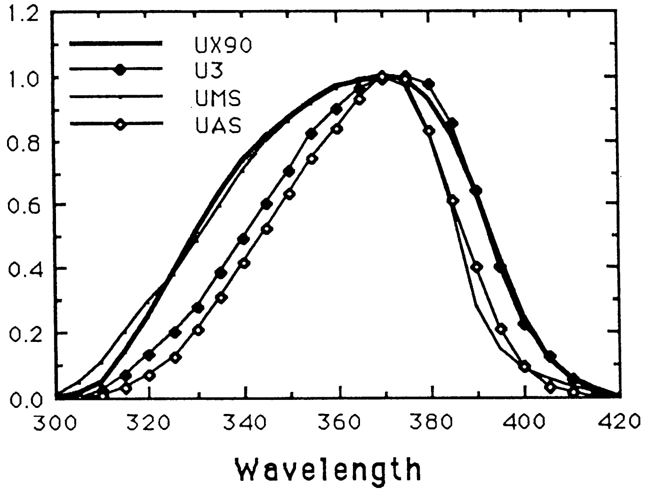

FIG. 11–The U passbands of Azusienis and Straizys (AS), Matthews and Sandage (MS), and this paper.

$$+107.6/[146-(1/\lambda^2)] + 0.93161/[41-(1/\lambda)^2]\}^2$$

Aerosol: $0.087^*\exp(-H/1.5)/\lambda^{0.8}$

A height of 2.5 km and an air mass of 1.0 were adopted for Johnson's observations, while a height of 1.1 km and an air mass of 1.3 km were adopted for observations at Siding Spring Observatory. Incidentally, the above extinction formulae predict extinctions per air mass for V of $0.191 - 0.004(B-V)$ and for $(B-V)$, $0.135 - 0.03(B-V)$, which are very similar to the average values at Siding Spring Observatory (SSO). The B_{90} response and the U responses of UG1 + 1P21 and UG5 + 1P21 were multiplied by the extinction curves to provide response functions BX_{90} and various U responses. The normalized transmissions of 1-mm UG1, 3-mm UG5, the transmission of 1.3 air mass at 1.1 km altitude (normalized to 1 at 420 nm), and the 1P21 senstitivity are shown in Figure 12.

In 1985 observations were made using an RCA 1P21 and 3UG5, 1UG2, and 1UG1 filters, and Cousins equatorial standards; these data were shown in Bessell (1986*b*). 3-mm UG5 was also shown to have very similar transmission to the Corning 9863 filter used by Johnson. After correction for the red leak of the UG5 filter the response differences between all three glasses were small, of the order of 1% or 2%.

In November 1988 and May 1989 additional observations of Cousins equatorial stars were made with a UG1 filter and several different B and V filters. The observations concerning the B and V filters were discussed above. In Figure 13a is plotted the relation between u(observed) $-$ U(standard) and $(U-B)$ for the two nights. A nonlinear relation is evident which is most apparent for the stars bluer than $(B-V) = 0$. Two linear relations, one for stars bluer than $(B-V) = 0$ and another for redder stars, would describe the observed regression, but a cubic relation clearly would be the better way to transform the observed U photometry.

If we assume that Johnson's photometer had good UV transmission, then the short-wavelength cutoff of his U passband should be close to that devised by multiplying the transmission of 3-mm UG5 by the 1P21 response and the extinction of at least an air mass of 1.0 at 2.5 km altitude. In Figures 13b and 13c are shown, respectively, the calculated differences from the Vilnius and CCD spectra between the U magnitudes measured with a 3UG5 filter at 2.5 km and air mass of 1 and the 1UG1 filter at 1.1 km and air mass of 1.3 (my observations at SSO). Apart from a slightly greater difference for the observed OB stars the comparison between observations and calculations is very similar indicating that the devised UG5* response is indeed close to standard U. We will call this response UX_{90}. The higher altitude and lower air mass assumed increases U by $-0.01(U-B)$; the 3UG5 glass increases U by $-0.015(U-B)$ compared to U measured with 1UG1. These theoretical color corrections are smaller if only stars redder than $(B-V) = 0$ are considered.

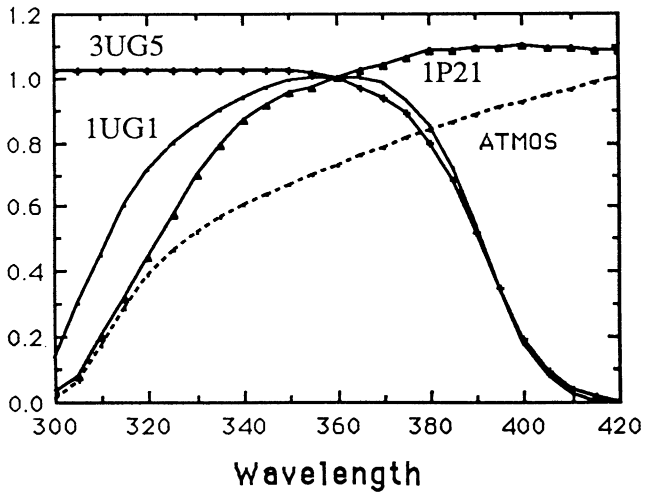

FIG. 12–The normalized transmissions of 3-mm UG5, 1-mm UG1, and the atmosphere, together with the normalized sensitivity of a 1P21 tube.

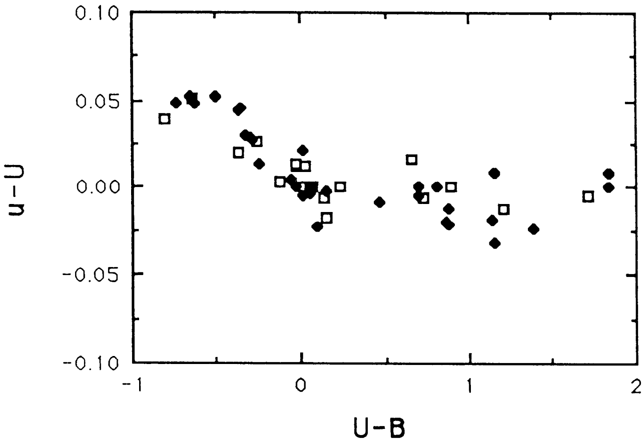

FIG. 13a–The difference in the sense observed U minus standard U for a 1-mm UG1 filter and 1P21 from Cousins equatorial stars. Observations of two different nights are shown.

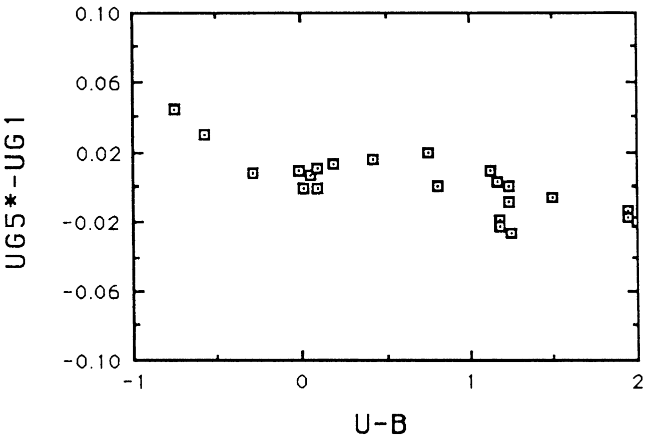

FIG. 13b–The calculated difference between 3UG5 at high altitude and a low-altitude 1UG1 passband with a 1P21 from the Vilnius spectra. See text for details.

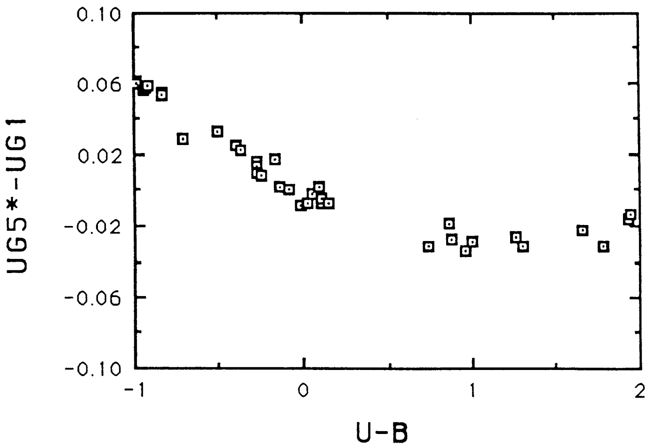

FIG. 13c–The calculated difference between 3UG5 at high altitude and a low-altitude 1UG1 passband with a 1P21 from CCD spectra. See text for details.

Unfortunately, we cannot use the CCD spectra or the Vilnius spectra for precise comparison of the absolute $(U-B)$ colors because the CCD spectra appear to have a small systematic flux error and the $(U-B)$ colors of the averaged Vilnius spectra are not known with certainty. The approximate $(U-B)$ colors given by Bessell (1986*a*) are, however, in good agreement with the computed $UX_{90} - BX_{90}$. In addition, the different $(U-B)$ systems effectively preclude the tying down of the U response as firmly as for the other colors; in particular, the $(U-B)$ system for stars bluer than $(B-V) = 0$ is not known very well.

The $(U-B)$ observations made with the same U filter but different B filters serve to show how the B-band differences can lead to large differences in $(U-B)$. In Figures 14a and 14b are shown the delta $(U-B)$ (observed minus standard) versus $(U-B)$ and $(B-V)$ diagrams for the UG1 U filter and the Corning 5030/2GG13 B filter described in Section 5. A linear relation against $(U-B)$ could introduce errors of up to 0.04 mag in $(U-B)$ for stars near $(U-B) = 0$ with $(B-V)$ colors between -0.3 and $+0.3$, unless the regression against $(B-V)$ is considered also. In Figure 14c is shown a similar diagram for the same stars, using the same U measurement but a 1BG12/2GG13 B filter. The $(U-B)$ difference has *already* been corrected by $0.11(U-B)$ (due to the effective wavelength of this B band being much bluer than standard B) so that the differences are on the same scale as Figures 14a and 14b. There is a slight nonlinearity evident, but no systematic difference with $(B-V)$. The Corning filter permits large excursions in effective wavelength resulting in significant differences in $(U-B)$ for $(B-V)$ values near 0. The 1BG12/2GG13 response, although being too blue, does not appear to introduce Balmer line effects, at least with Cousins standards. The B response of Landolt and Graham is much bluer and narrower than that of Johnson or Cousins, and this undoubtedly is responsible for some of the large deviations between the $(U-B)$ values of Cousins and Landolt and Graham discussed by Cousins (1984) and Ryan (1989).

It has always been inconvenient to use either crystalline $CuSO_4$ or liquid $CuSO_4$ to block the red light transmitted by the glass U filters, but there was no real

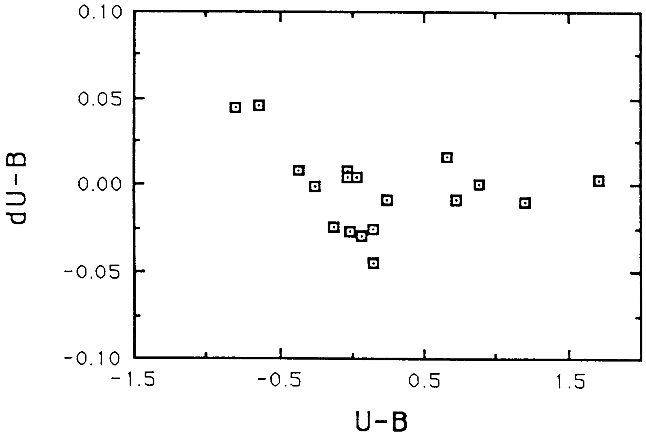

FIG. 14a–The observed $(U-B)$ difference for UG1 and 5030 filters plotted against $(U-B)$.

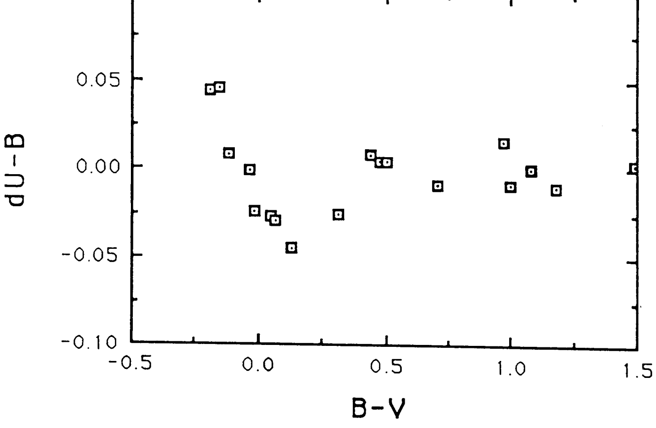

FIG. 14b–The observed $(U-B)$ difference for UG1 and 5030 filters plotted against $(B-V)$.

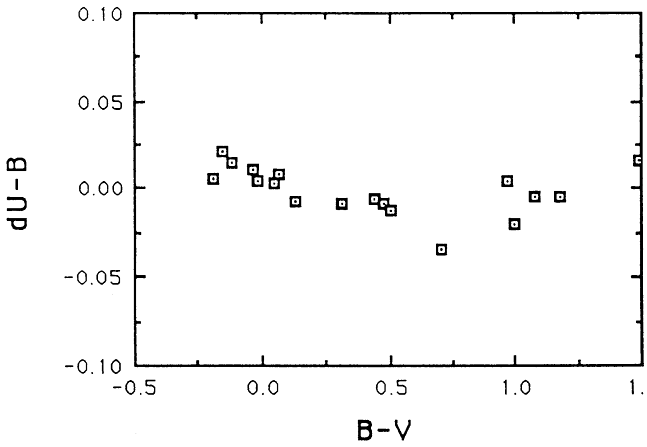

FIG. 14c–The observed $(U-B)$ difference for UG1 and 1BG12 filters plotted against $(B-V)$.

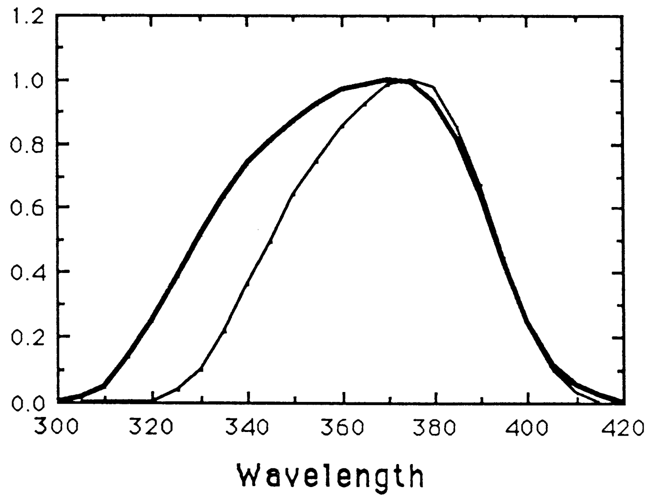

FIG. 15–The normalized passband of the U filter with BG39 as the red-leak blocker and the UX90 passband (thick line).

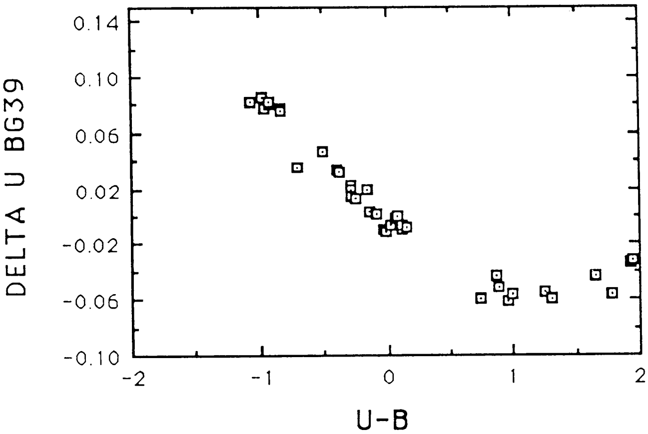

FIG. 16–The calculated difference between the BG39 blocked UG1 filter and the UX90 passband from CCD spectra.

substitute; BG18 had too low a UV transmission. However, the new Schott BG39/40 glasses have much better UV transmissions than do the BG18/38 glasses and, although they still restrict the far-UV transmission of the U band, this does not appear to cause great problems with transformations in particular for B stars. It does, however, result in systematic differences up to 0.05 mag in $(U-B)$ for the Vilnius F–K supergiants. Figure 15 shows the passband for the UG1 filter with the addition of 1-mm BG39 compared to the standard U passband. In Figure 16 we show the computed differences between UG1/BG39 and UX_{90} for some CCD spectra. Two straight lines could be used depending on the $(B-V)$ color of the stars, but a cubic regression gives good results. Neglecting stars later than K1 III or with $(B-V)$ redder than 1.2, a single linear relation could be used. A difference of $\sim -0.05(U-B)$ would then be added to measured $(U-B)$. UG1 is preferred to UG5 in filters because it is much more resistant to tarnishing in air.

In summary, UX_{90} is a good approximation to standard U but could be adjusted when better-calibrated spectra of standard stars are obtained. There are still significant differences between lists of $(U-B)$ standards, and these differences must be considered when comparing observations standardized using different authors' standards. 1UG1, 1UG2, and 3UG5 filters give similar results, but it would be best were 1UG1 to be used by all observers. It is even more important that the same B passband be used, as short-wavelength cutoff differences can lead to significant differences in $(U-B)$ for stars with $(B-V)$ colors between ± 0.3. 1BG39 can be used to block the red leak of the UG1 filter for all detectors but, in particular, for CCD imaging where $CuSO_4$ filters can be a problem. The resulting U can be easily transformed to standard U with some systematic differences mainly for supergiants.

7. The *I* Passband

Cousins (1980, 1981) discussed the R and I passbands used for the Cape-Cousins *RI* system. These bands are shown in Figure 17 (filled symbols). Bessell (1979, 1983) also published the similar passbands that he used with a dry-ice-cooled GaAs tube. The I passband with a GaAs tube had its long-wavelength edge defined by the tube cutoff, a cutoff that appears to be the same from tube to tube but which alters with temperature. This small shift does not appear to cause transformation problems, but the severely modified I response with S20R tubes introduces quite large nonlinearities for cool stars. Most problems with standardizing Cousins *RI* photometry result from the nonrectangular passband of the R band, which causes gross nonlinear transformations between systems, and from the lack of very red standards to tie down these nonlinearities and so get good colors for the reddest stars. Bessell (1990) has recently published values for some red stars, and Bessell and Weis (1987) present cubic relations that accurately transform Weis's Kron *VRI* colors of northern stars onto the Cousins system. Those data could hopefully define the system for the reddest stars.

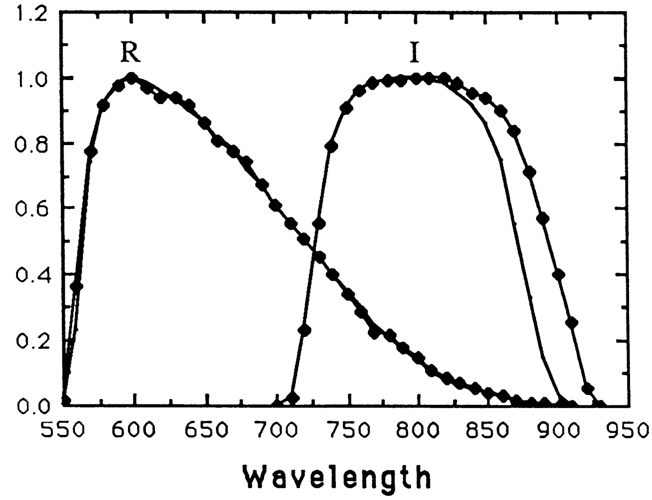

FIG. 17–Cousins passbands for R and I (solid symbols) and the passbands in this paper (line).

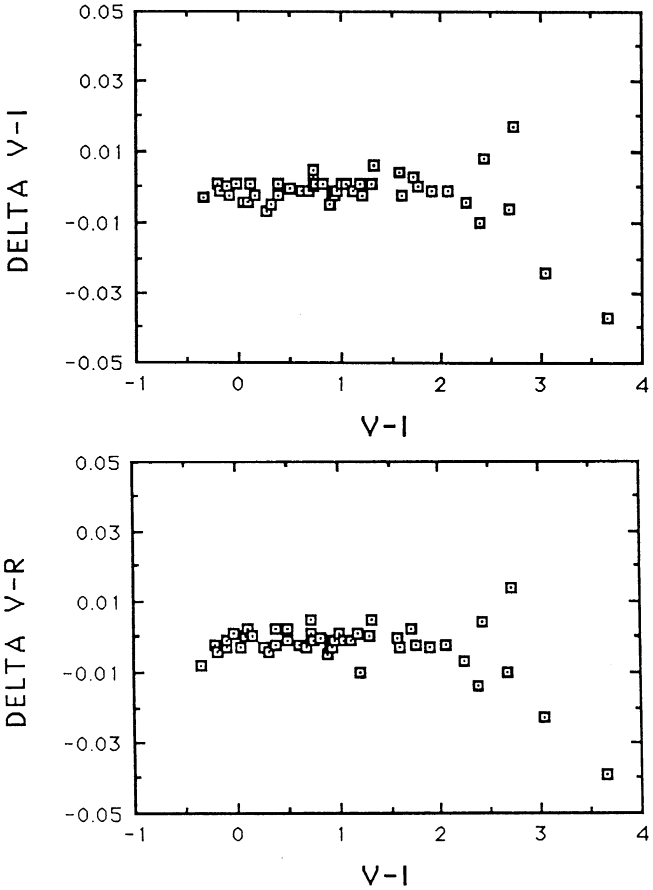

FIG. 18–The differences (normalized at zero) between $(V-I)$ and $(V-R)$ colors calculated using the passbands in this paper and Cousins tabulated Vilnius colors.

Cousins (1981), on the basis of calculations made with the Vilnius spectra, suggested that his tabulated I response was probably correct to within 25 Å. We have reexamined this question using the Vilnius, Oxford, and some CCD spectra and find the Cousins response needed moving blueward by at least $0.01(V-I)$. Such a shift is also supported by the fact that the difference between the red cutoff adopted by Cousins and the cutoff measured by Bessell for a dry-ice-cooled tube was larger than could be explained by the temperature difference. The red edge of Cousins' response function was therefore shifted toward the cutoff of Bessell, in line with the change of sensitivity cutoff with temperature measured by Cole and Ryer (1972), until the computed $(V-I)$ residuals showed no color term with the Oxford spectra or with Cousins $(V-I)$ colors for the Vilnius spectra. The computed regression of $(V-I)$ using the V_{90} and I_{90} responses and the Vilnius spectra is shown in Figure 18. The deviations for the reddest stars are due to the different V responses adopted by Bessell and Cousins, and not by the I responses.

8. The *R* Passband

The R passband is more difficult to tie down because the KG3 glass used for the red cutoff allows a great excursion in effective wavelength with spectral type. Nevertheless, it is possible to derive an acceptable band from the Cousins and Bessell responses. It was not possible to use the Oxford spectra for this purpose because it was clear that there were small systematic differences between the Vilnius data and the Oxford data involving the R band. Petford (private communication) informed me that the Oxford spectra comprised observations made at two different wavelength settings and joined near 600 nm with some uncertainty. Although *VRI* colors are not available for most of the spectra used for the Vilnius averaged spectral types, we can use the Vilnius spectra to examine the calculated regressions of $V_{90}-R_{90}$ and $R_{90}-I_{90}$ against $V_{90}-I_{90}$ and compare these with observed regressions of colors in the Cousins catalogs, and so establish the relative positions of V_{90}, R_{90}, and I_{90}. Cousins r band was likely to be accurate. Although Cousins did not measure his tube response, the differences between his adopted response and the responses measured for my tubes and that shown by Cole and Ryer (1972) would have little effect on r; the effect on V is much larger and is probably the explanation for the difference between Cousins observed and computed V response. Having shifted Cousins i to bring agreement with the Oxford spectra, it was necessary to alter Cousins r only very slightly by altering the blue cutoff and smoothing the slow red cutoff, to bring the $V_{90}-R_{90}$ and $R_{90}-I_{90}$ colors into line with $V_{90}-I_{90}$. The final $(V-R)$ result shown in Figure 18 is in good agreement with Cousins colors for the Vilnius spectra; the deviant points for the very red stars are due again to the different V passbands and not to the R passband. The $(R-I)$ colors are also in good agreement with the Vilnius colors, although using some CCD spectra which covered only the R and I bands gave $(R-I) = 0.992(R_{90}-I_{90})$ suggesting that I_{90} could be moved even closer to R.

However, until more-accurate red spectroscopy is available for more comparisons we will adopt the I_{90} and R_{90} bands.

Although Cousins claimed that his I response was at the correct wavelength he had to correct the computed $(R-I)$ colors by $-0.015(V-I)$. He also noted that his computed V passband differed from the observed band. By shifting the red cutoff of I to a more likely wavelength in comparison with measurements of Bessell (1983), and adopting the V_{90} passband, all the computed colors are now in agreement and no color terms need to be involved. The $(V-R)$ and $(R-I)$ colors calculated for the Oxford spectra when compared with the $(V-I)$ colors indicate that the Oxford R magnitude is systematically red by -0.025 $(V-R)$.

Undoubtedly the grossly nonrectangular passband of the photoelectric R band is unfortunate because it leads to nonlinear transformation problems for very red stars if not very well matched; in particular, it causes difficulties with transformations between photographic and photoelectric R photometry for very red stars (Bessell 1986*b*). However, the band can be reasonably well matched so that systematic differences should be small. On the other hand, for many purposes there is little reason to make R-band measurements: $(V-I)$ colors have twice the baseline of $(V-R)$ or $(R-I)$ and V is almost as easy to measure as is R with a CCD. (The $(V-I)$ colors of spectral type B to K stars change by the same amount as does $(B-V)$, and $(V-I)$ is insensitive to abundance for these stars.)

The RI photometry of Landolt is slightly different from that of Cousins. The following transformation aligns the $(V-I)$ colors: $(V-I) = 0.003 + 0.989(V-I)_L + 0.017 (V-I)_L^2$.

The T_1 and T_2 bands of the Washington system (Canterna 1976; Geisler 1990) are very close to R and I of the Cousins system. Transformations between $(R-I)$, $(V-I)$, and T_1-T_2 are

$$(R-I) = -0.002 + 0.9814(T_1-T_2) + 0.0089(T_1-T_2)^2 - 0.070(T_1-T_2)^3 ,$$

$$(V-I) = 0.004 + 1.777(T_1-T_2) + 0.869(T_1-T_2)^2 - 0.811(T_1-T_2)^3 ,$$

$$T_1-T_2 = 0.002 + 1.015(R-I) + 0.0047(R-I)^2 + 0.070(R-I)^3 .$$

9. Standard Passbands and Colors of Vilnius Spectra

In Table 2 are tabulated the standard *UBVRI* system responses discussed in the previous sections. The 90 has been dropped from the names in the table. UX and BX should be used for computing standard $(U-B)$ colors. B, V, R, and I should be used for the other colors and magnitudes. The extinction should be removed from the UX response before matching with instrumental U passbands.

In Table 3 are listed zero-point magnitudes and effective wavelengths which were derived for each passband using the Vega model spectrum of Dreiling and Bell (1980). These zero points are in good agreement with the synthetic photometry of the CCD spectra. In Table 4 are listed the Vilnius colors calculated using the standard passbands in Table 2. Additional zero-point corrections of $+0.01$, -0.01, -0.01, -0.03, and -0.04, respectively, were made to the calculated $(U-B)$, $(B-V)$, $(V-R)$, $(R-I)$, and $(V-I)$ colors for the Vilnius spectra to bring closer agreement with observed color-color relations. The Vilnius spectra are very useful for analyzing passbands but using coated CCDs; higher-resolution, precise, absolute spectrophotometry from 305 nm to 1000 nm of individual broad-band standard stars is possible and should supplant the Vilnius collection for such analysis.

10. Recommended Filter Passbands

In Table 5 are listed glass filter combinations that are recommended for *UBVRI* photometry with a GaAs, S20R, or S11/S4 tube. The best passband matches are possible with the GaAs tubes. If the BG39 glass is to be used as the red-leak blocker for much U photometry in the future, it would be worthwhile using it also for standard photoelectric photometry.

There is a range of CCDs now available for photometry.

TABLE 2

NORMALIZED STANDARD PASSBANDS

λ	UX	λ	BX	B	λ	V	λ	R	λ	I
300	0.000	360	0.000	0.000	470	0.000	550	0.00	700	0.000
305	0.016	370	0.026	0.030	480	0.030	560	0.23	710	0.024
310	0.068	380	0.120	0.134	490	0.163	570	0.74	720	0.232
315	0.167	390	0.523	0.567	500	0.458	580	0.91	730	0.555
320	0.287	400	0.875	0.920	510	0.780	590	0.98	740	0.785
325	0.423	410	0.956	0.978	520	0.967	600	1.00	750	0.910
330	0.560	420	1.000	1.000	530	1.000	610	0.98	760	0.965
335	0.673	430	0.998	0.978	540	0.973	620	0.96	770	0.985
340	0.772	440	0.972	0.935	550	0.898	630	0.93	780	0.990
345	0.841	450	0.901	0.853	560	0.792	640	0.90	790	0.995
350	0.905	460	0.793	0.740	570	0.684	650	0.86	800	1.000
355	0.943	470	0.694	0.640	580	0.574	660	0.81	810	1.000
360	0.981	480	0.587	0.536	590	0.461	670	0.78	820	0.990
365	0.993	490	0.470	0.424	600	0.359	680	0.72	830	0.980
370	1.000	500	0.362	0.325	610	0.270	690	0.67	840	0.950
375	0.989	510	0.263	0.235	620	0.197	700	0.61	850	0.910
380	0.916	520	0.169	0.150	630	0.135	710	0.56	860	0.860
385	0.804	530	0.107	0.095	640	0.081	720	0.51	870	0.750
390	0.625	540	0.049	0.043	650	0.045	730	0.46	880	0.560
395	0.423	550	0.010	0.009	660	0.025	740	0.40	890	0.330
400	0.238	560	0.000	0.000	670	0.017	750	0.35	900	0.150
405	0.114				680	0.013	800	0.14	910	0.030
410	0.051				690	0.009	850	0.03	920	0.000
415	0.019				700	0.000	900	0.00		
420	0.000									

TABLE 3

ZERO-POINT MAGNITUDES AND EFFECTIVE WAVELENGTHS (NM)

	UX	BX	B	V	R	I
ZP	0.790	-0.104	-0.102	0.008	0.193	0.443
A0V	365.9	438.2	436.3	544.8	640.7	798.2
K0III	365.6	453.7	452.0	552.4	653.5	802.8

TABLE 4

COMPUTED COLORS FOR VILNIUS SPECTRA

MK	U-B	B-V	V-R	R-I	V-I
O V	-1.16	-0.326	-0.158	-0.172	-0.33
B3 V	-0.765	-0.193	-0.073	-0.09	-0.163
B5 V	-0.576	-0.139	-0.032	-0.066	-0.098
B8 V	-0.28	-0.068	-0.024	-0.044	-0.068
A0 V	0.036	0.012	0.001	-0.002	-0.001
A5 V	0.111	0.128	0.063	0.077	0.14
F0 V	0.036	0.311	0.197	0.22	0.417
F5 V	-0.031	0.411	0.27	0.266	0.536
G0 V	0.078	0.575	0.352	0.363	0.715
G5 V	0.19	0.654	0.388	0.358	0.746
K0 V	0.422	0.823	0.461	0.392	0.853
K3 V	0.771	0.974	0.582	0.497	1.079
K5 V	1.048	1.182	0.733	0.626	1.359
K7 V	1.256	1.382	0.839	0.761	1.60
M0 V	1.26	1.444	0.886	0.849	1.735
M2 V	1.169	1.479	0.99	1.08	2.07
M4 V	1.191	1.513	1.092	1.36	2.452
M5 V	1.263	1.703	1.191	1.571	2.762
G5 IV	0.285	0.717	0.406	0.37	0.776
G8 IV	0.418	0.855	0.483	0.458	0.941
K0 IV	0.639	0.931	0.505	0.481	0.986
A5 III	0.10	0.14	0.095	0.08	0.175
F0 III	0.132	0.274	0.163	0.17	0.333
G5 III	0.411	0.852	0.471	0.436	0.907
G8 III	0.643	0.926	0.498	0.468	0.966
K0 III	0.866	0.977	0.495	0.459	0.954
K2 III	1.177	1.155	0.603	0.537	1.14
K3 III	1.507	1.31	0.664	0.566	1.23
K5 III	1.865	1.555	0.83	0.784	1.614
M0 III	1.959	1.554	0.878	0.898	1.776
M2 III	1.962	1.583	0.919	1.008	1.927
M3 III	1.871	1.621	1.029	1.22	2.249
M4 III	1.785	1.55	1.166	1.524	2.69
M5 III	1.556	1.57	1.302	1.742	3.044
M6 III	1.242	1.575	1.664	1.967	3.631
B0 Ia	-1.083	-0.232	-0.081	-0.107	-0.188
B5 Ib	-0.724	-0.085	-0.012	-0.056	-0.068
B8 Ia	-0.652	-0.053	0.029	0.045	0.074
A2 Ia	-0.252	0.034	0.053	0.062	0.115
F0 I	0.233	0.203	0.134	0.149	0.283
F5 Ib	0.254	0.393	0.214	0.214	0.428
F8 Ib	0.363	0.55	0.268	0.251	0.519
G0 Ib	0.447	0.716	0.358	0.295	0.653
G2 Ib	0.62	0.85	0.399	0.352	0.751
G5 Ib	0.816	0.969	0.413	0.351	0.764
G8 Ib	1.338	1.263	0.558	0.472	1.03
K2Ib	1.573	1.423	0.649	0.57	1.219
K3Ib	1.601	1.552	0.745	0.575	1.32
M2Iab	2.155	1.844	1.111	1.278	2.389

Some of these are thinned or UV flashed for UV-blue sensitivity enhancement, but others have dye-laser coatings (Cullum *et al.* 1985) which convert UV-blue photons to redder photons for which the CCD is more sensitive. In Table 6 are listed filter combinations that when used with coated CCDs should make good matches to the standard passbands. Because of differences between batches of filter glasses and differences in coatings, no two responses will precisely match but these combinations should be close. Figures 19a–e show the predicted differences (CCD−STD) computed between the CCD and standard passbands from the Vilnius spectrophotometry. The supergiants are not plotted in the U comparison. The R and I passband corrections are nonlinear, but the large deviations are for M stars; linear corrections of the order of $-0.004(V-I)$ and $0.007(V-I)$ are adequate to correct R_{CCD} and I_{CCD} for hotter stars. Figure 19f shows the expected difference between the CCD BJ response and the estimated IIIa-J plate with 2-mm GG385 filter. Figure 20 shows the standard *UBVRI* passbands devised in this paper and some calculated coated *UBVRI* responses for a coated Thomson or GEC CCD.

The Washington system passbands can also be matched with Schott filters. The broad C band is very useful as a metallicity indicator in faint GK stars, but V can replace M for most purposes.

TABLE 5

GLASS FILTERS FOR PHOTOTUBES

Band	Cathode	Filters
U	S11/S4	1UG1 + (2mmWG320 with UV tubes)
B		2GG395 + 1BG12
V		3GG515
U	GaAs/S20R	1UG1 + 1BG39
B		2GG385 + 1BG12 + 1BG18
V		2GG495 + 1BG18 + (1BG38 GaAs)
R		2OG570 + 2KG3
I		3RG9

TABLE 6

GLASS FILTERS FOR COATED CCDS

Band	Filters
U	1UG1 + 1BG39 + (3WG305 fill)
B	2GG385 + 1BG12 + 2BG39
V	2GG495 + 3BG39
R	2OG570 + 3KG3
I	3RG9 + (2WG305 fill)
BJ	2BG28 + 3BG39
Z	3RG1000

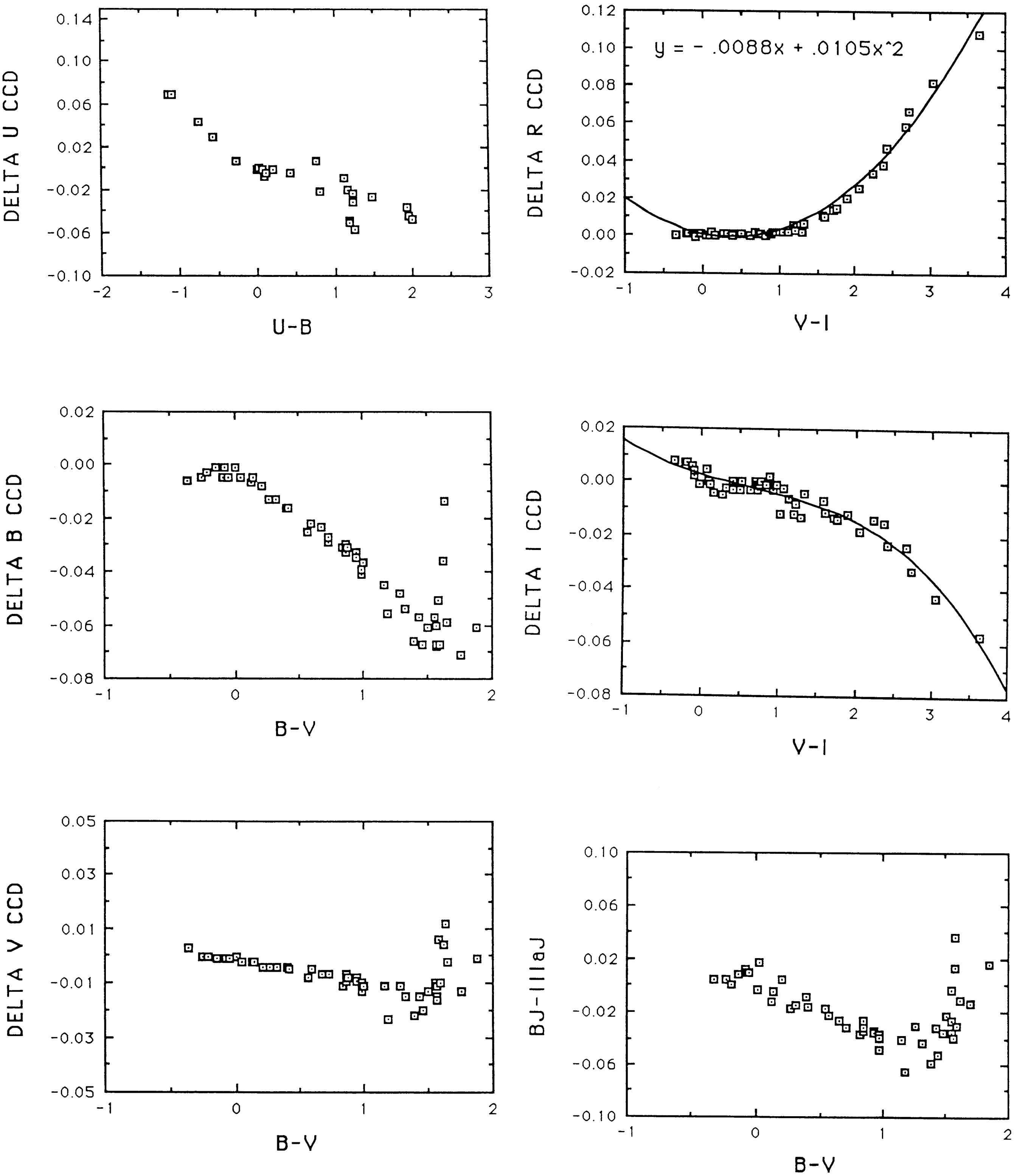

FIG. 19–The calculated differences between the CCD passbands and the standard passbands in this paper. Vilnius spectra were used. The *R* and *I* data have had cubic curves fitted.

CCD: C: 3BG3 + 2BG40 M: 2GG455 + 3BG23
GaAs: C: 2BG3 + 2BG40 M: 2GG455 + 2BG23

11. Summary

The *UBVRI* passbands have been reanalyzed using standard-star photometry and synthetic photometry from spectrophotometry of a range of stars. The passbands are listed in Table 2 and shown in Figure 20. These passbands are the best that can be estimated with the current data and can be used with theoretical fluxes for calibration of temperature, abundance, and gravity. $(B-V)$ calculated with the new bands is larger than that calculated using the AS and MS bands by approximately $0.012(B-V)$. The V passbands of AS and MS are bluer and redder than V90 by 0.007 and $0.024(B-V)$, respectively. Users wishing to work within the *UBVRI* system should match these passbands as closely as possible with their natural systems for the most reliable photometry. Matching B is of particular importance (especially the short-wavelength side of the band) as mismatches lead to systematic differences in $(U-B)$ and $(B-V)$ colors. Differences in V magnitudes may be evident for M stars measured in *UBV* or *VRI* programs because of different V passbands and because of the difference arising from using $(B-V)$ or $(V-R)$ as the color term in the V transformation equation.

Cousins standards are good matches to the Johnson *UBV* system and the E-region standards are recommended as the most precise and internally consistent set of secondary *UBVRI* standards. Cousins suggests that his E-region $(U-B)$ colors can be modified by the addition of $0.015(B-V)$ to better match the Johnson *et al.* (1966) colors. The Graham (1982) and Landolt (1983) natural *UBV* system is not a good match to the standard system and, although Graham reduced the photometry onto the Cousins system, it is certain that some systematic differences remain. Landolt's photometry is a mixture of Cousins system photometry and the original Landolt (1973) *UBV* system. It shows some systematic differences from Cousins photometry that can be corrected for, but the $(U-B)$ colors probably need regression against $(B-V)$ as well as $(U-B)$ to derive better corrections.

Glass filter mixes in Tables 5 and 6 should produce close matches to the standard systems when used with GaAs phototubes or coated CCDs. The new Schott BG39 glass can be used as a substitute for $CuSO_4$ as a red-leak blocker for the U filters in red-sensitive systems. This modifies the short-wavelength side of the U band but the resultant changes in U magnitudes are likely minimal for all but supergiants.

It is important that large-telescope CCD systems (CCD plus the filters) be able to be used on small telescopes so that the accurate standards of 7th–9th magnitude can be observed in order to precisely determine transformations between CCD magnitudes and standard photoelectric magnitudes. This would also enable better filters to be devised for CCDs. The same transformation equations can be used at the large telescope and faint standards observed to provide zero-point corrections only. This should increase the efficiency of observing and improve the reliability of CCD absolute photometry.

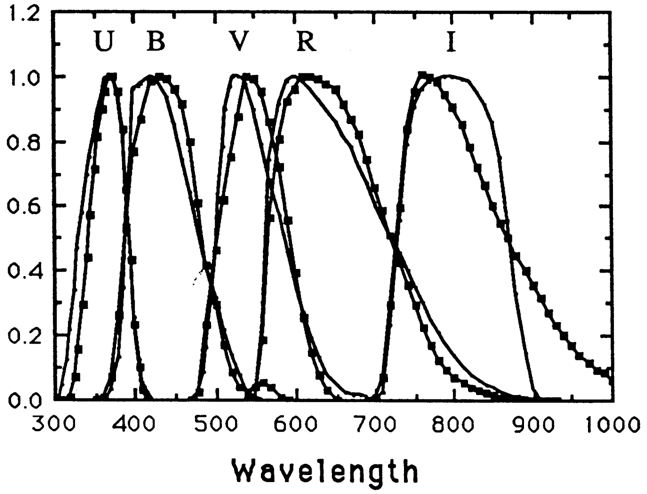

FIG. 20–The CCD passbands (solid symbols) calculated for a coated GEC CCD and the recommended glass filters in comparison to the standard passbands in this paper.

Finally, if users match passbands and use precise standards there is no reason why the broad-band *UBVRI* system cannot match the precision of any of the narrow-band systems.

I would like to thank Drs. A. W. Cousins and J. W. Menzies for their advice and comments on this paper.

Notes added in proof:

1. Menzies *et al.* (1990) present *UBVRI* photometry for 212 stars from Landolt's (1983) list of equatorial stars. These are tied to the system defined by Cousins' E-region standards. These data clearly delineate the systematic differences that have been discussed above. This new photometry will now enable northern observers to standardize their photometry, in particular their $(U-B)$ photometry, to the precisely defined E-region system. Menzies (1990) reports that the photometry was made with a GaAs tube and glass filters similar to those in Table 5 and that with regard to $(U-B)$ reductions, the procedure used is to reduce $(U-B)$ to outside the atmosphere, use a linear transformation in $(B-V)$, then apply a nonlinear correction to the result. This correction could be represented by a polynomial and is less than 0.02 mag over the whole range of colors in the E-region standards.

2. The 1-mm BG39 and copper sulfate blocked 1-mm UG1 filters for coated CCDs have been compared. The copper sulfate filter was constructed as described in Bessell (1976). It uses 1-mm WG305 windows for the cell and

has 5-mm thickness liquid copper sulfate prepared by filtering a saturated (at around 2° Celsius) solution. The cell is made from a 50 × 5-mm lucite block with a 40-mm diameter bore. It is filled through a threaded hole in the corner which is then sealed with a nylon screw and O-ring. The UG1 glass is cemented to the outside of one of the WG305 windows. The filter has been in use for over two years without problems apart from occasional removal of bubbles. The (1UG1 + 1BG39) filter has 15% less throughput than the (1UG1 + copper sulfate) filter. The glass filter has a small red-leak which is 0.4% of the average of the *R* and *I* magnitude. The copper sulfate blocked *U* filter has a virtually zero red-leak of 0.01%.

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