The Homogeneity of the UBV(RI)$_C$ System

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Abstract

There are two large sets of high precision standard star photometry which claim to represent the UBV(RI)c system, one in the E regions in the south established by Cousins and one at the equator due to Landolt. There appear to be systematic differences between them. Astrophysical interpretations which depend on photometric data may in consequence depend on which set of standards was used.

Introduction

Many photometric systems have been established in the visible wavelength range, often designed to address specific problems. The UBV system is undoubtedly the most widely used general-purpose system in the blue-visual part of the spectrum. In the red, Johnson's RI system is commonly used, but since it is based on the low-quantum-efficiency S1 photocathode, and observers normally use more sensitve tubes with different response functions, (nonlinear) transformation equations with relatively large coefficients are required. The Cousins (RI)$_C$ system is based on a GaAs photomultiplier and is somewhat easier to reproduce so it has become increasingly popular since its introduction.

Why reduce photometric data to a standard system? First, it makes intercomparison with other observations more straightforward, but more importantly it permits the use of standard relations to derive astrophysically interesting parameters like spectral type, reddening and temperature for faint stars, and ages of globular clusters from main sequence fitting. It also facilitates the comparison of population synthesis models with observation. The standard relations have only to be derived once, which consequently saves considerable effort and valuable observing time. To use them, one needs to have one's data on the standard system. It is usually necessary to transform the raw data via non-linear relations. To derive the transformations accurately, many stars covering the whole colour range of interest must be observed along with the programme stars.

Standard stars should not be concentrated in a small region but spread widely over the sky so that a representative sample of them is available to observers at all latitudes and at all times of the year; unreddened stars of some spectral types may be difficult to find in a group of standards confined to a small region. The system needs to be homogeneous over the sky for consistent interpretation of observations

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between different locations and at different times. As Johnson(1963) pointed out there is a risk of inhomogeneity if different sets of standard star data are combined. However, the standard system is normally an instrumental one, and if the original photometer no longer exists, observations obtained with other photometers must be used when fainter standards, or a better sky- or colour coverage is needed. The original UBV standards were relatively few and bright and their precision low compared with what is currently attainable. Two large sets of stars widely distributed in right ascension and extending to fainter magnitudes than the original, with an internal precision of a few millimagnitudes, are currently available as supplements to the primary UBV standards and also provide standards for photometry on the Cousins $(RI)_C$ system.

Systems

The E-region UBV system established by Cousins and Stoy (1962) (ROB49) is ultimately based on the Johnson UBV system as represented by the magnitudes and colours tabulated by Cousins (1971) (ROA7). The latter is a compilation of various series of photometry of bright stars in the equatorial regions and was produced in response to the adoption by IAU commission 25 in 1970 of the stars brighter than magnitude 5.0 in the band between declinations +10° and -10° as new primary standards for the UBV system to supplement those of Johnson & Harris (1954). In setting up the $V(RI)_C$ system, Cousins (1971) used the Johnson V magnitude and the natural R and I magnitudes of his photometer, with the zero point being set to give colours of 0.0 for a typical A0V star. Several series of observations made at the SAAO in Cape Town and in Sutherland have been used to augment the original E-region compilations (UBV and $V(RI)_C$) and the current working list of standard magnitudes and colours in use at SAAO incorporates the new data (Menzies *et al.* 1989.) The data in the current list conform to the original Cousins $UBV(RI)_C$ system (Cousins 1990) and can be considered now to define the E-region system.

Cousins has made continual checks on the degree of conformity of SAAO UBV photometry to the Johnson system. Most recently, in discussing some new photometry of stars in the equatorial region, he concludes that for V and B-V, the ROA7 system, and hence that of the E-regions, is essentially the same as that of Johnson & Harris (1954) and that of Johnson *et al.* (1966). However, there is evidently a systematic difference between the SAAO representation of (U-B) and that of Johnson such that $(U-B)_J = (U-B)_{E-regions} - 0.003 + 0.015(B-V)$.

Intending to establish a set of standards on the UBV system accessible to both northern and southern observers and with a consistent zero point around the sky, Landolt (1973) observed stars in the equatorial Selected Areas. His results were tied to the Johnson & Harris (1954) standards and he presented evidence that he had succeeded in reproducing the UBV system. In his second series, Landolt (1983) measured $UBV(RI)_C$ for a set of stars in the magnitude range $7 \leq V \leq 12.5$, and

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referred them the E-region standards. On finding non-linear differences between the new results and those from the 1973 series for B-V and U-B he applied corrections to the new data. Thus, Landolt's 1983 results for UBV are on his 1973 system and the $(V\text{-}R)_C$ and $(V\text{-}I)_C$ colours are tied to the E-regions.

Comparisons

With a view to checking that the Landolt (1983) and E-region (Menzies *et al.*1989) systems were the same, an observing program was carried out at Sutherland in which the Landolt stars were treated as programme stars and the measurements were referred directly to the E-regions. The analysis of the results revealed marked systematic differences between the SAAO and Landolt sets (Menzies *et al.* (1990). In an independent programme of equatorial star photometry, Cousins (1984) also included some of Landolt's (1983) stars.

Landolt's transfer of the $(RI)_C$ system to the equator worked well, with only small zero-point differences and very small colour terms between his and our results. Cousins (1984) found similar small differences. There is a hint of a change of slope in the $(V\text{-}R)_C$ differences for the reddest stars. Landolt evidently used a linear colour transformation, and the non-linearity is probably the result of a small bandwidth mismatch between his R filter and the standard one – a common problem resulting from the relative difficulty of matching the extended redward wing of the Cousins R passband.

The situation is not nearly so good for the differences in (B-V) and (U-B), which both show marked non-linear trends. That Cousins (1984) found similar trends from observations made at a different site and with a different photometer suggests that the origin of the differences probably lies in Landolt's use of linear transformation equations in his 1973 series, and in selection effects coupled with the relatively low precision of the original list of UBV standards.

Polynomials have been derived to allow Landolt's data to be transformed to the E-region $UBV(RI)_C$ system and these are listed in Table 1.

Table1. Conversion of Landolt System to Cousins System

$$\Delta(U-B) = 0.002 - 0.257(B-V), (B-V) \leq 0.08$$
$$\Delta(U-B) = -0.029 + 0.136(B-V) - 0.093(B-V)^2, (B-V) \geq 0.08$$

$$\Delta(U-B) = 0.013 - 0.014(U-B) + 0.026(U-B)^2 - 0.019(U-B)^3$$

$$\Delta(B-V) = -0.004 + 0.002(B-V) + 0.048(B-V)^2 + 0.032(B-V)^3$$
$$\Delta(V-R)_C = -0.002 + 0.005(V-R)_C + -0.018(V-R)_C{}^2$$
$$\Delta(V-I)_C = -0.001 - 0.005(V-I)_C$$

where $(B-V)_{Cousins} = (B-V)_{Landolt} + \Delta(B-V), etc.$

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Two different regressions are given for Δ(U-B). The fits for Δ(U-B) as a function of both (B-V) and (U-B) are illustrated in Figure 1. These also illustrate some of the pitfalls in making this kind of transformation. In both plots, the open symbols represent reddened B stars, for which the wrong correction would be given by the fitted curve using (B-V) as the independent variable. The colours must first be approximately dereddened before the correction is derived from the polynomial. Also, most of the stars with (B-V) $\geq$ 1.0 are giants and in this case the correction to (U-B) should be derived from the (U-B) curve. Better still, both curves should be used and an inconsistent pair of corrections should lead to further investigation as to the reason.

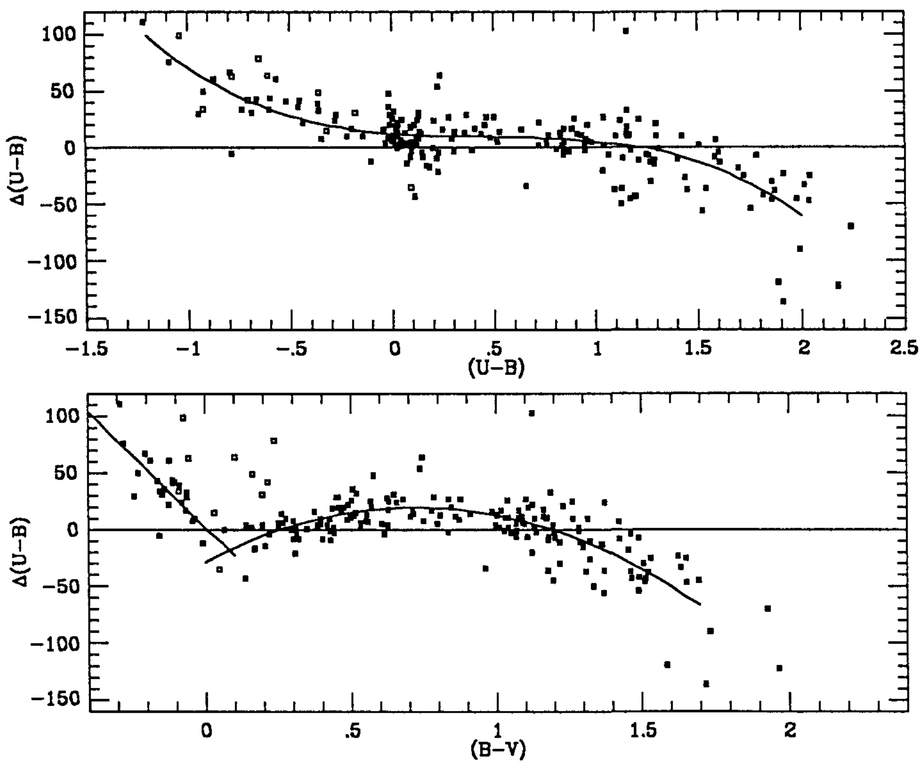

Figure 1. (U-B) differences, SAAO - Landolt, as a function of B-V and U-B. The open symbols represent reddene tars.

A zero-point difference was found in V, which was due to some unspecified right-ascension-dependent effect. Cousins (1984) did not find any such difference in his measurements of the Landolt stars. Subsequently, Cousins & Menzies (in preparation) have compared the magnitudes from a compilation of Walraven photometry over the whole sky provided by Pel (private communication) with those for stars

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in both the E regions and the equatorial sample (ROA7) and find no evidence for any right-ascension-dependent differences. Thus it is most likely that the error is in the Sutherland photometry, though the origin is still not clear.

Consequences

The Landolt and E-region systems are clearly not the same. Does this really matter? The differences are not very large. Landolt's data can be transformed to the E-region system via the equation in Table 1. The changes for V-I, V-R and B-V are small, except for the reddest stars in V-R and B-V. Even for U-B over most of the colour range, changes of less than 0.02 mag are required. The red stars will usually give trouble - in V-R because the Cousins system is not well defined in this colour range, although Bessel (1990a) has attempted to improve the situation in this range; and in B-V and U-B because of severe bandwidth effects, low signal at U and probable small scale variability amongst the majority of red stars.

What are the consequences of using the different systems? The standard two-colour diagram should be corrected by means of the equations in Table 1 before comparison with colours obtained on Landolt's system. The effects are small except for the bluest stars where errors of no more than about 0.02 mag would be incurred in determining $E_{(B-V)}$ if the standard curve were to be used instead of the transformed one. On the other hand, for the E-region system significant differences appear only for the very reddest stars where photometry becomes more uncertain anyway. Ages of globular clusters are determined by fitting unreddened cluster colour-magnitude diagrams to theoretical isochrones in the M_V,(B-V) plane. The turn-off region appears near $(B\text{-}V)_0 \sim 0.3$, where there is no significant difference between Landolt and the E-regions. Small differences appear on the lower main sequence and on the sub-giant branch which might lead to slightly poorer fits if the isochrones are not transformed before use with data on the Landolt system. Much larger errors due to uncertainties inherent in the reddening determination would swamp any problems due to mismatching photometric systems.

Conclusions

The E-region system and that of Landolt are clearly different though the two sets of standards probably have about the same internal precision. To preserve the high internal precision of one's own observations, care should be taken in matching the passbands used to those of the standard system to which the data are reduced. Nonlinear transformations should always be expected. If Bessel's (1990b) proposed glass filter combinations in practice give linear transformations with small coefficients to the E-region system then there would be some advantage in adopting them as the standard set for future use. The temptation to merge the Cousins and Landolt systems should be resisted considering the non-linearities involved in the transformation between them as the inherent internal precision of each would be compromised.

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Discussion

E. Budding: *If you fold theoretical flux distribution (e.g. Kurucz) with available transmission functions you ought to be able to check how the measured discrepancies compare with theoretical ones. Has this been done — and, for example, can your empirically derived transformation equation be theoretically substantiated?*

Menzies: We used several different photomultipliers and filter sets in the course of our work. For each combination we derived linear transformation equations and non-linear corrections, but did not measure tube response functions or filter pass bands. What you ask ought to be possible in principle but we don't have the information needed to do it.

J.D. Fernie: *If one wants to do Cousins RI photometry from the north, what is the best source of (secondary) standards?*

Menzies: You should see the paper by Cousins, 1984, SAAO Circulars No. 8, p59, for a discussion on this point. You could use the data in the paper I have been talking about, although you should be careful with the reddest stars.

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K. Oláh: *It seems everybody is happy with the equatorial standards you have as an extension of the system to the northern hemisphere. However, as my observatory is situated at about 48° N, the standard star measurements are quite complicated and, because they are so low in the sky, an additional error is introduced into the standardization. Do you plan to extend your otherwise really well defined, excellent system further north? It would be very important for many observatories, I think.*

Menzies: For us to set up standards north of the equator would be almost as difficult as for you to observe standards on the equator. It would be an ideal project for a small telescope at a good site in N. America, and would take only about a year to do. It would certainly be worth the effort.

T. Oja: *Are your observations of the equatorial stars available?*

Menzies: Yes, the reference is: J W Menzies et al, 1991. MNRAS, **248**, 642.

M.J. Bessell: *It would be very helpful for attempts to reproduce theoretically the $UBV(RI)_c$ system, and attempts to match your natural system, were you to publish your transformation techniques and transformations equations as well as the filter transmissions.*

Menzies: I agree that it is worth having such information in print. I shall investigate the feasibility of publishing it when I return to Cape Town.

A.J. Penny: *There is a distinct lack of metal-poor standards. I would urge that the list of $UBV(RI)_c$, standards is extended to include a large number of such stars.*

Menzies: We will consider this.

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