THE COLOURS OF THE SUN

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ABSTRACT. In this paper, arguments are developed for treating $(R-I)_C$ as the most important colour to be derived for the Sun. The solar value of $(R-I)_C$ is then found to be 0.335 ± 0.002 mag. This result updates a counterpart given by Taylor in 1992.

1. Introduction

Which colour index should be derived for the Sun?

Papers on this subject rarely consider this question. Authors sometimes explain that one wants to know the solar colours to learn how the Sun compares to similar stars. In addition, authors cite a number of previous studies—likely including those which piqued their interest in the first place. However, one seldom sees an explanation for the fact that (almost always) $B-V$ is being determined. Was $B-V$ the best choice historically? Is it still the best choice now? Let us see what answers these questions may have.

2. $B-V$: Blanketing Effect And Accidental Errors

When the solar-colours problem "came of age" in 1964, at least some people knew that field stars should be measured to the red of the V passband to minimize blanketing effects (see Sandage & Smith 1963). Putting this idea into practice for the Sun, however, seems to have been ruled out by a shortage of high-precision red photometry for solar stars and a tacit "1P21 limit" in general thinking. The Strömgren system was just getting started, so $b-y$ was not yet a realistic option. Only $B-V$ and $U-B$ were serious contenders, and since $B-V$ is less blanketed than $U-B$, one can see why $B-V$ would have been an obvious choice historically.

Let us re-examine that choice, using resources that were not available in 1964. The blanketing effect on $B-V$ is an obvious concern, so one should probably derive a numerical estimate of its size before doing almost

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anything else. This may be done by using the calculations of VandenBerg & Bell (1985). Data for stars with the solar temperature and surface gravity are used. The blanketing estimate may be expressed as the value of $|\Delta(B-V)|$ as [M/H] increases from −0.5 dex to 0.0 dex. $|\Delta(B-V)|$ is increased by a factor of 1.5 to allow for the difference between theoretical and empirical calculations (see Table 3 of Taylor 1994).

Since $(B-V)_\odot$ is often determined from field-star values of $B-V$, one would also like to know something about the rms errors of the field-star data. The best rms error found commonly for $B-V$ has been calculated by Nicolet (1978), who obtains a value of 0.009 mag. Since $|\Delta(B-V)|$ turns out to be 0.053 mag, one sees at once that the blanketing effect is inescapable if one cannot restrict attention to field stars with [Fe/H] ~ 0. This is an especially serious matter if $B-V$ is used as a temperature proxy.

3. Tactics For Deriving $(B-V)_\odot$

The next issue that might be considered is the best choice of tactics for determining a solar colour index. For $B-V$, one procedure which has attracted much attention is the search for solar twins. High-dispersion analysis is used to identify dwarfs whose metallicity resembles that of the Sun closely (see, for example, Cayrel de Strobel & Bentolila 1989). With a "short list" of such stars in hand, one can then correct their values of $B-V$ for residual temperature, gravity and metallicity differences between the stars and the Sun. (See Edvardsson et al. 1993, who use this procedure for $b-y$).

The obvious advantage in this procedure is that if the corrections are small, the uncertainties they introduce into the final value of $(B-V)_\odot$ will be small as well. There is also a disadvantage, though: can one obtain a reliable rms error for $(B-V)_\odot$ by using only a small number of stars? This question will be considered again below.

A second common tactic is to measure an index (usually a spectroscopic index) which can readily be secured for both field stars and the Sun. By comparing field-star indices and values of $B-V$ to the solar index, one can then determine $(B-V)_\odot$. The chief question here is what to do about the $B-V$ blanketing problem. If the adopted index has no metallicity sensitivity, the blanketing problem has its full scope, and metallicities for the field stars will be required in order to mitigate it (Cayrel de Strobel 1996). One might cancel out the blanketing problem by choosing an index with compensating metallicity sensitivity, and an assumption is often (if tacitly) made that such cancellation takes place. This assumption is not always tested, however (see, for example, Croft et al. 1972).

4. Is The Traditional Approach The Best Approach?

As of 1994, determinations of $(B-V)_\odot$ fell in two groups: a "short-wavelength" group with $(B-V)_\odot = 0.665 \pm 0.003$ mag, and a "long-wavelength" group with $(B-V)_\odot = 0.633 \pm 0.009$ mag. These two means differ at better than 99.5% confidence. (See Taylor 1994.)

Is this dichotomy the real problem here, or could the choice of colour index be more significant? For some time now, the real reason for this choice has been tradition, as Griffin & Holweger (1989) note. In a discipline which uses the traditional magnitude scale and the traditional name "planetary nebulae," the force of tradition is not surprising. Nonetheless, it is fair to ask whether one can improve on tradition.

5. The Solar-Colours Problem in 1997

An inducement for determining a different solar colour index in 1997 is the fact that the Cousins *VRI* system is now available. Measurements in this system are widely available, and they have high precision and coherency (see, for example, Cousins 1974 and Taylor & Joner 1996). This is in clear contrast to the state of *VRI* photometry in 1964.

Theoretical work shows that $(V-I)_C$ is the most blanketing-free Cousins index for G dwarfs (VandenBerg & Bell 1985, Buser & Kurucz 1992). $(R-I)_C$ is the next-best choice where blanketing is concerned, but one must also realize that especially in the northern hemisphere, $(R-I)_C$ is available for many more stars than $(V-I)_C$ (compare Tables 7 and 8 of Taylor 1986). Since astronomy, like politics, is the art of the possible, it seems better to determine $(R-I)_C$ for the Sun at the moment than it would be to determine $(V-I)_C$. (Note, though, that this judgment could easily change when the Hipparcos photometry becomes available.)

6. $(R-I)_C$: Blanketing Effect And Accidental Errors

What are the relative blanketing sensitivities of $(R-I)_C$ and $B-V$? In addition, what is the ratio of their best common rms errors? To answer these questions meaningfully, one must allow for the fact that $(R-I)_C$ and $B-V$ respond differently to temperature changes. To allow for this difference, one may use the Hyades relation between the two indices given by Taylor (1994, Eq. 1). The derivative of this relation is evaluated at the solar value of $(R-I)_C$ (see below).

Taylor (1996, Appendix B) gives pertinent information about rms errors for $(R-I)_C$. With this information and the dynamic-range allowance in hand, the basic procedure used above for $B-V$ may be employed.

The best commonly-found rms error for $(R-I)_C$ turns out to be 0.003 mag before the dynamic-range correction and 0.008 mag afterwards. Recalling that the counterpart for $B-V$ is 0.009 mag, one sees that there is no great difference between the two colour indices—at least where accidental error is concerned. Blanketing changes are a different story, however: $|\Delta(R-I)_C|$ is 0.008 mag before the dynamic-range correction and 0.021 mag afterwards. Recalling that $|\Delta(B-V)| = 0.053$ mag, the blanketing problem is reduced by a factor of 2.5 by replacing $B-V$ with $(R-I)_C$. (If the calculations of VandenBerg and Bell 1985 are replaced by those of Buser and Kurucz 1992, this estimate favors $(R-I)_C$ even more decisively.)

7. Deriving $(R-I)_C$ For The Sun

If $(R-I)_C$ replaces $B-V$, one has taken a step toward an analysis which allows minimum scope for blanketing effects. To be sure, this aim is also satisfied by using solar twins, as noted above. However, the change in colour index allows the use of many more data than are available if one restricts the analysis to solar twins. To secure this advantage, one collects published indices for the Sun and field stars which are insensitive to metallicity. If necessary, one also imposes the condition that $[Fe/H](*) \sim [Fe/H](\odot)$.

There are a number of indices that can be used for this problem. Photometry yields measurements of Hα and Hβ. From spectroscopy, one can use temperatures from Balmer-line wings, Gray's (1995) line-strength ratios, and excitation temperatures. As a precaution, the latter are adopted only if equivalent widths have been measured by the same observer for both the Sun and the field stars. [Taylor (1992) has done this kind of calculation, but without using Gray's ratios, excitation temperatures, or Balmer-line results published by Chmielewski et al. (1992) and Friel et al. (1993).]

Results from analyses based on these indices are given in Table 1. The analyses turn out to be very insensitive to the exact value one assumes for the blanketing derivative of $(R-I)_C$, but corrections based on that derivative have been made nonetheless. No allowance has been made for reddening, since the stars used for the analyses should be too close to the Sun for even small values of reddening to interfere (see, for example, Leroy 1993).

The results from Fuhrmann et al. (1994) attract first attention because they stand off from all the others. According to the Dixon (1951) statistics, the result from the Fuhrmann et al. Hα measurements may be rejected at 99% confidence. For this reason and because the Fuhrmann et al. data are on two different zero points, it seems fair to set all of those data aside. The next issue deserving notice is the scatter in the remaining results. The rms error per entry turns out to be 0.0068 mag (0.018 mag when rescaled

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TABLE 1. Results for the solar value of $(R-I)_C$

$(R-I)_C$	Original (secondary) source	Index
(0.300)	Fuhrmann et al. 1994	Balmer-line wings ($H\alpha$)
(0.307)	Fuhrmann et al. 1994	Balmer-line wings (other lines)
0.325	Herbig 1965 group	Excitation temperatures
0.328	(Taylor 1992)	Balmer-line wings, group
0.331	(Taylor 1992)	Balmer-line wings, group
0.332	Clegg et al. 1981	Excitation temperatures
0.332	(Taylor 1992)	Balmer-line wings, group 2
0.334	Wallerstein 1962	Excitation temperatures
0.334	Price 1966 (Taylor 1992)	Photometric $H\alpha$
0.337	Olsen 1976 (Taylor 1992)	Photometric $H\beta$
0.338	Gray 1995	Gray's ratios
0.343	(Taylor 1992)	Balmer-line wings, group 8
0.349	(Taylor 1992)	Balmer-line wings, group 4

to the $B-V$ dynamic range). These "external" errors are larger than the "internal" errors one can derive for the various entries. The external errors cannot be sampled adequately by using only a small number of stars, so one expects an analysis using solar twins to yield underestimated errors (and perhaps a systematic bias as well). This is an argument for performing the analysis done here instead.

By averaging the tabular data (except those of Fuhrmann et al.) and using the methods of Taylor (1992), one finds that $(R-I)_C = 0.335 \pm 0.002$ mag, $(V-K)_J = 1.474 \pm 0.012$ mag, and $B-V = 0.628 \pm 0.008$ mag. The quoted value of $(R-I)_C$ differs from that of Taylor (1992) by only 1σ. The quoted value of $B-V$ is an updated version of $B-V$ for the "long-wavelength group" mentioned above. This updated version appears to agree with Cayrel de Strobel's (1996) most recent result (0.642 ± 0.004 mag) to within the errors. However, it must not be forgotten that the redder value of $B-V$ from the "short-wavelength group" remains unexplained.

8. Summing Up: A Question Of Strategy

Given the agreement between Taylor's (1992) value of $(R-I)_C$ and the updated value, it seems fair to conclude that the $(R-I)_C$ analysis is mature in some sense. However, it is certainly not definitive, since one must expect it to be repeated yet again in the future. Note, in addition, that nothing

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has been said here about $(R-I)_C$ from the solar irradiance curve. For the present, it seems reasonable to say that if one uses $(R-I)_C$ in a minimum-metallicity analysis, the results look promising. Now the question to be settled is whether $B-V$ or $(R-I)_C$ is to be the colour index of choice. Astronomers are invited to consider the evidence and then make this choice.

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DISCUSSION

ROGER BELL: Have you considered determining the solar $V-R$, since this showed to be even less sensitive to abundance (as shown by the Barnes Evans effect) and would also avoid the extinction prob with the O_2 and H_2O bands in the I filter passband?

BENJAMIN TAYOR: Extinction problems in the I filter don't appear to compromise either the accuracy of the precision of $R-I$. Moreo - if I remember rightly - the theoretical colours show that $V-R$ is actually more metallicity-sensitive than $R-I$. Since $V-R$ has also been measured much less often in the northern hemisphere the choice in favor of $R-I$ seems to be clearcut for the moment.