ON THE USE OF EMPirical BOLOMETRIC CORRECTIONS FOR STARS

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ABSTRACT

When making use of tabulations of empirical bolometric corrections for stars (BCV), a commonly overlooked fact is that while the zero point is arbitrary, the bolometric magnitude of the Sun (MBol,⊙) that is used in combination with such tables cannot be chosen arbitrarily. It must be consistent with the zero point of BCV so that the apparent brightness of the Sun is reproduced. The latter is a measured quantity, for which we adopt the value V⊙ = −26.76 ± 0.03. Inconsistent values of MBol,⊙ are listed in many of the most popular sources of BCV. We quantify errors that are introduced by failure to pay attention to this detail. We also take the opportunity to reprint the BCV coefficients of the often used polynomial fits by Flower, which were misprinted in the original publication.

Key words: stars: fundamental parameters – stars: general – Sun: fundamental parameters – Sun: general

1. INTRODUCTION

Bolometric corrections are widely used in astronomy to infer either luminosities or absolute magnitudes of stars. Empirical corrections in the visual band, BCV, are perhaps the most frequently needed, and numerous tabulations exist in the literature that sometimes differ significantly. This has been a persistent source of confusion among users. The most common way in which these tables are employed is in combination with the bolometric magnitude of the Sun, MBol,⊙, which is not a directly measured quantity. Many different values of MBol,⊙ can be found in the literature as well, adding to the confusion. For a given table of bolometric corrections the choice of MBol,⊙ is not arbitrary, however, since there is an observational constraint that must be satisfied, given by the measurement of the visual brightness of the Sun. This fact is often ignored, and as a result it is common to see inconsistent uses of BCV that can lead to errors in the luminosity of 10% or larger, or errors in MV of 0.1 mag or more. The primary motivation for this paper is to call attention to this fact, to illustrate common misuses of some of the most popular BCV tables, and to offer some perspective on the problem.

One frequently used source of bolometric corrections is the tabulation by Flower (1996), which is an update on his earlier work (Flower 1977) based on a compilation of effective temperatures (Teff) and BCV determinations for a large number of stars. Many authors find this source convenient because, in addition to the table, it presents simple polynomial fits for BCV valid over a wide range of temperatures. Unfortunately, the original publication had misprints in the coefficients of those formulae that have prevented their use, and an erratum was never published. The present author has received numerous inquiries about this problem over the years. Thus, a second motivation for this paper is to make the correct coefficients available to the community, as well as to amend the form of the equation and one of the coefficients for a color/temperature calibration in the same paper that were also misprinted. We begin by presenting these corrections, and follow with a discussion of the practical use of BCV tables.

2. COEFFICIENTS FOR THE FLOWER (1996) BCV AND log Teff FORMULAE

Flower (1996) expressed the bolometric corrections as a function of the effective temperature of the star, and presented polynomial fits for BCV of the form

\[ \text{BCV} = a + b (\log T_{\text{eff}}) + c (\log T_{\text{eff}})^2 + \cdots, \]

for three different temperature ranges. The coefficients \(a, b, c, \cdots\) were given in his Table 6 for each interval, but are missing powers of ten. We rectify this situation here and present them with a larger number of significant digits (see Table 1).

One of original coefficients was also misprinted, and a correction was issued by Prša & Zwitter (2005). We present all coefficients again in Table 2 to higher precision.

A useful color/temperature calibration was also presented by Flower (1996) in his Table 5, separately for supergiants and for main-sequence, subgiant, and giant stars, but unfortunately the formula given there was printed incorrectly, and should have expressed the temperature (log Teff) as a function of the B − V color index, rather than the reverse. The polynomial fits are similar to those used for BCV:

\[ \log T_{\text{eff}} = a + b (B - V) + c (B - V)^2 + \cdots. \]

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3. THE USE OF EMPIRICAL BOLOMETRIC CORRECTIONS

As is well known, the apparent bolometric magnitude of a star is defined as

\[ m_{\text{bol}} = -2.5 \log \left( \int_{0}^{\infty} f_{\lambda} d\lambda \right) + C_1, \]

for a given table of bolometric corrections the choice of MBol,⊙ is not arbitrary, however, since there is an observational constraint that must be satisfied, given by the measurement of the visual brightness of the Sun. This fact is often ignored, and as a result it is common to see inconsistent uses of BCV that can lead to errors in the luminosity of 10% or larger, or errors in MV of 0.1 mag or more. The primary motivation for this paper is to call attention to this fact, to illustrate common misuses of some of the most popular BCV tables, and to offer some perspective on the problem.

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where \( f_\lambda \) is the monochromatic flux from the object per unit wavelength interval received outside Earth’s atmosphere, and \( C_1 \) is a constant. The bolometric correction is usually defined as the quantity to be added to the apparent magnitude in a specific passband (in the absence of interstellar extinction) in order to account for the flux outside that band:

\[
BC_V = m_{bol} - V = M_{bol} - M_V. \tag{4}
\]

Here we focus on the visual band because that is the context in which bolometric corrections were historically defined, although of course the definition can be generalized to any passband. Note that this definition is usually interpreted to imply that the bolometric corrections must always be negative, although many of the currently used tables of empirical BC\( _V \) values violate this condition. We return to this below. Equation (4) may also be written as

\[
BC_V = 2.5 \log \left( \int_0^{\infty} S_\lambda(V) f_\lambda d\lambda / \int_0^{\infty} f_\lambda d\lambda \right) + C_2, \tag{5}
\]

where \( S_\lambda(V) \) is the sensitivity function of the V magnitude system. The constant \( C_2 \) contains an arbitrary zero point that has been a common source of confusion. This zero point has traditionally been set using the Sun as the reference. By noting that

\[
BC_{V,\odot} = m_{bol,\odot} - V_\odot = M_{bol,\odot} - M_{V,\odot}. \tag{6}
\]

it is immediately clear that setting a value for the bolometric correction of the Sun is equivalent to specifying the zero point of the bolometric magnitude scale, since \( V_\odot \) is a known quantity. A common practice when using one of the many available tables of empirical bolometric corrections is to adopt a value for \( M_{bol,\odot} \), but all too often this is done without regard for whether the chosen value is consistent with \( BC_{V,\odot} \) from the same table. From Equation (6) we have

\[
M_{bol,\odot} = M_{V,\odot} + BC_{V,\odot} = V_\odot + 31.572 + BC_{V,\odot}. \tag{7}
\]

where the numerical constant corresponds (with the opposite sign) to the distance modulus of the Sun at 1 AU. This formulation shows that once a particular tabulation of BC\( _V \) values is adopted, the absolute bolometric magnitude of the Sun is no longer arbitrary. This fact has been emphasized by Bessell et al. (1998) and others, but is still largely overlooked.

Direct measurements of \( V_\odot \) are difficult to make because of the extreme difference in brightness between the Sun and the stars that are used as the reference in the V system, and also because the Sun is spatially resolved. Nevertheless, many careful determinations have been carried out over the years (although not very recently, as we are aware), and the most reliable of the photoelectric measurements have been reviewed by Hayes (1985). Among them, one that carries particularly high weight is that of Stebbins & Kron (1957), which was adjusted slightly (by \(-0.02 \) mag) by Hayes (1985) for an error in the treatment of horizontal extinction, and further updated by Bessell et al. (1998) using modern V magnitudes for the reference stars. The result is \( V_\odot = -26.76 \pm 0.03 \). Two additional determinations discussed by Hayes (1985) are those of Nikonova (1949), transformed to the standard Johnson system by Martynov (1960) and Gallouët (1964): \( V_\odot = -26.81 \pm 0.05 \) and \( V_\odot = -26.70 \pm 0.01 \), respectively. Because systematic effects likely dominate the differences, we follow Hayes (1985) and adopt as a consensus value a simple average of the three estimates, giving \( V_\odot = -26.76 \pm 0.03 \), with an error that is probably realistic. The absolute visual magnitude of the Sun then becomes \( M_{V,\odot} = 4.81 \pm 0.03 \).

Measurements of \( V_\odot \) based on absolute flux-calibrated spectra of the Sun (Colina et al. 1996; Thullier et al. 2004, and others) or synthetic spectra based on model atmospheres such as ATLAS9 and MARCS have also been made by many authors, and generally range from \(-26.74 \) to \(-26.77 \), with minor differences depending on the author even when using the same spectrum (see, e.g., Bessell et al. 1998; Casagrande et al. 2006). These estimates agree well with the direct measurements.

While the zero point of \( BC_V \) is completely arbitrary, and no particular scale has been officially endorsed by the International Astronomical Union (IAU) (but see Section 5), it is common for some authors of these tabulations to define the scale by adopting a certain value for \( BC_{V,\odot} \), sometimes for historical reasons. For example, the widely used reference by Cox (2000), the successor to Allen’s Astrophysical Quantities (Allen 1976, and earlier editions) indicates that it adopts \( BC_{V,\odot} = -0.08 \)

\begin{table}[h]
\centering
\caption{Empirical Bolometric Corrections for Stars}
\begin{tabular}{|c|c|c|c|}
\hline
Coefficient & Supergiants & Main-sequence Stars, Subgiants, Giants & \hline
\hline
\( a \) & \( -0.190537291496456 \times 10^5 \) & \( 3.797945106714099 \times 10^{-5} \) & \( -0.11811545038963 \times 10^{-6} \) \\
\( b \) & \( 0.15514866764412 \times 10^5 \) & \( 0.385672696804 \times 10^4 \) & \( 0.1374597383929 \times 10^4 \) \\
\( c \) & \( -0.4212781939717 \times 10^4 \) & \( -0.15065148361025 \times 10^4 \) & \( -0.63623812100225 \times 10^4 \) \\
\( d \) & \( 0.38147632824234 \times 10^3 \) & \( 0.14712923562346 \times 10^2 \) & \( 0.385672696804 \times 10^4 \) \\
\( e \) & \( ... \) & \( ... \) & \( ... \) \\
\( f \) & \( ... \) & \( ... \) & \( ... \) \\
\hline
\end{tabular}
\end{table}
In the chapter on the Sun, the latest edition of the popular *Allen’s Astrophysical Quantities* (Cox 2000, p. 341) adopts an internally consistent set of solar parameters given by $BC_{V,\odot} = -0.08$, $M_{bol,\odot} = 4.74$, $M_V,\odot = 4.82$, and $V_\odot = -26.75$. However, inspection of the table of bolometric corrections for dwarfs in the chapter on normal stars (p. 388), which is the one employed in practice, reveals that the $BC_{V,\odot}$ there is $-0.20$ rather than the value advocated earlier. This implies $V_\odot = -26.63$. Therefore, the use of this table together with $M_{bol,\odot} = 4.74$ will introduce a systematic error of 0.13 mag, which is the same as produced by a difference of 500 K in the input temperature. In order to be consistent with the measured value of $V_\odot = -26.76$ discussed in the previous section, the bolometric magnitude that should be used for the Sun is $M_{bol,\odot} = 4.61$. An earlier edition of *Allen’s Astrophysical Quantities* has inconsistencies of its own and adopts a rather different $BC_V$ scale which, interestingly, does not have as serious a problem. For example, the solar parameters in the third edition by Allen (1976) are also internally consistent, and again use $BC_{V,\odot} = -0.08$, but with $M_{bol,\odot} = 4.75$ (p. 162 of that work). The $BC_V$ table on p. 206, however, lists a bolometric correction for a normal star with the solar temperature as $BC_{V,\odot} = -0.05$. Nevertheless, if used in conjunction with the solar bolometric magnitude advocated, this table implies $V_\odot = -26.77$, which is much more accurate than in the later edition.

2. The solar values adopted by Schmidt-Kaler (1982) (p. 451) are $BC_{V,\odot} = -0.19$, $M_{bol,\odot} = 4.64$, $M_V,\odot = 4.83$, and $V_\odot = -26.74$, which are internally consistent. Schmidt-Kaler’s $BC_V$ table for main-sequence stars on p. 453 gives a slightly different value of $BC_{V,\odot} = -0.21$ for a star of solar temperature. This implies $V_\odot = -26.72$ rather than their adopted value. To be consistent with $V_\odot$ from the previous section, the bolometric magnitude to be used for the Sun is $M_{bol,\odot} = 4.60$.

3. The extensive compilation by Lang (1992) adopts the following values for the Sun (p. 103): $V_\odot = -26.78$, $M_V,\odot = 4.82$, and $M_{bol,\odot} = 4.75$. The first two are slightly inconsistent with the distance modulus of the Sun. The last two imply $BC_{V,\odot} = -0.07$, yet the listing of bolometric corrections on p. 138 gives $BC_{V,\odot} = -0.20$ for a star of solar temperature. According to Equation (7), the proper value of $M_{bol,\odot}$ to use with this table is $M_{bol,\odot} = 4.61$. Consequently, the systematic error incurred by using the Lang (1992) table in combination with their $M_{bol,\odot}$ is 0.14 mag.

4. A $BC_V$ table still often used mainly in the binary star field is that of Popper (1980). The bolometric correction and absolute visual magnitude adopted there for the Sun are $BC_{V,\odot} = -0.14$ and $M_V,\odot = 4.83$, from which $V_\odot = -26.74$. These imply $M_{bol,\odot} = 4.69$. To be in exact agreement with our apparent magnitude for the Sun, the solar bolometric magnitude should be adjusted slightly to $M_{bol,\odot} = 4.67$.

5. The $BC_V$ table in the textbook by Gray (2005) gives $BC_{V,\odot} = -0.09$ for a star of solar temperature, and adopts $V_\odot = -26.75$ (and the corresponding value of $M_V,\odot = 4.82$). Together these imply $M_{bol,\odot} = 4.73$. For exact consistency with $V_\odot$ from the previous section, we recommend using $M_{bol,\odot} = 4.72$.

6. The work of Straizys & Kuriliene (1980) contains many useful tables of average stellar properties, and adopts a
zero point for the $B_CV$ scale that is adjusted to give $B_CV,⊙ = -0.07$. These authors also adopt $M_{bol,⊙} = 4.72$, which leads to $M_V,⊙ = 4.79$ and $V,⊙ = -26.78$. Perfect agreement with our $V,⊙$ requires $M_{bol,⊙} = 4.74$.

7. Kenyon & Hartmann (1995) presented a table of bolometric corrections that is often used in the field of pre-main-sequence stars, and has been incorporated into some model isochrones for young stars such as those by Siess et al. (2000). It is compiled from a variety of sources, and the zero point is such that a star of solar temperature has $B_CV,⊙ = -0.21$. No value of $M_{bol,⊙}$ is specified.

8. Finally, as mentioned earlier, the $B_CV$ table by Flower (1996) gives $B_CV,⊙ = -0.08$ for a star of solar temperature, but there is no associated value of $M_{bol,⊙}$ given in the text. For consistency with $V,⊙$ from the previous section, the number to be used is $M_{bol,⊙} = 4.73$.

Table 3 summarizes the various empirical $B_CV$ scales, along with the $M_{bol,⊙}$ values listed by each source, as well as the $M_{bol,⊙}$ recommended here to maintain consistency with the adopted $V,⊙$. The systematic error introduced when using the former instead of the latter is presented in the last column.

## 5. DISCUSSION

From a practical point of view one may approach the use of published tables of empirical $B_CV$ values in several ways, but it is essential to always maintain consistency with the measured brightness of the sun, $V,⊙$. Errors introduced when overlooking this requirement are seen rather often in the literature, and are quantified in Table 3. Bessell et al. (1998) chose to define $M_{bol,⊙} = 4.74$, from which one derives $B_CV,⊙ = -0.07$. If one follows this path then it is necessary to adjust the $B_CV$ table one is using, in order to match this zero point. In general, each table will require a different offset. However, most users find it more convenient to adopt a particular $B_CV$ table “as is,” in which case care must be taken to use the proper $M_{bol,⊙}$ as listed in Table 3, and not an arbitrary value from another source (or even from the same source if it is inconsistent). Yet another approach is to use Equation (9) or Equation (10) directly, as advocated by Gray (2005), which dispenses with having to find a formal $M_{bol,⊙}$ value, and requires only to read off $B_CV$ for the Sun from the same table used for the star of interest. These three approaches are of course completely equivalent.

Somewhat surprisingly, the IAU has not issued a formal resolution on the matter of $B_CV$ zero points, although two of its Commissions did agree at the Kyoto meeting of 1997 (Andersen 1999, pp. 141 and 181) on a preferred scale that is equivalent to adopting a value for $M_{bol,⊙}$. The scale was set by defining a star with $M_{bol} = 0.00$ to have an absolute radiative luminosity of $L = 3.055 \times 10^{28} \text{ W}$ (see also Cayrel 2002). The rationale was that this value together with the nominal bolometric luminosity of the Sun adopted by the international Global Oscillation Network Group project ($L,⊙ = 3.846 \times 10^{26} \text{ W}$, according to the IAU Commission reports cited above) leads exactly to $M_{bol,⊙} = 4.75$, which is the bolometric magnitude for the Sun listed in the 1976 edition of Astrophysical Quantities (Allen 1976). This was a widely used source at the time (and still is, by some), so it was thought to be a logical choice. Effectively, therefore, the scale is set by this value of $M_{bol,⊙}$. Combined with our adopted solar brightness of $V,⊙ = -26.76$, it implies $B_CV,⊙ = -0.06$. As it turns out, however, the most recent edition of Astrophysical Quantities (Cox 2000) did not follow that recommendation and adopted a slightly different zero point. Neither have some other recent BC compilations (see Table 3). In practice, the adoption of a value of $B_CV,⊙$ or a value of $M_{bol,⊙}$ may not be the most convenient way to solve the immediate problem faced by users. The first alternative would not be of much help to those wishing to make use of an existing $B_CV$ table, and the second would force them to adjust the table to match $V,⊙$. To conclude, one may argue that it would perhaps be more useful instead to agree on the best value for the apparent visual magnitude of the Sun, which is directly measured.

I am indebted to Phillip Flower for providing me with the correct coefficients for his $B_CV$ and color/temperature relations, which were misprinted in his original work (Flower 1996). They are presented here with his permission. I also thank Gene Milone for stimulating discussions and motivation for this paper.

### Table 3
Empirical $B_CV$ Scales and $M_{bol,⊙}$ Values from the Literature

| Source                  | Advocated $B_CV,⊙$ (mag)$^a$ | Actual $B_CV,⊙$ (mag)$^b$ | Adopted $M_{bol,⊙}$ (mag)$^c$ | Recommended $M_{bol,⊙}$ (mag)$^d$ | Error (mag)$^e$ |
|-------------------------|-------------------------------|----------------------------|--------------------------------|-----------------------------------|----------------|
| Cox (2000)              | -0.08                         | -0.20                      | 4.74                           | 4.61                              | +0.13          |
| Allen (1976)            | -0.08                         | -0.05                      | 4.75                           | 4.76                              | -0.01          |
| Schmidt-Kaler (1982)    | -0.19                         | -0.21                      | 4.64                           | 4.60                              | +0.04          |
| Lang (1992)             | -0.07                         | -0.20                      | 4.75                           | 4.61                              | +0.14          |
| Popper (1980)           | -0.14                         | -0.14                      | 4.69                           | 4.67                              | +0.02          |
| Gray (2005)             | ...                           | -0.09                      | 4.73                           | 4.72                              | +0.01          |
| Straiˇzys & Kuriliene (1980) | ...                      | -0.07                      | 4.72                           | 4.74                              | -0.02          |
| Kenyon & Hartmann (1995)| ...                           | -0.21                      | ...                            | 4.60                              | ...            |
| Flower (1996)           | ...                           | -0.08                      | ...                            | 4.73                              | ...            |

Notes.

$^a$ Value that each source states to have adopted as the zero point of their $B_CV$ scale.

$^b$ Value read off from the relevant $B_CV$ table for each source.

$^c$ Bolometric correction for the Sun said to be adopted by each source.

$^d$ $M_{bol,⊙}$ value required for consistency with $V,⊙ = -26.76$ (Section 3), when using the $B_CV$ table as published.

$^e$ Error incurred when using the published $B_CV$ table combined with $M_{bol,⊙}$ from the source, instead of the recommended $M_{bol,⊙}$ value in the previous column.

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4 This scale was also adopted by IAU Division IV at the 2003 meeting of the IAU in Sydney (Engvold 2007).
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