A Silent Revolution in Fundamental Astrophysics

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Abstract

Arbitrariness in the zeropoint of bolometric corrections is a paradigm that is nearly a century old and leads to two more paradigms. “Bolometric corrections must always be negative,” and “the bolometric magnitude of a star ought to be brighter than its V magnitude”. Both were considered valid before the IAU 2015 General Assembly Resolution B2, a revolutionary document that supersedes all three aforementioned paradigms. The purpose of this article is to initiate new insight into and a new understanding of the fundamental astrophysics and present new capabilities to obtain standard and more accurate stellar luminosities and gain more from accurate observations in the era after Gaia. The accuracy gained will aid in advancing stellar structure and evolution theories and also Galactic and extragalactic research, observational cosmology, and searches for dark matter and dark energy.

Unified Astronomy Thesaurus concepts: Stellar physics (1621)

1. Introduction

According to Kuhn (1962), one of the preeminent philosophers of science in the twentieth century, scientists work under paradigms between scientific revolutions. This is the period in which scientists tend to ignore anomalies opposing the dominant paradigm. It is only when the odds are too great to hide that a crisis and then a revolution occur before the next normal science period begins and a new paradigm guides the scientists. The modern history of science attests to two main revolutions separating three such periods. First, the Copernican revolution advanced science from a geocentric to a heliocentric view, although both models could be considered static. Second, Einsteins theories of special and general relativity advanced science from a static to a dynamical (expanding) model. The discovery of Hubble’s law (Hubble 1929) led to a major revolution in observational astrophysics and cosmology and to the new world picture of a universe undergoing expansion. We also recall, however, that every branch of science has its minor as well as major revolutions. They can include less noticed and even silent revolutions.

The discovery that the expansion of the universe is apparently accelerating, based on observations of Type Ia supernovae, was a surprise that led to a partial revolution in cosmology (Perlmutter et al. 1998; Riess et al. 1998; Schmidt et al. 1998). Furthermore, a crisis in cosmology known as Hubble tension has developed. The Hubble constant ($H_0$) or universal expansion rate determined from the cosmic microwave background (CMB) of 67.4 ± 0.5 km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration et al. 2020), does not agree with the rate determined from Cepheid-calibrated Type Ia supernova, at 73.04 ± 0.04 km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 2022). The $4\sigma$–$5\sigma$ disparity appears potentially intractable because it continues to increase in severity as the sensitivity of measurements increases (Melia 2022). Melia (2022) also proposed the hypothesis that perhaps the observations are not fully consistent with an accelerating universe. Even if it were so, the incompatibility of the Hubble rates noted above cannot be explained by simply replacing the currently accepted cosmological model.

For us, the problem appears to be more fundamental than that. That is, there may not be an immediate solution, but rather a marathon of revising current extragalactic distances and distance indicators and of aiming to improve various methods of measuring $H_0$ in order to be consistent with the rate according to CMB observations. One of the intolerable negative effects of the paradigm of arbitrariness attributed to the zeropoint of the bolometric correction (BC) scale is the additional uncertainty in the predicted luminosity ($L$) caused by the preference of different zeropoints by different authors in the literature for more than 80 yr. It was first discussed by Torres (2010) that this uncertainty might be about 10% or larger. It is called the zeropoint error caused by arbitrariness by Eker et al. (2021a, 2021b), who not only confirmed Torres (2010), but also claimed that it is possible to avoid it if a standard BC is used when the standard $L$ for a star is computed. Being equivalent to a 5% error in parallax, a systematic 10% zeropoint error in a predicted $L$ in addition to its uncertainly caused by random observational errors associated with absolute magnitude $M_v$ and BC of a star, where $\zeta$ could be any photometric band, is intolerable today, especially after Gaia.

We suspect that it is not simple coincidence that the 10% systematic error in predicted $L$ is on par with the discrepancy involved in the Hubble tension (Planck Collaboration et al. 2020; Riess et al. 2022). Improving the accuracy of stellar luminosities is the starting point to improving galactic and extragalactic luminosities, luminosity functions, and distances because galaxies are mainly made of stars. An accurate determination of the luminous mass in galaxies and galaxy clusters would enable us to determine dark matter more accurately. On the other hand, improvements in extragalactic luminosities enable improved extragalactic distance estimates. Thus, cosmological models and the value of the Hubble constant cannot be independent of the current improvement in fundamental astrophysics. One step has already been taken to...
avoid the legacy problems caused by the arbitrariness of the BC scale by defining a truly standard BC and standard L (Eker et al. 2021a, 2021b). It has also been discussed and shown that standard stellar luminosities with accuracies at 1% are now possible (Eker et al. 2021b; Bakış & Eker 2022).

IAU 2015 General Assembly Resolution B2 is a revolutionary document in part because it has the potential to start a new revolution in astrophysics and to aid researchers in solving the current crisis in cosmology. First, it discards the paradigm of arbitrariness in the zeropoint of bolometric magnitudes. It furthermore discards the two following paradigms, “bolometric corrections must always be negative,” and “the bolometric magnitude of a star ought to be brighter than its V magnitude”.

We see IAU 2015 General Assembly Resolution B2 as a silent and so far unnoticed revolution. We believe its full potential is far from being realized. One may note that there are numerous articles in respected journals that continue to ignore the resolution, which we do not reference directly so as not to offend. Evidently, the three paradigms involved are so basic that many authors prefer to ignore the effects as trivial anomalies, typical of normal science. In this study, we show how and why adoption of the precepts, advantages, and advancements in the resolution will improve fundamental astrophysics, and as a result, advance modern cosmology and extragalactic as well as Galactic and stellar research.

2. Breaking Paradigms of Fundamental Astrophysics

The first paradigm that was broken was the arbitrariness attributed to the zeropoint constant of the BC scale. IAU 2015 General Assembly Resolution B2 (hereafter IAU 2015 GAR B2) superseded this paradigm by issuing

\[ M_{\text{bol}} = -2.5 \times \log(L/L_0) = -2.5 \times \log L + 71.197425 \ldots, \]

where \( L_0 = 3.0128 \times 10^{28} \) W is the radiative luminosity of a star with an absolute bolometric magnitude \( M_{\text{bol}} = 0 \) mag. It corresponds to the value of the zeropoint constant \( C_{\text{bol}} = 71.197425 \ldots \) mag if the star’s \( L \) is in SI units. Then, the following relation gives the absolute bolometric magnitude \( M_{\text{bol}} \) of a source of luminosity \( L \) expressed in the SI unit W,

\[ M_{\text{bol}} = -2.5 \times \log L + C_{\text{bol}}. \]

If \( L \) is replaced by \( L_V \), which is \( V \), the filtered luminosity of the same star, it can be written for its visual absolute magnitudes as

\[ M_V = -2.5 \times \log L_V + C_V. \]

Because \( L_V \) of a star is lower than its \( L \), the zeropoint constant for the \( V \) filter \( (C_V) \) must be smaller than \( C_{\text{bol}} \). Subtracting Equation (3) from Equation (2),

\[ BC_V = M_{\text{bol}} - M_V = 2.5 \times \log(L_V/L) + C_{\text{bol}} - C_V, \]

and identifying \( C_2 = C_{\text{bol}} - C_V \) as the zeropoint constant of the \( V \) band bolometric corrections \( BC_V \), it is obvious that \( C_2 \) is a positive number because both \( C_{\text{bol}} \) and \( C_V \) are positive and \( C_{\text{bol}} > C \).

Equation (4) indicates that the zeropoint of \( BC_V \) is not arbitrary because both \( C_{\text{bol}} \) and \( C_V \) are well-defined constants and the zeropoint constant is equal to their difference.

Therefore, the first superseded paradigm is that “the zeropoint constant of the bolometric correction scale is arbitrary”.

Like a chain reaction, the other two paradigms “bolometric corrections must always be negative” and “the bolometric magnitude of a star ought to be brighter than its visual magnitude” are also superseded. Because \( L_V/L \) is a number between zero and one \((0 < L_V/L < 1)\), indicating \( \log(L_V/L) \) is a negative number, while \( C_2 \) is a positive number, then \( BC_V \) is positive if the absolute value of the logarithmic term is lower than \( C_2 \), or else it is negative. Note that according to Equation (4), \( BC_V = C_2 \) and \( BC_V > C_2 \) are not allowed. Positive \( BC \) is also possible by the following equation derived from Equation (4):

\[ L_V = L \times 10^{(BC_V - C_2)/2.5}. \]

Because it is unphysical to have \( L_V = L \) or \( L_V > L \), Equation (5) indicates that all \( BC_V \) values lower than \( C_2 \) are valid. In other words, not only \( BC_V < 0 \), but also \( 0 < BC_V < C_2 \) are valid to produce \( L_V < L \). Therefore, BCs cannot be limited to negative numbers alone. There could be stars with positive BC (see Eker et al. 2020, 2021a, 2021b), satisfying the condition \( L_V < L \). Main-sequence stars having effective temperatures between 5859 K and 8226 K with positive \( BC_V \) have indeed been found (Eker et al. 2020).

Even a single occurrence of a positive BC (regardless of its value) breaks the paradigm that “the bolometric magnitude of a star ought to be brighter than its V magnitude” because a positive BC indicates \( M_{\text{bol}} > M_V \), which is an obvious case sufficient to break this paradigm if the word “brighter” means a smaller number. This paradigm is also incorrect factually and linguistically because by-eye comparisons of magnitudes are meaningful only if they are done in the same wavelength range within the visible part of the electromagnetic spectrum; otherwise, the comparison is meaningless due to the different eye sensitivity at different wavelengths. One final comment: BC and colors, e.g., \( U-B, B-V, V-R, \) and \( V-I \), are not defined to compare the brightness of a star at different bands, they are rather defined as physical entities to reveal information about the effective temperature and/or the spectral energy distribution (SED) of stars.

3. Superseding the Paradigms in Apparent Magnitudes

IAU 2015 GAR B2 did more than fix the zeropoint of absolute bolometric magnitudes. It also fixed the zeropoint of apparent bolometric magnitudes, because fixing the zeropoint of absolute bolometric magnitudes (Equation (2)) automatically fixes the zeropoint of apparent bolometric magnitudes. The same document also provides information about the zeropoint of the apparent bolometric magnitude scale by specifying that \( m_{\text{bol}} = 0 \) mag corresponds to an irradiance or heat flux density of \( f_0 = 2.518021002 \ldots \times 10^{-8} \) W m\(^{-2}\), and hence the apparent bolometric magnitude \( m_{\text{bol}} \) for an irradiance \( f \) (in W m\(^{-2}\)) is

\[ m_{\text{bol}} = -2.5 \times \log(f/f_0) = -2.5 \times \log(f - 18.997351 \ldots). \]

The irradiance \( f_0 \) corresponds to that from an isotropically emitting source with absolute bolometric magnitude \( M_{\text{bol}} = 0 \) mag (luminosity \( L_0 \) at a standard distance of 10 parsecs” (IAU 2015 GAR B2). Equation (6) also reveals that the zeropoint constant of the apparent bolometric magnitude scale is no longer arbitrary.

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5 https://www.iau.org/static/resolutions/IAU2015_English.pdf
either. Thus, its value is $c_{\text{bol}}(\text{irr}) = -18.997 \, 351 \ldots \, \text{mag}$, then

$$m_{\text{bol}} = -2.5 \times \log(f_{\text{bol}}) + c_{\text{bol}}(\text{irr}),$$  \(7\)

where $f$ is replaced by $f_{\text{bol}}$ to be more specific. Equation (7) could be adopted for $V$ apparent visual magnitudes as

$$V = -2.5 \times \log(f_V) + c_V(\text{irr}),$$  \(8\)

where $c_V(\text{irr})$ is the well-defined zeropoint constant for $V$ magnitudes, and $f_V$ is the $V$ filtered star flux reaching the telescope (if there is no extinction). Because the bolometric flux ($f_{\text{bol}}$) from a star exceeds its $V$ flux, $c_{\text{bol}}(\text{irr}) > c_V(\text{irr})$. Even if $c_{\text{bol}}(\text{irr})$ is a negative number (the numerical value of $f_{\text{bol}}$ is lower than one), $c_V(\text{irr})$ must also be a negative number but a higher absolute value, thus $c_{\text{bol}}(\text{irr})$ minus $c_V(\text{irr})$ is always positive. Subtracting Equation (8) from Equation (7), the following equation is written.

$$BC_V = m_{\text{bol}} - V = 2.5 \times \log(f_V/f_{\text{bol}}) + c_{\text{bol}} - c_V.$$  \(9\)

Because both $c_{\text{bol}}$ and $c_V$ are well-defined constants, Equation (9) also requires that the zeropoint of the BC $V$ scale is not arbitrary either. Even though the zeropoint constants are not the same as in Equation (4), where they were defined to give luminosities, here they are defined to give irradiance fluxes reaching the telescope, and the zeropoint constant $C_2$, which is defined before as $C_{\text{bol}} - C_V$ has the same value as $C_2 = c_{\text{bol}} - c_V$ in Equation (9). This holds because the left sides (BC $V$) of both equations are the same and

$$L_V = L \times 10^{(BC_V - C_2)/2.5}.$$  \(10\)

Despite the fact that the zeropoint constants in Equations (2), (3), and (4) are different than the zeropoint constants in Equations (7), (8) and (9), one ends up with the same numerical value for $C_2$. Taking it as $C_2 = c_{\text{bol}} - c_V$ from Equation (9), and replacing $f_V/f_{\text{bol}}$ by $L_V/L$ according to Equation (10), the following equation could be written:

$$L_V = L \times 10^{(BC_V - C_2)/2.5}.$$  \(11\)

This is the very same equation as we used above (Equation (5)) as an argument for superseding the paradigms of “bolometric corrections must always be negative” and “the bolometric magnitude of a star ought to be brighter than its visual magnitude”. It is clear that fixing $c_{\text{bol}} = -18.997 \, 351 \ldots$ by IAU 2015 GAR B2 not only breaks the paradigm of arbitrary zeropoint for apparent bolometric magnitudes, but also breaks the paradigm of an arbitrary zeropoint for the BC $V$ scale. It also breaks the other two paradigms. Because the value of $c_{\text{bol}}$ is derived from the value of $C_{\text{bol}}$, as explained in IAU 2015 GAR B2, fixing $c_{\text{bol}}$ is sufficient to break all three paradigms in a single step. This is so regardless of whether the BC $V$ value of the star is coming from its apparent (Equation (9)) or its absolute (Equation (4)) magnitude.

We note that the $V$ filter here represents any filter in any photometric system. The equations written for the $V$ filter are also valid for other filters with proper BC and $C_2$ in any photometric system.

4. Discussions

4.1. Vega System of Magnitudes and BC

One counter argument that has been used to advocate the arbitrariness of the BC $V$ scale is that IAU 2015 GAR B2 did not set the bolometric correction scale. It defined only the bolometric magnitude scale set to SI irradiance ($m_{\text{bol}}, f_{\text{bol}}$) and luminosity ($M_{\text{bol}}, L_{\text{bol}}$) values, whereas the photometric magnitudes are independently defined by standard stars (for Vega magnitudes, or fluxes for the ST or AB scale). The IAU could easily set the former, but not the latter, such as the Johnson $V$ system. Because the IAU did not set the BC scale, nothing new could be claimed about it, especially about the arbitrariness attributed to the BC scale that has been used for about eight decades.

This argument advocating the BC system used before 2015 for about eight decades is invalid now because Equation (9) could be generalized for any photometric system: e.g., the Johnson system of apparent magnitudes ($U, B, V, R, I$) as

$$m_{\text{bol}} = \zeta + BC_\zeta = U + BC_U = B + BC_B = V + BC_V = R + BC_R = I + BC_I,$$  \(12\)

and Equation (4) could be generalized to include the Johnson system of absolute magnitudes ($M_U, M_B, M_V, M_R, M_I$) as

$$M_{\text{bol}} = M_\zeta + BC_\zeta = M_U + BC_U = M_B + BC_B = M_V + BC_V = M_R + BC_R = M_I + BC_I,$$  \(13\)

where the subscripts indicate a filter in a photometric system. Apparently, whether it was intentional or not, the resolution conducted by IAU 2015 GAR B2 was the most easy and logical resolution. This is because it is illogical to set innumerable zeropoints for the BC of each band in various photometric systems while an easy way exists to resolve the problem in a single step. It is obvious in the equations above that fixing the zeropoint of bolometric magnitudes by Equation (6) (or by Equation (1)) is sufficient to fix the zeropoints of $BC_\zeta$ at once because the Vega system of magnitudes has already well-defined zeropoints, as expressed by Equation (8). The arbitrariness of the BC scale was removed automatically, together with the arbitrariness of the bolometric magnitude system at the moment IAU 2015 GAR B2 was issued. No additional setting was required.

IAU 2015 GAR B2 is revolutionary in part because it opens new insight into fundamental astrophysics, resolving chronic problems of lasting legacy while providing new opportunities toward a most accurate stellar $L$. The accuracy may even surpass that of the direct method (Eker et al. 2021b), which can provide a typical accuracy of $8.2\%$–$12.2\%$ based on accurate stellar $R$ and $T_{\text{eff}}$.

As indicated by the equal signs, it is obvious in Equations (12) and (13) that measurements at any filter are independent of the measurements at other filters. That is, it is possible to obtain independent BC–$T_{\text{eff}}$ relations at various filters using the most accurate $R$ and $T_{\text{eff}}$ of double-lined detached eclipsing binaries (DDEB) by the methods of Flower (1996) and Eker et al. (2020). Independent relations at Gaia filters ($G, G_{\text{BP}}$, and $G_{\text{RP}}$) and Johnson $B$ and $V$ were obtained by Bakos & Eker (2022). Coefficients and basic statistics of five independent BC–$T_{\text{eff}}$ relations (fourth-degree polynomials) are given in Table 1, where the columns are order, band,
Table 1

| Order | Band | \(a\)  | \(b\)  | \(c\)  | \(d\)  | \(e\)  | \(N\)  | \(SD\)  | \(R^2\)  |
|-------|------|--------|--------|--------|--------|--------|-------|--------|--------|
| 1     | Gaia \(G\) | -1407.14 | 1305.08 | -453.605 | 70.2338 | -4.1047 | 402  | 0.1107 | 0.9793 |
|       |       | ±256.7  | ±258.9  | ±97.67  | ±16.34  | ±1.023 |       |        |        |
| 2     | Gaia \(G_{BP}\) | -3421.55 | 3248.19 | -1156.82 | 183.372 | -10.9305 | 402  | 0.1266 | 0.9738 |
|       |       | ±293.6  | ±296.1  | ±111.7  | ±18.68  | ±1.169 |       |        |        |
| 3     | Gaia \(G_{RP}\) | -1415.67 | 1342.83 | -475.827 | 74.9702 | -4.44923 | 402  | 0.1092 | 0.9884 |
|       |       | ±253.3  | ±255.4  | ±96.34  | ±16.12  | ±1.009 |       |        |        |
| 4     | Johnson \(B\) | -1272.43 | 1075.85 | -337.831 | 46.8074 | -2.42862 | 342  | 0.1363 | 0.9616 |
|       |       | ±394.2  | ±394.4  | ±147.2  | ±24.53  | ±1.152 |       |        |        |
| 5     | Johnson \(V\) | -3767.98 | 3595.86 | -1286.59 | 204.764 | -12.2469 | 386  | 0.1201 | 0.9789 |
|       |       | ±288.8  | ±290.9  | ±109.6  | ±18.32  | ±1.146 |       |        |        |

Figure 1. Independent \(BC-T_{\text{eff}}\) relation at Gaia \(G\), \(G_{BP}\), and \(G_{RP}\) and Johnson \(B\) and \(V\) (Bakış & Eker 2022).

coefficients, and associated errors to define

\[
BC = a + bX + cX^2 + dX^3 + eX^4, \quad (14)
\]

where \(X = \log T_{\text{eff}}\), the number of DDEB stars \((N)\), the standard deviation \((SD)\), and the correlation coefficient \((R^2)\).

Figure 1 displays the curves of \(BC-T_{\text{eff}}\) relations in Table 1 as functions of \(\log T_{\text{eff}}\). Note that all five curves cross over one another, as displayed, at \(T_{\text{eff}} \lesssim 10,000\) K. This is not a coincidence. It is a natural result of using the Vega system of magnitudes.

Using \(\alpha\) Lyr (Vega) as the primary calibrating star, the Vega system is the most well known and has been deliberated for heterochromatic measurements. Although the zeropoints are often determined observationally from a network of standard stars, it is formally just a single object. A hypothetical star of spectral type AOV with a magnitude \(V = 0.0\) mag in the Johnson system is given in Table 16.6 (Cox 2000), where \(UBVRI\) bands and monochromatic fluxes at effective wavelengths are presented. Note that Vega is used as a calibrating star, but its apparent magnitude is not exactly zero. \(V = 0.03\) mag has been measured by Johnson (1966) and Bessell et al. (1998). The standard Johnson value of \(V = 0.03\) mag is cited by Bohlin (2014). The same value \((V = 0.03\) mag) was adopted by Cox (2000), Girardi et al. (2002), Bessell & Murphy (2012), and Casagrande & Vandenberg (2014). For the other bands, Vega is found to be just slightly positive \((0.02\) mag) at most bands (Rieke et al. 2008). For the heterochromatic bands of various photometric systems, Equation (8) could be written as

\[
\zeta = -2.5 \times \log(f) + c_{i}(\text{irr}), \quad (15)
\]

where the zeropoint constant \(c_{i}(\text{irr})\) needs to be derived for each bandpass \(\zeta\) using a star of known absolute flux, usually Vega (Casagrande & Vandenberg 2014), or Sirius and Vega (Bohlin 2014). Although \(c_{i}(\text{irr})\) are usually not given for the photometric systems in the literature, where only monochromatic fluxes making apparent magnitudes zero at effective wavelengths of the filters are listed, all of the zeropoint constants associated with the Vega system of magnitudes at various bands of different photometric systems are well-defined quantities (Bessell et al. 1998; Cox 2000; Girardi et al. 2002; Casagrande & Vandenberg 2014).

Figure 1 confirms the usage of the Vega system of magnitudes through Equations (12) and (13) because the \(BC-T_{\text{eff}}\) curves cut each other at a single point \((T_{\text{eff}} = \approx 10,000\) K) and the color curves would do the same because the colors of the hypothetical star AOV are taken to be \(U - B = B - V = V - R = V - I = 0\) mag. Curves intersecting at a single point are naturally expected because the difference of the \(BC_{i}\) values at two different bands is equal to the negative value of the colors defined in the photometric system according to the basic definition of BCs. All of these could be counted as undeniable evidence indicating that the zeropoint constants of \(BC_{i}\) are not arbitrary, but are well-defined constants as the zeropoint constants of Vega system of magnitudes.

Each curve in Figure 1 could be used to estimate a BC of a star if its effective temperature were known. Then this BC could be used to calculate its bolometric magnitude as \(M_{\text{bol}} = M_{i} + BC_{i}\) if its distance and \(E(B-V)\) color excess were known. Last, its standard luminosity \((L)\) could be calculated from \(M_{\text{bol}}\) using Equation (2). The accuracy of \(M_{\text{bol}}\) and the accuracy of \(L\) depend on the accuracies of \(M_{i}\) and \(BC_{i}\) if standard BC values are used, otherwise, zeropoint errors \((\sim 10\%)\) caused by arbitrary definitions (Torres 2010; Eker et al. 2021a, 2021b) must also be added. The SD column in Table 1 indicates the typical accuracy of a BC. That is, if \(M_{i}\) is errorless, it is possible to obtain \(M_{\text{bol}}\) with an accuracy \(\pm \text{SD}\), which means \(\Delta L/L \sim 0.921 \times \text{SD}\) (Eker et al. 2021b). Thus, according to Table 1, the most accurate \(L(\sim 10\%)\) could be
obtained using the BC from the BC–$T_{\text{eff}}$ relation at the band Gaia $G_{\text{BP}}$, which is obviously not better than the direct method.

It is most important that one may increase the accuracy of the predicted $L$ if many independent standard BC–$T_{\text{eff}}$ relations are used. For example, the primary of HP Aur has $M = 0.9543 \pm 0.0014 M_{\odot}$, $R = 1.0278 \pm 0.0042 R_{\odot}$ and $T_{\text{eff}} = 5810 \pm 120 \text{ K}$ (Lacy et al. 2014). The Stefan-Boltzmann law gives its $L = 4.149 \pm 0.344 \times 10^{26} \text{ W}$, with an accuracy of 8.302%. Using interstellar extinctions $A_V = 0.335$, $A_G = 0.298$, $A_{BP} = 0.366$, and $A_{BP} = 0.207$ mags and its Gaia EDRE trigonometric parallax $5.2432 \pm 0.0030 \text{mas}$ (Gaia Collaboration et al. 2021), Bakış & Eker (2022) calculated its absolute magnitudes as $M_V = 4.753 \pm 0.033$, $M_G = 4.583 \pm 0.033$, $M_{BP} = 4.860 \pm 0.042$, and $M_{\text{RP}} = 4.152 \pm 0.024$ mags. Using the BC values from Table 1, its bolometric absolute magnitudes were found to be $4.824, 4.688, 4.730,$ and $4.713 \text{ mags}$, which were then combined to a single value of $4.739 \pm 0.030$ mag. Last, its luminosity of $L = 3.831 \pm 0.096 \times 10^{26} \text{ W}$ is found with an uncertainty of 2.5%. This is about four times better than the direct method. So far, no available method was able to provide a stellar luminosity more accurate than the direct method. This is the first method that can do this, and it became possible only after IAU 2015 GAR B2. Accurate stellar luminosities are not only needed to test stellar structure and evolution theories, but they are also required to improve Galactic and extragalactic studies, the search for dark matter, and can even perhaps be used to finally resolve the Hubble tension because stars are one of the most important primary building blocks for understanding the universe.

4.2. Attention Required On ZeroPoint Constants

The apparent magnitude of a star disregards distance information. Thus, Equation (7) is valid only for the apparent magnitudes of stars. The very same equation could be adopted for absolute bolometric magnitudes as

$$M_{\text{Bol}} = -2.5 \times \log(F_{\text{Bol}}) + c_{\text{Bol}(\text{irr})},$$  \hspace{1cm} (16)

on the condition that the star is assumed to be at a fixed distance of $10 \text{ pc}$. It is only under this condition that an irradiance or heat flux density of $F_{\text{Bol}} = f_0 = 2.518021002 \times 10^{-8} \text{ W m}^{-2}$ at the focal point of the telescope makes it possible to write $M_{\text{Bol}} = 0 \text{ mag}$. It is obvious that this equation and Equation (2) appear different even though the left sides of both equations are the same. The same $M_{\text{Bol}}$ before the equal sign implies that

$$-2.5 \times \log(L) + C_{\text{Bol}} = -2.5 \times \log(f_{\text{Bol}}) + c_{\text{Bol}(\text{irr})}. \hspace{1cm} (17)$$

The algebraic sum of the two quantities on the right side of both equations must be the same. Thus, the zero-point constant associated with luminosities is different than the zero-point constant associated with irradiances.

When Equation (16) is subtracted from Equation (7), which has the same zero-point constant, they must cancel in the subtraction, thus

$$m_{\text{Bol}} - M_{\text{Bol}} = 2.5 \times \log(F_{\text{Bol}}/f_{\text{Bol}}). \hspace{1cm} (18)$$

Because $F_{\text{Bol}}$ and $f_{\text{Bol}}$ correspond to bolometric fluxes of the same star if it is at a distance of $10 \text{ pc}$ and $d \text{ pc}$ away (assuming no extinction) and the flux of a star is inversely proportional to the square of its distance, then $(F_{\text{Bol}}/f_{\text{Bol}}) = (d/10)^2$. Inserting this into Equation (18),

$$m_{\text{Bol}} - M_{\text{Bol}} = 5 \times \log d - 5, \hspace{1cm} (19)$$

the distance modulus of the star is obtained. So, one has to be careful using absolute magnitudes. Proper usage of the zeropoints is necessary. If $M_{\text{Bol}}$ is associated with $L$, then $C_{\text{Bol}}$ should be used as in Equation (2). Otherwise, $c_{\text{Bol}(\text{irr})}$ should be used as in Equation (16).

5. Conclusions

The results obtained in this study are listed below.

1. Although its primary aim was to set the zero-point constant of bolometric magnitudes, IAU 2015 GAR B2 was shown to be a revolutionary document in that it implied that the zero-point constants of BC$_{\odot}$, where $\zeta$ indicates various photometric bands, are not arbitrary, but are well-defined constants.

2. IAU 2015 GAR B2 is a revolutionary document not only because it solves problems that are nearly a century old, which were caused by the arbitrariness attributed to the BC scale, but also because it indicates that the paradigms “bolometric corrections must always be negative” and “the bolometric magnitude of a star ought to be brighter than its $V$ magnitude” are no longer correct.

3. The falsehood of the three paradigms (the BC scale is arbitrary, BC values must always be negative, and the bolometric magnitude of a star ought to be brighter than its $V$ magnitude) are not only proven mathematically, but are also confirmed from an observational point of view by the multiband BC–$T_{\text{eff}}$ relations calibrated by Bakış & Eker (2022), who used published observational data of DDEB stars.

4. Increasing the number of photometric bands with standard BC–$T_{\text{eff}}$ relations, which are to be used to calculate the standard stellar luminosity from $M_{\text{Bol}} = M_{\zeta} + \text{BC}_{\zeta}$ and $M_{\text{Bol}} = -2.5 \times \log L + C_{\text{Bol}}$, increases the accuracy of the standard luminosity of a star. Using this method to predict stellar luminosities is also a revolution because this method is shown to predict stellar luminosities that are much more accurate than the classical direct method of using stellar radii and effective temperatures through the Stefan-Boltzmann law. Achieving this accuracy became possible only after discarding the arbitrary zero-point errors caused by the arbitrariness attributed to the BC scale; this was possible, however, only after understanding the potential of IAU 2015 GAR B2.

5. This accuracy in calculated stellar luminosities is not only needed to refine stellar structure and evolution theories, but also to improve Galactic and extragalactic studies further, including observational and theoretical cosmology and the search for dark matter, because stars are the primary building blocks of the universe.
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\(^7\)  https://www.cosmos.esa.int/gaia
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