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REVISITING BOLOMETRIC CORRECTIONS: OLDER AND NEWER USAGES

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The concept of bolometric magnitude, introduced by Eddington in 1926, represented stellar luminosity for theoretical mass-luminosity studies, complementing photographic and visual magnitudes. Bolometric correction (BC), defined as BC = M_{bol} - M_v = m_{bol} − m_v, became a crucial tool in the 20^{th} century for calibrating stellar temperature scales, particularly when only B-V (photographic - visual) color indices were available. Despite advancements in multi-color photometry, classical BC usage persisted, leading to misconceptions: that BC must always be negative, bolometric magnitudes are inherently brighter than visual, and BC zero-points are arbitrary. These were clarified with IAU's 2015 GAR B2 resolution, which established a consistent zero-point, revealing BC's potential for accurately determining stellar luminosities. This study revisits the evolution of BC, addressing its historical and modern usage, and demonstrates how multi-color photometry combined with BC enables precise stellar luminosity measurements, accurate to a few percent.

Keywords: Stars: fundamental parameters; stars: general; solar and stellar astrophysics; astrophysics - instrumentation and methods for astrophysics

1. INTRODUCTION

The bolometric correction (BC) of a star is defined as the difference between its bolometric and visual magnitudes. This definition is first given by [26] as

$$BC = M_{bol} - M_{pv} = m_{bol} - m_{pv} \tag{1}$$

if

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$$M_{bol} = M_{bol}(sun) - 2.5logL \tag{2}$$

where the subscripts bol and pv indicate bolometric and photovisual, M and m are absolute and apparent magnitudes while L is the luminosity of the star in solar units. This definition is commonly accepted and used throughout of the century and even today, thus astronomers handbook "Allen's Astrophysical Quantities" [9] retained the same definition as "BC=bolometric correction=m_{bol}-V" with a note "always negative". If equation (1) is arranged as M_{bol}=M_V+BC and m_{bol}=V+BC, the term BC could be interpreted as the correction added to the visual magnitudes. There is no telescope nor a detector to observe a star at all wavelengths, thus the missing part, named BC, must be added to the observable magnitude (nowadays, could be at any band of any photometric system) in order to obtain the bolometric magnitude, which represents hypothetical brightness of the star at all wavelengths from zero to infinity.

This definition of BC, which has been used since [26], has chronic problems which [13] and [15] call them paradigms: 1) BC of a star must always be negative, 2) Bolometric magnitude of a star ought to be brighter than its V magnitude, 3) The zero point of BC scale is arbitrary. On the contrary, without recognizing them as paradigms, [36] says "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" for the problem one, "bolometric magnitude of a star ought to be brighter than its V magnitude according to equation (1)" for the problem two and writing the Kuiper's definition (equation 1) in the integral form for the V band BC

$$BC_V = 2.5log(\int_0^\infty S_\lambda(V) f_\lambda d\lambda / \int_0^\infty f_\lambda d\lambda) + C_2, \tag{3}$$

where S_λ (V) is the sensitivity function for the V magnitude system, "the constant C_2 contains an arbitrary zero point that has been a common source of confusion" for problem three as if defending them as natural problems solvable by using the correct values of M_{bol} and BC_V for the Sun. Actually, the problem is much bigger than [36] imagined. As it was described by [13], there are two schools of thought that treat the arbitrariness of the BC scale differently. One school [9, 21, 22, 26, 28, 29, 31, 37] intentionally and knowingly shifts computed BC values to make them all negative, that is, obeys all of the three paradigms, while the other school [5, 6, 8, 12, 17, 18, 23, 24, 35] prefers retaining BC values as computed, even if there are positive BC values.

The first group appears self-consistent according to the paradigms. However, the second group, which retains the BC values as they are, even if there are positive values, ignores the note 'BC = m_{bol} - V (always negative)' (page 381 in [9]) or a positive BC is not seen as a violation. It is not possible for both schools to be consistent.

It is obvious that a positive BC (BC $>$ 0), according to paradigms 1 and 2, is a serious problem according to the first school because a positive BC implies L_V, an observable part of the luminosity of a star corresponding to M_v, greater than its total luminosity L. This, however, is unphysical as if a part of a unit is greater than the unit itself. But on the other hand, according to the second school, the arbitrariness of the zero-point constant of the BC scale, which gives freedom to the first school to shift their BC numbers until all BC values are negative, is another dead end. This is because, for every other arbitrary value of C_2 in equation (3), there must be another BC_V. For every other value of BC_V, there must be another M_{bol} for the star having an M_v according to the original definition of BC by [26] (equation 1). Then, despite M_v is the single entity, every other value of M_{bol} implies the star has many different values of L according to equation (2). How can a single star, with a single M_v, have many different values of L as many as the number of arbitrary zero-point constants which could be used by different users. Arbitrariness implies a single star would have an infinite number of different L, which is also unphysical. Although the problems appear solvable according to [36], the current definition and usages of BC are so ill-posed that there could be no solution et al, in other saying, there is a crisis in the development of BC, as described by [27].

According to [27], who is one of the most distinguished philosophers of science in the twentieth century, science does not progress linearly. Science progresses through revolutions. Between the revolutions is called the period of normal science in which scientists work under dominant paradigm(s), thus, anomalies were ignored. By the time anomalies increase, become intolerable, then a crisis emerges. The crisis was overcome by a revolution, then a new normal science period with new paradigm(s) will start. The purpose of this study is to investigate the pre-science period in the development line of BC search for the origins of the three paradigms and then pronounce the silent revolution [15], that is, how the misleading three paradigms were already broken; meanwhile, older and newer usages of BC will be described automatically.

2. EARLY CONCEPTS OF BC AND ORIGINS OF THE PARADIGMS

2.1. Luminous Efficiency

The earliest concept of BC was introduced by Eddington [10], who called it "luminous efficiency" as an auxiliary parameter when he was upgrading mass-absolute magnitude relation dicovered independently by [20] and [33]. These were

the times in the history of science when the stellar temperature scale just recently (a decade ago) established by the spectral sequence and used in the newly established H-R diagrams by [19] and [32] in 1913. The primary purpose of [10] was to formulate a theoretical mass-luminosity relation, which retained absolute bolometric magnitude (M_{bol}) to indicate luminosity of a star against its mass. In these years, there were only three types of magnitudes: visual (M_v), photographic (M_p), and bolometric (M_{bol}) until the three color (UBV) photometry was introduced by Johnson and Morgan [25]. M_{bol} was chosen because the other two magnitudes were not suitable to represent total radiation of a star. Rather than being a hypothetical brightness to indicate luminosity of a star, the bolometric magnitude was just another observable quantity for Eddington and his colleagues who could obtain it by an instrument such as a bolometer, a radiometer or a galvanometer. Eddington commented:
"It is now practical to measure the heat received from a star by the use of a radiometer. Considerable sensitiveness in the method has been developed (It is said that the equipment at Mount Wilson could detect the heat of a candle on the banks of the Mississippi). But the results attained are as yet very limited and in general we have to infer the total amount of heat emitted from the light emitted (the deduction of bolometric magnitude from heat measurement is not really more direct than from light measurement, because large corrections must be applied on account of atmospheric absorption in the infra-red, and this involves assuming a spectral energy distribution just as the reduction of light measurements does). This involves of the luminous efficiency of the energy emitted by stars of different types."
and gave the definition of the luminous efficiency of a star with an effective temperature T_e as

$$< P >= \frac{\int p(\lambda) I'(\lambda, T_e) d\lambda}{I'(\lambda, T_e) d\lambda} \tag{4}$$

where I' (λ, T_e) is the black body intensity at a wavelength λ and p(λ) is the factor for the luminous efficiency thus <P> is the mean value of it for a star with T_e. Since nuclear reactions such as p-p chain and CNO cycle were not discovered, Eddington was assuming stars are hot spheres of gases. According to Eddington the maximum of <P> occurs for the stars of types F to G, presumably, that is because our visual sense has been developed respect to sunlight. Eddington continued *"It is convenient to take the maximum as standard, and to define the scale of bolometric magnitude at this effective temperature. At any other temperature P will be smaller and the star will be brighter bolometrically than visually".*

Readers should pay attention to the last sentence, which is nothing but the first verbal expression of the second paradigm. In fact, the definition of luminous efficiency resembles the definition of BC according to equation (3) if one replaces

Table 1. Effective temperatures, luminous efficiency (p) and magnitude difference between bolometric and visual (Eddington 1926).

T_e (K)	p	Δm (Vis.-bol.)
		m
2540	0.092	+2.59
3000	0.206	+1.71
3600	0.417	+0.95
4500	0.723	+0.35
6000	1.000	0.00
7500	0.985	+0.02
9000	0.893	+0.12
10500	0.749	+0.31
12000	0.616	+0.53

$p(\lambda)$ with S_λ (V) and black body intensity I' (λ,T_e) with the black body flux f_λ. Thus, the luminous efficiency of the human eye acts like the visual filter in the three color (UBV) photometry. The only difference is that the luminous efficiency is without an arbitrary constant as in equation (3).

Eddington gave a table (Table 1) for those who would have the star's visual magnitude but not its bolometric magnitude. Knowing T_e and the star's visual magnitude, one can estimate its apparent bolometric magnitude (Table 1). If the star's parallax is also available, one can get its absolute bolometric magnitude. At last, using the mass-luminosity relation of Eddington, the mass of the star could be obtained. Apparently, Eddington solved a very crucial problem of estimating masses of single stars for which Kepler's third law is not applicable.

2.2. Heat-index

Apparently, the term "luminous efficiency" did not thrill the successors of Eddington. First, [30] preferred to use the term "heat-index", which they define it as the difference between visual minus radiometric magnitudes of a star. Remembering that the radiometers were used for measuring the heat received from a star, and bolometric magnitudes also come from radiometers, then it is more meaningful to call the difference between visual and bolometric "heat-index" which is essentially the same quantity displayed in the third column of Table 1. The third column of Table 1, however, is nothing but the ten-based logarithm of the second column (luminous efficiency). If the ten-based logarithm of the luminous efficiency is multiplied by 2.5, then it is called “heat-index”. [30] gave the following formula for one to obtain the apparent bolometric magnitude of a star from its radiometric magnitude,

$$m_b = m_r - \Delta m_r + (H.I. + \Delta m_r)_s \tag{5}$$

where (H.I.+Δm_r)$_s$ was defined as the heat-index plus the reduction to no atmosphere for the particular star or class of stars for which the radiometric and bolometric scales were made to coincide. The “radiometric magnitude” of a star, however, was defined as equal to the apparent magnitude of an A0 star which will give the observed galvanometer deflection. [34] was also preferred to use the term “heat-index” but gave the formula

$$M_b = M_v - H.I. - \Delta m_r + 0.9 \tag{6}$$

for calculating absolute bolometric magnitudes, where H.I. and Δm_r have the same meanings as in equation (5). A number of 0.9 is added to equation (6) to make the zero-point of BC scales equal between Eddington [10], [30], and [34]. Note that, it is very obvious in (6) that H.I is equal to minus BC according to the definition of [26]. It is also same for equation (5) because the term $+\Delta m_r$ cancels first, then since H.I.= M_v - m_r, the term m_r also cancels then equation (5) could be written as m_b = M_v - H.I. which also indicate H.I is equal to minus BC. It is clear in the paragraphs and tables of [30], [34] and others using H.I .that the H.I . is used for calibrating stellar temperatures, which was obvious in the comment of [34] “Heat-index like color-index is also zero for F5-G5 stars”. That is, heat-index was used like color-index to indicate the effective temperatures of stars.

2.3. Surpassing definitions and the end of the pre-science period

At last, [26] preferred not to use the names previously existing as “luminous efficiency” nor “heat-index” but invented a new name “bolometric correction” (BC) also for calibrating the stellar temperature scale. Since BC is defined as M_{bol} − M_v or m_{bol} - V or as in the integral form given in equation (3) and because M_{bol} = M_v + BC or m_{bol} = V + BC or, that is, BC appears to be as a correction term to the visual (or photovisual) magnitudes, [26] preferred naming BC as bolometric correction. Despite its problems stated by [36], which were called paradigms by [13,15], this newest concept of BC has been used throughout the century and even today. The period after Kuiper [26] should be considered the normal science period that occurred first time in the development line (brief history) of BC (Figure 1) according to [27].

According to Eddington [10], the temperature scale set by spectral types was not certain. Consequently, one of the other purposes of Eddington was to improve

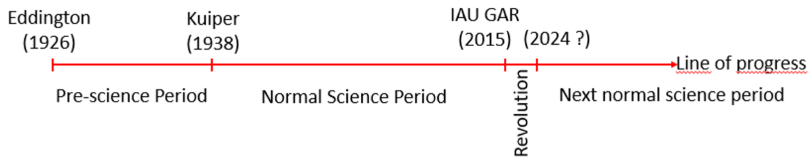

Fig. 1. Progress line of bolometric correction (BC) according to Kuhnian development of science.

the stellar temperature scale as well. He saw the potential of Table 1 for setting stellar temperatures. Since the radiation per unit area is proportional to T_e^4, he assumed the surface brightness (J) of a star is proportional to pT_e^4, where the parameter p is listed in the second column of Table 1. Thus, he expressed the surface brightness of stars in magnitudes as J=cons.-log $T_e+\Delta$m, where Δm is visual minus bolometric given in column 3. Nevertheless, Eddington was confused by assuming stars are like black bodies. For him, there were two effective temperatures. One comes from the Wien's law, Eddington named it $T_e^{'}$ (today $T_e^{'}$ is known as color temperature). The other is according to the Stefan-Boltzmann law, $L = 4\pi R^2\sigma T^4$, called T_e. Eddington Commented *"For the Sun $T_e^{'}$ is about 4 per cent higher than T_e (approximately 6000° against 5740) and the same ratio may be expected to hold for all stars"*. The dilemma of two effective temperatures has been solved by Kuiper [26] who defined effective temperature only through the Stefan-Boltzmann law.

Expressing it in solar units as

$$L = R^2(\frac{T_e}{T_{e,\odot}})^4 \tag{7}$$

Kuiper claimed, that since L is never known directly from observation, but usually only the absolute visual (or photovisual) magnitude, the above equation can be used in obtaining T_e only if a table of bolometric corrections is available. He means if R is available from the light curve solutions of eclipsing binaries, then the L of the stars with R, could be obtained from M_v as

$$M_{bol} = M_V + BC \tag{8}$$

$$M_{bol} - M_{bol,\odot} = 2.5log\frac{L}{L_\odot}. \tag{9}$$

With known, L, R and $T_{e,\odot}$, the effective temperature of the star could be calculated by equation (7). That is, according to [26], tables of BC should be produced mainly for calibrating stellar effective temperatures. Because BC appears to be a missing quantity or a correction term, equation (8) inspired Kuiper for the new name "bolometric correction" for the quantities M_{bol} - M_v = m_{bol} - V. The term "bolometric correction" was approved by others, thus the pre-science period, in which during many different hypotheses compete, ended for the line of progress (Figure 1), and the first normal science period started with the three paradigms: 1) BC of a star must always be negative, 2) Bolometric magnitude of a star ought to be brighter than its V magnitude, 3) The zero point of BC scale is arbitrary.

The origin of the first paradigm goes as far back as Eddington's comment: "At any other temperature P will be smaller and the star will be brighter bolometrically than visually". It is obvious in the definition of BC "M_{bol} - M_V = m_{bol} - V", BC becomes negative if $M_{bol} < M_v$ or $m_{bol} < V$, therefore, the origin of the second paradigm is the first paradigm.

Early BC producers were aware that BC values produced by different authors must agree with each other. Thus, they felt free to add a constant number, like 0.9 in equation (6), for consistency. This practice, however, later developed to be the third paradigm. Some may think that the integral form of BC, as in equation 3, requires an arbitrary constant because there are two integrals in the definition. This cannot be true because the definite integrals are written without constant. Only, indefinite integrals are written with a constant of integration.

2.4. Usages of BC in the normal science period before IAU GAR 2015

Although the concept of bolometric correction had been devised as an auxiliary parameter to be used primarily in the calibrations of stellar effective temperatures ([10], [26]), it was actively used in two more astrophysical applications: 1) for estimating masses and luminosities of single stars, 2) Double-checking or estimating parallaxes of double stars at least until the break caused by [2] occurred on the line of development of MLR [16] at the times when reliable observations of eclipsing binaries were limited, that is, before the quality and the quantity of the reliable solutions of detached double-lined eclipsing binaries (DDEB) giving accurate M and R within a few percent levels were used by [2]. Former was the only method in these years to obtain masses of singe stars at which Kepler's third law cannot be applicable. If a single star has a measured parallax or a distance (d), then its absolute visual magnitude M_v could be computed from an apparent magnitude by Pogson's relation

$$V - M_V = 5logd - 5 \tag{10}$$

assuming that the interstellar extinction does not exist or is corrected. Then, equation (8) was used to get M_{bol} from M_v and BC_V. For Eddington, M_{bol} was sufficient to get both the mass (M) and luminosity (L) of the star. However, the general application was to use equation (9) to get L and then use the main-sequence classical MLR to get M from L.

The second application was also very useful because it is possible to obtain absolute orbital parameters and the masses of both stars through Kepler's third law if the distance of the double star is known. During these years, parallax measurements were not very accurate, it was possible to double-check the parallax of a double star. The sequence of the steps was as follows: 1) use classical MLR to obtain L of the each star from their masses., 2) Use equation (9) or use Eddington's MLR to get M_{bol} of the stars. 3) Use equation (8) and the BC of stars to get their absolute visual magnitudes (M_v). 4) Use equation (10) to confirm computed distances with the measured or estimated parallax (π=1/d) of the double star. Thus, double stars (visual binaries) and detached double-lined eclipsing binaries (DDEB) provided the most accurate stellar masses as accurate as observational errors permit.

3. RESOLUTION: IAU 2015 GAR B2

Arbitrariness attributed to the zero-point of various BC scales was one of the primary issues discussed by earlier IAU commissions. Previously, two of its commissions agreed on the zero-point of the bolometric magnitude scale by adopting a value for $M_{bol,\odot}$ = 4.75 mag at the Kyoto meeting of 1997 ([3], pp. 141 and 181). On one occasion, the bolometric magnitude scale was set by defining a star with M_{bol} = 0.00 mag for an absolute radiative luminosity L=3.055x10^{28} W (see also [7]). At last the final resolution has been agreed in the IAU general assembly meeting in 2015 hereafter called IAU 2015 GAR B2.

The zero-point of the absolute bolometric magnitude scale was set according to

$$M_{bol} = -2.5logL + C_{bol} \tag{11}$$

with a statement "a radiation source with absolute bolometric magnitude M_{bol}= 0 has a radiative luminosity of exactly L_0=3.0128x10^{28} W and the absolute bolometric magnitude M_{bol} for a source of luminosity L (in W) is M_{bol} = -2.5 log (L/L_0) = -2.5 log L+71.197 425... That is, the zero-point constant for absolute bolometric magnitudes is C_{bol}=71.197 425... if L is in SI units, and C_{bol}=88.697 425... if L is in cgs units. Since nominal solar luminosity ($L_\odot$) is announced to be 3.828x10^{26} W in IAU 2015 GAR B2, using this value in equation (11), one can obtain $M_{bol,\odot}$ = 4.739 996 mag., which could be approximated as $M_{bol,\odot} \sim$ 4.74 mag., for the absolute bolometric magnitude for the Sun.

The zero-point constant of the apparent bolometric magnitudes cannot be independent of the $L_0 = 3.0128 \times 10^{28}$ W chosen for setting absolute bolometric magnitude $M_{bol} = 0$ for a star at the distance, d, which produces a heat flux of

$$f_0 = \frac{L_0}{4\pi d^2} \tag{12}$$

just above the Earth's atmosphere if interstellar extinction does not exist or is negligible. Therefore, IAU 2015 GAR B2 defined the zero point of the apparent bolometric magnitude scale by specifying that $m_{bol} = 0$ mag corresponds to an irradiance or heat flux density of f_0= 2.518 021 002 ... x 10^{-8} W m^{-2} and hence the apparent bolometric magnitude m_{bol} for an irradiance f (in W m^{-2}) is m_{bol} = -2.5 log (f/f_0) = -2.5 log f -18.997 351... In another saying, equation (11) is adopted for the apparent bolometric magnitudes as

$$m_{bol} = -2.5 log f + c_{bol} \tag{13}$$

which scales irradiance (energy received from a star in a unit area just above the atmosphere) of stars rather than luminosities of stars thus the zero-point constant is c_{bol}= -18.997 351... if f is in SI units. Because the standard distance is 10 parsecs, one can obtain the value of f_0 from L_0 by dividing it into the surface area of a sphere with a radius equal to the distance (d) of 10 pc. One must be careful using the same type of units both L_0 (W) and d (meter). Since nominal solar irradiance ($f_\odot$) is 1361 W m-2, using this value in equation (13), one can obtain $m_{bol,\odot}$ = -26.832 mag for the apparent bolometric magnitude for the Sun.

3.1. Resolution and the paradigms

3.1.1. Resolution and paradigm one

Equation (11) could be adopted for the absolute visual magnitudes similarly as

$$M_V = -2.5 log L_V + C_V \tag{14}$$

where C_V would be the zero-point constant for the absolute visual magnitudes and L_V could be called the part of the luminosity falling into the window of the visual filter. Equation (11) could also be generalized for any band (ξ) of any photometric system as M_ξ = -2.5 log $L_\xi + C_\xi$. Consequently, the classical definition of BC (equation 1) of Kuiper implies that

$$BC_V = M_{bol} - M_V = 2.5 log \frac{L_V}{L} + (C_{bol} - C_V) \tag{15}$$

where the rightmost end of the equation (15) is obtained simply by subtracting equation (14) from equation (11).

Similarly, if equation (13) is re-arranged for the apparent visual magnitudes such as

$$V = -2.5log f_V + c_V \tag{16}$$

where c_V is the zero-point constant for the apparent visual magnitudes and f_V is the part of the total flux (f) falling into the window of the visual filter. Equation (13) could also be generalized for any band (ξ) of any photometric system as $\xi =$ -2.5log $L_\xi + c_\xi$. Consequently, the classical definition of BC (equation 1) of Kuiper involving apparent magnitudes would imply that

$$BC_V = m_{bol} - V = 2.5log\frac{f_V}{f} + (c_{bol} - c_V) \tag{17}$$

where the part of the equation (17) after the second equal sign could be obtained similarly by subtracting equation (16) from equation (13).

Remembering that the integral form of BC_V (equation 3) is equivalent to equation (17) here, equations (3), (15) and (17) could be combined for expressing the BC of the visual filter as

$$\begin{aligned} BC_V &= 2.5log\frac{L_V}{L} + (C_{bol} - C_V) = 2.5log\frac{f_V}{f} + (c_{bol} - c_V) \\ &= 2.5log(\int_0^\infty S_\lambda(V) f_\lambda d\lambda / \int_0^\infty f_\lambda d\lambda) + C_2. \end{aligned} \tag{18}$$

This equation is more meaningful now after IAU 1015 GAR B2, where the value of C_{bol} and c_{bol} both were fixed up to the seventh digit in the magnitude scales. Using relative photometry, that is, comparing only similar kinds of magnitudes such as V_1-V_1= -2.5 log ([f_1 (V))/f_2 (V)], astronomers do not need to know the value C_V nor c_V because both cancel out automatically. Nevertheless,this does not change the fact both C_V and c_V are definite constants like C_{bol} and c_{bol}. Otherwise, astronomical photometry would not work.

Furthermore, because $f = \int_0^\infty f_\lambda d\lambda$ and $f_v = 2.5log(\int_0^\infty S_\lambda(V) f_\lambda d\lambda)$, equation (1) certifies that the constant C_2 was claimed arbitrary constant of integration since it is seen after the two integrals in equation (3). Apparently, It is not a constant of integration because a definite integral never takes a constant. Secondly, it is not an arbitrary number but a definite number, which is equal to $c_{bol} - c_V$, since both c_{bol} and c_V are constants with definite values. In another saying, C_2 is not an arbitrary constant, but a required constant as indicated by equation (18). Only if one subtracts the two magnitudes of the same kind, he/she does not net to know the value of the zero point constant because it cancels automatically, Otherwise, when subtracting two different kinds of magnitudes for a star, the zero-point constants do not cancel, thus treating this subtraction like subtracting the two visual magnitudes, or like two bolometric magnitudes, is a serious error. Because of this error of fallacy, that is, ignoring the zero-point constants of M_{bol} and M_v in the original definition of BC according to Kuiper, the paradigm 1 emerged.

Because the bolometric flux received from the star above the Earth's atmosphere f is proportional to the surface flux of the star σT^4, that is, $L = 4\pi R^2 \sigma T^4 = 4\pi d^2 f$, where f is the total flux at the d parsec away from the surface of the star, equation (18) implies also (C_{bol}-C_V) = (c_{bol}-c_V). Thus, from equation (18) we can conclude that C_2 = (C_{bol}-C_V) = (c_{bol}-c_V). Consequently we can also write:

$$BC_V - C_2 = 2.5log\frac{L_V}{L} = 2.5log\frac{f_V}{f} = 2.5log(\int_0^{\infty} S_\lambda(V) f_\lambda d\lambda / \int_0^{\infty} f_\lambda d\lambda). \quad (19)$$

which could be generalized for any band (ξ) of any photometric system as

$$BC_\xi - C_2(\xi) = 2.5log\frac{L_\xi}{L} = 2.5log\frac{f_\xi}{f} = 2.5log(\int_0^{\infty} S_\lambda(\xi) f_\lambda d\lambda / \int_0^{\infty} f_\lambda d\lambda). \quad (20)$$

Equation (19) clearly declares that it is not a bolometric correction in the visual band, but visual bolometric correction minus the zero-point of BC_V are always negative. On the other hand, equation (20) indicates that It is not the bolometric correction itself, but the bolometric correction minus the zero-point constant of the BC scale is always negative. This is because L_ξ/L, f_ξ/f and $(\int_0^{\infty} S_\lambda(\xi) f_\lambda d\lambda)/(\int_0^{\infty} f_\lambda d\lambda)$ are numbers between zero and one since $0 < L_\xi < L$ and $0 < f_\xi < f$. Logarithm of a number, which is between zero and one is always negative. Therefore, IAU 2015 GAR B2 literally cancels the paradigm 1: "BC of a star must always be negative" or one can say paradigm 1 must be corrected to indicate "BC of a star minus the zero-point constant of the BC scale is always negative"

Now, let us remember that the BC producers were divided into two schools; the school one assumed BC $<$ 0 (paradigm one) for all stars, but the school two ignored this paradigm, that is, for the second school, not all stars but some limited number of stars might have a positive BC. Let us also remember, according to the original definition of BC = M_{bol} - M_v by Kuiper, if the zero-point constants of M_{bol} and M_v are assumed to be zero or totally ignored, one can write:

$$BC_V = M_{bol} - M_V = 2.5log\frac{L_V}{L} \quad (21)$$

This equation could then be re-arranged for L as

$$L = L_V 10^{BC/2.5} \tag{22}$$

Therefore, according to school one, BC $>$ 0 is not possible, because if BC $>$ 0, equation (22) implies $L_V > L$, which is unphysical. Only if BC $<$ 0 would produce a valid L_V which is $L_V < L$. However, IAU 2015 GAR B2 indicate that equation (22) is not valid. The valid equation would be deduced from equation (20) as:

$$L = L_\xi 10^{(BC_\xi - C_2(\xi))/2.5} \tag{23}$$

Considering equation (11) and (14) for a star with $M_{bol} = 0$ and $M_v = 0$, one can also deduce that the zero point constants (both C_{bol} and C_V) are positive and $C_{bol} > C_V$. Knowing that $C_2 = (C_{bol} - C_V) = (c_{bol} - c_V)$, one can conclude that the constant C_2 is a positive number. This fact, however, implies that all of the BC_V values, which are less than C_2, are valid to produce a physical L_V according to equation (23). Ignoring zero-points as in equation (22) is not permitted because every magnitude scale must have a zero point, and energy distribution of A0 V star (Vega in practice) is not constant but changes according to wavelength (or frequences), thus any kind of magnitude scale has its own zero-point, which are artificially set the intrinsic colors such as U–B, B–V, V–R like Johnson colors are zero for Vega. Despite the fact that zero-points of intrinsic colors are zero for Vega, each of the photometric bands (difference of magnitudes) have their own zero points, which are not equal to each other. Otherwise, Vega would have a constant intensity at all wavelengths, which is not the case. The school one, who assume BC $<$ 0 always, are obviously in error. That is, it is possible for a star to have a BC which is positive according to equation (23). That means, equations (21) and (22) are not valid anymore after IAU 2015 GAR B2. In another saying, paradigm one is ruled out by IAU 2015 GAR B2.

3.2. Resolution and paradigm two

Influenced by the paradigm one, the followers of school one deduced the paradigm two from the first. An error occurred after previous error. That is, the followers of school one ignored the zero points constants of M_{bol} and M_v as in equation (21), thus, erroneous equation (22) was deduced, where only negative BC would produce a meaningful L, otherwise, if BC $>$ 0, L_V becomes greater than L, which is unphysical. Consequently, the phrase "Bolometric magnitude of a star ought to be brighter than its V magnitude" became paradigm two. This statement is a kind of statement that, even if there is only one star with a positive BC (which could be in any band of any photometric system), the statement "Bolometric magnitude of a star ought to be brighter than its V magnitude" would be abolished. Since paradigm one was shown to be abolished in the previous section, indicating that a BC value which is between zero and C_2 is possible according to equation (23), paradigms one and two were abolished together after IAU 2015 GAR B2.

3.2.1. Resolution and paradigm three

According to [15], IAU 2015 GAR B2 is a revolutionary document because it solves the problems related to the three paradigms, that is, it has a full potential to resolve the dilemma between the two schools [9,21,22,26,28,29,31,37] obeying and [5,6,9,12,17,18,23,24,35] disobeying the paradigms. First of all, it replaces equation (9) with equation (11) and establishes a direct relation between M_{bol} of a star and its L. This cancels out the complexities caused by choosing different $M_{bol,\odot}$ by different authors. This means the arbitrariness problem (paradigm three) attributed to both the BC and the bolometric magnitude scales were demolished. It is very clear that according to equations (11) and (13), the zero-point constants of both absolute and apparent bolometric magnitude scales are definite values. Infinite accuracy of the constants intended (see three dots) by convention (decided in the IAU general assembly), but an accuracy up to the seventh digit after decimal point in the magnitude scale was certified. Thus, transferring L values to M_{bol} or vice versa, and transferring irradiance measurements into m_{bol}, or vice versa could be done very accurately, that is, the error contributions of the zero-point constants are practically zero. The Classical definition of BC_V according to Kuiper could be generalized for any band of any photometric system as:

$$BC_\xi = M_{bol} - M_\xi = m_{bol} - \xi \tag{24}$$

Although the zero point constants of bolometric and filtered magnitudes do not appear in the above equation, according to IAU 2015 GAR B2 and principles of photometry neglecting or canceling the zero points of bolometric and filtered magnitude scales are definitely wrong. According to IAU 2015 GAR B2 and principles of photometry, bolometric correction of the filtered magnitude (BC_ξ) has a definite zero-point constant as:

$$C_2(\xi) = C_{bol} - C_\xi = c_{bol} - c_\xi \tag{25}$$

The above two equations tell us that specifying the bolometric corrections only to the visual band would be wrong. There must be many different kinds of bolometric correction scales as many as the total number of bands in various photometric systems. Consequently, equation (25) indicates that each bolometric correction scale has its own zero-point constant with a definite value specified to the band only. Considering the fact that there would be the unknown number of Bolometric correction scales, it would be meaningless for IAU to attempt fixing the unknown number of zero-point constants one by one. IAU 2015 GAR preferred the most logical way to fix the zero-point constant of the bolometric magnitude scale only. Fixing the zero-point of the bolometric magnitude scale ended up fixing the zero points of all bolometric corrections scales [13, 15].

4. NEW DEFINITIONS AND USAGES

With the same defining formula originally given for the visual magnitudes in equation (1) by Kuiper, which could also be generalized to any band of any photometric system, the verbal definition of BC must change. Equation (24) could be expressed as "BC of a star is the difference between its bolometric and one of its filtered magnitudes without ignoring both of the zero point-constants associated with the bolometric and the filtered quantities, unlike the other colors operating in relative scales such as U–B, B–V, V–R etc., which were set zero for a hypothetical A0V star artificially." One of the two main purposes of IAU 2015 GAR B2 was standardizing the bolometric magnitude scale accurately and repeatably for transforming photometric measurements into radiative luminosities and irradiances, independently of the variable Sun. Unfortunately, this revolutionary document was ignored or unnoticed [1, 6, 15] so its revolutionary potential was noticed about five years later by [12], who was trying to convince the referees that arbitrariness attributed to the zero-point of the BC scale is a paradigm demolished by IAU 2015 GAR B2 during the refereeing stage of newly determined bolometric corrections from DDEB stars in the solar neighbourhood. Unfortunately, [12] was forced to remove everything else other than newly determined BC_V values. Removed arguments were rearranged and improved later by [13], where the standard bolometric corrections were defined as the following: if a bolometric magnitude of a star is determined from its observed radius (R) and effective temperature (T_{eff}) to give L$= 4\pi R^2 \sigma T^4$, then if one plugs this L to equation (11) to get M_{bol} and at last calculates BC_ξ of any band by $BC_\xi = M_{bol} - M_\xi$, where M_ξ should be corrected for atmospheric and interstellar extinctions, then the obtained BC_ξ is a standard BC.

The luminosity of a star is not a directly observable parameter. While discussing the three methods and their accuracies providing L of a star from its observed quantities, [14] defined the standard luminosities later. If the L of a star is computed from its observed R and T_{eff}, it is standard by definition. Thus, this direct method relying on the Stefan-Boltzmann law was the only method to have standard luminosities, while other methods using the mass-luminosity law, and bolometric corrections providing stellar luminosities were not considered even reliable before IAU 2015 GAR B2. Thus, standard L was defined as: if the luminosity of a star is calculated from its M_{bol} using equation (11), where M_{bol} is from the relation $M_{bol} = M_{\xi} + BC_{\xi}$ using a standard BC, it is called a standard luminosity [14]. According to [14] a single band standard luminosity from a standard bolometric correction and absolute magnitude could have an accuracy about 10 per cent, that is, both methods, one using the Stefan-Boltzmann law and the other using a standard BC, are comparable. A method of improving standard stellar luminosities with multiband standard bolometric corrections was suggested recently by [4]. Multiband standard BC and BC – T_{eff} relations in the forms of fourth-degree polynomials were calibrated independently from the parameters of 209 DDEB binaries with main-sequence components. Standard L of 406 main-sequence stars with most accurate parameters were calculated by the two methods. The method one is the classical direct method with the Stafan-Boltzmann law. The method two used absolute magnitudes and standard bolometric corrections at Johnson B, V, and Gaia EDR3 G, G_{BP}, G_{RP}, filters. Curves of the standard BC – T_{eff} relations of [4] at five photometric bands are displayed in Figure 2.

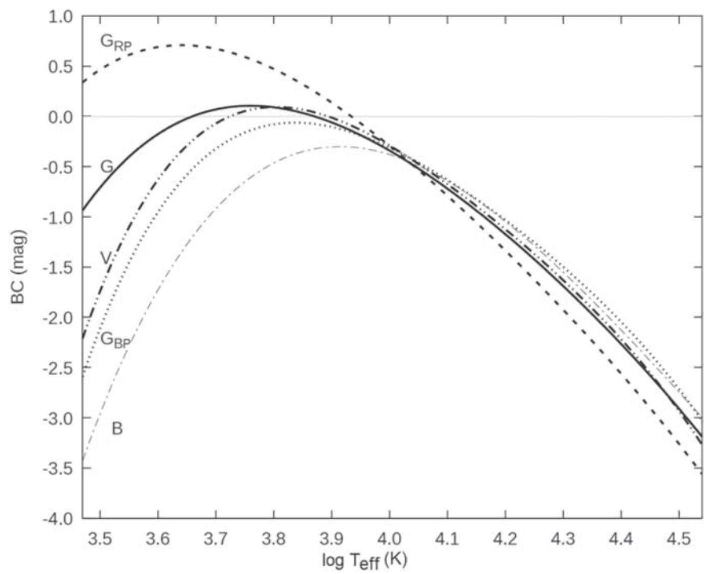

Fig. 2. Independent BC-T_{eff} relations at Gaia G, G_{BP}, G_{RP} and Johnson B,V [4]

A single-band standard BC – T_{eff} relation is expressed in the form of a fourth-degree polynomial as

$$BC = a + bX + cX^2 + dX^3 + eX^4 \tag{26}$$

Table 2. Coefficients of multiband BC-log T_{eff} relations taken from [4].

Coeff.	BC_B	BC_V	BC_G	$BC_{G_{BP}}$	$BC_{G_{RP}}$
a	1272.43	3767.98	1407.14	3421.55	1415.67
	±394.2	±288.8	±256.7	±293.6	±253.3
b	1075.85	3595.86	1305.08	3248.19	1342.38
	±394.4	±290.9	±258.9	±296.1	±255.4
c	337.831	1286.59	453.605	1156.82	475.827
	±147.7	±109.6	±97.67	±111.7	±96.34
d	46.8074	204.764	70.2338	183.372	74.9702
	±24.53	±18.32	±16.34	±18.68	±16.12
e	2.42862	12.2469	4.1047	10.9305	–4.44923
	±1.552	±1.146	±1.023	±1.169	±1.009
N	402	402	402	342	386
rms	0.136257	0.120071	0.11068	0.126577	0.109179
R^2	0.9616	0.9789	0.9793	0.9738	0.9884

where a, b, c, d, e are coefficients of a fourth-degree polynomial with a variable X = log T_{eff} . One needs to know the effective temperature of the star to calculate its multiband BC using empirically determined coefficients in Table 2. The number of stars used in the calibration (N), standard deviation (SD), and correlation coefficient (R^2) are also given in the table.

Knowing that, observations (apparent magnitudes), and BC - T_{eff} relations of each band are independent, at last, one obtains five independent L using independent multiband bolometric corrections. One can improve the accuracy of L by taking the average of the independently predicted L values. [4] preferred not to take the average of this L but to use independently predicted M_{bol} values of each band to calculate mean M_{bol} and its standard error first. Then, one could use equation (11) to calculate corresponding L and its uncertainty from the mean M_{bol} and its uncertainty. The mean M_{bol} was calculated by [4] as:

$$M_{bol} = \frac{1}{N}\Sigma_i^n M_{bol,i} \tag{27}$$

Where $M_{(bol,i)}=M_i+BC_i$, bolometric magnitude of the star at each band i = B, V, G, G_{BP}, and G_{RP}. n is the number of photometric bands having an available standard BC. It is clear in equation (27) that by increasing the number of bands (n), one can improve the accuracy of M_{bol} and consequently the accuracy of L could be improved.

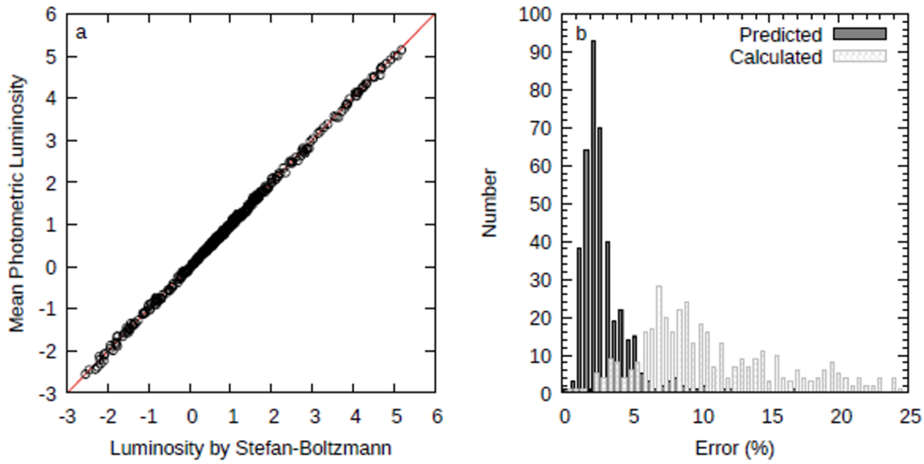

Fig. 3. a) Comparing predicted (from photometry) and calculated (from R and T_{eff}) L of the sample main-sequence stars. b) Histogram distributions of the errors associated with predicted (dark) L is compared to the histogram distributions of errors associated with calculated (gray) L. ([4])

Being limited to five photometric bands, [4] succeeded to obtain very accurate stellar luminosities, even more, accurate luminosities than the direct method could provide as displayed in Figure 3 where the left box shows a very high correlation (R^2= 0.9999) between the predicted luminosities involving multiband (B, V, G, G_{BP} and G_{RP}) standard bolometric corrections and calculated luminosities from the direct method using observed R and T_{eff} according to the Stefan-Boltzmann law. Because of IAU 2015 GAR B2 and standardization it caused, first time in the history of astrophysics, there is a new method providing standard stellar luminosities, which could be three or four times more accurate than the luminosities from the direct method with Stefan-Boltzmann law.

[11] tested multiband BC and BC $- T_{eff}$ relations by recovering luminosities of DDEB stars from which the standard multiband BC and BC - T_{eff} relations were calibrated. [11] added one more band, TESS, into the list and increased the number of bands having standard BC to six and then tested the six-band standard BC - T_{eff} relations by recovering the luminosities (L) and observed radii (R) of the most accurate 241 single host stars (281 Main-sequence, 40 subgiants, 19 giants and one-pre-main-sequence) successfully from their apparent magnitudes, Gaia DR3 parallaxes and standard BC at six-bans B, V, G, G_{BP}, G_{RP} and TESS. The main-sequence standard BC and BC-T_{eff} were found useful not only in recovering L and R of the main-sequence stars but also in other luminosity classes such as giants and subgiants.

5. CONCLUSIONS

- With the same defining formula first suggested by Kuiper, $BC_\xi = M_{bol} - M_\xi = m_{bol} - \xi$, the old verbal definition of BC, used in the first normal science period, must change to:

  BC of a star is the difference between its bolometric and one of its filtered (pass band) magnitudes without ignoring both of the zero-point constants associated with bolometric and filtered quantities in absolute scale, unlike the other colors operating in relative scale (U–B=B–V=V–R=...=0 of A0V star), which were set to be zero artificially for a hypothetical star A0V.

- The zero-point constants of BC scales are as many as the number of passbands. C_2 (ξ)=C_{bol}- C_ξ=c_{bol}- c_ξ, where ξ could be one of the passbands of various photometric systems and capital C imply absolute, while small c for apparent, magnitude scales.

- The Zero-point constant of a BC scale is not arbitrary. It is a definite number in magnitude scale unique to the passband.

- It is not the BC of a star but BC – C_2 is always negative, where C_2 is the zero-point constant of the BC scale in question.

- The Zero-point constant (C_2) of a BC scale could be a positive number (See Figure 2). This means all BC $<$ C_2 for a photometric band are valid, that is, bolometric magnitudes (M_{bol} or m_{bol}) of some stars could be dimmer than their filtered magnitudes (M_ξ, ξ). This, however, does not mean the part of the luminosity corresponding to M_ξ is greater than the total luminosity. This is because L_ξ=L x$10^{(BC_\xi - C_2(\xi))/2.5}$ is valid to produce $L_\xi <$ L for all photometric bands.

- The normal science period (Figure 1) was ended in 2015 in the year when IAU 2015 GAR 2 issued and the silent revolution [15] has been started because all of the problems associated with the three paradigms (1) BC of a star must always be negative, 2) Bolometric magnitude of a star ought to be brighter than its V magnitude, 3) The zero point of BC scale is arbitrary) were shown to be resolved.

- The new normal science period will start after the new definition of BC and the consequences itemized above are digested among contemporary astrophysicists.

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