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REVIEW ARTICLE

Fundamentals of Stars II: Revisiting Bolometric Corrections

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ABSTRACT

Luminous efficiency and heat index were two previously suggested auxiliary tools for calibrating stellar temperature scales before the term "bolometric correction" (*BC*) introduced for the same purpose by Kuiper in 1938, as $BC = M_{\rm bol} - M_{\rm V} = m_{\rm bol} - V$. Despite its ill-posed nature imposing no zero-point constant ($C_2 = 0$) for the *BC* scale and $L_{\rm V} = L \times 10^{BC/2.5}$, if $BC > 0$, $L_{\rm V}$ is unphysical, for the luminosity of a star from which "*BC* of a star must always be negative," "the bolometric magnitude of a star ought to be brighter than its *V*-magnitude," and "the zero point of bolometric corrections are arbitrary" (paradigms) were extracted. The most recent of the first three definitions of *BC* was accepted and used throughout the century. Therefore, the phase in the development of *BC* prior to Kuiper may be considered pre-science period in the Kuhnian philosopy of science. The rest is the normal science period in which astrophysicists work under the three paradigms. The rise of *BC* as a concept, how the ill-posed definition *BC* emerged/used, how inconsistencies (paradigms) of *BC* developed, and how the Resolution B2 of the General Assembly of the International Astronomical Union imposing $C_{\rm bol} = 71.197\,425\ldots$ mag, and $C_2 > 0$, for the zero-point constants of the $M_{\rm Bol}$ and *BC* scales resolve the long-lasting problems were discussed. Generalized new definition of *BC* implying $L_{\rm V} = L \times 10^{\frac{(BC - C_2)}{2.5}}$ were given to replace $L_{\rm V} = L \times 10^{BC/2.5}$.

Keywords: Stars: fundamental parameters, Stars: general; Solar and Stellar Astrophysics; Astrophysics - Instrumentation and Methods for Astrophysics

1. INTRODUCTION

The stellar magnitude scale is so well established today that with available technology, it is possible to measure as small as 0.3 mmag variation after *Gaia* with systematic errors less than one per cent, which means 0.028 per cent of brightness change of a star is detectable (Gaia Collaboration et al. 2021). The first star catalogue containing 850 naked eye stars with coordinates and a simple brightness classification, "of brilliant light", "of second degree", or "faint", which was introduced by Hipparchus of Nicaea (190-120 BC), represents the very first step in the advancement of astronomical photometry (Miles 2007). The original work of Hipparchus was lost (Zissell 1998). Thus, our knowledge about it comes mainly from Almagest of Claudius Ptolemy (100-170 AD), who increased the number of stars to 1028 in his list for an epoch of about 137 AD, almost three centuries later. Ptolemy was the one who classified naked eye stars into six brightness classes, which is still used today, where the brightest stars were the first class, while the dimmest ones were in the sixth (Miles 2007).

In these early times, magnitudes were not a continuous real-number scale as used today, but rather classes or bins in which observable stars were classified. Ptolemy's work and the magnitudes were revised later by Al-Sufi (903-986), who increased the number of stars to 1151, and had precessed Ptolemy's positions to the year 964 AD (Zissell 1998; Miles 2007). Al-Sufi's magnitudes were then revised by Ulugh Bey (1394-1449) into a system that indicates a rough position of a star within a magnitude class, e.g. 3, 4, 3-4, 4-3, 4-5 but still not a continuous scale. The brightness of 788 stars was listed in one-third magnitude steps in the Catalog of Tycho Brahe (1546-1601). This was because decimal points had not yet been invented (Zissell 1998).

The discovery of the optical telescope led Galileo Galilei (1564-1642) to discover stars dimmer than six magnitudes. Nonetheless, Galilei did not attempt to quantify their brightness. Edmond Halley (1656-1742) and John Flamsteed (1646-1719) were known to estimate stellar magnitudes using large sextants. Those early estimates, however, which could have errors up to 1.5 mag, cannot properly be considered attempts at visual photometry, but rather as an aid to the stellar identifications (Miles 2007). A strong need for a continuous magnitude scale was felt by William Herschel (1738-1822) for two reasons: First of all, Herschel started a project by a technique he called star-gauging to investigate Newton's (1643-1727) claim

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that stars distributed uniformly in an endless universe in order not to collapse because of universal gravity. Assuming all stars have the same absolute brightness, e.g. being like the Sun, and dimming occurs due to inverse square law, more distant stars must appear fainter and fainter proportional to their distances. So, Herschel thought it was possible to determine how the stars distributed on a line of sight by counting and comparing the number of one magnitude dimmer stars to the number of stars one magnitude brighter continuously in the field of a telescope. Working together with his sister Caroline, he made star-gauging towards 700 different directions in the sky and determined the disk-like shape of the Milky Way, imagined as the universe at that time. This is because the space density of stars was observed to be decreasing by going further out, and there were no stars after certain distances (Mihalas & Binney 1981). Thus, Herschel was interested in better brightness estimates than Halley and Flamsteed for his own sake. Secondly, and more importantly, Herschel sought to determine the brightness variations of certain known variable stars and to discover whether others existed (Miles 2007).

Soon after the invention of the visual photometer, the impulse initiated by Herschel gave its first fruit by Norman Robert Pogson, who formalized the magnitude system in 1856 by defining a first magnitude star as that is 100 times brighter than the sixth magnitude star (Zissell 1998; Cox 2000). Let us leave the details of how visual estimates were done, how visual photometers were constructed and worked, how catalogues such as the Henry Draper (HD) and Bonner Durchmusterung (BD) were initiated to Zissell (1998), Miles (2007) and the references therein. Here, in this article, we are mostly interested in investigating when, why and how the other kinds of magnitudes, e.g., bolometric, photographic, blue, and red magnitudes first appeared in the history of photometry. What were the practical purposes and difficulties in determining and using bolometric corrections? When did paradigms such as "the bolometric magnitude of a star ought to be brighter than its visual magnitude", "bolometric corrections must always be negative" and "the zero point of bolometric corrections are arbitrary" enter the literature? How has resolving these issues benefited contemporary astrophysics?

2. EMERGENCE OF PHOTOGRAPHIC AND BOLOMETRIC MAGNITUDES

Another milestone on the progress line of photometry is the usage of photographic plates. Despite the first photographs dating back to 1826, more than 30 years had to pass for early applications by wet collodion plates and at least another 30 years more to pass for the first successful applications by the dry plates that Revd Thomas Espin compiled 500 photographic magnitudes (Miles 2007). Despite complexities arising from various factors such as atmospheric seeing, edge effects, and plate-to-plate differences and so on, astronomical photometry was the forerunner of developments in astronomy during the late 19th and early 20th century because of its relative easiness with respect to visual photometry. In fact, it was easier and more reliable to measure the relative brightness of stars from their trailed images or by comparing the sizes of star images on an exposed plate. Jacobus Cornelius Kapteyn (1851-1922) and Henrietta Swan Leavitt (1868-1921) were two outstanding pioneers who used early photographic magnitudes. Kapteyn continued Herschel's star gauge with more reliable magnitudes from the catalogue of 454 000 stars in the Cape Photographic DM, where the image diameter was used as a function of magnitude, produced in the years 1885-1890 (Zissell 1998). Star-gauging studies were then successful with the first Galaxy model in which the Milky Way was an oblate star system approximately 8.5 kpc in width and 1.7 kpc in thickness, having the Sun at about the centre (Mihalas & Binney 1981). Henrietta Leavitt, on the other hand, became world-famous for discovering the period-luminosity relation of cepheid variables, which led to the establishment of a distance scale to nearby galaxies.

A new kind of magnitude other than visual was first noticed because of photographic plates, like those used by Kapteyn (Zissell 1998). This was because blue stars appeared brighter, while red stars appeared fainter on exposed plates in comparison to visual observations. The difference in the spectral sensitivity of photographic emulsions with respect to human eyes was a major issue. Filters had to be used until special emulsions imitating visual response were found. Blue-sensitive photographic magnitudes, derived from unfiltered exposures, coexisted with visual and photovisual magnitudes for many decades. What appeared as chaos turned out to be another step forward later in the line of development. The magnitude difference between a photographic magnitude $m_{\rm pg}$ and a visual $m_{\rm v}$ or photovisual $m_{\rm pv}$ is defined as the $(b-v)$ color index, which was an important parameter to construct early color-magnitude diagrams of nearby open clusters, e.g. Pleiades, and was useful for understanding stellar evolution; it is equivalent to the $B-V$ color index today. After the H-R diagrams constructed in 1911 by Hertzsprung (1911) and in 1913 by Russell (1914) independently for the first time, the year 1913 was just the correct time for the Pogson scale of intensity ratio to be formally adopted to photographic photometry. Consequently, the zero point of the colour index was defined so that a star with a spectral type A0 should have equal visual and photographic magnitudes (Miles 2007).

Although there were some careful observers of eclipsing binaries, such as Stebbins (1910), achieved probable errors of ±0.023 mag near the principal minimum, and even milli magnitude level (±0.006 mag) of probable errors near the secondary minimum and between the minima by selenium photometers, Miles (2007) estimated the systematic errors of the photographic system in the beginnings of the 20th century was about 0.2-0.3 mag and occasionally 0.5 mag, especially for the stars in the southern hemisphere, where transfer of magnitudes from NPS (North Polar Sequence) system was problematic. The problems were not only these but also those that some observers were choosing different stars for the zero-point of the magnitude scale in general. Eddington (1926) chose the brighter component of Capella as the basis for theoretical bolometric magnitudes, but uncertainties in the relative brightness of the components of Capella and its parallax made this star unacceptable as the zero point (Pettit & Nicholson 1928). At one point, the North Star Polaris—initially assumed to have

a magnitude of 2—was proposed as the reference star, but it was later found to be variable, fluctuating around 2.12 mag with four-day variations up to 0.17 mag, and was thus deemed unsuitable for the task (Zissell 1998). Today, α Lyr (Vega) is commonly accepted to be the primary calibrating star for observable magnitudes and colours.

While astronomers who lived in the late 19th and early 20th centuries were busy with photographic plates, which led them to invent a new kind of magnitude, symbolized $m_{\rm pg}$, in addition to the visual magnitudes ($m_{\rm v}$ or $m_{\rm pv}$), contemporary physicists working on radiometers, bolometers, and blackbody radiation were in the process of introducing bolometric magnitudes. After the inventions of the radiometer (Crookes 1874), the bolometer (Langley 1880), and numerous theoretical attempts associated with laboratory experiments on the radiation laws of Kirchhoff, Rayleigh-Jeans and Wien, the radiation of a black body at all frequencies as a function of absolute temperature was finally expressed by Planck (1900).

Although stars were recognized as radiating objects like blackbodies at different temperatures and sizes, discrepancies between observed stellar spectral energy distributions (SEDs) and the Planck radiation law were frequently emphasized (Eddington 1926; Kuiper 1938a). Kuiper (1938a) did not hesitate to say, "It is well known that the stars do not radiate as black bodies" while Eddington (1926) wrote: The radiation of a star is not distributed exactly in accordance with the law of black-body radiation. If $T_{\rm e}$ stands for the effective temperature corresponding to the quantity of the radiant energy according to the Plank Law, and if $T_{\rm e}'$ is the effective temperature obtained from the Wien Law; $\lambda_{\rm max} \cdot T_{\rm e}' = 0.288$ cm K, the general effect is that the quality of the radiation corresponds to a rather higher effective temperature than the quantity. "For the Sun, $T_{\rm e}'$ is about 4% higher than $T_{\rm e}$ (approximately 6000° against 5740°) and the same ratio may be expected to hold for all stars, at any rate as a first approximation". Furthermore, the following comment by Eddington (1926) is especially relevant for understanding the motivation behind the definition of bolometric magnitudes:

> 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 SED just as the reduction of light measurements does). This involves the luminous efficiency of the energy emitted by stars of different types.

Readers should pay extra attention to the two issues in the above comment. The first is that the bolometric magnitude of a star $m_{\rm bol}$ was described as a directly measurable quantity such as $m_{\rm pg}$ or $m_{\rm v}$. This view differs significantly from present-day convention, which treats $m_{\rm bol}$ as an unobservable quantity representing the total radiant energy from a star, called luminosity L. This is because no telescope or detector can operate across the entire electromagnetic spectrum, from zero to infinity in wavelength. The second is that the bolometric magnitudes come from heat measurements while $m_{\rm pg}$ or $m_{\rm v}$ comes from light measurements as though heat and light were distinct entities. The key term here is "luminous efficiency," which appears to be the initial concept that led to the later formulation by Kuiper (1938a), who named it "bolometric correction" to indicate the brightness difference of a star between its bolometric and visual magnitudes.

Nevertheless, a new type of magnitude-distinct from photographic and visual-entered the astronomical literature before the concept of "bolometric correction" was introduced at the beginning of the 20th Century. There were only three kinds of magnitudes (bolometric, b and v) until Johnson & Morgan (1953) who introduced the first standard three-colour photometry, where UBV in which ultraviolet magnitude U could be considered newest and 4th kind of magnitude because the blue (B) and visual (V) bands corresponded to the earlier b and v magnitudes.

3. ESTABLISHMENT OF THE CONCEPT OF BOLOMETRIC CORRECTION

3.1. The Earliest Concept: Luminous Efficiency

Before attempting to understand why Eddington (1926) advocated for bolometric magnitude as a measurable, rather than hypothetical, representation of a star's total luminosity, the following facts must be considered: 1) F. W. Anton made precise measurements of the masses of many different atoms, including hydrogen and helium, by the year 1920. Anton's results inspired Eddington to discover a fusion of hydrogen in the cores of stars (Bahcall 2000), but neutrons were not yet discovered by Chadwick (1933). Therefore, CNO cycle reactions were not yet written by Hans Bethe and Von Weizsacher (Clayton 1968), and the time was too early for Bethe (1939) to establish p-p reactions. The stellar structure and evolution theory with nuclear reactions had not yet existed for Eddington. 2) Although atmospheric extinction was recognized and corrections for Earth's atmosphere were applied, interstellar extinction was largely unaddressed prior to Trumpler (1930). 3) the famous main-sequence mass-luminosity relation (MLR) had only recently dicovered in its primitive form called mass-visual absolute brightness relation by Hertzsprung (1923) and Russell et al. (1923) independently, and Eddington (1926) upgraded it as one of the fundamental laws of nature, like Planck's law or Stefan-Boltzmann law (Eker et al. 2024).

The joint discovery inspired Eddington for a more fundamental relation between the mass of a star and its luminosity because among the observable magnitudes of the time ($m_{\rm bol}$, $m_{\rm pg}$ and $m_{\rm pv}$) $m_{\rm bol}$ appeared to be the most suitable one to be associated with the luminosity of a star. This was also because heat measurements were believed to be directly proportional to a star's luminosity, despite requiring correction for the atmospheric extinction in a similar manner $m_{\rm pg}$ and $m_{\rm pv}$ were done. Eddington first established tabulated numbers for a mass–absolute bolometric magnitude (Table 1) relation assuming stars are hot gases

Table 1. Data for the theoretical mass M and absolute bolometric magnitude m relation of Eddington (1926) ($\mu = 2.11$, $T_e = 5200°$).

$1-\beta$	M	m	$1-\beta$	M	m	$1-\beta$	M	m
0.0010	0.1284	14.143	0.04	0.879	5.211	0.26	3.774	-0.052
0.0015	0.1574	13.173	0.05	1.004	4.645	0.28	4.137	-0.312
0.0020	0.1820	12.484	0.06	1.123	4.178	0.30	4.529	-0.562
0.0025	0.2036	11.950	0.07	1.240	3.777	0.35	5.675	-1.156
0.0030	0.2233	11.513	0.08	1.354	3.426	0.40	7.117	-1.718
0.0040	0.2583	10.823	0.09	1.468	3.111	0.45	8.984	-2.264
0.0050	0.2895	10.286	0.10	1.582	2.825	0.50	11.46	-2.805
0.0060	0.3176	9.848	0.12	1.812	2.322	0.55	14.84	-3.354
0.0080	0.3683	9.154	0.14	2.050	1.884	0.60	19.62	-3.919
0.0100	0.4135	8.615	0.16	2.297	1.494	0.65	26.66	-4.516
0.0150	0.5117	7.632	0.18	2.557	1.138	0.70	37.67	-5.162
0.0200	0.5968	6.929	0.20	2.831	0.812	0.75	56.15	-5.882
0.0250	0.6739	6.381	0.22	3.124	0.507	0.80	90.63	-6.714
0.0300	0.7460	5.929	0.24	3.437	0.220	—	—	—

Add to m temperature term, $-2\log_{10} = (T_e/5200)$.

of spheres using,

$$\Delta m = -\frac{7}{2}\Delta \log M - \frac{15}{4}\Delta \log(1-\beta) - 2\Delta \log T_e, \qquad (1)$$

where M stands for mass, $(1-\beta)$ is the ratio of the radiation pressure to the whole pressure, T_e is the effective temperature corresponding to the quantity of the radiant energy according to the Planck's Law, and m is the bolometric magnitude. The mass–absolute bolometric magnitude ($M-M_{bol}$) relation would have been valuable for determining the masses of single stars, as no other method was available at that time.

Column m of Table 1 was computed by omitting the term with T_e in Equation (1). The zero-point of bolometric absolute magnitudes was adjusted using the observed mass and absolute bolometric magnitude of Capella, which was known to have $T_e = 5200°$ and chemical composition parameter $\mu = 2.11$. If a star has an effective temperature different from Capella's ($5200°$), the term $\Delta m = -2\Delta \log T_e$ must be added to the m value, as indicated in the table's footnote. Eddington (1926) claimed, "With the range of effective temperature commonly occurring in stars, this correction is comparatively small, and the bolometric magnitude of a star is mainly a function of its mass." Eddington (1926) was not content with presenting only a theoretical formula and data table; he also sought to validate his claim using contemporary observational data, as illustrated in Figure 1.

Soon after, Eddington noticed that some stars have absolute bolometric magnitudes different than their absolute visual magnitudes, which could be interpreted as a deficit in the visual brightness of a star on the magnitude scale. Why both hotter and cooler stars appear dimmer in the visual was a contemporary problem that could not be resolved using Planck's law alone. Eddington addressed this issue by suggesting a new concept, "*luminous efficiency*" of the energy emitted by stars of different types. If a star radiates as a blackbody of temperature T_e, the amount of radiation is $I'(\lambda, T_e)d\lambda$ within the wavelength range

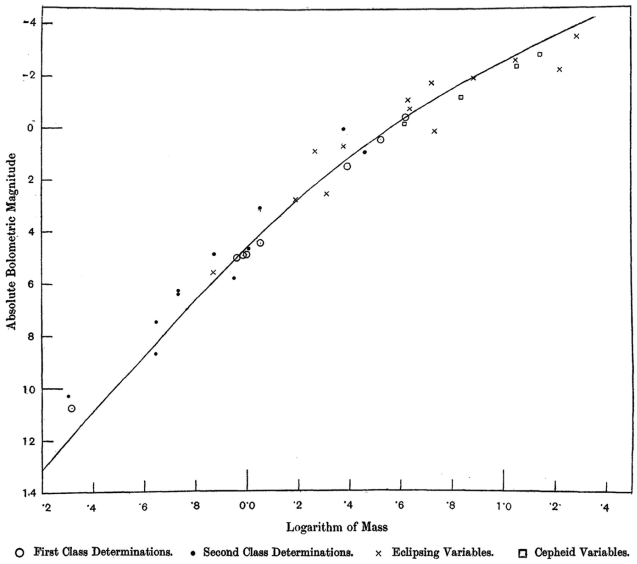


Figure 1. Mass-Absolute Bolometric Magnitude curve of Eddington (1926) according to the Equation (1) and stellar masses (data) available at that time. "O" are the masses of ordinary binaries of first-class determinations and Sun, filled circles are masses from ordinary binaries of second-class determinations, "X" are eclipsing variables, and "□" cepheid variables

from λ to $\lambda + d\lambda$. Let $P(\lambda)$ be the factor that, if multiplied by the amount of radiation at wavelength λ, one can get its luminous intensity. One can assume $P(\lambda)$ is like the transparency of a filter so that it is zero for the wavelengths human eyes cannot see; otherwise, it has a positive value. The average of $P(\lambda)$ for the whole radiation is then given by:

$$P = \frac{\int P(\lambda) I'(\lambda, T_e) d\lambda}{\int I'(\lambda, T_e) d\lambda}. \quad (2)$$

According to Eddington, the maximum value of P occurs at $T_e = 6500^o$, meaning that stars of spectral types F and G have the highest luminous efficiency—presumably because human vision evolved in response to sunlight. Eddington took the maximum of P as a standard and set the bolometric magnitude at this effective temperature to agree with the visual magnitude.

At any other temperature, P will be smaller, and the star will be brighter bolometrically than visually. The following table (Table 2) is given by Eddington (1926) to display effective temperatures and corresponding P values, which were converted to the light deficit Δm as $m_v - m_{Bol}$ in the last column using the formula:

$$\Delta m = -\frac{5}{2} \log P. \quad (3)$$

Eddington came remarkably close to defining the bolometric correction of a star by introducing the third column of Table 2, which shows the difference between a star's visual and bolometric magnitudes—termed the light deficit, Δm. Eddington added this column for those who cannot access bolometric measurements of a star, but only it's visual. Suppose a star has a visual brightness and a parallax. The mass could still be obtained from Figure 1 or Table 1 after its absolute visual magnitude converted to absolute bolometric magnitude through Table 2. The luminous efficiency (column 2) and the light deficit (column 3) in Table 2 also had the potential to serve as indicators of the stellar absolute temperature scale. Eddington did not notice it because his primary concern was to establish his famous mass-luminosity law.

Table 2. Effective temperature, and corresponding luminous efficiency and reduction of bolometric to visual magnitude (credit to Eddington 1926).

T_e	P	Δm (Vis - Bol)
2 540	0.092	2.59
3 000	0.206	1.71
3 600	0.417	0.95
4 500	0.723	0.35
6 000	1.000	0.00
7 500	0.985	0.02
9 000	0.893	0.12
10 000	0.749	0.31
12 000	0.616	0.53

3.2. The intermediate concept: Heat index

Unfortunately, the concept of luminous efficiency did not continue after Eddington (1926). Instead, the concept of "Heat-index" was defined by Pettit & Nicholson (1928) in a paper where radiometric and water cell absorption observations of 124 stars during the period 1922 to 1927 were discussed. First, radiometric magnitude is defined as equal to the apparent magnitude of an A0 star, which will give the observed galvanometer deflection. They defined the "Heat-index" as the difference between the visual and radiometric magnitudes, i.e., $(m_v - m_r)$.The bolometric magnitude scale was aligned with radiometric magnitudes at spectral type G0, differing from Eddington's scale by approximately 0.1 mag. The phrase "A0 stars were chosen for the determination of the zero point since photographic and visual magnitudes are equal for this spectral class; and, since the heat-index is visual minus radiometric magnitude, the heat-index, like the colour index, is also zero for these stars." from Pettit & Nicholson (1928) indicated that like the observed colour index of stars, their heat index could be used as stellar temperature indicators.

Pettit & Nicholson (1928) gave a table of 124 stars giving their spectral types, absolute visual magnitudes (M_v), Harvard apparent visual (m_v) and radiometric (m_r) magnitudes, heat-index, water cell absorption, correction to no atmosphere (Δm_r) including losses in the telescope, total radiation in units of cal cm^{-2} min^{-1} incident outside the atmosphere, absolute bolometric magnitude (M_B), absolute temperature (T) from the heat-index and water cell absorption. This paper suggests that total radiation estimates based on corrected radiometric magnitudes, bolometric magnitudes, and water-cell absorption were primarily intended for constructing the stellar absolute temperature scale. The absolute bolometric magnitude M_B of a star was calculated by the formula,

$$M_B = m_r - \Delta m_r + 5 \log \varpi + 5.9 = M_V - H.I. - \Delta m_r + 0.9, \quad (4)$$

so that the apparent bolometric magnitude of a star comes from its radiometric magnitude with atmospheric corrections, $m_b = m_r - \Delta m_r + 0.9$ if its parallax (ϖ) was known, thus, M_V is the absolute visual magnitude and H.I. is the heat-index. The constant 0.9 was used to fix the zero point of the bolometric magnitude scale to correspond with giant stars of spectral classes F5 to G5. The term "bolometric correction" (BC) was not also used by Pettit & Nicholson (1928), who gave the radiometric magnitude of the Sun -27.18 mag, which indicates the heat-index of the Sun is 0.46 mag, if Russell's value of the Sun's visual magnitude, -26.72 was used.

To convert the visual absolute magnitude (M_v) into bolometric values, Strömberg (1932) used the same formula: $M_b = M_v - H.I. - \Delta m_r + 0.9$ similarly. But, he introduced a new term $(M_b - M_v)$ besides the heat-index and presented a table giving spectral types from B1 to dM2 including the Sun in the first column. The second column listed the corresponding temperatures, while the remaining columns provided corrections for atmospheric extinction, the heat index, and the value of $(M_b - M_v)$. Contemporary astrophysicists would immediately recognize the term $(M_b - M_v)$ as bolometric correction. However, Strömberg (1932), like astrophysicists before him, did not prefer to use the term "bolometric correction" but instead referred to it as "the resulting corrections, $M_b - M_v$" when

describing his table. He also gave the formula:

$$\log E = \log E_s - 0.4\,(M_b - M_s), \tag{5}$$

where $M_s = 4.84$ is the bolometric absolute magnitude of the Sun, M_b is that of the star, and E_s is the total power output of the Sun, $E_s = 3.79 \times 10^{33}$ ergs s^{-1}.

The Final Concept: Bolometric Correction

The term "bolometric correction" was first used by Kuiper (1938a), who claimed that there must be a single effective temperature defined by the Stefan-Boltzmann law as:

$$L = 4\pi R^2 \cdot \sigma T_e^4, \tag{6}$$

in which L is the luminosity, R is the radius, and σ is the radiation constant. Thus, σT_e^4 is the total surface flux (at all wavelengths) of a black body with a unique effective temperature T_e for a star. Apparently, Kuiper (1938a) began his discussions by correcting Eddington (1926), who had claimed two effective temperatures: T_e from the quantity of the radiant energy according to the Planck law as the first and T_e' from Wien's law as the second. Kuiper's suggestion was commonly accepted, and even today. Equation (6) was started to be used as the standard definition of the effective temperature, and since then, the temperature T_e' from Wien's law is recognized as the colour temperature. The primary concern of Kuiper, therefore, appears to be the determination of effective temperatures of stars. As the common purpose of astronomers of that time, he said: "If L and R are known, T_e may be derived from Equation (6). But since L is never known directly from observation, and usually only the absolute visual (or photovisual) magnitude is available, Equation (6) can be used in practice only if a table of bolometric corrections is available." Consequently, Kuiper defined the bolometric correction of a star as:

$$\text{B.C.} = M_{bol} - M_{pv} = m_{bol} - m_{pv}, \tag{7}$$

if

$$M_{bol} = M_{bol,\odot} - 2.5 \log L. \tag{8}$$

The Equation (8) is valid only if L is in solar units. That is, the equation could also be written as: $M_{bol} = M_{bol,\odot} - 2.5 \log \left(\frac{L}{L_\odot}\right)$, where L and $L_\odot$ could be in any units. This formula is not different from Equation (5) above (Strömberg 1932), where L was denoted by E.

Here, Kuiper (1938a) was saying bolometric corrections of stars are independent of their distances, thus, $M_{bol} - M_{pv} = m_{bol} - m_{pv}$. If a BC is available for a star, its M_{bol} can be deduced by adding the BC to its M_{pv}. Once M_{bol} is ready (possible only if the parallax of the star were measured even if it was from radiometric observations), then the L of the star in solar units could be computed by Equation (8). If the R of the star is also known, which could be from interferometric observations or deduced from eclipsing light curves, Equation (6) could be used for deducing the effective temperatures of the stars. Thus, "A satisfactory table of bolometric corrections can be constructed without recourse to the assumption of black-body radiation (even without any need of radiometric measurements), and that also the scale of stellar effective temperatures can be brought into a fairly satisfactory state" said by Kuiper (1938a) to confirm his first sentence in the article "The purpose of this article is the selection or derivation of the most probable set of effective temperatures and bolometric corrections that can now be obtained. These data are required in the discussion of mass-luminosity relation given in the following paper, " which refers to Kuiper (1938b).

By revising and examining all radiometric, photographic, and visual observations of stars and the Sun, including those of Pettit & Nicholson (1928), he ended up a conclusion with: $m_{bol,\odot} = -26.95$, $M_{bol,\odot} = 4.62$, $m_{pv,\odot} = -26.84$, $M_{pv,\odot} = 4.73$, mags, indicating $BC_\odot = -0.11$ mag. Those basic data were then used by him to establish his table of effective temperatures and bolometric corrections for stars with effective temperatures ranging from 3000 to 50 000 K, as given in Table 3. To avoid bolometric corrections with different signs, 0.10 mag was subtracted from all values. Thus, all BC values in Kuiper (1938a) are negative in Table 3. The apparent photovisual magnitude of the Sun was later revised by Stebbins & Kron (1957), who introduced six-colour photometry (U, B, V, G, R, I) and determined: $m_{pv,\odot} = -27.73 \pm 0.03$ mag by comparing solar light to stars and a standard lamp.

A similar table (Table 4) indicating the primary purpose of calculating bolometric corrections is to set up a temperature scale for the spectral types of stars, where three different bolometric corrections were compared, is also prepared by Lohmann (1948). Notice again that all BC values are negative.

Table 3. Stellar effective temperatures and bolometric corrections by Kuiper (1938a).

Theoretical Values of Bolometric Corrections
(Temperatures in 1000°)

T_e	BC	T_e	BC
3.0	-3^m.2	13	-1^m.18
3.5	-2.10	14	-1.35
4.0	-1.30	15	-1.51
4.5	-0.63	16	-1.66
5.0	-0.34	17	-1.80
5.5	-0.17	18	-1.94
6.0	-0.06	19	-2.06
6.5	-0.00	20	-2.18
7.0	-0.01	22	-2.40
7.5	-0.12	25	-2.69
8.0	-0.22	30	-3.12
9.0	-0.40	35	-3.50
10	-0.57	40	-3.80
11	-0.78	45	-4.10
12	-0.98	50	-4.30

3.3. The First Critic; Similarities, and Dissimilarities of the Three Suggestions

From a mathematical standpoint, all three suggestions are equivalent, as they each represent the difference between a star's visual and bolometric magnitudes—one of the few commonalities among the concepts defined by Eddington (1926),

Table 4. Spectral types, effective temperatures, and bolometric corrections (credit to Lohmann 1948).

Die bolometrische Korrektion

Spektrum	Farbtemperatur	M_{vis}	bolometrische Korrektion		
			LOHMANN	KUIPER	EDDINGTON-PIKE
B0	33 000°		-3.06	-2.70	-2.9
B5	24 000		-2.00	-1.58	-2.0
A0	16 000		-0.98	-0.72	-1.2
A5	11 000		-0.37	-0.31	-0.4
F0	8 400	+1.7	-0.04	-0.00	0.0
F5	6 900	+1.0	0.00	-0.04	0.0
G0	6 100	-0.2	0.00	-0.25	0.0
G5	5 500	+0.3	-0.10	-0.39	0.0
K0	4 800	0.0	-0.28	-0.54	-0.2
K5	4 100	0.0	-0.78	-1.35	-0.6
M0	3 600	-0.3	-1.25	-1.55	-0.9
M5	3 100	-0.5	-1.90	-3.40	-1.6

Pettit & Nicholson (1928), and Strömberg (1932). The same entity was called "luminous efficiency" for the first, "heat-index" for the second to indicate visual-bolometric, while "bolometric correction" for the third to imply bolometric-visual, which may appear different, but in an absolute sense it is the same. However, the literal names given to the same entity recall different concepts physically.

Luminous efficiency appears to be an explanation for why human eyes (or one of the filters in a photometric system in today's terms) see stars cooler or hotter than the Sun dimmer in the visual than the bolometric despite having the same luminosity. The heat index, on the other hand, emphasises bolometric magnitudes coming from the heat measurements of the stars, which could be measured by a galvanometer, bolometer, or radiometer. In another saying, the term "heat index" reminds a reader that bolometric magnitudes are observable quantities.

Contrarily, the term "bolometric correction" implies that the bolometric magnitude of a star is an abstract quantity, unobservable like the luminosity of a star [remember Kuiper (1938a)'s comment:"... since L is never known directly from observation, but usually only the absolute visual (or photovisual) magnitude... " above]. The human eye can detect visual photons; thus, visual magnitudes are measurable. Photographic plates can detect additional photons beyond the range visible to the eye; therefore, photographic magnitudes are also measurable. Because no telescope or detector can detect photons across all frequencies representing the total radiation of a star, its bolometric magnitude is also unobservable—like its luminosity (L). Does this mean Kuiper (1938a)'s definition of BC rejects using radiometric measurements for determining BC of a star? The answer is no. "... we denote with Δm, bolometric corrections computed on the assumption of black-body radiation" and ". . . It is well known that the stars do nor radiate as black bodies. Therefore, the values Δm can not be used; they need a correction, which we denote by δm. This correction can be evaluated only if the whole spectral energy curve is known. Two approximations are available to this ideal case: (I) theoretical spectral energy curves, computed based on a certain assumed composition of stellar atmospheres, and (II) radiometric observations of low-temperature stars (for high temperatures, too much energy is radiated in the inaccessible ultraviolet" are two critical comments from Kuiper (1938a) for us to understand the details how and why he defined and produced bolometric corrections.

According to Pettit & Nicholson (1928), $BC = m_b - V = (m_r - \Delta m_r + K) - V$ where m_b and V are apparent bolometric and visual magnitudes, m_r and Δm_r are apparent radiometric magnitude and its correction to no atmosphere, including losses in the telescope as explained and cited by Eggen (1956), who adopted a value of 0.62 for the constant K, which establishes the zero-point of the BC in the magnitude scale.

Nevertheless, the word "correction" implies a missing part or a deficit. Since $BC = M_{bol} - M_V = m_{bol} - V$, then, $M_{bol} = M_V + BC$ and/or $m_{bol} = V + BC$, indicates visual magnitudes have a deficit, and if this deficit is added to V, the total brightness (a brightness without any deficit), M_{bol} and/or m_{bol} of the star representing photons of at all wavelengths from zero to infinity could be obtained. If this is the case, one might ask: if visual magnitudes have deficits, why not photographic magnitudes? According to this argument, the bolometric magnitude of a star could also be obtained from its photographic magnitude as $M_{bol} = M_P + BC_p$ or $m_{bol} = m_p + BC_p$ if the deficit of the photographic magnitudes (BC_p) were known. We did not see Kuiper (1938a) to define BC_p. He only defined BC for the visual.

A possible reason was that the photographic magnitudes were assumed monochromatic because they were measured from the sizes of star images on the black and white photographs of that time. Indeed Kuiper (1938a) commented, "It is seen that these corrections to photovisual magnitudes are very similar to those for visual magnitudes, although photovisual magnitudes are more nearly monochromatic". Photovisual magnitudes being similar to visual magnitudes must mean the opposite, that is, photovisual magnitudes cannot be considered monochromatic despite coming from black-and-white images, which is

also true for photographic magnitudes. Defining BC only for visual, and the above comment of Kuiper (1938a), imply that a photographic magnitude was considered monochromatic, and thus, it was meaningless for him to discuss a deficit for it.

Naming the same mathematical quantity (the difference between visual and bolometric mags) with dissimilar concepts has special implications for the zero-point problem of bolometric corrections and for the other problems that had become misleading paradigms by then.

3.4. Further Developments

A new formulation on the line of development for computing BC from a model atmosphere is given by McDonald & Underhill (1952) as

$$B.C. = 2.5 \log \frac{\int P_\lambda F_\lambda d_\lambda}{\int P_\lambda F_\lambda(\odot) d_\lambda} - 10 \log \frac{T_e}{T_e(\odot)} - 0.11, \quad (9)$$

where the bolometric correction of a star is to a scale giving $BC = -0.11$ for the Sun in which P_λ is the normalised visual sensitivity function and F_λ is the surface monochromatic flux. It appears new and different, but it is not. It is the combination of Equations (2) and (3); that is, it is the logarithmic form of P, the luminous efficiency, as it was called before. The only difference here is that it was expressed relative to the Sun's luminous efficiency, and the quantity $\int I'(\lambda, T_e) d\lambda$ (the total radiation output of the star) is replaced by σT_e^4 (bolometric flux on the surface of the star). The symbol σ cancels out in the division if P is written for the star and the Sun. Two things appear not right here: 1) the quantity $\int I'(\lambda, T_e) d\lambda$ should have been replaced by $L = 4\pi R^2 \cdot \sigma T_e^4$ not only σT_e^4 because there could be size difference between the star and the Sun. 2) BC should not be a relative quantity because it is impractical to use it for a star as a relative quantity.

The next most comprehensive study of bolometric corrections after Kuiper (1938a) is Popper (1959) which changed the tradition of giving BC against T_{eff}. Popper preferred to display BC against $B - V$ rather than T_{eff}. Figure 2 displays BC from radiometric and photoelectric magnitudes from Popper (1959).

"The zero point of the bolometric corrections is chosen so that Kuiper's values for main-sequence stars of spectral types G0-G8 are produced." "With the choice of zero point, the bolometric corrections of for individual stars are given by $BC = m_r - \Delta m_r - V + 0.58$, where m_r and Δm_r are as defined by Pettit & Nicholson (1928). The Δm_r cannot be evaluated for stars hotter than about type F0 because of the unknown ultraviolet fluxes", "Bolometric correction for a star of the same colour as the Sun, $B - V = 0.63$, is -0.07 mag" and "For the hotter stars, where BC have not yet been observed because of absorption in the earth's atmosphere, one must compute BC from stellar atmospheric modes" are some of the critical quotes from Popper (1959). Various BC scales which all without any positive BC are compared on $BC - (B - V)_0$ plane, including the ones from Popper are displayed by Wildey (1963) in Figure 3.

With the infrared photometric program, whose first report was published by Johnson (1962), the observing window of astronomers increased from 0.35 microns in the ultraviolet to 10 microns in the infrared. Subsequently, astronomers began using filters representing 10 different wavelength bands, which was defined by Johnson himself as $UBVRIJKLMN$. Computed BCs are given in separate tables containing spectral types as the first column and followed by $U - B$, $B - V$, $V - R$, $V - I$, $V - J$, $V - K$, $V - L$, $V - M$, and $V - N$ intrinsic colours, BC values and effective temperatures. The early results from the bright stars are given by Johnson (1964). Then, finalized results with additional observations at infrared are published by Johnson (1966).

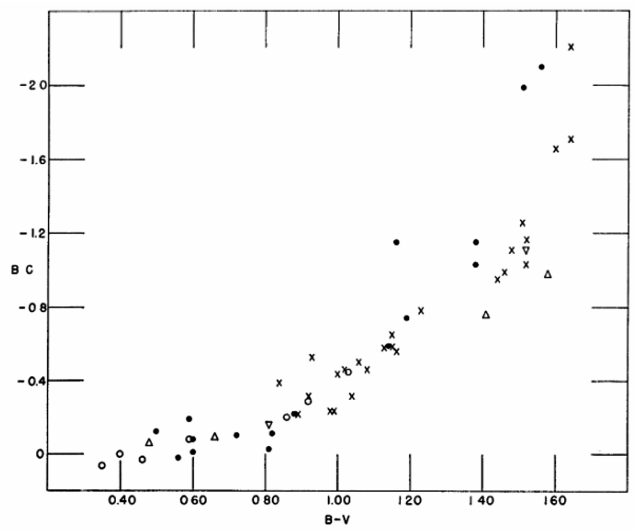


Figure 2. BC from radiometric and photoelectric magnitudes. Dots: luminosity class V; circles: IV; crosses: III; ∇: II; δ: I (credit to Popper 1959).

According to Johnson (1964, 1966), the bolometric correction is defined as $m_b - V$, where m_b and V are apparent bolometric and visual magnitudes of a star, and it is the correction to be applied to V to obtain the apparent bolometric magnitude. The apparent bolometric magnitude is basically integrated absolute intensity expressed in mag units. The zero points were set to make $BC_\odot = 0.0$ for the Sun. Bolometric corrections for A-type stars were found to be smaller (more positive) than those obtained before (Kuiper 1938a; Popper 1959) for such stars. These new values of BC are from rocket observations at 1314Å and 1427Å by Chubb & Byram (1963). For the stars cooler than the Sun, the values of BC were computed and are listed in the next-to-last columns of the three tables containing giants, main sequence, and supergiants, respectively. Only the table with main-sequence stars is shown here (Table 5). From the presented papers and the comment "... all of the bolometric corrections listed in the tables of this chapter are based upon actual observational data" it is not possible for one to understand whether or not Johnson used radiometric measurements or just only photometric data. Nevertheless, Johnson (1964, 1966) broke the old tradition and published tables containing both positive and negative BC values (see Table 5 here).

Publications discussing BC and effective temperature scales continued (Lee 1970; Heintze 1973; Code et al. 1976; Flower 1977; Hayes 1978; Habets & Heintze 1981; Malagnini et al. 1985; Fitzpatrick & Garmany 1990; Napiwotzki et al. 1993) with an increasing rate approximately up to the time of Flower

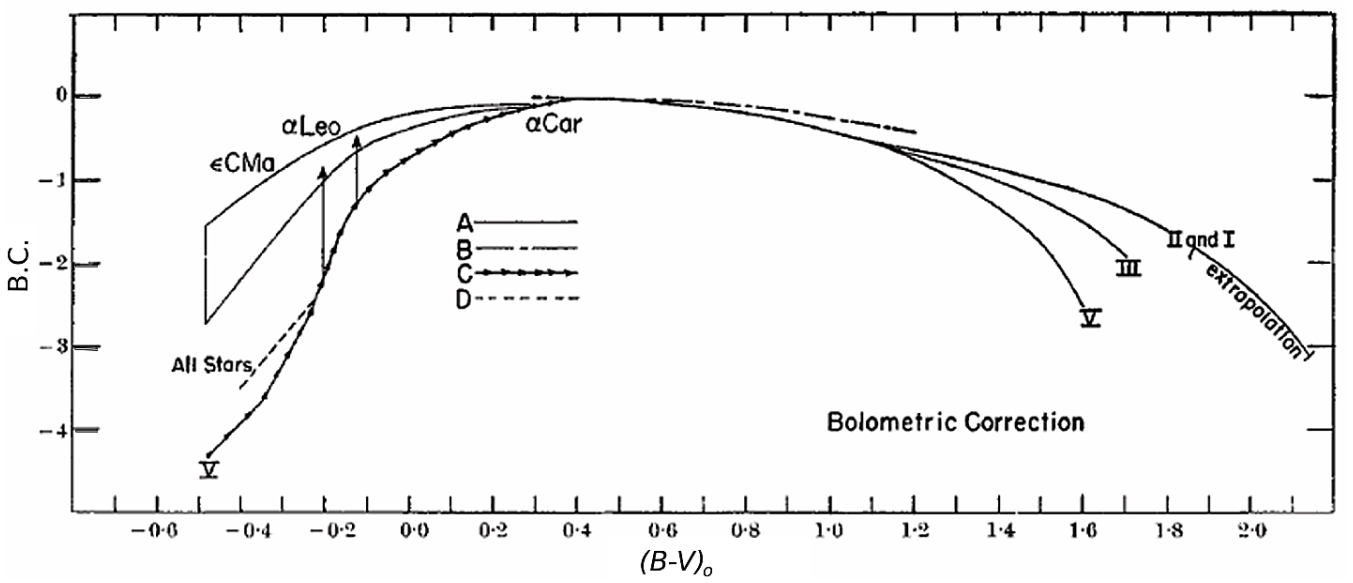


Figure 3. Bolometric correction scales during 1960's are compared on BC-$(B-V)_o$ plane (Wildey 1963).

Table 5. Spectral types, intrinsic colours, bolometric corrections and effective temperatures of main-sequence stars (credit to Johnson 1966).

Sp(V)	$U-V$	$B-V$	$V-R$	$V-I$	$V-J$	$V-K$	$V-L$	$V-M$	$V-N$	$B.C.$	T_e (^oK)
O5-7	-1.46	-0.32	-0.15	-0.47	-0.73	-0.94	-1.01	—	—	—	—
O8-9	-1.44	-0.31	-0.15	-0.47	-0.73	-0.94	-1.01	—	—	—	—
O9.5	-1.40	-0.30	-0.14	-0.46	-0.73	-0.94	-1.00	—	—	—	—
B0	-1.38	-0.30	-0.13	-0.42	-0.70	-0.93	-0.99	—	—	-2.27	26500
B0.5	-1.29	-0.28	-0.12	-0.39	-0.66	-0.88	-0.93	—	—	-1.92	24500
B1	-1.19	-0.26	-0.11	-0.36	-0.61	-0.81	-0.86	—	—	-1.59	21500
B2	-1.10	-0.24	-0.10	-0.32	-0.55	-0.74	-0.77	—	—	-1.31	18000
B3	-0.91	-0.20	-0.08	-0.27	-0.45	-0.61	-0.63	—	—	-1.00	13500
B5	-0.72	-0.16	-0.06	-0.22	-0.35	-0.47	-0.48	—	—	-0.70	13800
B6	-0.63	-0.14	-0.06	-0.19	-0.30	-0.41	-0.41	—	—	-0.56	12900
B7	-0.54	-0.12	-0.04	-0.17	-0.25	-0.35	-0.34	—	—	-0.48	12200
B8	-0.39	-0.09	-0.02	-0.12	-0.17	-0.24	-0.22	—	—	-0.30	11300
B9	-0.25	-0.06	0.00	-0.06	-0.09	-0.14	-0.11	—	—	-0.14	10600
A0	0.00	0.00	+0.02	0.00	-0.01	-0.03	0.00	-0.03	-0.03	-0.01	9850
A2	+0.12	+0.06	+0.08	+0.09	+0.11	+0.13	+0.16	+0.13	+0.13	+0.08	9120
A5	+0.25	+0.14	+0.16	+0.22	+0.27	+0.36	+0.40	+0.36	+0.36	+0.13	8260
A7	+0.30	+0.19	+0.19	+0.28	+0.35	+0.46	+0.52	+0.46	+0.46	+0.13	7880
F0	+0.37	+0.31	+0.30	+0.47	+0.58	+0.79	+0.86	+0.79	+0.79	+0.11	7030
F2	+0.39	+0.36	+0.35	+0.55	+0.68	+0.93	+1.07	+0.93	+0.93	+0.09	6700
F5	+0.43	+0.43	+0.40	+0.64	+0.79	+1.07	+1.25	+1.07	+1.07	+0.06	6400
F8	+0.60	+0.54	+0.47	+0.76	+0.96	+1.27	+1.45	+1.27	+1.27	+0.04	6000
G0	+0.70	+0.59	+0.50	+0.81	+1.03	+1.35	+1.53	+1.35	+1.35	0.00	5900
G2	+0.79	+0.63	+0.53	+0.86	+1.10	+1.44	+1.61	+1.44	+1.44	0.00	5770
G5	+0.86	+0.66	+0.54	+0.89	+1.14	+1.49	+1.67	—	—	-0.02	5660
G8	+1.06	+0.74	+0.58	+0.96	+1.24	+1.63	+1.85	—	—	-0.06	5440
K0	+1.29	+0.82	+0.64	+1.06	+1.38	+1.83	+2.00	—	—	-0.12	5240
K2	+1.60	+0.92	+0.74	+1.22	+1.57	+2.15	+2.24	—	—	-0.23	4960
K5	+2.18	+1.15	+0.99	+1.62	+2.04	+2.75	+2.84	—	—	-0.55	4400
K7	+2.52	+1.30	+1.15	+1.93	+2.36	+3.21	+3.40	—	—	-0.82	4000
M0	+2.67	+1.41	+1.28	+2.19	+2.71	+3.60	+3.78	—	—	-1.10	3750
M1	+2.70	+1.48	+1.40	+2.45	+3.06	+3.95	+4.15	—	—	-1.38	3600
M2	+2.69	+1.52	+1.50	+2.69	+3.37	+4.27	+4.47	—	—	-1.64	3400
M3	+2.70	+1.55	+1.60	+2.94	+3.66	+4.57	+4.79	—	—	-1.85	3300
M4	+2.70	+1.56	+1.70	+3.19	+3.97	+4.87	+5.20	—	—	-2.17	3200
M5	+2.80	+1.61	+1.80	+3.47	+4.28	+5.17	(+5.54)	—	—	-2.48	3100
M6	+2.99	+1.72	+1.93	+3.96	+4.63	+5.58	(+6.03)	—	—	-2.82	2950
M7	+3.24	+1.84	+2.20	+4.20	+5.20	+6.18	—	—	—	-2.35	(2850)
M8	(+3.50)	(+2.00)	(+2.50)	(4 .70)	(+5.80)	(+6.75)	—	—	—	-3.9	(2750)

(1996), who, for the first time in this line of development, provided intrinsic $(B-V)_0$ color and empirical BC coefficients as functions of effective temperature. Flower (1996) used 335 stars to calibrate BC, $(B-V)_0$ and $T_{\rm eff}$ scales, among them 297 with measured effective temperatures and 122 with reliable unreddened $B-V$ colours. Flower (1996) gave two analytical $(B-V)_0-T_{\rm eff}$ relations $[(B-V)_0 = a+b\log T_{\rm eff}+c(\log T_{\rm eff})^2+...]$, one for main sequence, giants and subgiants, and one for supergiants. He also provided three $BC-T_{\rm eff}$ relations $[BC = a+b\log T_{\rm eff}+c(\log T_{\rm eff})^2+...]$ each valid for three temperature ranges ($\log T_{\rm eff} \geq 3.9$ K, $3.9 < \log T_{\rm eff}$ (K) < 3.7, $\log T_{\rm eff}$ (K) ≤ 3.7 K), respectively, but usable for all luminosity classes.

Cayrel et al. (1997) investigated the behavior of the computed BC of the *Hipparcos* $H_{\rm p}$ band ($BC_{\rm Hp} = M_{\rm bol}-H_{\rm p}$) with basic physical parameters $T_{\rm eff}$, $\log g$ and, [Fe/H] using model atmosphere fluxes computed with Kurucz's ATLAS9 code. Bessell et al. (1998) have computed broadband colours, bolometric corrections and temperature calibrations for all spectral types (O to M) in the Johnson-Cousins-Glass system from the synthetic spectra from new model atmospheres available for the time (see references therein). Masana et al. (2006) have presented a method to determine effective temperatures, angular semi-diameters, and bolometric corrections for population I and II FGK type stars based on V and 2MASS ($JHK_{\rm s}$) photometric system (Skrutskie et al. 2006) for the temperature range 4000-8000 K. From the application to a large sample of FGK *Hipparcos* dwarfs and subdwarfs, Masana et al. (2006) provided calibrations for both effective temperature and bolometric correction as a function of $(V-K)_0$, [m/H] and $\log g$. Extensive tables of bolometric corrections and interstellar extinction coefficients for the WFPC2 and ACS (both WFC and HRC) photometric systems were derived from synthetic photometry covering a large range of effective temperatures, surface gravity, and metallicity by Girardi et al. (2008). Intrinsic colours, temperatures and bolometric corrections of pre-main-sequence stars are discussed by Pecaut & Mamajek (2013). Empirical colour-colour relations, zero-age main sequence relations, Spt-$M_{\rm V}$, Spt-$T_{\rm eff}$, colour-Spt relations, and $T_{\rm eff}-BC$ relations derived from Sejong Open Cluster Survey (SOS) are presented as tables by Sung et al. (2013). Chen et al. (2019) provided a database in which popular spectral libraries were assembled to compute BC tables homogeneously for a wide variety of photometric systems.

Flower (1996)'s relations had serious printing errors as pointed out by Torres (2010). However, one frequently used source of BC is the BC-$T_{\rm eff}$ relation by Flower (1996). Torres (2010) rectified the coefficients in the relation and republished them with a large number of digits (15). Moreover, he also corrected the misprint of the $(B-V)_0-T_{\rm eff}$ relations as $T_{\rm eff}-(B-V)_0[\log T_{\rm eff} = a+b(B-V)+c(B-V)^2...]$ and presented all coefficients in higher precision. Nevertheless, using 15-digit coefficients is impractical for many users, and rounding them to fewer digits may introduce a noticeable systematic shift in the BC values. It must be because of such complexities; some users may prefer to have tabulated BC tables. According to Lester (2011), the variation of BC with spectral types found by Johnson (1964) is similar to the more modern curves therefore, in some ways, the photometric data of the bulletin paper is still fresh.

4. HOW AND WHY MISLEADING PARADIGMS WERE DEVELOPED?

Examining all of the tabulated tables of BC and the empirical $BC-T_{\rm eff}$ relations from Flower (1996) and Eker et al. (2020), it is possible to classify BC producers into two groups: 1) those who publish tabulated BC values without any positive value (Kuiper 1938a; McDonald & Underhill 1952; Popper 1959; Wildey 1963; Hayes 1978; Habets & Heintze 1981; Cox 2000; Pecaut & Mamajek 2013) and 2) ones who published tabulated BC values, which are mostly negative but there could be a limited number of positive values (Code et al. 1976; Johnson 1964, 1966; Flower 1977, 1996; Bessell et al. 1998; Sung et al. 2013; Casagrande & VandenBerg 2018b,a; Eker et al. 2020). It appears that the first group adheres to, while the second group deviates from, the following paradigms 1) "Bolometric corrections must always be negative", 2)"the bolometric magnitude of a star ought to be brighter than its V magnitude" and 3) "the zero point of bolometric corrections are arbitrary". This is because it is quite possible that the first group is formed by BC producers who convinced themselves that BC of a star must always be negative as in the case of Kuiper (1938a) who subtracted 0.10 mag from each of the computed BC values in order to avoid BC numbers with different signs. In other words, the arbitrariness attributed to the zero-point constant of the BC scale allows the first group to ensure that their BC values are all negative by systematically shifting their original BC by any constant number. Nevertheless, a negative BC indicates both $M_{\rm bol} < M_{\rm V}$ and $m_{\rm bol} < V$, which verbally means that "a star is brighter bolometrically than visually" according to the definition $BC = M_{\rm bol}-M_{\rm V} = m_{\rm bol}-V$, first given by Kuiper (1938a).

At this point, the problematic aspect appears to be the behavior of the second group, which seems to disregard or challenge the established paradigms. We will come to this problem later together with the problems associated with the paradigms listed above, which, in reality, seem to forecast the end of the first normal science period and/or the onset of the first revolution in the developmental history of bolometric corrections (Figure 4), where the period before Kuiper (1938a) was shown as the pre-science period.

According to the Kuhn's philosophy of science, in the beginning, there could be numerous theories, hypotheses or worldviews which compete with each other. Thus, the period until one of them overcomes or dominates the others is called pre-science period. Assuming that each theory or hypothesis has its own paradigms, the paradigms associated with the victorious

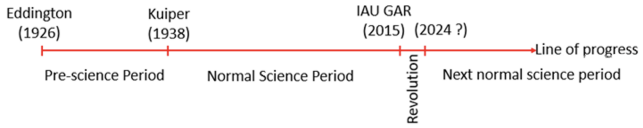


Figure 4. Progress line of bolometric corrections according to Kuhnian philosophy of science.

worldview become the paradigms of the first normal science period. Studying the pre-science period is important to understand how and why misleading paradigms were initiated and customized.

4.1. Initiations and Customizations of the First and the Second Paradigms

Heintze (1973) was the first who formulated BC of a star as

$$\begin{aligned} BC &= 2.5 \log \left(\frac{\int_0^\infty S_\lambda \mathcal{F}_\lambda \, d\lambda}{\int_0^\infty \mathcal{F}_\lambda \, d\lambda} \right) + c \\ &= 2.5 \log \left(\frac{\int_0^\infty S_\lambda f_\lambda \, d\lambda}{\int_0^\infty f_\lambda \, d\lambda} \right) + c \\ &= 2.5 \log \left(\frac{\int_0^\infty S_\lambda F_\lambda \, d\lambda}{\int_0^\infty F_\lambda \, d\lambda} \right) + c, \end{aligned} \tag{10}$$

with a symbol c to imply the zero-point constant of any value (arbitrary) for the BC scale, where $\mathcal{F}_\lambda$ is monochromatic emergent flux at the wavelength λ (ergs cm^{-2} s^{-1}) on the surface of the star, S_λ is the normalized photovisual sensitivity function as given by Matthews & Sandage (1963), f_λ is the monochromatic stellar flux at the Earth (corrected for atmospheric and interstellar extinction) in a relative scale, F_λ is the absolute monochromatic stellar flux at the Earth (if the star were moved to 10 pc away from the Earth). The terms, which their logarithm was taken, are not different from the luminous efficiency P defined by Eddington (1926), where $P = \int P(\lambda) I'(\lambda, T_e) d\lambda / \int I'(\lambda, T_e) d\lambda$, as in Equation (2). Only the symbols are different here, $P(\lambda)$ is replaced by S_λ and integrals were taken over black-body fluxes instead of monochromatic intensities. As long as the total radiation output of the star (L) is equal to $L = 4\pi R^2 \cdot \sigma T_e^4$ that is, if a star radiates like a black body, all of the four ratios (three above, and the one by Eddington 1926) would be equal under the condition that the sensitivity function S_λ is similar to $P(\lambda)$ because the ratio of the integrated luminous intensity to the total (integrated) intensity would be equal to the ratio of the passing flux to the total (integrated) flux. Therefore, Equation (2) given by Eddington (1926), which defines luminous efficiency, is roughly equivalent to the equations above defining a star's BC—provided that the constant c is not included in Heintze (1973) definition. That is, if there were a filter with a transparency profile, which could be expressed by frequencies or wavelengths, similar to the sensitivity profile of a human eye, then the BC of the star (if $c = 0$) would be the logarithm of the number representing integrated luminous efficiency of the human eye multiplied by 2.5.

Therefore, considering the following comment of Eddington (1926) about Table 1 and the P values,

> The maximum of P is found to occur at about $T_{\rm eff} = 6500^{\rm o}$ so that stars of types F to G have the greatest luminous efficiency. Presumably, that is because our visual sense has been developed with special reference to sunlight. It is convenient to take the maximum as standard and to define the scale of bolometric magnitude to agree with visual magnitude at this effective temperature. At any other, the temperature P will be smaller, and the star will be brighter bolometrically than visually.

One can argue that the first and second paradigms associated with the definition $BC = M_{\rm bol} - M_{\rm V} = m_{\rm bol} - m_{\rm v}$, as introduced by Kuiper (1938a), actually originate from the statement "At any other temperature P will be smaller and the star will be brighter bolometrically than visually" contained above comment of Eddington. This verse of Eddington, which was changed later as "the bolometric magnitude of a star ought to be brighter than its V magnitude", directly implies both $M_{\rm bol} < M_{\rm V}$, $m_{\rm bol} < m_{\rm V}$ and indirectly implies "bolometric corrections must always be negative" ($BC < 0$ always). ($BC < 0$ always) is possible mathematically only if both $M_{\rm Bol} < M_{\rm V}$ and $m_{\rm Bol} < m_{\rm v}$.

Although, the first ($BC < 0$ always) and the second ($M_{\rm Bol} < M_{\rm V}$ always) paradigms are initiated by Eddington (1926), they become unavoidable facts of the first normal science period after Kuiper (1938a), who added the paradigm 3 by subtracting 0.10 mag from each of his pre-computed BC values in order to avoid BC numbers with different signs. The tradition continued by Lohmann (1948); McDonald & Underhill (1952); Eggen (1956); Popper (1959) and Wildey (1963). The traditions were raised to levels of paradigms by the time of Johnson (1964, 1966), who published $BC - T_{\rm eff}$ tables including a few positive BC values implying that A-F stars have $M_{\rm Bol} > M_{\rm V}$. Not only Johnson (1964, 1966), there were others such as Code et al. (1976); Flower (1977, 1996); Bessell et al. (1998); Sung et al. (2013), recently Casagrande & VandenBerg (2018b,a) and Eker et al. (2020) who retained limited number of positive BC in their tables. Cox (2000) was an exception with tabulated BC, where all BC values are negative.

4.2. The Third Paradigm, the Main Source of Inconsistencies

Heintze (1973) who inserted arbitrary constant c in Equation (10) commented:

> For the Sun F_λ is measured over a sufficient large wavelength region and $BC_\odot$ is known from equation $BC = M_{\rm bol} - M_{\rm V}$ and the adopted zero point of the bolometric scale. So, c is known.

Verbal explanation of c after Equation (10) and the above comment is contradictory. If c is a known quantity, it cannot be arbitrary or vice versa. In fact, BC producers gave a certain value to it depending upon their private choice. Table 1 indicates $T_{\rm eff} = 6000$ K, while Eddington (1926) preferred $T_{\rm eff} = 6500$ K (see his comment above), whereas Kuiper (1938a) selected $T_{\rm eff} = 6000$ K as the stellar temperature associated with the zero-point constant of the BC scale as the maximum value of the BC (+0.10 mag) occurred for him at $T_{\rm eff} = 6600$ K. That is, the value $c = 0.1$ was subtracted systematically from all BC in order to adjust the maximum value to zero. Eggen (1956) adopted $c = 0.62$. Popper (1959) took $c = 0.58$. Some authors used the solar effective temperature, which could vary among sources; others preferred temperatures of A–F stars, and some took $M_{\rm bol,\odot}$ as the zero-point according to Equation (8) above, which may again change according to various authors. Code

et al. (1976) declared, "The choice of a value for the bolometric correction of the Sun is arbitrary (number) and is equivalent to specifying the zero point of the bolometric magnitude scale."

No one among the *BC* producers said that "any value of c would do the same job". Everyone had own reason, which could be different among the different users. Heintze (1973) introduced c just as a constant but not as an arbitrary constant. Otherwise, from minus to plus infinity, any value of c would have been equivalent. However, all the sampled values of c given above (0.1, 0.62, and 0.58) are positive. Thus, they had to be subtracted systematically from *BC* to adjust its maximum to be zero.

Nevertheless, considering the definition, $BC = M_{\rm bol} - M_{\rm V} = m_{\rm bol} - V$, of Kuiper, it is not possible for the constant c in Equation (10) to be negative. This is because it has been discussed above that the terms, which their logarithm was taken, are not different from the luminous efficiency P defined by Eddington (1926). That is the logarithmic terms in Equation (10) are negative or zero as indicated by the numbers in Table 1, where, at maximum, *BC* is expected to be zero. If this is the case, one cannot obtain zero for a *BC* by adding two negative numbers. On the other hand, if L and $L_{\rm V}$ are the total (at all wavelengths) and the visual (only the visible part) luminosities of a star represented by its $M_{\rm bol}$ and $M_{\rm V}$, a positive *BC* is not allowed by

$$BC = M_{\rm bol} - M_{\rm V} = 2.5 \log \frac{L_{\rm V}}{L}, \tag{11}$$

because a positive *BC* implies $L_{\rm V} > L$, which is impossible as if a part of a unit were bigger than the unit itself. If both positive and negative numbers are not allowed for c in Equation (10), there is only one number left without any sign; it is zero. Consequently, it can be concluded that the definition, $BC = M_{\rm bol} - M_{\rm V} = m_{\rm bol} - V$, of Kuiper, and Equation (10), if there is zero-point constant for *BC* values, it must be zero.

Neither the definition, $BC = M_{\rm bol} - M_{\rm V} = m_{\rm bol} - V$, of Kuiper (1938a), nor the concept of luminous efficiency (P) of Eddington (1926) required a constant. Then, why was Heintze (1973) obliged himself to insert it into his equation? This must be because it was a common practice in these years that the *BC* producers had to declare the difference of their *BC* values from the previously published ones. Thus, the constant c was there to indicate this difference for readers who compare the different sets of *BC* values by different authors.

Nevertheless, *BC* of a star were considered another observable colour like $b-v$, which was the only colour before Johnson & Morgan (1953) who later introduced the *UBV* photometry. This attitude, that is, considering *BC* of a star as one of its colours, continued throughout the century; see Table 5, where *BC* in the column before the last were displayed as one of the ten intrinsic colours for calibrating or predicting effective temperatures and/or spectral types of stars. Also covering these tables, Astronomers' handbook, "Allen's Astrophysical Quantities" (Cox 2000) confirms this attitude also.

A consistent hint why should be a constant in Equation (10), came from Pecker (1973), who declared:

$$M_{\rm bol} = -2.5 \log L + C, \tag{12}$$

which is the basic rule of the magnitude system revealing how L of a star is related to its absolute bolometric magnitude $M_{\rm bol}$. It is clear that if the constant C is equal to $+2.5 \log L$, then $M_{\rm bol} = 0.0$. Therefore, the constant C in Equation (12) is called the zero-point constant. $m = -2.5 \log (f/f_0)$ is given in Allen's Astrophysical Quantities (Cox 2000) when describing apparent magnitudes of photometric systems, where f is the measured flux (corrected for atmospheric effects), and f_0 is the corresponding flux for a star of zero apparent magnitude ($m = 0$). It is clear that if $f = f_0$, then $m = 0$. Since f_0 is a constant, the formula $m = -2.5 \log (f/f_0)$ could be written in the same format as:

$$m_{\rm bol} = -2.5 \log f + c, \tag{13}$$

where the constant c is $2.5 \log f_0$. Because an absolute magnitude is directly related to the L of a star, but the apparent magnitude is related to the flux coming to the eye of the observer from the same star, the zero-point constants associated with L and f are not the same. The difference is indicated by capitalization: C for the absolute, c for the apparent.

To understand what happens, let us assume that there is no atmosphere. Thus, the total flux (f) at all wavelengths will come to the eye of the observer and to the detector of the telescope with a blue-sensitive photographic plate from the star. Eye and the detector will sense visual and relatively bluer photons, Equation (13) will transform to $V = -2.5 \log f_{\rm V} + c_{\rm V}$ and $B = -2.5 \log f_{\rm B} + c_{\rm B}$ for the eye and the detector respectfully. Using relative photometry and one reference star with a known or assigned brightness such as V_0 or B_0, B and V magnitudes of all stars in the sky could be determined without knowing individual flux values ($f_{\rm V}$ and $f_{\rm B}$) or the zero-point constants ($c_{\rm V}$ and $c_{\rm B}$). This is because, when determining the apparent magnitude difference between two stars, the zero-point constants cancel out at the first step as

$$\begin{aligned} V(2) - V(1) &= -2.5 \log \left(\frac{f_V(2)}{f_V(1)} \right), \\ \text{while} \quad B(2) - B(1) &= -2.5 \log \left(\frac{f_B(2)}{f_B(1)} \right), \end{aligned} \tag{14}$$

if comparisons are made staying in the same optical band. This is just because the magnitude difference of the two stars is equal to the ratio of the received fluxes. If all stars are compared for the second step, one only needs to know the flux received from the reference star and its magnitude to determine the relative brightness (magnitudes) of all stars. Changing the wavelength sensitivity of the detector and/or changing the filter of the telescope, different sorts of magnitude scales with their special zero-point constants could be determined. Each one of the various magnitude scales has the same magnitude units but different zero-points, like temperature scales Celsius and Kelvin. Colours were devised as different types of magnitude scales, each with its own zero-point constant, to indicate the effective temperatures of stars—not to compare stellar magnitudes at two different parts of the spectrum. For example, the colours $U-B$, $B-V$, $V-R$, ..., displayed in Table 5, were set to be zero for a hypothetical star of A0V, in practice, Vega. This is also permitted in relative photometry, where one does not

need to know the zero-point constants of the magnitude scales involved (for example, zero points of V and B for the colour $B-V$) to determine the intrinsic colours of nearby stars with no interstellar extinction in a similar manner by determining magnitude difference of two stars.

Vega appears to be the reference star also for the intrinsic colours. That is, all the colours in Table 5 are zero for Vega. Note that the colours of the reference star were assumed to be zero, but not its apparent magnitude. $V = 0.03$ mag has been measured by Johnson (1966) and Bessell et al. (1998). The standard $V = 0.03$ mag is cited by Bohlin (2014); Cox (2000); Girardi et al. (2002); Bessell & Murphy (2012); Casagrande & VandenBerg (2014). For the other bands, Vega is found to be just slightly different (~ 0.02 mag) at most bands (Rieke et al. 2008).

Relative photometry not only permits one to determine apparent magnitudes but also absolute magnitudes of all stars in the sky if their parallaxes were measured and if their interstellar extinctions were also known without knowing the zero-point constants of the absolute magnitudes, that is, without knowing the capitalised C associated with individual photometric bands.

All of the advantages of relative photometry vanish if one tries to determine the bolometric magnitudes of the stars and the bolometric corrections appearing like the other colours in Table 5. This is because there is no telescope nor a detector to observe a star at all wavelengths. Moreover, unlike the other colours, which are special magnitude scales indicating effective temperatures, not for showing the difference of the two magnitudes fixed to be zero artificially using Vega, the BC values in Table 5 are the numbers indicating the differences between the total luminosity (or total flux) and the partial luminosity (or received flux) of a star constrained within a wavelength range proper to an eye or a filter. Therefore, it is not possible to bypass the zero-point constants of the bolometric magnitudes specified by Equations (12) and (13) nor the ones involving with the visual band, which could be symbolised $C_{\rm V}$ for the absolute, $c_{\rm V}$ for the apparent visual magnitudes. Having realised these facts, Code et al. (1976) suggested two new formulations

$$B.C. = -2.5\log\left(\int_0^\infty f_\lambda\, d\lambda\right) - V + C_1, \tag{15}$$

$$B.C. = 2.5\log\left(\frac{\int_0^\infty S_\lambda f_\lambda\, d\lambda}{\int_0^\infty f_\lambda\, d\lambda}\right) + C_2, \tag{16}$$

for calculating BC of a star according to the original definition, $B.C. = m_{\rm bol} - V$, of Kuiper (1938a), where $m_{\rm bol}$ and V are the apparent bolometric and visual magnitudes, f_λ is the flux per unit wavelength interval received outside the atmosphere from a star at wavelength λ, S_λ is the sensitivity function of the V magnitude system and C_1 and C_2 are just constants. Code et al. (1976) commented "Equations (15) and (16) are both completely equivalent to Equation (7) and while Equation (16) may be used to determine bolometric corrections for any SED irrespective of the units in which f_λ is expressed, Equation (15) can be applied only when f_λ is in the units for which the constant C_1 has been determined". Readers should note that neither of the two consonants (C_1 and C_2) was claimed to be arbitrary.

Using the sensitivity function $S_{\rm V}$, outside the atmosphere, from Matthews & Sandage (1963) and the Solar SED of Arvesen et al. (1969), Code et al. (1976) found $C_2 = 0.958$. while $C_2 = 0.946$ was calculated by them from the SED of the Sun by Labs & Neckel (1968). Consequently, the uncertainty of C_2 was estimated at 0.01 mag. Code et al. (1976) also estimated the zero-point constant of the visual apparent magnitudes $c_{\rm V} = -12.47$ from the mean of 21 stars with observationally estimated SEDs using the formula:

$$V = -2.5\log\left(\int_0^\infty S_\lambda f_\lambda\, d\lambda\right) + c_V. \tag{17}$$

Although $c_{\rm V} = -11.48 \pm 0.03$ mag was also found by Code et al. (1976) from the apparent magnitude $V = -26.74 \pm 0.03$ mag (Johnson 1965; Code 1973) and the total flux of the Sun, $f = 1.360 \pm 0.014 \times 10^6$ ergs cm^{-2} s^{-1} (Duncan 1969; Allen 1973), and $c_{\rm V} = -12.47$ mag were preferred to calculate the constant in Equation (15) from $C_1 = -12.47 + 0.959 = -11.51$ mag. It is important to note that a positive value assigned to C_2 invalidates the previous arguments on Equation (11), from which the first and the second paradigms originated. For advocating the third paradigm, "the zero point of bolometric corrections are arbitrary", Hayes (1978) expressed $m_{\rm bol}$ with apparent magnitudes from the definition of Kuiper as

$$m_{\rm bol} = -2.5\log_{10} f + C = V + B.C., \tag{18}$$

and

$$m_{\rm bol,*} - m_{\rm Bol,\odot} = -2.5\log_{10}(f_*/f_\odot). \tag{19}$$

argued "We see from Equations (18) and (19) that the zero-point of BC scale is arbitrary and that a BC scale may be measured by measuring f and V for the suitable number of stars". It must have been because of this comment of Hayes that many astronomers and astrophysicists, even today, may think the zero-point of the BC scale is arbitrary despite Hayes had already corrected himself by removing the statement "the zero point of BC scale is arbitrary" from the manuscript of the next paper (Hayes 1985). Is it not paradoxical to say, "the zero-point of BC scale is arbitrary" and then to say, "BC scale may be measured by measuring f and V for the suitable number of stars"? If something is a measured quantity, it is not arbitrary.

At last, Torres (2010) argued, "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) to account for the flux outside the band". Referring to $BC_V = m_{\rm bol} - V = M_{\rm bol} - M_{\rm V}$, which is the definition of Kuiper (1938a); Torres (2010) continued "Note that this definition is usually interpreted to imply that the bolometric corrections must always be negative...", (paradigm one), "... although many of the currently used tables of empirical $BC_{\rm V}$ values violates this condition" while he addressed the second and the third paradigms as:

> The scale adopted by Flower (1996) is such that $BC_{\rm V,\odot} = -0.080$. As a result, his bolometric corrections for stars between $T_{\rm eff} \approx 6400$ K and $T_{\rm eff} \approx 8500$ K (spectral types approximately

F5 to A5) are positive, seemingly conflicting the idea that the bolometric magnitudes ought to be brighter than V magnitudes, according to $BC_V = m_{\rm bol} - V = M_{\rm bol} - M_{\rm V}$. Other tables with a similar zero point as Flower's share the same problem. In reality, however, the contradiction is of no consequence because of the arbitrary nature of the zero point. Luminosities inferred for stars are never affected if a consistent value of $M_{\rm bol,\odot}$ is used.

After expressing the definition, $BC_V = m_{\rm bol} - V$, in its integral form as

$$BC_{\rm V} = 2.5 \log \left(\frac{\int_0^\infty S_\lambda(V) f_\lambda \, d\lambda}{\int_0^\infty f_\lambda \, d\lambda} \right) + C_2. \qquad (20)$$

Torres (2010) asserted "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" as if between the lines he reminded Hayes (1978), but not Hayes (1985), who corrected himself regarding the zero-point constant of the BC scale. After he complained by saying "While the zero point of $BC_{\rm V}$ is completely arbitrary, and no particular scale has been officially endorsed by the International Astronomical Union (IAU), it is common for some authors of these tabulations to define the scale by adopting a certain value for $BC_{\rm V,\odot}$, sometimes for historical reasons", Torres declared:

Somewhat surprisingly, the IAU has not issued a formal resolution on the matter of $BC_{\rm V}$ 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 $M_{\rm Bol,\odot}$[1]. The scale was set by defining a star with $M_{\rm bol} = 0.00$ to have an absolute radiative luminosity of $L = 3.055 \times 10^{28}$ 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 ($L_\odot = 3.846 \times 10^{26}$ W, according to the IAU Commission reports cited above) leads exactly to $M_{\rm bol,\odot} = 4.75$, which is the bolometric magnitude for the Sun listed in the 1973 edition of Astrophysical Quantities (Allen 1973). 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 $M_{\rm bol,\odot}$. Combined with our adopted solar brightness of $V_\odot = -26.76$, it implies $BC_{\rm V,\odot} = -0.06$. 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. ... the adoption of a value of $BC_{\rm V,\odot}$ or a value of $M_{\rm bol,\odot}$ may not be the most convenient way to solve the immediate problem faced by users

The problems with the definition of BC (Kuiper 1938a) were summarized by Torres (2010) without mentioning the word "paradigm" together with his opinions on the possible solutions, which could be initiated by IAU.

5. IAU 2015 GENERAL ASSEMLY RESOLUTION B2, NEW ERA OF B.C.

The IAU had two primary motivations for addressing the problems associated with bolometric magnitudes and bolometric corrections. 1) A strong need for standardized absolute and apparent bolometric magnitude scales, and 2) to stop problems originating from multiple zero points of bolometric corrections. Thus, the following comments were issued before the final statements of the resolution.

1. The need for a standardized absolute and apparent bolometric magnitude scale for accurately and repeatably transforming photometric measurements into radiative luminosities and irradiances, independently of the variable Sun,
2. that multiple zero points for bolometric corrections pervade the literature due to the lack of a commonly adopted standard zero point for the bolometric magnitude scale

The most logical and efficient way was chosen in contrast to Torres (2010), who expected a formal resolution on the matter of $BC_{\rm V}$ zero points. On the contrary, IAU 2015 General Assembly Resolution B2 (after IAU 2015 GAR B2) was issued to fix the zero point of the absolute bolometric magnitude scale according to the direct relation between $M_{\rm bol}$ and L of the stars as Pecker (1973) recommended (see Equation (12) above). The resolution is

A radiation source with absolute bolometric magnitude $M_{\rm Bol} = 0$ has a radiative luminosity of exactly $L_0 = 3.0128 \times 10^{28}$ W and the absolute bolometric magnitude $M_{\rm Bol}$ for a source of luminosity L (in W) is

$$M_{\rm Bol} = -2.5 \log \left(\frac{L}{L_0} \right) = -2.5 \log L + 71.197425... \qquad (21)$$

the zero point was selected so that the nominal solar luminosity corresponds closely to absolute bolometric magnitude $M_{\rm Bol,\odot} = 4.74$ mag, the value most commonly adopted in the recent literature (e.g. Bessell et al. 1998; Cox 2000; Torres 2010)[2].

declared together with a reminder: the notations of $M_{\rm Bol}$ and $m_{\rm Bol}$ were adopted by Commission 3 (Notations) at the 6th IAU General Assembly in Stockholm in 1938. It is declared that $M_{\rm Bol}$ and $m_{\rm Bol}$ refer specifically to absolute and apparent bolometric magnitudes, respectively. Thus, the zero-point constant of the absolute bolometric magnitude scale is $C_{\rm Bol} = 71.197425...$ if L is in SI units, and $C_{\rm Bol} = 88.697425...$ if L is in cgs units. The zero point of apparent bolometric magnitudes was also fixed similarly as

Apparent bolometric magnitude $m_{\rm Bol} = 0$ mag corresponds to an irradiance or heat flux density of $f_0 = 2.518021002...10^{-8}$ W m^{-2} and hence the apparent bolometric magnitude $m_{\rm Bol}$ for

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

[2] https://www.iau.org/static/resolutions/IAU2015_English.pdf

an irradiance f (in W m^{-2}) is

$$m_{\rm Bol} = -2.5\log(f/f_0) = -2.5\log f - 18.997351... \quad (22)$$

At first glance, Equations (21) and (22) may appear independent, but they are not because the irradiance f_0 corresponds to a measurement from an isotopically emitting radiation source with absolute bolometric magnitude $M_{\rm Bol} = 0.0$ mag (luminosity L_0) at the standard distance of 10 pc (based on the IAU 2012 definition of the astronomical unit).

5.1. Vega System of Magnitudes and Multi-band *BC*

One possible counterargument supporting the arbitrariness of the *BC* scale—and, by extension, the other two paradigms—is that IAU 2015 GAR B2 did not define the bolometric correction scale. It defined only the bolometric magnitude scale set to SI irradiance ($m_{\rm Bol}$, $f_{\rm Bol}$) and luminosity ($M_{\rm Bol}$, $L_{\rm Bol}$) values, whereas the photometric magnitudes are independently defined by standard stars (for Vega system 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. A firm knowledge such as the arbitrariness of the *BC* scale, which has been actively used at least for about eight decades, cannot be changed.

First, it is not true to think that the arbitrariness of the *BC* scale has been a firm knowledge for about eight decades. As explained above, only one author -(Hayes 1978)-claimed that the zero point of the BC scale was arbitrary before Torres (2010). This author, Hayes (1978), too, corrected himself by removing the statement "the zero-point of *BC* scale is arbitrary" from the discussions of the same Equations (18), (19) in the new paper (Hayes 1985). The unknown constants in Equations such (10), (12), (13), (15)-(18), (20) were interpreted as arbitrary by Torres (2010) and the others who are heavily influenced by the three paradigms related to *BC*.

Second, from the original definition of Kuiper (1938a), Equation (18) above, from Hayes (1978, 1985) could be adapted to any photometric system: e.g., for the Johnson system of apparent magnitudes (U, B, V, R, I) as

$$\begin{aligned} m_{\rm Bol} &= \xi + BC_\xi = U + BC_{\rm U} = B + BC_{\rm B} = V + BC_{\rm V} \\ &= R + BC_{\rm R} = I + BC_{\rm I}, \end{aligned} \quad (23)$$

and for the absolute magnitudes as

$$\begin{aligned} M_{\rm Bol} &= M_\xi + BC_\xi = M_{\rm U} + BC_{\rm U} = M_{\rm B} + BC_{\rm B} \\ &= M_{\rm V} + BC_{\rm V} = M_{\rm R} + BC_{\rm R} = M_{\rm I} + BC_{\rm I}, \end{aligned} \quad (24)$$

where the subscripts indicate a filter in a photometric system. It would have been illogical to set innumerable zero-points for the *BC* of each band (BC_ξ) in various photometric systems while an easy way exists to resolve the problem in a single step, as IAU 2015 GAR B2 did. It is very obvious that fixing the zero-point constant of absolute bolometric magnitudes as in Equation (21) automatically fixes all of the zero-points of the *BC* scales of various bands of various photometric systems including the zero-points of apparent bolometric and the corresponding apparent magnitudes.

IAU 2015 GAR B2 is a revolutionary document not only because it initiated the steps of the three paradigms, "bolometric corrections must always be negative", "the bolometric magnitude of a star ought to be brighter than its V magnitude" and "the zero point of bolometric corrections are arbitrary" are wrong and inconsistent (Eker et al. 2022), but also because it removes problematic classical equation,

$$M_{\rm Bol} = M_{\rm Bol,\odot} - 2.5\log(L/L_\odot). \quad (25)$$

from the classical steps for calculating the absolute magnitude of a star from its observables: R and $T_{\rm eff}$.

Before, and even after, IAU 2015 GAR B2, Equation (25) was claimed to be the main source of the arbitrariness attributed to the zero points of bolometric magnitudes and corrections (Hayes 1978; Torres 2010; Eker et al. 2021a,b; Casagrande & VandenBerg 2018b,a; Andrae et al. 2018). The Solar luminosity varies according to Fröhlich & Lean (1998), with an amplitude about 1.5×10^{-3} (≈ 0.004 mag) because of magnetic activity. Therefore, Equation (25) cannot be the fundamental relation to calculate absolute bolometric magnitudes of stars. See the first motivation of IAU for the resolution, IAU 2015 GAR B, where avoiding the variable the Sun stated clearly. In another saying, it was not the choice of $M_{\rm Bol,\odot}$ and the luminosity of the Sun ($L_\odot$) to determine the zero-point constant of absolute bolometric magnitude scale which is $C_{\rm Bol} = 71.197425...$ if L is in SI units, and $C_{\rm Bol} = 88.697425...$ if L is in cgs units. On the contrary, it was the choice of $C_{\rm Bol} = 71.197425...$ and the best estimate of solar luminosity $L_\odot = 4\pi(1\ {\rm au})^2 S_\odot = 3.8275 \pm 0.0014 \times 10^{26}$ W, which is a value computed from the recently estimated best value of the solar constant $S_\odot = 1361 \pm 1$ W m^{-2}, obtained from the total solar irradiance (TSI) data of 35 years of space-born observations during the last three solar cycles (Kopp 2014), which determined the absolute bolometric magnitude of the Sun as $M_{\rm Bol,\odot} = 4.739996...$ mag. Therefore, $M_{\rm Bol,\odot} = 4.74$ mag and $L_\odot = 3.828 \times 10^{26}$ W were suggested as the nominal solar absolute bolometric brightness and the nominal solar luminosity for the ones who still want to use Equation (25).

6. DISCUSSIONS

6.1. New Definitions and Concepts

There are two different definitions of bolometric corrections. Both are still functioning. The one which was suggested by Kuiper (1938a) as $B.C. = M_{\rm bol} - M_{\rm pv} = m_{\rm bol} - m_{\rm pv}$, listed as "$BC = m_{\rm bol} - V$ (always negative)" in the handbook of astronomers in page 381, Allen's Astrophysical Quantities (Cox 2000), but could be adapted for any passband (ξ) in any photometric system as $BC_\xi = M_{\rm bol} - M_\xi = m_{\rm bol} - \xi$, therefore, the very first definition could be expressed verbally as "the difference between the bolometric and apparent magnitudes of a star". The second and relatively more modern definition is "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 the band" as given by Torres (2010).

Both of the definitions could be considered correct but incomplete. The *BC* of a star is better defined as: "The bolometric correction of a star is the difference between its bolometric and one of its apparent magnitudes in their absolute scales, that is, without ignoring both of the zero-point constants associated with bolometric and filtered quantities, unlike the other

colours operating in relative scale thus the difference between the two apparent (or absolute) magnitudes were conventionally assumed to be zero for a hypothetical star of the spectral type A0V".

IAU 2015 GAR B2 declared Equation (21) as the direct relation between the absolute bolometric magnitude of a star ($M_{\rm Bol}$) and its luminosity (L). $M_{\rm Bol} = M_{\rm Bol,\odot} - 2.5\log(L/L_\odot)$, the classical formula is cancelled and replaced by Equation (21). Knowing L of a star, its $M_{\rm Bol}$, or knowing $M_{\rm Bol}$, its L can be calculated directly. Equation (21) could be adopted for any passband of any photometric system, such as:

$$M_\xi = -2.5\log L_\xi + C_\xi, \tag{26}$$

where L_ξ is the partial luminosity, and C_ξ is the zero-point constant of the absolute magnitude scale for the photometric band ξ. Unlike, $C_{\rm Bol} = 71.197425...$ if L is in SI units for the bolometric magnitudes, C_ξ may not be found in literature because astronomers commonly prefer relative photometry, and one can do relative photometry without knowing the zero-point constant. Therefore, C_ξ is left as an unknown in this study, but it is a definite value, as accurate as the photometric system practised.

IAU 2015 GAR B2 declared Equation (22) as the direct relation between the apparent bolometric magnitude of a star and its irradiance or the heat flux density, assuming no extinctions. A similar relation can be adopted between the apparent magnitude (ξ) of a star at any passband in a photometric system and heat flux density (irradiance) received from the star limited by the wavelength range of the passband as

$$\xi = -2.5\log f_\xi + c_\xi, \tag{27}$$

where f_ξ is the heat flux density (irradiance) within the wavelength range of the pass band if there is no extinction and c_ξ is the zero-point constant of apparent magnitudes for the passband chosen. The relation between L_ξ and f_ξ and the relation between C_ξ and c_ξ are not independent. A similar relationship between L and f must also exist between L_ξ and f_ξ. A similar relationship between $C_{\rm Bol}$ and $c_{\rm Bol}$ must also exist between C_ξ and c_ξ. Unlike Equation (22) where $c_{\rm Bol} = -18.997351...$ corresponding to the heat flux density $f_0 = 2.518021002...10^{-8}$ W m^{-2}, c_ξ may not be found in the literature because astronomers commonly use relative photometry. Therefore, c_ξ is left as an unknown in this study, but it must be a definite value, as accurate as the photometric system practised. Note that Equation (27) is the generalized form of Equation (22), which is valid for apparent visual magnitudes.

One can obtain BC of a star for the passband ξ according to the generalized form with absolute magnitudes ($BC_\xi = M_{\rm Bol} - M_\xi$) by subtracting Equation (26) from Equation (21) as:

$$BC_\xi = M_{\rm Bol} - M_\xi = 2.5\log\left(\frac{L_\xi}{L}\right) + (C_{\rm Bol} - C_\xi). \tag{28}$$

while the generalized form with apparent magnitudes ($BC_\xi = m_{\rm Bol} - \xi$) by subtracting Equation (27) from Equation (22) as:

$$BC_\xi = m_{\rm Bol} - \xi = 2.5\log\left(\frac{f_\xi}{f}\right) + (c_{\rm Bol} - c_\xi). \tag{29}$$

Combining Equation 28 and Equation 29,

$$\begin{aligned} BC_\xi &= 2.5\log\left(\frac{L_\xi}{L}\right) + (C_{\rm Bol} - C_\xi) \\ &= 2.5\log\left(\frac{f_\xi}{f}\right) + (c_{\rm Bol} - c_\xi) \\ &= 2.5\log\left(\frac{\int_0^\infty S_\lambda(\xi) f_\lambda\, d\lambda}{\int_0^\infty f_\lambda\, d\lambda}\right) + C_2(\xi), \end{aligned} \tag{30}$$

is the formula to calculate BC of the star according to the new definition of BC for the passband ξ, where $C_2(\xi) = C_{\rm Bol} - C_\xi = c_{\rm Bol} - c_\xi$ is the zero point constant of the BC scale for passband ξ. The part after the first equal sign is the BC from the absolute bolometric magnitudes, which indicates the BC_ξ is related to the fractional luminosity (L_ξ/L) within the passband ξ. The part after the second equal sign is the BC from the apparent magnitudes, showing that BC_ξ is also related to the fraction of the heat flux (f_ξ/f) passing through the filter ξ above the atmosphere if there is no extinction. The last part of the equation is an integral form of the fractional heat flux, which allows one to calculate BC_ξ numerically if the SED of the star and transition profile ($S_\lambda(\xi)$) of the filter is known. Equality of (28) and (29) depends on the equality of $C_{\rm Bol} - C_\xi$ to $c_{\rm Bol} - c_\xi$, which was already confirmed (Eker et al. 2022), and on the assumption that radiation is isotropic, thus, $L = 4\pi d^2 \cdot f$ and $L_\xi = 4\pi d^2 \cdot f_\xi$, where d is the distance of the star.

6.2. Replacements

According to Kuhn (1970), the next normal science period does not start until the misleading paradigms of the previous period are replaced by the new ones. We hope that the replacements proposed in this study are sufficiently convincing for the paradigms of the previous period to be entirely discarded.

The third paradigm, "the zero point of bolometric corrections are arbitrary," is clearly stated and advocated by Torres (2010). However, according to the new definition and the new formula for BC_ξ, the zero-point constant $C_2(\xi)$ is a firm constant with accuracy, which could be determined by observations. The subscript 2 indicates that it is defined by the difference between the two zero-point constants, as shown in Equations (28) and (29). Furthermore, it must have a positive value because: Let us assume a star has $M_{\rm Bol} = 0.0$, then according to Equation (21), $C_{\rm Bol} = 71.197425...$ if L is in SI units, and $C_{\rm Bol} = 88.697425...$ if L is in cgs units. On the other hand, Equation (27) implies $M_\xi = 0.0$ for the same star if BC_ξ of this star is zero. Then, $L_\xi < L$, which is true for all stars, implies $C_\xi < C$ and both are positive. Lastly, Equations (28) and (30) indicates $C_2(\xi) = C_{\rm Bol} - C_\xi$ is a positive number.

Code et al. (1976) determined it for the visual band as $C_2(V) = 0.958 \pm 0.010$ mag using observed SEDs of 21 nearby stars. We are aware of an official two-year project (TÜBİTAK 123C161), which aims to determine the zero-point constant of BC, primarily, for the Johnson V filter and, if possible, for the B filter (Yücel, 2025)[3] from the numerous high-resolution

[3] private communications

spectra of stars distributed all over the H-R diagram is ongoing. Therefore, the third paradigm must be discarded with a firm knowledge that "the zero point constants of bolometric corrections are not arbitrary. Both could be determined observationally as accurate as up to the sixth digits after the decimal, that is, as accurate as $C_{\rm Bol}$ given in Equation (21)".

According to Equation (30), it is not that the bolometric correction itself (BC_ξ), but the bolometric correction minus the zero-point constant [BC_ξ - $C_2(\xi)$] is always less than zero. Therefore, this represents the second proposed replacement for discarding the first paradigm "bolometric corrections must always be negative". This is because, Equation (30) could be re-written as

$$\begin{aligned} BC_\xi - C_2(\xi) &= 2.5 \log \left(\frac{L_\xi}{L} \right) \\ &= 2.5 \log \left(\frac{f_\xi}{f} \right) \\ &= 2.5 \log \left(\frac{\int_0^\infty S_\lambda(\xi) f_\lambda \, d\lambda}{\int_0^\infty f_\lambda \, d\lambda} \right), \end{aligned} \tag{31}$$

where it is clear that the fractional luminosity (L_ξ/L), fractional flux (f_ξ/f) and integral form of the fractional flux ($\int_0^\infty S_\lambda(\xi) f_\lambda d\lambda / \int_0^\infty f_\lambda d\lambda$) are the same number, which is positive and less than one. The Logarithm of a number which is positive and less than one is a negative number. Therefore, $BC_\xi - C_2(\xi) < 0$ always.

It can be written from Equation (31) that

$$\frac{L_\xi}{L} = 10^{\frac{BC_\xi - C_2(\xi)}{2.5}}. \tag{32}$$

which indicates the fractional luminosity of a star within the wavelength range covering the filter ξ could be computed if its BC and corresponding zero-point constant are known. Similarly, it can be written from Equation (31) that

$$\frac{f_\xi}{f} = 10^{\frac{BC_\xi - C_2(\xi)}{2.5}}. \tag{33}$$

which indicates fractional luminosity (L_ξ/L) of a star is equal to its fractional heat flux (f_ξ/f) at above the Earth's atmosphere if there is no interstellar extinction.

Because the zero-point constant, $C_2(\xi)$, is a positive number, as discussed, not only $BC_\xi < 0$ but also $0 < BC_\xi < C_2(\xi)$ are valid to produce a consistent fractional luminosity according to Equation (32) and a true fractional flux according to Equation (33). Only if $BC_\xi \geq C_2(\xi)$, invalid consequences are inevitable. This is because, if $BC_\xi \geq C_2(\xi)$, Equations (32) and (33) imply $L_\xi \geq L$ and $f_\xi \geq f$, which are unphysical. Therefore, the statement (the second paradigm) "the bolometric magnitude of a star ought to be brighter than its V magnitude" cannot be generalized to all stars even if there is only one star with a positive BC_ξ. We do not have a replacement for the second paradigm, so it must be forgotten.

6.3. Standardization and Future Research

The primary purpose of IAU 2015 GAR B2 was to stop producing inconsistent bolometric corrections and ensure standardization. The standard bolometric corrections were defined verbally by Eker et al. (2021a), while Eker et al. (2021b) defined the standard stellar luminosities. If a BC is produced using observed R and $T_{\rm eff}$ of a star, giving its L first, and then by using the equation $M_{\rm Bol} = -2.5 \log L + 71.197425...$ (if L is in SI units) as proposed by IAU 2015 GAR B2, and $BC_\xi = M_{\rm Bol} - M_\xi$ to include its absolute ξ magnitude free from extinctions, the produced BC_ξ are called standard. If $M_{\rm Bol}$ of a star is obtained directly from a pre-computed standard BC_ξ and M_ξ first, then its L is computed using $M_{\rm Bol} = -2.5 \log L + 71.197425...$ (if L is in SI units) as proposed by IAU 2015 GAR B2, the obtained L is called standard luminosity.

Accuracy of standard luminosities in the era after *Gaia* were also studied (Eker et al. 2021b). It has been found that the accuracy of standard luminosities is comparable to the accuracy of the luminosities from the direct method with the Stefan-Boltzmann law, $L = 4\pi R^2 \cdot \sigma T_{\rm eff}^4$. Using multiband bolometric corrections at Johnson B, V, and *Gaia* G, $G_{\rm BP}$, $G_{\rm RP}$ filters of 209 double-lined detached eclipsing binaries with main-sequence components and *Gaia* EDR3 parallaxes, Bakış & Eker (2022) proposed a new method to improve the accuracy of the standard luminosities much better (≈3 times) than the accuracy of the luminosities from the classical method with the Stefan-Boltzmann law. This multiband bolometric correction method was tested by Eker & Bakış (2023), who recovered the luminosities and radii of 341 host stars with the most accurate effective temperatures. The error histograms of the recovered and calculated L showed peaks at ∼2 and ∼4%. The recovered L values were then used to recover the radii of 281 MS, 40 subgiants, 19 giants, and one pre-main-sequence star (total of 341). The peak of the predicted R errors is found at 2%, which is equivalent to the peak of the published R errors.

IAU 2015 GAR B2 opened up a new platform to study the standard bolometric corrections and standard luminosities of stars, which is still virgin to be explored. Thus, we encourage new studies producing more and more standard BC for all the bands of all photometric systems. Studies like estimating BC of a star from its spectrum seem to be even more promising also to get interstellar extinction up to the distance of the star from its spectra independently of the other methods which could be used to produce a 3D dust map of the solar neighbourhood to confirm existing ones independently.

7. CONCLUSIONS

1. With the same defining formula first suggested by Kuiper (1938a), $BC_\xi = M_{\rm bol} - M_\xi = m_{\rm bol} - \xi$, 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 (passband) magnitudes without ignoring both of the zero-point constants associated with bolometric and filtered quantities in the absolute scale, unlike the other colours operating in the relative scale ($U-B = B-V = V-R = ... = 0$ of A0V star), which were set to be zero artificially for a hypothetical star A0V.
2. 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.
3. The zero-point constants of BC scales are as many as the number of passbands. $C_2(\xi) = C_{\rm Bol} - C_\xi = c_{\rm Bol} - c_\xi$, where ξ

represents one of the passbands of various photometric systems and capital C implies absolute, while small c for apparent.

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

5. The zero-point constant (C_2) of a BC scale could be a positive number. This means all $BC < C_2$ for a photometric band are valid, that is, bolometric magnitudes ($M_{\rm bol}$ or $m_{\rm bol}$) 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 $L_\xi = L \times 10^{\frac{BC_\xi - C_2(\xi)}{2.5}}$ is valid to produce $L_\xi < L$ for all photometric bands.

6. The normal science period (Figure 4) was ended in 2015 in the year when IAU 2015 GAR B2 issued and the silent revolution (Eker et al. 2022) 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.

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

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