# IAU 2015 Resolutions B2 & B3

## IAU Inter-Divisional A-G Working Group on Nominal Units for Stellar & Planetary Astronomy

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# Overview

- **Resolution B2** on recommended zero points for the absolute and apparent bolometric magnitude scales
- **Resolution B3** on recommended nominal conversion constants for selected solar and planetary properties

# History

- Working Group organized by Petr Harmenec & Andrej Prsa, supported by Divisions A and G
- **2012-2015 triennium plan**: draft IAU resolution on recommended nominal conversion constants for stellar & (exo)planetary astronomy (constants for parameters for Sun, Jupiter, Earth), address standardization of bolometric magnitude scales and bolometric corrections (if possible)
- Single resolution address both issues was too lengthy, decided to **split into two draft resolutions** (now #ed B2, B3) submitted to IAU Resolutions Committee March 2015
- Eric Mamajek, chair, March 2015
- Solicitation of feedback and editing of resolutions March-July 2015.
- **Response has been very positive from IAU membership. Revisions have been minor.**

# B3 nominal units: Motivation

- **Some parameters related to stars and exoplanets can now be measured with sufficient precision that when their values are quoted in units related to Sun/Jupiter/Earth, the actual adopted unit value in SI may differ among authors** (different choices of "current best estimate"), leading to (unnecessary) systematic differences in quoted estimates. Effort led by eclipsing binary community (e.g. Harmanec, Prsa, Torres, etc.).

- **Sun/Jupiter/Earth parameters are not secularly constant anyway, and their current best estimates are being improved over time** (bouncing around within statistical limits – **useful to pick reasonable, accurate values for use as standard rulers.**

- Resolution B3 presents "**nominal units**" – this should *not* be interpreted as "current best estimates" (CBEs) – but usually these are rounded versions of the CBEs. The nominal units are meant to be useful rulers for the foreseeable future.

# Call to adopt a nominal set of astrophysical parameters and constants to improve the accuracy of fundamental physical properties of stars.

(Harmanec & Prsa, 2011, PASP, 123, 976)

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## ABSTRACT

The increasing precision of astronomical observations of stars and stellar systems is gradually getting to a level where the use of slightly different values of the solar mass, radius and luminosity, as well as different values of fundamental physical constants, can lead to measurable systematic differences in the determination of basic physical properties. An equivalent issue with an inconsistent value of the speed of light was resolved by adopting a nominal value that is constant and has no error associated with it. Analogously, we suggest that the systematic error in stellar parameters may be eliminated by: (1) replacing the solar radius $R_\odot$ and luminosity $L_\odot$ by the nominal values that are *by definition* exact and expressed in SI units: $1\mathcal{R}_\odot^{\rm N} = 6.95508 \times 10^8$ m, and $1\mathcal{L}_\odot^{\rm N} = 3.846 \times 10^{26}$ W; (2) computing stellar masses in terms of $M_\odot$ by noting that the measurement error of the product $GM_\odot$ is 5 orders of magnitude smaller than the error in $G$; (3) computing stellar masses and temperatures in SI units by using the derived values $\mathcal{M}_\odot^{2010} = 1.988547 \times 10^{30}$ kg and $\mathcal{T}_\odot^{2010} = 5779.57$ K; and (4) clearly stating the reference for the values of the fundamental physical constants used. We discuss the need and demonstrate the advantages of such a paradigm shift.

# B2 bol mags: Motivation

- **Bolometric magnitudes quoted by astronomers since at least 1920s, but no standardization of zero point. This has led to different bolometric magnitude and bolometric correction (BC) scales. Problem discussed at length by Bessell, Castelli, & Plez (1998), Torres (2010)**
- **Picking inconsistent combinations of BC scale and solar absolute magnitude can lead to systematic errors at ~10% level. => systematic errors in luminosities, radii, ages, etc.** *Inexcusable in Gaia era of precise parallaxes!*
- **1997 effort led by R. Cayrel almost solved this – reached discussion by IAU Comms 25 & 36, but did NOT reach IAU GA vote.**

# Bessell, Castelli, Plez (1998)

**Table A4.** Comparison of tabulated solar V magnitude, bolometric correction and flux

| Compiler | V | $M_V$ | $M_{bol}$ | $BC_V$ | f $\times 10^6$ | F $\times 10^{10}$ | L $\times 10^{33}$ | Ref |
|---|---|---|---|---|---|---|---|---|
| | mag | mag | mag | mag | erg $cm^{-2}s^{-1}$ | erg $cm^{-2}s^{-1}$ | erg $s^{-1}$ | |
| BCP97 | -26.76 | 4.81 | 4.74 | -0.07 | 1.371 | 6.334 | 3.856 | this paper |
| Allen | -26.74 | 4.83 | 4.75 | -0.08 | 1.360 | 6.284 | 3.826 | AQ 76 |
| Durrant | -26.70 | 4.87 | 4.74 | -0.13 | 1.370 | 6.329 | 3.853 | LB VI/2a 81 |
| Schmidt-Kaler | -26.74 | 4.83 | 4.64 | -0.19 | 1.370 | 6.33 | 3.85 | LB VI/2b 82 |
| Lang* | -26.78 | 4.82 | 4.75 | -0.07 | 1.372 | 6.34 | 3.86 | AD 91 |

*The apparent V and apparent bolometric magnitude for the sun given by Lang are inconsistent with his absolute magnitudes (differs by 0.03 mag).

# Cayrel's 1997 Proposed Resolution

**IAU COMMISSION 26**

2.6. PROPOSAL FOR DEFINITION OF BOLOMETRIC MAGNITUDE

The following resolution, proposed to the Commission by Roger CAYREL, was approved by the Commission in principle. (The present form has evolved somewhat from that which was presented at the Commission business meeting, but the substance is the same.)

**Noting** the absence of a strict definition for the zero point of bolometric magnitudes, and the resulting proliferation of different zero points in the literature, the Commission

**Recommends** to define the zero point by specifying that the absolute radiative luminosity, $L$, of a star of absolute bolometric magnitude $M_{bol} = 0$ has the value $L = 3.055 \times 10^{28}$ W. This choice is intended to be close to the most common practice, and is equivalent to taking the value $M_{bol} = 4.75$ (Allen, *Astrophysical Quantities*) for the nominal bolometric luminosity adopted for the Sun by the international GONG Project, ($L_{\odot} = 3.846 \times 10^{26}$ W).

**IAU COMMISSION 35**

**On the Zero Point of the Scale of Bolometric Magnitudes**

Noting the absence of a strict definition for the zero point of bolometric magnitudes, and the resulting proliferation of different zero points in the literature, Commission 36 resolves to define the zero point by specifying that the absolute radiative luminosity, $L$, of a star of absolute bolometric magnitude $M_{bol} = 0$ has the value:

$$L = 3.055 \times 10^{28} \text{ W.}$$

This choice is intended to be close to the most current practice, and its equivalent to taking the value $M_{bol} = 4.75$ (C. Allen, "Astrophysical Quantities") for the nominal bolometric luminosity adopted for the Sun by the international GONG project ($L_{\odot} = 3.846 \times 10^{26}$ W).

- **Unfortunately, Cayrel's proposal was mostly ignored by community (judging by past 15 years of publications).**
- **The 1997 adopted solar luminosity is now obsolete (~0.5%, ~6$\sigma$ too high compared to modern mean TSI) and majority of studies over past ~decade and a half adopt different Mbol than Cayrel's value (most adopt 4.74 following Bessell +1998 and Cox 2000 Allen's Astrophysical Quantities 3rd Ed., *not* 4.75).**
- **As Cayrel's definition is not in common use, the WG decided to follow Cayrel's style for the definition, but modernize it using new TSI-derived nominal solar luminosity, and extend to apparent bolometric magnitude**

**Bessell, Castelli, Plez (1998)**

## Appendix D: bolometric corrections and the zeropoint of the bolometric magnitude scale

The definition of apparent bolometric magnitude is

$$m_{bol} = -2.5 \log(f_{bol}) + \text{constant}$$

or

$$m_{bol} = -2.5 \log(\int f_\lambda d\lambda) + \text{constant}$$

where $f_{bol}$ is the total flux received from the object, outside the atmosphere. The usual definition of bolometric correction

$$BC_V = m_{bol} - m_V$$

is the number of mags to be added to the V magnitude to yield the bolometric magnitude. The value of $BC_V$ does not change when magnitudes at the stellar surface or absolute magnitudes are considered. In fact they differ from the apparent magnitudes only for the distance, which is eliminated when the difference between the bolometric and V magnitude is taken.

# Johnson V magnitude estimates for the Sun

| Vmag(Sun) | Ref. |
|---|---|
| -26.70(1) | Gallouet64 |
| -26.70 | Durrant81 (Landolt Bornstein vol VI/2A, p.82) |
| -26.705 | Engelke10 (Rieke08 synthetic + Engelke08 zero reference) |
| -26.706 | Engelke10 (Rieke08 synthetic + Vega from Rieke08) |
| **-26.71** | **Pecaut & Mamajek (2013) [adopted]** |
| -26.723 | Engelke10 (ASUN model + Engelke08 zero reference) |
| -26.723 | Engelke10 (Kurucz model + Engelke08 zero reference) |
| -26.724 | Engelke10 (ASUN model + Vega from Rieke08) |
| -26.724 | Engelke10 (Kurucz model + Vega from Rieke08) |
| -26.730(44) | Stebbins & Kron (1957,ApJ,126,266) [original value, p.e.=0.03 quoted)] |
| -26.74 | Allen76 (Astrophysical Quantities, 2nd ed.) |
| -26.74 | Schmidt-Kaler82 (Landolt Bornstein, Num. Data..., Vol 2, p.451) |
| -26.740(44) | Stebbins & Kron (EEM recalc with new Vmags, adopting p.e.=0.03) |
| -26.740 | Casagrande06 (ATLAS9 ODFNEW w/Grevesse & Sauval abundances) |
| -26.741 | EEM calculated for 22 solar analogs using Casagrande10 bolometric fluxes |
| -26.742 | Casagrande06 (Colina96 synthetic) |
| -26.743 | Casagrande06 (Thuillier04 synthetic) |
| -26.744(15) | Stebbens & Kron (1957; updated by Bessell98) |
| -26.746 | Casagrande06 (Kurucz04 model R=100,0000 synthetic) |
| -26.75(2) | Hayes85 (1985IAUS..111..225H, synthetic) |
| -26.75(6) | Hayes85 (1985IAUS..111..225H, direct measurements N=3) |
| -26.75 | Colina96 (synthetic) |
| -26.75 | Cox00 (Allen's Astrophysical Quantities, 4th Ed., p.341) |
| -26.753 | Casagrande06 (MARCS synthetic) |
| -26.76(3) | Torres11 (adopted) |
| -26.76 | Bessell+98 (A&A 333, 231) [adopted] |
| -26.760(44) | Stebbins & Kron (EEM recalc with new Vmags, applying Hayes85 corr.) |
| -26.764 | Stritzinger05 (PASP, 117, 810) (synthetic) |
| -26.77 | Bessell+98 (A&A 333, 231)[SUN-OVER(ATLAS9, overshoot)] |
| -26.77 | Bessell+98 (A&A 333, 231)[SUN-NOVER(ATLAS9, no overshoot)] |
| -26.77 | Lang74 (Astrophysical Formulae, p. 562) |
| -26.78 | Lang91 (Astrophysical Data: Planets and Stars, p.103) |
| -26.78 | Allen63 (Astrophysical Quantities, 2nd ed.) |
| -26.81(5) | Nikonova49 tranformed to V-mag by Martynov60 |

**Most observed estimates are ancient. Plenty of recent synthetic photometry estimates.**

**V(Sun) probably between -26.7 and -26.8**

**Best to avoid tying any zero points to the solar Vmag or Mv (or any other bands for that matter)**

Although originally defined for the V magnitude only, the definition has now been generalised to all passbands (hence the V subscript above). Although the definition of bolometric magnitude is a straightforward one, there is some confusion in the literature resulting from the choice of zeropoint. Traditionally it had been generally accepted that the bolometric correction in V should be negative for all stars (but with generalisation of the correction to all passbands this rationale vanishes) and this had resulted in F dwarfs having a BC near zero and consequently the BC for solar-type stars was between -0.07 (Morton & Adams, 1968) and -0.11 mag (Aller, 1963). However, with the publication of his grid of model atmospheres, Kurucz (1979) formalised this tradition and based the zeropoint of his $BC_V$ scale on the computed bolometric correction of a ($T_{\rm eff}$=7000, log g=1.0) model, which had the smallest BC in his grid, resulting in $BC_V$ = -0.194 for his solar model. This zero-point based on model atmospheres was adopted by Schmidt-Kaler (1982) who assigned $BC_V$ = -0.19 to the Sun.

Problems in the literature have occurred when $BC_V$ tables have been used from various empirical and theoretical sources without addressing the different zeropoints involved. As emphasized by Cayrel (1997), the traditional basis of the zeropoint is no longer useful and we should adopt a fixed zeropoint, disconnected formally from other magnitudes, but related to fundamental solar measurements for historical reasons.

**Bessell, Castelli, Plez (1998)**

# "Nominal Units" recent example

- Recent example: *astronomical unit* – was tied to Gaussian constant, known only as accurate as $GM_{Sun}$. The *au* is/was *not* the semi-major axis of Earth-Sun orbit, nor mean Earth-Sun distance! 2012 IAU resolution defined to be exact SI length: *au=149,597,870,700 m*. For astronomical purposes, it doesn't matter that this value =/= exact semi-major axis of Earth's orbit. Dynamicists will continue to refine $GM_{Sun}$, but with 2012 IAU resolution, the rest of community can use the *au* as a conversion constant for a SI length that has no uncertainty.

# B3:Nominal Units

| | | SOLAR CONVERSION CONSTANTS |
|---|---|---|
| $1\mathcal{R}^{\mathrm{N}}_{\odot}$ | = | $6.957 \times 10^{8}$ m |
| $1\mathcal{S}^{\mathrm{N}}_{\odot}$ | = | $1361\ \mathrm{W\,m^{-2}}$ |
| $1\mathcal{L}^{\mathrm{N}}_{\odot}$ | = | $3.828 \times 10^{26}$ W |
| $1\mathcal{T}^{\mathrm{N}}_{\mathrm{eff}\odot}$ | = | 5772 K |
| $1(\mathcal{GM})^{\mathrm{N}}_{\odot}$ | = | $1.327\,124\,4 \times 10^{20}\ \mathrm{m^3 s^{-2}}$ |

| | | PLANETARY CONVERSION CONSTANTS |
|---|---|---|
| $1\,\mathcal{R}^{\mathrm{N}}_{e\mathrm{E}}$ | = | $6.3781 \times 10^{6}$ m |
| $1\,\mathcal{R}^{\mathrm{N}}_{p\mathrm{E}}$ | = | $6.3568 \times 10^{6}$ m |
| $1\,\mathcal{R}^{\mathrm{N}}_{e\mathrm{J}}$ | = | $7.1492 \times 10^{7}$ m |
| $1\,\mathcal{R}^{\mathrm{N}}_{p\mathrm{J}}$ | = | $6.6854 \times 10^{7}$ m |
| $1\,(\mathcal{GM})^{\mathrm{N}}_{\mathrm{E}}$ | = | $3.986\,004 \times 10^{14}\ \mathrm{m^3\,s^{-2}}$ |
| $1\,(\mathcal{GM})^{\mathrm{N}}_{\mathrm{J}}$ | = | $1.266\,865\,3 \times 10^{17}\ \mathrm{m^3\,s^{-2}}$ |

# B3 Footnotes

[3] The TSI is variable at the ~0.08% (~1 $W\,m^{-2}$) level and may be variable at slightly larger amplitudes over timescales of centuries. Modern spaceborne TSI instruments are absolutely calibrated at the 0.03% level (Kopp 2014). The TIM/SORCE experiment established a lower TSI value than previously reported based on the fully characterized TIM instrument (Kopp et al. 2005, Kopp & Lean 2011). This revised TSI scale was later confirmed by PREMOS/PICARD, the first spaceborne TSI radiometer that was irradiance-calibrated in vacuum at the TSI Radiometer Facility (TRF) with SI-traceability prior to launch (Schmutz et al. 2013). The DIARAD/PREMOS (Meftah et al. 2015), ACRIM3/ACRIMSat (Willson 2014), VIRGO/SoHO, and TCTE/STP-Sat3 (http://lasp.colorado.edu/home/tcte/) flight instruments are now consistent with this new TSI scale within instrument uncertainties, with the DIARAD, ACRIM3, and VIRGO having made post-launch corrections and the TCTE having been validated on the TRF prior to its 2013 launch. The Cycle 23 observations with these experiments are consistent with a mean TSI value of $S_\odot = 1361\ W\,m^{-2}$ ($\pm 1\ W\,m^{-2}; 2\sigma$). The uncertainty range includes contributions from the absolute accuracies of the latest TSI instruments as well as uncertainties in assessing a secular trend in TSI over solar cycle 23 using older measurements.

[4] Resolution B2 of the XXVIII General Assembly of the IAU in 2012 defined the astronomical unit *to be a conventional unit of length equal to 149 597 870 700 m exactly*. Using the current best estimate of the TSI (discussed in endnote 3), this is consistent with a current best estimate of the Sun's mean radiative luminosity of $L_\odot = 4\pi\,(1\ \mathrm{au})^2\,S_\odot = 3.8275\,(\pm 0.0014) \times 10^{26}$ W.

[5] The CODATA 2014 value for the Stefan-Boltzmann constant is $\sigma = 5.670\,367\,(\pm 0.000\,013) \times 10^{-8}\ W\,m^{-2}\,K^{-4}$. The current best estimate for the solar effective temperature is calculated to be $T_{\mathrm{eff},\odot} = 5772.0\,(\pm 0.8)$ K.

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- Mike Bessell for 1998 paper discussing $M_{bol}$/BCs
- Roger Cayrel for previous work on bol mag resolution
- Bill Folkner, Bob Jacobson for discussions on GMs
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