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REVIEW OF "THE COLORS, BOLOMETRIC CORRECTIONS AND EFFECTIVE TEMPERATURES OF THE BRIGHT STARS" BY JOHNSON (1964)

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RESUMEN

H. L. Johnson, 1964, BOTT, 3, 25, 305 determinó estrellas estándar para su fotometría JKL y M, y desarrolló una calibración que le permitió determinar correcciones bolométricas y temperaturas efectivas. De muchas formas Johnson se anticipó a los desarrollos que vendrían. Muchas de las observaciones de Johnson de las estrellas brillantes posiblemente todavía sean de las mejores disponibles debido a que posteriormente al trabajo de Johnson la astronomía se ha concentrado fuertemente en objetos débiles.

ABSTRACT

H. L. Johnson, 1964, BOTT, 3, 25, 305 established standard stars for his JKL and M photometry, and developed a calibration that enabled him to determine bolometric corrections and effective temperatures. In many ways Johnson anticipated the developments that were about to come forth. Many of Johnson's observations of the bright stars might still be the best available because astronomy has concentrated heavily on fainter objects following the end of Johnson's career.

Key Words: Hertzsprung-Russell and C-M diagrams — infrared: general — stars: fundamental parameters — techniques: photometric

1. INTRODUCTION

Harold L. Johnson was a pioneer and an innovator of astronomical instrumentation. His Ph.D. thesis at the University of California, Berkeley in 1948, *The Development of an Electronic Device for the Measurement of Stellar Spectrograms for Radial Velocity*, was telling because of his investigation of a new measuring device, even though it was applied to stellar spectroscopy. However, in his very next publication (Johnson 1948) he turned his attention to photoelectric photometry using a 1P21 photomultiplier, which led within a few years to the development of the UBV system (Johnson & Morgan 1953). While there had been previous magnitude systems, the rigor with which the UBV system was defined made it the standard that was copied by the magnitude systems that followed it, and it was not surpassed in terms of the sheer number of measurements until the appearance of the $u'g'r'i'z'$ system of the massive Sloan Digital Sky Survey (Fukugita et al. 1996).

In the decade following the introduction of the UBV system, Johnson applied it to study a variety of objects, but it seems clear that he was thinking about other instrumental developments. Then, beginning in 1962, he began to turn his attention to the spectral region beyond a wavelength of 1 μm (Johnson 1962). Other observers (Whitford 1948, 1958; Felgett 1951) had begun this exploration, but, in his characteristic approach, Johnson defined the field with the introduction of his JKL and M magnitudes, with $\lambda_{\rm eff} = 1.3, 2.2, 3.6$ and 5.0 μm, although he provided data only for the K magnitude and the $K - L$ color. In some ways, this turn toward the infrared was going against the trend of the decade. The 1960s were strongly influenced by the growth of NASA and the interest in space, which led naturally to the development of ultraviolet and X-ray astronomy, first using sounding rockets and then dedicated satellites. Johnson was leading in the opposite spectral direction, which is now fully embraced by the development of dedicated ground-based, airborne and satellite infrared observatories.

2. *BOLETÍN* PAPER

In his seminal *Boletín* paper, Johnson (1964) took ownership of infrared photometry, pushing it much farther than in his paper of just two years earlier (Johnson 1962). He enlarged his list of standard stars from 52 to 256, almost all of which had complete coverage from U to K, and a small number of

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stars were observed at L, M and even out to the N magnitude at 9 μm, which he had pioneered in Low & Johnson (1964). His standard stars spanned much of the Hertzsprung-Russell diagram, although he was limited to the types present among the stars of the brightest apparent magnitudes because he used relatively small telescopes. He did, however, make judicious use of larger telescopes to push to fainter magnitudes to obtain data for some notable stars, such as Barnard's star and three subdwarfs.

2.1. *Intrinsic Colors*

With his photometry completed, Johnson turned to consider the intrinsic colors of his standard stars after dividing them into three luminosity classes: I, III and V. For the class III stars, which ranged from spectral type G8 to M, he found no indication of interstellar reddening because the measured colors showed no dependence on apparent magnitude. This conclusion was reasonable because none of these stars were fainter than $V = 5.5$. Having reached this conclusion, Johnson either averaged his colors for each spectral type, with some smoothing, or plotted his colors against spectral type and fit a smooth curve through the points by eye to determine the intrinsic colors. Today, of course, we would use a more elaborate mathematical procedure, but Johnson's method was characteristic of his style and of his times. In fact, Johnson's brief discussion of a dip in his Figure 1 plot of $K - N$ versus $V - K$ colors seems rather quaint today, when we would do a numerical synthesis of the spectrum to investigate the cause of the dip. However, in 1964 numerical stellar atmospheres were still in their infancy, with the foundational work of Mihalas (1964) and Strom & Avrett (1964) just on the cusp of publication, and even those calculations included only continuous opacity sources.

Johnson next considered the intrinsic colors of the luminosity class I. Here, however, interstellar reddening could not be assumed to be negligible. Because no single method could be used for all these stars, Johnson achieved his goal by a patchwork approach. For stars hotter than type A0, he used data from Johnson (1963) and the method of Johnson & Borgman (1963). For stars cooler than type G8 he adopted the colors for luminosity class III. For the spectral types between these two regions he drew in the intrinsic color curve "as well as possible". Note that for some colors he had to adopt different procedures, in particular the results from Kron (1958).

Finally, for luminosity class V he used a combination of the methods employed for the other classes.

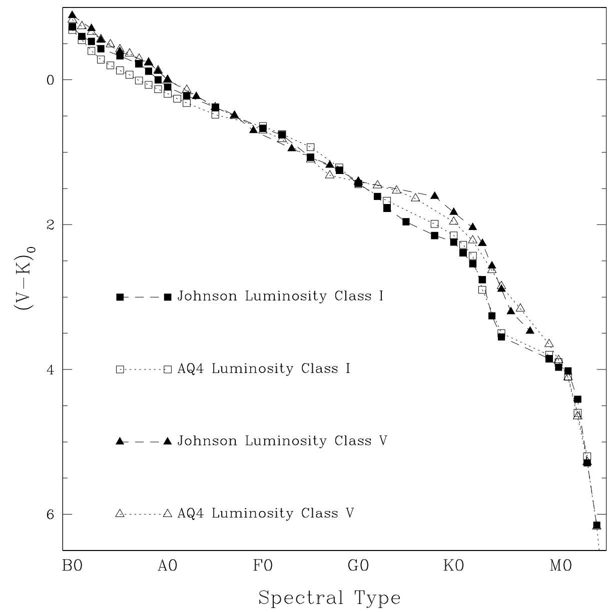

Fig. 1. Plots of intrinsic $V - K$ colors for luminosity classes I and V as a function of spectral type. The solid symbols and dashed lines are Johnson's values. The open symbols and dotted lines are from Tokunaga (2000) in Astrophysical Quantities 4th edition (AQ4).

In particular, stars cooler than type A0 were assumed to be unreddened, while the hotter types were corrected using an assumed reddening law.

How well have Johnson's intrinsic color stood up? To test this, Figure 1 plots his intrinsic $V - K$ color index as a function of spectral type for luminosity classes I and V. For comparison, Figure 1 also shows the intrinsic $V - K$ colors tabulated by Tokunaga (2000), which were compiled from several sources on the Johnson-Glass system established by Bessell & Brett (1988). The agreement between Johnson's original intrinsic $V - K$ colors and the more recent values is quite good overall. The largest deviations are for luminosity class I, particularly for spectral types hotter than A5, where the Johnson colors are up to 0.2 magnitudes more negative, and in the range from G0 to K0, where Johnson's colors are up to 0.16 magnitudes larger. Of course, for a given apparent magnitude the luminosity class I stars are the most distant, and, therefore, the stars most subject to interstellar reddening. As described above, the two regions of deviation are those where Johnson had to rely on the dereddening procedures that were available in 1964.

2.2. *Absolute Intensities*

Magnitudes and colors are, of course, relative quantities referenced to arbitrary zero points, but

TABLE 1

SOLAR COLORS

	$U-V$	$B-V$	$V-R$	$V-I$	$V-K$
Johnson	0.73	0.63	0.53	0.87	1.45
AQ4	0.845	0.65	0.54	0.88	1.49

Johnson wanted to express his flux measurements on an absolute basis. In attempting this, he was just slightly ahead of what was about to happen because Oke (1964) was on the verge of publishing the first modern measurements of stellar absolute spectrophotometry. However, Stebbins & Kron (1957) had measured the colors of the Sun and some of the stars measured by Johnson. Using the stars in common, Johnson was able to derive the colors of the Sun on his system. These colors are shown in Table 1, along with the values tabulated by Livingston (2000) in Astrophysical Quantities 4th edition. Except for the $U-V$ color, the differences are consistent with the expected photometric errors.

Johnson's next step was to convert his colors to ratios of energy using the Solar Constant and the Sun's apparent V magnitude, which he took from Allen (1963). Once again Johnson was pushing ahead of what was in progress because 1964 was five year before Arvesen et al. (1969) published one of the first modern determinations of the Sun's spectral energy distribution, and the later work of Neckel & Labs (1984) was still at the preliminary stage of measuring the intensity at the center of the Sun's disk (Labs & Neckel 1962). In addition, the value of the Solar Constant available to Johnson was 1.99 cal/cm^2/min, which corresponds to 1387.7 W/m^2. Our current value of the Total Solar Irradiance, as the Solar Constant is now called, is about 1367 W/m^2, which has been established by a succession of satellites. Therefore, Johnson's results were based on a foundation that was about 1.5% too large. Nevertheless, Johnson followed this admittedly indirect path to finding the total stellar energy reaching Earth for the stars he had observed.

To test his results, Johnson compare his total stellar energies to the much earlier radiometry of Pettit & Nicholson (1928). This comparison found two systematic difference. First, Johnson's energies were greater than those of Pettit & Nicholson (1928) by an average factor of 1.21, and, second, there was a trend of decreasing difference with increasing $V-K$ color, i.e., going toward cooler stars.

It is difficult to assess these difference because Johnson does not publish his values of the integrated stellar fluxes. However, he does provide two quantities related to the integrated stellar fluxes: the bolometric correction, defined as $B.C. = m_{\rm bol} - V$, and the effective temperature, $T_{\rm eff}$. Figure 2 shows Johnson's bolometric corrections for luminosity classes I and V as a function of spectral type. Also shown are the bolometric corrections tabulated by Drilling & Landolt (2000). The variation of the bolometric corrections with spectral types found by Johnson is similar to the more modern curves, but there are obvious differences. For one, Johnson's curves lie below the modern curves. This is a consequence of his decision to normalize to $B.C. = 0.0$ for the Sun. In fact, the modern value of the Sun's bolometric correction is $B.C. = -0.08$ as given by Livingston (2000) based on our ability to measure the Sun's Total Spectral Irradiance from space. Even beyond this, the bolometric corrections shown in Figure 2 from the tabulation of Drilling & Landolt (2000) give $B.C. = -0.20$ for spectral type G2V. The combination of these two factors explains most of the offset in Figure 2.

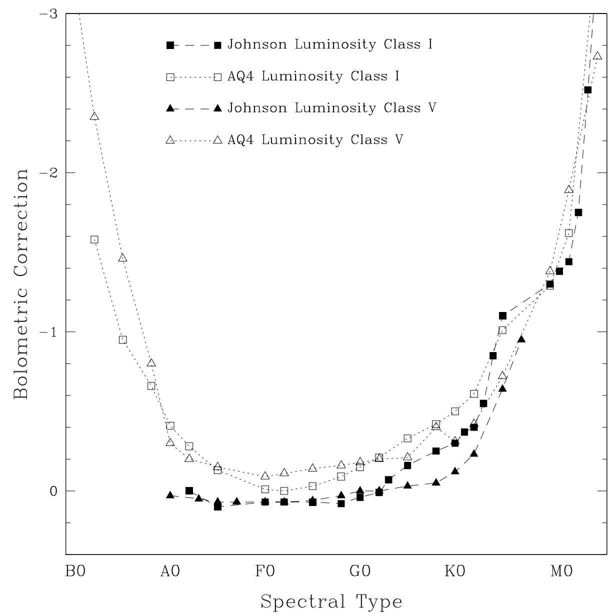

Fig. 2. Plots of bolometric corrections for luminosity classes I and V as a function of spectral type. The solid symbols and dashed lines are Johnson's values. The open symbols and dotted lines are from Drilling & Landolt (2000) in Astrophysical Quantities 4th edition (AQ4).

We also see the start of another difference at spectral type A0. Johnson's photometry was fairly complete to the K band at 2.2 μm, with some stars being measured as far as the N band at 9.0 μm, so he achieved a largely complete sampling of the radiation of the cooler stars. However, he was limited to the U band in the ultraviolet, which missed the large amount of radiation emitted by the hotter stars. Johnson did make use of some of the earliest ultraviolet rocket data (Chubb & Byram 1963) that had just become available, but, strangely, these new ultraviolet data were less that had been expected, pushing down the bolometric correction. In any case, at spectral type A0 we are beginning to see the modern bolometric corrections turn up, a trend that Johnson was unable to follow in 1964.

2.3. *Effective Temperatures*

The effective temperature of a star is one of the key parameters used to characterize the stellar atmosphere. Johnson had already found the integrated stellar fluxes arriving at Earth, but the angular diameters were also required for the star to find their effective temperatures. In 1964 only a small number of Johnson's stars had measured angular diameters. Using the data available for the Sun, for α CMA from early intensity interferometry (Hanbury Brown 1956), for α Ori from the pioneering optical interferometry of Michelson & Pease (1921) and from the measurement of eclipsing binary stars made by different observers, Johnson created a table of ten stars with sufficient data to make empirical determinations of their effective temperatures. (Johnson's Table 8 also included effective temperatures for α Lyr and σ Boo, but these were given no weight in his analysis because they were not directly determined values.) The stars used by Johnson spanned the range 2015 $K \leq T_{\rm eff} \leq 10084$ K. To apply these limited data to his large table of stars, Johnson devised in interpolation scheme for $10^4/T_{\rm eff}$ as a function of the quantity $(R + I) - (J + K)$. The empirical points in Johnson's Figure 5 were used to anchor a fit based on blackbody radiation passing through the R, I, J and K bands. With this calibration curve, Johnson used his measured R, I, J and K magnitudes to find $T_{\rm eff}$ for his 256 stars.

In the years since Johnson's *Boletín* paper there have been numerous calibrations of $T_{\rm eff}$. Figure 3 compares Johnson's values for luminosity classes I and V with the values tabulated by Drilling & Landolt (2000) in *Astrophysical Quantities 4^{th}* edition. The calibrations clearly track each other, but there are substantial differences, particularly for the luminosity class I stars. For example, around spectral type A0 I Johnson's calibration is cooler by up to 600 K, corresponding to about 7% less than the current value. On the other hand, in the region from F5 I to G0 I Johnson's values for $T_{\rm eff}$ are up to 500 K, or more than 9% hotter. Of course, there have been

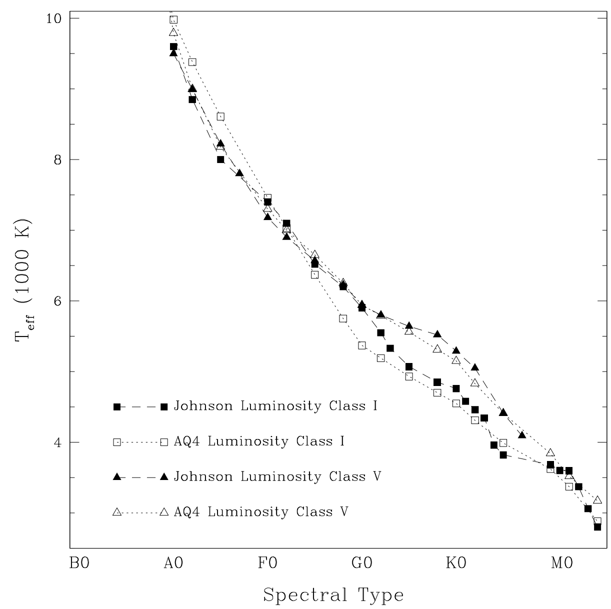

Fig. 3. Plots of effective temperature for luminosity classes I and V as a function of spectral type. The solid symbols and dashed lines are Johnson's values. The open symbols and dotted lines are from Drilling & Landolt (2000) in Astrophysical Quantities 4th edition (AQ4).

tremendous advances in the decades since Johnson's efforts, and, given the number of calibrations he had to assemble just to reach his values, his results are amazingly close.

2.4. *Zero-Age Main Sequence*

Another of Johnson's lasting contributions to stellar astronomy was his recognition of the importance of the Zero Age Main Sequence (ZAMS) (Johnson & Hiltner 1956). Using the work of Johnson (1963) and Johnson & Iriarte (1958) together with the data in the *Boletín* paper, he was able to tabulate the ZAMS is several ways. One was in terms of $M_{\rm V}$ as a function of $(B - V)_0$. Figure 4 shows a comparison of Johnson's ZAMS and the tabulation of Drilling & Landolt (2000). The agreement is very close, but there are deviations. For the stars with $(B-V)_0 < 0.0$, Johnson's absolute visual magnitudes are about 0.1 magnitudes brighter, and for stars in the color range $0.0 \leq (B - V)_0 \leq 0.8$, Johnson's $M_{\rm V}$ values are up to 0.15 magnitudes fainter.

Figure 4, however, does not convey fully the advances that have taken place since Johnson's work. Johnson's ZAMS stops in the early B-type stars, while work after 1964 pushed well into the O-type stars. Maybe more significantly, the infrared awareness that Johnson initiated has continued toward

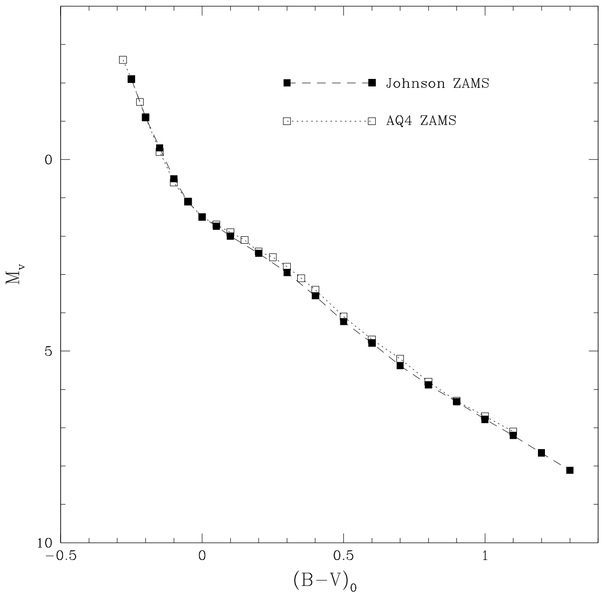

Fig. 4. The Zero Age Main Sequence. The solid symbols and dashed lines are Johnson's values. The open symbols and dotted lines are from Drilling & Landolt (2000) in Astrophysical Quantities 4th edition (AQ4).

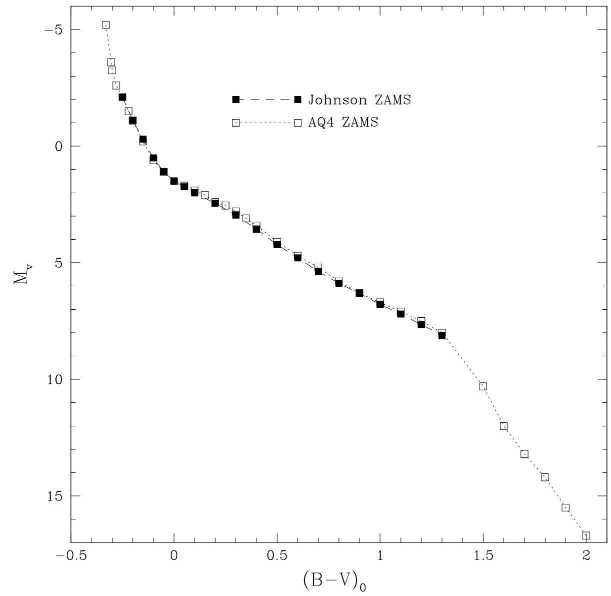

Fig. 5. The full extent of the Zero Age Main Sequence. The solid symbols and dashed lines are Johnson's values. The open symbols and dotted lines are from Drilling & Landolt (2000) in Astrophysical Quantities 4th edition (AQ4).

cooler and cooler spectral types. Johnson commented that his table included very few red dwarfs, and some of these stars might not be reliable examples, so his ZAMS stopped at spectral type K7 V with the note that further observations were needed to extend toward cooler spectral types. These observations have now been made, going to the end of the stellar main sequence and continuing into the substellar region of the brown dwarfs that had not been discovered in Johnson's time. To appreciated the advances that have been made since 1964, Figure 5 shows the ZAMS from spectral type mid-O to mid-M, again taken from the tabulation of Drilling & Landolt (2000).

2.5. *Deficiencies*

In summarizing his *Boletín* paper, Johnson recognized that it was deficient in several ways. As noted in § 2.4, he pointed out that there were only a few observations of M-dwarf stars, but he had already begun an observational program to address this. Second, he clearly identified the need to make additional measurements of stellar angular diameters. The pioneering work of Hanbury Brown (1956) was cited as a particularly attractive method, but its limitation to hot stars was recognized. The much older work of Michelson & Pease (1921) seemed a possibility for cooler stars, but the development of modern optical/infrared interferometry was still far in the future in 1964 (Armstrong et al. 1998; ten Brummelaar et al. 2005). Finally, Johnson clearly understood that the lack of photometric data at wavelengths less than 0.3 μm was critical to improving the determination of effective temperatures for stars hotter than spectral type A0, and this situation has now been addressed by decades of space observations.

3. CONCLUSIONS

Johnson's important paper in the *Boletín* was significant on many levels. It continued his pioneering photometry, begun with the establishment of the UBV system, to longer wavelengths by establishing the J, K, L, M and N bands. As was the case with the UBV photometry, Johnson was careful to define in this paper an extensive set of standard stars given his Table 2 (Johnson 1964). Because he was concerned with the information present in the photometry, he used his data to find integrated fluxes, bolometric corrections and effective temperatures. Much of this effort was premature because of the developments that were yet to occur in the areas of absolute spectrophotometry, ultraviolet astronomy and the measurement of angular diameters. Therefore, Johnson served as a harbinger of what was coming. Finally, his revised zero-age main sequence was an important tool in 1964 when using computers to calculate stellar structure was still in its early stages.

In some ways, the photometric data of the *Boletín* paper are still fresh. In the decades since Johnson's careful observations, astronomy has entered an era of huge surveys, enabled by the development of telescopes with larger and large diameters and fields of view, highly efficient array detectors for visible and infrared radiation, and automated reductions procedures. A byproduct of these technological advances is a shift from observing individual bright stars to observing masses of fainter and fainter objects. For example, the extremely successful 2 Micron All Sky Survey (2MASS) has measurements for approximately 300 million stars (and other unresolved objects), but they are limited to stars with $K_{\rm s}$ fainter than fourth magnitude. For comparison, almost all the stars in Johnson's (1964) Table 2 are brighter than this limit. Therefore, Johnson's data may still be the most recent available for a large number of the bright stars. This is in keeping with the approach followed by Johnson for the remainder of his career. In one of his final papers (Johnson et al. 1978) he used a novel Fourier Transform Spectrometer to observe some of the brightest stars in the sky and found interesting spectral features that had not be reported in previous spectroscopy. For Johnson, faint magnitudes were not the goal. For him it was more important to push the instrument to new limits to learn new things about even the brightest stars, and he was innovating to the end.

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