The Metallicity Sensitivity of a Surface Brightness Temperature Scale

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Abstract

To obtain the accuracy now sought in the extragalactic distance scale through standard candles and rulers, the calibration of stellar photometry must be improved. The sensitivity of the $V-K$ color surface brightness relation is examined here by means of model atmosphere fluxes. It has previously been neglected, but is shown here to be a significant term in the error budget of a recent high-precision distance of the Large Magellanic Cloud, an anchor in galaxy distances based on Cepheids.

Key words: binaries: eclipsing – galaxies: distances and redshifts – stars: abundances

Online material: color figures

1. Introduction

The goal of 1% accuracy in the extragalactic distance scale places new demands on stellar astrophysics. ESA’s Gaia mission has opened up new possibilities in the classes of stars that can be standard candles (e.g., Mould et al. 2019). Pietrzynski et al. (2019) employ the surface brightness color relation to attain the required accuracy in the distance of the Large Magellanic Cloud (LMC). Both works require accurate calibration of photometry to temperatures and luminosities.

In this paper we explore the metallicity dependence of the surface brightness color relation using the surface fluxes of Kurucz model atmospheres.

2. Surface Brightness and Effective Temperature

Eclipsing binaries allow accurate measurements of stellar radii (e.g., Elgueta et al. 2018). Physically, we can understand this as combining the definition of effective temperature, $T_e$, 

$$L = 4\pi\sigma R^2 T_e^4,$$

where $L$ and $R$ are the stellar luminosity and radius, respectively, with a geometric measurement of $R$. Dividing by stellar surface area, we obtain a flux

$$F = \sigma \theta^2 T_e^4,$$

where $\theta$ is the stellar angular radius and $\sigma$ is the Stefan–Boltzmann constant. If the flux is measured photometrically, the effective temperature can be estimated from $V-K$ (e.g., Di Benedetto 1998, 2005). One combines $\theta$ and $R$ to obtain the distance.

In these terms, we can express the error propagation: $\delta\theta/\theta = 2\delta T_e/T_e$. If $V-K = f(T_e, g, Z)$, then

$$\delta(V-K) = \frac{\partial f}{\partial T_e} \delta T_e + \frac{\partial f}{\partial g} \delta g + \frac{\partial f}{\partial Z} \delta Z.$$

It is possible to ignore the second term for the time being, supposing the ratio of stellar mass to $R^2$ to be perfectly determined by a spectroscopic eclipsing binary solution and investigate the third term using the predictions of Kurucz model atmospheres.

3. Synthetic Color Temperature Relation

The relation between $V-K$ and $T_e$ can be modeled using Buser & Kurucz (1992) fluxes and Bessell (2005), together with Bessell & Brett (1988) filter responses. The fluxes of these models are not well sampled in the near-infrared, and were therefore interpolated in the $K$ bandpass. Results are independent of whether linear or parabolic interpolation was used. The dependence of color on metallicity at fixed gravity is illustrated in Figure 1. Similar results are obtained using model atmosphere fluxes with nearly two orders of magnitude more spectral resolution (Allard 2016). These models include TiO in the $V$ bandpass and CO in the $K$ bandpass, and so they are superior in their predictions for $K$ giants and M stars.

Spherical models are also available to complement the standard plane parallel atmosphere models (e.g., SATLAS, Lester & Nielson 2008). At one solar mass MARCS models1 by Gustafsson et al. (2008) are redder in $V-K$ at 5000 K and log $g = 3$ in the spherical case than the plane parallel case, but $\partial f/\partial \log Z$ is almost identical.

1 marcs.astro.uu.se
4. Red Clump Stars

Pietrzynski et al. (2019) employ eclipsing binaries from the red clump in the LMC. Onozato et al. (2019) find a mean value $K \approx 16.82$ mag for the red clump in star clusters, and if the LMC is $50\text{ kpc}$ distant, a bolometric correction $BC_K = 1.92$ mag (Johnson 1966) gives $\log \frac{L}{L_\odot} \approx 2.0$. For solar mass stars, the gravity is $\log g = 2.2$. Figure 2 shows that $d(V - K)/d\log Z \approx 0.2$ mag dex$^{-1}$.

If $d(V - K)/d\log T_e = 2/0.176$, then $d\log T_e/d\log Z = 0.1 \times 0.176$. This means that if an error $\delta \log Z = 0.3$ is made, then $d\log T_e = 0.434 \delta T/T = 1.76 \times 10^{-3}$ and $\delta T/T = 0.004$, corresponding to a 0.8% error in distance.

5. Giant Branch Stars

If the stars lie on a giant branch, appropriate gravities for each temperature should be employed. In solar logarithmic units, $[g] = [M] - [L] + 4[T_e]$. Modeling the giant branch as a one solar mass line commencing at the Sun and linear in log L, log T to $L_{\text{tip}}$, $T_{\text{tip}}$, we can write $[L] = [L_{\text{tip}}]/[T_{\text{tip}}] [T_e]$ If $L_{\text{tip}} = 2000 L_\odot$ and $T_{\text{tip}} = 3500 K$, then $[g] = 18.9 [T_e]$ With these assumptions, we derive Figure 3.

6. Main Sequence Stars

The surface brightness $V - K$ relation is also employed on the main sequence. We show the modeled gravity dependence of $V - K$, the second term in the error propagation equation, in Figure 4.

7. Conclusion

For precision of 1% in distance the metallicities of eclipsing binaries should not be neglected, as the surface brightness color relation is affected by $V - K$ metallicity dependence at this level. In the range they explore, Onozato et al. (2019) find that population effects on JHK colors of LMC red clump stars are small. It may be possible to control the metallicity dependence noted here by small correction to...
the $V - K$ colors in the $V$ bandpass where blanketing by absorption lines is greater than in the infrared.

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**Figure 4.** Modeled $V - K$ color dependence on gravity for three stellar temperatures at solar metallicity (above) and approximately one third solar metallicity (below). As in the previous figures, red symbols are $T_e = 4500$ K, green = 5000 K, and blue = 5500 K. (A color version of this figure is available in the online journal.)