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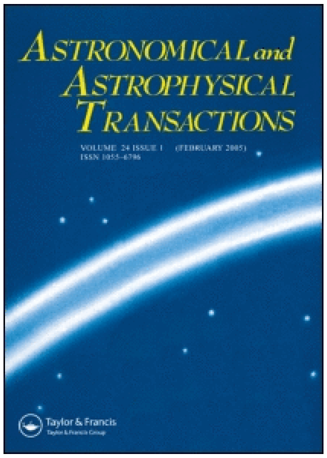

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THE LUMINOSITIES OF RED SUPERGIANTS FROM WING'S EIGHT-COLOR NARROW-BAND INFRARED PHOTOMETRY

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(11 February, 1992)

Calibration relations have been obtained for the intrinsic color index θ_0 ($\theta = 5040/T_c$, T_c being the observed color temperature of a star) and absolute magnitudes M(104) (at $\lambda = 1.04\,\mu$, in Wing's narrow-band photometric system), M_V and M_K as functions of TiO and CN photometric indices for K5–M5 supergiant stars. The accuracy of the distance moduli obtained when using these calibrations is about $0\overset{m}{.}2$. The distance moduli have been calculated for red supergiants which are members of open clusters. The distance scale for red supergiants based upon the M(104) (TiO, CN) absolute magnitude calibration (the distance modulus of $11\overset{m}{.}4$ being assumed for the Per OB1 stellar association) agrees with the distance scale for young open clusters based upon $uvby\beta$-photometry and Crawford's (1978) ZAMS for B-type stars.

KEY WORDS Red supergiants—luminosities, red supergiants—color temperatures, calibrations.

1. INTRODUCTION

Red supergiants, that are young stars of high luminosity, should become an efficient tool for the study of spiral structure, stellar complexes and large-scale kinematics of the galactic disk. But at present these stars do not play a very important role in such studies because they are relatively rare (as compared to OB-stars) and their distances could not be estimated accurately enough (as, for instance, the distances of open clusters and cepheids), the only method being based on two-dimensional MK spectral classification and UBV photometry. More than two decades ago Wing (1970) has developed a special eight-color narrow-band photometric system to study late-type stars in the near infrared and it was shown (White and Wing, 1978) that the reddening-free photometric indices of the system characterizing TiO and CN molecular band intensities could be used for the accurate two-dimensional classification of late-type supergiants. Wing (1966) has proposed to use the I(104) narrow-band magnitude with $\lambda = 1.04\,\mu$ (measured using one of the filters of the eight-color system), which wavelength is situated in an atmospheric window and contains no blanketing lines, as the main brightness measure for late-type stars. Wing (1989) has also proposed to calibrate the luninosity-sensitive CN index in terms of the M(104) absolute magnitude but he considered the number of red supergiants with available eight-color data belonging to the open clusters of known distance to be insufficient for this purpose. Here we attempt at preliminary calibration of the M(104), M_V and M_K

absolute magnitudes as functions of the TiO and CN indices using only the red supergiants belonging to the well-studied Per OB1 stellar association which contains a large population of such stars, 26 of them having their eight-color data published (White and Wing, 1978). We have also calibrated the TiO index in terms of the intrinsic θ-index ($\theta = 5040/T_c$, T_c being the color temperature of a star derived from the eight-color data—see White and Wing, 1978).

2. EIGHT-COLOR OBSERVATIONAL DATA FOR RED SUPERGIANTS

The most complete catalogue of Wing's eight-color photometry for red supergiants was published by White and Wing (1978) where, along with the observed magnitudes in eight filters of the system, the derived values of the TiO and CN indices as well as the θ-indices are given for 128 K5-M5 supergiant stars. In addition, eight-color data for 5 highly reddened M supergiants situated in the direction towards the galactic center have been published by Warner and Wing (1977). Since then many more red supergiants have been observed in the eight-color system (Wing, MacConnell and Costa, 1987) but the photometric data still has not been published.

3. THE CALIBRATION OF THE INTRINSIC COLOR TEMPERATURE INDEX θ_0 AS A FUNCTION OF THE TiO INDEX

Here the intrinsic (dereddened) color temperature index θ_0 is assumed to be a linear function of the TiO index:

$$\theta_0 = a + b * \text{TiO}, \tag{1}$$

and the color excess $\Delta\theta = \theta - \theta_0$ is assumed to be proportional to the E_{B-V} color excess (Warner and Wing, 1977):

$$\Delta\theta = a * E_{B-V}. \tag{2}$$

From Eqs. (1) and (2), the following formula for $\theta = \theta_0 + \Delta\theta$ can be derived:

$$\theta = a + b * \text{TiO} + \alpha * E_{B-V}. \tag{3}$$

For 93 stars from the list of White and Wing (1978) with published (B-V) indices (Nicolet, 1978; Humphreys and McElroy, 1984) and without early-type companions (which could contaminate the (B-V) index), the color excess $E_{B\text{-}V} = (B\text{-}V) - (B\text{-}V)_0$ has been estimated, $(B\text{-}V)_0$ being derived from the spectral class of the star using Table 11 from Straizys (1977). The solution of the system of linear equations (3) for 92 stars with VY Cma excluded from the final fit because of a large deviation from the mean relation which may be due to the contamination of the (B-V) index by the contribution of the surrounding reflection nebula (see Figure 1), by the least squares method yields the following

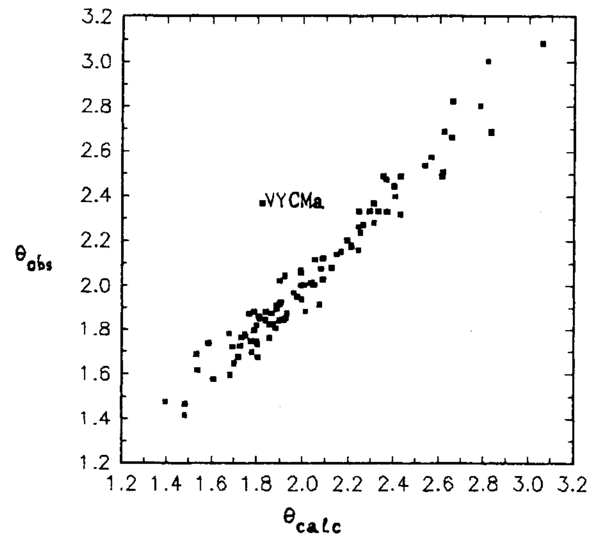

Figure 1 The observed θ ($\theta_{\rm obs}$) vs. calculated θ ($\theta_{\rm calc} = 1.330 + 0.00289 \times \text{TiO} + 0.824 \times E_{B\text{-}V}$, see equations (3) and (4) in the text), *VY* CMa being an evident outlier.

values of a, b and α:

$$
\begin{aligned}
a &= +1.330 \pm 0.022, \\
b &= +0.00289 \pm 0.00031, \\
\alpha &= \ \ +0.824 \pm 0.020, \\
\sigma\theta &= \ 0.073, \text{ the standard deviation for a single star.}
\end{aligned} \tag{4}
$$

Hence:

$$
\begin{aligned}
\theta_0 &= +1.330 + 0.00289 \times \text{TiO}, \\
\sigma\theta_0 &\leq 0.073(\sigma\theta_0 = \sqrt{\sigma\theta^2 - \sigma(\Delta\theta)^2} \leq \sigma\theta)
\end{aligned} \tag{5}
$$

and

$$\Delta\theta / E_{B\text{-}V} = 0.824. \tag{7}$$

Wing (1967) has found $E_{B\text{-}V}/\Delta\theta = 1.25$, i.e., $\Delta\theta/E_{B\text{-}V} = 0.80$ and our result is in a good agreement with this estimate. By transforming the spectral type into the TiO value (see Table 4 in White and Wing, 1978) we can derive from Eq. (5) a calibration of the spectral type in terms of θ_0 which is in a good agreement with that for the stars of the luminosity class Iab reproduced (in a graphical form only) in Warner and Wing (1977) (see Figure 2).

4. THE CALIBRATION OF THE M(104), M_V *AND* M_K ABSOLUTE MAGNITUDES OF RED SUPERGIANTS AS FUNCTIONS OF TiO AND CN INDICES

Here we assume the M(104) absolute magnitude of red supergiants to be linear function of the $\sqrt{\text{TiO}}$ and CN index ($\sqrt{\text{TiO}}$ is used instead of TiO for purely

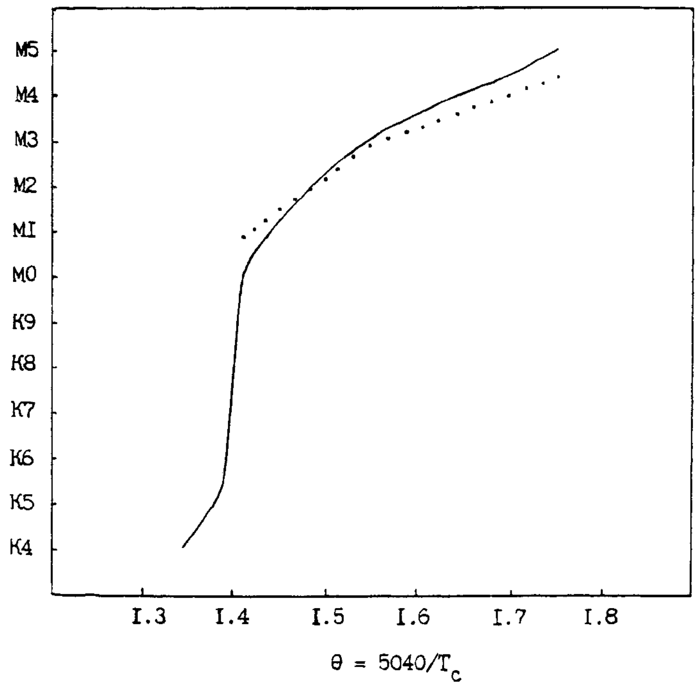

Figure 2 Color-spectral type relation for red supergiants in the eight-color system of Wing. The special type (based on the TiO strength) is plotted against the θ-index ($\theta = 5040/T_c$, T_c being the color temperature obtained by fitting the blackbody curves to the eight-color data), the solid line representing the calibration (5) and the dotted one, the calibration of Warner and Wing (1977) for the stars of the luminosity class Iab.

technical reasons since in this way the scatter of the resulting calibrations for the absolute magnitudes in all passbands under examination, $M(104)$, M_K and M_V, is reduced):

$$\mathrm{M}(104) = h + p \times \sqrt{\mathrm{TiO}} + q \times \mathrm{CN}, \tag{7}$$

and the absorption $A(104)$ at $1.04\,\mu$ is assumed to be proportional to $\Delta\theta$ (Warner and Wing, 1977):

$$A(104) = \beta \times \Delta\theta, \tag{8}$$

Using the distance modulus of a star, DM_*,

$$DM_* = I(104) - A(104) - M(104), \tag{9}$$

we have

$$I(104) = M(104) + A(104) + DM_*. \tag{10}$$

Taking into account Eqs. (7) and (8), the following relation can be derived for $I(104)$:

$$I(104) = (h + DM_*) + p \times \sqrt{\mathrm{TiO}} + q \times CN + \beta \times \Delta\theta. \tag{11}$$

We further assume that all 26 red supergiant member stars of the Per OB1 stellar association with published eight-color data (White and Wing, 1978) have the same distance modulus as the double star cluster χ and h Per at the core of the association: $DM_* = DM_{\chi \text{ and } h \text{ Per}} = 11.4$—this value was derived by Shobbrook (1984) from the $uvby\beta$-photometry of early-type stars using $M_V(c_0)$ *ZAMS* of Crawford (1978). Solving the system of linear equations (11) for these stars by the least squares method ($\Delta\theta = \theta - \theta_0$, θ_0 calculated from Eq. (5)) we obtain the following values for $h + DM_*$, p, q and β (see Figure 3 for $I(104)_{obs}$ vs. $I(104)_{calc}$):

$$\begin{aligned} &h + DM_{\text{Per OB1}} = +6.77 \pm 0.27, \\ &h = -4.73 \pm 0.27 \text{ (for } DM_{\text{Per OB1}} = 11.4), \\ &p = -0.240 \pm 0.020, \\ &q = -0.0768 \pm 0.0121, \\ &\beta = +1.25 \pm 0.19, \\ &\sigma(I(104)) = 0^{\text{m}}.19, \text{ standard deviation for a single star.} \end{aligned} \tag{12}$$

Hence (for $DM_{\text{Per OB1}} = 11.4$):

$$M(104) = -4.63 - 0.240 \times \sqrt{\text{TiO}} - 0.768 \times \text{CN}, \tag{13}$$

$\sigma(M(104)) \leqslant 0^{\text{m}}.19$ $(\sigma(M(104)) = \sqrt{(\sigma(I(104))^2 - \sigma(A(104))^2)} \leqslant \sigma(I(104))$, standard deviation for a single star, and

$$A(104) = 1.25 \times \Delta\theta, \tag{14}$$

$$\sigma(A(104)) \leqslant 0^{\text{m}}.19; \ \sigma(A(104)) \leqslant \sigma(I(104)).$$

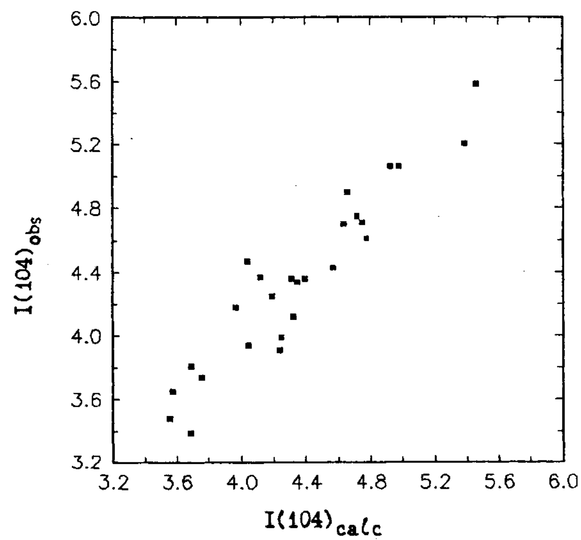

Figure 3 The observed $I(104)$ magnitude ($I(194)_{obs}$) vs. the calculated value of $I(104)$ ($I(104)_{calc} = 6.77 - 0.24 \times \sqrt{\text{TiO}} - 0.0768 \times \text{CN} + 1.25 \times \Delta\theta$, see equations (11) and (12) in the text) for the red supergiants of the Per OB1 stellar association.

The value of $\beta = A(104)/\Delta\theta$ is identical to that found by Wing (1970). In the same way, the calibrations for the M_V and M_K absolute magnitudes have been derived. We have for the V-band magnitude:

$$V - DM_* = M_V + A_V.$$

Assuming that

$$A_V = \beta_V \times \Delta\theta,$$
$$M_V = h_V + p_V \times \sqrt{\mathrm{TiO}} + q_V \times \mathrm{CN},$$

we obtain from the data for 22 stars in the Per OB1 association (V-band mangitudes taken from Nicolet, 1978 and Humphreys and MacElroy, 1984) the following values for unknown constants:

$$h_V = -3.25 \pm 0.41 \text{ for } DM_{\mathrm{Per\ OB1}} = 11.4,$$
$$p_V = -0.046 \pm 0.029,$$
$$q_V = -0.0726 \pm 0.0170,$$
$$\beta_V = 3.98 \pm 0.23,$$

$\sigma(V) = 0\overset{\mathrm{m}}{.}22$, standard deviation for a single star. This implies that

$$M_V = -3.25 - 0.046 \times \sqrt{\mathrm{TiO}} - 0.0726 \times \mathrm{CN}, \qquad \sigma(M_V) \leqslant 0\overset{\mathrm{m}}{.}22, \tag{15}$$

and

$$A_V = 3.98 \times \Delta\theta, \qquad \sigma(A_V) \leqslant 0\overset{\mathrm{m}}{.}22. \tag{16}$$

From the data for 22 red supergiants in the Per OB1 association with known K-band magnitudes (Gezari *et al.*, 1984) the following relations have been derived:

$$\begin{aligned} M_K = {} & -6.34 - 0.257 \times \sqrt{\mathrm{TiO}} - 0.0607 \times \mathrm{CN} \\ & \pm 0.43 \pm 0.027 \qquad\qquad \pm 0.0182 \\ \sigma(M_K) & \leqslant 0\overset{\mathrm{m}}{.}21, \end{aligned} \tag{17}$$

and

$$A_K = (0.34 \pm 0.22) \times \Delta\theta, \qquad \sigma(A_K) \leqslant 0\overset{\mathrm{m}}{.}21. \tag{18}$$

The distance modulus and $\Delta\theta$ color excess for red supergiant stars in open clusters estimated from the eight-color photometry of White and Wing (1978) using relations (5), (13) and (14) are given in Table 1. For five red supergiants in open clusters, with published $uvby\beta$-data for the early-type members, the calculated values of the distance modulus agrees well with distance modulus estimates derived from the Stroemgren photometry of early-type member stars ($\langle \Delta DM \rangle = \langle DM_{\mathrm{Star}} - DM_{\mathrm{Cluster}} \rangle = 0\overset{\mathrm{m}}{.}0 \pm 0\overset{\mathrm{m}}{.}1$). The intrinsic scatter of the distance modulus estimates for four red supergiant member stars in NGC 3766 is $0\overset{\mathrm{m}}{.}22$. These results confirm a high accuracy of the distance moduli calculated using the calibrations derived above (the typical error being $\sim 0\overset{\mathrm{m}}{.}2$) as well as the absence of the systematical difference between the constructed red-supergiant distance scale and the intermediate-band-photometry-based distance scale of young open clusters.

Table 1 The distance moduli of red supergiants in open clusters from Wing's Eight-Color Narrow-Band Infrared Photometry

Cluster	*Star*	*Distance modulus of the star*	$\Delta\theta$	*Distance modulus of the cluster (uvbyβ-photometry)*	*Reference to the uvbyβ-photometry*
NGC 457	HDE 236697	12.02	0.31	—	—
NGC 581	BD + 59°274	11.92	0.31	—	—
NGC 654	BD + 60°310	11.81	0.51	—	—
NGC 663	BD + 60°335	11.88	0.50	—	—
NGC 3766	CD − 60°3621	11.44	0.18	11.3	
NGC 3766	HD 100930	11.45	0.20	11.3	Shobbrook (1985, 1987)
NGC 3766	CD − 60°3636	11.52	0.18	11.3	
NGC 3766	HD 101007	11.04	0.17	11.3	Shobbrook (1984)
NGC 4755	CD − 59°4459	11.24	0.41	11.5	

4. CONCLUSION

Eight-color narrow-band infrared photometry of White and Wing (1978) for red supergiants has been used to construct calibrations of the intrinsic color index θ_0 and the absolute magnitudes $M(104)$, M_K and M_V as functions of the molecular band strength indices TiO and CN (derived from the photometric data alone). The absolute magnitude calibrations derived are very precise, the standard deviation for a single star being $\sim 0\overset{\text{m}}{.}2$. The calculated distance moduli for the red supergiant member stars of open clusters are in a good agreement with Crawford's (1978) *ZAMS*-based distance moduli of young open clusters calculated from the *uvbyβ*-data.

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