INTRINSIC COLOR INDICES AND LUMINOSITY SEQUENCES
OF STARS IN THE 2MASS TWO-COLOR DIAGRAM

V. Stražys¹ and Romualda Lazauskaitė¹, ²

¹ Institute of Theoretical Physics and Astronomy, Vilnius University,
Gostauto 12, Vilnius LT-01108, Lithuania; straizys@itpa.lt
² Department of Theoretical Physics, Pedagogical University, Studentų 39,
Vilnius, LT-08106, Lithuania; laroma@itpa.lt

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Abstract. Intrinsic sequences of luminosity V and III stars in the
J–H vs. H–Kₙ diagram of the 2MASS system are determined using about 1250 unreddened
and dereddened stars. Intrinsic color indices for MK spectral classes are
tabulated and compared with the results in other JHK systems.

Key words: stars: fundamental parameters – photometric systems: infrared, 2MASS

1. INTRODUCTION

Due to its ability to identify many types of stars, all-sky coverage and a faint
limiting magnitude, the 2MASS JHKₙ system has become one of the most popular
photometric systems. However, until now the accuracy of intrinsic colors in the
system is still insufficient. The users of the 2MASS system usually apply intrinsic
colors transformed from the Glass JHKₙ system (Bessell & Brett 1988) with the
equations given by Carpenter (2001). However, these equations are linear, and
they may not be valid for all types of stars, especially, at the edges of the tem-
perature scale, or for stars of different luminosities, metallicities and peculiarities.
Consequently, a direct determination of the intrinsic colors of stars in the 2MASS
system is desirable.

A direct calibration of color indices of 2MASS stars in spectral and luminosity
classes is not trivial. Most stars with the best known values of physical parameters
and spectral types were too bright for 2MASS photometry. According to Skrutskie
et al. (2006), images of stars brighter than Kₙ = 4.5 mag were saturated, and
their uncertainties are of the order of 0.2–0.4 mag. On the other hand, most
of fainter stars, especially of early types or giants and supergiants, are affected
by interstellar reddening. For their dereddening a knowledge of the slopes of
interstellar reddening lines and color excesses is essential. These data, however,
are not always known with sufficient accuracy.

Recently, Stražys, Corbally & Laugalys (2008) have determined mean intrinsic
color indices (J–H)₀ and (H–Kₙ)₀ in the 2MASS system of O8, B5.5 and B8.5
spectral classes by dereddening stars with small color excesses. In the present work we extend the investigation to main-sequence stars of all spectral classes and to late-type giants. To obtain the mean intrinsic lines of luminosity V and III stars in the $J-H$ vs. $H-K_s$ diagram we use both unreddened stars and stars with small color excesses.

The $J$, $H$ and $K_s$ magnitudes are taken from the 2MASS database. We used only those stars which have the accuracy of magnitudes $\leq 0.05$ mag. All stars with magnitudes $J$, $H$ or $K_s$ brighter than 4.5 mag (i.e., with saturated images) were rejected.

2. MAIN-SEQUENCE STARS

For the determination of intrinsic color indices of main-sequence stars we tried to use, where possible, unreddened stars with reliable spectral classification available. One of such lists was published by Gray et al. (2003), covering many F, G and K dwarfs within 40 pc from the Sun. In the same spectral range we used stars from the three open clusters – Praesepe, Pleiades and M39 – selecting the main-sequence stars unsaturated in 2MASS photometry. In the clusters, Am and Ap stars as well as visual and spectroscopic binaries were rejected. The Praesepe stars were considered to be unreddened, but for the Pleiades and M39 stars the $J-H$ and $H-K_s$ colors were slightly corrected for reddening. Their spectral types and $B-V$ color indices were taken from the WEBDA database.

The Pleiades also contain a good sample of B and A stars, but most of these B stars were too bright for precise 2MASS photometry. Thus, the B-star sample was supplemented by members of the Orion OB1 association of spectral classes B0–B2 from the Humphreys & McElroy (1984) list and of spectral classes B5–A2 from Černis et al. (1998). Additionally, B-type stars of the association/cluster Collinder 121 with the data from the WEBDA database were used. The Orion association and Collinder 121 stars were dereddened individually, their $E_{B-V}$ mostly are $\leq 0.10$. To increase the number of stars, we added some B-stars of luminosity IV since there is no evidence that they differ from luminosity V in the near infrared.

O-type stars of luminosities V–III having little interstellar reddening were selected from the catalog published by Maíz-Apellániz et al. (2004). From these, 16 stars of spectral classes O6.5–O9.5 have color excesses $E_{B-V} \leq 0.25$ and 9 stars of classes O3–O6 have $E_{B-V}$ in the range 0.28–0.39. Magnitudes $J$, $H$ and $K_s$ for these stars were taken from the original 2MASS catalog since in the Maíz-Apellániz et al. catalog they have systematic differences. For dereddening their $J-H$ and $H-K_s$ color indices we used their $B-V$ from the above mentioned catalog and the intrinsic color indices $(B-V)_0 = -0.315$.

M-type dwarfs, mostly of early subclasses, were taken from the Praesepe and Pleiades clusters (Adams et al. 2002, Table 4). More M-dwarfs of the early subclass group (M0–M5.5 V) were taken from Kirkpatrick et al. (1991) and Henry et al. (1994). Late M-dwarfs (M6–M9.5) were taken from Kirkpatrick et al. (1991), Gizis et al. (2000) and Liebert & Gizis (2006). A few K-dwarfs from Kirkpatrick et al. (1991) were added to the Gray et al. (2003) list. A sample of L-type dwarfs, which includes 83 stars, was selected from Gizis et al. (2000), Liebert & Gizis (2006), Sheppard & Cushing (2009) and Kirkpatrick et al. (2008).

1 http://univie.ac.at/webda/navigation.html
Intrinsic color indices and sequences in the 2MASS two-color diagram

Fig. 1. The $J-H$ vs. $H-K_s$ diagram for unreddened or dereddened main-sequence stars. The symbols are explained in the insert.

Intrinsic color indices $(J-H)_0$ and $(H-K_s)_0$ for the selected 980 main-sequence stars are plotted in Figure 1. Different groups of stars are shown by different symbols explained in the insert. A few stars deviate considerably from the general dependence; such outliers were not plotted. The remaining stars form a rather broad band with the $H-K_s$ amplitude increasing from about 0.1 mag for O to K stars up to 0.2 mag for M dwarfs of late subclasses. A similar diagram for M and
Fig. 2. Intrinsic color indices $(J - H)_0$ of the main-sequence stars plotted as a function of spectral class. Crosses denote stars with chromospheric emission lines.

L dwarfs (for a somewhat different sample of stars) was plotted by Kirkpatrick et al. (2000). The dispersion of stars in the diagram mostly is the result of the observational errors of color indices, since $\sigma$ values of color indices for some stars can be $\pm 0.07$ mag. Additional effects contributing to this dispersion can be differences in age and chromospheric activity, the presence of warm circumstellar gas and dust disks or envelopes, unknown stellar or substellar companions, differences in chemical composition, etc. We will discuss these possible effects in more detail.

It is known that up to 20\% of field K–M2 dwarfs have active chromospheres and exhibit emission components of $H\alpha$, Ca H and K and other lines. In young clusters with ages $< 100$ Myr (like the Pleiades) almost all stars cooler than K4 show chromospheric activity. In the Hyades and Praesepe this happens at spectral class M2. The majority of stars of subclass M4 and cooler, both in the field and in
clusters, are flare stars with strong and variable emission lines. In Figure 1, late K and early M dwarfs lie at the upper edge of the main sequence belt. The most outstanding examples are the chromospherically active Pleiades and Praesepe stars located at the top of the belt with $J-H \approx 0.7$. Active M dwarfs of cooler subclasses with strong Hα emission do not show increase in their $J-H$.

Flat circumstellar dust disks are present around main-sequence stars of spectral classes A, F, G and K (Habing et al. 2001). Although for M-dwarfs the results are discordant (Plavchan et al. 2005; Riaz et al. 2006), at least part of them also hold warm dust and debris disks. Such disks create excesses of infrared flux, contributing to the $J$, $H$ and $K_s$ magnitudes.

To estimate the metallicity effect, on the $J-H$ vs. $H-K_s$ diagram we plotted a few F-G-K subdwarfs with [Fe/H] $\approx -2$. All of them lie in one sequence, together with dwarfs of solar metallicity. However, it is known that metal-deficient M-dwarfs (or subdwarfs) in this diagram deviate down from their metal-rich counterparts (see Leggett 1992 and references therein).

In Figures 2 and 3 we plot color indices $J-H$ and $H-K_s$ against spectral classes without differentiating stars into physical groups. Instead, the known emission-line stars of K- and early M-subclasses with active chromospheres are plotted.
Table 1. 2MASS intrinsic color indices for luminosity V stars.

| Sp. type | \((J - H)\)_0 | \((H - K_s)\)_0 | Sp. type | \((J - H)\)_0 | \((H - K_s)\)_0 |
|----------|----------------|----------------|----------|----------------|----------------|
| O5 V     | -0.17          | -0.06          | K1 V     | 0.415          | 0.105          |
| B0 V     | -0.15          | -0.05          | K2 V     | 0.44           | 0.11           |
| B2 V     | -0.13          | -0.04          | K3 V     | 0.49           | 0.12           |
| B5 V     | -0.09          | -0.03          | K4 V     | 0.54           | 0.135          |
| B8 V     | -0.06          | -0.02          | K5 V     | 0.59           | 0.145          |
| A0 V     | -0.04          | 0.01           | K6 V     | 0.62           | 0.15           |
| A2 V     | -0.01          | 0.02           | K7 V     | 0.64           | 0.16           |
| A5 V     | 0.03           | 0.035          | M0 V     | 0.65           | 0.18           |
| A7 V     | 0.06           | 0.04           | M1 V     | 0.64           | 0.20           |
| F0 V     | 0.09           | 0.045          | M2 V     | 0.63           | 0.23           |
| F2 V     | 0.12           | 0.05           | M3 V     | 0.60           | 0.245          |
| F5 V     | 0.18           | 0.055          | M4 V     | 0.56           | 0.28           |
| F8 V     | 0.23           | 0.06           | M5 V     | 0.60           | 0.34           |
| G0 V     | 0.26           | 0.07           | M6 V     | 0.63           | 0.38           |
| G2 V     | 0.28           | 0.075          | M7 V     | 0.65           | 0.41           |
| G5 V     | 0.30           | 0.08           | M8 V     | 0.67           | 0.44           |
| G8 V     | 0.34           | 0.09           | M9 V     | 0.72           | 0.47           |
| K0 V     | 0.39           | 0.10           |          |                |                |

Table 2. Open clusters with red giants used for the determination of the intrinsic colors.

| Cluster       | \(E_{B-V}\) | Number of giants | Number of MK spectra |
|---------------|-------------|------------------|----------------------|
| NGC 2099 = M37 | 0.30        | 29               | 4                    |
| NGC 2506      | 0.08        | 34               | –                    |
| NGC 2682 = M67 | 0.06        | 53               | 10                   |
| NGC 6067      | 0.38        | 12               | 5                    |
| NGC 6791*     | 0.12        | 73               | 3                    |
| NGC 6819      | 0.24        | 47               | –                    |
| NGC 7789      | 0.22        | 123              | 6                    |

* Only three stars of this cluster were used, see the text.

as crosses. It is evident that these stars exhibit larger color indices \(J-H\) than non-emission stars. A similar tendency (however milder) is noticeable for \(H-K_s\). The mean intrinsic color indices for various spectral classes were calculated by the least-square method. After plotting them as a function of spectral class a smooth curve was drawn through the points and the resulting color indices were read out from the curve. The results are given in Table 1. The standard deviations for most of these indices are 0.02–0.05 mag.

3. LATE-TYPE GIANTS

The determination of intrinsic 2MASS colors for red giants is more complicated since most of the unreddened field giants are too bright and the accuracy of their colors is rather low due to saturation. The visual magnitude, at which the
saturation of $JHK$ images takes place, depends strongly on spectral type: $V \approx 6.0$ mag for spectral type G5 III, 7.5 mag for K5 III and 10 mag for M5 III. If the stars are reddened or, in case of late M subclasses, have warm dust envelopes, the corresponding $V$ magnitudes are even fainter.

Field giants can be used for determining the intrinsic colors only if we estimates of their color excesses. Interstellar reddening is usually rather low at high Galactic latitudes, especially at the Galactic poles, where color excesses in the infrared may be neglected. In all other cases, color indices should be dereddened. To do this, we must have knowledge of MK spectral types and $B-V$ color indices. Since accurate photometry for many field stars is not available, their reddening cannot be estimated individually. Therefore, we decided to use red giants which are either located at high Galactic latitudes or known to be members of old- or medium-age open clusters with color excesses estimated from photometry in the $UBV$ or other systems. To reduce dereddening errors, we used only clusters with $E_{B-V} \leq 0.4$, these are listed in Table 2. However, in the case of NGC 6791, only three K-giants with available MK types have been taken, since other giant-branch stars exhibit large scatter in the cluster’s color-magnitude diagram.

However, the majority of red giants in open clusters cover a relatively narrow range of spectral classes, from G8 to K5. More G–K–M giants with small interstellar reddening can be found near the Galactic poles. It is known that $E_{B-V}$ at the NGP is only about 0.03 mag up to the Galaxy edge (see the review by
Thus, we are safe to expect that for field giants in this direction $E_{J-H}$ will be less than 0.01 mag, and $E_{H-K_s}$ less than 0.005 mag. We selected about 170 late-type giants with MK types and unsaturated 2MASS images in the vicinity of NGP from the Upgren (1960, 1962) catalogs. Upgren’s spectral types were determined from low dispersion objective-prism plates, so their accuracy is not high. About 50 stars were added from Helfer & Sturch (1970), Schild (1973) and from the Skiff (2009) compilation. All of the stars used are at Galactic latitudes $b > 65^\circ$. Metallicity effect in the $J-H$ vs. $H-K_s$ diagram was verified by plotting dereddened field metal-deficient giants with [Fe/H] between −2.0 and 3.0. No systematic deviations from the sequence of solar composition giants were found.

Almost all giants cooler than M5 are long-period variables of semiregular or Mira types with variable magnitudes, color indices and spectral classes. Most of them are too bright in the near infrared, and their magnitudes in the 2MASS catalog are of low accuracy. Thus their positions in the $J-H$ vs. $H-K_s$ diagram are uncertain due to both variability and the saturated images. Therefore, in the present investigation we limit ourselves only to giants of spectral type M5 III and earlier.

In Figure 4 (panels a and b) we show the 2MASS two-color diagram for 298 dereddened giants from open clusters and 280 field giants from the vicinity of NGP, their spectral interval being from G5 to M5. For the cluster giants we see the well-known clustering around $J-H = 0.46$ and $H-K_s = 0.09$, corresponding to the red clump giants (RCGs) in their color-magnitude diagrams. We shall return to RCGs below in this section. Since the NGP stars do not represent a specific volume of space, we should not pay attention to the distribution of points in Figure 4b. These stars were chosen just to cover the whole giant-sequence length between spectral classes G5 and M5.

MK spectral types are available for 28 stars in our open cluster sample (most of luminosity class III, a few of II/III and II classes) and for 280 field stars. Figures 5 and 6 show plots of color indices of these stars as a function of spectral class. The mean intrinsic colors for different MK types given in Table 3 were determined by combining smooth lines drawn through the middle of scattered points in Figures 4, 5 and 6. Due to large scatter the mean intrinsic colors are rather uncertain, with their standard deviations being as large as 0.04–0.06 mag. This scatter is a result of errors in spectral classes and 2MASS color indices, as well as due to unresolved binarity and peculiarity of the stars. The most uncertain are the $J-H$ colors for the giants of spectral type G5 III. All of the stars lying in Figure 4b lower than $J-H = 0.35$ were classified by Upgren (1962) as G5–G6 giants. We do not exclude that some of them can be subgiants or even dwarfs. In this case the mean $J-H$ color of true G5 giants can be larger than the value given in Table 3.

Some differences between the two panels of Figure 4 can be noticed. For some reason, the cluster K-giants, including the RCGs, show a small systematic deviation to the left from the grey curve and a larger scatter in the range of K3–K5 subclasses. This cannot be explained by dereddening errors since the reddening line shown in the diagrams of Figure 4 is approximately parallel to the sequence of giants.

Special attention should be paid to the intrinsic colors of the red clump giants, i.e., stars burning helium in the cores and hydrogen in the shells. In Straizys et al. (2008) the values of $(J-H)_0 = 0.502$ and $(H-K_s)_0 = 0.136$ were obtained by averaging color indices of seven RCGs of the cluster M 67, which were considered
**Fig. 5.** Intrinsic color indices \((J - H)_0\) of luminosity III stars plotted as a function of spectral class. The gray curve corresponds to the data of Table 3.

**Fig. 6.** Intrinsic color indices \((H - K_s)_0\) of luminosity III stars plotted as a function of spectral class. The gray curve corresponds to the data of Table 3.
Table 3. 2MASS intrinsic color indices for luminosity III stars.

| Sp. type | (J − H)_0 | (H − K_s)_0 | Sp. type | (J − H)_0 | (H − K_s)_0 |
|----------|-------------|-------------|----------|-------------|-------------|
| G5 III   | 0.40        | 0.09        | K5 III   | 0.76        | 0.205       |
| G8 III   | 0.45        | 0.105       | M0 III   | 0.80        | 0.22        |
| K0 III   | 0.50        | 0.125       | M1 III   | 0.82        | 0.24        |
| K1 III   | 0.54        | 0.14        | M2 III   | 0.84        | 0.26        |
| K2 III   | 0.59        | 0.155       | M3 III   | 0.85        | 0.285       |
| K3 III   | 0.65        | 0.17        | M4 III   | 0.86        | 0.31        |
| K4 III   | 0.71        | 0.185       | M5 III   | 0.87        | 0.34        |

Fig. 7. Differences between the intrinsic color indices (J − H)_0 given in Tables 1 and 3 and those of Bessell & Brett (1988) and Bessell (1991).

Fig. 8. Differences between the intrinsic color indices (H − K_s)_0 given in Tables 1 and 3 and those of Bessell & Brett (1988) and Bessell (1991).
to be unreddened. If little reddening of the cluster is taken into account ($E_{B-V} = 0.06$), the intrinsic values of RCGs become 0.48 and 0.13. Figure 4a shows that we have in the present paper more than 100 stars in six clusters, which fall near the RCG location. Values of their $J-H$ colors concentrate within 0.44 and 0.48 and of $H-K_s$ within 0.06 and 0.12. The mean values, $J-H = 0.46$ and $H-K_s = 0.09$, are close to the intrinsic colors of a mean G8 III star.

4. DISCUSSION AND CONCLUSIONS

In this investigation we have determined the intrinsic sequences of luminosity V and III stars in the $J-H$ vs. $H-K_s$ diagram of the 2MASS photometric system using about 980 stars of the main sequence and about 270 of late-type giants. Based on stars with known spectral classification, the intrinsic colors $(J-H)_0$ and $(H-K_s)_0$ for different MK spectral types were determined. To our knowledge, this is the first direct calibration of the $J-H$ vs. $H-K_s$ diagram of the 2MASS photometric system in MK types covering a broad range of temperatures. We find that the red clump giants of open clusters concentrate at $J-H = 0.46$ and $H-K_s = 0.09$, but the spread of points around this point is of the order of ±0.03. The location of the clump center corresponds approximately to intrinsic color indices for spectral class G8III (Table 3).

The range of spectral subclasses, estimated from color indices of RCGs in different photometric systems, is from about G8 to K1. According to Grocholski & Sarajedini (2002), the red clump giants in open clusters have $J-K$ values of 0.6. This is not very different from our value for the clump, 0.55, but closer to spectral type K0III. For red clump giants in the solar neighborhood Alves (2000) finds $V-K$ in the range 2.1–2.5, what corresponds to spectral types from G8III to K1III (with the calibration from Stražys 1992). The same range of spectral subtypes is covered by 72% of the RCGs from the Alves list supplemented with spectral types from Simbad. This spectral range corresponds to $B-V$ between 0.9 and 1.1 in the well-known HR diagram based on the Hipparcos data (Perryman et al. 1995, 1997).

In Figures 7 and 8 we compare the intrinsic color indices from Tables 1 and 3 with those for B8–K5 V and G5–M5 III stars from Bessell & Brett (1988), taking for K7–M7.5 V stars the corrected values from Bessell (1991). The intrinsic colors in these two papers have been determined in a homogenized $JHK$ system, named the Johnson-Glass system. It is evident that the differences between the two systems are non-linear and multivalued. By indirect comparison of the 2MASS and Bessell color indices, Carpenter (2001) finds that the differences are almost constant and color independent. Zero point differences of the linear transformation equations given by Carpenter, −0.045 for $J-H$ and +0.028 for $H-K_s$, are in satisfactory agreement with Figures 7 and 8. However, in some ranges of colors, especially for M-type stars, there are systematic deviations from the Carpenter equations, depending on color and luminosity: up to 0.04 mag in $J-H$ and 0.03 mag in $H-K_s$.

The mean color indices for M dwarfs in the CIT $J,H,K$ system were also published by Leggett (1992), separately for the young disk, old disk and halo objects. Recently, Kirkpatrick et al. (2000) and Liebert & Gizis (2006) investigated intrinsic colors for late M- and L-dwarfs in the 2MASS system. Our colors of M-dwarfs are in good agreement with their results, despite the large scatter of stars used for averaging in both studies.
One more possibility of determining the intrinsic colors is to calculate synthetic color indices for spectral energy distributions of model atmospheres by convolving them with response functions of the passbands. However, our test calculations of color indices for the Kurucz (2001) and Castelli & Kurucz (2003) models show considerable systematic differences between the synthetic and observational data, especially for O–B and M stars.

For more exact determination of the intrinsic colors, observations in the 2MASS filters of a set of bright stars with well-known physical parameters are needed. To avoid saturation, either much smaller telescope or grey filters should be applied.

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