

2MASS TWO-COLOR INTERSTELLAR REDDENING LINES: THE BAND-WIDTH EFFECT

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Abstract. The band-width effect on interstellar reddening lines in the $J-H$ vs. $H-K_s$ diagram of the 2MASS survey is investigated using synthetic color indices and color excesses based on the Kurucz model atmospheres. At large interstellar reddenings ($E_{H-K_s} \geq 1.0$) reddening lines deviate considerably from a straight line. The lines can be approximated by a parabolic equation: $E_{J-H} = rE_{H-K_s} + sE_{H-K_s}^2$ where the slope coefficient, r , and the curvature coefficient, s , depend slightly on the intrinsic energy distribution of the source. The curvature of the reddening lines is confirmed by the $J-H$ vs. $H-K_s$ diagrams plotted by Straizys and Laugalys (2008) from 2MASS observations.

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

1. INTRODUCTION

The color excess in a two-color monochromatic system (defined by the wavelengths λ_1 and λ_2) is a difference of interstellar extinctions $A(\lambda_1)$ and $A(\lambda_2)$ expressed in stellar magnitudes. The values of the monochromatic extinctions for the unit dust mass x can be taken from the interstellar extinction law, i.e., the dependence of A on λ or λ^{-1} . In the monochromatic or narrow-band photometric systems the extinction increases linearly with increasing of the dust mass.

In the case of a heterochromatic photometric system the extinctions are defined by the equation

$$A_m = -2.5 \log \frac{\int F(\lambda) R_m(\lambda) \tau^x(\lambda) d\lambda}{\int F(\lambda) R_m(\lambda) d\lambda}, \quad (1)$$

where $F(\lambda)$ is the spectral energy distribution function of a star or a model atmosphere, $R_m(\lambda)$ is the response function of the passband, $\tau(\lambda)$ is the transmittance function of the unit mass of dust and x is the number of dust masses.

This means that the heterochromatic extinction depends on the spectral energy distribution and the amount of interstellar dust. A red star, affected by the same cloud of interstellar dust, will exhibit smaller extinction $A(\lambda)$ than a blue star. Also, if a dust cloud gives the extinction $A(\lambda)$, the addition of the second identical cloud will raise the extinction not to up $2A(\lambda)$ but to a smaller quantity. The

broader the response function, the larger is the dependence of the extinction on the spectral energy distribution and the amount of interstellar reddening. This dependence is known as the band-width effect. The reason for the effect can be understood as the dependence of the effective wavelength on spectral type and interstellar reddening.

Since color excesses are differences of extinctions in two passbands, the dependence of $A(\lambda_1)$ and $A(\lambda_2)$ on spectral energy distribution of the star and on its interstellar reddening transfers the band-width effect to color excesses and color-excess ratios. However, in an exceptional case the band-width effect on a color excess can be zero, when the band-width effect in both passbands is the same.

The band-width effect was well known to stellar photometrists long ago; see, e.g., the reviews by one of the authors (Straizys 1977, 1992). However, in some new photometric systems the effect sometimes becomes forgotten. The near-infrared J , H , K system is one of such examples.

Jones & Hyland (1980) were probably the first who tried to estimate the band-width effect on the form of reddening line in the $J-H$ vs. $H-K$ diagram. By synthetic photometry they found some deviation of heavily reddened stars at $J-H > 3.5$. A similar effect was also calculated by Nagata et al. (1993). Naoi et al. (2006) found the decline of the reddening line slope in Ophiuchus and Chamaeleon star-forming regions by observations in the SIRIUS J , H , K_s system, but failed to confirm the effect by synthetic photometry.

One of the authors of the present paper (Straizys 1992) has estimated the band-width effect in the $UBVRIJHKLM$ system by calculating color excesses and their ratios for black bodies of different temperatures. A clear decline of the ratio E_{J-H}/E_{H-K} from 2.0 to 1.7 was found when the temperature of the radiation source has decreased from 20 000 K to 2000 K.

Recently, during the investigation of the E_{J-H}/E_{H-K_s} ratios in various Milky Way directions and in star-forming regions (Straizys & Laugalys 2008), we have noted that in most directions heavily reddened stars deviate down from the linear reddening line of red giants. This stimulated the investigation of possible band-width effect for heavily reddened stars in the two-color diagram of the 2MASS system.

2. CALCULATIONS AND RESULTS

Interstellar extinctions in the passbands of the 2MASS system were calculated by Equation (1) with the functions taken from the following sources. Spectral energy distributions $F(\lambda)$ were taken for 409 synthetic spectra of solar metallicity and various temperatures and gravities from Kurucz (2001). Response functions of the 2MASS passbands were taken from Cutri et al. (2006) and Skrutskie et al. (2006). The transmittance function of the interstellar dust for a unit mass ($x = 1$, this corresponds to $E_{B-V} = 1.0$) is taken from Straizys (1992, Table 3), with some small modification at wavelengths longer than $2.0 \mu\text{m}$ to adjust the extinction law to the ratio of color excesses $E_{J-H}/E_{H-K_s} = 1.9$. In calculations the dust mass x was varied from 2 to 10; these values correspond to $A_V = 6.2$ and 31 mag.

In Table 1 we present the calculated color excesses and their ratios for a selected set of 87 models with different temperatures and gravities and for five values of x to show the significance of the band-width effect. For the model with $T_{\text{eff}} = 35\,000$ K, which corresponds to the spectral class O8, the ratio of color excesses

Table 1. Ratios of color excesses E_{J-H}/E_{H-K_s} for the Kurucz models with various interstellar extinctions.

$T_{\text{eff}}, \log g$	$x=2$	$x=4$	$x=6$	$x=8$	$x=10$	$T_{\text{eff}}, \log g$	$x=2$	$x=4$	$x=6$	$x=8$	$x=10$
3500, 1.0	1.942	1.906	1.871	1.838	1.808	7500, 5.0	1.972	1.930	1.894	1.862	1.830
3500, 2.0	1.939	1.901	1.867	1.836	1.806	8000, 1.0	1.989	1.954	1.916	1.882	1.850
3500, 3.0	1.942	1.905	1.868	1.836	1.807	8000, 2.0	2.000	1.958	1.921	1.887	1.853
3500, 4.0	1.943	1.903	1.870	1.837	1.807	8000, 3.0	1.996	1.954	1.916	1.883	1.850
3500, 5.0	1.940	1.902	1.868	1.834	1.804	8000, 4.0	1.982	1.945	1.910	1.874	1.844
4000, 1.0	1.932	1.900	1.864	1.832	1.803	8000, 5.0	1.975	1.937	1.900	1.866	1.835
4000, 2.0	1.939	1.898	1.865	1.832	1.802	8500, 2.0	2.004	1.961	1.922	1.888	1.855
4000, 3.0	1.936	1.898	1.864	1.831	1.801	8500, 3.0	2.000	1.959	1.920	1.887	1.854
4000, 4.0	1.939	1.900	1.864	1.831	1.802	8500, 4.0	1.989	1.952	1.915	1.881	1.849
4000, 5.0	1.936	1.902	1.869	1.836	1.807	8500, 5.0	1.982	1.942	1.906	1.873	1.840
4500, 1.0	1.943	1.906	1.870	1.838	1.807	9000, 2.0	1.996	1.958	1.921	1.887	1.855
4500, 2.0	1.940	1.904	1.868	1.835	1.805	9000, 3.0	1.996	1.960	1.923	1.888	1.856
4500, 3.0	1.943	1.900	1.866	1.834	1.804	9000, 4.0	1.993	1.953	1.919	1.882	1.852
4500, 4.0	1.936	1.900	1.864	1.833	1.802	9000, 5.0	1.986	1.947	1.912	1.876	1.845
4500, 5.0	1.940	1.899	1.863	1.833	1.802	9500, 2.0	1.996	1.960	1.921	1.888	1.855
5000, 1.0	1.947	1.908	1.873	1.841	1.811	9500, 3.0	2.000	1.961	1.926	1.888	1.857
5000, 2.0	1.943	1.906	1.871	1.840	1.809	9500, 4.0	1.993	1.958	1.920	1.886	1.854
5000, 3.0	1.940	1.906	1.871	1.839	1.808	9500, 5.0	1.993	1.951	1.914	1.880	1.848
5000, 4.0	1.943	1.908	1.871	1.837	1.808	10000, 2.0	1.996	1.960	1.921	1.886	1.853
5000, 5.0	1.940	1.903	1.867	1.836	1.805	10000, 3.0	2.004	1.960	1.925	1.888	1.857
5500, 1.0	1.954	1.917	1.881	1.847	1.816	10000, 4.0	1.996	1.960	1.922	1.888	1.855
5500, 2.0	1.958	1.915	1.881	1.846	1.816	10000, 5.0	1.993	1.953	1.917	1.882	1.850
5500, 3.0	1.951	1.913	1.876	1.844	1.813	11000, 3.0	2.000	1.961	1.924	1.889	1.857
5500, 4.0	1.947	1.910	1.875	1.842	1.812	11000, 4.0	1.990	1.958	1.921	1.888	1.855
5500, 5.0	1.947	1.910	1.874	1.842	1.811	11000, 5.0	1.996	1.956	1.919	1.884	1.853
6000, 1.0	1.965	1.926	1.890	1.856	1.826	12000, 3.0	1.993	1.958	1.921	1.886	1.855
6000, 2.0	1.961	1.921	1.887	1.853	1.822	12000, 4.0	2.000	1.960	1.922	1.889	1.857
6000, 3.0	1.951	1.919	1.883	1.849	1.819	12000, 5.0	1.993	1.954	1.919	1.883	1.853
6000, 4.0	1.951	1.917	1.880	1.848	1.817	13000, 3.0	1.993	1.958	1.921	1.887	1.855
6000, 5.0	1.947	1.915	1.878	1.847	1.815	13000, 4.0	2.000	1.958	1.922	1.887	1.855
6500, 1.0	1.975	1.937	1.900	1.866	1.834	13000, 5.0	1.990	1.954	1.919	1.884	1.853
6500, 2.0	1.972	1.933	1.896	1.863	1.832	14000, 3.0	1.996	1.958	1.922	1.887	1.855
6500, 3.0	1.968	1.929	1.892	1.859	1.827	14000, 4.0	2.000	1.960	1.920	1.888	1.854
6500, 4.0	1.958	1.923	1.888	1.854	1.822	14000, 5.0	1.993	1.956	1.918	1.884	1.852
6500, 5.0	1.954	1.919	1.882	1.850	1.819	15000, 3.0	2.000	1.960	1.922	1.887	1.854
7000, 1.0	1.986	1.947	1.910	1.876	1.843	15000, 4.0	2.000	1.960	1.922	1.887	1.854
7000, 2.0	1.982	1.942	1.907	1.871	1.841	15000, 5.0	1.993	1.954	1.920	1.885	1.852
7000, 3.0	1.968	1.933	1.900	1.865	1.834	20000, 5.0	1.993	1.956	1.919	1.885	1.852
7000, 4.0	1.965	1.930	1.893	1.860	1.828	25000, 5.0	1.997	1.954	1.919	1.885	1.853
7000, 5.0	1.965	1.928	1.891	1.855	1.824	30000, 5.0	2.000	1.958	1.922	1.887	1.855
7500, 1.0	1.986	1.951	1.915	1.881	1.849	35000, 5.0	1.997	1.958	1.922	1.886	1.854
7500, 2.0	1.993	1.951	1.915	1.880	1.849	40000, 5.0	2.000	1.958	1.922	1.886	1.854
7500, 3.0	1.986	1.945	1.908	1.875	1.843	50000, 5.0	2.000	1.958	1.922	1.888	1.856
7500, 4.0	1.975	1.938	1.901	1.868	1.836						

is 1.99 at $x = 2$ and 1.85 at $x = 10$. For the model with $T_{\text{eff}} = 4500$ K and $\log g = 2.5$, which corresponds to red clump giants (K2 III), the ratio is 1.95 for $x = 2$ and 1.81 for $x = 10$.

In Figure 1 we plot the reddening line of red clump giants on the $J-H$ vs. $H-K_s$ diagram in a 1° diameter area in the direction of $\ell = 330^\circ$, $b = 0^\circ$ (Norma) taken from Straizys & Laugalys (2008). The theoretical line fits the observed points very well. In other Milky Way areas investigated by Straizys & Laugalys (2008) the

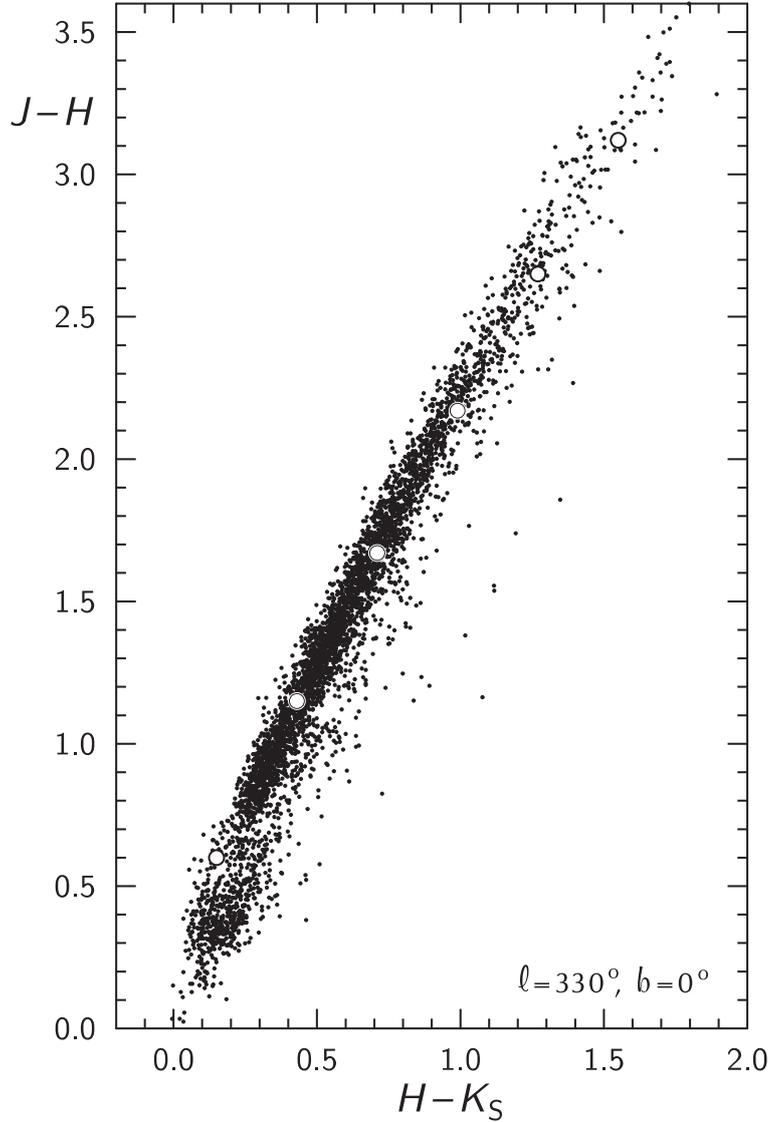


Fig. 1. Synthetic reddening line for the Kurucz model $T_{\text{eff}} = 4500$ K, $\log g = 4.0$ (white circles) plotted on the observational 2MASS $J-H$ vs. $H-K_s$ diagram in the direction with the Galactic coordinates $\ell = 330^\circ$, $b = 0^\circ$.

correspondence is not so good since the observed reddening lines exhibit a slightly larger slope. In most of the star-forming regions investigated in that paper, the observed reddening lines end at lower values of color indices and are not suitable for verification of the reddening line curvature.

The reddening line can be expressed by a parabolic equation

$$E_{J-H}/E_{H-K_s} = r - sE_{H-K_s}. \quad (2)$$

The coefficient r due to the band-width effect shows the usual dependence on the temperature (or on spectral class), decreasing from 2.03 for O-stars down to 1.96 for M-stars. The coefficient s is almost constant, its average value is -0.12 .

We also calculated effective wavelengths of the J , H and K_s passbands for various temperatures and gravities defined by the following equation:

$$\lambda_{\text{eff}} = \frac{\int F(\lambda) R_m(\lambda) \tau^x(\lambda) \lambda d\lambda}{\int F(\lambda) R_m(\lambda) \tau^x(\lambda) d\lambda}. \quad (3)$$

The results for five selected models of different temperatures are listed in Table 2. The largest change of the effective wavelengths both with the temperature and interstellar reddening is observed for the J passband: $0.01\text{--}0.02 \mu\text{m}$ between $T_{\text{eff}} = 3500 \text{ K}$ and 35000 K and $0.04\text{--}0.06 \mu\text{m}$ between $x = 0$ and 10 . For the H passband the corresponding variations are $0.01 \mu\text{m}$ and $0.02 \mu\text{m}$. For the K_s passband these variations are $0.002 \mu\text{m}$ and $0.018 \mu\text{m}$.

The variations of λ_{eff} for the three passbands help to understand why the reddening line in the $J\text{--}H$ vs. $H\text{--}K_s$ diagram at large reddenings is curved down: with increasing reddening the shift of λ_{eff} for J is much larger than for H and this leads to decrease of the base-line of the $J\text{--}H$ color. As a consequence, the increase of $J\text{--}H$ is slowed down in comparison with the dust mass x . At the same time, the difference of λ_{eff} variation between the H and K_s passbands is much smaller, and the values of $H\text{--}K_s$ color remain almost proportional to x with increasing reddening.

Since the effective wavelengths depend on the temperature and reddening, their change should be taken into account when plotting the interstellar extinction law: the values of A_λ determined for early-type or less reddened stars should be plotted at shorter wavelengths than for late-type or heavily reddened stars.

3. CONCLUSIONS

Applying the method of synthetic photometry for the Kurucz models we show that interstellar reddening lines in the 2MASS $J\text{--}H$ vs. $H\text{--}K$ diagram due to the band-width effect are of parabolic form with a curvature coefficient of $s = -0.12$. The slope of the reddening line at constant reddening also decreases with decreasing temperature, but this effect is much smaller. The theoretical results are confirmed by the observed reddening lines in the inner Galaxy investigated by Straizys & Laugalys (2008).

The knowledge of the band-width effect in the J , H , K_s system on the slope and curvature of reddening lines, as well as on the effective wavelengths, is important in determining the interstellar extinction law in the infrared range (see, e.g., Fitzpatrick 1999; Fitzpatrick & Massa 2005, 2007; Indebetouw et al. 2005; Flaherty et al. 2007; Román-Zúniga et al. 2007). If one accepts that the reddening line is straight and solves all stars together, the ignorance of the curvature can lead to a smaller ratio of color excesses. Also, the ignorance of the curvature of reddening lines can lead to wrong classifications of heavily reddened stars from photometric data.

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Table 2. Effective wavelengths of the 2MASS passbands J , H and K_s in μm for Kurucz models of five values of temperatures and different values of interstellar dust masses ($x = 0, 2, 4, 6, 8$ and 10).

$T_{\text{eff}}, \log g$	J	H	K_s	J	H	K_s
	$x = 0$			$x = 6$		
3500, 4.0	1.253	1.644	2.145	1.290	1.656	2.156
4500, 4.0	1.250	1.640	2.144	1.288	1.653	2.155
6000, 4.0	1.244	1.637	2.144	1.283	1.651	2.155
10000, 4.0	1.238	1.636	2.143	1.277	1.650	2.155
35000, 4.0	1.236	1.634	2.143	1.275	1.648	2.154
	$x = 2$			$x = 8$		
3500, 4.0	1.266	1.648	2.148	1.300	1.660	2.160
4500, 4.0	1.264	1.645	2.147	1.299	1.657	2.158
6000, 4.0	1.258	1.642	2.147	1.294	1.655	2.159
10000, 4.0	1.251	1.641	2.147	1.288	1.654	2.158
35000, 4.0	1.249	1.639	2.146	1.287	1.652	2.158
	$x = 4$			$x = 10$		
3500, 4.0	1.278	1.652	2.152	1.310	1.664	2.163
4500, 4.0	1.276	1.649	2.151	1.308	1.661	2.162
6000, 4.0	1.271	1.646	2.151	1.304	1.659	2.162
10000, 4.0	1.264	1.645	2.151	1.299	1.658	2.162
35000, 4.0	1.263	1.643	2.150	1.297	1.656	2.161

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