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ASTRONOMY AND ASTROPHYSICS

IRAS far-infrared colours of normal stars*

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Summary. We present the analysis of IRAS observations at 12, 25, 60 and 100 μm of bright stars of spectral type O to M. Our main objective is to identify the "normal" stellar population and to characterize it in terms of the relationships between $(B-V)$ and $(V-[12])$, between $(R-I)$ and $(V-[12])$, and as function of spectral type and luminosity class. We find a well-defined relation between the colour of normal stars in the visual $((B-V),(R-I))$ and in the IR $((V-[12]))$, which does not depend on luminosity class. Using the $(B-V),(V-[12])$ relation for normal stars we find that B and M type stars show a large fraction of deviating stars, mostly with IR excess that is probably caused by circumstellar material. A comparison of IRAS $(V-[12])$ colours with the Johnson $(V-N)$ colours as a function of spectral type shows good agreement except for the K0 to M5 type stars. The comparison of the observed $(B-V)$, $(V-[12])$ relation with the predicted relation based on the grid of Kurucz (1979) LTE models shows that the models underestimate the 12 μm flux by about 10 percent (average) for all OBA spectral types. The results of this study will be useful in identifying the deviating stars detected with IRAS.

Key words: stars – IR photometry; stars – colours of

1. Introduction

The intrinsic energy distribution of 'normal' stars in the IR is an important tool to refine photospheric models and to identify the abnormal stars, mostly stars that exhibit an excess of radiation. Johnson (1966) gives an extensive list of intrinsic colours in the wavelength region between 0.33 and 10 μm, for a wide range of spectral types and luminosity classes.

The IRAS satellite has carried out a survey of the sky at 12, 25, 60 and 100 μm, thus providing us with a vast number of observations of stars. In this paper we will use the fluxes quoted in the IRAS Point Source Catalogue (1985, hereafter referred to as IRAS PSC) for all stars contained in the Bright Star Catalogue (Hoffleit and Jaschek, 1982; hereafter referred to as BSC) that were detected at 12 μm to derive the relation between the colours of a star in the visual (B,V,R,I) and those in the IR. The BSC was chosen as the input catalogue for this study because of the high reliability of the data on individual stars contained therein. The results of this study, i.e. the colours of normal stars in the IR, will be very useful for the study of deviating stars, such as stars with IR excess due to circumstellar dust or free-free radiation. We will present the colours of normal stars as a function of spectral type and as function of $(B-V)$ or $(R-I)$.

2. The data

The stars of the BSC form the basis of this study. This catalogue is almost complete to visual magnitude +6.6 and contains accurate data on the individual stars such as spectral type, V, $(B-V)$, $(R-I)$ etc. The stars in the BSC were selected based on their visual magnitudes. This is not a good selection criterion for the study of the IR behaviour of normal F to M type stars, since for these late type stars the 12 μm flux can be high enough to be detected with IRAS, even if the visual magnitude is too weak to be included in the BSC. However, the high reliability of the data in the BSC allows an accurate determination of the relation between the colours in the visual and those in the IR.

The selection of the program stars was made by comparing the positions of the stars in the BSC with the sources in the IRAS PSC. We excluded from this list all stars that had no detection at 12 μm. We also excluded fluxes of poor quality, i.e. fluxes with a point source correlation coefficient of less than 97 (on a scale of 87 to 100). A number of 6013, 3950, 926 and 234 stars were detected at 12, 25, 60 and 100 μm respectively.

The fluxes were converted to magnitudes using the magnitude scale defined in the IRAS Explanatory Supplement (1985). This magnitude scale defines zero magnitude for a source radiating as a 10^4 K blackbody that fills a solid angle of $1.57\,10^{-16}$ sr. This definition corresponds to fluxes of $5.13\,10^{-12}$, $4.48\,10^{-13}$, $4.0\,10^{-14}$ and $4.86\,10^{-16}\,\mathrm{Wm^{-2}}$ in the 12, 25, 60 and 100 μm bands respectively. We estimate the accuracy of the 12 μm magnitudes for the majority of the stars to be of the order of $0\overset{\mathrm{m}}{.}10$.

The visual photometry used in this study was taken from the BSC. This catalogue contains photometry from various sources, obtained using different photometric systems. Most of the B and V photometry was taken from the compilation by Nicolet (1978), who estimates its accuracy in most cases better than $0\overset{\mathrm{m}}{.}01$. In general the visual photometry is much more accurate than the IRAS photometry.

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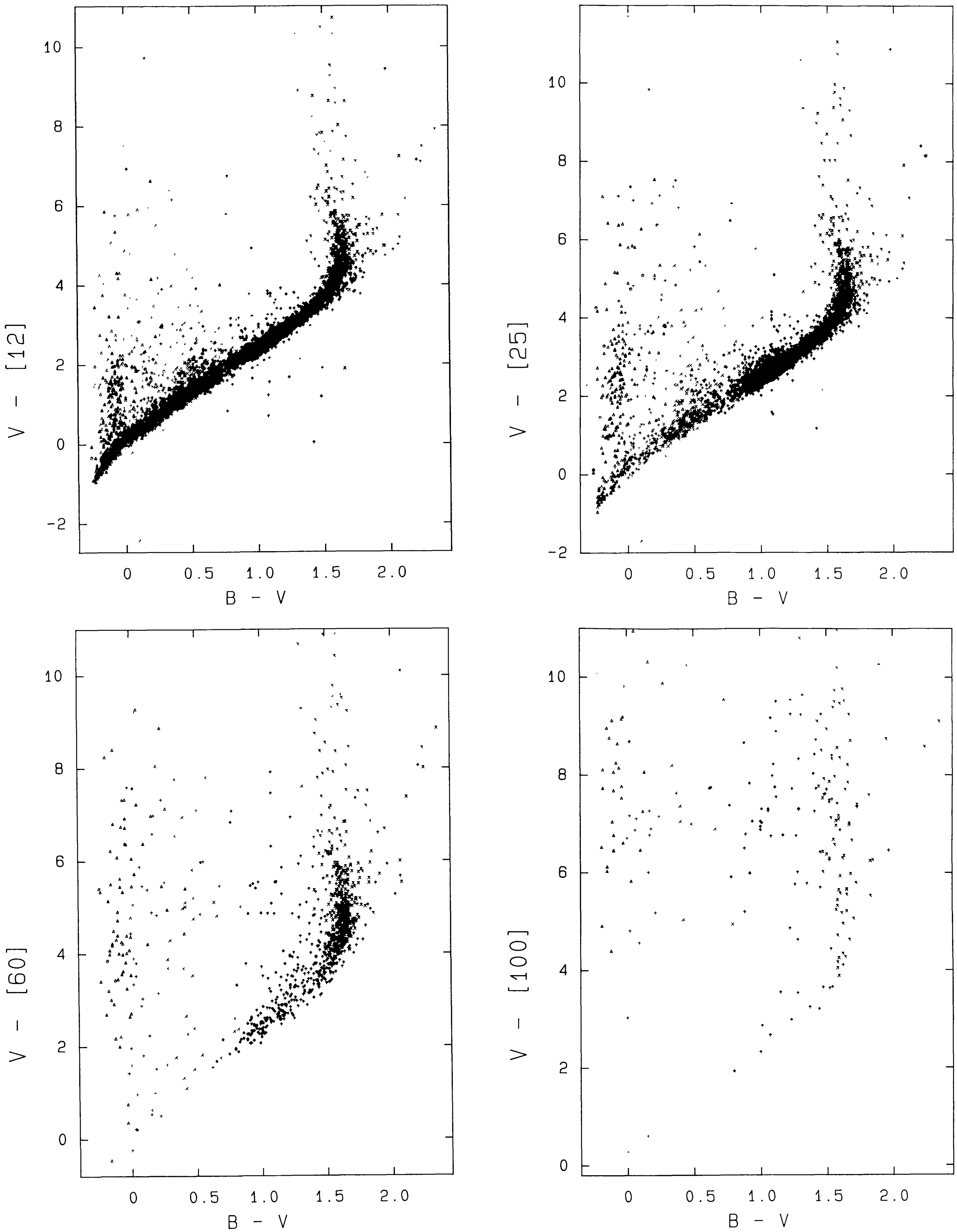

Fig. 1. a The observed ($V - [12]$) colour for all stars in the Bright Star Catalogue observed with IRAS at $12\,\mu$m is plotted versus the ($B - V$) colour. No extinction correction was applied. The symbols indicate the spectral type of the stars: o = O type stars, Δ = B type stars, + = A stars, x = F stars, ↑ = K stars and ⅄ = M stars. Notice that there is a well-defined relation between ($B - V$) and ($V - [12]$) for the vast majority of the stars. Stars with IR excess lie above the relation for normal stars. **b** The same as **a**, but with ($V - [25]$) versus ($B - V$). Notice that the number of "normal" stars has decreased compared to $12\,\mu$, especially for $(B - V) < 0\overset{\mathrm{m}}{.}8$. This is due to the decrease in intrinsic stellar flux and the decrease in sensitivity of the IRAS Survey Instrument. **c** The same as **a**, but ($V - [60]$) is plotted versus ($B - V$). The number of normal stars has decreased more compared to 12 and $25\,\mu$, and the percentage abnormal stars increases drastically. **d** The same as **a**, but ($V - [100]$) versus ($B - V$). Almost all stars are deviating at $100\,\mu$m

In the case of the R and I photometry, we used the data given in the Johnson photometric system, and ignored the data obtained in the Kron system.

In Figs. 1a to 1d we have plotted the $(B-V)$ colours given in the BSC versus the $(V-[\lambda])$ colours, where $[\lambda]$ is the magnitude found from the IRAS PSC at wavelength λ (in μm). No extinction correction was applied. The plots in Fig. 1 show a wealth of information about the behaviour of stars in the IR relative to that in the visual. The most significant aspect of these plots is the existence of well-defined relations between the visual and IR colours. This is best observed at 12 and 25 μm, where the IRAS survey instrument was most sensitive and the stars are brightest. The mean relation is less obvious at 60 μm, and virtually disappears at 100 μm, due to the decrease in intrinsic stellar flux and sensitivity of the Survey Instrument. The percentage of abnormal stars observed with IRAS which deviate from the 'mean' relation will therefore increase drastically with wavelength. However, the plots in Fig. 1, especially at 60 and 100 μm, may be affected by confusion with extended sources, particularly for stars close to the galactic plane.

In the remainder of this paper, we will limit the determination of the colour-colour relations for normal stars to the 12 μm data. Furthermore, normal stars are expected to radiate essentially as a hot blackbody at the far-IR wavelengths, so the magnitudes of normal stars are not expected to change significantly between 12 and 100 μm.

A well-defined relation can be observed between $(B-V)$ and $(V-[12])$ in Fig. 1a. In Sect. 3, we will quantitatively give this colour-colour relation. The upturn at $(B-V) \simeq 1^{\rm m}.60$ is due to the fact that $(B-V)$ does not change any more with decreasing temperature for the M-type stars. From Fig. 1a it is immediately clear which stars are abnormal. Nearly all the deviating stars lie above the 'mean relation', and thus show an IR excess. This excess is in most cases due to circumstellar material, either dust or, in the case of the early-type stars, gas emitting free-free radiation. The few stars lying below the mean relation can probably be accounted for in terms of duplicity, variability and misidentifications, and will not be considered further. A concentration of stars with IR excess can be seen among the early-type stars ($(B-V) < 0^{\rm m}.3$) and for the M-type stars. It is interesting to note the small number of K stars with IR excess. Using the relation between $(B-V)$ and $(V-[12])$ for normal stars (Sect. 3), we find that 50 percent of the B stars show IR excess at 12 μm larger than $0^{\rm m}.20$. The $(B-V)$, $(V-[12])$ diagram shows a clear deficiency of stars around $(B-V) \simeq 0^{\rm m}.75$. This gap is due to the decreasing number of main sequence stars with increasing $(B-V)$ and the sudden appearance of giant stars at $(B-V) = 0.80$, and is found in any sample selected on apparent magnitude.

3. Colour-colour relations for normal stars

In this Section, we will discuss the method used to derive the mean relations between the visual and IR colours of normal stars.

3.1. The interstellar reddening

Numerous studies (e.g. Wesselius et al., 1980) deal with the extinction at visual and UV wavelengths. The results of these studies indicate that extinction is negligible for bright stars with spectral types later than about A0 with luminosity class IV or V. For the moment, we will assume that the interstellar reddening is negligible for all stars in our sample. In Sect. 3.3 we will show that the neglect of extinction will not affect the colour-colour relations within errors for the stars with $(B-V) \geq 0^{\rm m}.20$. In Sect. 3.4, we will derive the intrinsic $(B-V)_0$, $(V-[12])_0$ relation for the O, B and A type stars. In Sect. 3.5 we will derive the $(V-[12])$ colour as function of spectral type with and without extinction correction.

3.2. The selection of the sample

From Fig. 1a it is clear that a number of stars deviate from the mean relation for (what we define as) normal stars. We used two steps to eliminate the deviating stars: 1/ we excluded a priori all stars that are known or suspected to show IR excess, and 2/ we applied an iterative process to eliminate the remaining deviating stars.

We used the following three criteria to exclude a star a priori:

i all supergiants
ii all peculiar and emission line stars
iii all stars with $[12]-[25] > 0^{\rm m}.25$.

The third criterion was used to eliminate all those sources that behave 'normal' in the visual spectrum, but deviate at the IRAS wavelengths. It is based on the assumption that stars radiate as hot blackbodies at $\lambda > 12\,\mu$m, so that the colour $[12]-[25] = 0^{\rm m}.0$ by definition. The adopted limit of $0^{\rm m}.25$ is approximately two standard deviations from the mean value of $[12]-[25]$.

In addition, we also excluded double stars from the sample, based on the spectral type information in the BSC. A star was

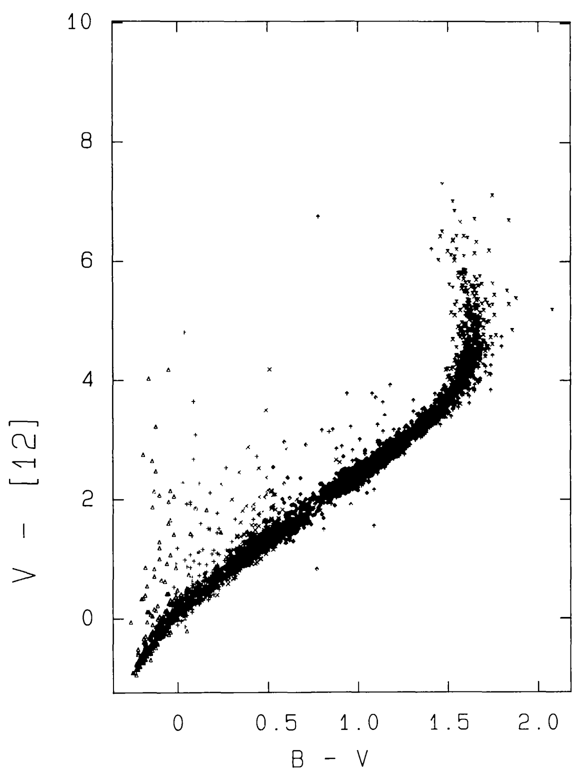

Fig. 2. $(V-[12])$ is plotted versus $(B-V)$ for all stars except supergiants, emission line stars and peculiar stars, most of the double stars (see text), as well as the stars with a far-IR colour $[12]$–$[25] > 0^{\rm m}.25$. Notice that the number of deviating stars is considerably smaller than in Fig. 1a. A small number of deviating stars still remains in the sample

rejected as a double star when the spectral type contained two separate designations (e.g. A + M). This means that double stars with two separate entries in the BSC for each component were *not* eliminated, since they might be separated far enough to be detected by IRAS as individual sources. This may lead to an erroneous identification of the far-IR flux of some members of double star systems. These stars will show up as deviating stars in the colour-colour plots (Fig. 1a), and will be eliminated by the second step in the procedure, the iterative process.

We did not exclude stars that are known to be variable from the sample. Stars with small amplitude variability (typically less than $0^m.15$ in V) will cause an additional scatter in the colour-colour relations. Stars with large amplitude variations will show up as deviating stars, and will be eliminated in the iterative process.

The remaining stars after exclusion of the groups mentioned above are plotted in Fig. 2. Notice that most (but not all) of the stars that deviate from the mean relation in Fig. 1a have been eliminated. An iterative method was used to exclude the remaining deviating stars from the sample. For this purpose, the $(B-V)$ axis was divided into intervals of $0^m.03$, and the $(V-[12])$ colours in each interval were averaged. This results in an average, $(V-[12])_{av}$, and its standard deviation σ. In the next iteration, stars with a colour $(V-[12])_*$ fulfilling the following criterion:

$$(V-[12])_* - (V-[12])_{av} > 2\sigma \tag{1}$$

were excluded from the sample. This was repeated until the average did not change any more. Usually, only two to three iterations were needed for each $(B-V)$ interval, except for the small $(B-V)$ values, where 5 to 7 iterations were necessary.

In Fig. 3 we have plotted $(B-V)$ versus $(V-[12])$ for all stars that remained in the sample after the iteration. Figure 3 shows that the iterative process eliminated the deviating stars, except for three stars at $(B-V) = -0^m.20$. We excluded those stars from the sample as well. We will refer to this sample as the "final sample".

3.3. Colour-colour relations for normal stars

In Table 1 we give the mean values of $(V-[12])$ as a function of $(B-V)$, with the 1σ standard deviation, the error in the mean and the total number of stars in each interval. A 4th degree polynomial was fitted through the points in Table 1, and is given below:

$$V-[12] = 0.05 + 3.13(B-V) - 1.26(B-V)^2 + 0.29(B-V)^3 + 0.16(B-V)^4 \tag{2}$$

Equation (2) is valid for the $(B-V)$ interval $-0.25 < (B-V) < 1.60$, and it reproduces the mean values of $(V-[12])$ within $0^m.03$ to $0^m.05$. Equation (2) may be affected by the neglect of interstellar reddening, certainly for the O and B type stars. For these stars, the intrinsic $(B-V)_0$, $(V-[12])_0$ relation will be derived in Sect. 3.4.

Using the method described above, the mean relation between $(R-I)$ and $(V-[12])$ was derived. The $(R-I)$ axis was divided in intervals of $0^m.04$. The result is plotted in Fig. 4, where we

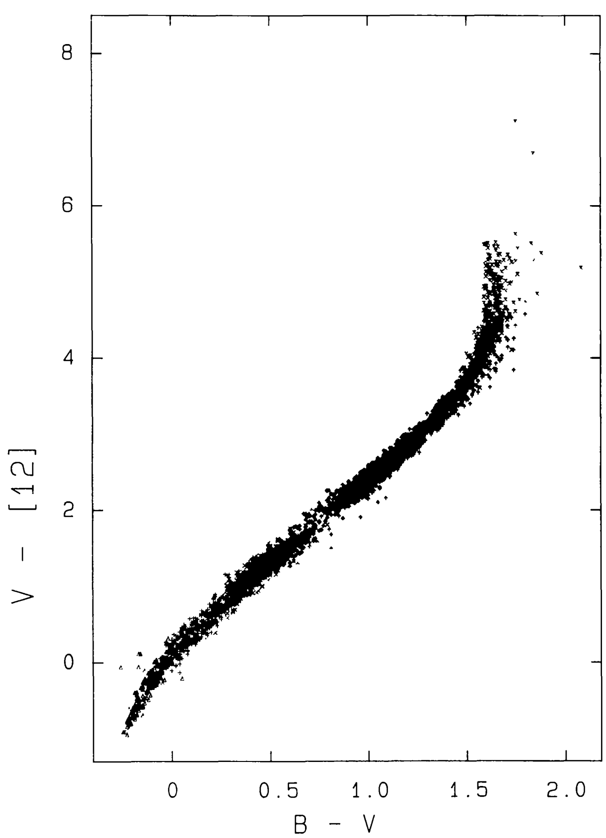

Fig. 3. The $(B-V)$, $(V-[12])$ diagram for all stars in the final sample. The deviating stars (Figs. 1a and 2) were eliminated using an iterative process. The width of the band is about $0^m.15$

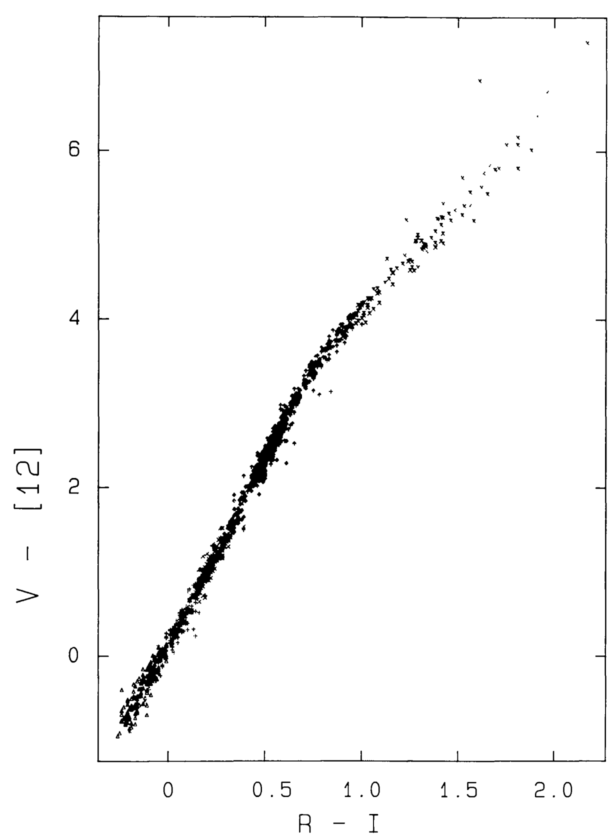

Fig. 4. The $(R-I)$, $(V-[12])$ relation for all stars in the final sample that have $(R-I)$ colours in the Johnson system is plotted

Table 1. $B - V$, $V - [12]$ relation for normal stars

$B-V$	$V-[12]$	σ	$\bar{\sigma}$	N	$B-V$	$V-[12]$	σ	$\bar{\sigma}$	N
−0.225	−0.77	0.10	0.026	15	0.735	1.78	0.13	0.031	18
−0.195	−0.61	0.13	0.023	33	0.765	1.86	0.27	0.060	20
−0.165	−0.55	0.05	0.081	8	0.795	2.04	0.15	0.038	16
−0.135	−0.39	0.15	0.031	24	0.825	2.03	0.17	0.037	21
−0.115	−0.26	0.09	0.016	33	0.855	2.11	0.09	0.017	28
−0.085	−0.13	0.10	0.017	34	0.885	2.20	0.10	0.011	89
−0.055	−0.04	0.10	0.020	25	0.915	2.25	0.09	0.012	57
−0.015	0.11	0.11	0.019	33	0.945	2.27	0.09	0.008	117
0.015	0.16	0.11	0.015	55	0.975	2.34	0.10	0.008	170
0.045	0.20	0.14	0.023	38	1.005	2.40	0.10	0.009	118
0.075	0.30	0.10	0.016	40	1.035	2.46	0.09	0.008	129
0.105	0.39	0.10	0.018	32	1.065	2.51	0.09	0.009	110
0.135	0.45	0.13	0.020	44	1.095	2.59	0.13	0.011	149
0.165	0.48	0.10	0.024	17	1.125	2.67	0.07	0.009	61
0.195	0.57	0.11	0.019	35	1.155	2.73	0.10	0.011	76
0.225	0.69	0.12	0.018	43	1.185	2.82	0.10	0.010	91
0.255	0.73	0.09	0.024	14	1.215	2.88	0.09	0.012	61
0.285	0.88	0.15	0.024	38	1.245	2.95	0.09	0.014	42
0.315	0.90	0.10	0.015	44	1.275	2.99	0.09	0.012	57
0.345	0.98	0.11	0.013	68	1.305	3.12	0.08	0.011	55
0.375	1.08	0.14	0.025	31	1.335	3.17	0.10	0.019	27
0.405	1.14	0.12	0.014	78	1.365	3.25	0.10	0.014	48
0.435	1.19	0.11	0.011	96	1.395	3.34	0.10	0.013	63
0.465	1.25	0.09	0.009	93	1.425	3.42	0.08	0.011	49
0.495	1.34	0.12	0.016	57	1.455	3.52	0.10	0.016	37
0.525	1.36	0.09	0.013	51	1.485	3.62	0.13	0.018	55
0.555	1.43	0.12	0.015	60	1.515	3.74	0.17	0.019	78
0.585	1.48	0.07	0.013	31	1.545	3.93	0.22	0.034	42
0.615	1.54	0.13	0.017	62	1.575	4.01	0.22	0.026	72
0.645	1.60	0.12	0.018	45	1.605	4.51	0.51	0.044	132
0.675	1.73	0.14	0.027	27	1.635	4.58	0.48	0.055	75
0.705	1.77	0.14	0.037	14					

give the $(R - I)$ from the BSC (in the Johnson photometric system) versus the $(V - [12])$ colour for the final sample. In Table 2, we list the average $(V - [12])$ colour for each $(R - I)$ interval, with the 1σ errors, the errors in the mean and the total number of stars in each interval. We fitted two straight lines through the averages:

$$V - [12] = 4.33(R - I) + 0.14 \quad \text{for} \quad (R - I) < 0.72 \tag{3a}$$

$$V - [12] = 2.69(R - I) + 1.40 \quad \text{for} \quad (R - I) > 0.72 \tag{3b}$$

The colour-colour relations given in Eqs. (2) and (3) were derived using the final sample, thus including stars close to the detection threshold of the Survey Instrument (estimated to be $+5^{m}.0$ at $12\,\mu$m (IRAS Explanatory Supplement, 1985)) and stars in or near the galactic plane. The point source detection algorithm used to extract point source fluxes from the data tends to overestimate the flux close to the detection limit, imitating an IR excess. Sources near the galactic plane may suffer from confusion, even at $12\,\mu$m. Both effects may introduce errors when deriving colours for normal stars.

Therefore we recalculated the $(B - V)$, $(V - [12])$ relation for the stars in the final sample excluding the stars with a $12\,\mu$m magnitude $[12] > 4^{m}.5$, and also excluding stars with $[12] > 4^{m}.5$ and galactic latitude $|b| < 10^{0}$. Both selection criteria will mainly affect the early type stars. The differences were always less than $0^{m}.05$, and usually less than $0^{m}.03$. Therefore we feel that Eq. (2) still represents a good fit between $(B - V)$ and $(V - [12])$ for normal A to M type stars.

As stated earlier, the average colour-colour relations derived above may be affected by the neglect of interstellar extinction, since this will cause a systematic reddening of the $(V - [12])$ colours. We can estimate the error in $(V - [12])$, $\Delta(V - [12])$, when neglecting extinction:

$$\Delta(V - [12]) = \left\{ \frac{d(V - [12])}{d(B - V)} - 3.1 \right\} E(B - V) \tag{4}$$

where 3.1 is the slope of the reddening line in Fig. 3 (neglecting extinction at $12\,\mu$m) (Savage and Mathis, 1979), and $d(V - [12])/d(B - V)$ is the slope of the mean relation. The slope of the $(B - V)$, $(V - [12])$ relation can be estimated from Eq. (2), and lies in the range $1.5 - 2$ for the A to K type stars. Adopting a value of 1.75 for this slope, we find from Eq. (4) that a star

Table 2. $R-I$, $V-[12]$ relation for normal stars

$R-I$	$V-[12]$	σ	$\bar{\sigma}$	N
−0.24	−0.72	0.17	0.057	9
−0.20	−0.70	0.11	0.022	25
−0.16	−0.51	0.13	0.023	33
−0.12	−0.32	0.14	0.026	29
−0.08	−0.19	0.10	0.017	36
−0.04	−0.01	0.08	0.014	34
0.00	0.16	0.10	0.020	26
0.04	0.27	0.10	0.014	48
0.08	0.45	0.09	0.013	46
0.12	0.60	0.14	0.030	22
0.16	0.78	0.15	0.027	32
0.20	0.98	0.12	0.019	38
0.24	1.15	0.10	0.018	32
0.28	1.32	0.11	0.035	35
0.32	1.49	0.10	0.018	31
0.36	1.69	0.12	0.026	22
0.40	1.84	0.18	0.044	17
0.44	2.13	0.09	0.015	34
0.48	2.25	0.11	0.011	103
0.52	2.42	0.10	0.010	98
0.56	2.59	0.10	0.012	71
0.60	2.76	0.12	0.015	67
0.64	2.93	0.14	0.024	26
0.68	3.09	0.06	0.013	21
0.72	3.30	0.09	0.017	27
0.76	3.40	0.09	0.017	27
0.80	3.52	0.15	0.042	13
0.84	3.64	0.17	0.044	15
0.88	3.81	0.08	0.017	21
0.92	3.92	0.10	0.025	16
0.96	4.03	0.08	0.023	12
1,00	4.10	0.09	0.030	9
1.04	4.16	0.11	0.042	7
1.08	4.28	0.10	0.041	6

with $E(B-V)=0^{m}.10$ will cause an error of $0^{m}.14$ in the $(B-V)$, $(V-[12])$ relation.

Table 2 shows that the 1σ errors in $(V-[12])$ for individual stars are in the order of $0^{m}.10$ to $0^{m}.15$, i.e. comparable to the errors in $(V-[12])$ when neglecting extinction. If a large fraction of the stars were reddened considerably ($E(B-V)>0^{m}.10$), the neglect of extinction would give erroneous results. Therefore we calculated the average $(B-V)$, $(V-[12])$ relation excluding the stars with $E(B-V)>0^{m}.10$. We determined $E(B-V)$ by using the spectral type of the stars to derive the intrinsic $(B-V)_0$ colour, with $(B-V)_0$ as function of spectral type taken from FitzGerald (1970). The result of this test showed that the average $(B-V)$, $(V-[12])$ relation was not affected within errors by the stars with $E(B-V)>0^{m}.10$, except for the early-type stars.

The $(R-I),(V-[12])$ relation is even less sensitive to the effects of the interstellar extinction, since the slope of the reddening line in that diagram (3.78; Savage and Mathis, 1979) is close to the slope of the colour-colour relation itself (Eq. (3)). Adopting $E(B-V)=0^{m}.10$, the neglect of extinction results in an error in the $(R-I),(V-[12])$ diagram of only $0^{m}.05$, if $(R-I)<0^{m}.72$, i.e. well within the 1σ errors for the individual points.

We conclude that the neglect of extinction introduces no serious errors in the colour-colour relations derived in this Section, except for the early-type stars.

3.4. The intrinsic (B − V), (V − [12]) relation for OBA stars

In the previous Subsections, the colour-colour relations were derived neglecting the interstellar extinction correction. In this Subsection, we give the intrinsic $(B-V)_0$, $(V-[12])_0$ relation for normal OBA stars.

The observed $(B-V)$ colours of the OBA stars in the final sample were converted to $(B-V)_0$ colours using the intrinsic $(B-V)_0$ colours as function of spectral type given by FitzGerald (1970), and the spectral classification given in the BSC. The visual magnitude V was corrected for extinction using $A_V=3.1E(B-V)$. We assumed that extinction is negligible at 12 μm, since $A_{12}/E(B-V)\leq 0.05$ (Savage and Mathis, 1979). We excluded the stars with $[12]>+4^{m}.5$ from the final sample. In Fig. 5, we have plotted the intrinsic $(B-V)_0$, $(V-[12])_0$ colours for the OBA stars in this sample. As can be seen, the use of spectral type as the indicator of intrinsic properties causes the stars to

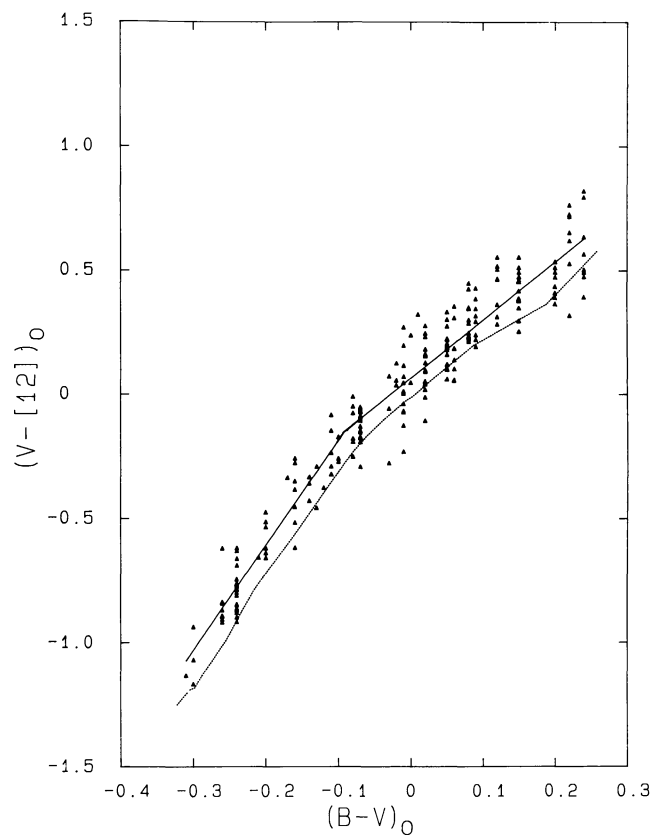

Fig. 5. The intrinsic $(B-V)_0$, $(V-[12])_0$ relation for OBA stars in the final sample, excluding the stars with $[12]>4^{m}.5$. We fitted two straight lines through the points, given in Eq. (5) (the solid line). Also plotted is the theoretical $(B-V)_0$, $(V-[12])_0$ relation based on the Kurucz (1979) model atmospheres (dotted line). The Kurucz models underestimate the 12 μm flux by about 10 percent

Table 3. $V - [12]$ as function of spectral type

	Class IV–V			Class II–III		
	$V-[12]$	σ	$\bar{\sigma}$	$V-[12]$	σ	$\bar{\sigma}$
B2	−0.75	0.12	0.02			
B3	−0.58	0.08	0.02			
B4	−0.40	0.11	0.05			
B5	−0.47	0.15	0.04			
B6	−0.22	0.23	0.08			
B8	−0.20	0.14	0.03			
B9	−0.04	0.17	0.03			
A0	0.05	0.11	0.02			
A1	0.16	0.14	0.02			
A2	0.26	0.11	0.01			
A3	0.37	0.15	0.02			
A4	0.47	0.13	0.03			
A5	0.53	0.15	0.03			
A7	0.59	0.16	0.03			
A8	0.75	0.12	0.03			
A9	0.88	0.17	0.05			
F0	0.84	0.16	0.02	0.89	0.15	0.04
F1	1.01	0.16	0.03			
F2	1.06	0.17	0.02	1.05	0.18	0.04
F3	1.11	0.13	0.02			
F4	1.20	0.13	0.02			
F5	1.20	0.11	0.01	1.17	0.08	0.02
F6	1.27	0.13	0.01	1.39	0.25	0.07
F7	1.32	0.11	0.01			
F8	1.40	0.11	0.01			
F9	1.46	0.12	0.02			
G0	1.50	0.14	0.02			
G1	1.51	0.11	0.03			
G2	1.57	0.11	0.02	2.14	0.33	0.11
G3	1.64	0.14	0.03			
G4	1.68	0.19	0.06			
G5	1.84	0.29	0.05	2.18	0.15	0.03
G6	1.91	0.27	0.08	2.25	0.12	0.02
G7				2.28	0.11	0.02
G8	2.20	0.28	0.04	2.31	0.13	0.01
G9	2.49	0.13	0.04	2.38	0.14	0.02
K0	2.42	0.31	0.04	2.48	0.17	0.01
K1	2.52	0.17	0.03	2.65	0.21	0.01
K2	2.46	0.26	0.06	2.89	0.25	0.02
K3	2.46	0.12	0.05	3.19	0.26	0.02
K4				3.51	0.21	0.02
K5				3.73	0.20	0.02
M0				4.08	0.23	0.03
M1				4.37	0.22	0.03
M2				4.56	0.26	0.03
M3				4.93	0.24	0.03
M4				5.53	0.35	0.05
M5				6.02	0.43	0.10

group at discrete values of $(B-V)_0$. Therefore we decided to use the individual stars to obtain a fit, rather than averaging the $(V-[12])_0$ colours in each $(B-V)_0$ interval before calculating the fit. We fitted two straight lines through the points, with a change in slope at $(B-V)_0 = -0\overset{\mathrm{m}}{.}09$. A least squares fit with equal weights yields the following relations:

$$(V-[12])_0 = (4.22 \pm 0.20)(B-V)_0 + (0.23 \pm 0.04)\,, \qquad (B-V)_0 < -0.09 \tag{5a}$$

$$(V-[12])_0 = (2.35 \pm 0.09)(B-V)_0 + (0.07 \pm 0.01)\,, \qquad -0.09 < (B-V)_0 < 0.25 \tag{5b}$$

3.5. $(V-[12])$ as function of spectral type

The $(V-[12])$ colours were also derived as a function of spectral type and luminosity class. For this purpose, we divided the stars of the final sample into two groups, based on their luminosity class given in the BSC, viz. class II to III, and class IV to V. We excluded stars with unknown luminosity class from the final sample.

The average $(V-[12])$ colours for stars earlier than A1 were calculated with extinction correction, where the extinction $E(B-V)$ was based on spectral type (see Sect. 3.3). For stars later than A1 we assumed that the interstellar extinction can be neglected. We checked this assumption by comparing the average $(V-[12])$ colours with and without extinction correction. The differences were within errors for the A1 to F type stars. For stars later than about G0 the instrinsic spread in $(B-V)$ for a given spectral type is too large (typically $0\overset{\mathrm{m}}{.}10$) to derive an accurate value of $E(B-V)$ based on spectral type. Since extinction is negligible for the A1 to F type stars, we assumed that it can also be neglected for the later type stars.

In Table 3, we list the average $(V-[12])$ colours for the dwarfs and giants with the standard deviation and the error in the mean $\bar{\sigma}$. Blank entries indicate that no reliable average could be determined.

3.6. Discussion

In Fig. 6, we compare the predicted and observed $(V-[12])$ colours as a function of spectral type for all stars that were observed at $12\,\mu$m (including the deviating stars). The predicted $(V-[12])$ colours were calculated using Eq. (2) from the V and $(B-V)$ given for each star in the BSC. We excluded the stars with $(B-V) > 1\overset{\mathrm{m}}{.}60$, since Eq. (2) is not valid for those values of $(B-V)$. Mostly M-type stars are excluded by this criterion.

Figure 6 shows that especially among the B and A type stars a large fraction of the stars show IR excess, i.e. $\{(V-[12])_{\mathrm{obs}} - (V-[12])_{\mathrm{pred}})\} > 0\overset{\mathrm{m}}{.}0$. For the M-type stars the individual stars show very large deviations from the mean. This indicates that the $(B-V)$, $(V-[12])$ relation is not useful for these stars. In Table 4 we list the percentage of stars with excess above $0\overset{\mathrm{m}}{.}20$ and $0\overset{\mathrm{m}}{.}50$ for the different spectral types. The values for the B-type stars may be affected somewhat by the interstellar extinction (neglected in the calculation of $(V-[12])_{\mathrm{pred}}$).

We want to stress that the determination of the $(V-[12])$ colours as function of $(B-V)$ gives much more accurate results than the determination of $(V-[12])$ as function of spectral type, especially for the late type stars. This can be understood by noting that the observed intrinsic spread in $(B-V)$ for a given spectral type and luminosity class can be considerable for late type stars.

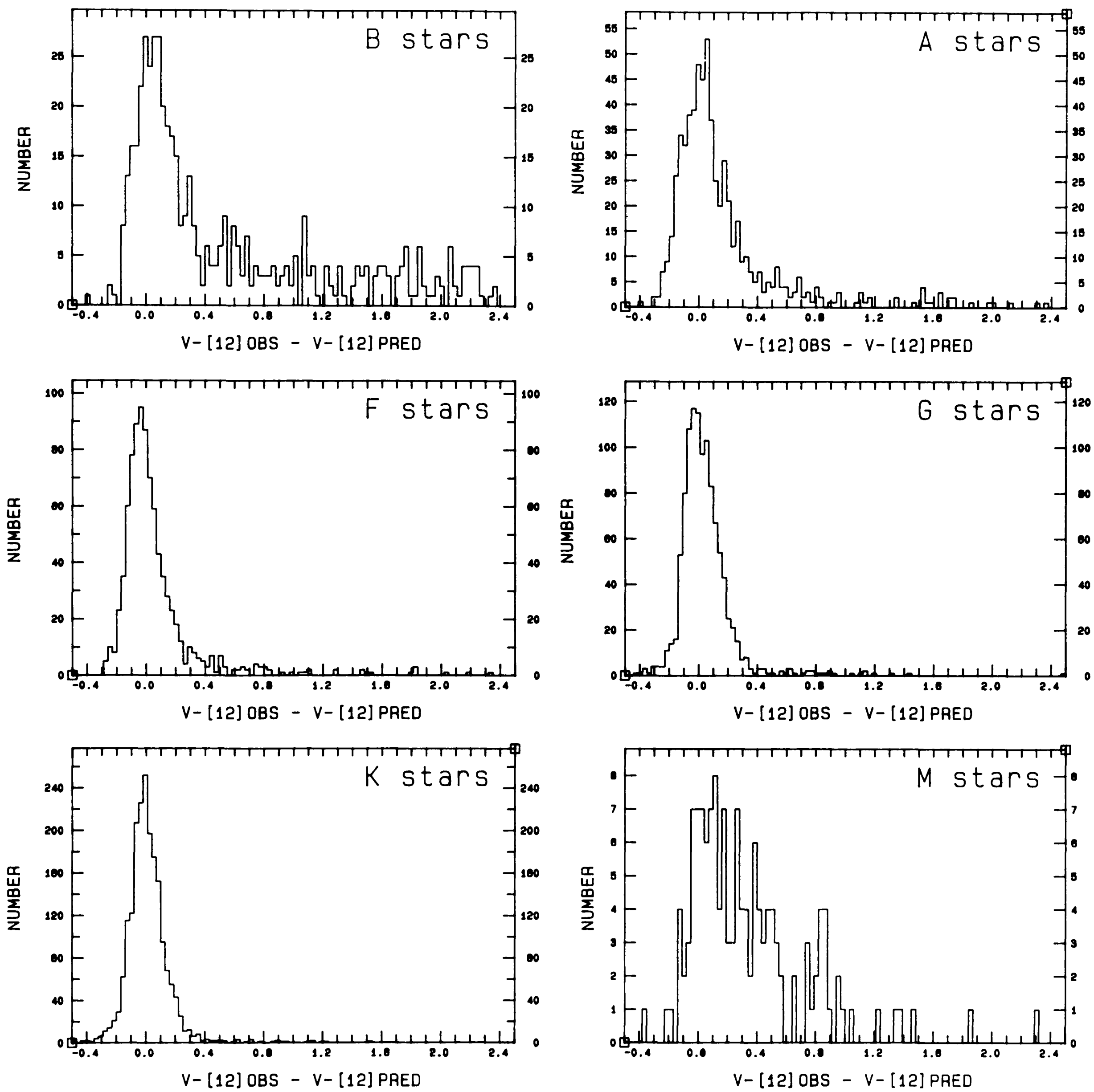

Fig. 6. Histograms of the comparison of observed and predicted ($V-[12]$) colour. The predicted ($V-[12]$) colour is based on the ($B-V$), ($V-[12]$) relation derived in Sect. 3. We excluded stars with $(B-V) > 1^{m}.60$. Notice that especially the B and A type stars show a large fraction of deviating stars. The K stars behave very "normal"

Table 4. The percentage of stars with excess as function of spectral type

Spectral type	Total number of stars	Excess (%) $>0^{m}.20$		Excess (%) $>0^{m}.50$	
B	527	273	51.8	208	39.5
A	648	166	25.6	87	13.4
F	876	109	12.4	46	5.3
G	1094	90	8.2	27	2.5
K	1957	97	5.0	24	1.2
M[a]	154	86	55.8	45	29.2

[a] Stars with $(B-V) > +1.60$ were excluded, i.e. mostly M-type stars

4. Comparison with model atmospheres

It is interesting to compare the intrinsic $(B-V)_0$, $(V-[12])_0$ relation with the predicted relation based on model atmospheres. In Fig. 5, we have plotted the intrinsic colour-colour relation based on the grid of model atmospheres published by Kurucz (1979). For this purpose, we calculated the theoretical 12 μm magnitude for the models by folding the energy distribution of the models with the shape of the 12 μm passband given in the Explanatory Supplement. We used the models in the temperature range 8000 to 50000 K, and with $\log g = 4.0$, i.e. corresponding to main sequence stars. In Table 5 we compare the intrinsic $(B-V)_0$, $(V-[12])_0$ relation derived in Sect. 3 with the relation based on the Kurucz models.

Table 5. Comparison of $(B-V)$, $V-[12]$ relation with model atmospheres

$(B-V)$	$V-[12]$ This paper	$V-[12]$ Models
−0.30	−1.04	−1.18
−0.28	−0.95	−1.10
−0.26	−0.87	−1.01
−0.24	−0.78	−0.91
−0.22	−0.70	−0.82
−0.20	−0.61	−0.72
−0.18	−0.53	−0.64
−0.16	−0.45	−0.56
−0.14	−0.36	−0.48
−0.12	−0.28	−0.40
−0.10	−0.19	−0.31
−0.08	−0.12	−0.23
−0.06	−0.07	−0.17
−0.04	−0.02	−0.10
−0.02	0.02	−0.06
0.00	0.07	0.01
0.02	0.12	0.04
0.04	0.16	0.09
0.06	0.21	0.14
0.08	0.26	0.18
0.10	0.31	0.22
0.12	0.35	0.24
0.14	0.40	0.29
0.16	0.45	0.32
0.18	0.49	0.35
0.20	0.54	0.40
0.22	0.59	0.46
0.24	0.63	0.52

Kurucz (1979) models used with $\log g = 4.0$ and $\log A = 0.0$.

Figure 5 clearly shows that the shape of the observed and theoretical colour-colour relation agree very well, but that there is an offset by about $0^m.10$ in the $(V-[12])_0$ direction, in the sense that the models predict a $(V-[12])_0$ colour that is too low compared to the observations. We conclude that the models do not predict the $(V-[12])_0$ colour correctly, but underestimate the 12 μm flux by about $0^m.10$ (average).

The results of this Section are in agreement with the comparison of observed 12 μm absolute fluxes with models for a small number of early A-type dwarfs by Rieke et al. (1985). They report an excess of about 10 percent at 12 μm for their program stars (including α Lyr and α CMa) relative to the Kurucz models. Their conclusion can now be extended to other (OBA) spectral types. Mountain et al. (1985) have studied the absolute fluxes of α Lyr in the wavelength region 1–5 μm, and find an excess relative to the Kurucz model appropriate for the star that is increasing with wavelength to about 8 percent at 5 μm.

Castor and Simon (1983) studied the 1 to 5 μm energy distribution of a large sample of O-type stars, and found that at 5 μm the Kurucz LTE models underestimate the flux by about 10 percent. They suggest that this discrepancy could be due to non-LTE effects in the outer layers of the atmospheres.

A comparison of the temperature structure of LTE and non-LTE models published by Mihalas (1972) shows that the temperature in the non-LTE models increases outwards again after it has reached a minimum. This rise is not seen in the LTE models, and is mainly due to heating of the outer layers through Hα. However, the colours of the Mihalas (1972) LTE and non-LTE models do not differ between 1 and 5 μm. At 300 μm, the longest wavelength tabulated by Mihalas, the LTE models are about $0^m.20$ fainter than the non-LTE models. So the non-LTE models indeed predict a higher far-IR flux than the LTE models, but the wavelength at which the difference becomes notable is not in agreement with the observations. This might indicate that non-LTE effects influence the temperature structure in deeper layers than suggested by the Mihalas models.

5. Comparison with Johnson's colours

Johnson (1966) has published a list of intrinsic colours in the wavelength region 0.33–10 μm for a large range of spectral types and luminosity classes. The $(V-N)$ colours given by Johnson (1966) cannot be compared directly with the $(V-[12])$ colours derived in Sect. 3 without a correction for the zero magnitude scale adopted for IRAS. Johnson defines $m_\lambda = 0^m.0$ at 10.2 μm for a flux of 43 Jy. Converting this to 12 μm using an $F_\nu \propto \nu^2$ dependence, this corresponds to a zero magnitude flux of 31 Jy at 12 μm. The IRAS magnitude scale defines $m_\lambda = 0^m.0$ at 12 μm for $F_\nu = 28.3$ Jy (Explanatory Supplement, 1985). Therefore the Johnson colours have to be corrected by adding $0^m.10$ in order

Table 6. Comparison of IRAS colours with Johnson's intrinsic colours

Spectral type	$\{(V-N)-(V-[12])\}$ III	V
A0	–	0.02
A2	–	−0.03
A5	–	−0.07
A7	–	−0.03
F0	–	0.05
F2	–	−0.03
F5	–	−0.03
F8	–	−0.03
G0	–	−0.05
G2	–	−0.03
G5	0.03	–
G8	−0.09	–
K0	−0.10	–
K1	−0.16	–
K2	−0.31	–
K3	−0.29	–
K4	−0.30	–
K5	−0.09	–
M0	−0.33	
M1	−0.49	
M2	−0.49	
M3	−0.38	
M4	−0.49	
M5	0.08	

to be comparable with the IRAS colours. Note that this is only valid if stars do not change in magnitude between 10.2 and 12 μm. This is a reasonable assumption for the vast majority of the stars.

In Table 6, we compare the IRAS and Johnson colours for the spectral types in common. We find that within errors, there is good agreement with the Johnson colours and the results of this study for spectral types earlier than K, although there is a tendency for the difference $\{(V-N)_J-(V-[12])\}$ to be negative. For spectral types K0–M5 the agreement is worse, in the sense that our results indicate a brighter 12 μm magnitude for these stars.

For the M type stars, the difference between the Johnson and IRAS colours may be caused by the different band shapes of the photometric systems. Many M-types giants show broad emission or absorption features in their spectra around 10 μm, probably caused by circumstellar dust. It is not clear what is causing the difference between the Johnson and IRAS colours for the KK–K5 type stars. The inclusion of luminosity class II stars in the sample introduces no serious errors, since the number of class II stars is negligibly small. We checked the possibility that the neglect of extinction might cause the difference between our result and that of Johnson by calculating the average $(V-[12])$ colour for giants with $V < +4\overset{m}{.}0$, i.e. selecting the nearby stars in our sample. The results were within errors in agreement with the averages derived in Sect. 3.

6. Conclusions

The purpose of this study was the determination of the relation between the visual and IR colours of stars. This is a first step in order to be able to discriminate between "normal" and "abnormal' stars in the far-IR. The most important results can be summarized as follows.

The majority of the stars observed with IRAS at 12 μm show a well-defined relation between the colours in the visual and in the IR. Most deviating stars are of spectral types B and A, and also the M-type stars show a large scatter. The deviating stars show an excess of IR radiation, most likely due to circumstellar material. The percentage of deviating stars decreases towards the late type stars. In particular the G and K type stars show very few stars with excess.

The comparison of the intrinsic $(B-V)_0$, $(V-[12])_0$ relation for the OBA stars with the predicted relation based on the Kurucz LTE model atmospheres shows that the models underestimate the 12 μm flux for all OBA stars by about 10 percent. The cause of this discrepancy may be the temperature structure of the outer layers of the LTE models.

A comparison of the IRAS $(V-[12])$ colours with those of Johnson (1966) shows good agreement except for the K0–M5 type stars. For the M-type stars this may be due to features in the energy distribution and the difference between the passbands in both systems.

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