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Interstellar Reddening and IR-excess of O and B Stars

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Summary. 350 O and B stars were selected according to specific criteria. Two-colour diagrams were used to derive a mean law of interstellar reddening for the various directions of our galaxy included in this study.
The reddening constant was derived to be

$$R = A_V/E_{B-V} = 3.14 \pm 0.10\,.$$

Only 20 out of 350 stars were found above the determined upper scattering limit, and therefore show an apparent infrared excess. We conclude from our investigation that we are able to distinguish between normally reddened O and B stars and stars which show anomalous infrared excess.

Key words: interstellar reddening — IR-excess — OB-stars

Introduction

The existence of interstellar dust can be proved by interstellar extinction or by dust emission. Both can best be measured by infrared photometry or spectroscopy. The physical nature of interstellar reddening is treated in numerous reviews, e.g. Sharpless (1963), Greenberg (1963), Johnson (1968), Borgman (1968), Lynds and Wickramasinghe (1968), Aannestad and Purcell (1973). We will show that infrared photometry of stars defines one reddening law in the important long wavelength range $\lambda^{-1} \to 0$, and thus enables one to determine more exactly the value of $A(\lambda)$. Neutral extinction is negligible (Sherwood, 1975). Johnson (1968) has summarized his infrared photometric results as follows: The reddening law is a function of galactic longitude with a value for the reddening constant R varying between 3 and 6.
A similar picture has been published by Fernie and Marlborough (1963), Crézé (1972). Other authors (e.g. Underhill, 1964, 1966; Walker, 1964; Schmidt-Kaler, 1967; Harris, 1973) have concluded that for all directions of our galaxy a mean reddening law exists with $R \approx 3$, and that deviations from this value, if they occur, must be small. It was shown that for some of the stars investigated by Johnson the colour indices can also be explained under the assumption of normal extinction ($R \approx 3$). But in general the interpretation of Johnson has not been disproved until now. In the present paper a unique mean reddening law with $R = 3.14$ is established based on B, V, R, I, J, K and L magnitudes of 350 selected O- and B-type stars. This law is valid at least for all directions of our galaxy covered by the selected stars. Deviations from this law are explained as variations and anomalies of the intrinsic colours of the stars or as additive emission in the vicinity of the stars.
All published observations of O- and B-stars in the standard filter bands (Johnson, 1965a; Lamla, 1965) were used for the present investigation, including the stars measured by Johnson subject to the following criteria:
1. stars must have normal spectra,
2. no stars with anomalous continua,
3. no close visual binaries with small magnitude differences,
4. no Be stars or stars with peculiar spectra.
An additional 42 stars were measured to determine the accuracy and comparability of the values published by different authors and to complete the measurements for all directions of the galaxy, which are accessible with the 76 cm and 102 cm telescopes at Jungfraujoch and Hoher List respectively. Our measurements were performed with a multichannel photometer (Schultz and Wiemer, 1972, 1973), whose channels have been fitted with the standard filter bands $U, B, V, R, I, J, H, K, L$. The results, including data on atmospheric extinction, were published in detail by Wiemer (1973).

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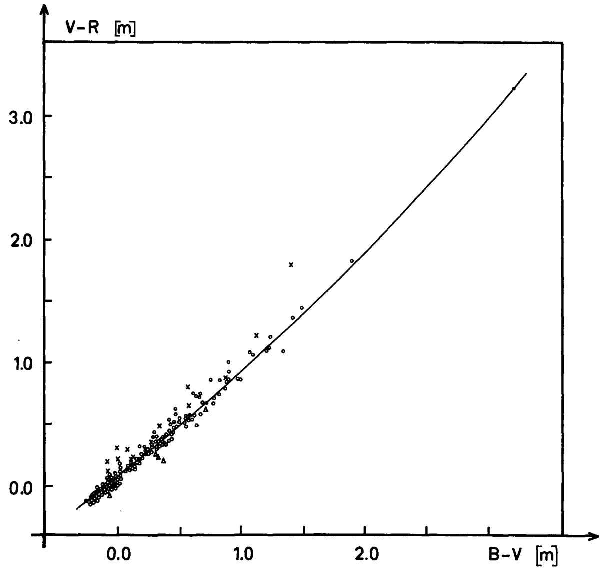

Fig. 1a. Two-colour diagram (ordinate $V-R$) showing the mean reddening line. Stars located above the upper scattering limit are marked as crosses and stars located below the lower limit as triangles

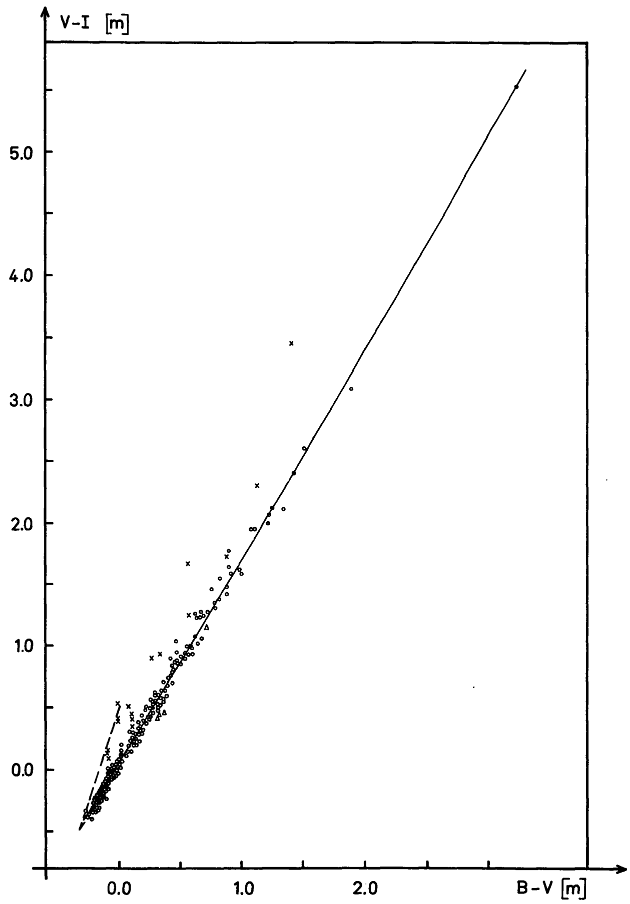

Fig. 1b. Two-colour diagram (ordinate $V-I$) showing the mean reddening line. The broken-line is taken from Johnson (1966a). A wedge-shaped distribution marked by the broken-line and the reddening line is certainly not present

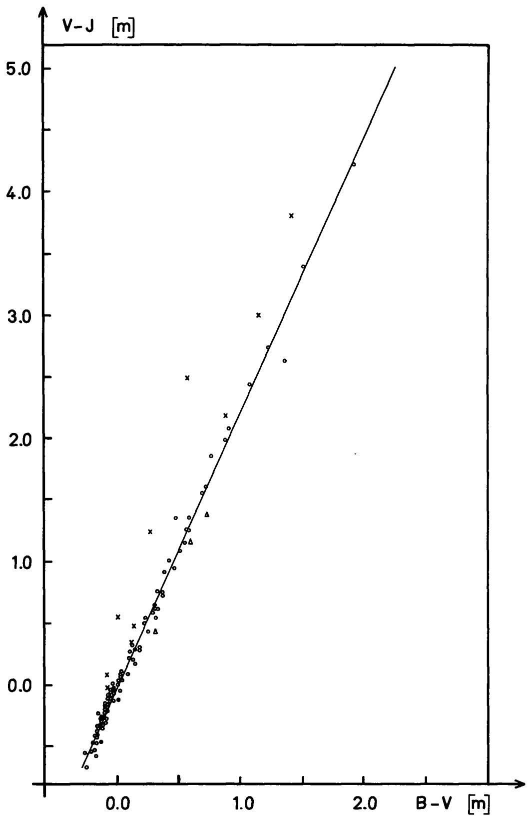

Fig. 1c. Two-colour diagram (ordinate $V-J$) showing the mean reddening line

Two-colour Diagrams

The intensity ratio at two wavelengths can be expressed in magnitudes by:

$$m(\lambda_1)-m(\lambda_2)=m^0(\lambda_1)-m^0(\lambda_2)+2.5\log e \cdot \bar{n}d[a(\lambda_1)-a(\lambda_2)] \tag{1}$$

where $a(\lambda)$ is the extinction cross-section of one particle, $\bar{n}$ the mean number of particles in the line of sight per parsec, and d the distance between telescope and source in parsec. Or shorter:

$$C_{1,2}=C^0_{1,2}+\text{const}\cdot E_{1,2}\,. \tag{2}$$

For two different colours the elimination of const. gives:

$$C_{3,4}=(E_{3,4}/E_{1,2})C_{1,2}+C^0_{3,4}-(E_{3,4}/E_{1,2})C^0_{1,2}\,. \tag{3}$$

The function $C_{3,4}=f(C_{1,2})$ is called the two-colour diagram and is a straight line with the slope $E_{3,4}/E_{1,2}$, if bandwidth effects are neglected. The stars are reddened according to the same law, if all stars with same intrinsic colours $C^0_{1,2}$ and $C^0_{3,4}$ are located on a straight line, the reddening line. Stars of the same spectral type and luminosity class may, however, show small deviations in intrinsic colours and are thus uniformely scattered around the mean reddening line. But if the distribution in the two-colour diagram (Johnson, 1966a)

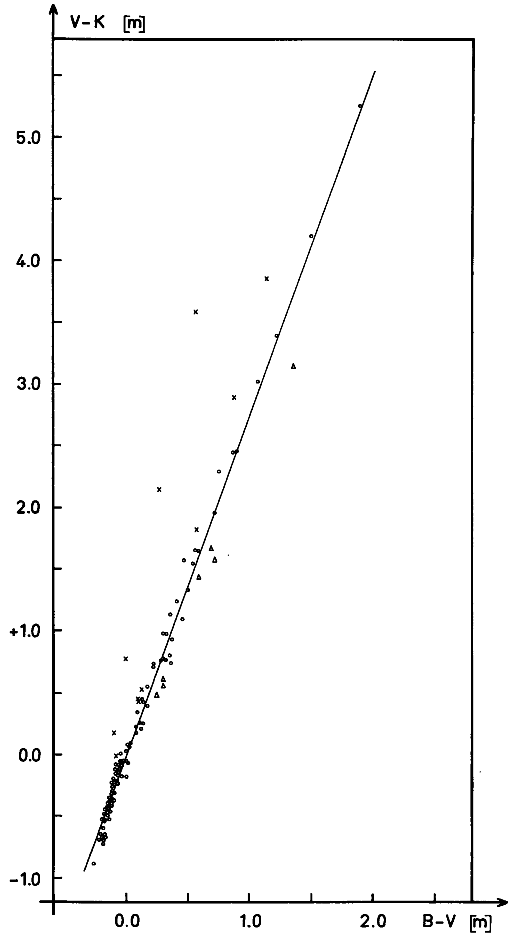

Fig. 1d. Two-colour diagram (ordinate $V-K$) showing the mean reddening line

appears wedge-shaped, deviations from the reddening law exist. Therefore it is possible to separate between deviations from the reddening law on one side and general scatter due to intrinsic colours of the stars on the other. Bandwidth effects demand a correction of the relations derived above. In the cases $C_{3,4}=V-R$ and $V-I$, one has to add a quadratic term.

The colours of O and B stars are plotted in the two-colour diagrams of Figs. 1a—e. These values are taken from the following papers:

Reference number:
1. Johnson *et al.*, 1966.
2. Johnson, 1968.
3. Mendoza, 1968.
4. Mendoza, 1967.
5. Johnson and Borgman (1963) with remarks from Johnson (1968).
6. Johnson, 1967a.
7. Wiemer, 1973.
8. Lee, 1968.
9. Iriarte, 1969.
10. Johnson, 1966b.

If more than one star has the same colour coordinates only one point is marked in the Figs. 1a—e. That is often the case where the points are clustered. From the distribution of values in the two-colour diagrams of Figs. 1a—e, we conclude that only *one* mean reddening law exists for our galaxy. A systematic increase of scatter with increasing reddening, i.e. a wedge-shaped distribution as found by Johnson (1966a) can definitely be excluded, as one can see from Fig. 1b. To obtain the

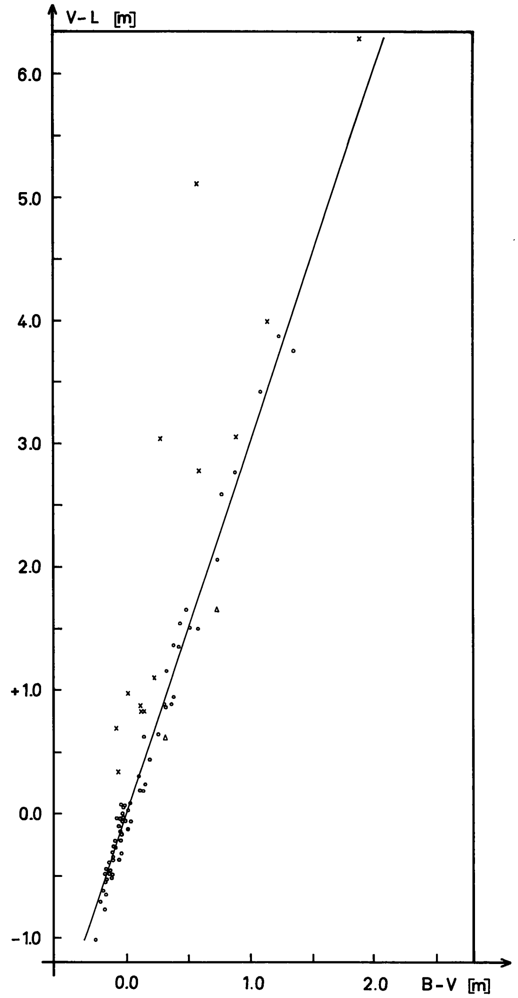

Fig. 1e. Two-colour diagram (ordinate $V-L$) showing the mean reddening line

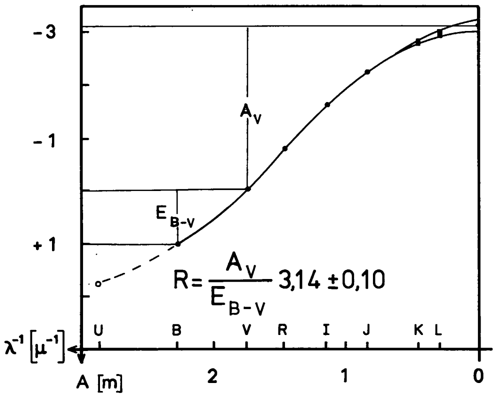

Fig. 2. The mean law of interstellar reddening on our galaxy

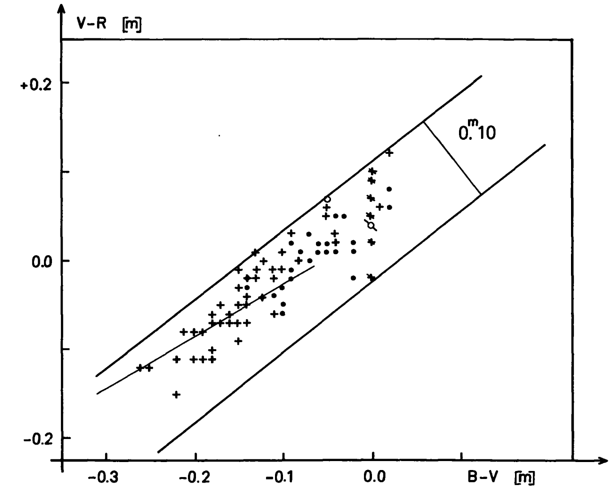

Fig. 3a. Limits of scatter for main sequence B stars (ordinate $V-R$). Stars of spectral types B 0...B 5 are marked as crosses and B 6...B 9.5 as points. For comparison O stars are marked by *o*. The straight line inside of the limits characterizes the intrinsic colours of main sequence stars. Stars which are marked by a diagonal streak are highly reddened and only to simplify the presentation were transferred parallel to the mean reddening line to $B-V=0$

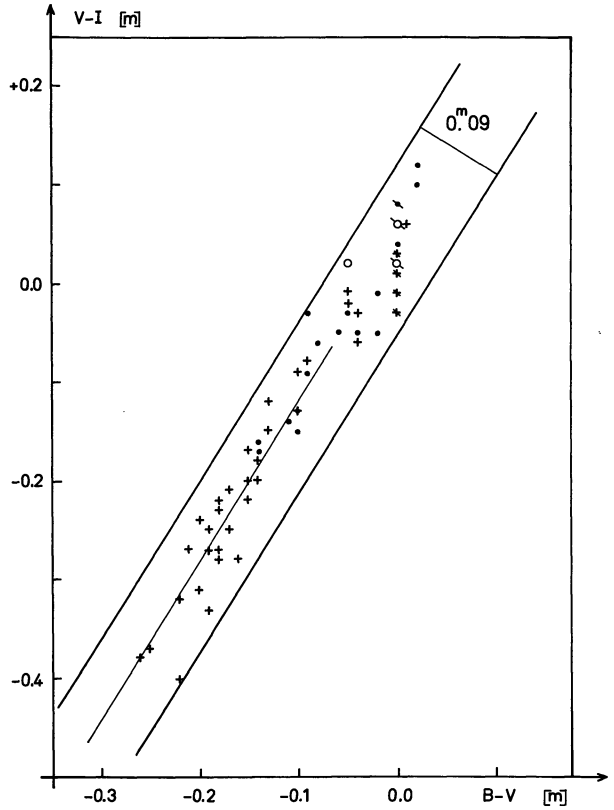

Fig. 3b. Limits of scatter for main sequence B stars (ordinate $V-I$)

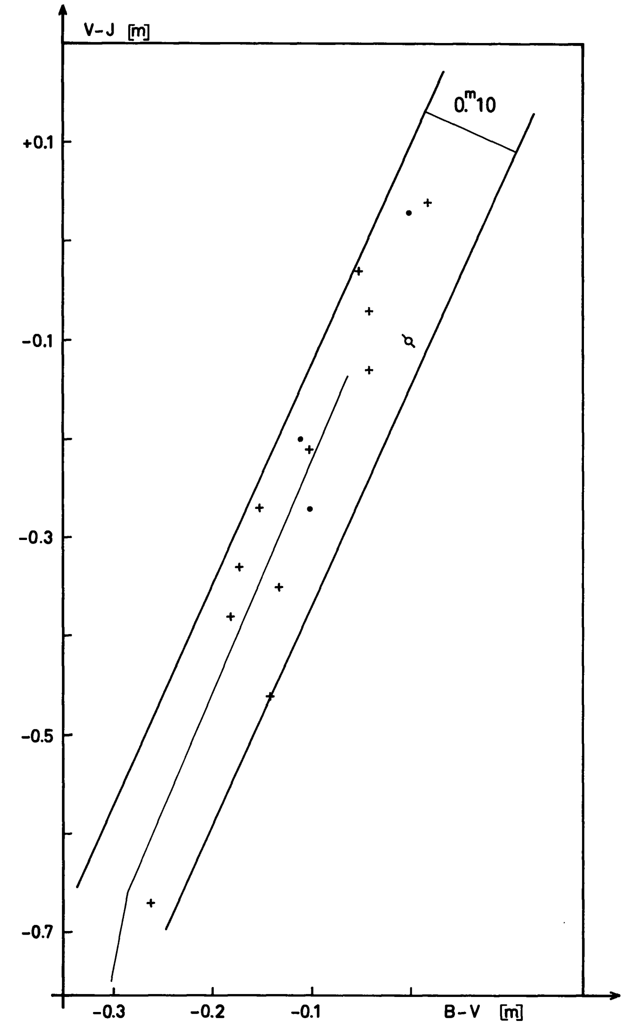

Fig. 3c. Limits of scatter for main sequence B stars (ordinate $V-J$)

mean reddening law, which is represented in Fig. 2, the slopes are taken from the two-colour diagrams (Table 5). The value for (E_{U-V}/E_{B-V}) is taken from the curve "van de Hulst Nr. 15" (Johnson, 1968). The slopes are determined by the method of least squares with the $(B-V)$ coordinate assumed to be error free. The long base-lines insure that the slope is not affected by scatter in $B-V$. Extrapolation of the reddening curve to $1/\lambda \rightarrow 0$, with an error given especially by the values of K and L, leads to

$$R = 3.14 \pm 0.10 .$$

This is a mean value for all direction of the galaxy covered by photometry of 350 selected O and B stars. The error of ± 0.10 is the maximum allowed from Fig. 2 and includes the error of ± 0.07 in the slope $(V-L)/(B-V)$. With better L values the error could be further reduced. To date the best value for R is given by Harris (1973). From the cluster diameter method he obtained $R = 3.15 \pm 0.20$, very close to our value, but with an error twice as large as ours. The scatter for three groups of stars was discussed separately by Wiemer (1973):

a) B stars of luminosity classes IV and V,
b) B stars of luminosity classes I, II and III,
c) O and Of stars of all luminosity classes.

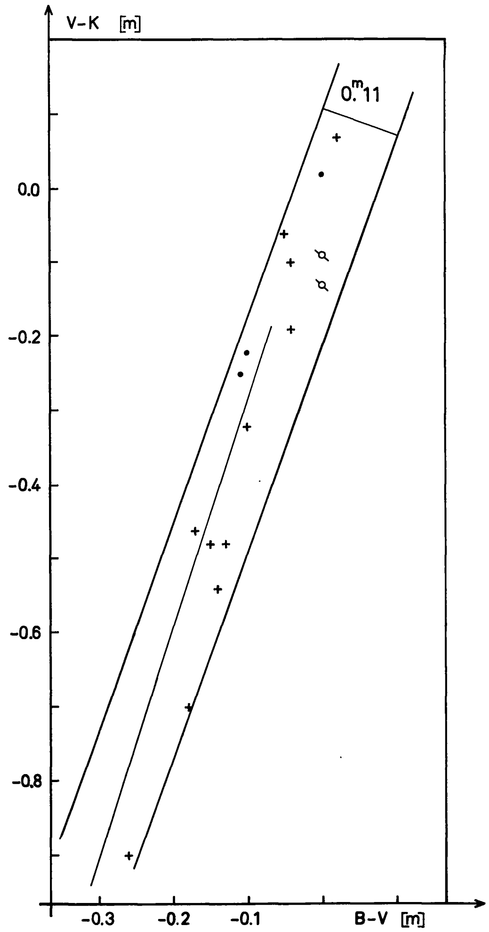

Fig. 3d. Limits of scatter for main sequence B stars (ordinate $V-K$)

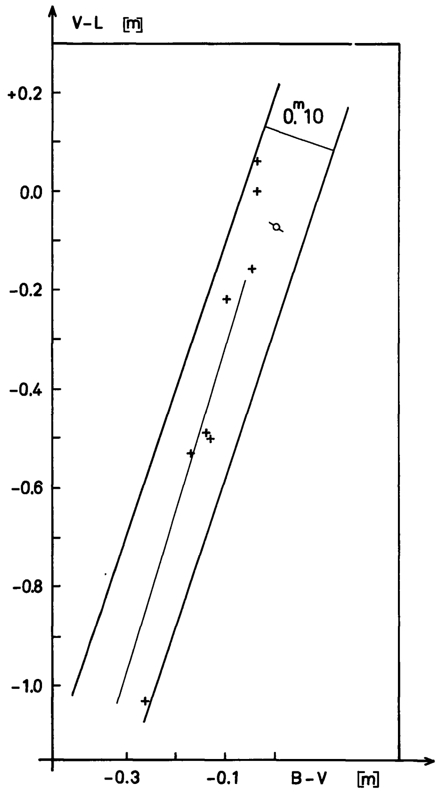

Fig. 3e. Limits of scatter for main sequence B stars (ordinate $V-L$)

An example is represented in Figs. 3a—e. To determine the scattering limits all B stars of luminosity class V which fulfill the criteria mentioned earlier, were taken from the references cited above. These stars are hardly affected by interstellar extinction. Hence the scatter of the measured colours may be interpreted as a scatter of the intrinsic colours to a good approximation. No systematic shifting is found between early and late B-type stars. Therefore it is not justified to differentiate between different B-type stars. The limits of the scatter shown in Fig. 3 are parallel to the corresponding mean reddening line. Their values for $B-V=0$ are listed in Table 1. It is assumed that these limits are also valid for B stars of luminosity class IV.

Stars Outside the Scattering Limits

All stars inside the scattering limits are called "normal". The measured colours of these stars correspond to their mean intrinsic colours (except for small permitted deviations), if one assumes an interstellar reddening as derived in this paper. Stars outside the limits are called "anomalous". In Table 2 all stars are listed which in the two-colour diagrams are found far above the upper limits. (Crosses in Figs. 1a—e.) Only twenty out of 350 stars i.e. remarkable less, than the number assumed by

Table 1. Intrinsic scatter of B stars

	LC I, II, III		LC IV, V	
	Lower limit	Upper limit	Lower limit	Upper limit
$V-R$	$+0^{\mathrm{m}}.01$	$+0^{\mathrm{m}}.14$	$-0^{\mathrm{m}}.02$	$+0^{\mathrm{m}}.11$
$V-I$	$-0^{\mathrm{m}}.03$	$+0^{\mathrm{m}}.14$	$-0^{\mathrm{m}}.05$	$+0^{\mathrm{m}}.12$
$V-J$	$-0^{\mathrm{m}}.12$	$+0^{\mathrm{m}}.12$	$-0^{\mathrm{m}}.15$	$+0^{\mathrm{m}}.09$
$V-K$	$-0^{\mathrm{m}}.16$	$+0^{\mathrm{m}}.15$	$-0^{\mathrm{m}}.21$	$+0^{\mathrm{m}}.10$
$V-L$	$-0^{\mathrm{m}}.20$	$+0^{\mathrm{m}}.27$	$-0^{\mathrm{m}}.27$	$+0^{\mathrm{m}}.20$

Table 2. Stars above the upper scattering limit. Spectral types of HD 37140 and 38087 were taken from Schild and Chaffee (1971), Ref. "S". Ref. "C" means Conti and Alschuler (1971)

Star	Name	Spectr.	Ref.
HD 37020	θ^1 Ori A	B 0.5 Vp	1, 5
HD 37022	θ^1 Ori C	O 7:	5, 8, C
HD 37023	θ^1 Ori D	B 0.5 Vp	1, 5
HD 37041	θ^2 Ori A	O 9 V	1, 2, 5, 8, C
HD 37042	θ^2 Ori B	B 0.5 Vp	5, 6, 2
HD 37130		(B 8–9):	8
HD 37140		B 8 p	8, S
HD 37903		B 1.5 V	3, 5
HD 38087		B 5 V	8, S
HD 38563 A		B 5:	3
HD 38563 B		B 1–5:	3
HD 46106	NGC 2244 Nr. 5	B 0 V	2, 6
HD 46223	NGC 2244 Nr. 3	O 5 f	2, 3, 5, 6, C
HD 99556		B 5 IV	4
HD 164865	NGC 6530 Nr. 45	B 9 Iab	6
CoD−24°13806	NGC 6530 Herschel 36	O 7	6
BD−4°1181		B 3:	8
BD−5°1318		B 2:	3
	VI Cyg Nr. 9	O 5 f	2, 5
	NGC 2024 Nr. 1	B 1 V	2

Table 3. Stars located distinctly below the lower scattering limit. Reference "C" means Conti and Alschuler (1971)

Star	Spectr.	Ref.
HD 14956	B 2 Ia	7
HD 15570	O 4 f	2, C
HD 148605	B 2 V	1
HD 163800	O 7 If	2, C
HD 169467	B 3 III	1
HD 206165	B 2 Ib	1, 2
HD 210839	O 6 f	1, 2, C
HD 228779	O 9.5 Ib	7
O° 978	B 1.5 V	4
2185	B 3 V	4
2246	B 2 III	4

other authors, show such behaviour. The separation of the really anomalous stars from the apparently red ones was the main aim of our investigation. Table 3 shows stars found below the lower scattering limit. (Triangles in Figs. 1a—e.) Table 4 contains all stars found only slightly outside the limits. These stars are treated as "normal" stars. The exact deviations from the allowed scatter for all these stars and a thorough discussion of

Table 4. Stars outside but close to the scattering limits

Star	Spectr.	Ref.
HD 2905	B 1 Ia	1, 2
HD 3360	B 2.5 IV	1
HD 14134	B 3 Ia	2
HD 14322	B 8 Ib	2, 3
HD 14331	B 0 III	4
HD 16310	B 1 II:	4
HD 36371	B 5 Iab	1, 7
HD 58350	B 5 Ia	1
HD 79186	B 3 Ia	1
HD 110956	B 3 IV	1
HD 149212	B 9 IV	1
HD 184915	B 0.5 III	1
HD 198478	B 3 Ia	1, 5, 7
HD 204710	B 8 Ib	5
HD 213087	B 0.5 Ib	7
HD 218376	B 0.5 IV	1
BD−0°1050	B 8–A 0:	8

stars far outside the scattering limits are given by Wiemer (1973). Most of the "anomalous red" stars have infrared excess as shown by Ney *et al.* (1973), or are spectroscopic binaries.

Conclusions

The photometric values of 350 O and B stars in the filter bands B, V, R, I, J, K and L are used for this investigation. These stars were selected from data of different authors and our own measurements according to special criteria: The stars had to have typical non-peculiar and unambiguous spectra as far as known and as Tables 2 and 3 show this requirement was fulfilled to 91%. Two-colour diagrams permitted us to derive a mean law of interstellar reddening (Table 5) with $R=3.14\pm0.10$. Based on this reddening law and on the scattering limits anomalous stars were separated. Only 20 out of 350 stars are located above the upper limit in the two-colour diagram. Most of these stars proved to have additional infrared emission by themselves or by dust nearby. We feel this to be responsible for the deviation found, rather than anomalous interstellar reddening.

With the method described above it seems possible to distinguish between normally reddened O and B stars and stars which show additional infrared emission.

Table 5. Ratios taken from the two-colour diagrams and van de Hulst

	$\frac{E_{U-V}}{E_{B-V}}$	$\frac{E_{V-R}}{E_{B-V}}$	$\frac{E_{V-I}}{E_{B-V}}$	$\frac{E_{V-J}}{E_{B-V}}$	$\frac{E_{V-K}}{E_{B-V}}$	$\frac{E_{V-L}}{E_{B-V}}$
van de Hulst Nr. 15	1.71	0.80	1.62	2.30	2.78	2.91
This paper		0.78 ± 0.02	1.60 ± 0.03	2.23 ± 0.02	2.75 ± 0.04	3.01 ± 0.07

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