THE ASTRONOMICAL JOURNAL VOLUME 76, NUMBER 3 APRIL 1971

Interstellar Absorption and Color Excesses in Sco OB-1*

R. SCHILD
Smithsonian Astrophysical Observatory, Cambridge, Massachusetts
G. NEUGEBAUER AND J. A. WESTPHAL
California Institute of Technology, Pasadena, California, and Cerro Tololo Inter-American Observatory, Cerro Tololo, Chile†

(Received 11 January 1971)

New spectral types and photometry are reported for numerous stars in Sco OB-1 and in the foreground of the association. The new data permit reddening in the local spiral arm to be subtracted out in a discussion of reddening in the gas and dust of an adjacent spiral arm. The reddening that occurs within the association Sco OB-1 itself appears to be normal and to have $R = 3$. Infrared fluxes indicate no deviations (in the reddening law from the ultraviolet to 2.2 μ) from the law for the local spiral arm in Scorpio. The new data show no evidence for a recently reported correlation between absolute magnitude and color excess.

I. INTRODUCTION

IN a recent analysis of photometric data, Reddish (1967) has found that the brightest stars in many young clusters and associations have abnormally large color excesses. Reddish has attributed these excesses to circumstellar remnants of the prestellar clouds from which the stars recently condensed. We have reexamined the association Sco OB-1, which contains cluster NGC 6231, to see whether the correlation is valid, since selection effects may be responsible in part where observations are made to a magnitude limit. In addition, we explore the possibility that the color excesses are due to other effects in the tenuous outer atmospheres of the OB supergiants, such as the infrared emission observed for the luminosity class III to V emission-line stars by Johnson (1967).

In any discussion of reddening anomalies in the vicinities of distant associations, it is necessary to distinguish between the reddening that occurs in the solar neighborhood and local spiral arm and the reddening component that is associated with the gas and dust surrounding the hot stars. We have investigated this point specifically for the association Sco OB-1 through the observation of foreground stars. Before discussing the interstellar medium in the direction of Sco OB-1, we shall redetermine the distance modulus.

II. THE DISTANCE MODULUS FOR SCO OB-1

The distance modulus of 11.5 for Sco OB-1 derived by Schild, Hiltner, and Sanduleak (1969, referred to as Paper I) was noted to be uncertain because it is based primarily on observations of supergiants, for which the absolute-magnitude calibration is considerably less certain than for dwarfs. New observations of fainter main-sequence stars are reported in Table I, which is complete to a magnitude limit of 10.2 for stars in NGC 6231 that were not reported in Paper I and also contains data for other association members. The new spectral types are based on spectrograms obtained with the 60-inch reflector at Cerro Tololo and the small spectrograph described by Hiltner, Garrison, and Schild (1969). All new UBV photometric data are based on at least two observations made on separate nights with the Cerro Tololo 36-inch reflector. Stars for which photometric data have been determined by Braes (1969) were not reobserved; for these stars there are no entries in the $(U-B)$ and n columns of Table I. Intrinsic colors and absolute visual magnitudes used to derive color excesses and distance moduli are from Johnson (1963) and Blaauw (1963), respectively.

The new H–R diagram for the association is qualitatively the same as that in Paper I and is not reproduced here. However, the fainter stars indicate a somewhat larger distance modulus than that reported previously. The magnitudes of the Ia supergiants are systematically brighter than those ordinarily assigned for the luminosity classes. Since the absolute-magnitude calibration for these extremely hot, luminous stars is less certain than that for dwarfs, we have derived a new distance modulus of 11.9 ± 0.3 (rms), based on data from Table I and Paper I, where equal weight has been given to all stars for which the absolute-magnitude calibration is thought to be known.

III. PLACE OF ORIGIN OF THE REDDENING

In addition to the observation of fainter cluster members reported above, numerous bright B stars were observed in the hope of discovering additional supergiant members, and in order to obtain information on the distance-reddening law in the direction of the association. Table II lists stars that are inferred to be foreground stars on the basis that their distance moduli differ from the cluster mean by more than a magnitude.

Results of the observations of foreground stars are shown in Fig. 1, where color excess is plotted as a function of distance from the sun. The scatter is quite large, presumably because of intrinsic scatter in the determination of spectroscopic parallaxes as well as

* *Contributions from the Cerro Tololo Inter-American Observatory*, No. C1022.

† Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE I. Sco OB-1 association members.

Star	Braes (1969)	Sp.	V	$(B-V)$	$(U-B)$	n	E_{B-V}	V_0	$m-M$
151003	···	O9 II	7.11	0.16	−0.79	4	0.47	5.7	11.7
151212	···	B0.5 IV	9.25	0.10	−0.78	4	0.38	8.1	12.6
151458	···	B3 IVn	9.71	0.12	−0.43	2	0.32	8.7	11.2
152686	···	B0 V	8.97	0.23	−0.66	4	0.53	7.4	11.8
322417	314	O5	10.23	0.82	···	···	1.14	6.8	···
322421	···	B2 IV	9.84	0.13	−0.63	3	0.37	8.7	12.0
326006	···	B1.5 V	10.18	0.15	−0.69	4	0.41	9.0	12.0
326176	571	O9.5 II	9.12	0.67	−0.36	2	0.97	6.2	11.6
326327	669	B0.5 IV	9.74	0.27	−0.60	4	0.55	8.1	12.6
326328	670	B1.5 V	10.23	0.22	−0.61	3	0.47	8.8	11.8
326330	672	B0.5 V	9.30	0.20	···	···	0.48	7.9	11.9
326332	674	B0.5 V	9.66	0.24	−0.63	6	0.52	8.1	12.1
326916	···	O9.5 V	···	···	···	···	···	···	···
−41°7715	932	B2 IV–Vn	10.05	0.16	···	···	0.40	8.8	11.7
−41°7227	939	B1 V	9.45	0.18	−0.63	4	0.44	8.1	11.7
−41°7736	943	B1 Vn	10.21	0.26	···	···	0.52	8.6	12.2
−41°7742	945	O8 V	8.64	0.23	···	···	0.54	7.0	12.2
−41°7743	946	B0.5 V	9.79	0.26	···	···	0.54	8.2	12.2
−41°7753	948	B1 V	9.83	0.25	−0.63	4	0.51	8.3	11.9
−41°7755	949	B1 V	10.12	0.24	−0.61	5	0.50	8.6	12.2

patchiness in distribution of the interstellar matter. Nevertheless, it is apparent that most of the reddening observed in the stars in NGC 6231 occurs within 1 kpc of the sun. A linear increase of reddening with distance to NGC 6231 does not fit the data. A similar result has been found by Roslund (1966) and Roslund and Ardeberg (1968) for a region 9° away along the galactic equator from Sco OB-1. The region in which little absorption occurs is presumably an interarm region with little interstellar matter. We conclude, therefore, that most of the reddening found in stars in Sco OB-1 occurs in the local spiral arm.

TABLE II. Observational data for foreground stars.

HD	Sp.	V	$(B-V)$	$(U-B)$	n	E_{B-V}	V_0	$m-M$	r (kpc)
150742	B2.5 V	5.71	−0.12	−0.64	4	0.10	5.41	7.5	0.32
150772	B8 III	9.33	0.12	−0.32	4	0.21	8.70	9.7	0.87
151039	B3 IV	8.73	0.18	−0.41	3	0.38	7.59	10.1	1.05
151109	B8 V	7.00	−0.06	−0.25	3	0.03	6.91	6.8	0.23
151110	A1 V	8.48	0.13	0.09	2	0.10	8.18	6.7	0.22
151139	B1.5 III	7.60	0.29	−0.60	2	0.54	5.98	10.0	1.00
151241	A0 IV	7.88	0.18	0.14	3	0.18	7.34	7.0	0.25
151946	A1 V	8.44	0.09	···	···	0.06	8.26	6.8	0.23
151965	B9p:Si	6.33	−0.13	···	···	0.07	6.12	···	···
152197	B2 V	8.98	0.14	···	···	0.38	7.84	10.3	1.15
152269	B7 III	8.52	0.14	···	···	0.26	7.74	9.3	0.72
152354	B9.5 V	9.23	0.12	−0.13	4	0.15	8.78	8.0	0.40
152459	B6 IV	8.58	0.19	···	···	0.33	7.59	9.1	0.66
152685	B1.5 III	7.48	0.19	···	···	0.41	6.20	10.2	1.10
152741	B6 V	9.66	0.10	−0.33	4	0.24	8.94	9.7	0.87
152755	B5 V	8.05	0.05	···	···	0.21	7.42	8.4	0.48
152769	B2 V	9.18	0.22	−0.40	2	0.46	7.80	10.3	1.15
152785	B7 III	8.89	0.24	0.15	4	0.36	7.81	9.4	0.76
152871	B6 V	9.85	0.16	−0.32	3	0.30	8.95	9.6	0.83
153177	B9 IV	8.53	0.19	0.00	4	0.25	7.78	8.0	0.40
153295	B2e	9.10	0.53	−0.59	4	0.77	6.79	···	···
153382	B8 III	7.33	0.12	−0.27	4	0.21	6.70	7.7	0.35
326514	B8 V	10.16	0.11	−0.21	4	0.20	9.56	9.5	0.79

TABLE III. Photometry for faint stars surrounding NGC 6231.

Star (HDE)	V	$B-V$	$U-B$	E_{B-V}	M_V
326324	10.76	0.48	−0.31	0.72	−3.2
326339	10.14	0.44	−0.38	0.68	−3.7
326340	9.95	0.27	−0.60	0.53	−3.4
326347	11.31	0.36	−0.19	0.52	−2.1
326348	9.92	0.35	−0.55	0.61	−3.7
326349	10.89	0.38	−0.27	0.58	−2.7
326350	10.96	0.32	−0.42	0.56	−2.5
326351	9.24	0.33	−0.62	0.61	−4.4
326364	9.62	0.34	−0.61	0.62	−4.0
326365	9.80	0.30	−0.26	0.48	−3.4

IV. THE VALUE OF R IN SCO OB-1

We assume now that the $(B-V)$ color excess of 0.48 observed for stars in Sco OB-1 is produced primarily in the local spiral arm. Thus, a value of R appropriate to the solar neighborhood must be used. Garrison (1967) has shown, on the basis of the variable extinction method applied to stars in the Scorpio–Centaurus association, that R is probably 3.0 and is no higher than 3.2. We adopt a value of $R=3.0$ for reddening in the local spiral arm.

Can anything be said about the value of R in the Sagittarius arm from observations of reddened stars in Sco OB-1? To answer this question, observations were concentrated in the northeast portion of the association, where nebular emission and very low star density are visible on direct photographs.

The search yielded two heavily reddened O stars. HDE 326176 is found to have a $(B-V)$ excess of 0.97 and a spectral type of O9.5 II. If we assume that 0.48 of the excess, the mean for stars in NGC 6231, is due to dust in the local arm for which $R=3$, and if we adopt the distance modulus of 11.9 and an absolute magnitude of −5.7, we derive $R=3.0$. The situation is less certain for the other O star discovered, HDE 322417, because the luminosity calibration for the spectral type O5 is not accurately known. If we adopt an absolute magnitude of −5.1 (Johnson and Hiltner 1956; see also Underhill 1966), a similar calculation yields $R=3.0$. Somewhat higher luminosities for O5 sometimes quoted would yield values of R slightly in excess of 3. If we allow an uncertainty of 0.3 mag in the distance modulus and 0.3 mag for the uncertainty of its spectroscopically determined absolute magnitude (corresponding to an error of a single luminosity class), then we derive an uncertainty of 0.5 for the value of R determined for HDE 326176. The possibility of a very unusual reddening law appears to be definitely excluded.

We conclude that reddening in the local spiral arm through which Sco OB-1 is seen and the reddening in the interstellar dust of the Sagittarius arm concentrated in the northeast portion of Sco OB-1 obey the normal reddening law with $R=3$.

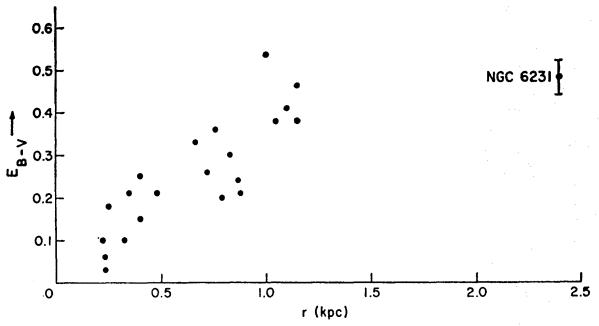

FIG. 1. Color excess in $(B-V)$ as a function of distance for stars in the direction of Sco OB-1. The mean color excess for all stars in NGC 6231 is also shown.

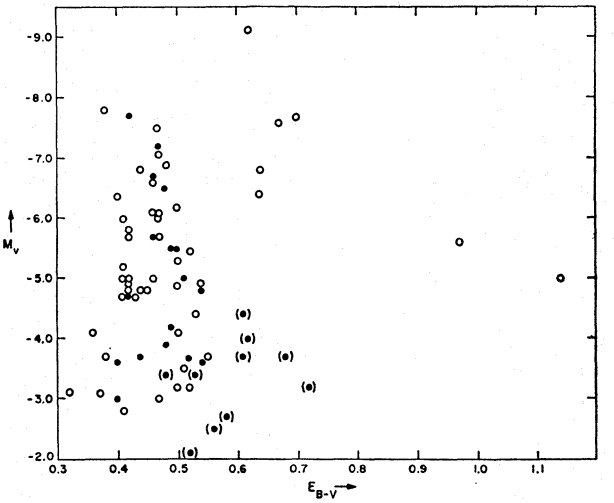

FIG. 2. Color excesses of stars in Sco OB-1 as a function of absolute visual magnitude: The *large dots* are stars in NGC 6231; the *open circles* are other stars in Sco OB-1; and the *dots in parentheses* are stars for which spectral types are unavailable. The two stars with the largest excess lie in the extremely dusty northeast region of the association.

V. HEAVILY REDDENED STARS

Reddish (1967) lists NGC 6231 as one of the clusters with a strong positive correlation between color excess and luminosity. This cluster also contains the Wolf–Rayet star HD 152270. Figure 2 (large dots) shows M_V plotted against color excess for stars within a 10 arc min diameter field centered on NGC 6231. The cluster diameter was chosen to include all the supergiants in the obvious concentration of NGC 6231. Color excesses were determined from the intrinsic colors for the known spectral types. No correlation between luminosity and color excess is evident for NGC 6231.

Color excesses for the other stars in Sco OB-1 are similarly plotted in Fig. 2 as open circles. Five supergiants have appreciably greater color excesses than most stars in the association; these five lie in the southern end of the association and may be affected

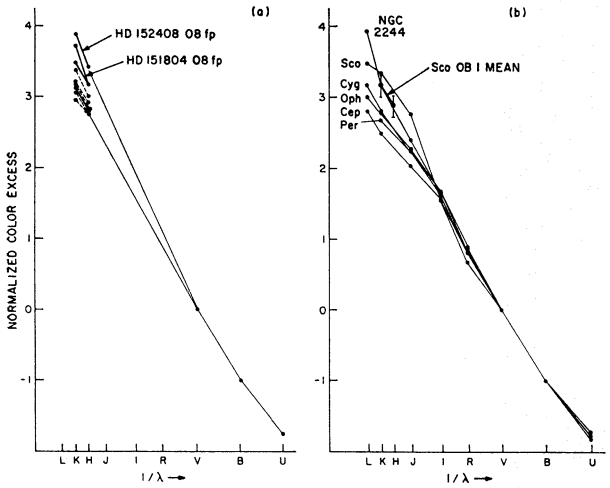

FIG. 3. (a) Color excesses E_{V-H}, E_{V-K}, etc., normalized to unit E_{B-V} for supergiants in Sco OB-1. The two supergiant O stars with P Cygni lines are seen to have unusually high $(V-H)$ and $(V-K)$ color excesses. Points for the supergiants with abnormally large $(B-V)$ color excesses are connected by *dashed line* segments. (b) Normalized color excesses for Sco OB-1 compared with those for other parts of the sky.

by somewhat heavier interstellar extinction. For investigation of this possibility, ten faint stars in the vicinity of the reddened supergiants were photoelectrically observed in the spring of 1970 with the 16-inch telescope at Cerro Tololo; the new data are listed in Table III. Spectra are unavailable, and the photometrically derived color excesses are plotted in Fig. 2 in parentheses.

It is clear from the data for these faint stars that reddening in the southern part of the association is quite variable, and greater, on the average, than reddening in the immediate vicinity of NGC 6231. Thus, there is no evidence that there is anything unusual about the reddening of the supergiants. In particular, we find no correlation between luminosity and color excess for stars in Sco OB-1.

VI. INFRARED MAGNITUDES OF THE SUPERGIANTS

In July 1968 at Cerro Tololo, infrared observations of nine supergiants in Sco OB-1 were made in the H and K bands, which have effective wavelengths of 1.65 and 2.2 μ. These stars comprised five with large $(B-V)$ excesses and four others of comparable luminosity. All the observations were made on a single night. The results, based upon only a single observation of each magnitude, are given in Table IV and illustrated in Fig. 3, where normalized color excesses are plotted against reciprocal wavelengths. Intrinsic infrared colors are taken from Johnson (1966). Lines are drawn to connect H and K ratios for individual stars. The two stars with the largest excess ratios are identified in Fig. 3(a). These two, HD 151804 and HD 152408, are Of stars with P Cygni lines in their spectra. The intrinsic colors for these stars may be in slight error, or the infrared colors may be affected by circumstellar emission. For the remaining seven stars, E_{V-H}/E_{B-V} and E_{V-K}/E_{B-V} are independent of the $(B-V)$ color excess. Thus, the reddening law for the luminous, strongly reddened stars is found to be the same as that for the stars with a normal $(E-V)$ color excess. This tends to confirm our finding that there is nothing unusual about the heavily reddened supergiants.

The mean color-excess ratios for seven stars in Sco OB-1 are found to be $E_{V-H}/E_{B-V}=2.89\pm0.15$ and $E_{V-K}/E_{B-V}=3.19\pm0.18$. These ratios are connected by a heavy line in Fig. 3(b), where data for other parts of the sky (Johnson 1968) are shown for comparison. Figure 3(b) shows that the reddening law in the direction of Sco OB-1 is similar to that for NGC 2244 and possibly for other stars in Scorpio observed by Johnson (1968), while it may be different from reddening laws observed in Ophiuchus, Cygnus, Cepheus, and Perseus. [Use of the improved spectral type of B0.5 IV for δ Sco as given by Garrison (1967) does not change the reddening law derived for Scorpio by Johnson (1968).] The data also imply a value of R greater than 3 in Scorpio, although this is inconsistent with results based on the variable extinction method (Sec. IV). This may reflect the uncertainty of the adopted infrared colors of the supergiants.

VII. SUMMARY AND CONCLUSION

The most important results obtained are the following:

(i) Almost all the reddening observed in most stars in Sco OB-1 occurs in the local arm.

(ii) For the reddening that occurs in the gas and dust of the association, $R=3$.

(iii) Infrared magnitudes to 2.2 μ indicate no significant difference between the reddening law in the local spiral arm and that of the Sco OB-1 region of the Sagittarius arm.

(iv) The most recent and comprehensive data on spectral types and colors show no correlation between

TABLE IV. Infrared data for supergiants.

Star	Sp.	V	E_{B-V}	H (1.65 μ)	K (2.2 μ)	E_{V-H}/E_{B-V}	E_{V-K}/E_{B-V}
151804	O8fp	5.22	0.38	4.84	4.75	3.18	3.71
152003	O9.5 Ib	7.00	0.64	6.00	5.98	2.77	2.94
152147	O9.5 Ib	7.23	0.64	6.20	6.06	2.81	3.17
152234	B0.5 Ia	5.44	0.42	4.85	4.79	2.79	3.12
152235	B1 Ia	6.30	0.70	4.89	4.74	2.76	3.06
152236	B1.5 Ia	4.71	0.62	3.30	3.11	3.00	3.39
152408	O8fp	5.77	0.47	4.99	4.88	3.43	3.89
152424	O9 Ia	6.27	0.67	5.15	5.06	2.91	3.21
152667	B0.5 Ia	6.22	0.47	5.31	5.26	3.17	3.45

color excess and absolute magnitude for stars in NGC 6231 and for Sco OB-1.

The literature contains several recent references to longitude variations of the reddening law (Wampler 1962, 1963; Johnson 1968). Such variations are presumably due in part to variations of the reddening law along the line of sight, although tests for such line-of-sight variations are considerably more difficult to make. In this connection, the finding that the reddening in an adjacent spiral arm is very similar to that in our own is reassuring.

ACKNOWLEDGMENTS

We thank Dr. V. M. Blanco and the Cerro Tololo staff for extending to us the use of the southern observing facilities; we especially thank Ricardo Gonzales for his help in making the observations.

This work was supported in part by National Science Foundation Grant GP 15-25 and National Aeronautics and Space Administration Grant NGL 05-002-007.

REFERENCES

Blaauw, A. 1963, *Basic Astronomical Data*, K. Aa. Strand, Ed. (University of Chicago Press, Chicago), p. 383.
Braes, L. L. E. 1969, thesis, Groningen University, The Netherlands.
Garrison, R. F. 1967, *Astrophys. J.* **147**, 1003.
Hiltner, W. A., Garrison, R. F., and Schild, R. E. 1969, *ibid.* **157**, 313.
Johnson, H. L. 1963, *Basic Astronomical Data*, K. Aa. Strand, Ed. (University of Chicago Press, Chicago), p. 204.
——. 1966, *Ann. Rev. Astron. Astrophys.* **4**, 193.
——. 1967, *Astrophys. J.* **150**, L39.
——. 1968, *Nebulae and Interstellar Matter*, B. M. Middlehurst and L. H. Aller, Eds. (University of Chicago Press, Chicago), p. 167.
Johnson, H. L., and Hiltner, W. A. 1956, *Astrophys. J.* **123**, 267.
Reddish, V. C. 1967, *Monthly Notices Roy. Astron. Soc.* **135**, 251.
Roslund, C. 1966, *Ark. f. Astron.* **4**, 101.
Roslund, C., and Ardeberg, A. 1968, *ibid.*, 441.
Schild, R. E., Hiltner, W. A., and Sanduleak, N. 1969, *Astrophys. J*, **156**, 609 (Paper I).
Underhill, A. B. 1966, *The Early Type Stars* (D. Reidel, Dordrecht, Holland), p. 36.
Wampler, J. 1962, *Astrophys. J.* **136**, 100.
——. 1963, *ibid.* **137**, 1071.