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# A SPECTROSCOPIC STUDY OF THE ASSOCIATION SCORPIUS OB 1*

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## ABSTRACT

New spectral classifications and *UBV* photometry are reported for the southern association Sco OB 1 which contains the cluster NGC 6231. For an assumed ratio of total to selective absorption of 3.0, a distance of 2.0 kpc is derived.

The H-R diagram shows a turnup at spectral type O9–O9 5 NGC 6231 is younger than h Per, and an age of 5 million years is estimated from a comparison with stellar models.

Two Wolf-Rayet stars, one WC7 and one WN7-A, have similar colors and luminosities The colors and luminosities of the W-R continua are found to be like those of early B supergiants. Other stars of special interest are discussed.

## INTRODUCTION

The association Sco OB 1, formerly known as I Sco, is a concentration of O–B stars containing, near its southern edge, a single cluster, NGC 6231 at 1950 coordinates $\alpha = 16^h50^m.5$, $\delta = -41°43'$. Photographs showing the association and its surrounding emission nebula, IC 4678, have been published by Morgan, González, and González (1953). A recent study of proper motions in Sco OB 1 by Braes (1967) is accompanied by a montage of 48-inch Palomar-Schmidt plates showing NGC 6231 and IC 4678. The association also contains two Wolf-Rayet stars and two O stars with P Cygni line profiles. It is hoped that some of the properties of these peculiar stars can be further specified in a study of the association in which they are located.

## OBSERVATIONS

Classification spectrograms with a dispersion of 86 Å mm$^{-1}$ at H$\delta$ were obtained with the Cassegrain-focus spectrograph of the 82-inch Otto Struve telescope at the McDonald Observatory. The stars were trailed with the slit oriented north-south to prevent any possible systematic effects from atmospheric dispersion. The spectrograms were 0.7 mm in width. Classifications of these spectrograms, listed in Table 1, were made without reference to previous classifications or photometry, except that the classification of the two W-R stars are from Hiltner and Schild (1966).

*UBV* photometry was obtained in the spring of 1967 and 1968 with the 16- and 36-inch reflectors at Cerro Tololo Inter-American Observatory. All photometric data in

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TABLE 1

DATA FOR STARS IN SCO OB 1

| Braes | HD/BD | SP | V | B-V | U-B | n | $E_{B-V}$ | $V_o$ | $M_v$ |
|---|---|---|---|---|---|---|---|---|---|
| 92 | 151515 | O7 | 7.14 | .14 | -.77 | 2 | .46 | 5.76 | -5.74 |
| 95 | 151564 | O9.5IV | 7.96 | .11 | -.73 | 2 | .41 | 6.73 | -4.77 |
| 103 | 151804 | O8fp | 5.22 | .07 | -.85 | 3 | .38 | 4.08 | -7.42 |
| 104 | 151805 | | 8.86 | .13 | -.72 | 2 | | | |
| 114 | 151932 | WN7-A | 6.47 | .24 | -.66 | 7 | .44 | 5.15 | -6.35 |
| 120 | 152003 | O9.5Ib | 7.00 | .37 | -.60 | 6 | .64 | 5.08 | -6.42 |
| 121 | 152042 | B0IV | 8.16 | .12 | -.74 | 4 | .42 | 6.90 | -4.60 |
| 123 | 152076 | B0III | 8.47 | .21 | -.68 | 6 | .50 | 6.97 | -4.53 |
| 125 | 152147 | O9.5Ib | 7.23 | .37 | -.58 | 7 | .64 | 5.31 | -6.19 |
| 129 | 152198 | B0IVn | 8.28 | .16 | -.71 | 2 | .46 | 6.90 | -4.60 |
| 130 | 152199 | O9.5IV | 8.60 | .24 | -.69 | 3 | .54 | 6.98 | -4.52 |
| 131 | 152200 | O9.5III | 8.41 | .12 | -.76 | 5 | .42 | 7.15 | -4.35 |
| 133 | 152217 | B0III | 8.44 | .16 | -.72 | 2 | .45 | 7.09 | -4.41 |
| 134 | 152218 | O9.5IIIn | 7.61 | .17 | -.76 | 5 | .47 | 6.20 | -5.30 |
| 135 | 152219 | O9.5IV | 7.62 | .16 | -.77 | 3 | .46 | 6.24 | -5.26 |
| 136 | 152233 | O6 | 6.56 | .14 | -.80 | 4 | .46 | 5.18 | -6.32 |
| 137 | 152234 | B0.5Ia | 5.44 | .20 | -.73 | 10 | .42 | 4.18 | -7.32 |
| 138 | 152235 | B1Ia | 6.30 | .51 | -.45 | 7 | .70 | 4.20 | -7.30 |
| 139 | 152236 | B1.5Ia | 4.71 | .46 | -.53 | 4 | .62 | 2.85 | -8.65 |
| 140 | 152245 | O9.5III | 8.37 | .12 | -.78 | 2 | .42 | 7.11 | -4.39 |
| 141 | 152246 | O9III | 7.29 | .16 | -.76 | 4 | .47 | 5.88 | -5.62 |
| 142 | 152247 | O9II | 7.16 | .19 | -.74 | 5 | .50 | 5.66 | -5.84 |
| 143 | 152248 | O7f | 6.1v | .15 | -.79 | 7 | .47 | 4.69 | -6.81 |
| 144 | 152249 | O9Ib | 6.44 | .20 | -.74 | 7 | .48 | 5.00 | -6.50 |
| 146 | 152268 | B0IV | 8.10 | .11 | -.75 | 3 | .41 | 6.87 | -4.63 |
| 147 | 152269 | | 8.47 | .14 | -.46 | 2 | | | |
| 148 | 152270 | WC7 | 6.60 | .23 | -.56 | 8 | .46 | 5.22 | -6.28 |
| 152 | 152314 | O9III | 7.86 | .19 | -.70 | 4 | .50 | 6.36 | -5.14 |
| 153 | 152333 | O9.5IV | 8.02 | .22 | -.68 | 2 | .52 | 6.46 | -5.04 |
| 157 | 152405 | O9.5Ib | 7.17 | .14 | -.78 | 3 | .41 | 5.94 | -5.56 |
| 160 | 152408 | O8fp | 5.77 | .16 | -.76 | 4 | .47 | 4.36 | -7.14 |
| 162 | 152424 | O9Ia | 6.27 | .39 | -.58 | 7 | .67 | 4.26 | -7.24 |
| 164 | 152437 | | 9.14 | .14 | +.08 | 2 | | | |
| 167 | 152459 | | 8.52 | .18 | -.25 | 2 | | | |
| 171 | 152559 | O9.5III | 8.42 | .14 | -.75 | 2 | .44 | 7.10 | -4.40 |
| 172 | 152560 | B0.5IV | 8.27 | .13 | -.73 | 2 | .41 | 7.04 | -4.46 |
| 173 | 152590 | O7 | 8.46 | .11 | -.82 | 4 | .43 | 7.17 | -4.33 |
| 174 | 152591 | B0IV | 8.43 | .11 | -.74 | 4 | .41 | 7.20 | -4.30 |
| 177 | 152622 | O9.5III | 8.10 | .20 | -.72 | 2 | .50 | 6.60 | -4.90 |
| 178 | 152623 | O7 | 6.67 | .08 | -.80 | 3 | .40 | 5.47 | -6.03 |

TABLE 1—*Continued*

| Braes | HD/BD | SP | V | B-V | U-B | n | $E_{B-V}$ | $V_o$ | $M_v$ |
|---|---|---|---|---|---|---|---|---|---|
| 179 | 152667 | B0.5Ia | 6.22 | .25 | -.68 | 4 | .47 | 4.81 | -6.69 |
| 180 | 152685 | B1.5III | 7.43 | .17 | -.59 | 3 | .42 | 6.17 | -5.33 |
| | 152723 | O7 | 7.31 | .10 | -.82 | 4 | .42 | 6.06 | -5.44 |
| 330 | 322447 | B1IV | 8.90 | .10 | -.70 | 4 | .36 | 7.82 | -3.68 |
| 571 | 326176 | | 9.12 | .67 | -.36 | 2 | | | |
| 646 | 326305 | | 9.95 | .18 | -.64 | 2 | | | |
| 648 | 326307 | | 10.49 | .24 | -.45 | 2 | | | |
| 649 | 326308 | | 10.26 | .20 | -.18 | 2 | | | |
| 658 | 326317 | | 10.12 | .21 | -.61 | 3 | | | |
| 660 | 326319 | | 10.58 | .36 | +.27 | 2 | | | |
| 661 | 326320 | | 9.83 | .17 | -.61 | 3 | | | |
| 669 | 326327 | | 9.74 | .27 | -.60 | 4 | | | |
| 670 | 326328 | | 10.23 | .22 | -.61 | 3 | | | |
| 671 | 326329 | O9V | 8.4v: | .20 | -.70 | 4 | .51 | 6.87 | -4.63 |
| 673 | 326331 | | 7.51 | .18 | -.73 | 4 | | | |
| 674 | 326332 | | 9.66 | .24 | -.63 | 6 | | | |
| 675 | 326333 | B1V | 9.63 | .20 | -.62 | 5 | .50 | 8.13 | -3.37 |
| 679 | 326338 | | 9.98 | .47 | +.33 | 5 | | | |
| 680 | 326339 | | 10.12 | .42 | -.37 | 3 | | | |
| 681 | 326340 | | 9.94 | .24 | -.60 | 4 | | | |
| 688 | 326348 | | 9.91 | .34 | -.54 | 4 | | | |
| 691 | 326351 | | 9.19 | .30 | -.61 | 4 | | | |
| 931 | -41°7712 | B0IV | 9.19 | .19 | -.73 | 2 | .49 | 7.72 | -3.78 |
| 933 | -41°7717 | | 10.21 | .19 | -.60 | 3 | | | |
| 934 | -41°7719 | B1V | 9.47 | .14 | -.68 | 4 | .40 | 8.27 | -3.23 |
| 936 | -41°7723 | B1V | | | | | | | |
| 939 | -41°7727 | | 9.45 | .18 | -.63 | 4 | | | |
| 941 | -41°7733 | O9III | 7.90 | .18 | -.75 | 3 | .49 | 6.43 | -5.07 |
| 945 | -41°7742 | O8V | | | | | | | |
| 946 | -41°7743 | B0.5V | | | | | | | |
| 947 | -41°7746 | | 9.24 | .23 | -.68 | 2 | | | |
| 948 | -41°7753 | | 9.83 | .25 | -.63 | 4 | | | |
| 949 | -41°7755 | | 10.12 | .24 | -.61 | 5 | | | |
| 1013 | | | 10.92 | .25 | -.48 | 3 | | | |
| 1017 | | | 10.61 | .23 | -.50 | 4 | | | |

Table 1 are based on at least two observations per star made on separate nights. Photometric reductions were carried out with reference to the fundamental standards where possible.

All observational data are summarized in Table 1. Successive columns for each star list the catalogue number, spectral type, $V$-magnitude, $(B - V)$ and $(U - B)$ colors, number of photometric observations, $V_o$, the observed visual magnitude corrected for extinction, and $M_v$ for the distance modulus of 11.5 derived below.

## DISTANCE MODULUS

Reddening of stars in Sco OB 1 is relatively uniform, and it may be shown from observations of foreground stars that the reddening originates primarily in the local spiral arm. This will be the subject of another paper. Johnson (1968) has derived a value of $R = 3.6$ from infrared observations of stars in Scorpio, but this value is thought by Johnson to be imprecise because it is based on stars which have little reddening. Garrison (1967) has derived a value of $R = 3.0$ by the color-difference method for stars in Scorpio Centaurus. We have used Garrison's value in computing $V_o$.

The mean absolute magnitudes for the MK luminosity classes as tabulated by Blaauw (1963) have been used to derive a mean distance of 2.2 kpc, and a distance modulus of $11.7 \pm 0.4$ (standard deviation). This value is not definitive, for it can be improved upon by observation of still fainter main-sequence stars for which the absolute-magnitude calibration is more precise. Distance moduli have been given by other authors. Brownlee and Cox (1953) gave 10.7, but this distance modulus was based on an assumed mean absolute-magnitude calibration where the O9 stars were fainter than the revised calibration used here. Code and Houck (1958) gave 11.8 and Graham (1965) derived a distance modulus of 11.5 from H$\beta$ photometry.

Several comments should be made regarding the present determination. First, the O9.5 and B0 III–IV stars were not used, since it appears from the H-R diagram that these luminosity classes were not successfully distinguished. The difference in mean absolute magnitude between these luminosity classes as tabulated by Blaauw (1963) is only 0.4 mag at O9 and 0.2 mag at B0. Second, O8 stars and earlier were not used, since the luminosity calibration is uncertain. Third, the presence of spectroscopic binaries demonstrated by Struve (1944*a*) will cause the cluster distance to be slightly underestimated. Fourth, since the spectral classification was carried to a magnitude limit, the faintest main-sequence stars at B0.5 and B1 have been discriminated against.

An independent estimate of the distance modulus has been made by fitting the standard zero-age main sequence of Blaauw (1963) to the lower envelope of the main sequence in a color-magnitude diagram. The reddening for each star was estimated by following stars back to the main sequence along the reddening trajectory in a $(U - B) - (B - V)$ two-color plot. This procedure permits the use of more stars in the clusters, since the photometry extends to fainter stars than the spectral classifications. The distance modulus thus derived is 11.3. An average of the two, or 11.5, will be accepted in the remaining discussion. This corresponds to a distance of 2.0 kpc.

## THE H-R DIAGRAM

The H-R diagram with spectral type plotted against absolute magnitude for a distance modulus of 11.5 is shown in Figure 1. Luminosity classes are indicated for the supergiants. The position of the zero-age main sequence (ZAMS) given by Blaauw (1963) is shown as a solid line. The line in the supergiant region in Figure 1 shows where helium burning occurs in a 30 $M_\odot$ star according to the models of Stothers (1966) with bolometric corrections and effective temperatures from Johnson (1966).

The H-R diagram shows a turnup at spectral types O6–O9.5. It is uncertain whether there is an age separation as found by Schild (1967) in Per OB1, indicating repeated star formation. The three clusters $\chi$ Per, h Per, and NGC 6231 are seen, from a comparison of their H-R diagrams, to form a sequence of increasingly youthful clusters rich in massive stars. Within this sequence it has been found that $\chi$ Per has five Be stars, h Per has two, and NGC 6231 has none. Moreover, $\chi$ Per has two red supergiants, whereas h Per and NGC 6231 have none.

A comparison of the H-R diagram of NGC 6231 with models as given in Figure 1 of Schild (1967) gives an age estimate of 5 million years. This estimate is in conflict with the interpretation of 72 Col as a runaway star from the association. A kinematical age of 14 million years was derived by van Albada (1961) based on the assumption that 72 Col was ejected from the association during a period of star formation. An accumulative error of 1.5 mag in the comparison of the supergiants with models, together with large errors in the effective temperature scale, would be required to bring the two age estimates into agreement.

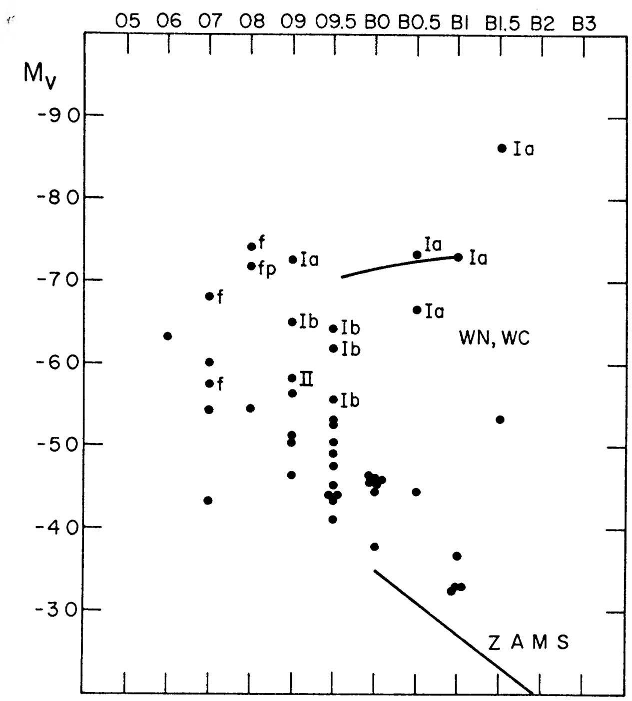


FIG. 1.—H-R diagram of the association Sco OB 1. Absolute magnitudes given are for a distance modulus of 11.5. Approximate locations of the W-R stars are shown.

HD 151397 and HD 152408 have also been considered runaway stars from Sco OB 1 (Blaauw 1961).

## THE WOLF-RAYET STARS

HD 152270 (WC7) was identified as a spectroscopic binary by Struve (1944*a*). The period is 8.82 days (Struve 1944*b*). It lies in NGC 6231 where the reddening is uniform and of the value $E_{(B-V)} = 0.46 \pm 0.04$. If a correction for line emission derived for another star of the same spectral type (Pyper 1966) is applied, as well as that for extinction, we find that the continuum of HD 152270 has intrinsic colors of $(B - V) = -0.16$ and $(U - B) = -1.00$ and an absolute magnitude of $M_V = -6.3$.

HD 151932 lies in the WN sequence that contains many spectroscopic binaries (Hiltner and Schild 1966). Struve (1944*a*) reported that this star is not a spectroscopic binary. However, the published radial velocities do show a periodicity of 3.3 days, but of small amplitude. Spectroscopically it is very similar to CQ Cep, a well-known binary. The question of the binary nature of HD 151932 remains open. A $(B - V)$ color excess of $0.44 \pm 0.03$ (rms) was derived from that of the nearby stars. The line-emission corrections for two other stars of the same spectral type as derived by Pyper (1966) give a mean of $\delta(B - V) = 0.0$ and $\delta(U - B) = 0.0$. These corrections, when applied to the observed data for HD 151932, give $M_V = -6.3$, $(B - V) = -0.20$ and $(U - B) = -0.98$. It is seen that the absolute magnitudes and colors of the WC7 and the WN7-A stars are strikingly similar.

The absolute visual magnitudes found for these two stars are large ($-6.3$), but comparable with those found by some other observers. Graham (1965) also found $M_V = -6.3$ for the average value of four WR stars in the $\eta$ Car region and $-6.4$ for the WC7 binary $\gamma_2$ Vel. However, on the assumption that the Large Magellanic Cloud has a distance modulus of 18.7, Westerlund and Smith (1964) derived absolute magnitudes of $-5.2$ for WN stars in associations and clusters, $-4.2$ for WN field stars, and $-5.3$ for all WC stars.

The colors and absolute magnitudes of the W-R stars in Sco OB 1 are more like those of supergiants than of main-sequence stars. For this reason it does not seem justified to unredden the W-R stars back to the main sequence in studies of W-R continuum fluxes and colors. Moreover, since the value of the reddening-free parameter $Q$ corresponding to the intrinsic colors found here is that of a main-sequence star having an intrinsic $(B - V)$ color of about $-0.29$, unreddening to the main sequence would cause luminosities to be overestimated by about 0.3 mag.

## OTHER STARS OF SPECIAL INTEREST

HD 152248 (O7) has been identified by Struve (1944*a*) as a two-lined spectroscopic binary. No correction to its magnitude has been made in Figure 1. Brownlee and Cox (1953) note that it is also probably an eclipsing binary. Its variability is confirmed, for on one night the star was 0.2 mag fainter than normal. Further photometric and spectroscopic observations may lead to a reliable effective temperature for this O star.

HD 152236 ($\zeta^1$ Sco) has been discussed as an association member by Code and Houck (1958), who find it to be one of the most luminous stars in the Galaxy.

HD 152424 was classified O9 Ia, although this luminosity class is not ordinarily used at spectral type O9. The spectral type was determined primarily from the He II/He I ratio, and the luminosity from the strengths of ionized Si and C. Position in the H-R diagram confirms the luminosity class assigned to this unique star.

HD 151804 (O8f) and HD 152408 (O8fp) are supergiants with P Cygni lines. Blaauw (1961), on the basis of its radial velocity, suggested that HD 152408 is a runaway star, although it is still seen in projection against the association. These two stars have essentially the same spectral type and luminosity, yet in one the P Cygni character is pronounced whereas in the other it is weak. A more detailed study may reveal the origin of the P Cygni characteristic, which according to these two stars is independent of age and mass. HD 151804 and HD 152408 appear to be the brightest O stars known in the Galaxy. A recent discussion of the luminosities of O stars by Underhill (1966, p. 36) showed that stars of spectral type O8.5 or earlier, and brighter than $M_V = -6.0$, are extremely rare. The Sco OB 1 association has four. No O5–O8 stars brighter than $-7.0$ mag have previously been recognized, and it is likely that the bolometric magnitudes of HD 151804 and HD 152408 rival that of HD 152236 ($\zeta^1$ Sco, B1.5 Ia).

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