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# A spectroscopic study of the Scorpio-Centaurus association

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**Abstract.** Rotational velocities as well as hydrogen and helium line intensities of one hundred and twelve members of the Scorpio-Centaurus association have been derived. For stars with $M_v < 0\cdot0$, the distribution of rotational velocities of both the upper Scorpius subgroup and the upper Centaurus-Lupus subgroup are similar and closely resemble those of the field stars. Stars with $M_v > 0\cdot0$, all of which are found in the dense upper Scorpius region, rotate much faster than their counterparts amongst field stars, the Pleiades and Alpha-Persei cluster members.

The measured equivalent width of $H_\gamma$ for 77 stars provide a distance modulus of $6\cdot0 \pm 0\cdot09$ magnitudes for the association. Evolutionary effects in the derived hydrogen line intensities are found between the two subgroups. The hydrogen-line intensities at all spectral types in the upper Centaurus-Lupus subgroup are systematically smaller than those of members in the upper Scorpius subgroup.

Analysis of high dispersion spectra of five members of the association yield a helium abundance of $N_{He}/N_H = 0\cdot096 \pm 0\cdot004$. Along with data available in the literature, the mean helium abundance of thirteen stars of this association is found to be $0\cdot098 \pm 0\cdot004$ by number. For the two main subgroups of this association, we derive a value of $0\cdot105 \pm 0\cdot001$ for the upper Centaurus-Lupus group from three stars and $0\cdot096 \pm 0\cdot005$ for the upper Scorpius group from ten stars.

Within the capabilities of our present methods, there seems to be no difference between the two subgroups as far as rotational velocities and initial helium abundance are concerned, a fact that must be borne in mind in the interpretation of the difference found between the two subgroups from photoelectric photometry.

**Keywords.** Stellar association; stellar rotation; helium abundance.

## 1. Introduction

The Scorpio-Centaurus association is the nearest and richest source of early B-stars and as such plays a fundamental role in the calibration of absolute magnitudes. The geometrical distance to this association was first derived by Blaauw (1946) with proper motions based on the Boss General Catalogue and radial velocities determined from the Lick Southern Survey. Subsequent studies using proper motions have been made by Bertiau (1958) and Jones (1971), the latter deriving a distance modulus of 5·8 magnitudes. There have been in the past, questions raised by Smart, Petrie and Eggen on the reality of the association as a physical group. These objections have been satisfactorily answered by Blaauw (1963). The work of Jones (1971) shows that if the discussion is confined to the immediate neighbourhood of Scorpio-Centaurus, a firm list of 47 co-movers towards $l = 236°$ and

$b = 25°$ can be easily isolated. Also the association of the upper Scorpius members with bright and dark nebulosities strongly suggests the validity of a physical group.

There have been several photometric and spectroscopic studies of this association in recent years. Photometric measurements of the upper Scorpius members were published by Hardia and Crawford (1961). Their UBV and $H_\beta$ measurements were confined to the northern regions for stars with spectral types earlier than Ao observable from the Dyer and McDonald observatories. Bappu *et al* (1962) made $\Gamma$ index measures of stars in both the upper Scorpius and upper Centaurus-Lupus area. From $\Gamma$ index (U–B) plots they showed that the Scorpio-Centaurus association was older than the Orion association which in turn was more evolved than the II Persei and II Monocerotis associations. Extensive UBV observations of 251 stars in this region were made by Moreno and Moreno (1968) from Chile. They also made $H_\beta$ observations of stars brighter than 6·5 magnitudes and which can be considered as definite or probable members from UBV photometry. Glaspey (1971) made *uvby* and $H_\beta$ observations of the association. The membership down to Fo was extended by Garrison (1967) from accurate MK classification and UBV photometry. Rotational velocities of the brighter members of the association were derived by Huang and Struve (1954) and later by Buscombe (1965) from width parameters of weak lines derived by Huang (1953) from spectra available in the Lick Observatory plate file. ' Slettebak (1968) measured rotational velocities of 82 members north of $-42°$ declination with spectra at 40 Å/mm and 20Å/mm dispersion. The roational velocities of the 40 Å/mm plates were derived by visual estimates relative to standard rotational velocity stars. For objects observed at 20 Å/mm dispersion, he derived the rotational velocities from a calibration of the line widths of 4471 at half intensity and *vsini* values of standard stars.

The only attempt to derive helium abundances systematically, in different clusters and associations is that due to Peterson and Shipman (1973). They have derived the helium abundance for 5 stars in NGC 2264, for 13 stars in the upper Scorpius complex and for 8 stars in I Lacertae. The derived mean helium abundance from plate material with dispersions less than or equal to 20 Å/mm in these three associations are $0·081 \pm 0·004$ for NGC 2264; $0·097 \pm 0·005$ for II Scorpii, and $0·102 \pm 0·005$ for I Lacertae (the numbers are defined such that $N_{He} + N_H = 1$). They come to the improbable conclusion that the helium abundance is decreasing on a time scale of $10^7$ years.

In what follows, an attempt is made:

(i) to derive homogeneous and accurate rotational velocities utilising the entire line profile, for as many members of this association as possible, in order to find if any differences exist in the distribution of rotational velocities between the younger upper Scorpius subgroup and the more evolved upper Centaurus-Lupus subgroup of this association;

(ii) to determine whether the line intensities amongst the upper Scorpius members are abnormal as suggested by the work of Glasspey from narrow band photometry;

(iii) to use a much larger sample of member stars and see if the discrepancy still exists between a value of distance modulus as derived from $H_\gamma$ equivalent width measures and that obtained from proper motion and radial velocity studies;

(iv) to determine the helium abundance of as many member stars as possible and study if any difference exists in the initial helium abundance between the two major subgroups of this association.

## 2. Rotational velocities

### 2.1. *Observations*

In the present study, we have used a dispersion of 47 Å/mm and cover the members of this association brighter than $m_v = 8.5$. The spectra were obtained mostly with the 102 cm reflector at Kavalur while some of the bright members were observed with the 51 cm reflector at Kodaikanal. The same spectrograph was employed at the cassegrain foci of both the telescopes. The projected slit width was always kept at 20 $\mu$ and the spectra were widened to 200–400 $\mu$ depending upon the brightness of the objects. Most of the spectra were obtained on baked IIa–o plates while some spectra were taken on Eastman 103 *a–o*. The plates were developed in D 19 along with the calibration spectrum obtained on a plate from the same box. The calibration was provided by a rotating sector and a quartz prism spectrograph. The rotating sector has seventeen intensity steps with $\log I$ intervals of 0.1 between adjacent steps.

### 2.2. *Results and discussion*

Rotational velocities of 112 members of the Scorpio-Centaurus associations, drawn from the lists of Garrison (1967) and Bertiau (1958) as derived in the present study are listed in table 1. The method followed in deriving the rotational velocities is the one essentially developed by Shajin and Struve (1929). The observed profile of He I 4026 in $\tau$ Sco and Mg II 4481 in $\alpha$-Canis Majoris were used as zero velocity standards.

The present determination contains 30 additional new *vsini* values over those obtained by Slettebak (1968). The entire set is more accurate and homogeneous since the use of line profiles avoids subjective eye-estimates and accidental errors in the determination of rotational velocities by visual methods. Errors of measurements of *vsini* in this study range from $\pm$ 10 km/sec for the slower rotations, to $\pm$ 20 km/sec for values of *vsini* greater than 250 km/sec.

A characteristic of *vsini* for early stars in the general galactic field is the existence of high values of rotational velocity for stars in the spectral type range B5–B7 (Slettebak and Howard 1955). When all the stars of the Scorpio-Centaurus association are plotted individually on a *vsini*-$M_v$ diagram, the envelope of highest values of axial rotations has a broad peak ranging from B5–B9. When mean values of *vsini* are used instead, we get the curves shown in figure 1. The absolute magnitudes used are those given by Bertiau (1958) and for stars not found in his list are taken from Hardie and Crawford (1961) or Garrison (1967). Spectroscopic binaries, peculiar stars and evolved objects were omitted in forming this mean curve. The stars were grouped into 4 magnitude intervals, *viz.*,

$$M_v < -2\cdot 5, -2\cdot 5 < M_v \leq -1\cdot 5, -1\cdot 5 < M_v \leq 0\cdot 0 \text{ and } 0\cdot 0 < M_v \leq 1\cdot 5.$$

Table 1. Rotational velocities and line intensities

| HD number | Spectral type | Line intensities (Å) 4340 | 4101 | 3970 | 3889 | 4026 | 4471 | *v* sin *i* km/sec Present | Stettebak | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 103079 | B4 IV | 7·6 | 8·3 | 7·2 | 9·0 | 0·8 | 1·4 | 140 | | |
| 103884 | B3 V | .. | .. | .. | .. | .. | .. | 150 | | |
| 105382 | B6 III–IV | 5·1 | 5·5 | 5·4 | 4·9 | 0·8 | 0·8 | 200 | | |
| 105435 | B2 V p.e. | 0·9 | 2·5 | 2·7 | 2·6 | 0·9 | 1·4 | 200 | | |
| 105937 | B4 V | 7·2 | 6·1 | 6·1 | 5·8 | 1·5 | 1·2 | 210 | | |
| 106490 | B2 V | 3·6 | 3·2 | 4 3 | 3·2 | 1·0 | 0·8 | 120 | | |
| 106983 | B3 IV | 7·0 | 7·4 | 9·2 | .. | 1·1 | 1·8 | 140 | | |
| 108257 | B4 IV | 5·6 | 5·8 | 6·6 | 6·0 | 0·8 | .. | 150 | | |
| 108483 | B2 V | 6·9 | 6·0 | 7·4 | 5·0 | 1·7 | 1·6 | 220 | | |
| 109026 | B5 V | 10·6 | .. | .. | .. | .. | .. | 180 | | |
| 109668 | B2 V | 4·7 | 5·2 | 6·2 | 4·5 | 1·7 | 1·5 | 190 | | |
| 111123 | B0·5 III | .. | .. | .. | .. | .. | .. | < 50 | | 1 |
| 112078 | B5 Vn | 8·7 | 10·9 | 7·9 | 10·0 | 1·8 | .. | 330 | | 2 |
| 112091 | B5 Ve | 6·1 | 5·9 | 7·3 | 6·0 | 0·8 | 1·1 | 330 | | |
| 112092 | B3 IV | 4·2 | 4·3 | .. | .. | 1·3 | 1·6 | .. | | |
| 113703 | B5 V | 9·6 | 8·3 | 7·9 | 7·3 | 1·3 | 1·1 | 160 | | |
| 113791 | B2 V | 5·1 | 6·7 | 3·9 | 4·7 | 1·7 | 1·2 | ≤ 50 | | |
| 115823 | B5 III | 10·3 | 11·1 | .. | .. | 1·2 | 1·1 | 160 | | |
| 116087 | B5 V | 11·1 | 8·6 | 10·2 | .. | 1·7 | 1·8 | 300 | | |
| 118716 | B1 V | 4·0 | 2·9 | 2·5 | 3·0 | 0·8 | 1·1 | 80 | | |
| 120307 | B2 IV | 4·8 | 4·4 | .. | .. | 1·6 | 1·2 | 100 | 90 | 1,4 |
| 120324 | B2 V p, n.e | 4·8 | 4·5 | 4·1 | 4·0 | 2·0 | 1·7 | 210 | 190 | |
| 120709 | B5 III | .. | .. | .. | .. | .. | .. | < 50 | ≤ 20 | |
| 120908 | B5 V | 12·4 | 9·8 | 6·6 | 6·4 | 1·1 | 1·2 | 180 | | |
| 120955 | B5 III | 7·6 | 6·6 | 10·3 | 8·4 | 1·2 | .. | ≤ 50 | ≤ 20 | |
| 121743 | B2 IV | 4·4 | 4·4 | 4·4 | 3·5 | 1·4 | 1·4 | 120 | 100 | |
| 121790 | B2 V | 4·4 | 3·9 | 3·6 | 3·4 | 1·4 | 1·7 | 200 | | 3 |
| 122980 | B2 V | .. | .. | .. | .. | .. | .. | ≤ 50 | < 20 | |
| 125823 | B3 V | .. | .. | .. | .. | .. | .. | 100 | < 20 | |
| 127972 | B3 III | 4·4 | 4·2 | 4·2 | 3·7 | 0·7 | .. | 350 | 300 | 2 |
| 129056 | B1 V | 3·8 | 2·8 | 3·1 | 2·3 | 1·2 | 1·2 | ≤ 50 | .. | 1 |
| 129116 | B3 V | 5·7 | 4·1 | 3·8 | 4·5 | .. | 1·2 | 170 | 200 | |
| 130807 | B6 III | 5·6 | 5·4 | 4·6 | 5·9 | 0·7 | 1·7 | < 50 | .. | |
| 132058 | B2 IV | 3·9 | 3 4 | 4·4 | 3·5 | 1·0 | 1·5 | 110 | 130 | |
| 132200 | B2 V | 4·8 | 5·0 | .. | .. | 1·2 | 1·1 | < 50 | < 20 | |
| 132955 | B3 V | .. | .. | .. | .. | .. | .. | < 50 | < 20 | |
| 133937 | B7 Vnn | 4·6 | 3·3 | 3·1 | 3·9 | 0·3 | 0·5 | 330 | 350 | 3 |
| 133955 | B3 V | .. | .. | .. | .. | .. | .. | 180 | .. | |
| 136298 | B2 IV | 4·0 | 4·0 | 3·2 | 4·1 | 1·1 | 1·5 | 240 | 230 | |
| 136664 | B5 V | 5·7 | 6·2 | 4·5 | 3·4 | 0·9 | 1·2 | 220 | 210 | |
| 137432 | B5 V | 9·8 | 6·7 | 8·5 | 8·7 | 0·6 | 1·6 | 160 | 330 | 2 |
| 138485 | B2 Vnn | 6·0 | 4·5 | 5·3 | 3·6 | 1·1 | 1·6 | 300 | 250 | |
| 138690 | B2 Vn | 3·7 | 3·3 | .. | .. | 1·0 | 0·8 | 250 | 270 | |
| 138764 | B7 IV | 7·8 | 5·5 | 7·0 | 5·0 | 0·8 | 0·4 | ≤ 50 | < 20 | |
| 138769 | B5 IV | .. | .. | .. | .. | .. | .. | 150 | .. | |

Table 1 (*contd.*)

| HD number | Spectral type | Line intensities (Å) 4340 | 4101 | 3970 | 3889 | 4026 | 4471 | $v \sin i$ km/sec Present | Stettebak | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 139094 | B7 V | 8·0 | 7·4 | 12·0 | 7·9 | 0 6 | 0 6 | 180 | .. | |
| 139160 | B7 IV | 11 9 | 11·8 | 12·0 | 9·1 | 1·0 | 0·5 | 200 | 130 | |
| 139365 | B2 5 V | 5·7 | 5·3 | 6 9 | 4·1 | 1·2 | 1 3 | 140 | 130 | 2 |
| 139486 | B9·5 V | 19·1 | 18·8 | 19·4 | 15 9 | .. | .. | 220 | 250 | |
| 140008 | B6 V | 7·5 | 4·3 | 6 4 | 7 0 | 0 8 | 1 0 | 70 | 50 | 2 |
| 141404 | B9 5 V | 9·3 | 9·8 | 11·2 | 10·3 | 0 2 | .. | 200 | .. | |
| 141637 | B1 5 Vn | 5·0 | 4 9 | 4 8 | 4·5 | 1·3 | .. | 270 | 300 | |
| 141774 | B9 V | 9·8 | 9 5 | 8·0 | 8·0 | .. | .. | 210 | 160 | |
| 142096 | B2 5 V | 8 9 | 7·1 | 6·8 | 6·2 | 1 2 | 1 3 | 200 | 200 | 4 |
| 142114 | B2·5 Vn | .. | .. | .. | .. | .. | .. | 330 | 330 | |
| 142165 | B6 IVn | .. | .. | .. | .. | .. | .. | 250 | 240 | |
| 142184 | B2·5 Vn | 5·6 | 5·2 | 4 8 | 3·9 | 1·1 | 1·0 | 400 | 350 | |
| 142250 | B6 Vp | 7·6 | 7·6 | 8·5 | 5·9 | 0·7 | 0·6 | $\leq$ 50 | $\leq$ 50 | |
| 142301 | B8 p | 5·9 | 5·4 | 5·2 | 6·2 | 0·4 | 0 3 | < 50 | .. | |
| 142315 | B8 V | 11 9 | 10 1 | 9 7 | 8·6 | 0·5 | 0 5 | 250 | 300 | |
| 142378 | B3 V | 8 2 | 6·0 | 6·6 | 6·2 | 1 0 | 1 1 | 240 | 240 | |
| 142669 | B2 IV–V | 5·8 | 5·7 | .. | .. | 0·9 | 1·0 | 120 | 140 | |
| 142805 | AO III | 15·3 | 13 6 | 11 0 | 12·2 | .. | .. | .. | .. | |
| 142883 | B3 V | 9·1 | 8·2 | 8·4 | 7 4 | 1·4 | 1 7 | 110 | 100 | |
| 142884 | B9 p | .. | .. | .. | .. | .. | .. | 220 | 200 | |
| 142983 | B p | 4·2 | 3·5 | 3·6 | 3 4 | 1·0 | 0 9 | 400 | 400 | |
| 142990 | B5 IV | 7·4 | 6·3 | 6 3 | 5 1 | 0·6 | 1·1 | 150 | 200 | |
| 143018 | B1 V + B2 V | 4·7 | 3·7 | 3·8 | 5·4 | 0 5 | 0 7 | .. | .. | 4 |
| 143118 | B2 V | 4 7 | 4 7 | .. | .. | 1 8 | 1 4 | 270 | 240 | 2 |
| 143275 | B0·5 IV | 3 1 | 4 1 | .. | .. | 1·6 | 1·4 | 190 | 180 | 4 |
| 143567 | B9 V | 14 0 | 12 0 | 13 7 | 11·9 | 0 6 | .. | 290 | 180 | |
| 143600 | B9 Vn | 15·1 | 8·9 | 12 8 | 9·8 | 0 3 | .. | 320 | 300 | |
| 143699 | B7 IV | 7·8 | 5 4 | 7 6 | 6·4 | 1·0 | 0·6 | 180 | 170 | |
| 144217 | B0·5 V | 7·5 | 3·7 | 3 5 | 3·3 | 1·1 | 1·8 | 150 | 120 | 4 |
| 144218 | B2 IV–V | 6·7 | 4·0 | 3·7 | 4·0 | 0 9 | 1 1 | 60 | 80 | |
| 144334 | B8 p | 8·3 | 8·0 | 9 4 | 8·2 | 0 4 | 0 2 | <50 | .. | |
| 144470 | B1 V | .. | .. | | .. | | .. | 130 | .. | |
| 144661 | B7 III p | 8·7 | 7 3 | 8·7 | 10 3 | .. | | 50 | 100 | |
| 144844 | B9 IV p | 15·5 | 10 7 | 8·7 | 8·7 | 0·2 | .. | 190 | 180 | |
| 145353 | B9 IV | 12·9 | 9 6 | 10 2 | 9 6 | .. | .. | 220 | | |
| 145482 | B2 V | 5·5 | 5·6 | 4·4 | 4 1 | 1·4 | 1 7 | 220 | 240 | |
| 145483A | B9 V | 13 3 | 10·2 | 11·4 | 8·9 | .. | .. | 200 | .. | |
| 145502 | B2 IV | 5 4 | 5·0 | 4·9 | 5·4 | 1·7 | 1·1 | 270 | 200 | 4 |
| 145519 | B9 Vn | 13 3 | 10 9 | 11·7 | 10 2 | .. | | 300 | 300 | |
| 145554 | B9 Vn | 14 0 | 13 4 | 12·2 | 11·7 | .. | .. | 180 | 180 | |
| 145631 | B9·5 Vn | 17·1 | 13·9 | 15·6 | 14 2 | .. | .. | 200 | 160 | |
| 145792 | B5 V | 9·6 | 8 7 | 7·7 | 6 9 | 1·6 | 1·2 | < 50 | < 50 | |
| 146001 | B7 IV | 12·0 | 8·1 | 8·1 | 7 2 | 0·7 | 0 9 | 240 | 200 | |
| 146029 | B9 V | 12 2 | 11·3 | 10·8 | 9 3 | 0 3 | .. | .. | .. | |
| 146284 | B8 IV | 12·4 | 9 2 | 9·2 | 7·1 | 0 4 | 0 3 | 200 | .. | |
| 146285 | B8 V | 12·9 | 12 1 | 13·8 | 11·1 | .. | | 200 | 160 | |
| 146416 | B9 V | 14·2 | 13·6 | 12 7 | .. | .. | .. | 330 | 300 | |
| 146706 | B9 V | 12·6 | 12·5 | 12 0 | 10 8 | 0 8 | 0 4 | 270 | | |
| 147009 | B9·5 V | 20 0 | 16·9 | 13·0 | 12 3 | .. | .. | 200 | 160 | |
| 147010 | Ap | 9·8 | 9 0 | 7·5 | 8·1 | 0·3 | 0 3 | < 50 | $\leq$ 50 | |

**Table 1** (*contd.*)

| HD number | Spectral type | Line intensities (Å) 4340 | 4101 | 3970 | 3889 | 4026 | 4471 | *vsini* km/sec Present | Stettebak | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 147084 | A5 II | 11·2 | 9·9 | 10·8 | 11·0 | .. | .. | ⩽ 50 | ⩽ 20 | |
| 147165 | B1 III | 4·7 | 3·4 | 3·2 | 3·7 | 1·1 | .. | ⩽ 50 | 60 | 1 |
| 147196 | B8 V nnp | 10·1 | 9·7 | 7·2 | 7·6 | . | .. | 350 | .. | 3 |
| 147703 | B9 V n | 13·4 | 14·8 | 13·4 | 12·7 | .. | .. | 280 | .. | |
| 147888 | B5 V | .. | .. | .. | .. | . | .. | 180 | 180 | |
| 147890 | B9·5 p | 12·2 | 10·4 | 9·3 | 9·5 | .. | .. | ⩽ 50 | ⩽ 50 | |
| 147932 | B5 V | 5·5 | 4·5 | .. | .. | 0·8 | 1·6 | 200 | 180 | |
| 147933 | B2 IV | 4·5 | 6·6 | 5 0 | .. | .. | .. | 290 | 300 | |
| 147934 | B2 V | 6·2 | 4·7 | 4·9 | 4·8 | .. | .. | 280 | 300 | |
| 147955 | B9·5 V | 13 9 | 12·7 | 12·9 | 12 7 | .. | . | 280 | .. | |
| 148199 | Ap | 9·2 | 9·7 | 10·4 | 8·6 | .. | . | ⩽ 50 | ⩽ 50 | |
| 148321 | A5 mp | 17·1 | 16 9 | 16·3 | 12 8 | . | .. | 100 | .. | |
| 148475 | M2 I | .. | .. | .. | .. | .. | .. | ⩽ 50 | ⩽ 20 | |
| 148562 | A3 V | 18 6 | 17·5 | 14·5 | 12·9 | .. | .. | | | |
| 148579 | B9 V | 12·5 | 13·3 | 11·3 | 11·6 | .. | .. | 250 | 150 | |
| 148594 | B8 V nn | 8 7 | 6·6 | 8·7 | 5·2 | .. | .. | 300 | 300 | |
| 148605 | B2 V | .. | 5 6 | 5·7 | 6·3 | 1·3 | 1·7 | 270 | 230 | |
| 148703 | B2 IV | 5·3 | 4·2 | 4·5 | 4·7 | 1·2 | 1·5 | 50 | 80 | |
| 148860 | B9 5V | 14·2 | 13·8 | 15·7 | .. | .. | .. | 300 | .. | |
| 149438 | B0 V | 3 5 | 3·0 | .. | .. | 1·1 | 1 8 | ⩽ 50 | ⩽ 20 | |
| 151346 | B7 p | 5·4 | 5·6 | 7 9 | 5 4 | .. | . | .. | .. | |
| 151985 | B2 IV | 4·4 | 4·6 | 3·7 | 3·4 | 0·7 | 1·4 | ⩽ 50 | 40 | |
| 157056 | B2 IV | 4 8 | 3 8 | 3 2 | 4·1 | 1 1 | 1·8 | ⩽ 50 | ⩽ 20 | 1 |

*Remarks*

1. Beta Cephei type variable.
2. Probable spectroscopic binary.
3. Hα plate shows emission in the core.
4. Spectroscopic binary.

The error bars shown, correspond to two standard deviations in both *vsini* and $M_v$. Also drawn in on each of the curves is the Abt-Hunter (1962) mean curve for field stars. There is little difference in the distribution of points about those of the mean field curves especially for stars earlier than spectral type B7. Objects with $M_v > 0 \cdot 0$ rotate very much faster compared to the field stars. The number of stars available in this grouping is fairly large. The reality of enhanced *vsini* values for these stars' cannot be questioned.

The upper Centaurus-Lucus-Crux stars follow the Abt-Huntar curve fairly closely. From a comparison of the plots for this group, one sees the validity of the inference that the mean behaviour of the stars in the galactic field has little difference from that of the recognised members of the upper Centaurus-Lupus and Lower Centaurus-Crux formations taken together. These two subgroups are more evolved in the entire association as compared to the upper Scorpius stars. It seems a clear conclusion to make that if rotational characteristics at these early spectral types can be used as an age criterion, then there is little difference between the present stage of evolution between the two subgroups and the individual B-stars

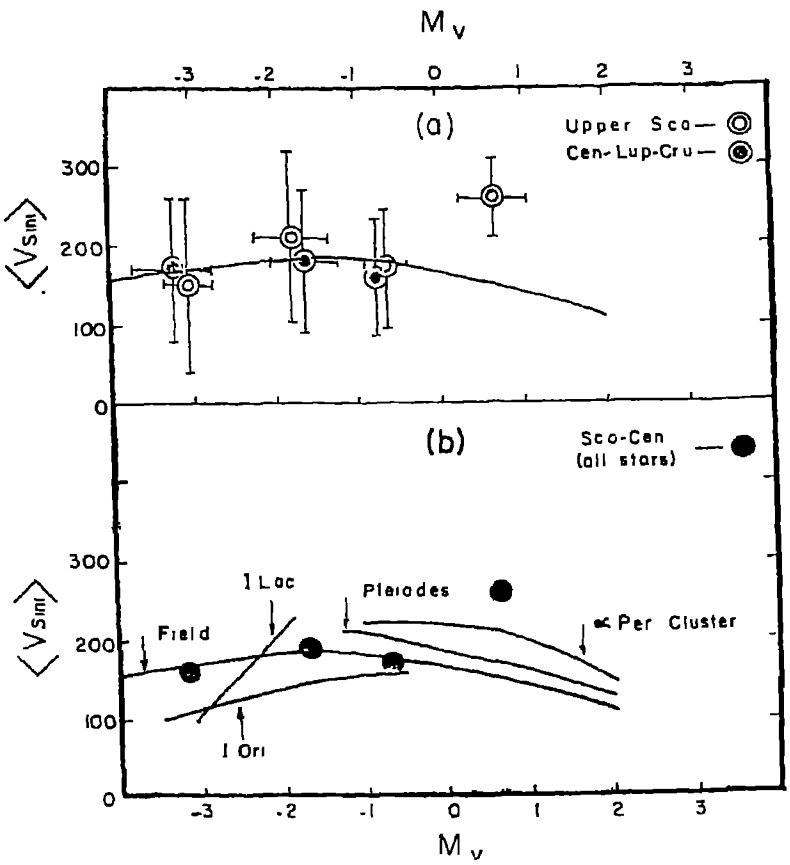


**Figure 1.** (*a*) Mean rotational velocities as a function of $M_v$ for Scorpio-Centaurus members. The filled circles represent members of the Upper Scorpius subgroup and open circles represent the stars in the upper Centaurus-Lupus and Lower Centaurus-Crux subgroups taken together. The solid line corresponds to the mean relation defined by the field stars. The error bars correspond to two standard deviations for both $\langle v\sin i\rangle$ and $M_v$.

(*b*) Composite diagram of $\langle v\sin i\rangle$, $M_v$ for a few clusters and field stars. The same function for the Scorpio-Centaurus association as a whole is plotted as filled circles. The source of rotational velocities of clusters other than Scorpio-Centaurus is from Kraft (1970).

of the galaxy. If the field stars have drifted away from inadequately bound associations, the indivudual B-stars of the upper Centaurus and lower Centaurus-Crux subgroups are close to their final stages of existence together. Also, the early-type field stars are not much older than those in existing associations. One would come to a similar conclusion regarding stars of the upper Scorpius complex but for the very high rotational velocities of its late type members.

The distribution of rotational velocities in a cluster or association is an important parameter in a study of the physical aspects of origin. Deutsch (1967) has argued that a Maxwell-Boltzmann law does indeed represent the frequency function for each group of stars categorised by spectral type. Kraft (1965) has shown that in the Coma and Hyades clusters the distribution of true rotational velocities agrees with the Maxwellian law, though the latter is by no means a unique possibility. If the observed distribution of rotational velocities is denoted by $(y)$ where $y = v\sin i$ and if the rotational axes are distributed at random, the relation between the observed and true distribution of rotational velocities is given in the well-known form by

$$\phi(y) = \int_0^{\pi/2} f(y/vsini)\, di.$$

If $f$ is Maxwellian, the first and the second moments of $f$ will satisfy the condition

$$\langle vsini \rangle = (\sqrt{\pi}/2)\, [\, \langle (vsini)^2 \rangle\, ]^{1/2}.$$

Table 2 gives the second moment of $f$ derived from the *vsini* values given in table 1. The stars were divided into four spectral ranges, Bo–B3, B4–B6, B7–B9, B9–later types. The two subgroups and the entire association as a whole have been treated separately. Only the main sequence stars were considered for this purpose. The O–C values indicate a good fit with the Maxwellian law for the Bo–B3 spectral range in all three groups. The major discrepancies are in the range B7–B9 and B9–later types. Especially in the upper Scorpius subgroup this deviation is striking. This is due to the large values of *vsini* in this group at these spectral types. It would be of interest to follow up these deviations to later spectral types in this association. We have a composite plot of *vsini* for several galactic clusters and associations in figure 1b. For absolute magnitudes fainter than $m_v = -1.0$ the Pleiades stars as well as those of the $\alpha$-Persei cluster show the trend of a slow fall after maximum, similar to that shown by the field stars, but with higher values of mean velocity. The stars with spectral types corresponding to $m_v = 0 \cdot 0$ and fainter, in Scorpio-Centaurus, have values of *vsini* at least 120 km/sec larger than the field stars and about 40–50 km/sec greater than equivalent $\alpha$-Persei stars. While normal stars are known to have this tendency of possessing no slow rotators in the B7–Ao range (Abt *et al* 1967), the upper Scorpius members have a very high value that calls for interpretation.

Slettebak (1968) has in his paper a diagramatic representation of the distribution of rotational velocities in the Scorpio-Centaurus association with location in sky. The diagram shows up in a striking manner Buscombe's (1965) finding that the rotation appears to be different in different parts of the association with the

Table 2. Test for Maxwellian distribution

| Spectral type | Number of stars | $[\langle (Vsini)\rangle]^{1/2}{}_{obs.}$ | $\langle Vsini \rangle_{obs.}$ | $\langle Vsini \rangle_{a}$ | O–C |
|---|---|---|---|---|---|
| Upper Scorpius Group | | | | | |
| B0–B3 V | 12 | 221·3 | 190·4 | 196·2 | − 5·8 |
| B4–B6 V | 5 | 128·1 | 108·0 | 113·5 | − 5·5 |
| B7–B9 V | 15 | 269·0 | 264·0 | 238·4 | +25 6 |
| B9·5–later V | 5 | 243·6 | 240·0 | 215·9 | +24·1 |
| Lower Centaurus-Crux and Upper Centaurus-Lupus | | | | | |
| B0–B3 V | 17 | 191·1 | 167·4 | 169·3 | − 1·9 |
| B4–B6 V | 8 | 225·7 | 217·5 | 200·0 | +17·5 |
| All stars in Scorpio-Centaurus association | | | | | |
| B0–B3 V | 29 | 204·1 | 176·9 | 180 9 | − 1·0 |
| B4–B6 V | 13 | 194·1 | 175·4 | 172·0 | + 3·4 |
| B7–B9 V | 15 | 269·0 | 264·0 | 238·4 | +25·6 |
| B9–later V | 5 | 243·6 | 240·0 | 215·9 | +24·1 |

denser regions of the association having the highest values, and small values typical of the remote areas from the nucleus. A similar feature is also seen in the Pleiades. Tai (1962) explains its origin as due to the impulse acquired from fragmentation of pre-stellar matter. Such an impulse causes the protostar to have a velocity of expansion and by suitable geometry an enhancement of the angular velocity. The phenomenon of run-away stars in association is thus explained. On this interpretation, stars which have the largest velocities of expansion and which still retain their association characteristic must be at the outer periphery of the associations. If such stars have angular velocity changes by fragment impulses, then such a possibility would be the greatest on those members that have experienced the most violent catastrophy. Hence the conclusion is necessary that the outermost stars should also have the largest rotational velocities, which is contrary to our experience with the Scorpio-Centaurus association.

The nucleus of the upper Scorpius subgroup is located in the midst of large cloud complexes of Ophiuchus and Scorpius. The fastest rotators in the $M_v$ domain can be seen on the Palomar charts to be associated with the dense clouds of this region. Two possibilities exist as a result of such an association. There is the phenomenon of accretion of matter by the star that can increase its angular momentum similar to the reverse situation experienced at a time of mass-loss. If so, one should see a general departure towards higher values of *vsini* for stars that have visible association with interstellar matter. NGC 2264 should provide several good candidates for verification of this possibility.

If individual stars are plotted, on the *vsini*, $M_v$ diagram one sees very few stars with *vsini* values $< 50$ km/sec in the $0{\cdot}0 < M_v \leqslant 1{\cdot}5$ domain. One can have such a situation if there is by virtue of interaction with the dense interstellar medium even a mild preference for orientation of rotational axes with respect to the galactic plane. Kraft's (1965) comprehensive studies on this point in other galactic clusters show that a strong preferred orientation is unlikely. These do not rule out the possibility of a mild preference caused by the uncommon situation of being deeply involved in large cloud complexes, even if the stars have been in existence for some time.

## 3. Hydrogen and helium lines intensities

### 3.1 *The distance modulus*

The spectra of the members of this association discussed in section 2 for deriving rotational velocities were utilised to derive the hydrogen and helium line intensities. The line strengths of hydrogen at $\lambda$ 4340, 4101, 3970 and 3889 as well as of the neutral helium lines at $\lambda$ 4026 and 4471 are given in table 1. The equivalent width of $H\gamma$ derived in the present work is plotted in figure 2 against the values on the Victoria system as given by Balona and Crampton (1974). A few objects not included in this study, but for which the equivalent widths with the same spectrograph have been derived are plotted in this figure. The 45° line for a perfect fit is shown as a continuous line. Denoting the observations of Petrie, Balona and Crampton as 'Victoria' a least square fit to the points yield

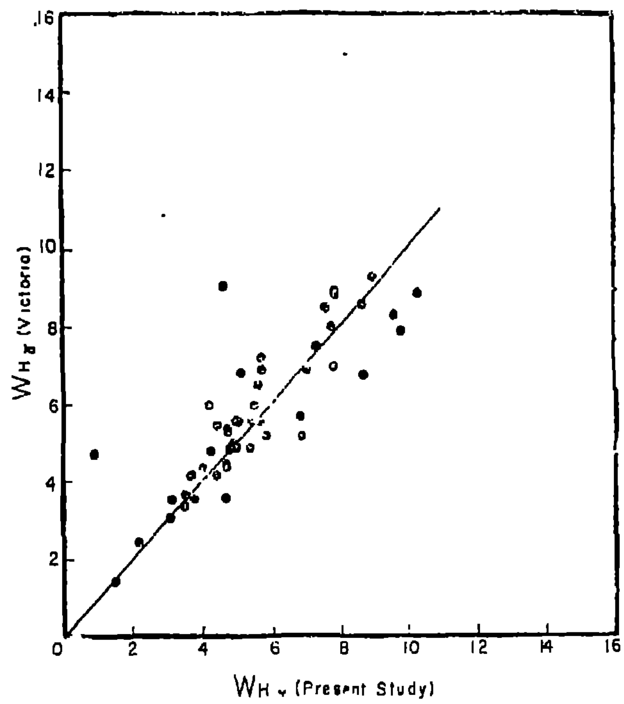


**Figure 2.** Comparison of $W_{H\gamma}$ obtained in the present study with those determined by Petrie, Balona and Crampton. The 45° line for a perfect fit is also shown.

$$(W_{H\gamma})_{\text{present}} = 0{\cdot}9961\,(W_{H\gamma})_{\text{victoria}} + 0{\cdot}004.$$

This shows that there are no systematic differences between equivalent widths of $H_\gamma$ derived in this study and those derived at Victoria. The Victoria absolute magnitude calibration was therefore used to derive the individual absolute magnitudes of the Scorpio-Centaurus members. Balona and Crampton (1974) have given two relationships between $M_v$ and $WH_\gamma$. The first one involves a knowledge of spectral type and the second one involves a knowledge of the unreddened (B–V) colour. The spectral types were taken from Garrison (1967) and for objects not found in his list, from Bertiau (1958). The (B–V) colours for all these objects were taken from Moreno and Moreno (1968). A correction of $+0{\cdot}01$ magnitudes was applied to these values (*see* section 4). After omitting the peculiar stars, spectroscopic binaries and stars later than spectral type Ao, a total of 77 stars remained in the list. The absolute magnitude for these 77 stars were derived from both the relationships. Practically no difference was found in the two derived values except for objects later than B7 where a difference of as much as 0·4 magnitudes between the two derived values was seen. The individual distance moduli for the 77 stars were computed using $V_0$ values given by Moreno and Moreno (1968) and Garrison (1967). The mean distance modulus from these 77 objects is found to be $6{\cdot}0 \pm 0{\cdot}09$ magnitudes. For the three different sub-groups, the derived values are: Lower Centaurus-Crux $= 5{\cdot}8 \pm 0{\cdot}06$ magnitudes (15 stars); upper Centaurus-Lupus $= 6{\cdot}2 \pm 0{\cdot}10$ magnitudes (19 stars) and upper Scorpius $= 6{\cdot}0 \pm 0{\cdot}09$ magnitudes (43 stars).

The distance modulus derived by Balaona and Crampton (1974) for this association is $6{\cdot}49 \pm 0{\cdot}07$ magnitudes. The difference is probably caused by the inclusion of a few $H_\beta$ measurements by them of Moreno and Moreno transformed to the $H_\gamma$ scale. However, this has not been investigated in detail. The $H_\alpha$ measurements of Andrews (1968) lead to a distance modulus of 6·45 magnitudes (Jones 1971). The geometric distance modulus derived by Bertiau (1958) from proper motions based on the N30 system is 6·2 magnitudes while that by Jones (1971) is 5·8 magnitudes. The difference of 0·4 magnitudes between the two geometric distance modulus determination is caused by the 20% systematic higher values of the proper motions on the FK4 system employed by Jones over that of the N30 system used by Bertiau. The distance modulus derived here is in excellent agreement with that of the photoelectric determination of Crawford *et al* (1970). The distance modulus derived by Crawford *et al* from $H_\beta$ photometry is 6·0 magnitudes.

### 3.2. *Evolutionary effects*

Figure 3 is a plot of the mean equivalent width of $H_\gamma$ and $H_\delta$ against $(B-V)_0$. The continuous line is that of the $H_\gamma$ equivalent width spectral type relation given by Balona and Crampton. The $(B-V)_0$ values for the corresponding spectral types are taken from Johnson (1966). It is evident from this plot that the upper Scorpius members plotted as open circles fall systematically below the relationship defined by the upper Centaurus-Lupus members. The upper Centaurus-Lupus members are plotted as filled circles in this diagram. These members are well dispersed and are not associated with any nebulosities, while the upper Scorpius members are compact with conspicuous dark clouds around Oph and bright nebulosities near 22 Sco. The upper Scorpius members are younger and this evolutionary effect is very well noticeable in this diagram.

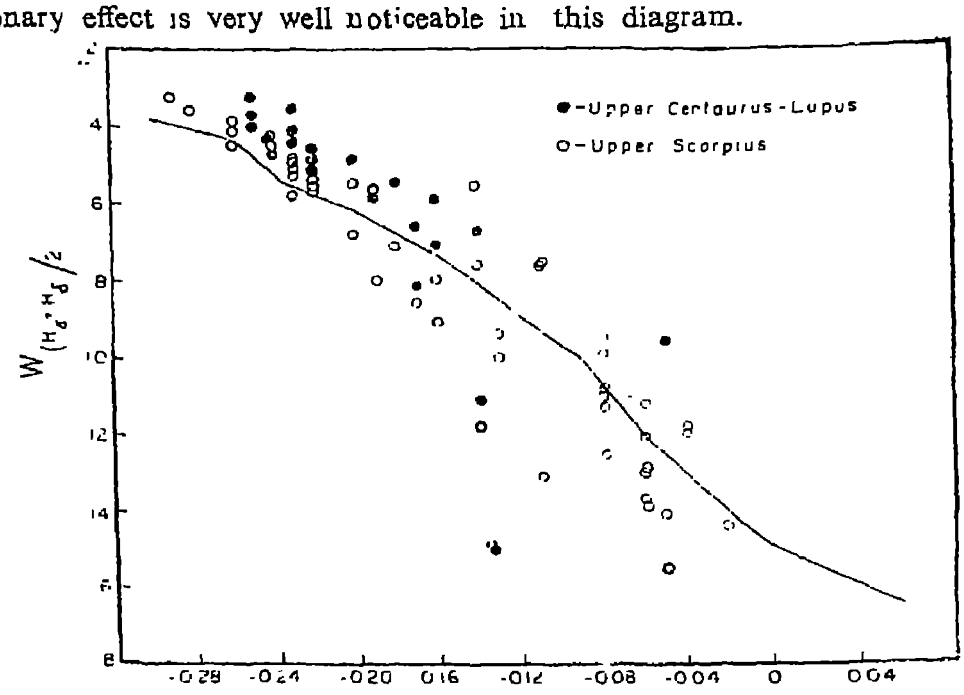


**Figure 3.** The mean of $H_\gamma$ and $H_\delta$ line intensities is plotted against the unreddened (B–V) colour. The upper Scorpius members are plotted as open circles and upper Centaurus-Lupus members as filled circles. Solid line refers to $H\gamma$-spectral type relationship of Balona and Crampton (1974). The $(B-V)_0$-spectral type relation is taken from Johnson (1966).

These observations do not of course completely explain the difference found by Glaspey (1971) between the two subgroups in the Co, Mo diagram. He found that the upper Centaurus-Lupus members behave like field stars while the upper Scorpius members behave differently. The effect was found to persist even when the peculiar stars were eliminated. The V filter contains the $H_\delta$ line and since difference exist in the hydrogen line strengths between the subgroups, this effect shows up in the *m*-indices of narrow band photometry. However, Glaspey remarks that the differences in the $H_\delta$ line strengths due to evolutionary stages can be ruled out since the differences in *m*-indices are greatest for the mid-B-star range and are smallest for the early B-stars where evolutionary effects are most noticeable. He, therefore, comes to the conclusion that the *m*-index of narrow band photometry indicates anomalous line absorption in the stars of the upper Scorpius region. This remark cannot be reconciled with the present observations. There are no differnces between the two subgroups as far as their rotational velocities are concerned except that the B7–B9 stars in the upper Scorpius rotate much faster than the field stars. The helium abundance derived for objects in the two subgroups are normal (*see* section 4). .The abundance of helium from 3 stars in upper Centaurus-Lupus is $0{\cdot}105 \pm 0{\cdot}001$ and from 10 stars in upper Scorpius is $0{\cdot}096 \pm 0{\cdot}004$ by number. The differences are not significant and even if it were to be so it is in the opposite sense from Glaspey's experience.

The equivalent width of He 4026 Å from table 3 is plotted against spectral type in figure 4. The expected relationships between the equivalent width and spectral type for a helium abundance of $N_{He}/N_H = 0{\cdot}10$ and $0{\cdot}05$ for $\log g = 4{\cdot}0$ based on Morton's model atmsopheres are shown as full lines. It is evident from this figure that as long as we assume that the mean gravity of the two subgroups is the same, there is no helium abundance difference between the two subgroups. This qualitative analysis is further strengthened by analysis of high dispersion material of a few bright objects presented in section 4.

At least part of the differences found from narrow band photometry are accounted for by the high strength of the hydrogen lines of the upper Scorpius members. The remaining differences are probably due to anomalous reddening in the upper Scorpius region. UBV observations of Moreno and Moreno (1968) do indicate

Table 3. Hydrogen line profiles

| Star | $n^*$ | 0 | 1 | 2 | 4 | 6 | 8 | 10 | 15 |
|---|---|---|---|---|---|---|---|---|---|
| | | $H\gamma$ ($\Delta\lambda$Å) | | | | | | | |
| $\kappa$ Cen | 3 | 0·38 | 0·59 | 0·67 | 0·79 | 0·87 | 0·92 | 0·95 | 0·99 |
| $\mu^2$ Sco | 2 | 0·46 | 0·59 | 0·69 | 0·81 | 0·87 | 0·90 | 0·93 | 0·98 |
| $\tau$ Sco | 2 | 0·52 | 0·64 | 0·73 | 0·84 | 0·90 | 0·84 | 0·96 | 0·99 |
| $\delta$ Sco | 2 | 0·58 | 0·61 | 0·69 | 0·84 | 0·91 | 0·94 | 0·96 | 0·99 |
| $\epsilon$ Cen | 2 | 0·54 | 0·58 | 0·65 | 0·78 | 0·87 | 0·92 | 0·95 | 0·99 |
| | | $H\delta$ ($\Delta\lambda$Å) | | | | | | | |
| $\kappa$ Cen | 3 | 0·42 | 0·56 | 0·66 | 0·81 | 0·89 | 0·94 | 0·97 | 0·99 |
| $\mu^2$ Sco | 2 | 0·46 | 0·54 | 0·69 | 0·84 | 0·90 | 0·94 | 0·97 | 0·99 |
| $\tau$ Sco | 2 | 0·48 | 0·62 | 0·73 | 0·84 | 0·90 | 0·94 | 0·97 | 0·99 |
| $\delta$ Sco | 2 | 0·57 | 0·62 | 0·70 | 0·82 | 0·88 | 0·92 | 0·95 | 0·99 |
| $\epsilon$ Cen | 2 | 0·48 | 0·56 | 0·68 | 0·82 | 0·90 | 0·94 | 0·97 | 0·99 |

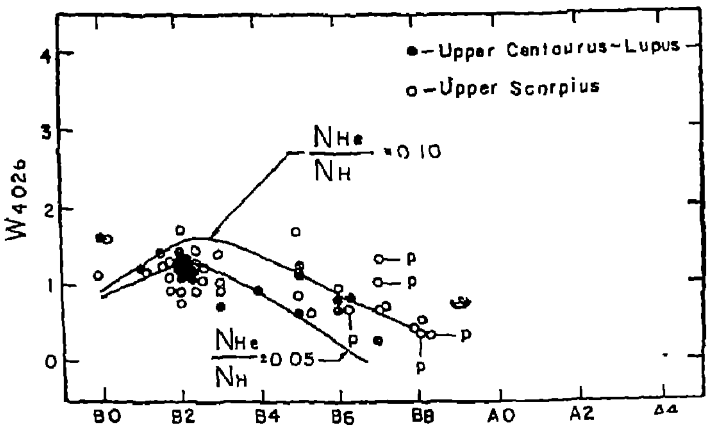


**Figure 4.** The equivalent width of λ4026 in the members of the Scorpio-Centaurus association is shown as a function of spectral type. The expected relationship for two helium abundances and $\log g = 4\cdot 0$ based on Morton model atmospheres are shown as full lines.

that the value of $R$ may be as high as 6·0 in the upper Scorpius region. That the mid-B-star range exhibits large differences can be understood, if we assume that star formation ranges over a period of time and that the stars of spectral classes B0–B2 were formed much later than stars with spectral types B4–B7. This is in general conformity with Herbig's suggestion that star formation in a cloud ceases once the early O and B stars are formed.

## 4. The helium abundance

### 4.1. *Observations at high dispersion of some stars in the Scorpio-Centaurus association*

Several good spectra of five bright members of the Scorpio-Centaurus association were obtained during June–July 1974 with an echelle spectrograph at the coude focus of the 102 cm reflector telescope at Kavalur. The echelle has 73 grooves per mm and is crossed with a 600 groove/mm grating to give on a 9 cm × 12 cm plate in the focal plane of a 25 cm camera the entire spectrum from 3800–6600 Å. The dispersion at 4026 Å is 4·8 Å/mm in the 55th order of the grating. Intensity calibrations were provided by a rotating sector prism spectrograph combination. The free spectral region of the echelle used is 100 Å. In this interval, the density falls off rapidly as one goes away from the centre of each order. For the hydrogen lines, the continuum was defined at ± 20 Å from the line centre irrespective of the rotational velocity of the object under consideration. A smooth curve was drawn over ± 7 Å at ± 20 Å from the line centre, to represent the continuum at these regions. The density values were read at these regions and a third degree polynomial was fitted to represent the continuum over ± 30 Å from the hydrogen line centre.

In the case of helium, the continuum was defined at ± 12 Å from the line centre and a similar procedure as described above followed. The lines HeI 4388 and 4471 Å fall in regions where the density is rising fast, while HeI 4026 Å, $H_\gamma$ and $H_\delta$ are almost centrally placed in their respective strips. Under these circumstances, the present procedure in representing the continuum is probably the best and should not introduce any systematic errors in the derived line profiles and equivalent widths. Any such expected systematic error should show up in the derived hydrogen line profiles. Comparison with published line profiles of $\tau$ Sco and $\kappa$ Cen by Norris (1971) shows excellent agreement to within 1% of the continuum.

### 4.2. *Temperatures, gravities and helium abundance*

Temperatures and gravities have been estimated from the published UBV data and the hydrogen line profiles derived from the echelle coude spectra. The reddening slope was assumed to be 0·72 and the reddening independent parameter $Q$ was derived from $Q = (U\text{–}B) - 0{\cdot}72\,(B\text{–}V)$.

The UBV values of the five stars discussed in this study were taken from Moreno and Moreno (1968). The $Q$, $\theta_e$ relationship used is that due to Schild *et al* (1971). This relationship is given by

$$\theta_e = 0{\cdot}378\,Q + 0{\cdot}500.$$

The temperatures derived with the above two equations were corrected in $\theta_e$ by $+\,0{\cdot}01$ since there seems to be a systematic error of $+\,0{\cdot}025$ in the derived, $Q$ when the (U–B), (B–V) values of Moreno and Moreno (1968) are used. Since the Schild *et al* relationship fits the UBV observations of Hardie and Crawford (1961), we believe it is the observations of Moreno and Moreno that need to be corrected by about 0·01 magnitudes in (B–V) and (U–B). The mean differences quoted by Moreno and Moreno between their observations and that of Hardie and Crawford is $(MM\text{–}HC) = -0{\cdot}01 \pm 0{\cdot}007$ in B–V and $-0{\cdot}01 \pm 0{\cdot}009$ in U–V. Since we have two stars, in the upper Centaurus-Lupus region for which observations of Hardie and Crawford do not exist, and also because the UBV observations of Moreno and Moreno seem to be of very high quality except for this systematic error, we decided to use the values derived at Chile after taking into account the systematic error.

The observed $H_\gamma$ line profiles given in table 3 were used to derive the gravity at the appropriate temperature from the $Q$ method discussed above. The full width $D_{10}$ and $D_{20}$ at 10 and 20% absorption respectively of the $H_\gamma$ line was used in deriving $\log g$. The model atmospheres used are those due to Morton and his co-workers (Mihalas and Morton 1965, Adams and Morton 1968, Hicock, and Morton 1968, Morton and Bradley 1968). The ESW theory of hydrogen line broadening is used in these calculations. Actually, the resultant hydrogen line profile given in a fine grid form by Norris (1971) was used.

To take into account the controversy over the two hydrogen line broadening theories discussed earlier and in view of the fact that the Griem line broadening theory is more in accord with the Schild *et al* temperature scale used in this investigation, we have applied a correction of $-0{\cdot}1$ to the derived $\log g$ values. No corrections due to the slightly higher helium abundance of $N_{He}/N_H = 0{\cdot}11$ used by Norris (1971) in his calculations, were applied since the observations of Peterson and Shipman (1973) indicate that the helium abundance is probably higher in the Scorpio-Centaurus association. The final adopted values of $\theta_e$ and $\log g$ for the five stars studied here are given in table 5. In view of the differences between various hydrogen line broadening theories and the temperature scales, we expect that the values quoted here are accurate to $\triangle \log g = \pm 0{\cdot}1$ and $\triangle\theta_e = \pm 0{\cdot}01$. The helium lines available for this study are $\lambda$ 4009, 4026, 4143, 4388 and 4471. HeI 4121 was found to be seriously blended with OII lines and therefore we have not made use of it here. HeI 4438 was not measured. The derived equivalent widths of the helium lines together with those $H_\gamma$ and $H_\delta$ are given in table 4.

The equivalent widths were directly interpolated in Norris' (1971) tables which employed Morton model atmospheres and the calculations of Griem *et al* (1962) for the lines 4438 Å and 4713 Å, the data of Griem (1968) for 4471 Å, and of Gieske and Griem (1969) for 4026 Å, 4143 Å and 4388 Å. The derived helium abundance for the individual lines are tabulated in table 5. The last column gives the mean helium abundance for each star from a logarithmic summation of all lines.

### 4.3. *Helium line profiles*

Line profiles of HeI $\lambda$ 4026, 4388 and 4471 for the three fairly sharp lined stars $\tau$ Sco, $\kappa$ Cen and $\mu^2$ Sco are listed in table 7. Figures 5, 6 and 7 show the observed line profiles (plotted as filled circles) corrected for instrumental profile. The corrections for instrumental broadening was found to be extremely small, of the order of 1 to 2% at the core. The method of successive iterations, suggested by de Jager and Neven (1964), was followed to deconvolve the observed profile

**Table 4.** Equivalent widths (Å) of the hydrogen and neutral helium lines.

| Star | (A) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 4340 | 4101 | 4009 | 4026 | 4143 | 4387 | 4471 |
| $\kappa$ Cen | 3·64 | 4·47 | 0·660 | 1·470 | 0·795 | 0·985 | 1·330 |
| $\mu^2$ Sco | 3·89 | 4·74 | 0·638 | 1·380 | 0·729 | 0·862 | 1·415 |
| $\tau$ Sco | 3·55 | 3·64 | 0·688 | 1·024 | 0·411 | 0 599 | 0·996 |
| $\delta$ Sco | 3·90 | 4·11 | 0 567 | 1·262 | 0·771 | 0·620 | 1·293 |
| $\epsilon$ Cen | 3·68 | 4·77 | 0·656 | 1·496 | 0 765 | 0·711 | 1·720 |

**Table 5.** Effective temperatures, gravities and helium abundances

| Star | $\theta_e$ | Log g | $N_{He} / N_H$ | | | | | $(N_{He} / N_H)$ |
|---|---|---|---|---|---|---|---|---|
| | | | 4009 | 4026 | 4143 | 4387 | 4471 | |
| $\kappa$ Cen | 0·261 | 3·70 | 0·086 | 0·100 | 0·116 | 0·204 | 0·096 | 0·114 |
| $\mu^2$ Sco | 0·238 | 3 78 | 0·084 | 0·091 | 0·097 | 0·080 | 0·101 | 0·090 |
| $\tau$ Sco | 0·186 | 4·10 | 0·153 | 0·066 | 0·045 | 0 100 | 0·070 | 0·080 |
| $\delta$ Sco | 0·196 | 4·15 | 0·078 | 0·098 | 0·126 | 0·085 | 0·098 | 0·096 |
| $\epsilon$ Cen | 0·222 | 4·05 | 0 081 | 0 093 | 0·108 | 0·090 | 0 156 | 0·103 |

Mean helium abundance = $0{\cdot}096 \pm 0{\cdot}004$.

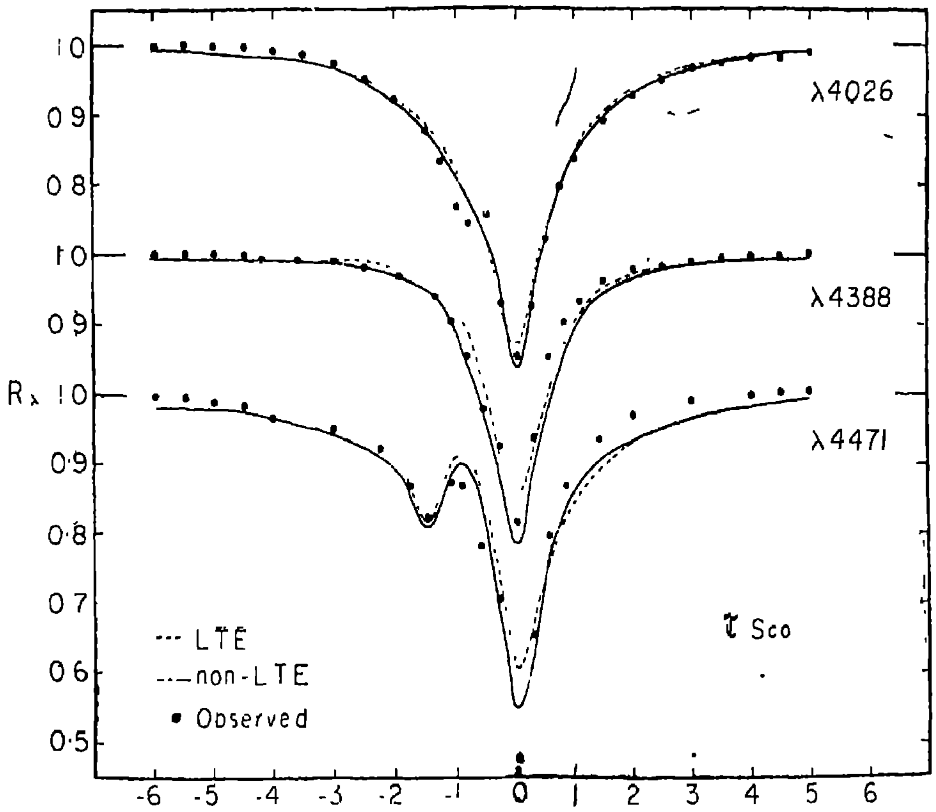


**Figure 5.** Comparison of the observed and computed profiles for $\tau$ Sco. The solid line corresponds to non LTE models while the dotted line corresponds to LTE models. The assumed limb darkening coefficient is 0·4. The profiles correspond to Te = 30,000°, $\log g = 4 \cdot 0$, *vsini* = 15 km/sec.

with the instrumental profile. The instrumental profile was derived from the iron lines in the spectrum of the Fe–Ne hollow cathode comparison source. For the three strong helium lines studied here, the series converged within three approximations.

In figures 5, 6 and 7 the non-LTE and LTE theoretical predictions of Auer and Mihalas (1973) and Mihalas *et al* (1974) are shown as continuous and dotted lines respectively. In fitting the observed line profiles to non-LTE models, several iterations had to be performed in $\theta_e$, $\log g$ and *vsini* with the initial parameters being given by the derived values in table 5. In the convolution of the broadening functions with non-LTE profiles, the value of the limb darkening coefficient was assumed to be 0·4. The final adopted values for the three stars are $\kappa$ Cen ($T_e = 22500$, $\log g = 3 \cdot 9$, *vsini* = 15), $\tau$ Sco ($T_e = 30000$, $\log g = 4$, *vsini* = 15) and $\mu^2$ Sco ($T_e = 22500$, $\log g = 3 \cdot 9$, *vsini* = 40). No attempt was made to find the best fitting LTE profiles for these stars; we have just plotted the LTE profiles, given by Auer and Mihalas (1973), and Mihalas *et al* (1974), that correspond to the values of $T_e$, $\log g$ and *vsini* derived for the non-LTE case.

For HeI 4026 and 4388, the LTE and non-LTE predicted profiles which utilise a helium abundance of $N_{He}/N_H = 0.10$, were taken from Auer and Mihalas (1973) except for $\tau$ Sco for which the earlier calculations of Auer and Mihalas (1972) are used. For HeI 4471, the most recent calculations of Mihalas *et al* (1974) employing

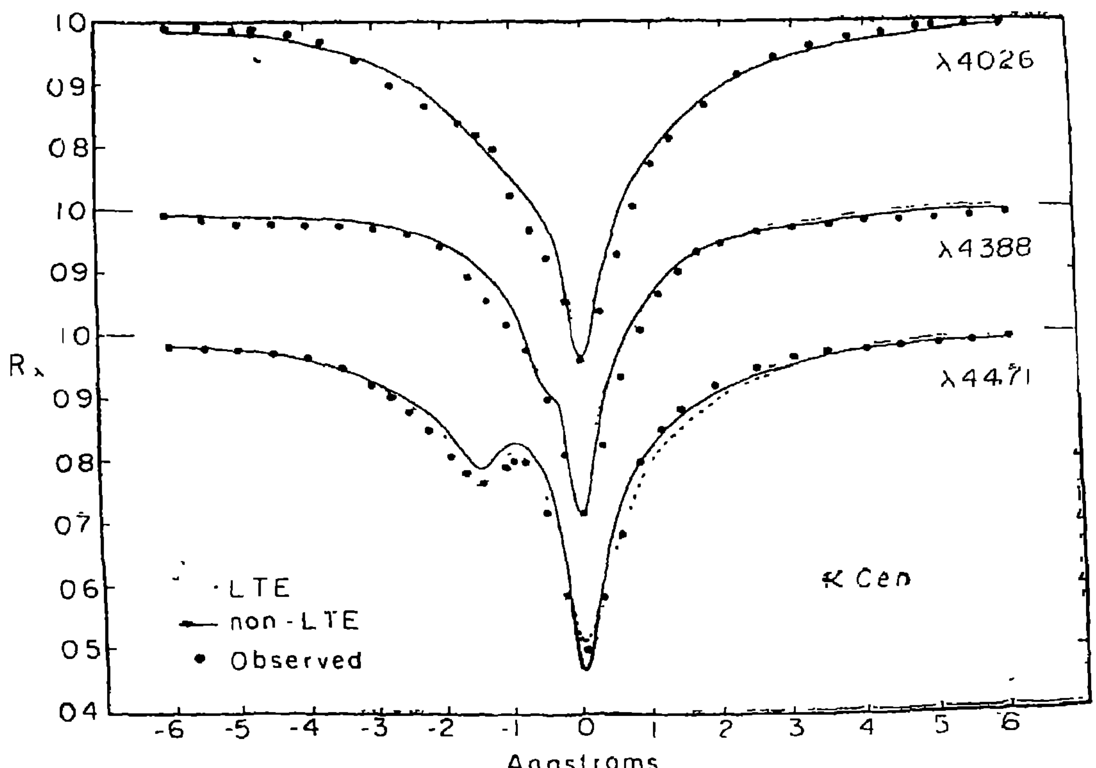


**Figure 6.** Same as figure 5 for $\kappa$ Cen. The profiles correspond to Te = 22500°, $\log g = 3\ 9$, $v\sin i = 15$ km/sec.

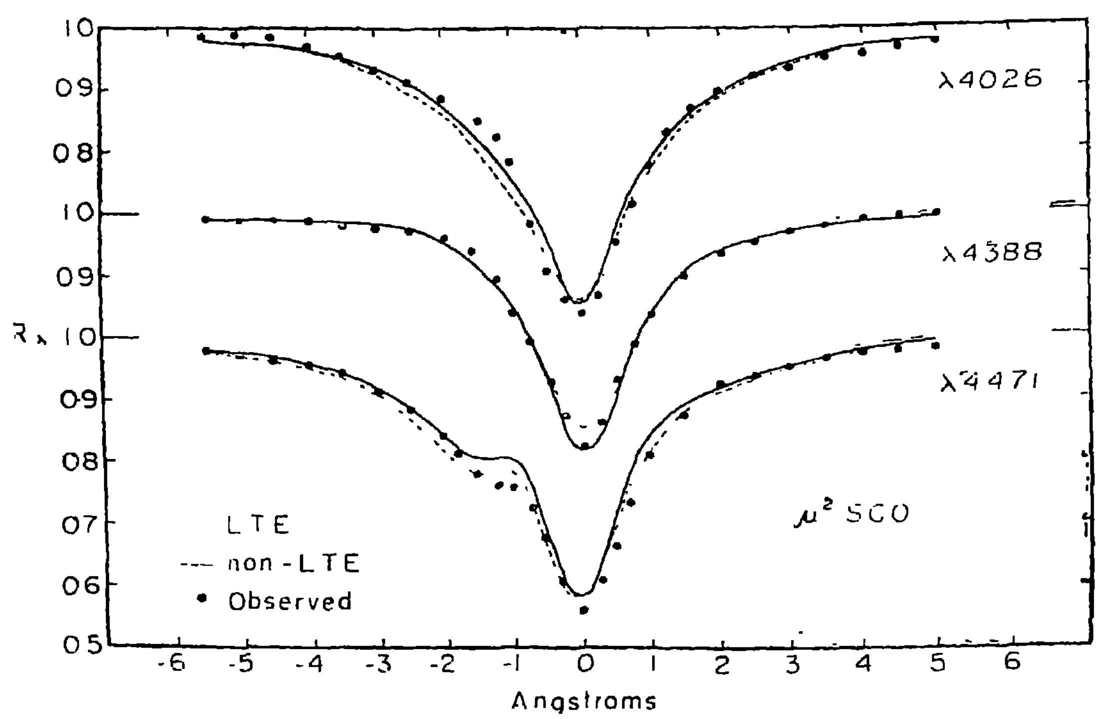


**Figure 7.** Same as figure 5 for $\mu^2$ Sco. The profiles correspond to Te = 22500° $\log g = 3{\cdot}9$, $v\sin i = 40$ km/sec.

helium Stark broadening calculations of Barnard, *et al* (1974) were utilised to fit the observations. However, the temperature range for which these calculations are available extend only up to 27500° at the hot end. Therefore for $\tau$ Sco, for which a temperature of at least 30000° is required to fit the observations, the earlier work of Auer and Mihalas (1972) was used by employing helium Stark broadening calculations of Barnard *et al* (1969).

$\kappa$ *Cen*: The non-LTE and LTE line profile calculations of Auer and Mihalas (1973) used to fit the observations utilises unblanketed model atmospheres of Mihalas (1972) and ESW hydrogen line broadening theory. This does not completely explain the high temperature required to fit the helium line profiles. The temperature derived from the line profile is 22500°. The small difference of $\triangle \log g = 0{\cdot}2$ can be understood in terms of the difference between the two hydrogen line broadening theories. In section 4.2 we had corrected the derived $\log g$ values from use of ESW theories by $\log g = -0{\cdot}1$. The temperature derived from the unblanketed models of Mihalas and the blanketed models of Morton and his co-workers differs by 1000°, while the actual difference in temperature derived in section 4·2 and that used to fit the profiles here is 3200°. One possibility could be that the line profiles of HeI 4388 derived here is slightly in error and that the continuum is probably overestimated by 3 to 4%. But the profile utilised is the mean derived from three plates. A likely error in equivalent width can also cause the high helium abundance derived from this line in section 4.2. However, the three parameters, $\theta_e$, $\log g$ and *vsini* utilised, fit the other two lines also extremely well and this must be considered before one can come to any definite conclusion.

There is no indication of any gross errors in either $\log g$ or *vsini* [*vsini* = 15 km/sec utilised here is the same as that derived by Norris (1971)] and the LTE, non-LTE models utilise a value of $N_{He}/N_H = 0{\cdot}1$ which is not much different from that derived from the equivalent widths and LTE diagnostics in the present work and by Norris (1971). The high value of temperature required to fit the observations may be real.

$\mu^2$ *Sco*: A good fit is obtained with $T_e$, $\log g$, *vsini* values of 22500, 3·9 and 40 km/sec respectively. The different temperatures found in section 4·2 and that utilised to fit the profiles can be explained in terms of the differences between blanketed models utilised to derive helium abundances and the unblanketed models of Mihalas utilised to fit the profiles.

$\tau$ *Sco*: The fit between observations and theory is quite good except for HeI 4471. Such a difficulty already had been encounted by Auer and Mihalas (1972). However, the observations presented here for $\tau$ Sco are in much better agreement with theory than the ones shown by Auer and Mihalas. They had used a mean profile derived from all observation of this object published in the literature. The *vsini* value used by them is 30 km/sec, while we find that a value of 15 km/sec fits the observations very well. Other *vsini* values for this object published in the literature are 0 km/sec by Norris (1971) and $\leq$ 20 km/sec by Slettebak (1968).

For $\lambda$ 4471 the discrepancy near $\triangle\lambda = -1{\cdot}0$ Å, between the predicted and observed profiles can be eliminated with the new quantum mechanical Stark broadening calculations of Bernard *et al* (1974) with model atmospheres calculated at the appropriate temperature and gravity. Also the observed central intensity is deeper than predicted by theory though non-LTE profiles tend to fit better than LTE profiles.

### 4 4. *Results and discussion*

The mean helium abundance for the five stars studied here is $N_{He}/N_H = 0 \cdot 096 \pm 0 \cdot 004$ by number. This can be compared with the mean helium abundance of $0 \cdot 094 \pm 0 \cdot 005$ derived by Peterson and Shipman (1973) from a study of 13 stars in the upper Scorpius complex. To find if any helium abundance difference exists between the upper Centaurus Lupus members and the upper Scorpius members, we have used along with the helium abundance derived here, those obtained by Norris (1971) as well as by Peterson and Shipman (1973) for the members of Scorpio-Centaurus association. The Beta Cephei stars included in Norris' list were left out. To express the Mt. Stromle observations on the present scale, the helium abundances were derived afresh from the equivalent widths of the five helium lines utilised in this study and with temperatures derived by the $Q$ method and log $g$ determined from their hydrogen line profiles corrected by $-0 \cdot 1$.

The mean helium abundance from all these data is $N_{He}/N_H = 0 \cdot 098 \pm 0 \cdot 004$. The mean helium abundance from 10 upper Scorpius members alone is $0 \cdot 096 \pm 0 \cdot 005$ while those from the three upper Centaurus-Lupus members is $0 \cdot 105 \pm 0 \cdot 001$. In the above calculations, four stars in Peterson and Shipman's list have been left out. These four stars according to Garrison (1967) are of low luminosity for the helium spectral type given by him. However, even if these four are included in the averages, the numbers quoted here do not change significantly.

It appears that there is no significant difference in the helium content of the two major subgroups of this association. The helium profiles are normal as far as the three objects studied here are concerned and can be represented within the framework of non-LTE diagnostics of Mihalas and his co-workers.

## 5. Conclusion

Stellar rotations in the Scorpio-Centaurus association have been investigated in detail. The results show that the mean rotational velocities in this association follow the Abt-Hunter field curve very closely except for stars of spectral types B7 and later. For objects earlier than B7, there is no difference in the distribution of rotational velocities between the two major subgroups, *viz.*, the upper Scorpius subgroup and upper Centaurus-Lupus subgroup. Its rotational characteristics at these early spectral types can be utilised as an age criterion, then there is little difference between the present stage of evolution between these two subgroups and the individual B-stars of the galaxy. They seem to be close to the final stages of evolution together.

However, the members with spectral types B7 and later, all of which are found in the upper Scorpius region rotate very much faster than the field stars and the $\alpha$ Persei cluster members of similar spectral types. These are found to be closely associated with the dense cloud complexes surrounding $\rho$ Ophiuchus and 22 Scor pius. Therefore, the possibility of deviation from a random orientation of rotational axes caused by the uncommon situation of being deeply involved in large cloud complexes cannot be ruled out. The possibility of increased angular momentum by accretion of matter exists. All peculiar objects discovered by Garrison (1967) fall in this spectral range and all of them are extremely slow rotators. Also the discordant objects with a difference of more than two spectral sub divisions from classification by photometry and spectroscopy belong to spectral types B7 and later. It would be of interest to see if a general departure towards higher values of *vsini* exists for stars visibly associated with nebulosities and if so whether the slow rotators amongst them are all peculiar. NGC 2264 should provide several good candidates for verification of these possibilities.

The helium abundance in this association is $0 \cdot 098 \pm 0 \cdot 004$. With the limited number of stars studied here, no discernible difference could be found in the helium abundance between the two subgroups of this association. HeI $\lambda$ 4026, 4388 and 4471 line profiles in three fairly sharp lined stars are given and compared with non-LTE theoretical predictions. It is well known that non-LTE effects are negligible in the blue violet region of the spectrum. However, the core and the wings even in this region of the spectrum can be represented simultaneously only if non-LTE effects are taken into account.

The distance modulus to this association, from $H_\gamma$ equivalent width of 77 stars, is found to be $6 \cdot 0 \pm 0 \cdot 09$ magnitudes. It is shown that the hydrogen line intensities in the upper Scorpius subgroup members are higher relative to the upper Centaurus-Lupus members. This is interpreted as an evolutionary effect since the upper Scorpius members are younger and are associated with bright and dark nebulosities while the upper Centaurus-Lupus subgroup is older, well dispersed and devoid of any nebulosities. The upper Scorpius members are normal and our observations cannot be reconciled with the remark of Glaspey (1971) that they are peculiar. The differences found by him are caused by the evolutionary effects found here combined with anomalous reddening in the upper Scorpius region.

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