SOME PHYSICAL ASPECTS

OF THE

SCORPIO-CENTAURUS ASSOCIATION

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Certificate from the Supervisor

I certify that the thesis entitled "SOME PHYSICAL ASPECTS OF THE SCORPIO-CENTAURUS ASSOCIATION" by R.Rajamohan is a record of the research carried out by him at the Kodaikanal Observatory of the Indian Institute of Astrophysics. The candidate has worked on this thesis under my supervision since October, 1969. I declare that the thesis has not previously formed the basis for the award of any Degree, Diploma, Associateship, Fellowship or similar title. The thesis contains an account of spectroscopic observations made by the candidate of a very important stellar association in the southern hemisphere. They form the basis of detailed interpretation by him of physical aspects of the aggregate such as rotational velocities, distance measurement and helium abundances.

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CONTENTS

CONTENTS

SUMMARY

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. Some investigations of this association have questioned its reality. Many others have assigned definite members to the association. In this thesis, I have presented information obtained from spectrographic studies of as many members as possible in order to resolve some of these issues, of the past.

The data that I have obtained for this thesis have been collected mainly to answer certain specific questions enumerated at the end of the first Chapter. Also in this Chapter, I have given a comprehensive history of early work on the association with a bias towards those studies which are of immediate importance for the pages to follow.

Rotational velocities of 112 members of the Scorpio-Centaurus association are derived and discussed in Chapter two. The spectra of members drawn from the

lists of Bertiau and Garrison brighter than $m_v = 8.5$, were obtained with the 51 cm reflector at Kodaikanal and the 102 cm reflector at Kavalur. The same spectrograph was utilised at the cassegrain foci of the two telescopes. The dispersion of the spectrograms is 47Å/mm.

The rotational velocities were derived by the graphical method of Shajn and Struve, from a comparison of the observed HeI 4026 and Mg II 4481 profiles with a family of theoretically broadened contours for various values of vsini. The profile of HeI 4026 in τ Sco was used as the zero velocity standard for the early B-star range and the Mg II 4481 in α Canis Majoris for the later spectral sub classes. The earlier investigations of rotational velocities in the Scorpio-Centaurus association had based their analyses on line width measurements with a comparator or on visual eye estimates of rotational velocities. I have followed the elaborate procedure of utilising the entire line profile in order to eliminate any accidental and systematic errors that are likely to affect estimates of rotation by subjective methods.

It is shown that the rotational velocities in this association closely resemble those of the field stars except at spectral types B7 and later. The distribution of rotational velocities of both the Upper Scorpius sub-group and the Upper Centaurus-Lupus sub-group is similar for stars with $M_V < 0.0$. However the stars with $M_V > 0.0$, all of which are found in the Upper Scorpius region rotate much faster than their counterparts amongst field stars, the Pleiades and α Persei cluster members.

Hydrogen line intensities of λ 4340Å to λ 3770Å and the neutral helium line intensities of λ 4026Å and λ 4471Å as well as of the Mg II line intensity of λ 4481Å amongst the members of the Scorpio-Centaurus association obtained from the same spectra, which were utilised to derive rotational velocities, are presented in Chapter three. The equivalent widths of H_γ derived here are in excellent agreement with those of Petrie and his collaborators. The most recent W_{H_γ}-M_V relationship derived by Balona and Crampton was utilised to derive the distance modulus to this association. The distance modulus of 6.0 ± 0.09 derived here is in excellent agreement with the determination of distance modulus by Crawford, Glaspey and Perry from photoelectric $H\beta$ measurements and the geometric distance determination by Jones and Bertiau from proper motions and radial velocity data.

Evolutionary effects in the derived hydrogen line intensities are found between the two sub-groups of the association. The H-line intensities in the Upper Centaurus-Lupus sub-group are systematically smaller than in the younger Upper Scorpius sub-group members at all spectral types.

An attempt is made to find the "aspect effect" of rotation on the derived H-line intensities. The results are negative indicating that such effects are small essentially confirming Petrie's earlier conclusions. These may therefore, be neglected without introducing any systematic errors in the results obtained by the use of hydrogen line intensities.

In Chapter four, the analysis of high dispersion spectra of five bright members of the Scorpio-Centaurus association is presented. The spectra were obtained with an echelle spectrograph at the coude focus of the 102 cm reflector at Kavalur and have a dispersion of 4.8 Å/mm at 4026 Å.

The observations were restricted to the blue violet region of the spectrum in order to derive reliable helium abundances for the five stars selected in this study. In view of the fact that high dispersion analysis involves large amounts of telescope time, and elaborate data reduction procedures, I have restricted the number of stars studied. The methods adopted in deriving the helium abundance is outlined in this Chapter with a detailed discussion of the results which incorporate some data already available in the literature. The mean helium abundance N_{He}/N_H for the five objects derived here is 0.096 ± 0.004. When results of others are incorporated with my values, and transferred to the same temperature scale, the mean helium abundance from 13 stars for the entire association is 0.098 ± 0.004. The β Cephei stars and objects regarded by Garrison as peculiar were omitted in forming the mean. For the two sub-groups I derive a value of 0.105 ± 0.001 for Upper Centaurus from three stars, and 0.096 ± 0.005 for Upper Scorpius from 10 stars. Within the capabilities of our present methods, there seems to be no difference between the two sub-groups as far as their initial helium abundance is concerned, a fact that must be borne in mind in the interpretation of the difference found between the two sub-groups from photoelectric photometry.

In the fifth Chapter, the observed line profiles of HeI 4026, 4388 and 4471Å, in the three sharp line stars, τ Sco, κ Cen and μ^2 Sco are compared with theoretical LTE and non-LTE profiles. It is found that the non-LTE profiles tend to fit the observations better, especially in the line core where the differences between LTE and non-LTE are most pronounced. However the effects on non-LTE on the equivalent widths in the blue-violet regions of the spectrum, to which our studies are restricted, are very small and therefore the conclusions arrived in the earlier chapter remain unaffected.

An accidental discovery of a β Cephei variable is reported in Chapter six. Radial velocity measures of ν Centauri, one of the spectroscopic binaries in the Scorpio-Centaurus association, shows that this object is also a β Cephei variable with a fundamental period of 0.1750 days.

A brief resume of the present work and suggestions regarding future possible effects are given in the concluding part of the thesis.

CHAPTER I

THE SCORPIO-CENTAURUS ASSOCIATION

1.1 Introduction   The study of star aggregates plays a fundamental role in the development of Astronomy. Present day concepts of distances within the galaxy and beyond it, of spiral structure as well as of stellar evolution have all emerged from studies of diverse aspects of star clusters and associations. For, the star grouping represents a near similarity of origin, chemical composition and age effects of a close family held together by the gravitational field of its members.

The study, therefore, of a common characteristic in such an aggregate, has the advantages of stability of sample and a range in behaviour that is unaffected by uncertainties in distance or the circumstances of birth and subsequent evolution.

Distinct in the degree of compactness from the globular and galactic clusters are the associations of O and B stars or of the later spectral types known as the T associations. These are synonymous with youth in terms of a star's life cycle, and while they retain a distinctness and identity characteristic of the group as a whole, their motions are principally governed by the gravitational field of the Galaxy. Dynamical arguments show that in the solar neighbourhood, groupings with space densities below a threshold value cannot withstand for a long time the shearing effects of galactic rotation. An association of O and B stars has a short life-time during which interval its brightest members may show only minor changes caused by evolution. A study of some aspect of such an association has the capability of furnishing information on the parameter near to the epoch of stellar birth in the grouping.

We owe to Ambartsumian (1947) principally, the introduction of the term "association" in the sense we employ it today and of several postulates on the kinematic behaviour of the members of such a grouping. He pointed out that their ages must be of the order of 10^7 years, and that they must be in a state of expansion. Subsequent studies with the aid of astrometric and photoelectric techniques have supported these early hypotheses.

The structures of these associations in general are such as to contain one or more open clusters, multiple stars as we see in the Trapezium in Orion, and sometimes star chains. These are typically nuclei of the associations. Another characteristic is that of the existence of sub-groups within the association, representative of slightly different evolutionary stages. The Scorpio-Centaurus and the I Orionis formations are examples of this kind, where it seems that over a large area of a complex in the interstellar medium where star birth at a given epoch happens, a near simultaneity of origin may not be a common occurrence. Star formation in one domain of the complex may have ceased when it has either begun or is in progress in an adjoining region. Studies of such sub-groupings in the future are likely to improve our information on the conditions in the interstellar medium that trigger star formation for a limited duration.

The oldest such sub-groups of associations known to us have ages of 1.5×10^7 years. The increase in size of these sub-systems with age, indicates that when they disperse over a large area, they seldom retain the characteristics that enable us to recognize them as of common orgin. It is likely that many of the O and B stars we see in the general galactic field have originated in associations that at the present epoch are unrecognizable.

1.2 <u>The Scorpio-Centaurus Association</u> The boundaries of the Scorpio-Centaurus association lie approximately between $l^{II} = 2°$ and $312°$ and $b^{II} = 5°$ and $26°$. At the lower longitude end, it crosses over the galactic plane and merges into the background B-star population which makes it difficult to separate out the members. Kapteyn (1914) first pointed out that the proper motions of the bright B-stars in the Scorpio-Centaurus region indicate that they converge to a point as in the well-known case of the Hyades. Its geometrical distance was derived by Blaauw (1946) with proper motions based on the Boss General Catalogue and radial velocities determined from the Lick Southern survey. He gave a list of certain, probable and doubtful members (36, 47, and 31 respectively). Bertiau (1958) redetermined the convergent point with proper motions based on the N30 system and well determined radial velocities. He obtained a distance modulus of 6.2 mag. for the association. Jones (1971) rediscussed the earlier work, and with proper motions based on the FK4 system made a fresh determination of the convergent point. He obtained a distance modulus of 5.8 which makes all luminosities fainter by 0.4 magnitudes. This difference between the two geomatric distance determinations is caused by the fact that proper motions based on the FK4 system are larger by 20% compared to that of the N30 system used by Bertiau.

However, Smart (1939) Petrie (1961) and Eggen (1961) have argued that the association is not a physical group and that they are part of the Gould's belt of early type stars. The objections raised by them have been satisfactorily answered by Blaauw (1963). Clube (1967) using the same data as Eggen, linked the Scorpio-Centaurus members to the bright B-stars of Gould's belt and showed that the radial velocities observed are consistent with a uniform velocity plus an expansion towards the galactic centre. Similar arguments were put forward by Lesh (1968) with proper motions based on the FK4 system. The work of Jones (1971) shows that if the discussion is confined to the immediate neighborhood of Scorpio-Centaurus, a firm list of 47 co-movers towards $l^{II} = 236°$, $b^{II} = 25°$ can easily be isolated. And while it is not an argument that should clinch the issue, 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 the association in recent years. Photometric measurements of the Upper Scorpius members were published by Hardie and Crawford (1961). Their UBV and Hβ measurements were confined to the northern regions, for stars with spectral types earlier than A0, which were observable from Dyer and McDonald observatories. Bappu, Chandra, Sanwal and Sinvhal (1962) made Γ index measures of stars in both the Upper Scorpius and Upper Centaurus-Lupus areas. From Γ index-$(U-B)_0$ plots they showed that the Scorpio-Centaurus association was older than the Orion association, which in turn was more evolved than the II Persei or II Monocerotis associations. Extensive UBV observations of 251 stars in this region were made by Moreno and Moreno (1968) from Chile. They also made Hβ observations of stars brighter than 6.5 magnitude, considered as definite or probable members from UBV photometry. Glaspey (1971) made uvby and Hβ observations of the association. The membership down to F0 was extended by Garrison (1967) from accurate MK classification and UBV photometry. Rotational velocities of the Scorpio-Centarus association members were first investigated by Huang and Struve (1954) from measured line widths. Rotational velocities of 82 members north of $-42°$ declination were recently published by Slettebak (1968). Hydrogen line strengths of the association members have been measured by various investigators. Andrews' $H\alpha$ measures lead to a distnace modulus of 6.34 (Jones 1971) while from $H\gamma$ line strengths, Balona and Crampton (1974) derive a distance modulus of 6.45. Moreno et.al. (1967, 1969) have measured the $H\beta$, $H\gamma$ and $H\delta$ line strengths of many B stars in the association with a low dispersion spectrum scanner at Cerro-Tololo.

1.3 <u>The Sub-groups</u> In almost all associations, one can distinguish a concentration of members in one region while the other members are much more dispersed. In some associations, more than two sub-groups with different concentrations can be easily distinguished. Though they all have the same convergent point they represent different stages of evolution as seen from the color magnitute arrays. It has been found that the proportion of early type stars associated with nebulosities is higher in the most concentrated sub-system than in the more dispersed one. In the case of the Scorpio-Centaurus association, two sub-systems, the "Upper Scorpius" and the "Upper Centaurus - Lupus" sub-groups have distinct features.

There is less evidence of a third one, the "Lower Centaurus-Crux" group. The Upper Centaurus-Lupus sub-group is older, well dispersed, tends to be more evolved from the zero ago main sequence (ZAMS), and is devoid of nebulosities, while the younger Upper Scorpius sub-group contains conspicuous dark clouds like those around ρ Ophiuchi and the bright nebulosities near 22 Scorpii. The Upper Scorpius group is still on the main sequence and the turn off point is near B2 (Carrison 1967). The distinct difference between the sub-groups is very well evident in the $\beta,(u-b)_0$ diagrams of Glaspey (1971), which show that the hottest members of Upper Centaurus-Lupus lie appreciably above the ZAMS and that there are no stars with $(u-b)_0 < 0.0$. A different situation holds good for the Upper Scorpius group. Similar results have originated from photometric studies by Walraven and Walraven (1960), Borgman and Blaauw (1964) and Moreno and Moreno (1968).

Blaauw (1964), determined the distance from proper motions, to be 170, 170, 160 parsecs for the Upper Scorpius, Upper Centaurus-Lupus, and the Lower Centaurus-Crux sub-groups respectively. He found that the average rate of expansion of the association as a whole is 40.05 Km.

per second per parsec leading to an "expansion age" of 20 million years.

1.4 <u>Peculiar Stars in the association</u> Garrison (1967) first pointed out the large number of peculiar B and A stars in the Upper Scorpius region with strong metallic lines. In a number of cases, the photometric colors implied a higher temperature than that given by the MK spectral class. The main sequence was found close to the ZAMS, but 0.6 magnitudes below the recent absolute magnitude calibration of Blaauw (1963), when a distance modulus of 6.2 mag. is utilised. This discrepancy would increase further if we use the value of 5.8 derived recently by Jones. Garrison finds that in addition to the strong hydrogen lines, all other luminosity criteria indicate low luminosity at a given spectral type, in support of Blaauw's work which suggests an intrinsically lower luminosity of the Scorpio-Centaurus members. Glaspey (1971) found that in c_0-MK type plots for the Upper Scorpius and the Upper Centaurus-Lupus groups, the peculiar stars were displaced from the mean relationship defined by normal stars. Also, in the c_0-m_0 diagram, the two sub-groups define different mean relationships. Since the Upper Centaurus-Lupus group falls along the same band as defined by the field normal stars, it appears that the Upper Scorpius members are peculiar. This effect was found to persist even when the peculiar stars were eliminated. Glaspey believes that this effect may be due to anomalous line absorption in the stars of the Upper Scorpius group.

1.5 Helium abundances 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 abundances, from plate material with dispersions $\leqslant$ 20Å/mm in these three associations are 0.081 ± 0.004 for NGC 2264; 0.097 ± 0.005 for II Scorpii, and 0.102 ± 0.005 for I Lacertae. (The numbers are defined such that $N_{He} + N_H = 1$). The ages of these three clusters are NGC 2264 - 10^6 years, II Scorpii - 10^7 years and 1.2×10^7 years for I Lacertae. They come to the improbable conclusion that the helium abundance is decreasing on a time scale of 10^7 years!

1.6 A preview of the present work In what follows, I shall attempt to provide information on the following questions.

(a) Are there any differences in the distribution of rotational velocities between the two sub-groups, the Upper Scorpius and the Upper Centaurus-Lupus, of the Scorpio-Centaurus association?

(b) Are there any differences in the line intensities between the two sub-groups as suggested by the work of Glaspey from narrow band photometry?

(c) Does any helium abundance difference exist between the two sub-groups?

(d) Are there non-LTE effects in the atmospheres of these stars which may be responsible for some of the anomalous aspects of the spectra?

CHAPTER II

ROTATIONAL VELOCITIES IN THE SCORPIO-CENTAURUS ASSOCIATION

2.1 Introduction In the early decades of the present century, Schlesinger and subsequently Rossiter and McLaughlin had effectively demonstrated stellar rotation as an astronomical phenomenon of common occurrence. An extension to single stars by Shajn and Struve (1929) and Elvey (1930) called for a radical change in earlier conservative estimates of maximum observable rotational velocities and introduced the technique followed subsequently for such measurement. In recent years systematic studies of rotation in early and late type stars of the general galactic field as well as in clusters and associations have aided much in our interpretative efforts of stellar evolution. The studies of Slettebak, Abt, Kraft, Huang and Herbig provide much of the information that we possess today.

2.2 A summary of the principal findings Some of the results obtained by various investigators of stellar rotation amongst field stars are summarised below.

(1) Studies of Slettebak and others either of the general field or the members of galactic clusters

(Kraft 1965) show that the axes of rotation are oriented at random. They have no preferential orientation and are not correlated with galactic latitude. This is an important factor to be taken into account in studies of stellar evolution. However, there is some indication that A-stars at very large distances from the galactic plane might be rotating slightly slowly than the stars nearby (Slettebak et.al. 1968).

(2) Metallic line stars and peculiar A-type stars as a group are characterised by small axial rotation.

(3) Rotational velocities decrease along the main sequence from middle B-type to late F-type. Rapid rotations occur at types O, B and A. There is an abrupt drop at about spectral type F5 which is probably related to the inner covection zones, magnetic fields and chromospheric activity of these objects at F5 and later.

(4) Rotation in supergiants is small and large atmospheric motions play an important role in the these high luminosity stars.

2.3 Rotational velocities in Clusters and Associations

Data regarding the distribution of J(M), the angular momentum as a function of mass are required for an understanding of the formation of stars from the interstellar medium. The members of a cluster can be assumed to be coeval and studies of the members of galactic clusters are needed to establish this distribution. Eventually the comparison of this distribution between different clusters and that of the field stars would provide important clues for better formulation of stellar structure and theories of stellar evolution.

A number of papers on rotational velocities in galactic clusters have appeared. Kraft (1970) has summarised these in detail in the Struve memorial volume. In general the field stars rotate slowly compared to the clusters though large differences exist from cluster to cluster. The Abt-Hunter hypothesis (1962) that low binary frequency is correlated with high mean rotational velocity in a cluster is confirmed from studies of many different clusters. For example, the Alpha Persei cluster and the Pleiades rotate faster at all spectral types than the field stars and have similar $\langle v \sin i(M_v)\rangle$ distributions. Both these clusters are characterised by similar low frequency of binaries (Kraft, 1967). The distribution function for IC 4665 is lower than that of the field stars and the Pleiades cluster (Abt and Chaffee 1967). The cluster has a high frequency of binaries thus confirming the Abt-Hunter hypothesis.

2.4 Predicted theoretical effects on T_e, g etc. The theoretical calculations of the effects of rotation on observable parameters have been numerous. Sweet and Roy (1953), Ireland (1966), Roxburgh, Griffith and Sweet (1965), Roxburgh and Strittmatter (1966), Collins (1963, 1965, 1968, Collins and Harrington (1966) have been principal contributors. Qualitatively, the effect of rotation is to increase the gravity at the poles relative to the equator. Hence by von Zeipel's theorem both T_e and surface brightness will be greater at the poles than at the equator. An aspect effect is therefore apparent. There is also the possibility of a difference in luminosity between a rotating star and a non-rotating one of identical mass and chemical composition.

The effect of rotation is also to decrease the Balmer line strengths, and increase the values of color indices and Balmer jump, namely $(U-V)_e$, $(B-V)_e$ and D, compared to the values obtained for a non-rotating star.

2.5 Rotational Velocities of Scorpio-Centaurus members

Huang (1953) systematically derived the width parameters of weak lines in the spectra of many stars for whom spectra were available in the Lick observatory plate files. Using this material Huang and Struve (1954) and later Buscombe (1965) derived the rotational velocities of the brighter members of the Scorpio-Centaurus association. Slettebak (1968) measured rotational velocities of 82 members north of -42° declination with spectra at 40 and 20Å/mm. The rotational velocities from the 40Å/mm plates were derived from visual estimates relative to standard rotational velocity stars. For objects observed at 20Å/mm dispersion, he derived the rotational velocities from a calibration of the line-width of 4471Å at half intensity and vsini of standard stars. The main conclusions reached by Slettebak are:

(1) Early and middle B-type stars as a whole rotate somewhat slowly compared to the field stars of the same spectral type; The same result was obtained by Huang and Struve (1954).

(2) Denser, nuclear region members rotate faster than the stars of the outlying regions. A similar result was

obtained by Buscombe (1965) based on Huang's measures.

(3) The late B-stars, rotate considerably faster than the field stars while the most luminous stars rotate slightly slowly compared to the field stars of the same spectral type. He found that in the spectral range B7-A0, the 14 stars he investigated had all vsini $>$150 km/sec in confirmation of the suggestion by Abt Chaffee and Suffolk (1967) that there are no slowly rotating normal stars in the range B7-A0 with vsini $<$ 100 km/sec.

2.6 <u>The present observations</u> Rotational velocities of 112 members of the Scorpio-Centaurus association, drawn from the list of members by Bertiau (1958) and Garrison (1967), derived in this present study are listed in Table II-1. The method followed in the determination of rotational velocities is the one essentially developed by Shajn and Struve (1929). To construct the contour of any line in the spectrum of a rotating star, we take as an initial contour, the observed contour of the same line in a non-rotating star of similar spectral class. Giving various values to the equatorial velocity of rotation of star, we construct for each of these values, the theoretical contour distorted by rotation. By interpolating the observed contour, of the same line in the spectrum of a rotating star, in the family of computed contours for different values of vsini, we find the projected rotational velocity.

Let us represent the line contour broadened by rotation by $R(\lambda)$ and the contour undistorted by rotation to be $R'(\lambda')$. Let the broadening function be $B(y)$. If we represent all wavelength differences in units of maximum wavelength shift $\Delta\lambda_R$ at the equator, then

$$R(x) = \int_{-1}^{+1} R'(x-y)\, B(y)\, dy \qquad (2\text{-}1)$$

where the broadening function $B(y)$ is given by

$$B(y) = \frac{\frac{2}{\pi}\sqrt{1-y^2} + \frac{\beta}{2}(1-y^2)}{1+\frac{2}{3}\beta} \qquad (2\text{-}2)$$

Here β is the limb darkening coefficient. The broadening function is normalised such that

$$\int B(y)\, dy = 1 \qquad (2\text{-}3)$$

Equation (2-1) can be integrated mechanically.

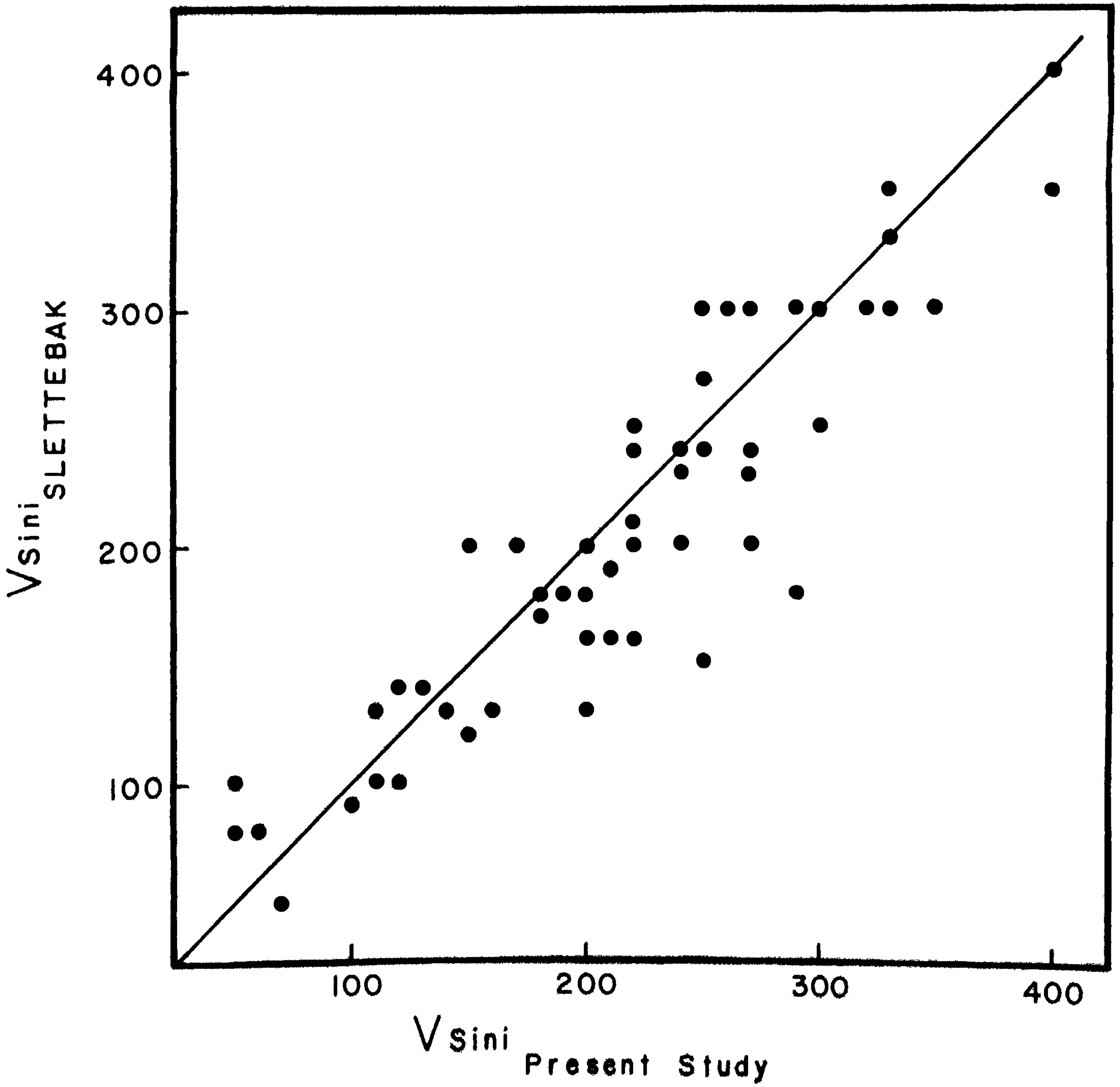
I have used for R'(x-y), the observed profile of HeI 4026 in τ Scorpii, which was assumed to be non rotating. Slettebak (1968) gives the rotational velocity of τ Scorpii as $\leqslant$20 km/sec., while my value for this parameter obtained from high dispersion spectra is 15 km/sec. In the present study for the rotational velocities, I have used a dispersion of 47Å/mm and cover the members of this association brighter than V = 8.5. The spectra were obtained mostly with the 102 cm. reflector at Kavalur while some of the bright members were taken with the 51 cm. reflector at Kodaikanal. The same spectrograph was employed at the cassegrain foci of both telescopes. The projected slitwidth was always kept at 18μ and the spectra were widened to 200-400μ depending on the brightness of the objects. Most of the spectra were obtained on IIa-o, and baked IIa-o plates while for some objects the 103a-o emulsion was employed. The plates were developed in D19 for four minutes along with the calibration spectrum obtained on a plate from the same box. The calibration was provided by a rotating sector and quartz prism spectrograph. The rotating sector has seventeen intensity steps with log I intervals of 0.1 between adjacent steps.

The contour of HeI 4026 in τ Scorpii and that of the visible disc of the star was divided into 40 strips and the integration of equation (1) was performed for values of vsini ranging from 50 to 500 km/sec. The effect of gravity darkening was neglected in these computations, since its contribution is important only in the case of extremely fast rotators. There are no B-stars in our list which have vsini $>$ 400 km/sec. The approximation introduced by neglecting the gravity darkening effect should have therefore a negligible effect in the derived rotational velocities. For the late B-stars, in the association, Mg II 4481 was utilized in determing the rotational velocities. The profile of Mg II 4481 as observed with our instrument in Sirius (AO V) was used as the initial zero velocity standard.

Stars having vsini values in common between Slettebak (1968) and the present study are plotted in Figure II-1. In general the agreement is very good. The present determinations, with 30 more new vsini values, is considered more accurate since the use of line profiles avoids subjective eye estimates and

FIGURE 2 - 1

Comparison of the rotational velocities of the members of the Scorpio-Centaurus association determined in this study and those by Slettebak (1968).



400
300
200
100
V sini SLETTEBAK
100
200
300
400
V sini Present Study

TABLE II-1

Serial Number	HD Number	Spectral type	vsini (km/sec) Present	vsini (km/sec) Slettebak	Remarks
1.	103079	B4 IV	140		
2.	103884	B3 V	150		
3.	105382	B6 III	200		
4.	105435	B2? Vpe	200		
5.	105937	B4 V	210		
6.	106490	B2 IV	120		
7.	106983	B3 IV	140		
8.	108257	B4 IV	150		
9.	108483	B2 V	220		
10.	109026	B5 V	180		
11.	109668	B3 IV	190		
12.	111123	B0.5 V	<50		
13.	112078	B5? Vn	330		1, 2
14.	112091	B5 Ve	330		
15.	113703	B5 V	160		
16.	113791	B2 V	≤ 50		
17.	115823	B5 III	160		
18.	116087	B5 V	300		
19.	118716	B1 V	80		
20.	120307	B2 IV	100	90	
21.	120324	B2 Vpne	210	190	
22.	120709	B5 III	≤ 50	≤ 20	
23.	120908	B5 V	180		
24.	120955	B5 III	≤ 50	≤ 20	
25.	121743	B2 IV	120	100	
26.	121790	B2 V	200		3
27.	122980	B3 V	≤ 50	≤ 20	
28.	125823	B3 V	100	≤ 20	
29.	127972	B1.5 V?ne	350	300	2
30.	129056	B2 II	≤ 50		

TABLE II-1 continued

Serial Number	HD Number	Spectral type	vsini (km/sec) Present	Slettebak	Remarks
31.	129116	B3 V	170	200	
32.	130807	B6 III	<50		
33.	132058	B2 IV	110	130	
34.	132200	B2 V	≤50	≤20	
35.	132955	B3 V	≤50	≤20	
36.	133937	B7 Vnn	330	350	3
37.	133955	B3 V	180		
38.	136298	B2 IV	240	230	
39.	136664	B5 V	220	210	
40.	137432	B5 V	160	130	2
41.	138485	B2 Vnn	300	250	
42.	138690	B2 Vn	250	270	
43.	138764	B7 IV	≤50	≤20	
44.	138769	B5 IV	150		
45.	139094	B7 V	180		
46.	139160	B8 V	200	130	
47.	139365	B2.5 V	140	130	2
48.	139486	B9.5 V	220	250	
49.	140008	B6 V	70	50	2
50.	141404	B9.5 V	200		
51.	141637	B2.5 n	270	300	
52.	141774	B9 V	210	160	
53.	142096	B3 V	200	200	4
54.	142114	B2.5 Vn	330	330	
55.	142165	B6 V	250	240	
56.	142184	B2 Vnn	400	350	
57.	142250	B7 V	≤50	≤50	
58.	142301	B7 IV			
59.	142301	B8 V	250	300	
60.	142378	B5 V	240	240	

TABLE II-1 continued

Serial Number	HD Number	Spectral type	vsini (km/sec) Present	vsini (km/sec) Slettebak	Remarks
61.	142669	B2 V	120	140	
62.	142883	B3? V	110	100	
63.	142884	B9 p	220	200	
64.	142983	B p	400	400	
65.	142990	B3? V	150	200	
66.	143118	B2 V	270	240	2
67.	143275	B0 V	190	180	4
68.	143567	B9 V	290	180	
69.	143600	B9 Vn	320	300	
70.	143699	B7 IV?	180	170	
71.	144217	B0.5 V	150	120	4
72.	144218	B2 V	60	80	
73.	144334	B9? III	≤50		
74.	144470	B1 V	130	140	
75.	144661	B7 IV	50	100	
76.	144844	B9 V	190	180	
77.	145353	B9 IV	220		
78.	145482	B2.5 Vn	220	240	
79.	145483A	B9 V	200		
80.	145502	B2 IV-V	270	200	4
81.	145519	B9 Vn	300	300	
82.	145554	B9 Vn	180	180	
83.	145631	B9.5 Vn	200	160	
84.	145792	B7 IV	≤ 50	≤ 50	
85.	146001	B8 IV	240	200	
86.	146284	B8 IV	200		
87.	146285	B8 V	200	160	
88.	146332	B5 II	100		5
89.	146416	B9 V	330	300	
90.	146706	B9 V	270		

TABLE II-1 continued

Serial Number	HD Number	Spectral type	vsini (km/sec) Present	Slettebak	Remarks
91.	147009	B9.5 V	220	160	
92.	147010	Ap	≤50	≤ 50	
93.	147084	A5 II	≤50	≤ 20	
94.	147165	B3 IV	≤50	60	1
95.	147196	B8 Vnnp	350		3
96.	147703	B9 Vn	280		
97.	147888	B5 V	180	180	
98.	147890	B9.5 p	≤ 50	≤ 50	
99.	147932	B5 V	200	180	2
100.	147935	B3 IV	290	300	
101.	147934	B2 V	260	300	
102.	147955	B9.5 V	280		
103.	148199	Ap	≤ 50	≤ 50	
104.	148321	A5 mp	100		
105.	148478	MA Ib	≤50	≤ 20	
106.	148579	B9 V	250	150	
107.	148594	B8 Vnn	300	300	
108.	148605	B2 V	270	230	
109.	148703	B2 IV	50	80	
110.	148860	B9.5 V	300		
111.	149438	B0 V	≤ 50	≤ 20	
112.	151985	B2 IV	≤ 50	40	
113.	157056	B2 IV	≤ 50	≤ 20	1

Remarks

1. Beta Cephei variable
2. Probable Spectroscopic binary
3. Hα plate shows emission in the core
4. Spectroscopic Binary
5. Non member

TABLE II-2

Test for Maxwellian Distribution

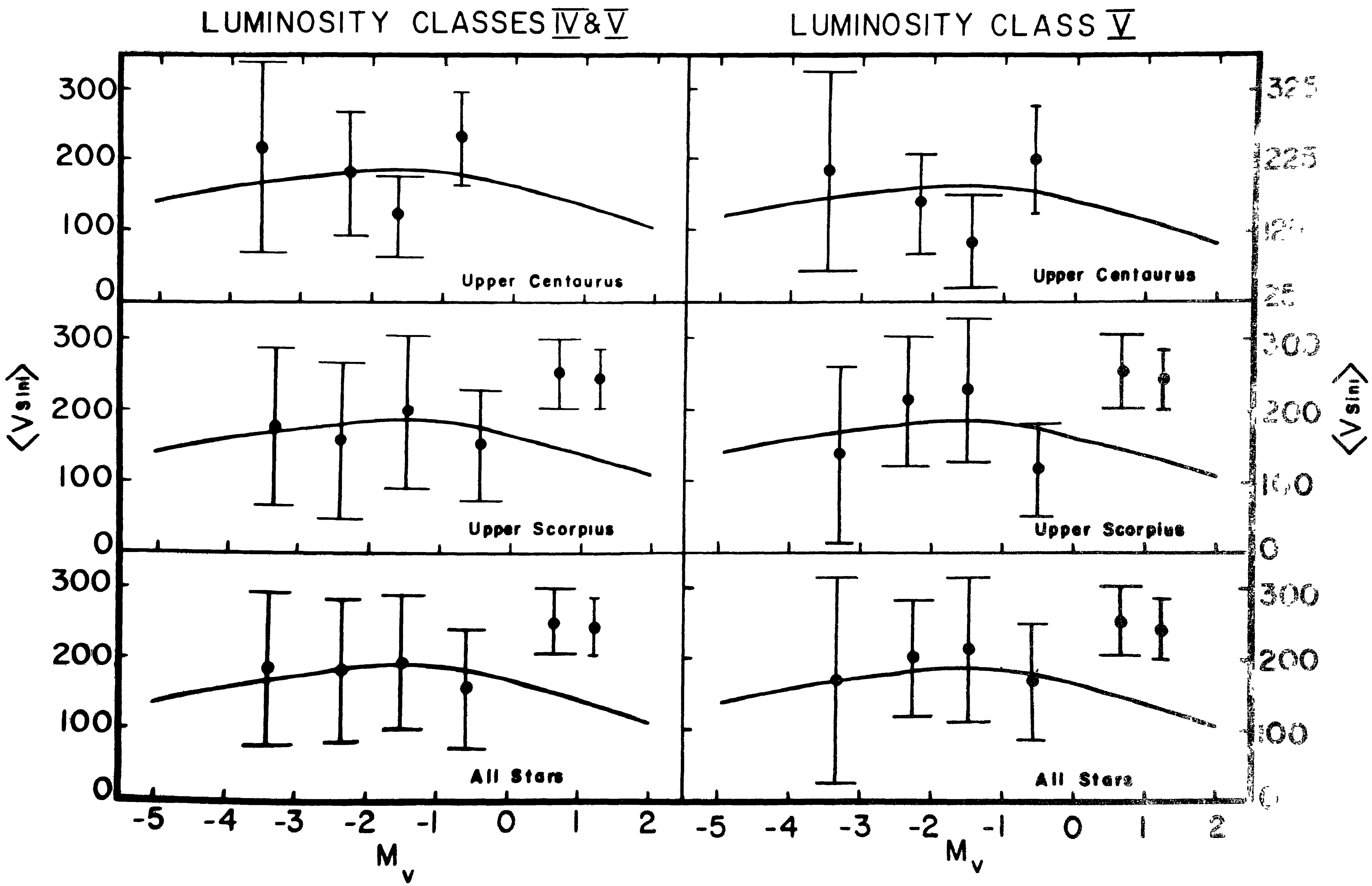
Spectral type	Number of stars	$[\langle(v\sin i)^2\rangle]^{\frac{1}{2}}_{obs}$	$\langle v\sin i\rangle_{obs}$	$\langle v\sin i\rangle_c$	O-C
Upper Scorpius Group					
B0-B3 V	12	221.3	190.4	196.2	- 5.8
B4-B6 V	5	128.1	108.0	113.5	- 5.5
B7-B9 V	15	269.0	264.0	238.4	+25.6
B9.5 later V	5	243.6	240.0	215.9	+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 Scorpious Centaurus Association					
B0-B3 V	29	204.1	176.9	180.9	- 4.0
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

accidental errors introduced in determination of rotational velocities by visual inspection of spectrograms. A similar view has been expressed by Treanor (1960). Errors of measurement of vsini for my determinations of rotational velocity range from ±10 km/sec. for the slower rotators to ±20 km/sec. for values of vsini > 300 km/sec. Measures of this kind obtained from a match with rotationally broadened contours, have a capability of uniformity in performance with lack of subjective errors, which the visual estimates of vsini, while very much less time consuming in application, can hardly hope to equal.

2.7 Results and Discussion A characteristic of the vsini values for early type stars in the general galactic field is the existence of high values of the roation velocity for stars in the B5-B7 range. Slettebak and Howard (1955) note this in their study of the bright northern early B-stars. When all 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 to B9. Two stars have the highest values of rotation measured of vsini equal to 400 km/sec. One of them is the well known shell star 48 Librae. When mean values of vsini are used instead we get the curves of Figure 2-2. Taking the main sequence stars first into account we have here the two sub-groups along with the composite whole. The Upper Scorpius plot covers M_V from -3.5 to +1.5. Also drawn in on each of the curves of Figure 2-2, is the Abt and Hunter (1962) mean curve obtained from a large number of observations of the field stars. There is little scatter of the points about those of the mean field, specially for spectral types earlier than B7. The limited number of stars available precludes a possible better fit to the Abt and Hunter mean line. To increase the statistical significance of the Upper Scorpius sample, I have in the second half of Fig.2-2 treated luminosity classes IV and V together. The improvement in the fits is considerable. But there still remains the enhanced values of vsini at absolute magnitudes around +1.0. The number of stars available in this grouping at M_V + 1.0 is fairly large. The reality of enhanced

FIGURE 2 - 2

$\langle v\sin i \rangle$ as a function of M_V for Scorpio Centaurus members. Luminosity classes IV & V, and V are shown separately. The same function for field stars is shown by the solid line. The error bars correspond to two standard deviations for both $\langle v\sin i \rangle$ as well as M_V.


LUMINOSITY CLASSES IV & V
LUMINOSITY CLASS V
Upper Centaurus
Upper Scorpius
All Stars
⟨V sin i⟩
M_v

vsini values for these stars cannot be questioned.

The Upper Centaurus stars follow the Abt-Hunter curve fairly closely. There is an appreciable scatter here presumably due to paucity of numbers of stars studied. Even so from a comparison of the plots for this sub-group of luminosity classes V as well as IV and V put together, one sees the validity of the inference that the mean behaviour of stars in the galactic field has little difference from that of the recognized members of the Upper Centaurus-Lupus and Lower Centaurus-Crux formations, taken together. These two sub-groups are the more evolved in the entire association when compared to the Upper Scorpius stars. It seems a clear conclusion to make that if rotational characteristics at these early spectral types can be utilized as an age criterion, then there is little difference between the present stage of evolution between these two sub-groups and the individual B-stars of the galaxy. If the field stars have drifted away from inadequately bound associations, individual B-stars of the Upper Centaurus and Lower Centaurus sub-groups are close to their final stages of existence together.

Also, the early type field stars are not much older than those in existing associations.

Slettebak (1968) has from his plots of <vsini> for three absolute magnitude groups, concluded that the mean rotational velocities of the most luminious stars in the Scorpio-Centaurus association are somewhat smaller than for field stars of similar absolute magnitude. With the larger number of stars utilized in this study, my conclusion differs from that of Slettebak. Slettebak's absolute magnitude intervals are larger than the one magnitude interval I have chosen as the basis for Figure 2-2, and while Slettebak's procedure may lead to greater stability of value by virtue of numbers, it minimizes the variation in trend which is a useful indicator of identity.

The distribution of rotational velocities in a cluster or association is an important parameter in a study of the physical aspect of origin. Deutsch (1967) has argued that a Maxwell-Boltzmann law does indeed represent the frequency function for each group of stars categorized 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 $\phi(y)$ 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

$$\phi(y) = \int_0^{\pi/2} f\,(y/\sin i)\,di \qquad (2\text{-}4)$$

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

$$\langle v\sin i\rangle = (\sqrt{\pi}/2)\left[\langle (v\sin i)^2\rangle\right]^{1/2} \qquad (2\text{-}5)$$

Table II-2 gives the values of the second moment of f derived from the observations of vsini. I have divided the stars into four spectral ranges; B0-B3, B4-B6, B7-B9, B9-later types. The two sub-groups and the entire association as a whole have been separately considered. Only main sequence stars have been taken for this purpose. The O-C values indicate a good fit with the Maxwellian law for the B0-B3 spectral range in all three groups. The major discrepancies are in the ranges B4-B6 and B7-B9.

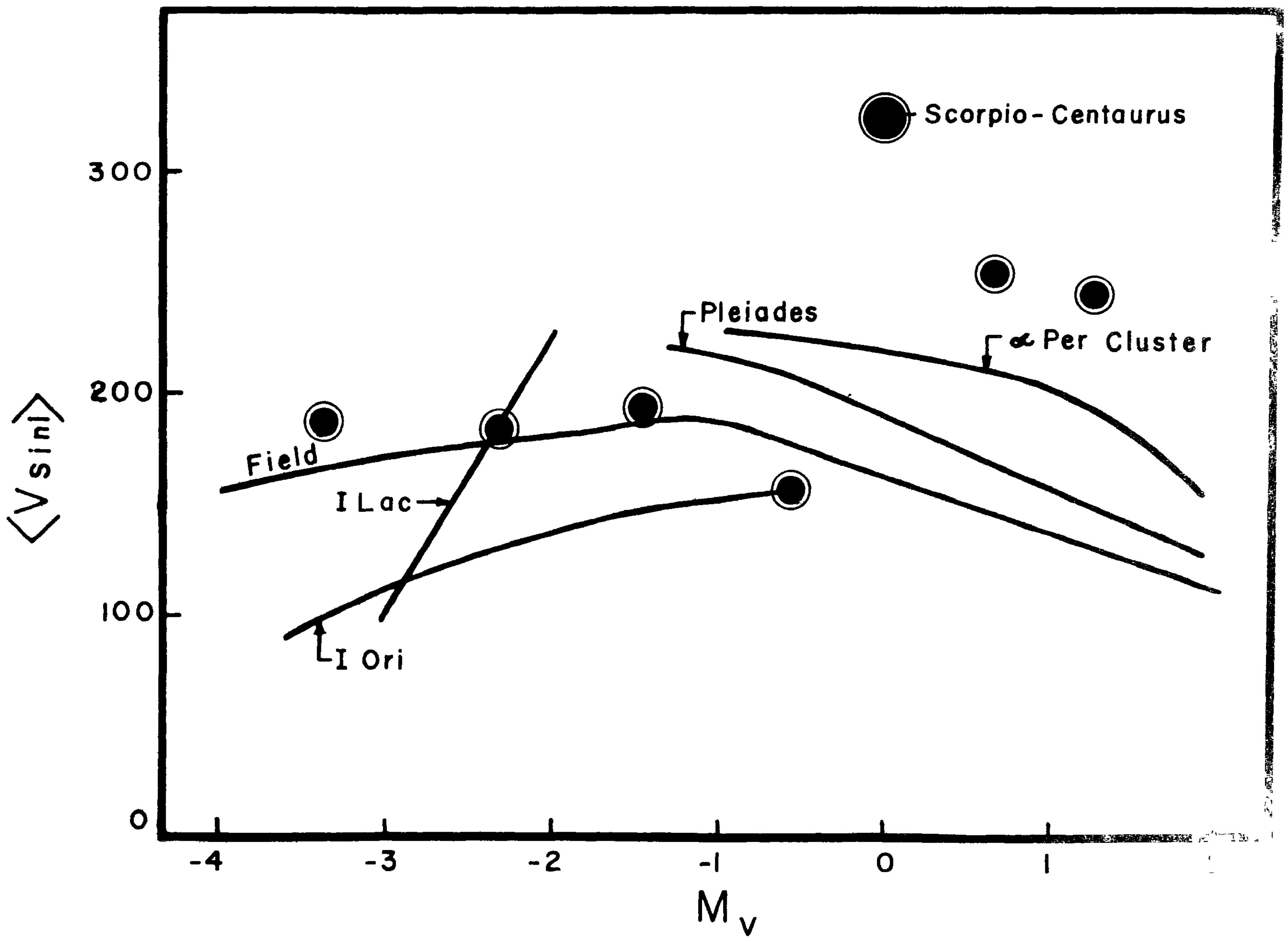
Especially in the Upper Scorpius group is this deviation striking. This is due to the large values ⟨vsini⟩ in this group at these spectral types. It would be of interest to follow up these deviations into the B9-later spectral types in this association.

We have a composite plot of vsini for several galactic clusters and associations in Figure 2-3. For absolute magnitudes fainter than $M_V = -1.0$, the Pleiades stars as well as those of the α 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 spectral types corresponding to $M_V = 0.0$ and fainter in Scorpio-Centaurus, have values of vsini atleast 120 km/sec. larger than the field stars and about 40-50 km/sec. greater than equivalent α Persei stars. While normal stars are known to have this tendency of possessing no slow rotators in the B7-A0 range, (Abt, Chaffee, and Suffolk 1967) the Upper Scorpius members have a high value that calls for interpretation.

Slettebak (1968) has in his paper a diagramatic representation of the distribution of rotation velocities

FIGURE 2 - 3

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 is plotted as filled circles. The source of rotational velocities of clusters other than Scorpio-Centaurus is Kraft (1970).



Scorpio - Centaurus
Pleiades
α Per Cluster
Field
I Lac
I Ori
300
200
100
0
-4
-3
-2
-1
0
1
$\langle V \sin i \rangle$
M_V

in the Scorpio-Centaurus association with location in the 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 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 Wen-Sai (1962) explains its origin as due to the impulse acquired from fragmentation of prestellar 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 associations 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 association. If such stars have angular velocity changes by fragment impulses, then such a possibility would be greatest on those members that have experienced the most violence of the catestroohe. 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 sub-group is located in the midst of the large cloud complexes of Ophiuchus and Scorpius. The fastest rotators in the M_v domain can be seen on Palomar charts to be associated with the dense clouds of the region. Two possibilities exist as a result of such an association. There is the phenomenon of accretion of the matter by the star that can increase its angular momentum similar to the reverse situation experienced at time of mass-loss. If so, one should see a general departure towards higher values of $\langle vsini \rangle$ for stars that have a visible association with interstellar matter. NGC 2264 should provide several good candidates for verification of this possibility.

If individual stars are plotted, on the $\langle vsini \rangle$ M_v diagram, one sees very few stars with vsini values < 50 kms in the $0.0 < M_v < +1.5$, domain. One can have such a situation if there is by virtue of interaction with the dense interstellar medium even a mild preference or 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. But at the same time it does not categorically rule out the chance 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. And might not such a situation prevail in the context of the high velocities of the later spectral types in Upper Scorpius? One would need more data on this and other clusters to extend the argument.

CHAPTER III

HYDROGEN AND HELIUM LINE INTENSITIES

3.1 Introduction The hydrogen line strengths in early type stars play a fundamental role in astronomical distance determination. They are excellent indicators of the absolute magnitude and as such an accurate calibration of this luminosity Criteria has been one of the primary objectives for optical studies of spiral structure of our galaxy.

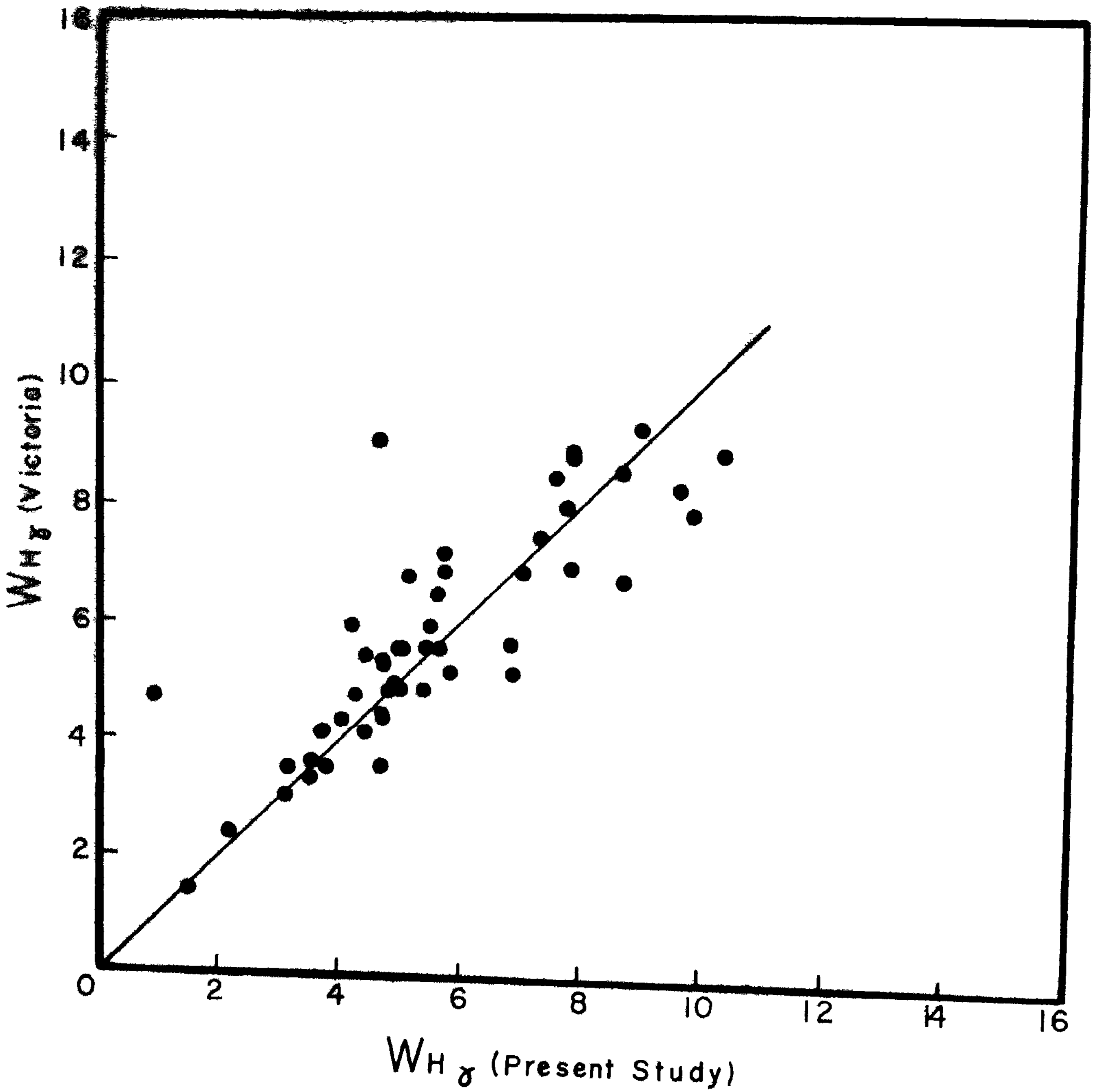
Petrie (1953, 1965) developed the Victoria system of absolute magnitudes based on Hγ line strengths derived from photographic spectra. Bappu et.al. (1961), Crawford (1958, 1970) and Andrews (1968) utilised narrow band photoelectric measurements of Hγ, Hβ and Hα respectively and showed that photoelectric techniques are superiod in speed compared to the photographic width measurements of Hγ by Petrie. The two methods have their own advantages and disadvantages. Photographic spectra are a permanent record, and peculiarities if any in the spectrum can be noticed. They are also capable of yielding much more information if required while photoelectric techniques have the advantage of high accurracy, speed and capability of extension to faint limits.

Spectra of the 114 members discussed in the previous chapter in deriving rotational velocities were utilised to derived hydrogen and helium line intensities. The observations and technique of reduction procedures employed have already been outlined earlier.

3.2 Results and Discussion The derived line intensities of hydrogen at 4340A, 4101A, 3970A, 3889A, 3835A, 3798A and 3770A as well as of the neutral helium lines at 4026Å and 4471Å are given in Table III-1. The equivalent width of $H\gamma$ as derived by me is plotted in Figure 3-1 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 I had derived the equivalent widths with the same spectrograph have also been plotted in this figure. The 45° degree line for a perfect fit is shown as a continuous line. Denoting the observations of Petrie,

FIGURE 3 -1

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



16
14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
$W_{H\gamma}$ (Victoria)
$W_{H\gamma}$ (Present Study)

Balona and Crampton as "Victoria", a least squares fit to the points yield

$$(W_{H_\gamma})_{Present} = 0.9961\ (W_{H_\gamma})_{Victoria} + 0.004$$

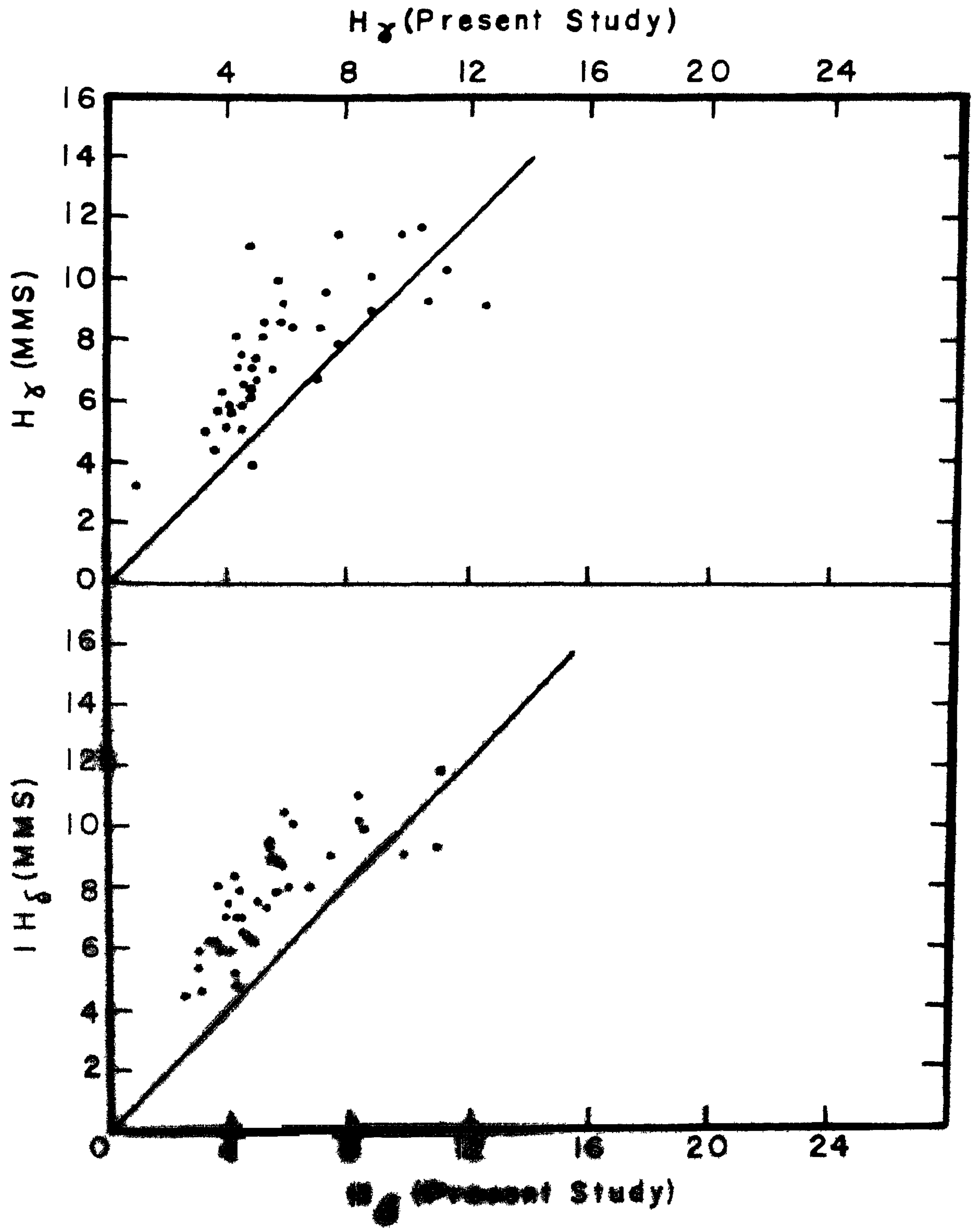
This shows that there are no systematic differences in the equivalent widths of H_γ derived in this study. The agreement is excellent inspite of the fact that these equivalent widths are measurements from single spectra.

The H_γ and H_δ photoelectric measures by Moreno et.al. (1967, 1969) are plotted against my values in Figure 3-2. This plot shows that the photoelectric values of Moreno et.al. are overestimated by 2Å at all values of W_{H_γ} and W_{H_δ}.

Assuming that the relationship is one to one between my H_γ measures and those of Balona and Crampton, their absolute magnitude calibration were utlised to derive the individual absolute magnitudes of the Scorpio Centaurus members, All peculiar stars, spectroscopic binaries, and stars later than spectral type A0 were omitted. A total of 77 stars remained in the list. Balona and Crampton (1974) have given two relationships

FIGURE 3 - 2

Comparison of the photoelectric measures of H_{γ} and H_{δ} line intensities obtained by Moreno et al (1967, 1969) plotted against the photographic determinations of the present work. The 45° line for a perfect fit is also shown.



Hγ (Present Study)
4
8
12
16
20
24
16
14
12
10
8
6
4
2
0
Hγ (MMS)
16
14
12
10
8
6
4
2
0
Hδ (MMS)
16
20
24
Study)

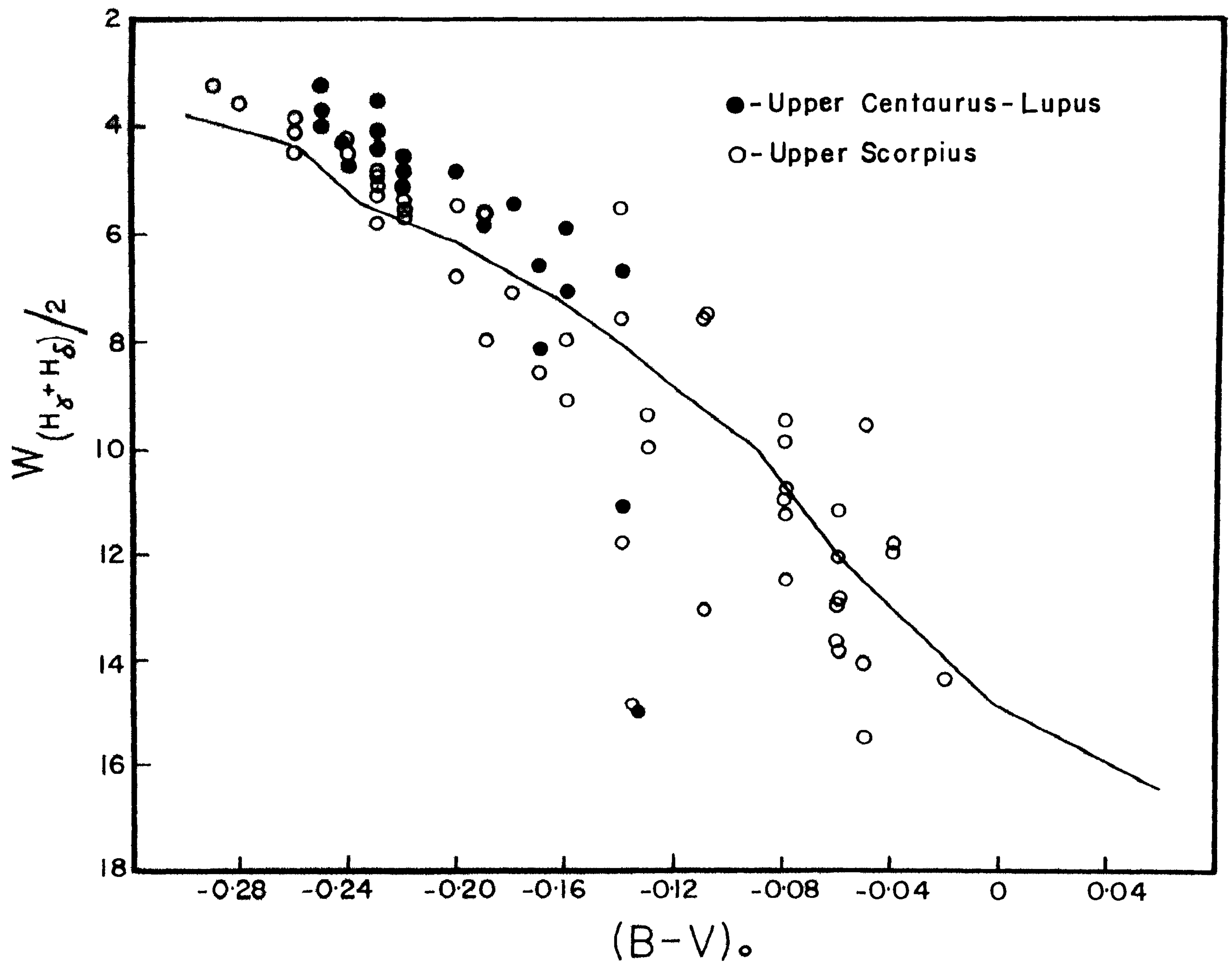
between M_V and $W_{H\gamma}$. The first one involves a knowledge of spectral type and the second one involves a knowledge of the unreddened (B-V) colour. The spectral types of the Upper Scorpius members were taken from Garrison (1967) and for the other objects from Bertiau (1958). The $(B-V)_0$ colours for all these objects were taken from Moreno and Moreno. A correction of +0.01 magnitudes was applied to these values (see Chapter IV). The absolute magnitudes were derived from both these 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 is seen. The mean of the two determinations was adopted as final. The individual distance moduli for the 77 stars were computed using V_0 values given by Moreno and Moreno (1968) and for stars not found in his list, from Garrison (1967). The mean distance modulus from these 77 objects is found to be 6.02±0.06 magnitudes. For the three different sub-groups, the derived values are: Lower Centaurus-Crux = 5.82±0.06 magnitudes (15 stars); Upper Centaurus-Lupus 6.19±0.10 magnitudes (19 stars); and Upper Scorpius = 6.00±0.09 magnitudes (43 stars).

The distance modulus derived by Balona and Crampton for the Scorpio-Centaurus association is 6.49±0.07 magnitudes. The difference is probably caused by the inclusion of a few Hβ measurements of Moreno and Moreno transformed to the Hγ scale. However this has not been investigated in detail. The distance modulus derived by Crawford et.al. of the Scorpio-Centaurus association from Hβ photometry is 6.0 magnitudes. The recent geometric distance modulus determination by Jones is 5.8. The Hα measures of Andrews (1968) lead to a distance modulus of 6.45 (Jones 1971). The earlier geometric distance modulus determined by Bertiau (1958) with proper motions on N30 system is 6.2 magnitudes. The difference of 0.4 magnitude between the two geometric distances modulus determination is caused by a 20% systematic higher values of the proper motions on the FK4 system used by Jones over that of the N30 system employed by Bertiau. The distance modulus derived here is in excellent agreement with that of the photoelectric determination of Crawford, Glaspey and Perry (1970).

Figure 3-3 is a plot of the mean equivalent width

FIGURE 3 - 3

The mean of H_γ and H_δ 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. The full line refers to the H_γ -spectral type relationship of Balona and Crampton (1974). The $(B-V)_0$ values for the corresponding spectral type are taken for Johnson (1966).


●-Upper Centaurus-Lupus
○-Upper Scorpius
2
4
6
8
10
12
14
16
18
-0·28
-0·24
-0·20
-0·16
-0·12
-0·08
-0·04
0
0·04
$W_{(H_\gamma + H_\delta)/2}$
$(B-V)_0$

of H_γ and H_δ against $(B-V)_0$. The continuous line is H_γ equivalent widths, spectral type relation given by Balona and Crampton. The $(B-V)_0$ values for the corresponding spectral types were 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 are well dispersed and are not associated with any nebulosities, while the Upper Scorpius members are compact with conspicuous dark clouds as around ρ oph and bright nebulosities near 22 Sco. The Upper Scorpius members are younger and this evolutionary effect is very well noticeable in this diagram.

These observations do not of course explain completely the differences found by Glaspey between the two sub-groups in the c_0, m_0 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_δ line and since differences exist in the hydrogen line strengths between the two sub-groups, this effect shows up in the m-indices of narrow band photometry. However, Glaspey remarks, "Relative differences in H_δ line strengths due to evolutionary stages can be ruled out since the differences in m-indices are greates for the mid B-star range and are smallest for early B-stars where evolutionary effects are most noticeable. Also there is no obvious correlation between Δm and $\Delta\beta$ taken relative to ZAMS at a given $(u-b)_0$ colour for the Upper Scorpius stars .... The m_1 index could be performing the same function with B-type stars as it is known to do with the late A and F stars, namely to indicate anomolous line absorption".

This remark cannot be reconciled with the observations presented in this thesis. There are no differences between the two sub-groups as far as their rotational velocities are concerned except that the B7-B9 stars in Upper Scorpius rotate much faster than the field stars. The helium abundances derived

TABLE III-1

Equivalent width in Angstroms

Serial Number	HD Number	H							HeI		Mg II
		4340	4101	3970	3889	3835	3798	3770	4026	4471	4481
1.	103079	7.6	8.3	7.2	9.0	7.8	6.6	7.8	0.79	1.41	0.90
2.	105382	5.1	5.5	5.4	4.9	4.1	-	-	0.85	0.75	0.56
3.	105435	0.9	2.5	2.7	2.6	1.7	2.3	1.6	0.89	1.41	-
4.	105937	7.2	6.1	6.1	5.8	4.9	4.8	3.2	1.52	1.22	-
5.	106490	3.6	3.2	4.3	3.2	2.6	3.0	2.1	0.96	0.76	-
6.	106983	7.0	7.4	9.2	-	-	-	-	1.11	1.81	0.45
7.	108257	5.6	5.8	6.6	6.0	4.0	4.4	-	0.76	-	-
8.	108483	6.9	6.0	7.4	5.0	-	-	-	1.73	1.55	-
9.	109026	10.6	-	-	-	-	-	-	-	-	-
10.	109668	4.7	5.2	6.2	4.5	-	5.8	4.2	1.71	1.50	-
11.	112078	8.7	10.9	7.9	10.0	8.4	-	-	1.82	-	-
12.	112091	6.1	5.9	7.3	6.0	-	-	-	0.77	1.08	0.50
13.	112092	4.2	4.3	-	-	-	-	-	1.36	1.62	-
14.	113703	9.6	8.3	7.9	7.3	-	-	-	1.32	1.08	-
15.	113791	5.1	6.7	3.9	4.7	3.9	4.0	-	1.73	1.24	-
16.	115823	10.3	11.1	-	-	-	-	-	1.21	1.11	-
17.	116087	11.1	8.6	10.2	-	-	-	-	1.71	1.82	-
18.	118716	4.0	2.9	2.5	3.0	3.0	2.4	1.7	0.78	1.07	-
19.	120307	4.8	4.4	-	-	-	-	-	1.60	1.20	-
20.	120324	4.8	4.5	4.1	4.0	4.0	5.0	2.8	2.18	1.72	-

TABLE III-1 continued

Serial Number	HD Number	H 4340	H 4101	H 3970	H 3889	H 3835	H 3798	H 3770	HeI 4026	HeI 4471	Mg II 4481
21.	120908	12.4	9.8	6.6	6.4	4.6	-	-	1.10	1.24	0.84
22.	120955	7.6	6.6	10.3	8.4	10.0	-	-	1.17	-	-
23.	121743	4.4	4.4	4.4	3.5	3.1	3.5	2.9	1.41	1.38	-
24.	121790	4.4	3.9	3.6	3.4	-	-	-	1.38	1.78	-
25.	127972	4.4	4.2	4.2	3.7	3.2	-	-	0.68	-	-
26.	129056	3.8	2.8	3.1	2.3	3.5	3.6	2.7	1.22	1.19	-
27.	129116	5.7	4.1	3.8	4.5	5.2	4.7	3.0	-	1.19	-
28.	130807	5.6	5.4	4.6	5.9	3.0	3.0	3.6	0.65	1.75	-
29.	132058	3.9	3.4	4.4	3.5	3.8	4.2	3.1	1.00	1.55	-
30.	132200	4.8	5.0	-	-	-	-	-	1.20	1.10	-
31.	133937	4.6	3.3	3.1	3.9	3.4	-	-	0.25	0.47	-
32.	136298	4.0	4.0	3.2	4.1	4.0	5.0	2.7	1.10	1.50	-
33.	136664	5.7	6.2	4.5	3.4	4.1	5.7	-	0.92	1.19	0.51
34.	137432	9.8	6.7	8.5	8.7	8.3	-	-	0.60	1.61	-
35.	138485	6.0	4.5	5.3	3.6	-	-	-	1.13	1.60	-
36.	138690	3.7	3.3	-	-	-	-	-	1.0	0.80	-
37.	138764	7.8	5.5	7.0	5.0	4.3	5.7	-	0.81	0.42	0.33
38.	139094	8.0	7.4	12.0	7.9	8.0	5.0	-	0.65	0.59	-
39.	139160	11.9	11.8	12.0	9.1	12.4	11.6	-	1.03	0.51	0.48
40.	139365	5.7	5.3	6.9	4.1	4.2	3.2	-	1.23	1.29	-

TABLE III-1 continued

Serial Number	HD Number	H 4340	H 4101	H 3970	H 3889	H 3835	H 3798	H 3770	HeI 4026	HeI 4471	Mg II 4481
41.	139486	19.1	18.8	19.4	15.9	13.2	-	-	-	-	1.71
42.	140008	7.5	4.3	6.4	7.0	6.1	4.4	3.5	0.79	0.99	-
43.	141404	9.3	9.8	11.2	10.3	9.9	-	-	0.22	-	0.57
44.	141637	5.0	4.9	4.8	4.5	3.7	4.1	2.3	1.36	1.21	-
45.	141774	9.8	9.5	8.0	8.0	7.7	-	-	-	-	0.39
46.	142096	8.9	7.1	6.8	6.2	6.4	5.0	-	1.19	1.31	-
47.	142184	5.6	5.2	4.8	3.9	3.6	3.8	2.3	1.11	1.00	-
48.	142250	7.6	7.6	8.5	5.9	8.3	-	7.0	0.69	0.64	0.54
49.	142301	5.9	5.4	5.2	6.2	5.8	-	-	0.35	0.30	-
50.	142315	11.9	10.1	9.7	8.6	7.6	5.8	5.7	0.50	0.54	0.39
51.	142378	8.2	6.0	6.6	6.2	5.6	4.4	3.4	1.02	1.12	-
52.	142669	5.8	5.7	-	-	-	-	-	0.90	1.00	-
53.	142805	15.3	13.6	11.0	12.2	-	-	-	-	-	0.80
54.	142883	9.1	8.2	8.4	7.4	6.9	4.8	3.3	1.40	1.67	0.49
55.	142983	4.2	3.5	3.6	3.4	3.5	4.1	-	0.96	0.94	0.67
56.	142990	7.4	6.3	6.3	5.1	5.0	4.0	3.4	0.62	1.09	-
57.	143018	4.7	3.7	3.8	5.4	3.3	4.5	3.7	0.46	0.73	-
58.	143118	4.7	4.7	-	-	-	-	-	1.80	1.40	-
59.	143275	3.1	4.1	-	-	-	-	-	1.60	1.40	-
60.	143567	14.0	12.0	13.7	11.9	11.0	8.7	-	0.59	1.00	-

TABLE III-1 continued

Serial Number	HD Number	H							HeI		Mg II
		4340	4101	3970	3889	3835	3798	3770	4026	4471	4481
61.	143600	15.2	8.9	12.8	9.8	9.7	8.8	-	0.33	1.95	2.10
62.	143699	7.8	5.4	7.6	6.4	5.5	4.9	3.6	0.96	0.60	0.20
63.	144217	7.5	2.7	3.5	3.3	-	-	-	1.13	1.79	-
64.	144218	6.7	4.0	3.7	4.0	-	-	-	0.92	1.14	-
65.	144334	8.3	8.0	9.4	8.2	7.6	5.2	4.0	0.37	0.24	0.47
66.	144661	8.7	7.3	8.7	10.3	7.7	5.1	3.6	-	0.24	0.49
67.	144844	15.5	10.7	8.7	8.7	8.0	5.7	4.7	0.20	0.08	0.26
68.	145353	12.9	9.6	10.2	9.6	9.7	9.2	-	-	-	1.34
69.	145482	5.5	5.6	4.4	4.1	3.4	3.6	4.09	1.38	1.68	-
70.	145483A	13.3	10.2	11.4	8.9	9.6	-	-	0.52	-	0.30
71.	145502	5.4	5.0	4.9	5.4	4.5	4.1	2.84	1.71	1.07	0.20
72.	145519	13.3	10.9	11.7	10.2	8.4	8.2	7.28	-	-	0.47
73.	145554	14.0	13.4	12.2	11.7	10.7	-	-	-	-	1.03
74.	145631	17.1	13.9	15.6	14.2	12.9	-	-	-	-	0.92
75.	145792	9.6	8.7	7.7	6.9	5.3	3.4	3.00	1.66	1.25	1.20
76.	146001	12.0	8.1	8.1	7.2	6.0	4.7	3.45	0.65	0.89	-
77.	146029	12.2	11.3	10.8	9.3	9.5	9.2	7.50	0.31	0.73	0.65
78.	146284	12.4	9.2	9.2	7.1	7.2	5.1	4.54	0.43	0.31	0.30
79.	146285	12.9	12.1	13.8	11.1	10.0	-	-	1.48	1.04	1.01
80.	146416	14.2	13.6	12.7	-	-	-	-	-	-	1.84

TABLE III-1 continued

Serial Number	HD Number	H 4340	H 4101	H 3970	H 3889	H 3835	H 3739	H 3770	HeI 4026	HeI 4471	Mg II 4481
81.	146706	12.6	12.5	12.0	10.8	–	–	–	0.87	0.44	0.60
82.	147009	20.0	16.9	13.0	12.3	9.9	9.7	–	–	–	0.76
83.	147010	9.8	9.0	7.5	8.1	6.4	5.4	4.85	0.27	0.31	0.55
84.	147084	11.2	9.9	10.8	11.0	10.2	6.9	6.84	–	–	0.65
85.	147165	4.7	3.4	3.2	3.7	2.8	–	–	1.12	–	–
86.	147196	10.1	9.7	7.2	7.6	7.2	6.7	–	–	–	0.87
87.	147703	13.4	14.8	13.4	12.7	–	–	–	–	–	0.74
88.	147890	12.2	10.4	9.3	9.5	8.2	–	–	–	–	0.93
89.	147932	5.5	4.5	–	–	–	–	–	0.84	1.61	–
90.	147933	4.5	6.6	5.0	–	3.8	–	–	1.25	–	–
91.	147934	6.2	4.7	4.9	4.8	4.8	5.0	–	0.88	1.20	0.76
92.	147955	13.9	12.7	12.9	12.7	10.4	6.5	–	–	–	0.61
93.	148199	9.2	9.7	10.4	8.6	–	–	–	–	–	0.48
94.	148321	17.1	16.9	16.3	12.8	11.8	6.8	–	–	–	0.79
95.	148562	18.6	17.5	14.5	12.9	–	–	–	–	–	1.07
96.	148579	12.5	13.3	11.3	11.6	–	–	–	–	–	0.48
97.	148594	8.7	6.6	8.7	5.2	6.4	5.3	4.11	–	–	0.50
98.	148605	–	5.6	5.7	6.3	7.6	4.7	3.87	1.33	1.75	0.78
99.	148703	5.3	4.2	4.5	4.7	4.9	4.2	–	1.20	1.49	–
100.	148860	14.2	13.8	15.7	–	–	–	–	–	–	1.37

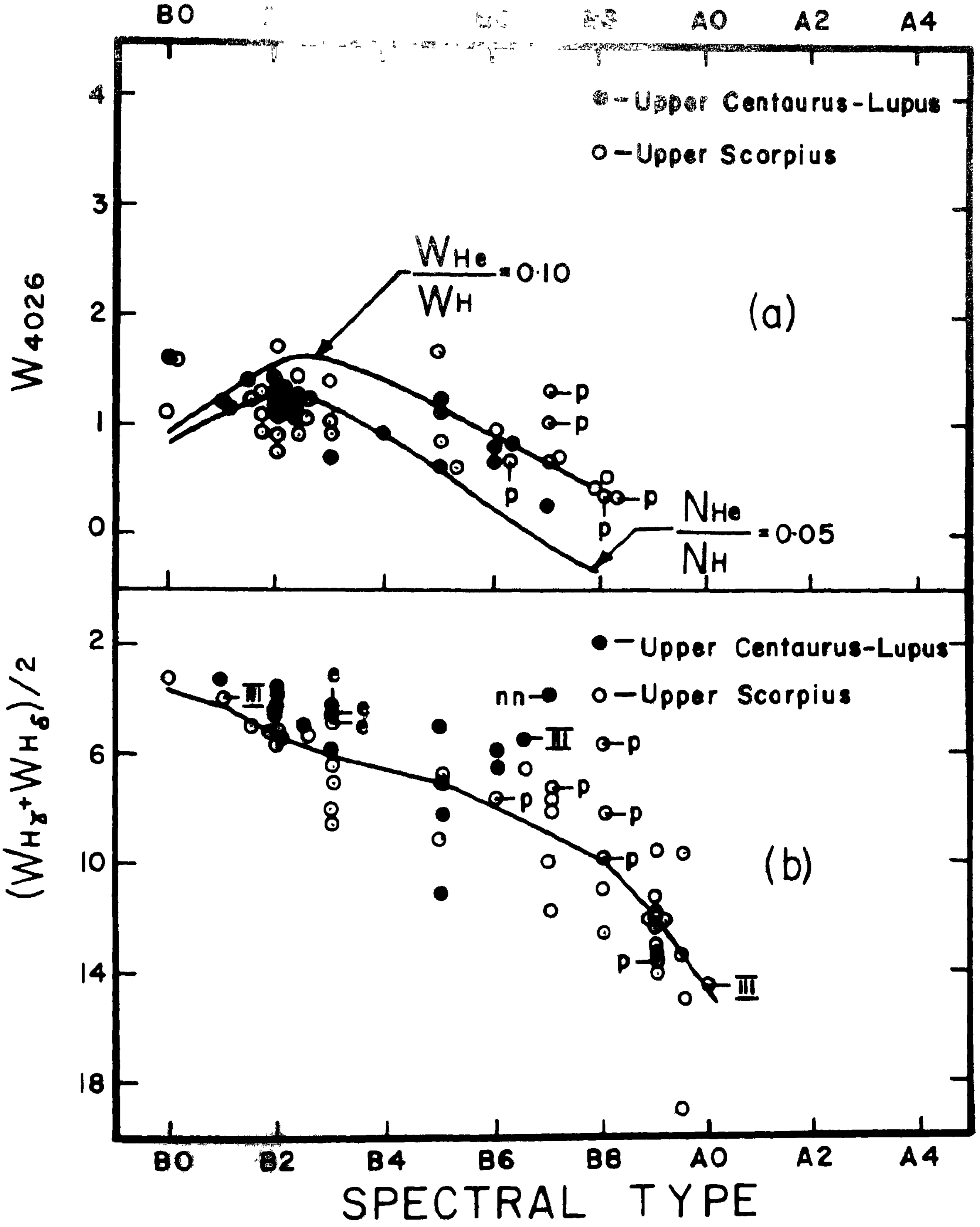
TABLE III-1 continued

Serial Number	HD Number	H							HeI		Mg II
		4340	4101	3970	3889	3835	3798	3770	4026	4471	4481
101.	149438	3.5	3.0	-	-	-	-	-	1.1	1.8	-
102.	151346	5.4	5.6	7.9	5.4	-	-	-	-	1.0	-
103.	151985	4.4	4.6	3.7	3.4	4.1	2.8	2.16	0.68	1.38	-
104.	157056	4.8	3.8	3.2	4.1	3.6	3.6	2.12	1.13	1.78	-

FIGURE 3 - 4

a. Equivalent width of 4026Å in the members of the Scorpio-Centaurus association shown as a function of spectral type. The expected relationship for two helium abundances for log g = 4.0 based on Morton model atmospheres are shown as full lines.

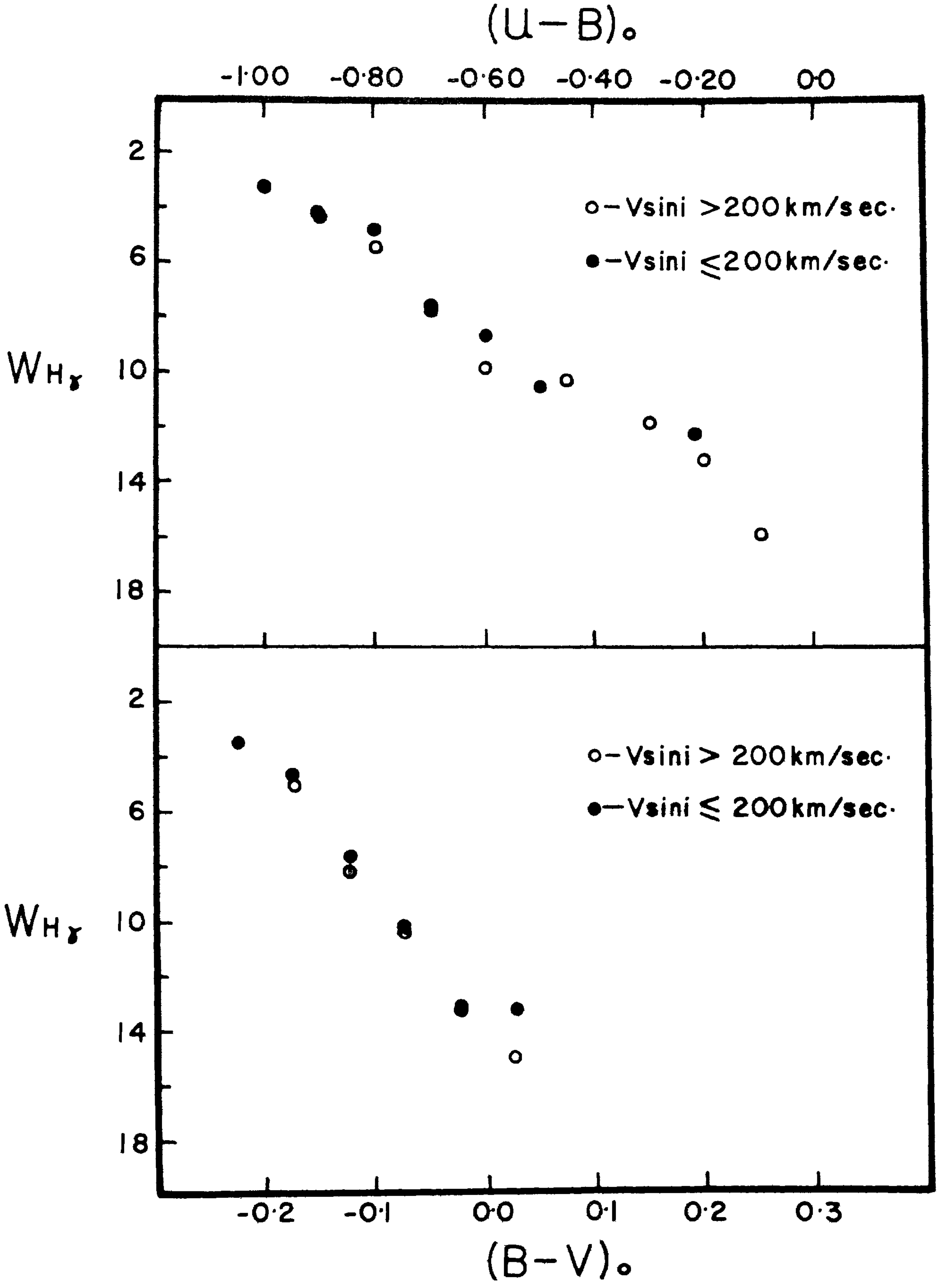
b. The mean of the equivalent width of H_γ and H_δ is plotted as a function of spectral type. The full line corresponds to the recent calibration of H_γ equivalent width by Balona and Crampton (1974).



B0
A0
A2
A4
● — Upper Centaurus-Lupus
○ — Upper Scorpius
W_He / W_H = 0·10
(a)
N_He / N_H = 0·05
W4026
4
3
2
1
0
● — Upper Centaurus-Lupus
○ — Upper Scorpius
(b)
(WHγ + WHδ)/2
2
6
10
14
18
B0
B2
B4
B6
B8
A0
A2
A4
SPECTRAL TYPE

FIGURE 3 - 5

The H_γ-colour relation of slow and fast rotators. Effects of rotation on the derived equivalent widths are seen to be negligible.



(U−B)∘
-1·00
-0·80
-0·60
-0·40
-0·20
0·0
2
6
10
14
18
WHγ
○−Vsini >200km/sec·
●−Vsini ≤200km/sec·
○−Vsini > 200km/sec·
●−Vsini ≤ 200km/sec·
-0·2
-0·1
0·0
0·1
0·2
0·3
(B−V)∘

for objects in the two sub-groups are normal (vide Chapter IV). The actual abundance of helium from 3 stars in Upper Centaurus Lupus is 0.105 ± 0.001 and from 11 stars in Upper Scorpius is 0.095 ± 0.004 by number. The differences are not significant. Even if it were to be, its in the opposite sence from Glaspey's experience. Atleast part of the differences is accounted for by the high strengths of the hydrogen lines of the Upper Scorpius members. The remaining differences are probably due to anomolous reddening in the Upper Scorpius region. UBV observations of Moreno and Moreno (1968) do indicate that the value of R may be as high as 6.0 in the Upper Scorpius region.

The equivalent width of HeI 4026 is plotted against spectral type in Figure 3-4a. The expected relationship between the equivalent width and spectral types for a helium abundance of $N_{He}/N_H = 0.10$ and 0.05 for $\log g = 4.0$ based on Mortons model atmospheres is shown as full line. The stars of the Upper Centaurus-Lupus group are plotted as filled circles and the Upper Scorpius members as open circles. It is evident from this figure that as long as we assume that the mean gravity of the two sub-groups is the same, there is no helium abundance difference between the two sub-groups. This qualitative analysis is further strenthened by analysis of high dispersion material of a few bright objects presented in Chapter IV.

In order to find the "aspect effect" of rotation, I have plotted in Figure-3-5 the averaged value of $W_{H\gamma}$ and $W_{H\delta}$ for stars with vsini < 200 km/sec and stars with vsini > 200 km/sec. against $(B-V)_0$ and $(U-B)_0$. The $(B-V)_0$, $(U-B)_0$ values for these objects were taken from the Moreno and Moreno (1968). The expected effect of high rotation is to decrease the Balmer line intensities and increase the colours. No such effect is found in the diagram indicating that the effect are smaller than the errors of observation. These are in accordance with the results of Petrie (1965). Any such differences introduced by rotation will not alter the results derived from employing hydrogen line equivalent widths. Thus, the difference in H-line strengths between the two sub-groups is real and the distance modulus derived from the

FIGURE 3 - 6

The relationship between equivalent widths of higher and lower Balmer series as determined in this study.

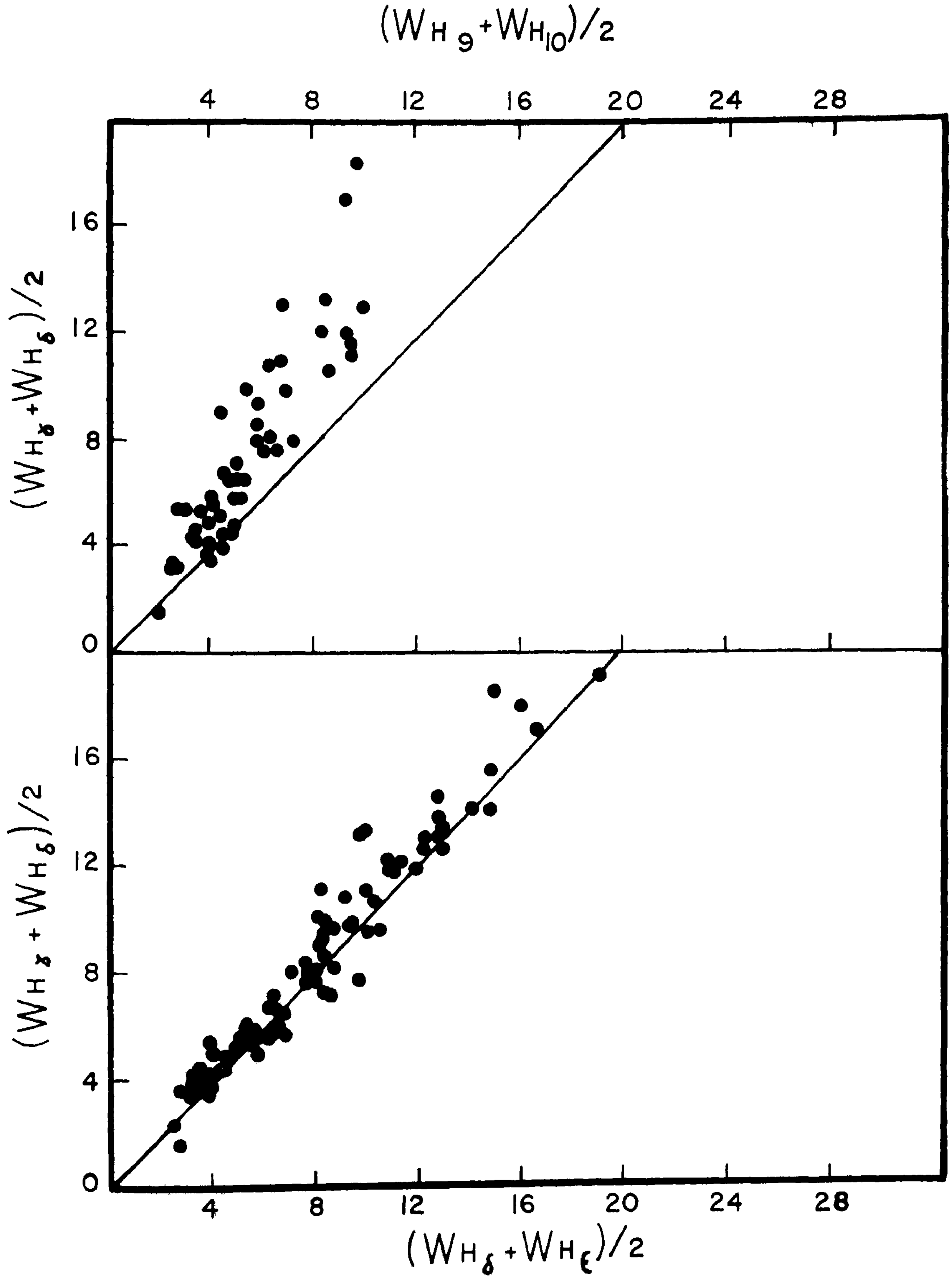
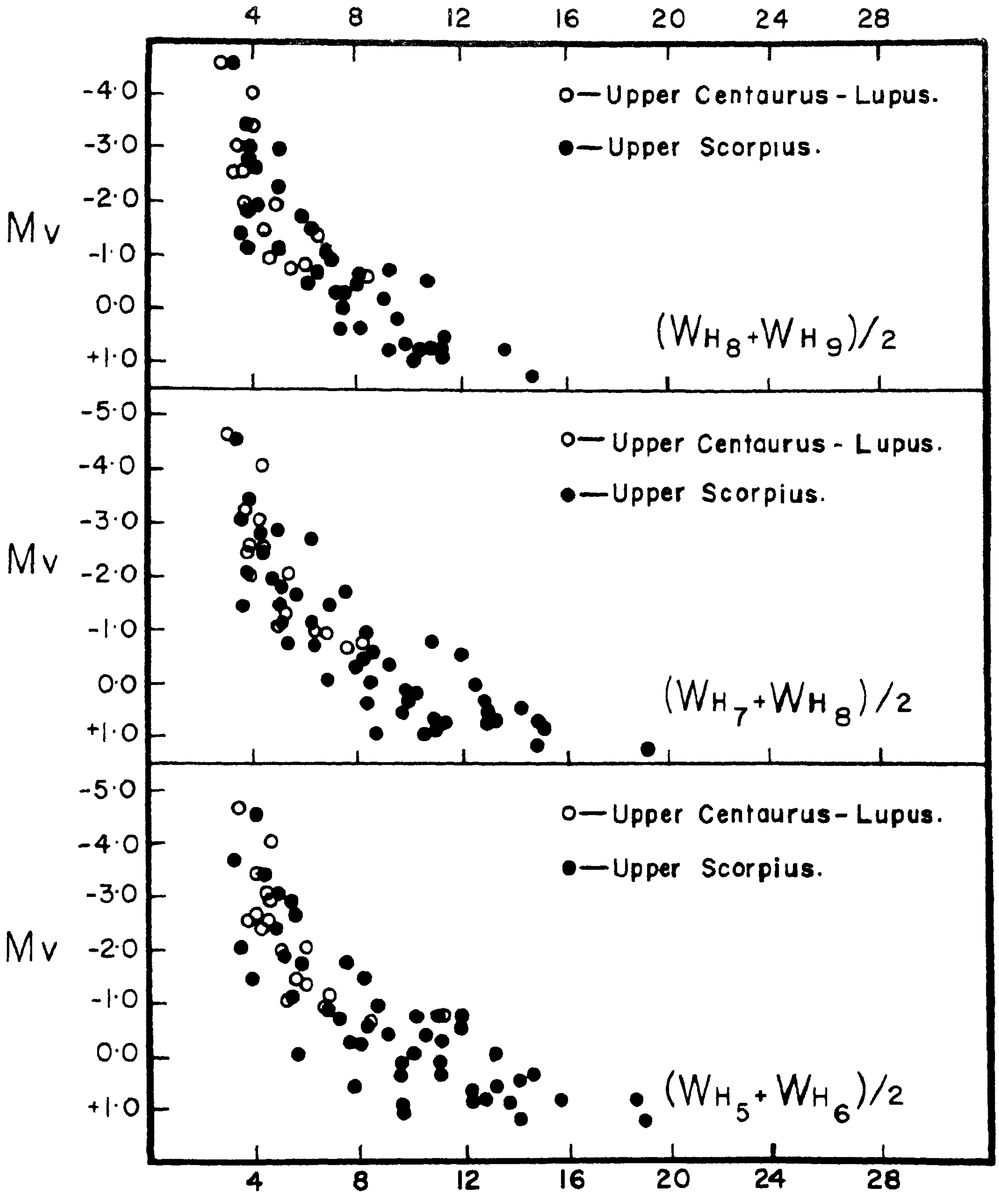

(WH9 + WH10)/2
4
8
12
16
20
24
28
16
12
8
4
0
(WHγ + WHδ)/2
16
12
8
4
0
(WHγ + WHδ)/2
4
8
12
16
20
24
28
(WHδ + WHε)/2

FIGURE 3 - 7

The absolute magnitude, equivalent width relationship for different Balmer lines. The absolute magnitudes used are those of Bertian.


4
8
12
16
20
24
28
Mv
-4·0
-3·0
-2·0
-1·0
0·0
+1·0
o— Upper Centaurus - Lupus.
●— Upper Scorpius.
(WH8+WH9)/2
Mv
-5·0
-4·0
-3·0
-2·0
-1·0
0·0
+1·0
o— Upper Centaurus - Lupus.
●— Upper Scorpius.
(WH7+WH8)/2
Mv
-5·0
-4·0
-3·0
-2·0
-1·0
0·0
+1·0
o— Upper Centaurus - Lupus.
●— Upper Scorpius.
(WH5+WH6)/2
4
8
12
16
20
24
28

H_γ equivalent widths are not in any way affected by the rotational velocities.of the members of the association.

And finally in order to assess the suitability of the higher members of the Balmer series for luminosity measures, I have plotted in Figure 3-6 the mean equivalent width of H_γ and H_δ against mean values of $W_{H_\delta} + W_{H_\epsilon}$ and $W_{H_9} + W_{H_{10}}$. As one goes to higher members the range in equivalent width diminishes as is to be expected when the Balmer decrement is operative. In Figure 3-7 three sets of equivalent width measures for the same stars are plotted against their respective visual absolute magnitudes. These are the mean equivalent width of the combinations, $H_5 + H_6$, $H_7 + H_8$ and $H_8 + H_9$. In going to the later members of the Balmer series one seeks an advantage of increasing sensitivity of the profile to Stark broadening. The effect seems to be offset by the decreasing total equivalent width of the higher members. Hence there seems to be little to gain by going beyond H_6 in any such effort.

CHAPTER IV

HELIUM ABUNDANCE DETERMINATIONS

4.1 The Helium Problem The determination of the helium content in the galaxy has manyfold objectives. The primeval He content has a bearing on cosmological models. The variation of chemical composition as a function of position in the galaxy gives us an idea of the chemical enrichment of the galaxy and the history of stellar nucleosynthesis.

If the proponents of the big-bang cosmology are correct, the primeval He content from which the galaxies have formed should have an helium content of 27% by mass. The helium produced inside the stars by conversion of hydrogen cannot be brought out by the presently understood stellar structure theories except probably by supernova explosions. The present results broadly indicate that $N_{He}/N_H = 0.1 \pm 0.02$ by number in support of the primeval fireball cosmological model. The observed 3°K background radiation seems to support such a model.

However, the observations indicate sizable fluctuations in the derived helium abundances. Many investigators have obtained a helium abundance significantly lower than 10% for quasi-stellar objects. Peimbert and Spinrad (1970) from studies of H II regions in four galaxies find a value of $N_{He}/N_H = 0.1 \pm 0.01$ while Churchwell (1970) obtains values ranging from 0.062 for W3 to 0.086 for NGC 6357. Other determinations of the helium abundance in extragalactic objects are by Aller and Faulkner (1962), Johnson (1959), Mathis (1965), Schmidt (1962) and others. The helium abundances derived by them are all close to 0.1 by number.

Certain population II stars and horizontal-branch stars in globular clusters have abnormally low helium abundances while hot normal O and B stars and the interstellar medium indicate a helium abundance of 0.1 ± 0.02 by number. Amongst the hot population II stars, there are two groups of objects with considerably low helium abundances. These are firstly the weak-line field stars (type BW) and their analogues on the horizontal branch of globular clusters that have normal gravities and low helium abundance. A second group consists of the sub-dwarf B-stars with low helium abundances. (Danziger 1970). There are a few population

II objects which have helium abundances close to those obtained from pupulation I objects and the interstellar matter. One interesting example is the O-star studied by Strom and Strom (1970) in the metal-poor globular cluster M3. The chemical composition of this object resembles the normal population I objects.

Before these quoted variations in the helium abundance are taken seriously, one should take into consideration the nature of observing techniques, data reduction and the theories used in deriving these abundances. For example, the initial helium abundance derived for the Sun is still controversial.. With a neutrino flux of $3x10^{-36}$ neutrinos/sec./^{37}Cl nucleus given by Davis et.al.(1968), Bahcall et.al. (1968) derive an initial helium abundance 0.07 by number. This has been questioned by Iben (1968). He suggests that the present heavy element abundance parameter must be considered a free parameter. This leads to an upper limit of 0.05 consistent with the neutrino flux derived by Davis et.al. From a discussion of the observed abundances in solar cosmic rays, Lambert (1967) derives a value of N_{He}/N_H=0.05 while Hundhausen et.al. (1967)

from long term monitoring of solar wind derive a value of 0.04. From solar prominence spectra, Unsold (1969) derived a value of 0.16. These values are not only inconsistent amongst themselves but are also so with our present understanding of the physics of the solar interior.

It is probably premature to conclude one way or the other about the origin of the primeval helium content of the universe. Attempts to explain the spatial variation of the helium content have been made by the proponents of the primeval fireball in terms of primordial temperature and density fluctuations in the early universe (Harrison 1968, Silk and Shapiro 1971). These observations are also consistent with the production of helium in explosions of supermassive objects which can also qualitatively explain the 3°K background radiation (Burbidge 1969). These problems are discussed in detail in the reviews by Tayler (1967). Burbidge (1969) and Danziger (1970). Here we shall restrict ourselves to the spectroscopic determination of the helium abundance from early type stars.

4.2 Some remarks regarding He abundance determination

The presence of well developed HeI lines in the spectrum of B-stars is a well known feature. These lines provide an important source of information regarding the abundance of helium, the most abundant element, other than hydrogen, in the Universe. Progress in utilizing the helium spectrum has been hampered by the inadequacy of broadening theories. Only recently has satisfactory progress been made in this direction. During the past few years good theoretical descriptions of the HeI lines with overlapping forbidden components have appeared (Griem 1968, Gieske and Griem 1969, Barnard, Cooper and Shamey 1969, Barnard Cooper and Smith 1974). These developments have largely improved the comparison between theory and observations, though inadequacies in the broadening theories are still present (eg: 4921Å). Such discrepancies that are present are matters of detail in fitting the observed forbidden components and as such we may safely conclude that reliable helium abundances can be obtained from observations of B-star spectra today. These developments have taken us a long way towards understanding B-star spectra since the time Struve (1928, 1931) pointed out the singlet-triplet anomaly.

In order to derive the helium abundance of a star, an accurate knowledge of the temperature and gravity of the object is required. The present methodology is to derive these quantitites from various combinations of the observable parameters of the object and model atmospheres. In deriving a temperature scale, the model atmosphere predictions are intimately tied down to the continuum flux and the Balmer jump observed in normal stars (the Balmer jump is extremely sensitive to temperature in the B-star range). The derived temperature of a star depends finally on the temperature scale used, [Morton and Adams (1968), Wolf, Kuhi and Hayes (1968), Hyland (1969) and Schild, Peterson and Oke (1971)] and the absolute calibration of Vega, [Hayes (1970), Oke and Schild (1970)] to which all continuum flux measurements are referred to. The differences among the various temperature scales given above are small except at spectral types B8 and later where the Schild, Peterson and Oke (1971), hereinafter referred to as SPO, scales are substantially hotter than the others.

The hydrogen line profiles, which are extremely sensitive to Stark broadening, together with the derived temperatures are utilised to derive the gravities. The model atmospheres together with the hydrogen line broadening theories are used to predict the hydrogen line profiles for various temperatures and gravities. A comparison of the observed line profiles of hydrogen at the appropriate temperatures with the predicted line profiles gives us the gravity of the object. This again depends on the hydrogen line broadening theory utilised in the calculations. The Edmond, Schluter and Wells (1967), herein afterwards referred to as ESW, and the Griem (1967) theory of hydrogen Stark broadening give results systematically different by $\Delta \log g = 0.2$, in the sense that ESW theories predict higher gravities.

The presently available observations do not resolve this controversy. In their analysis of τ Scorpii, Hardorp and Scholz (1970) could not decide between the two theories while Olson (1968) finds that the gravities derived from light and radial velocity solutions of eclipsing binary systems are more consistent with the ESW theory. However SPO find, with their new temperature calibration, which is substantially hotter at A0 than other temperature scales, that the observed hydrogen line profiles by Peterson (1968) of Vega are in excellent agreement with those obtained by using Griem's theory. The mean gravity derived by Peterson and Shipman (1973) for NGC 2264 (log g=4.42) with Griem's line broadening theory is in better agreement with the mean gravity of the zero main sequence (log g=4.4), than that given by the ESW theory. The ESW theory leads to a mean gravity of 4.55 for the 5 stars observed by them.

With the derived temperatures and gravities, the line profiles and equivalent widths of the observed helium lines can be used to derive the helium abundances. Model atmospheres have been constructed for appropriate values of temperatures and gravities for a grid of helium abundances. A comparison of the observed profile and equivalent widths, with those interpolated from the grid of profiles and equivalent widths predicted by models, enables one to derive the actual helium abundance in the star. The entire procedure depends on the quality of observations, the temperature scales used, the line broadening theories used and the model atmospheres employed for the computations.

4.3 <u>Observations at high dispersion of some stars in the Scorpio-Centaurus association</u> In all, I obtained eleven good spectra of five bright members of the Scorpio-Centaurus association 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 9cm x 12cm plate in the focal plane of a 25 cm. camera the entire spectrum from 3800-6600A. The dispersion at 4026A is 4.8A/mm (55th order) and 8A/mm at 6600A. The details of the spectra are given in Table IV-1. The various columns are self explanatory. The calibrations were provided by the same rotating sector prism spectrograph combination utilized for the low dispersion studies. The calibration exposure durations were comparable to those employed on the star. Two calibration spectra of different density ranges were obtained to ensure well defined calibration curves from 4000-4600Å. The star exposure together with the calibration plates were developed simultaneously for four minutes in D19 at 68°F. All plates were traced with a Zeiss microphotometer operating in the density mode. Wavelength regions from 3900-4100A, 4100-4300A, and 4300-4500Å were analysed with different calibration

TABLE IV - 1a

Plate No.	Star	Exposure Time		Date	Plate (Kind)	Remarks
		h	m			
36	^{2}SCO	4	30	14-6-74	IIa-O baked.	
44a		2	05	19-6-74	IIa-O baked.	Slightly overexposed
35	K Cen	2	50	17-6-74	IIa-O baked.	
31		2	50	8-6-74	103a-D	
29		3	00	7-6-74	103a-D	Slightly underexposed
21	SCO	2	20	1-6-74	103a-D	Slightly overexposed
28		2	54	6-6-74	103a-D	Slightly overexposed
42a	SCO	0	46	18-6-74	IIa-O baked.	Slightly overexposed
		0	26	18-6-74	IIa-O baked.	
40a	Cen	0	37	18-6-74	IIa-O baked.	
40b		0	58	18-6-74	IIa-O baked.	Slightly overexposed

curves obtained at 4000 Å, 4200 Å and 4400 Å respectively. 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 center, 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 center.

The inconvenience that exists in fitting continuum curves to echelle spectra are more than offset by the enhanced resolutions available. In the case of helium lines, the continuum was defined at ± 12 Å from the line center and a similar procedure as described above followed. The lines HeI 4388 and 4471A fall in regions where the density is rising fast, while HeI 4026, H_γ and H_δ 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 τ Sco and κ Cen by Norris (1971) show excellent agreement to within 1% of the continuum.

4.4 Temperatures, Gravities and Helium abundance

I have estimated temperatures and gravities from the published UBV data and the hydrogen line profiles obtained in this study from the echellespectra. The reddening slope was assumed to be 0.72 and the reddening independent parameter Q was derived from

$$Q = (U-B) - 0.72\ (B-V)$$

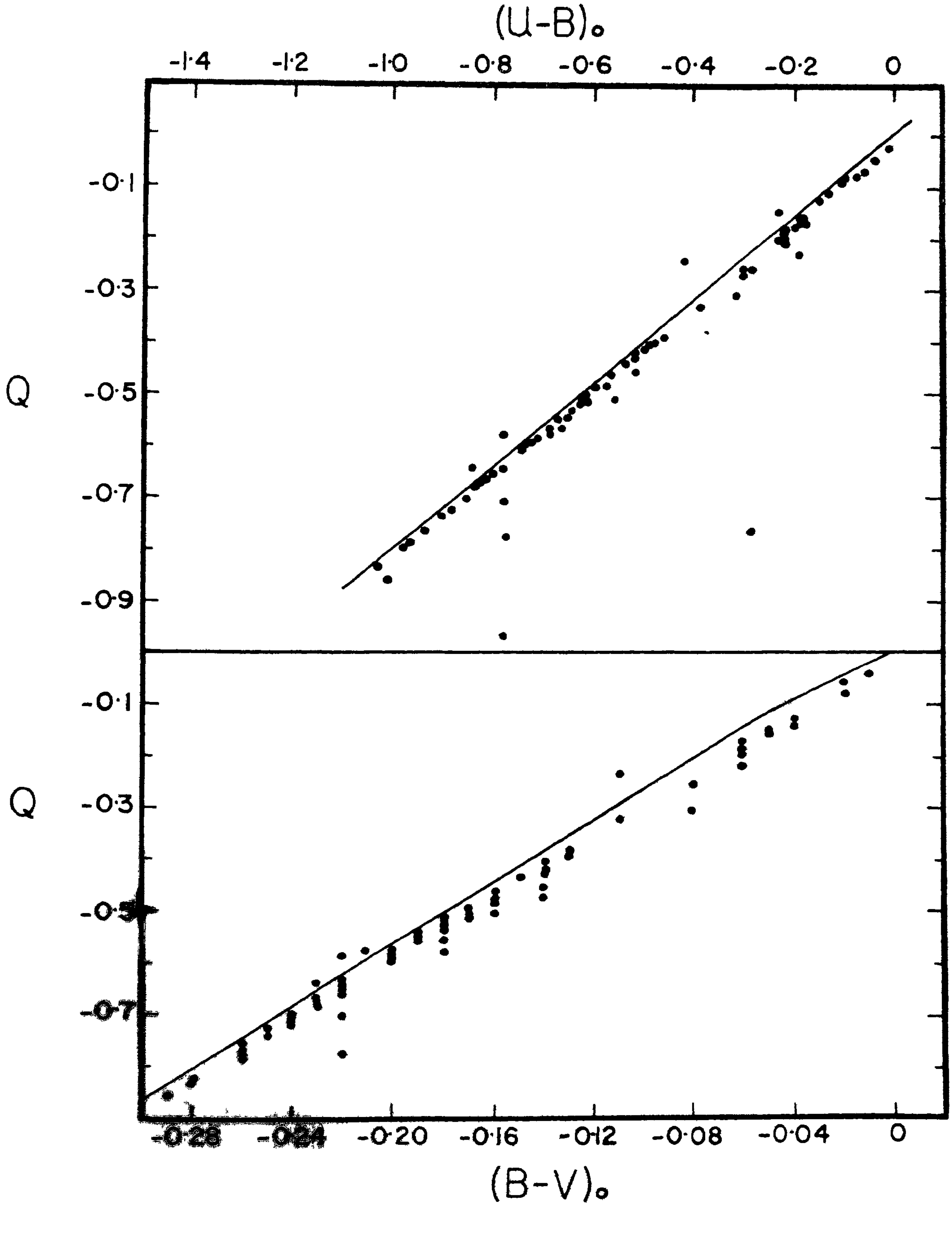
The UBV values of the five stars discussed in this study were taken from Moreno and Moreno (1968). The Q, θ_e relationship used is that due to Schild, Peterson and Oke (1971). This relationship is given by

$$\theta_e = 0.378\ Q + 0.500$$

The temperatures derived with the above two equations were corrected in θ_e by +0.01 since there seems to be a systematic error of +0.025 in the derived Q when the (U-B), (B-V) values of Moreno and Moreno are used. I have plotted in Figure IV-1, the $(B-V)_0$ and $(U-B)_0$ values of the Scorpio-Centaurus members against Q. The $(B-V)_0$, $(U-B)_0$ values are those obtained by Moreno and Moreno. They have used a value of R, the ratio of total extinction to color extinction, equal to 3 in deriving the unreddened colors. The Q, $(B-V)_0$ and Q, $(U-B)_0$ relationships given by SPO are plotted as full lines. All the observed points fall systematically below the relationship given by SPO. Since the SPO relationship fits the UBV observations of Hardie and Crauford (1961), I 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-HC) = -0.01 ± 0.007 in B-V and -0.01 ± 0.009 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, I decided to use the values derived at Chile after taking into account the systematic error.

FIGURE 4 - 1

The reddening independent parameter Q as a function of $(B-V)_0$ and $(U-B)_0$. The $(B-V)_0$ and $(U-B)_0$ values are from Moreno and Moreno (1968). The SPO relationship is shown by the solid line.



(U-B)₀
-1·4
-1·2
-1·0
-0·8
-0·6
-0·4
-0·2
0
Q
-0·1
-0·3
-0·5
-0·7
-0·9
Q
-0·1
-0·3
-0·5
-0·7
-0·28
-0·24
-0·20
-0·16
-0·12
-0·08
-0·04
0
(B-V)₀

The observed H_γ line profiles, given in Table IV-1 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 percent absorption respectively of the H_γ 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, I used the resultant hydrogen line profile given in a fine grid form by Norris (1971).

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 SPO temperature scale used in this investigation, I have applied a correction of -0.1 to the derived log g values. No corrections due to the slightly higher helium abundance of $N_{He}/N_H = 0.11$ used by Norris (1971) in his calculations, was 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 θ_e and log g for the five stars studied here are given in Table IV-3. 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 $\Delta \log g = \pm 0.1$ and $\Delta\theta_e = \pm 0.01$.

The equivalent widths derived from the observed helium and hydrogen line profiles were calculated using the Simpson quadrature formula. The helium lines available for this study are, λλ 4009, 4026, 4143, 4388 and 4471. HeI 4121 was found to be seriously blended with O II lines and therefore I have not made use of it here. HeI 4438 was not measured. The derived equivalent widths of the helium lines together with those of H_γ and H_δ are given in Table IV-2.

The equivalent widths were directly interpolated in Norris' (1971) tables which employed Morton model atmospheres and the calculation of Griem et.al. (1962) for the lines 4438A° and 4713A°, the data of Griem (1968) for 4471 and of Gieske and Griem (1969) for 4026A, 4143A° and 4388A°. The derived helium abundances for the individual lines are tabulated in Table IV-3. The last column gives the mean helium abundance for each star from a logarithmic summation of all lines.

4.5 <u>Results and Discussion</u> The mean helium abundance for the five stars studied here is 0.096 ± 0.004 by number. This can be compared with the mean helium abundance of 0.094 ± 0.005 derived by Peterson and Shipman (1973) from a study of 13 stars in the Upper Scorpius Complex. I have made a logarithmic summation of the individual abundances given by them after converting them to N_{He}/N_H. The value quoted by them is 0.097 ± 0.005 where the abundance is defined such that $N_{He} + N_H = 1$ To find if any helium abundance difference exists between the Upper Centaurus Lupus members and the Upper Scorpius members, I have used along with the helium abundances derived in this study those obtained by Norris' (1971) as well as Peterson and Shipman (1973) for the members of the Scorpio-Centaurus association. The Beta Cephei stars included in Norris' list were left out. To express the Mt Stromlo observations on the present scale, the equivalent widths of the 5 He lines utilised in this study were taken from their list, and with temperatures derived by the Q method and log g determined from their hydrogen line profiles corrected by +0.1, the helium abundances were derived afresh for the 6 stars they studied in the Sco-Cen association.

The mean helium abundance from all these data is $N_{He}/N_H = 0.098 \pm 0.004$. The mean helium abundance from 10 Upper Scorpius members alone is 0.096 ± 0.005 while that from the 3 Upper Centaurus-Lupus members is 0.105 ± 0.001.

In the above calculations, four stars in Peterson's 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 in the previous paragraph do not change significantly.

It appears that there is no significant difference in the helium content of the two major sub-groups of this association. The hydrogen line strength differences found in Chapter 3 must therefore be explained in terms of evolutionary effects. There is no difference in the rotational velocities between the two sub-groups except that the B7-B9 stars of Upper Scorpius rotate faster than the field stars. However, the Upper Centaurus region does not contain any late B-stars. There is only one B7 star in the list of Peterson and Shipman which does not in any way alter the above conclusions.

The study by Watson (1972) of β Cephei stars include 4 stars from Scorpio-Centaurus association, two of which belong to Upper Scorpius, one to Upper Centaurus-Lupus and one in the Lower Centaurus-Crux sub-group.

The metal abundances derived for α Lup in Upper Centaurus-Lupus region is slightly lower compared to the other stars. However the differences are probably not significant to evoke any metal deficiency in the Upper Centaurus Lupus members.

Thus it appears that the two sub-groups, are nearly similar as far as their rotational velocity distribution and helium abundances are concerned. The observations of Glaspey from narrow band photometry that the Upper Scorpius members are peculiar cannot be explained from the present spectrographic observations. Perhaps, there may be differences in the ultraviolet fluxes received from these two groups of stars, which may offer some clue.

TABLE IV-1

Hydrogen Line Profiles

Star	H_γ ($\Delta\lambda$ Å) 4340							
	0	1	2	4	6	8	10	15
Cen	0.380	0.590	0.666	0.788	0.874	0.921	0.949	0.992
Sco	0.460	0.594	0.686	0.808	0.870	0.904	0.928	0.982
Sco	0.520	0.638	0.733	0.840	0.897	0.835	0.965	0.996
Sco	0.585	0.607	0.687	0.843	0.907	0.940	0.965	0.995
Cen	0.540	0.580	0.647	0.780	0.875	0.922	0.947	0.993

Star	H_δ ($\Delta\lambda$ Å) 4101							
	0	1	2	4	6	8	10	15
Cen	0.415	0.560	0.658	0.809	0.892	0.943	0.969	0.996
Sco	0.455	0.540	0.690	0.840	0.900	0.945	0.973	0.990
Sco	0.477	0.624	0.731	0.838	0.898	0.940	0.973	0.990
Sco	0.575	0.619	0.700	0.825	0.881	0.923	0.955	0.990
Cen	0.485	0.555	0.679	0.825	0.900	0.942	0.966	0.987

TABLE IV-2

Star	Equivalent Widths (Å)							
	4340	4101	4009	4026	4143	4387	4438	4471
Cen	3.64	4.47	0.660	1.470	0.795	0.985	0.154	1.330
Sco	3.89	4.74	0.638	1.380	0.729	0.862	--	1.415
Sco	3.55	3.64	0.688	1.024	0.411	0.599	--	0.996
Sco	3.90	4.11	0.567	1.262	0.771	0.620	--	1.293
Cen	3.68	4.77	0.656	1.496	0.765	0.711	--	1.720

TABLE IV-3

Effective Temperatures, Gravities and Helium Abundances

Star		log g	(He)					(He) Mean
			4009	4026	4143	4387	4471	
Cen	0.261	3.70	0.086	0.100	0.116	0.204	0.096	0.114
Sco	0.238	3.78	0.084	0.091	0.097	0.080	0.101	0.090
Sco	0.186	4.10	0.153	0.066	0.045	0.100	0.070	0.080
Sco	0.196	4.15	0.078	0.098	0.126	0.085	0.098	0.096
Cen	0.222	4.05	0.081	0.093	0.108	0.090	0.156	0.103

Mean helium abundance = 0.096±0.004

CHAPTER V

HELIUM LINE PROFILES: COMPARISON WITH NON-LTE MODEL ATMOSPHERES

5.1 Introduction The analysis of helium line strengths and the effect of departures from local thermodynamical equilibrium (LTE) have been a subject of controversy since the time Struve (1928, 1931) pointed the so called 'Helium singlet-triplet' anomaly. As early as 1939, Goldberg (1939) argued that the singlet-triplet behaviour can easily be explained by differing saturation effects without invoking departures from LTE. However, the validity of his treatment continued to be questioned, till improved helium line broadening theories and model atmospheres became available. It was shown by Norris' (1970), and Leckrone (1971) that in the blue violet region of the spectrum, the singlet triplet anomaly can be fully explained within the frame work of LTE. Further, the analysis of Norris' (1971), Leckrone (1971), O'Mara and Simpson (1972) showed that departures from LTE have negligible effects in the blue violet region of the spectrum and becomes dominant only for 5876Å and 6678Å.

Also that it is not possible to match simultaneously an observed line core and the line wings within the LTE frame work and that the observed line cores are systematically deeper and broader than that predicted by LTE calculations. In addition LTE analysis does not satisfactorily predict the observed forbidden components, especially for 4471A and 4922A.

These observations were further strengthened by the calculations of Johnson and Poland (1969) and Poland (1970) who showed that the LTE calculations satisfactorily represent the wings and the forbidden components while non-LTE is important only in the line core atleast for lines in the blue violet region of the spectrum. The significance of non-LTE was reopened again by Hearn (1970). Based on his calculations, Underhill and Hearn (1971), Snijders and Underhill (1971) criticised the work of Johnson and Poland (1969) and Poland (1970) and insisted that departures from LTE should have significant effects in the analysis of HeI lines in the B-star spectra. These criticisms have been answered by Poland and Skumanich (1971) and Poland (1972).

The controversy remained till the calculations of Auer and Mihalas (1973) became available for a wide range of temperatures and gravities which essentially confirm the conclusions reached earlier by Johnson and Poland (1969) and Poland (1970). The main conclusions from the recent work of Mihalas and his co-workers are:

(1) Departures from LTE, in B-star spectral range have little effect on the equivalent widths in the blue violet region of the spectrum. The non-LTE effects become larger at longward wavelengths and is extremely significant for lines such as 5876Å and 6678Å. This explains the derived LTE abundances as a function of λ first noted by Norris (1971).

(2) The singlet-triplet ratio is not changed for lines in the blue violet region by significant amounts while a ratio like 5876/6678 can be satisfactorily represented only if departures from LTE are taken into account.

(3) Excepting near spectral type B0 and B1, the core and the wings can simultaneously be represented only

if non LTE effects are taken into account.

(4) The effects of departures from LTE upon equivalent widths of a given line often are larger when the line is weak than when it is strong.

Though extremely satisfactory representation could be obtained by Auer and Mihalas with published line profiles, they still encountered difficulties in representing the forbidden components of diffuse lines especially $\lambda\lambda$ 4471 and 4921 with the available helium line broadening theories. They had employed the line broadening theories of Barnard, Cooper and Shamey (1969) and Shamey (1969) in their calculations and to extrapolate to far line wings they followed the suggestion of Barnard and Cooper (1974). Such difficulties, especially near the forbidden components had already been noticed from laboratory work by Burgess (1970), Burgess and Cairns (1970) and from comparison of theory with observations by Leckrone (1971), Norris (1970, 1971), Snijders and Underhill (1971). In all these works it was found that the existing broadening theories, predicted forbidden components which was too narrow and deep and the line opacity between the forbid and permitted components, too low.

These difficulties have now been overcome, atleast in the case of HeI 4471 with the new quantum mechanical calculations of Barnard Cooper and Smith (1974) of HeI 4471 stark profiles having become available. Computations of HeI 4471 line profile over a wide range of temperatures and gravities (T_e= 15000-27500, log g = 2.5-4.0) have been made by Mihalas et.al. (1974). They have shown that these calculations are in excellent agreement with the presently available observational material.

5.2 Observations and Results High dispersion spectra of κ cen, τ Sco and μ^2 Sco, the three fairly sharp-lined stars in my list were utilised for a comparison of non-LTE and LTE line profiles with observations.

The observations and reduction procedures are described in Chapter IV. The observed line profiles of HeI $\lambda\lambda$ 4026, 4388 and 4471 are listed in table V-1.

Figure 5-2, 5-3 and 5-4 show the observed line profiles (plotted as filled circles) corrected for instrumental profile. The correction 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 DeJager and Neven (1964) was followed to deconvolve the observed profile with the instrumental profile. The instrumental profile, was derived from the iron lines in the Fe-Ne hollow cathode used as a comparison source for the spectra obtained in this study. This is shown in figure 5-1 (not normalised).

If R (λ) is the observed profile, T, the true profile, A the apparutus profile, then

$$R(\lambda) = \int_{-\infty}^{\infty} T(x)\, A(\lambda - x)\, dx \qquad \text{---------------(1)}$$

The unknown function T (λ) is solved from this integral equation in successive steps, with the n^{th} approximation given by

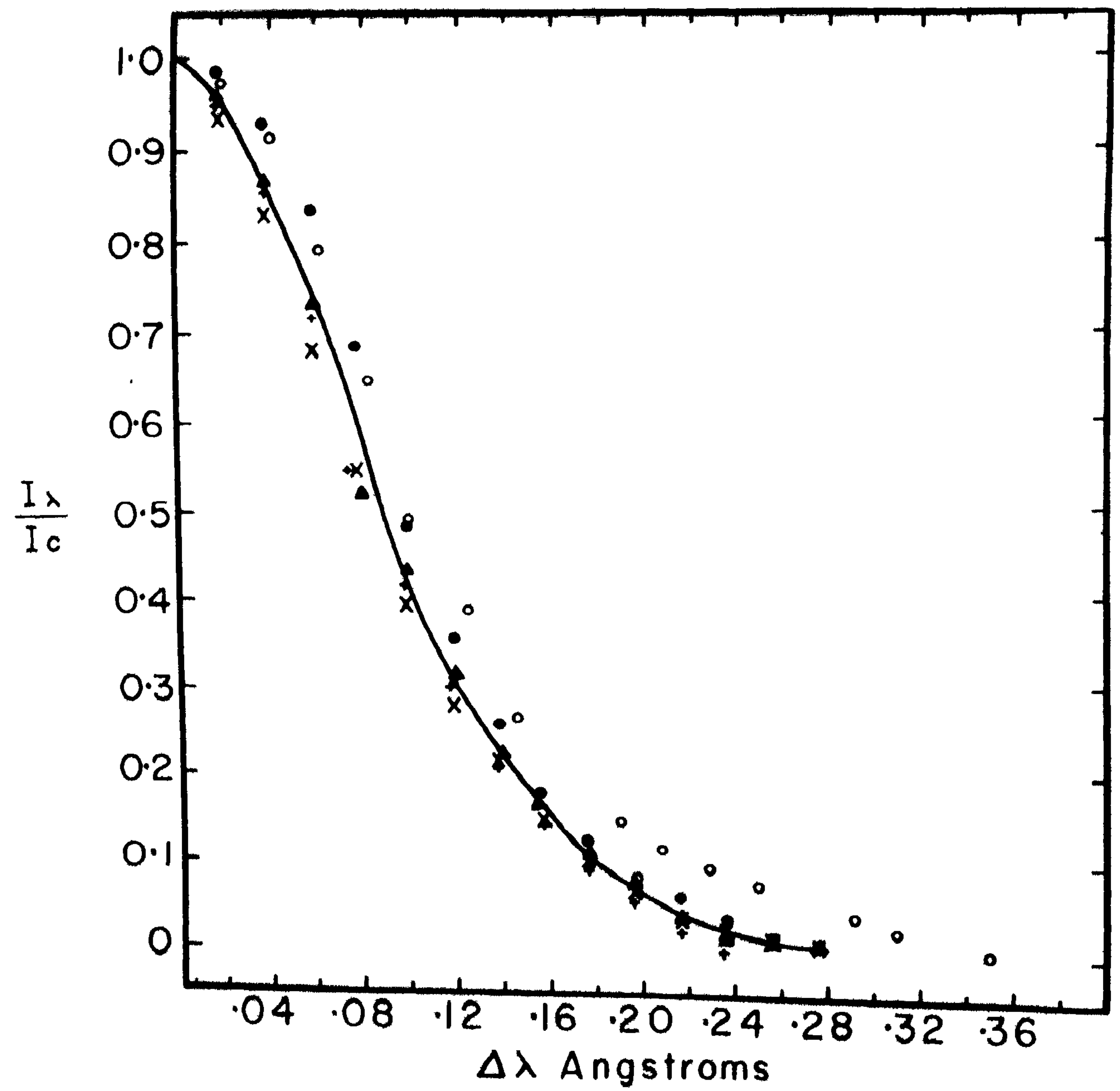
$$T_n(\lambda) = T_{n-1}(\lambda) + R(\lambda) - \int_{-\infty}^{\infty} T_{n-1}(x)\, A(\lambda - x)\, dx \qquad \text{--------------(2)}$$

and with the first approximation being given by

$T_1(\lambda) = R(\lambda)$.

FIGURE 5 - 1

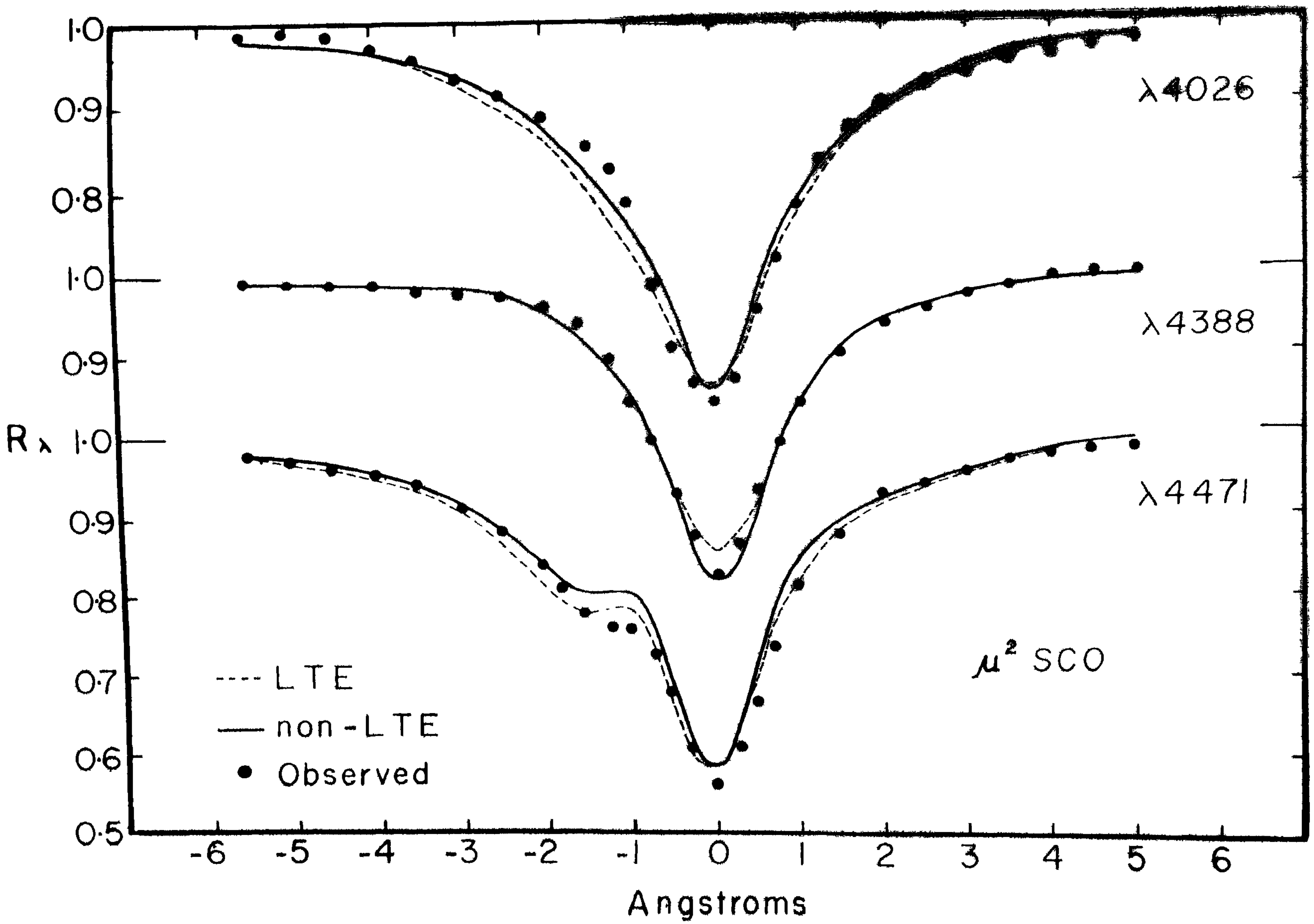
The instrumental profile corresponding to a projected slit width of 33μ employed in this study at high dispersion. Five sharp comparison lines from a Fe-Ne hollow cathode source were utilised to derive the instrumental profile. The final adopted profile is shown by the solid line.



1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
Iλ / Ic
·04
·08
·12
·16
·20
·24
·28
·32
·36
Δλ Angstroms

FIGURE 5 - 2

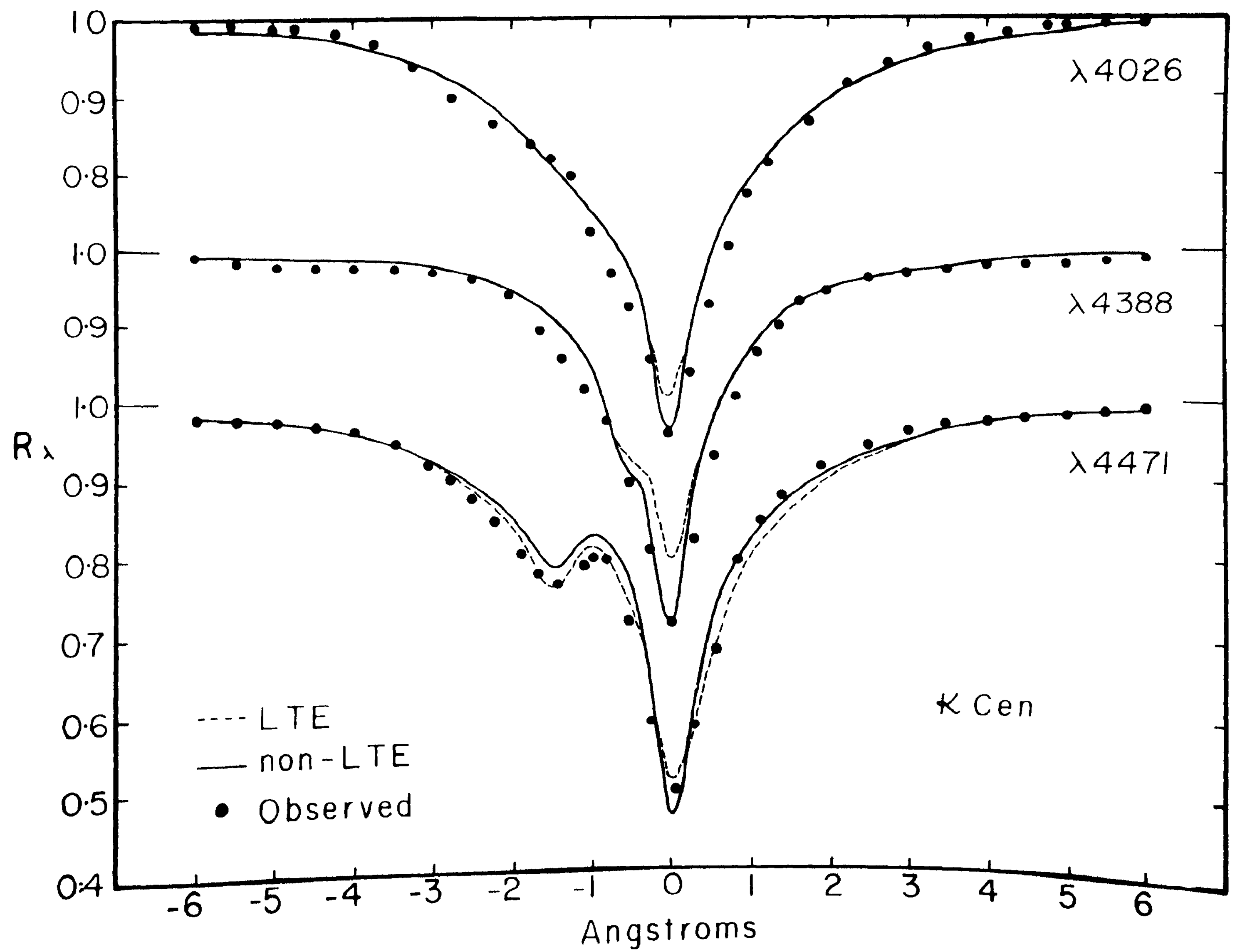
Comparison of the observed and computed profiles for μ^2 Sco. The solid line corresponds to non-LTE models. The dotted line corresponds to LTE models. The profiles correspond to T_e = 22,500, log g = 3.9, v sin i = 40 km/sec. The assumed limb darkening coefficient is 0.4.



λ4026
λ4388
λ4471
μ² SCO
---- LTE
—— non-LTE
● Observed
R λ
1·0
0·9
0·8
1·0
0·9
1·0
0·9
0·8
0·7
0·6
0·5
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6
Angstroms

FIGURE 5 - 3

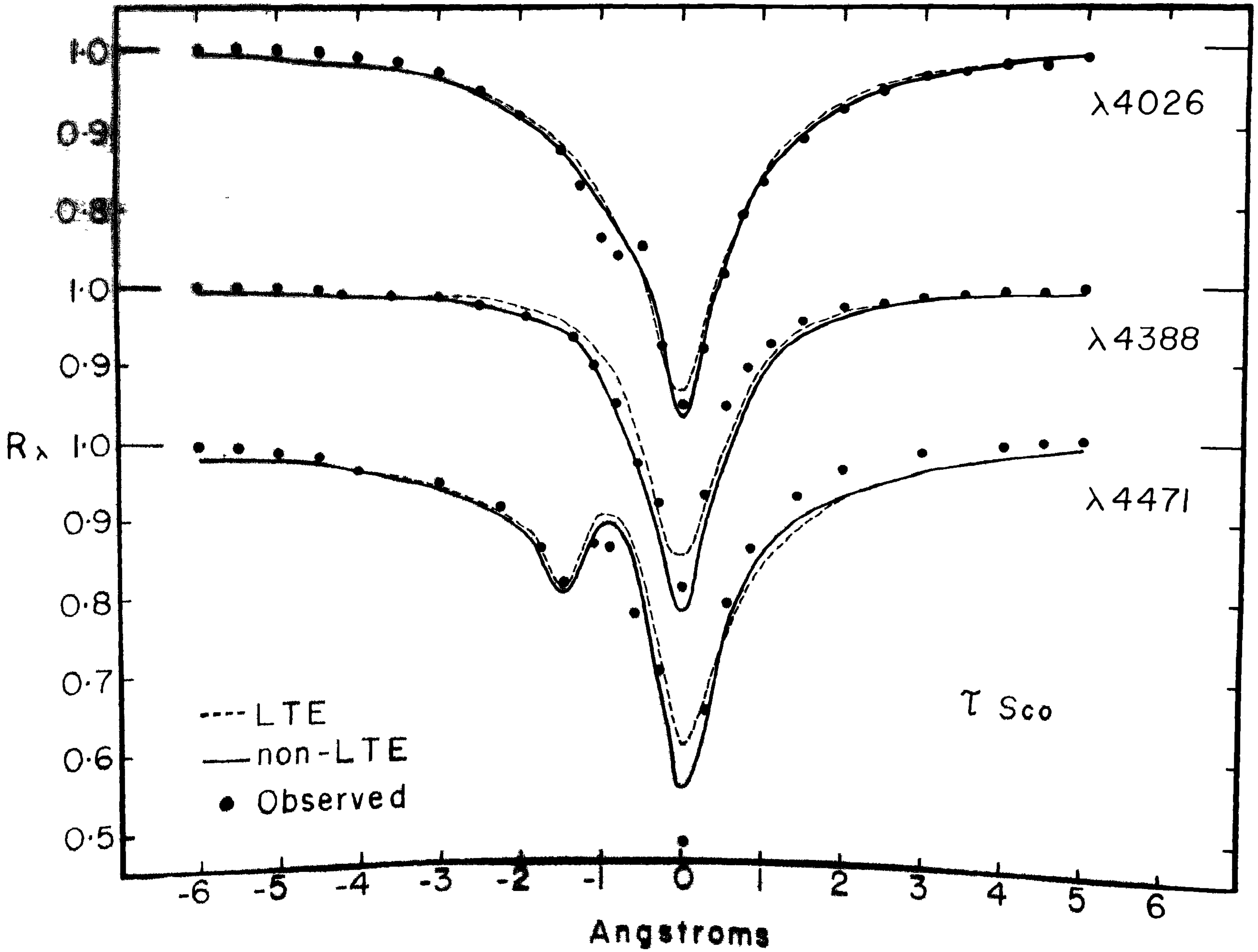
Comparison of the observed and computed profiles for κ Cen. The solid line corresponds to non-LTE models. The dotted line corresponds to LTE models. The profiles correspond to T_e= 22,500 log g = 3.9 v sin i = 15 km/sec. The assumed limb darkening coefficient is 0.4.



λ4026
λ4388
λ4471
κ Cen
LTE
non-LTE
Observed
Rλ
Angstroms

FIGURE 5 - 4

Comparison of the observed and computed profiles for τ Sco. The solid line corresponds to non-LTE models. The dotted line corresponds to LTE models. The profiles correspond to T_e = 30,000 log g = 4.0, v sin i = 15 km/sec. The assumed limb darkening coefficient is 0.4.



λ4026
λ4388
λ4471
τ Sco
R λ
1·0
0·9
0·8
0·7
0·6
0·5
---- LTE
—— non-LTE
• Observed
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6
Angstroms

For the three strong helium lines considered in this study, the series converged within three approximations.

In figures 5-2, 5-3 and 5-4 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 θ_e, log g and vsini with the initial parameters θ_e, log g being given by the values in Table IV-3. In the convolution of the broadening functions with non-LTE and LTE profiles, the value of the limb darkening coefficient was assumed to be 0.4. The final adopted values for the three stars are κ cen (T_e= 22500, log g = 3.9, vsini = 15) τ Sco (T_e = 30000, log g = 4, vsini = 15) and μ^2 Sco (T_e=22500 log g = 3.9, vsini = 40). No attempt was made to find the best fitting LTE profiles for these stars; we have simply shown the LTE profiles given by Auer and Mihalas (1973) and Mihalas et.al. (1974) corresponding to the values of T_e, log g and vsini quoted above.

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 τ Sco for which the earlier calculations of Auer and Mihalas (1972) are used. For HeI 4471, the most recent calculations of Mihalas, Barnard, Cooper and Smith (1974) employing helium stark broadening calculations of Barned, Cooper and Smith (1974) were utilised to fit the observations. However, the temperature range for which these calculations are available extends only upto 27,500° at the hot end. Therefore for τ Sco, for which a temperature of atleast 30,000° is required to fit the observations, I used the earlier work of Auer and Mihalas (1972) employing helium Stark broadening calculations of Barnard, Cooper and Shamey (1969).

<u>K Cen</u> The non-LTE and LTE line profile calculations of Auer and Mihalas (1973) used to fit the observations utilise unblanketted model atmospheres of Mihalas (1972) and ESW hydrogen line broadening theory. Still this does not completely explain the high temperature that was required to fit the helium line profiles. The temperature that was derived in Chapter IV for this

object is 19,300° while the temperature derived from the line profile is 22,500°. The small difference of $\Delta \log g = 0.2$ can be understood in terms of the differences between the two hydrogen line broadening theories. In Chapter IV we had corrected the derived log g values from use of new theories by $\Delta \log g = -0.1$.

The difference in unblanketed models of Mihalas and the blanketted models of Morton his co-workers at this temperature is about $\Delta T = 1000°$. While the actual difference in temperature derived in Chapter IV and that used to fit the profiles here is 3200°. One possibility is that the line profile of HeI 4388 derived here is slightly in error and the continuum is probably overestimated by 3 to 4%. But is is well to recall that the profile utilized 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 Chapter IV. However, the three parameters, θ_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 utilize a value of $N_{He}/N_H = 0.1$, which is not much different from that derived from the equivalent widths and LTE diagnostics by me and by Norris (1971), I believe that this high temperature required to fit the observations may be real.

<u>μ^2 Sco</u> A good fit is obtained with T_e, log g, vsini values of 22500, 3.9 and 40 km/sec. respectively. The difference between temperatures found in Chapter IV and that utilised to fit the profiles can be explained in terms of the differences between blanketed models utilised in Chapter IV and the unblanketted models of Mihalas utilised to fit the profiles.

<u>τ Sco</u> The fit between observations and theory is quite good except for HeI 4471. Such a difficulty already had been encountered by Auer and Mihalas (1972). However, the observations presented here for τ 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 observations of this object published.

in literature. The vsini value used by them is 30 km/sec. while I find that a value of 15 km/sec. fits the observations very well. Other vsini values published for this object in literature is 0 km/sec. - Norris' (1971), <20 km/sec. Slettebak (1968).

The discrepancy near the intercomponent flux maximum in 4471A near $\Delta\lambda = -1.0\text{Å}$, between the predicted and observed profiles can be eliminated with the new quantum mechanical stark broadening calculations of Barnard, Cooper and Smith (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. The difficulties encountered at these temperatures are discussed in detail by Auer and Mihalas (1972).

Whatever discrepancies that still remain between theory and observations can be overcome by use of model atmospheres constructed at the relevant temperatures and gravities for a grid of helium abundances such that all the information in the continuum and lines can be utilised to get a better insight of the interaction of radiation with matter in the Stellar atmospheres.

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TABLE V-1 continued

Helium line Profile λ 4388

Δλ \ Star	κ Cen	μ^2 Sco	τ Sco
-6.00	995	999	999
-5.00	977	992	999
-4.00	977	987	992
-3.00	974	977	987
-2.50	965	975	980
-2.00	940	960	967
-1.50	876	942	947
-1.25	842	897	925
-1.00	802	845	882
-0.75	763	798	835
-0.50	683	740	765
-0.25	605	675	715
0.00	520	650	612
0.25	620	662	710
0.50	732	730	835
0.75	792	790	887
1.00	847	840	920
1.25	890	877	940
1.50	920	902	957
2.00	950	935	975
2.50	965	955	982
3.00	972	970	988
4.00	980	992	994
5.00	984	995	997
6.00	992	999	999

TABLE V-1 continued

Helium line Profile λ 4471

$\Delta\lambda$ \ Star	κ Cen	μ^2 boo	τ boo
-6.00	985	982	995
-5.00	977	972	985
-4.00	965	958	965
-3.50	950	942	957
-3.00	916	917	950
-2.50	875	887	930
-2.00	822	840	898
-1.75	790	805	862
-1.50	767	778	815
-1.25	780	762	835
-1.00	802	760	874
-0.75	790	737	823
-0.50	700	675	755
-0.25	575	597	675
0.00	500	558	472
0.25	565	592	615
0.50	667	662	760
0.75	762	745	838
1.00	830	812	880
1.25	867	852	910
1.50	892	875	936
1.75	912	902	955
2.00	930	925	965
2.50	948	940	978
3.00	964	955	984
4.00	980	977	994
5.00	985	982	999
6.00	992	985	999

CHAPTER VI

NU CENTAURI: A NEW BETA CEPHEI STAR

6.1 Introduction As part of a long term effort to study the binaries of the Scorpio-Centaurus association, I had included ν Centauri on my list. This chapter details my findings on this system from radial velocity measures alone. The binary character of ν centauri was first announced by Palmer (1906) and the only orbit that exists for this object is by Wilson (1914) who found it to be circular with a period of 2.62516 days. Its spectral type is B2 IV and the rotational velocity is of the order of 100 km/sec. (90 km/sec. - Slettebak 1968, 100 km/sec.-Levato and Malaroda 1970, 100 km/sec. present study). This is a member of the Scorpio-Centaurus association and absolute magnitude determinations for it range from -2.9 (Bertiau 1958) to -2.01 (Jones 1971). The light is variable (Bailey 1895) and photometry by Johnson et.al. (1966) indicate a range in V of 0.16 magnitudes and 0.12 magnitudes in B-V.

6.2 The Observations Twenty nine spectrograms of ν Centauri were obtained during the years 1968-1972 with the 51 cm. reflector at Kodaikanal and were supplemented with nine additional spectra obtained with the 102 cm. reflector at Kavalur. All these spectra were obtained with the same grating spectrograph and have a mean dispersion of 47Å/mm at H_γ. The lines measured in this study and the wavelengths used are listed in Table VI-1. All spectra were measured with an Abbe comparator. Table VI-2 lists the plate number, phases computed from T, the time of periastron passage, and the measured mean radial velocity obtained from the helium and hydrogen lines. Since the velocities in Table VI-2 indicate that the primary component of ν Centauri may be a Beta Cephei variable, fourteen spectrograms in an interval of 4 hours, were obtained on April 26, 1974 at a dispersion of 26Å/mm. The measured radial velocities are listed separately in Table VI-3. Though the velocities obtained for each line showed the general pattern of the radial velocity changes to be discussed below, it must be mentioned that their behaviour is difference from one another in the amplitude of the radial velocity change. The amplitude derived from the H_γ line is the least, indicating a slight filling-in of the line, probably due to emission.

TABLE VI-1

Wavelengths used for radial velocity measurement

Wavelength Å	Line
4471.325	HeI
4387.928	HeI
4340.468	H_γ
4101.737	H_δ
4026.140	HeI
3970.074	H_ϵ

TABLE VI-2

Plate No.	Julian Day of Observation	Phase (Period)	Observed radial Velocity	
			He km/sec.	h km/sec.
	2400000+			
722	39926.271	0.003	+26.9	+33.1
1645	41404.365	0.028	+10.3	+45.2
1646	41404.385	0.036	- 5.6	+39.2
1858	41727.339	0.053	+19.4	+ 0.8
1859	41727.356	0.059	+14.7	+ 6.3
1474	41042.253	0.095	-20.5	+37.7
1623	41399.299	0.098	-44.5	- - -
2243	41785.228	0.104	+ 2.2	-34.3
1475	41042.303	0.114	+ 7.4	+41.8
708	39921.335	0.123	- 9.0	+ 9.6
1435	41029.285	0.155	+ 5.8	+15.2
1477	41042.441	0.166	-32.1	+17.7
689	39916.426	0.254	- 8.5	+22.7
1439	41032.304	0.306	-40.8	+ 8.4
1440	41032.335	0.317	-26.4	+19.1
1467	41040.271	0.340	-26.2	+11.4
1769	41704.488	0.348	-40.2	-46.3
1656	41426.296	0.382	-13.0	-23.6
1471	41040.424	0.398	+ 3.2	+10.1
2204	41778.256	0.448	-41.8	-33.1
2205	41778.268	0.452	-17.4	-34.3
1873	41728.490	0.491	- 7.3	-19.5
1874	41728.505	0.497	- 6.2	-19.9

TABLE VI-2 continued

Plate No.	Julian Day of Observation	Phase (Period)	Observed radial Velocity He km/sec.	Observed radial Velocity H km/sec.
	2400000+			
1459	41038.254	0.572	-11.9	+25.6
1461	41038.358	0.611	-30.5	+ 7.3
1462	41038.410	0.631	- - -	+ 5.8
1445	41033.288	0.680	+18.4	+37.4
1618	41398.257	0.701	- 8.3	+ 4.3
704	39920.290	0.725	+14.8	+29.8
1658	41427.306	0.766	- 0.6	+52.2
1450	41036.240	0.805	+22.2	+25.2
1452	41036.317	0.832	+17.5	+12.7
680	39915.328	0.836	+34.5	+ 6.3
2256	41787.242	0.870	+20.5	+21.1
1455	41036.426	0.875	+28.5	+24.8
715	39923.333	0.885	+70.2	+48.3
1464	41039.276	0.961	+18.0	+26.2
1611	41396.340	0.971	+41.0	- 5.9

TABLE VI-3

Plate No.	Mid exposure U.T. April 26, 1974 h	m	Observed radial velocity km/sec.
2834	16	58	00.3
2835	17	15	-14.6
2836	17	29	- 2.7
2837	17	44	- 3.5
2838	17	57	- 8.0
2839	18	10	- 1.2
2840	18	19	- 9.0
2841	18	30	-15.1
2842	18	44	-11.0
2843	18	55	- 8.6
2846	19	53	- 6.7
2847	20	08	-13.6
2848	20	28	- 3.4
2849	20	46	+ 0.2

However two spectra at 17 Å/mm dispersion taken at phases of 0.96 and 0.77 do not show any detectable emission. H_ϵ is possibly affected by contamination with Ca II, H, and H_8 due to HeI 3889. I have, therefore, used only H_γ and H_δ as representative of the hydrogen lines and HeI 4471 and 4388 as representative of the helium lines in this object. HeI 4026 was neglected because of its slightly different behaviour from those of 4471Å and 4388Å.

6.3 <u>The new orbit</u> The orbital variations seem to be best represented by HeI 4471Å and 4388Å. Consequently, these lines were used in deriving the new orbit. A comparison with Wilson's radial velocity curve shows that the period needs to be increased from 2.62516 days to 2.625275 days to bring the two observations into agreement. Though Wilson's measures are averaged velocities obtained from both the hydrogen and helium lines, the need for change in the period is indicated by the individual lines as well as their average.

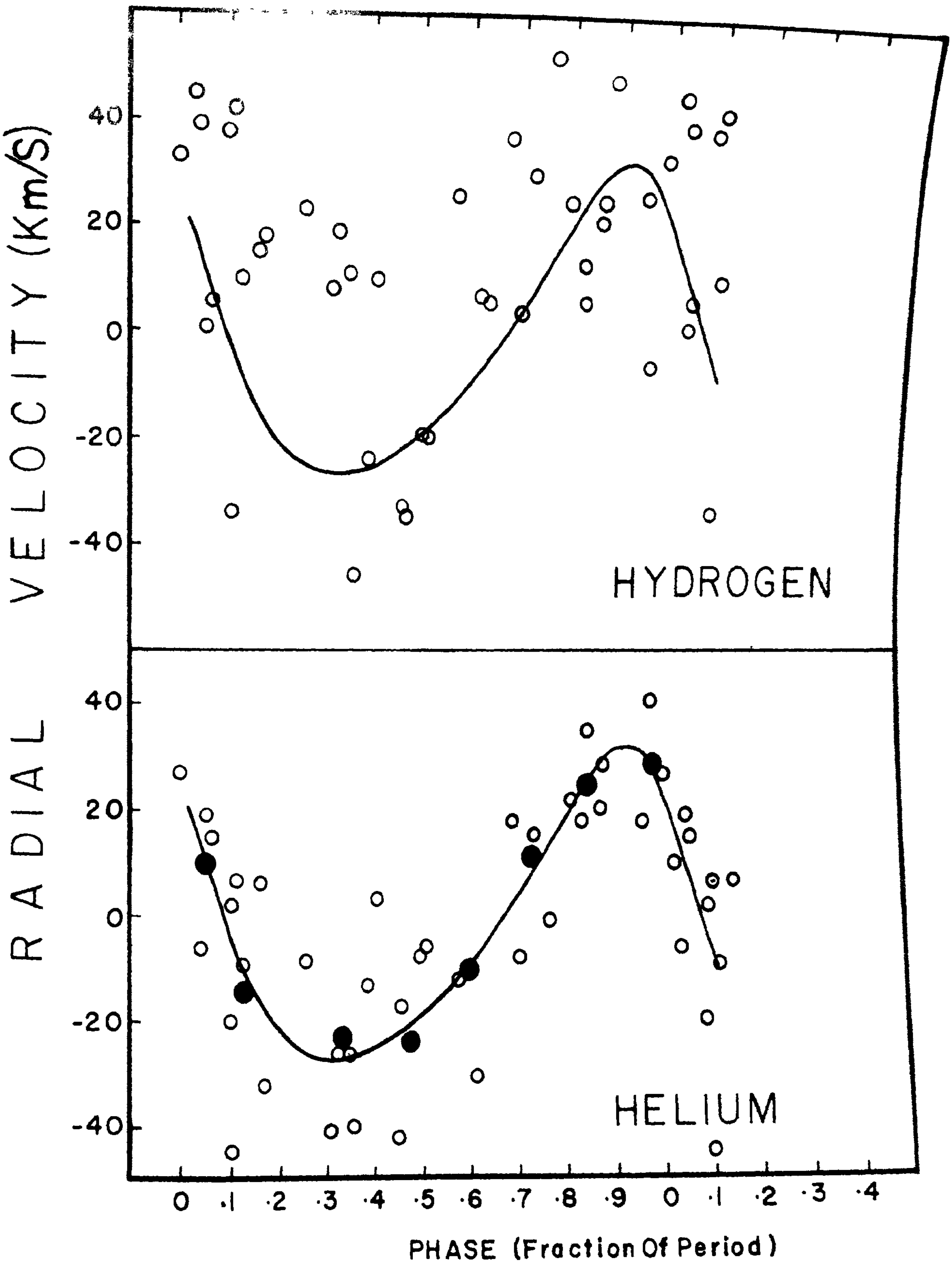
Thirtyfour of the thirtyeight plates obtained at 47Å/mm dispersion (Table VI-2) were used to form eight normal places. All the points were treated with equal weight and preliminary elements obtained by the method of Lehmann-Filhes were improved by the least squares procedure of Schlesinger (1908). Following Sterne (1941) T was replaced by To. (To is the time at which the mean longitude $\omega+M$ is zero).

The computed radial velocity curve with the final elements together with the observed mean velocities from helium and hydrogen are shown in Figure 6.1. The final elements derived by Wilson are also given. No probable errors are quoted for the oribital elements derived in this study since the scatter of the individual observations about the mean is large and whatever short-period oscillations (see below) are present, have not been taken into account in determining the new orbital elements.

6.4 Nature of Pulsations The large deviations of the individual measurements from the computed curve indicates that oscillations other than orbital motion are present. An inspection of Figure 6.1 indicates that the situation is worse in the case of the hydrogen line measures. Just immediately after the node on the descending branch of the

FIGURE 6 - 1

Radial velocity curve of Nu centauri. Top figure was derived from H_γ and H_δ . Bottom figure was derived from 4471 A and 4388 A. The normal points used in deriving the new orbit are shown as filled circles. Measured velocities from individual plates are shown as open circles. The computed curve from the elements derived in this study is shown by the solid line. Notice the large positive velocities given by hydrogen lines at phase 0.25.



RADIAL VELOCITY (Km/S)
40
20
0
-20
-40
HYDROGEN
40
20
0
-20
-40
HELIUM
0 ·1 ·2 ·3 ·4 ·5 ·6 ·7 ·8 ·9 0 ·1 ·2 ·3 ·4
PHASE (Fraction Of Period)

TABLE VI-4

Orbital elements of Nu Centauri

	R.E.Wilson	Present
P	= 2.62516 days	2.625275 days
V_o	= 9.05 ± 0.54 km/sec.	−2.8 km/sec.
K	= 20.63 ± 0.77 km/sec.	29.9 km/sec.
e	= 0.00	0.26
ω	= ——	44°64
T	= 2420301.39 ± 0.015 days	JD 2440855.608

radial velocity curve, where one expects the primary eclipse to occur if the inclination of the orbit were favourable, the hydrogen lines give large positive velocities. The hydrogen lines seem to be affected by gas streams and this conclusion is further augmented by the relative strengthening of HeI 3965 found on a few spectra, indicating dilution effects. I have therefore used the residuals found from the helium lines alone (listed in Table VI-2) and these are plotted against a period of 0.1750 days in Figure 6.2. This value of the period can at best be only provisional since observations are spread over a long interval of time and more than one dominant period seems to be present.

The maximum amplitude of the short period oscillation is about 45 km/sec. The presence of more than one dominant period is also suggested by the radial velocity observations of April 26, 1974. The measured radial velocities from 14 spectra taken within an interval of 4 hours is plotted in Figure 6.3. The observations fit in very closely a period of 0.1750 days but the amplitude is only of the order of 10 km/sec. This suggests that atleast two dominant oscillations are present with periods

FIGURE 6 - 2

The residuals found from helium lines plotted against a period of 0.1750 days.

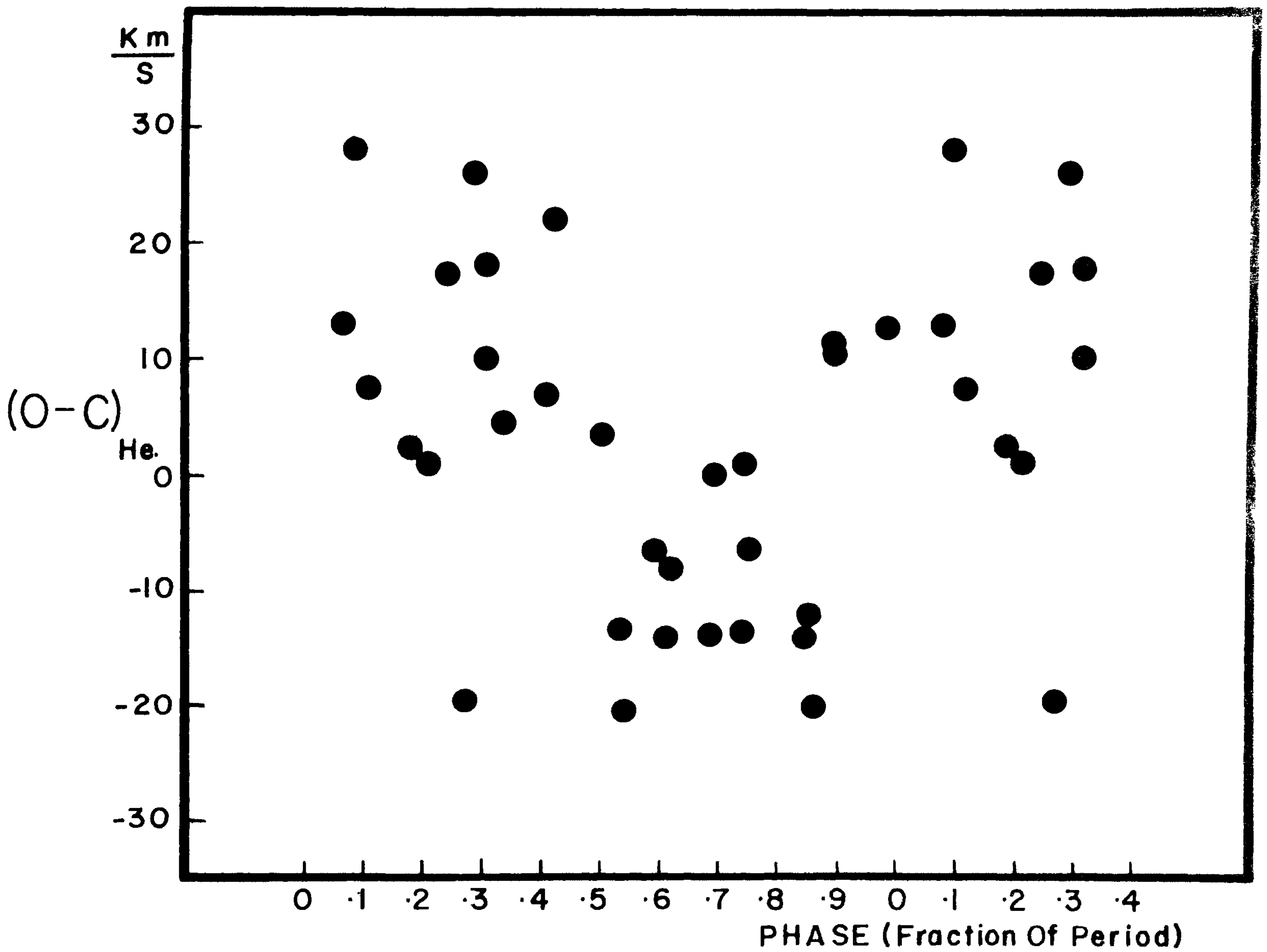
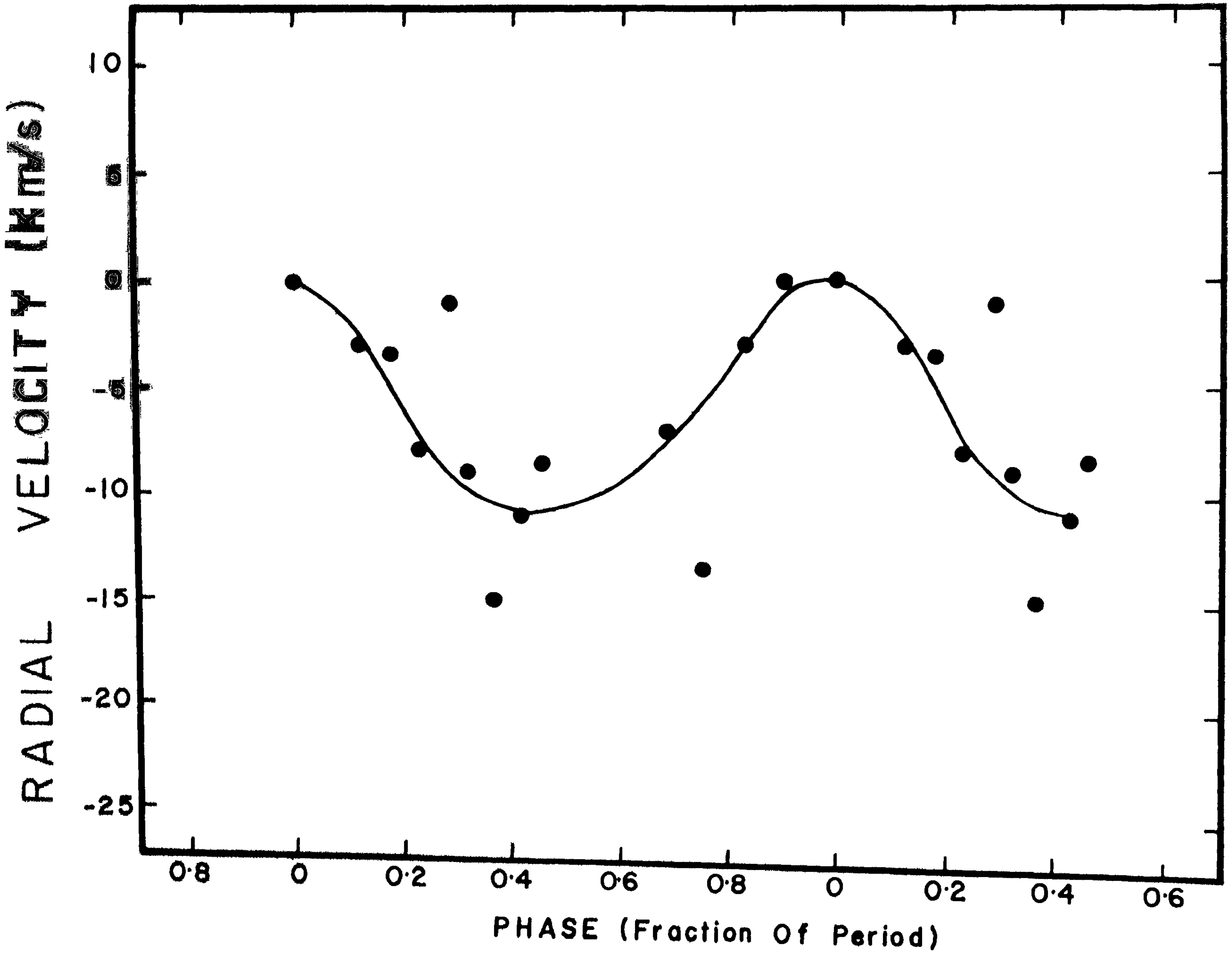

Km/S
30
20
10
(O-C)He.
0
-10
-20
-30
0 ·1 ·2 ·3 ·4 ·5 ·6 ·7 ·8 ·9 0 ·1 ·2 ·3 ·4
PHASE (Fraction Of Period)

FIGURE 6 - 3

The observed radial velocities on April 26, 1974 plotted for a period of 0.1750 days.



RADIAL VELOCITY (Km/s)
10
5
0
-5
-10
-15
-20
-25
0·8
0
0·2
0·4
0·6
0·8
0
0·2
0·4
0·6
PHASE (Fraction Of Period)

close to 0.1750 days as in other well known Beta Cephei type variables exhibiting multiple periodicities.

On atleast, one plate, all the helium lines are found to be double and the measured radial velocities show that it cannot be attributed to the secondary component. Visual inspection of all the spectra indicate that the lines are broader than normal on a few plates. Indeed, these spectrographic observations demonstrate that ν Centauri is a Beta Cephei type variable with a period of 0.1750 days. The fact that this is exactly one fifteenth of the orbital period is intriguing. Extensive photoelectric observations to determine the exact values of the various periods of oscillation are necessary for further study of this interesting system.

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CHAPTER VII

IN RETROSPECT

The results presented in Chapters II, III, IV and V are in answer to a few questions for which I have attempted to provide information. The questions given in page 1-11 are repeated here once again for convenience:

(a) Are there any differences in the distribution of rotational velocities between the two sub-groups, the Upper Scorpius and the Upper Centaurus-Lupus of the Scorpio-Centaurus association?

(b) Are there any differences in the line intensities between the two sub-groups as suggested by the work of Glaspey from narrow band photometry?

(c) Does any helium abundance difference exist between the two sub-groups?

(d) Are there non-LTE effects in the atmospheres of these stars which may be responsible for some of the anomalous aspects of the spectra?

Except for question (b), the answer is 'NO' for each of the questions listed above. However, the difference in hydrogen line intensities found between the two sub-groups can be explained in terms of the evolutionary differences due to differences in age between the two sub-groups. The V-filter of the uvby narrow band photometric system employed by Glaspey, contains the H_δ line and since differences in H_δ line strengths exist between the two sub-groups, these are reflected in the indices of narrow band photometry. That the mid B-star range exhibits larger differences can be understood if we can assume that star formation ranges over a period of time and that stars of spectral classes BO-B2 are formed much later than stars with spectral types B4-B7. This is in general conformity with Herbig's suggestion that star formation ceases once the early O and B stars are formed.

Both the rotational velocities of the two sub-groups and their helium content estimates show no dissimilarities that could be utilised to understand these differences. Though the Upper Scorpius members in the spectral range BO-B7 seem to rotate slightly faster than the Upper Centaurus-Lupus members of the same spectral class, the difference is not significant.

They both resemble the field stars in this spectral range. However, the B7-A0 stars in Upper Scorpius rotate much faster than, the field stars, stars in the α Persei cluster, as well as the Pleiades Cluster members of the corresponding spectral type. Their rotational velocities are not compatible with a Maxwellian distribution. The reason for this high incidence of rotation amongst B7-A0 stars is not understood. In the Scorpio-Centaurus association, almost all the fast rotating B7-A0 normal stars are associated with bright and dark nebulosities. Probably they have acquired their high angular momenta due to accretion of matter in which they are imbedded. I have also discussed the possibility of a mild non-randomness of orientation of axes.

A better understanding can be reached if rotational velocity determinations are extended to faint limits of as many clusters and associations with early type stars. The need to determine this function over all spectral types is very essential. Since these young formations are characterised by high rotation, low dispersion spectra, in the range 50-80Å/mm should suffice to determine the rotational velocities for a large number to the faintest possible limit. This is lacking at present. For example in the case of I Orionis or I Lacertae, it would be very helpful to increase such determinations to greater numbers and to fainter limits. There are undoubtedly numerous difficulties in such a venture. We need to have as a prerequisite, information on memberships of these clusters and associations; this can be done by photometric and kinematic procedures. A factor that would complicate the situation would be the incidence of binaries amongst these stars. These have to be eliminated before a comparison between different clusters of similar evolutionary stage can be understood. These restrictions naturally involve an appreciable effort with large telescopes. A "simple" way would be to develop photoelectric methods to determine rotational velocities, similar to that recently introduced for radial velocity measurement. Photoelectric techniques have the great advantage of speed and accuracy and eliminate the labour and inaccuracies involved in photographic methods. Photographic techniques have ofcourse the advantage of providing, besides a permanent record, much additional information on line and continuum, than is needed normally for any specific investigation. Peculiarities in spectral features can be easily recognised and taken into account Probably the photoelectric indices when properly chosen could also indicate as much with greater accuracy. Its potentiality of speed and the ability to penetrate deep in the sky is one advantage that renders the photoelectric technique incresingly the favourite of the future.

The hydrogen line intensities have been utilised extensively as an indicator of absolute magnitude. However the H_β indices developed by Crawford have the minor defect of incorrect values caused by incipient emission in the early type stars which are fast rotators, and which are prone to have Balmer-line emission. The advantages of going to higher Balmer series have been known for some time but no attempt has been made to utilise the advantages offered by them. Bappu et.al. (1962) have utilised the H_γ indices successfully. But probably the best line to choose could be H_δ where the effects of emission would not be noticeable. Lines other than H_δ suffer from blends. H_ϵ is blended with CaII H. Interstellar H would create serious difficulties at this wavelength if H_ϵ in luminous objects are used to measure luminosity. H_ζ (3839A) suffers from blends due to HeI 3888. As we go to higher members the series begins to converge rapidly and their strengths begin to decrease rapidly. Extinction increases towards the ultraviolet and may introduce large scatter in the observations. Under these circumstances, it is time, that a beginning be made to utilise H_δ as a luminosity indicator.

The helium abundances and the helium line profile studies reported here do not lend credence to any differences between the two sub-groups of the association. Even in this field, photoelectric techniques have come to surpass the photographic techniques. Photoelectric spectrum scanners with very high resolving power and multi-channel pulse counting techniques or the use of image dissectors will yield results today that are vastly superior to those obtained by photographic methods. One very good example of this kind is the study of HeI 5876A line profiles made by Anderson with an echelle spectrograph attached to a 91 cm reflector. These high resolution observations have considerably minimized the discrepancy between non-LTE theory and observations, that earlier photographic material available in the literature could not achieve. Here then is obviously a technique for future line profile studies with exactness.

Finally, I believe that such differences that exist between the two sub-groups of the association can be understood better when observations in the ultraviolet become available. The recent discovery of ultraviolet flux differences between the Hyades and the Pleiades, which could not be understood in terms of differences known in the visual part of the spectrum, lends support to the above suggestion. Observations made in the entire electromagnetic spectrum, followed up by theoretical developments to represent the atmospheres and predict their emergent flux, both in the continuum and the lines, hold forth every promise of a rapid attainment of our goals.

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