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THE UPPER CENTAURUS ASSOCIATION

by

John Warren Glaspey

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GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my direction by **John Warren Glaspey**

entitled **The Upper Centaurus Association**

be accepted as fulfilling the dissertation requirement of the degree of **Doctor of Philosophy**

Bart J Bok — Feb. 10 '71

Dissertation Director — Date

After inspection of the final copy of the dissertation, the following members of the Final Examination Committee concur in its approval and recommend its acceptance:*

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SIGNED: John Warren Glaspey

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ABSTRACT

The Scorpio-Centaurus association is one of the nearest groups of young B-type stars to show common streaming motions, and as such has played an important role in the determination of absolute magnitudes of B-type stars. Subgroups have been recognized within the Association; however, very little information was available concerning the Upper Centaurus-Lupus section, which we shall call the Upper Centaurus association. To supplement the published data on the brighter B-type stars, photoelectric uvby and Hβ photometric data have been obtained for a large number of faint B-, A-, and F-type stars in the Upper Scorpius and Upper Centaurus regions.

With this information the published absolute magnitudes of the bright B-type star members as determined by a moving cluster analysis are used to check the accuracy of a preliminary calibration of M_v in terms of the β-index provided by D. L. Crawford of the Kitt Peak National Observatory. For the Upper Scorpius and the Upper Centaurus subgroups, the two types of absolute magnitudes show satisfactory agreement. For the Lower Centaurus-Crux B-type stars, however, the moving cluster absolute magnitudes are brighter than the Hβ absolute magnitudes by

an average of $0^{m}.4$. No explanation is given for this difference, if it is significant.

Ages of B-type stars in the subgroups have been estimated using theoretical evolutionary calculations. Isochrones are transformed into a β, $(u-b)_o$ diagram for direct comparison with the observed stellar sequences. For the Upper Centaurus association, age estimates range from 12 million to 16 million years, depending on the assumed chemical composition. A less certain estimate of 10 million years is obtained for the Upper Scorpius association.

The Upper Centaurus and Upper Scorpius subgroups differ in two additional aspects, which may be related. A large percentage of B-type stars having peculiar spectra are known to exist in the Upper Scorpius association, whereas for the Upper Centaurus association less complete data do not show a similar effect. Also, the m_1-indices of the Upper Scorpius B-type stars are, on the average, $\sim 0^{m}.02$ greater than the m_1-indices of the Upper Centaurus B-type stars. We suggest that the spectral peculiarities are being detected by the m_1-index.

The uvby and Hβ photometric systems provide luminosity-dependent parameters which have been used to select a number of apparently zero-age late B-, A0-, A-, and F-type stars in the Upper Centaurus region. Those stars in this list which also lie at approximately the same distances as the B-type star members are candidates for membership in the Upper Centaurus association. Accurate radial velocity information could be used to confirm or reject membership; however, the data presently available for some of these stars are insufficient to provide tests of memberships. Radial velocity and proper motion work should obviously be undertaken for this purpose.

CHAPTER 1

INTRODUCTION AND HISTORICAL REVIEW

The unusual way in which the bright stars in the southern sky are distributed in a belt noticeably inclined to the Milky Way was first described by John Herschel (1847). Gould (1879) showed that this phenomenon occurs in both hemispheres. Shapley and Cannon (1921) used the spectral types and magnitudes from the Henry Draper Catalogue (Cannon and Pickering 1918) to confirm the discovery by Charlier (1916) that it is actually only the brightest B-type stars that form what is now referred to as Gould's Belt. The fact that there seems to be some sort of physical subsystem of Gould's Belt present in the constellations of Scorpius and Centaurus was pointed out by Kapteyn (1914) and others from the parallelism of the proper motions of the bright B-type stars in the area. But, whether or not these stars form a real group was disputed from the beginning. Kapteyn (1914) wrote: "While Eddington and I held that they do, this view was contested, even before my [earlier] paper had appeared in print by Campbell and B. Boss" (p. 43).

It is the actual appearance of the group in the sky that has fascinated and convinced many astronomers of the reality of the Scorpio-Centaurus association as a distinct subgroup in what is now called the Local System. Blaauw (1946), in particular, has referred to this aspect of the problem when challenging the arguments of non-believers on the reality of the group and the group expansion.

Blaauw (1964) distinguished between the northern part of the association, referred to as the Upper Scorpius region (also the II Sco association), and the southern two sections, referred to as the Upper Centaurus-Lupus and the Lower Centaurus-Crux regions. The upper two sections lie well above the Milky Way and are sufficiently separated from the other nearby bright stars to be easily distinguished. This can be seen on map 18 of Norton's (1959) Star Atlas, which plots galactic longitude versus latitude for bright stars. In Lower Centaurus-Crux, the association is nearer to the galactic equator, so that the Centaurus members gradually blend into the Milky Way.

In this dissertation I shall concentrate on the Upper Centaurus-Lupus (hereinafter called Upper Centaurus) section of the Scorpio-Centaurus association. Comparisons will be made with the well-studied Upper Scorpius section, adding in some instances to the significant differences known to exist between the two groups.

Analysis of the Group Motion

Although Smart (1939) disputed the claim that Scorpio-Centaurus is a moving cluster, Blaauw (1946) found in an analysis of the proper motions and radial velocities that Smart had included many distant nonmembers in his discussion, thus biasing his results. After restricting the membership to only the brightest B-type stars, Blaauw found a small dispersion in the space velocities, implying common stream motion.

Blaauw was able to set rather definite limits on the magnitude limits of B-type stars which were members of the moving cluster. After correcting the observed radial velocities for the reflex solar motion, he plotted diagrams of these residual velocities versus apparent magnitude for different groups of stars which had been separated according to spectral type. For B0-B2 stars he found that the faint limit is $5^{m}.25$; for B3 stars, $5^{m}.5$; and for B5 stars, $6^{m}.0$.

Blaauw divided the association into subgroups by galactic longitude and latitude and computed mean spectroscopic parallaxes for each region. Space motions were calculated for each subgroup from the mean tangential and radial velocities. Within the errors in the data, the space motions for each of the five regions above galactic longitude l=270°* agreed in both magnitude and direction. This established the common stream motion for the group.

The projected size of the association on the sky could easily be calculated, and Blaauw found it to be 290 pc by 70 pc. To estimate the depth of the association along the line of sight, Blaauw carried out a statistical analysis of the proper motions and radial velocities, and found the depth to be approximately 100 pc.

Blaauw also discussed the past history of the association, by analyzing the individual orbits of stars moving in the galactic plane. He concluded that the present size and orientation of the association could be explained by differential galactic rotation acting on a group of stars which had been ejected about 10^8 years ago with slightly differing velocities from a "point" moving in a circular orbit around the galactic center approximately 1 kpc interior to the sun's present position.

Blaauw (1952) revised this approach to include the possibility that the original cluster was expanding at a certain rate. By comparing the size and orientation of the model at various epochs to the observed size and direction of elongation of the Scorpio-Centaurus association, Blaauw estimated that the age of the group was 72×10^6 years.

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*New galactic longitudes are used throughout the present study.

Bertiau (1958) made use of new proper motions and radial velocities of the Scorpio-Centaurus B-type stars in his moving cluster analysis of the association. The proper motions were used to determine the convergent point, then the radial velocities were used to compute the stream motion. Bertiau found that a rather large constant term was needed in the radial velocity relation, which he interpreted as a manifestation of a linear expansion of the association, inasmuch as the effects of differential galactic rotation could not account for the size of the constant term. At a distance of 170 pc, the mean distance to the association adopted by Bertiau, this constant term implies an expansion age of 20×10^6 years for the association.

The individual parallaxes for each member which could be obtained from the computed group stream motion make the Scorpio-Centaurus association extremely important for the calibration of absolute magnitudes of B-type stars. However, the sample of stars with accurate MK classifications was too small to give Bertiau a good calibration of the MK system. In connection with this difficulty, the final part of Bertiau's study consisted of a brief discussion of the possible membership of faint B-type stars in the Upper Scorpius region. For the benefit of future workers he presented a table of stars brighter than $m_v = 8^m$ that have HD spectral types between B0 and B9 and which are included in the GC proper motion catalogue (Boss 1937). Bertiau also commented that many of the provisional proper motions tend to have similar sizes and direction as the brighter, known members.

Petrie (1962) disputed the reality of the common stream motion and the absolute magnitudes derived from moving cluster analyses of the Scorpio-Centaurus association. In examining the B star proper motions Petrie removed the reflex solar motion using the individual distances given by Bertiau (1958) and found what appeared to be negligibly small proper motions. Because he did not quote the corrections for solar motion which he used, we may only assume that Petrie used the wrong solar motion corrections, for the reflex solar motion in the proper motions in Scorpius and Centaurus at the distance of the B-type stars is $0\overset{''}{.}016$ p.a., approximately half of $0\overset{''}{.}028$ p.a., the mean of the observed proper motions. Petrie (1965) essentially retracted his criticisms of the Scorpio-Centaurus association in a recalibration of the Hγ system because he had to correct the earlier M_v, Hγ calibration by $0\overset{m}{.}4$, thus bringing it into agreement with the absolute magnitudes given by Bertiau (1958).

A moving cluster analysis of the B-type stars in the Scorpio-Centaurus association had led Bertiau (1958) to conclude that an expansion term must be included in the radial velocity solution. Although the magnitude of this term depends strongly on the location of the convergent point of the proper motions, the amount of change in the convergent point needed to eliminate the expansion term seemed to be too large to be justified on the basis of the available proper motions. However, Eggen (1961) pointed out that the apparent expansion could also be caused by an undetected systematic error in the declination components of the proper motions. Because the systematic errors in southern hemisphere proper motions are, indeed, not well known, Eggen's criticism has led to a general mistrust of moving cluster analyses of the Scorpio-Centaurus association as a reliable means of calibrating absolute magnitudes of B-type stars. As will be described below, one of the purposes of the present dissertation is to compare the absolute magnitudes given by Bertiau (1958) with those derived from an independent calibration of the uvby and Hβ photometric systems.

Thackeray (1967) presented a preliminary report on results of an analysis of the radial velocities of Scorpio-Centaurus B-type stars in which new velocity measures had been included. He did not find any evidence for expansion of the association.

Relationship With Gould's Belt

Before proceeding further, it should be pointed out that the problem of determining the nature of the

Scorpio-Centaurus association is probably closely related to the interpretation of the entire phenomenon of Gould's Belt. A concise review of the history of Gould's Belt was given by Bok (1937). In addition to the bright B-type stars described above, the other objects that share the same areal distribution which were listed by Bok are: Be stars, A-type stars in the HD catalogue, some diffuse nebulae, and extended dark nebulae. Heeschen and Lilley (1954), Davies (1960), and Wesselius and Sancisi (1971) showed that there is also a strong correlation between the distribution of neutral hydrogen (HI) above the galactic plane and the interstellar dust clouds in Gould's Belt. Clube (1967b) has pointed out that this nearby neutral hydrogen feature may be confusing the interpretation of the large-scale distribution of HI in the galactic plane. His point is that the Carina spiral feature as drawn by Kerr and Westerhout (1965) appears to be quite circular. The same feature could be caused by the HI in Gould's Belt, which presumably has the same slightly positive velocity as the B-type stars, and which intersects the galactic plane in the same longitude interval.

Several kinematical discussions of the B-type stars in Gould's Belt have also been given. Eggen (1961) considered all B-type stars brighter than $m_v = 5^m.0$ to be members of the same moving group, and many Scorpio-Centaurus B-type stars were included in his sample.

Bonneau (1964) created models of large expanding clusters to compare with the space and velocity distributions obtained by Eggen.

With more observations and better quality data available to her than was available to Eggen and Bonneau, Lesh (1968) re-analyzed the space velocities of only those members of Gould's Belt north of declination -20°. Her distance scale depended on Borgman and Blaauw's (1964) absolute magnitudes of Scorpio-Centaurus B-type stars. Her approach was suggested by an earlier paper by Blaauw (1952). She derived expressions for velocity gradients of the space velocities of a group of stars moving in circular orbits around the galactic center. If there is no expansion of the group, then the velocity gradients have certain fixed values. If the group is expanding, then the gradients should change with time. By using the computed space velocities of the stars in Gould's Belt, she computed observed values for each gradient. Comparison of these observed values with the time dependent model gave an estimate of the expansion age from each gradient. The solutions she found gave no unique age; however, the cross gradients in the galactic plane $\frac{\partial U}{\partial Y}$ and $\frac{\partial V}{\partial X}$, are close to the results expected from differential galactic rotation. (The X and Y axes are directed towards (l,b) = (0°,0°) and (90°,0°) respectively, and U and V are the corresponding velocities along these axes.) For this reason Lesh concluded that the true picture is probably one of a combined expansion and differential galactic rotation.

Clube (1967a) analyzed published radial velocity and distance information for stars earlier than spectral type B2 and within 500 pc of the sun. To avoid uncertainties in the proper motions, he worked with only the radial velocity data in his computations of space velocity components. He considered several models to describe the general state of motion of the stars in Gould's Belt assuming: (1) common stream motion, (2) uniform expansion, and (3) linear expansion along the line connecting the sun and the galactic center. Although the three solutions appear to be indistinguishable, Clube considered it to be significant that the U, V space velocities of each solution are almost identical to the mean motion of the Pleiades group as given by Eggen (1963). He also pointed out that the convergent point for the Scorpio-Centaurus cluster appears to be quite close to the direction of motion of the Pleiades group. For these reasons Clube suggested that the Scorpio-Centaurus members, the Pleiades group, and the stars in Gould's Belt have a common origin. He also pointed out that the expansion age of 37×10^6 years which he derived for Gould's Belt is typical for evolutionary ages of early B-type stars. We shall see in Chapter 7 that the evolutionary age for the Pleiades is roughly twice this age and that Scorpio-Centaurus is less than half this age.

Therefore, we should be skeptical of this part of Clube's conclusion.

Subgroups in Associations

In examining the spatial extent of the B-type stars that share in the Scorpio-Centaurus stream motion, Blaauw (1946) divided the B-type stars into seven smaller groups, ranging from l = 232° to l = 2°. He found that the association probably does not extend past l = 270°, but the most reliable lower limit is l = 290°. For longitudes greater than that, most of the members are north of the galactic equator.

In the regions referred to as the Upper Scorpius and the Upper Centaurus regions, we find some striking general features. In Upper Scorpius, for example, there are both dark and bright interstellar nebulae, and a considerable amount of nearby interstellar absorption is present. The Scorpio-Centaurus members are also highly concentrated in this region. In Upper Centaurus, however, there are apparently neither bright nor isolated dark nebulae; there is very little general interstellar absorption; and, furthermore, the B-type stars are more widely distributed across the sky. We note also that Slettebak (1968) has found that the rotational velocities of stars in the Upper Scorpius region seem to be significantly higher than in the Centaurus stars.

These different characteristics between two subgroups within what is normally considered to be just one association are prime examples of a phenomenon that also occurs in other associations. In some of his early discussions of the properties of associations, Ambartsumian (1954, 1955, 1959) mentioned the existence of stars of apparently different ages within groups like the Orion association. Blaauw (1958, 1959, 1964) showed that Scorpio-Centaurus is one of several associations which have subgroups with varying ages. The III Cep, I Ori, and I Lac associations are the other examples cited by Blaauw. For the Scorpio-Centaurus association, Blaauw used the absolute magnitudes and spectral types given by Bertiau (1958) to draw separate Hertzsprung-Russell (HR) diagrams for the Upper Scorpius and the Centaurus regions. In addition to the fact that the Upper Scorpius region contains stars which have earlier spectral types than any of the Centaurus stars, the mean Upper Scorpius sequence is approximately $0\overset{m}{.}4$ less luminous at a given spectral type than the mean Centaurus sequence.

Other general features associated with the subgroups, besides the correlation of the higher concentration of stars and nebulae with the youngest stars, were listed by Blaauw, such as: (1) an age of about fifteen million years for the oldest subgroups, (2) separations between the subsystems of the same order of magnitude as the individual sizes of the subsystems, (3) separations of the subsystems roughly parallel to the galactic plane, and (4) similar numbers of stars in each subsystem.

In this dissertation I shall examine in some detail the possible age differences between the Upper Scorpius stars and the Upper Centaurus stars. This approach had been done earlier in a somewhat cursory fashion by Walraven and Walraven (1960) and Borgman and Blaauw (1964). In the two papers cited above, calibrations are reported of intermediate band filter systems in terms of absolute magnitudes. The fact that the few stars in the two subgroups of the Scorpio-Centaurus association for which observations were available showed different mean luminosities is encouraging, for it implies different ages of the subgroups; otherwise it seems to be incidental to the purposes of the Borgman and Blaauw and the Walravens' papers.

A detailed photometric study of all B-type stars in the Scorpio-Centaurus association was reported by Gutierrez-Moreno and Moreno (1968), who obtained UBV photometry for all B-type stars which had ever been considered as possible members of the association. They also observed Hβ-indices (see Crawford 1958) for those stars considered most likely to be members. Since the strengths of the hydrogen Balmer lines in B-type stars depend primarily upon luminosity, a plot of the β-indices versus the $(U-B)_o$-color, which is dependent mostly on effective temperature, gives a diagram quite analogous to an HR diagram. Photometric indices also provide (mathematically) continuous measures of temperature and luminosity, and can be determined relatively impartially, unlike the discrete subclasses obtained from spectral classifications. The resulting sequences reported by the Morenos do, indeed, show the same age differences described previously.

For the present investigation it was decided to use the β-index and the uvby system described by Strömgren (1963) and by Crawford and Barnes (1970c). Kelsall and Strömgren (1966) published evolutionary models for B- and A-type stars and used Strömgren's (1964) calibration of the intrinsic color $(u-b)_o$ to relate the observed colors directly to the computed ages of stars in the last stages of their main sequence lifetimes. In Chapter 4 we shall re-examine the effective temperature calibrations and, with the aid of a calibration of β in terms of M_v, and a bolometric correction-effective temperature calibration, shall transform the theoretical isochrones into a β, $(u-b)_o$ diagram for a direct determination of cluster ages.

The calibration of the β-index in terms of absolute magnitude for B-type stars is also important to this dissertation. D. L. Crawford and his co-workers at the Kitt Peak National Observatory are on the verge of completing such a calibration. The curve relating the β-index to apparent magnitude is taken to be the mean curve defined by several young open clusters and associations, and the zero point of the calibration is set by the adopted distance moduli of the Pleiades and α Persei clusters, as these last two clusters relate the calibration for the B-type stars to the independent calibration for A-type stars. An additional check on the reliability of the calibration will be to compare the values of M_V predicted by the β-indices with the absolute magnitudes determined by Bertiau (1958) from his moving cluster analysis of the Scorpio-Centaurus association. No attempt will be made here to carry out a new analysis of the moving cluster on the basis of proper motions and radial velocities. We shall see in Chapter 7 that for such a study better quality data will be needed than those presently available.

Another prime objective of this dissertation concerns the detection and study of possible faint members of Scorpio-Centaurus with spectral types ranging from mid-B to F. Garrison (1967) was successful in establishing the provisional membership of many such stars in the Upper Scorpius region by concentrating his efforts on those faint stars contained in a small area of the sky enclosed by the stars α Sco, σ Sco, 19 Sco, 22 Sco, and ρ Oph. He was able to obtain a well defined main sequence extending to spectral type F0 by using UBV photometry and accurate MK spectral classifications. Gutierrez-Moreno and Moreno (1968) obtained UBV photometry of eleven late B-type stars in

Upper Centaurus. However, they considered these stars to be foreground stars, based upon their location in the color-magnitude diagrams. To find out which fainter stars in Upper Centaurus may be members of the association we will make use of the luminosity-sensitive indices of the uvby and Hβ photometric systems to eliminate evolved field stars. The remaining, presumably unevolved stars, which also happen to lie in the appropriate distance interval, would be possible members of the association.

Summary of Objectives

We have seen from the short review of the extensive previous research on the Scorpio-Centaurus association that there are several instances in which spectroscopic and photometric information imply different ages in different regions of the association. By using calculations of stellar evolutionary tracks, we shall attempt to obtain certain qualitative results about the ages. Also, with the exception of the results of Garrison's (1967) examination of faint stars in Upper Scorpius, little is known about the membership of stars later than approximately spectral type B5, other than that in this region Shapley and Cannon (1921) showed that there appears to be a higher than expected density of late B- and early A-type stars tabulated in the HD catalogue. The uvby and Hβ photometric indices of such stars should allow us to identify the unevolved stars at the proper distance which may be members of the association.

Since this nearby association is also considered by some workers to be a moving cluster, we can also test the accuracy of the absolute magnitude calibrations of the uvby and Hβ photometric systems described in later sections.

CHAPTER 2

OBSERVATIONS AND DATA REDUCTIONS

A large amount of observational material on stars in the region of the Scorpio-Centaurus Moving Cluster is available, mostly in the literature. These data include objective prism plates, photoelectric uvby and Hβ photometry, radial velocities, and spectral classifications, as well as additional observations obtained by the present author. This chapter is devoted to descriptions of these observations and the reduction techniques, as well as the methods used to combine the recent observations with previously published information.

Objective Prism Survey

In a study of the Scorpio-Centaurus Moving Cluster, Bertiau (1958) examined the available proper motions of some fainter stars in Upper Scorpio having spectral types later than those of the well known bright, B-type stars. He presented a list of some possible members based only on these motions and suggested that a more thorough search should be made using objective prism classifications of stars in the region.

With just such a survey in mind, Mr. Robert Barnes of the Kitt Peak National Observatory (K. P. N. O.)

obtained 35 plates at Cerro Tololo on the 24-36 inch Curtis Schmidt telescope in July and August, 1967. Each plate is a 5-minute exposure with the 4° ultraviolet transmitting prism, giving a dispersion of 270 A/mm at Hγ. The faintest stars that could be classified on these plates were approximately 10th visual magnitude. These plates were made available to this writer through the courtesy of Dr. D. L. Crawford of K. P. N. O.

A few faint stars in the Upper Scorpio region had MK classifications available from the study by Garrison (1967) and these were used initially to determine the classification scheme. Due to the overall scarcity of such stars, however, it was decided to proceed with the classification using only the judgment of the classifier, and, if possible, to determine the systematic errors at a later time.

In the Upper Centaurus region the interstellar reddening is known to be quite small. The V_o magnitudes (apparent visual magnitudes in the UBV system corrected for interstellar absorption) of the later-type stars in Upper Scorpio listed by Garrison were used to estimate approximate magnitude ranges for each spectral range of stars at the same distance as the Scorpio-Centaurus cluster. Based on a rough calibration of magnitude and apparent brightness on the objective prism plates, possible members were indicated on each plate. The distribution of these stars subdivided according to spectral groups in the region of the sky covered by the plates is shown in Figure 1. The non-random nature of this distribution is a clear indication that the stars of later spectral types share the same distribution in the sky as the B-type stars in the Scorpio-Centaurus cluster. In selecting stars for the photometry program an attempt was made to include as many stars as possible along the ridge of high apparent density shown in Figure 1. The distribution of stars in the final observing program is shown in Figure 2, again subdivided into spectral groups.

With the photoelectric photometry available for analysis, a plot of the observed $(b-y)_o$ values vs. the objective prism spectral types (Sp(JG)) (Figure 3) shows that the spectral classification scheme correlates quite well with color index. Figure 4 (Sp(HD) vs. $(b-y)_o$) shows that the HD spectral types of these stars have a less uniform distribution compared with the objective prism spectral types, and a few obviously wrong classifications stand out from the rest. The direct comparison of Sp(HD) vs. Sp(JG) shown in Figure 5 is quite similar to Figure 4 in that many of the HD types are too early. As a check on the system, spectral types (Sp(color)) were assigned to each star on the basis of its $(b-y)_o$ index using the calibration of Barry (1967). Figure 6 (Sp(color) vs. Sp(JG)) shows that there is apparently a systematic

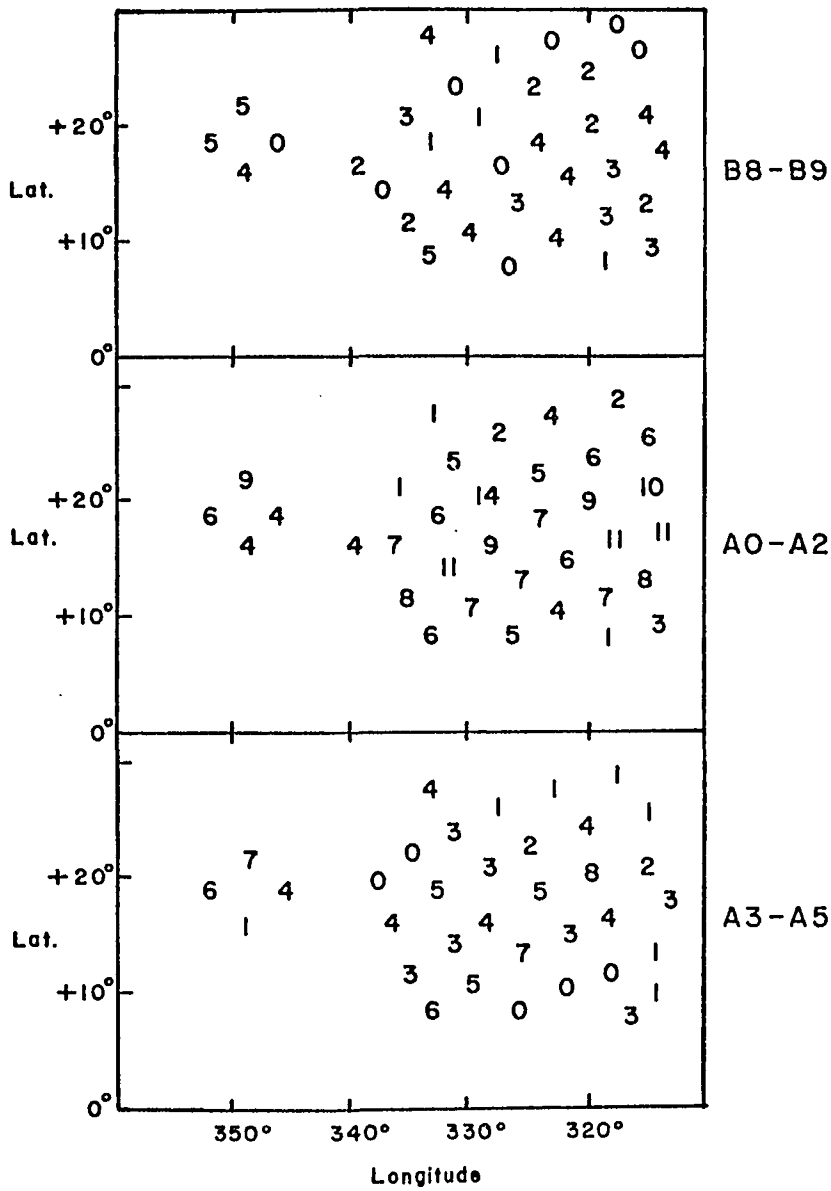

Figure 1. Areal Distribution of Faint Stars in Scorpius and Centaurus -- The number of stars on the objective prism plates are plotted for three spectral ranges.

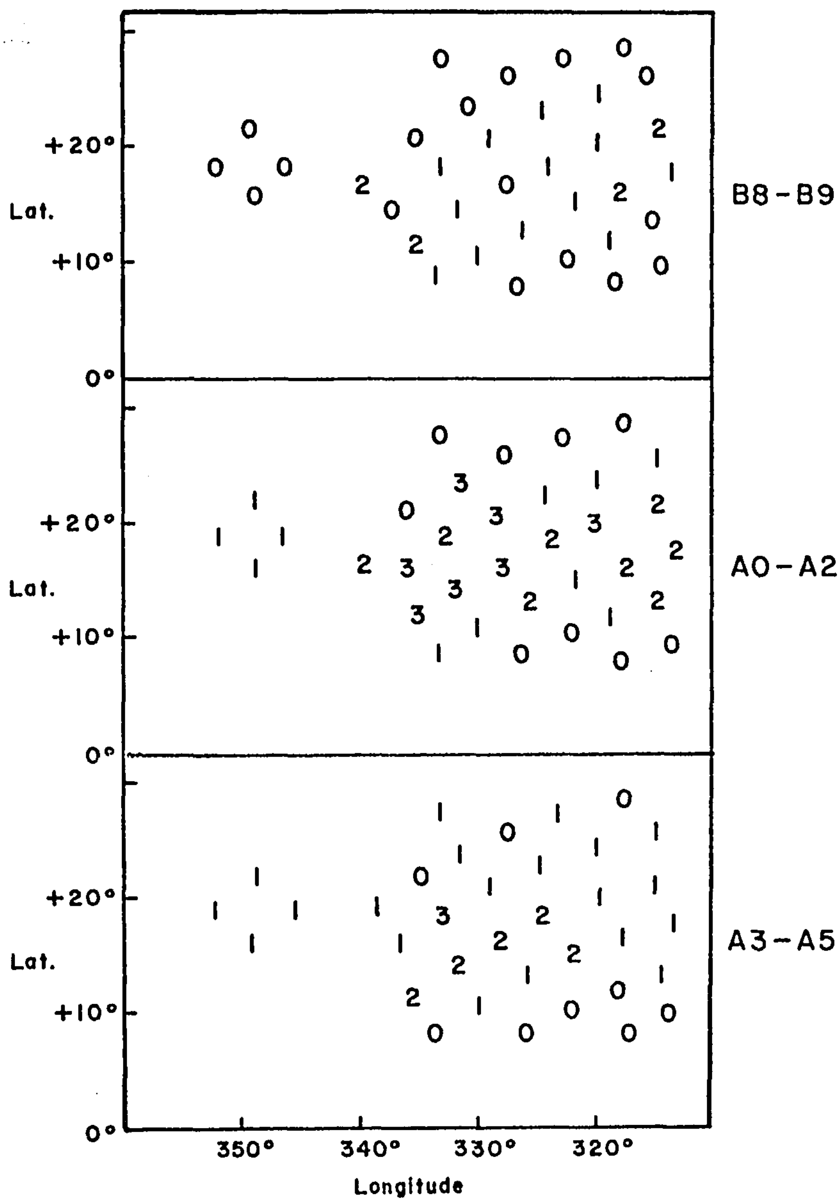

Figure 2. Areal Distribution of Faint Stars Selected for Study -- The number of stars selected for observation on each objective prism plate are plotted for three spectral ranges.

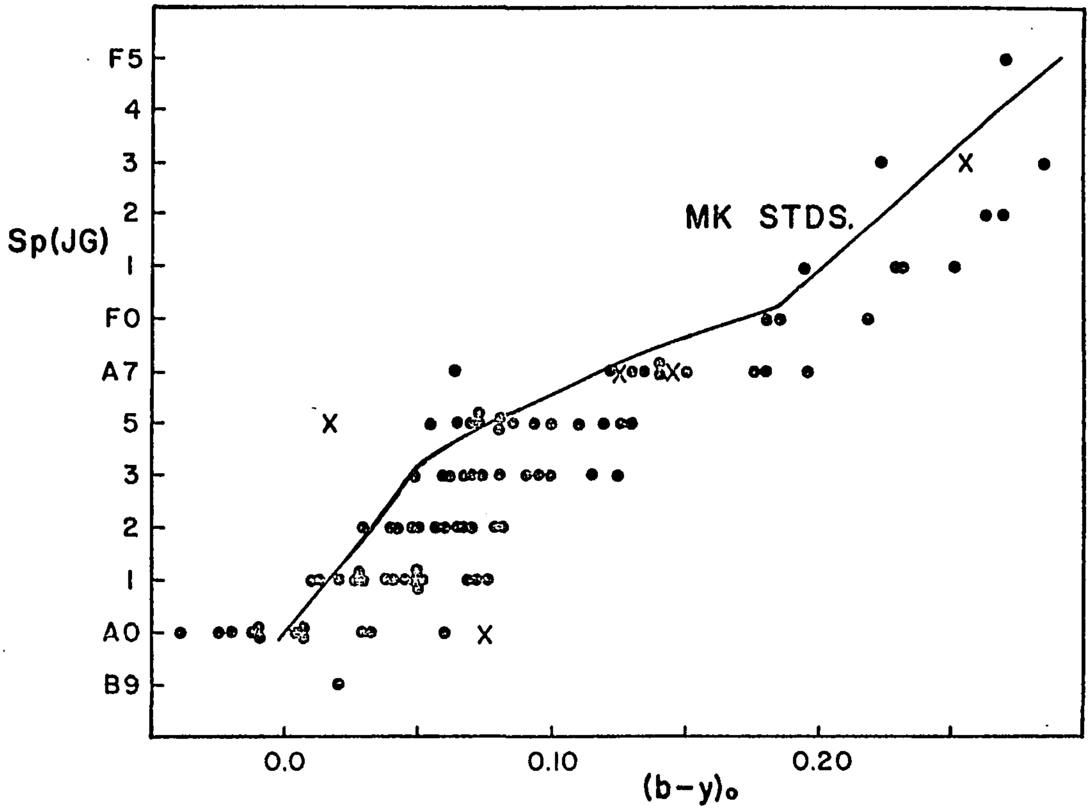

Figure 3. Comparison of Objective Prism Classifications with $(b-y)_o$ -- Filled circles represent stars observed in the present program; crosses, stars in Upper Scorpius observed by Garrison (1967).

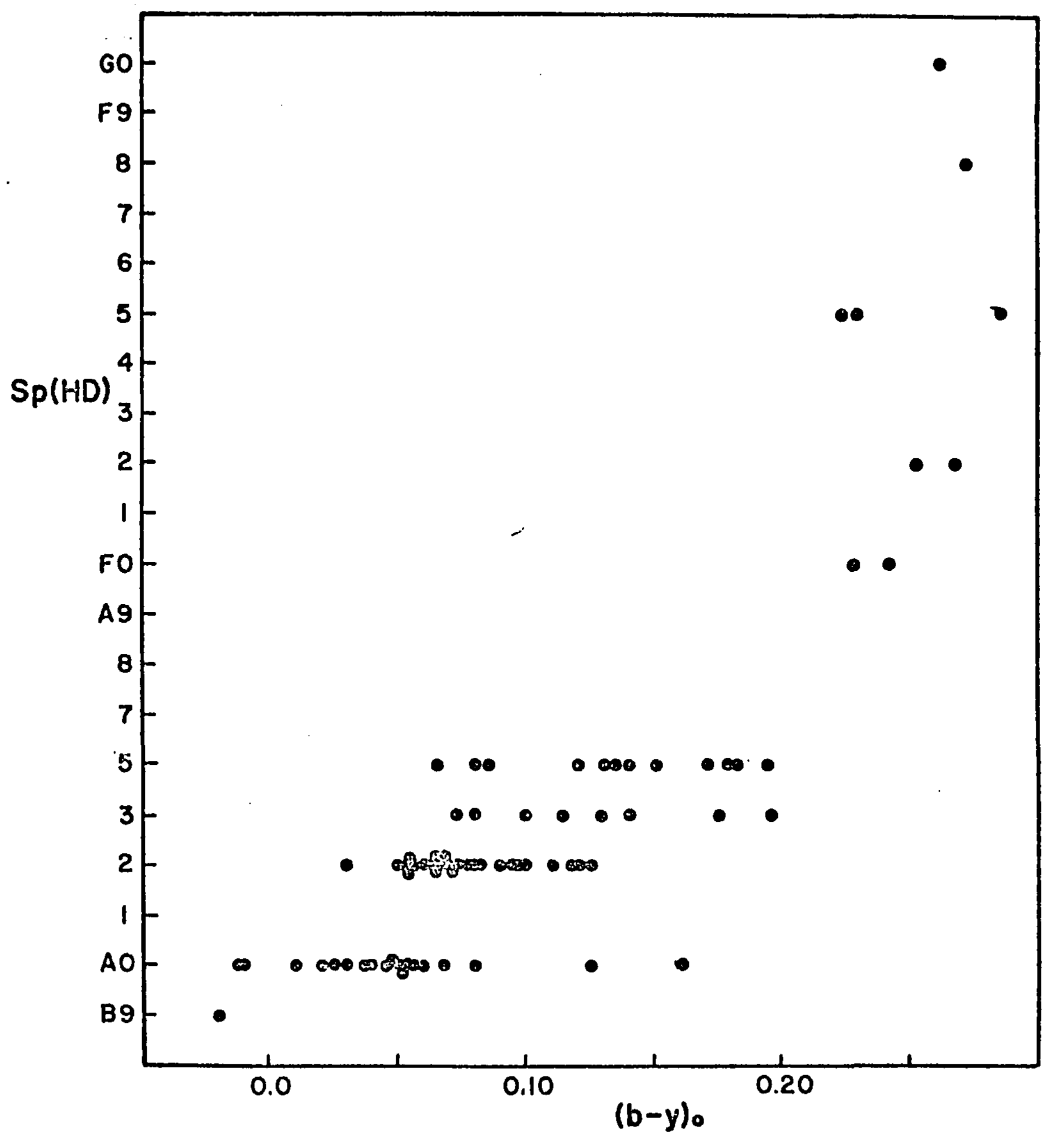

Figure 4. Comparison of HD Classifications with $(b-y)_o$

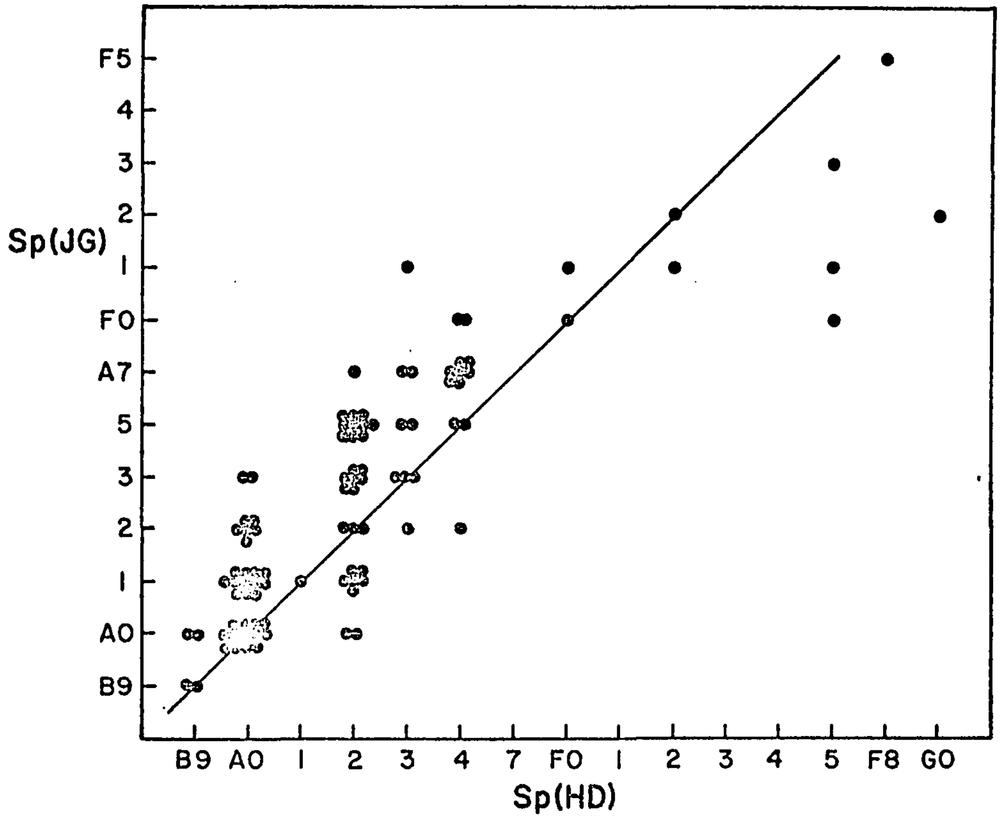

Figure 5. Comparison of Objective Prism Classifications with HD Classifications

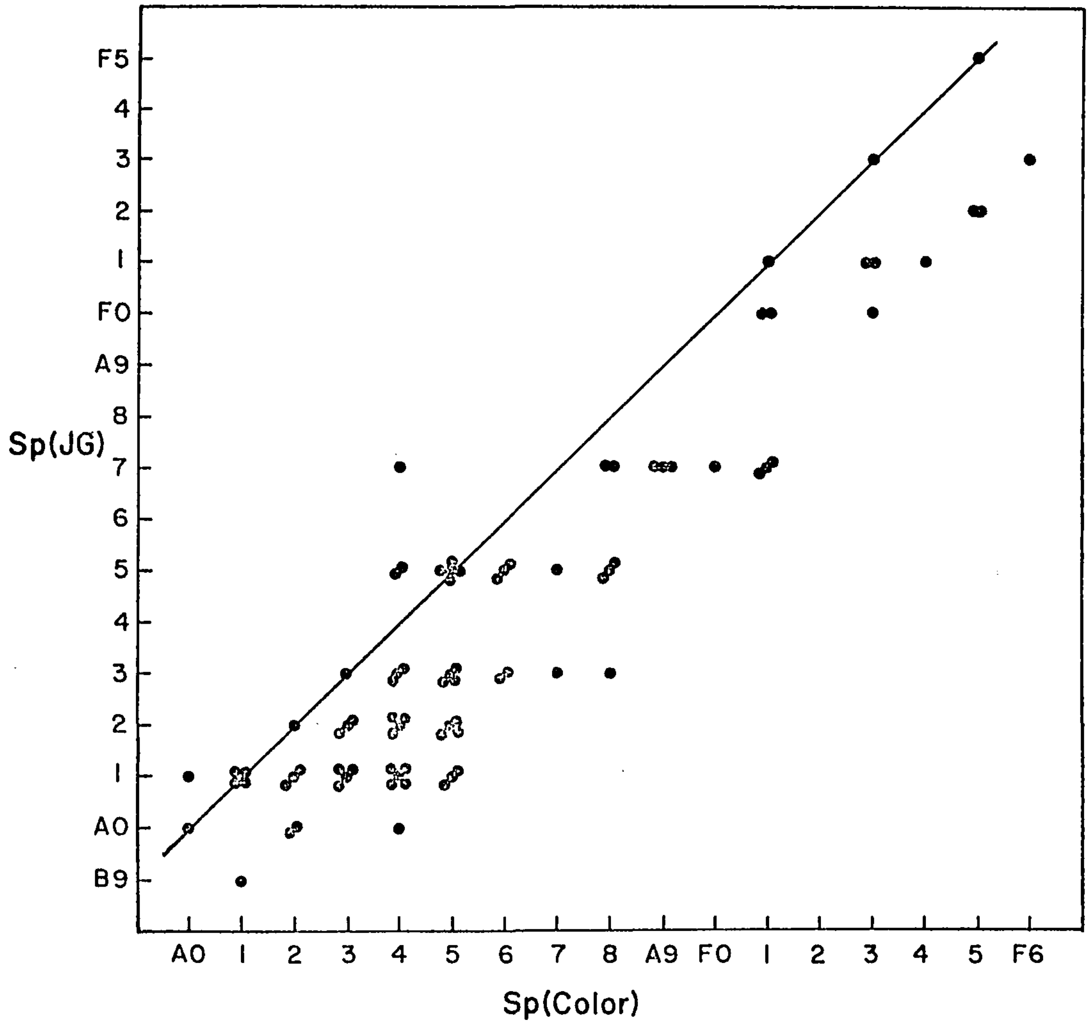

Figure 6. Comparison of Objective Prism Classifications with Photometric Classifications

difference of two tenths of a spectral class between the two systems, in the sense that the objective prism types are too early.

Classifications from Slit Spectra

The spectral types adopted from the classification of the slit spectra are listed below in Table 8, along with the radial velocity measurements described in a later section. Several stars having published MK types were used as standards for the classification. No stars with MK type later than A3 were available, so the later types are uncertain. A comparison of the spectral types assigned after inspection of the slit spectra, originally taken for radial velocity measurements, with the objective prism classifications is shown in Figure 7. We again see the tendency for the objective prism classifications to be too early by approximately two tenths of a class. Figure 8 shows the slit spectra classifications plotted against the intrinsic color-index, $(b-y)_o$. The mean relation between MK types and (b-y) as given by Barry (1967) is included, and the agreement with the observed points is satisfactory. This confirms our earlier contention that the objective prism classifications are systematically too early, apparently by less than a tenth of a class at A0, but up to two tenths of a class for later type stars. With so few stars

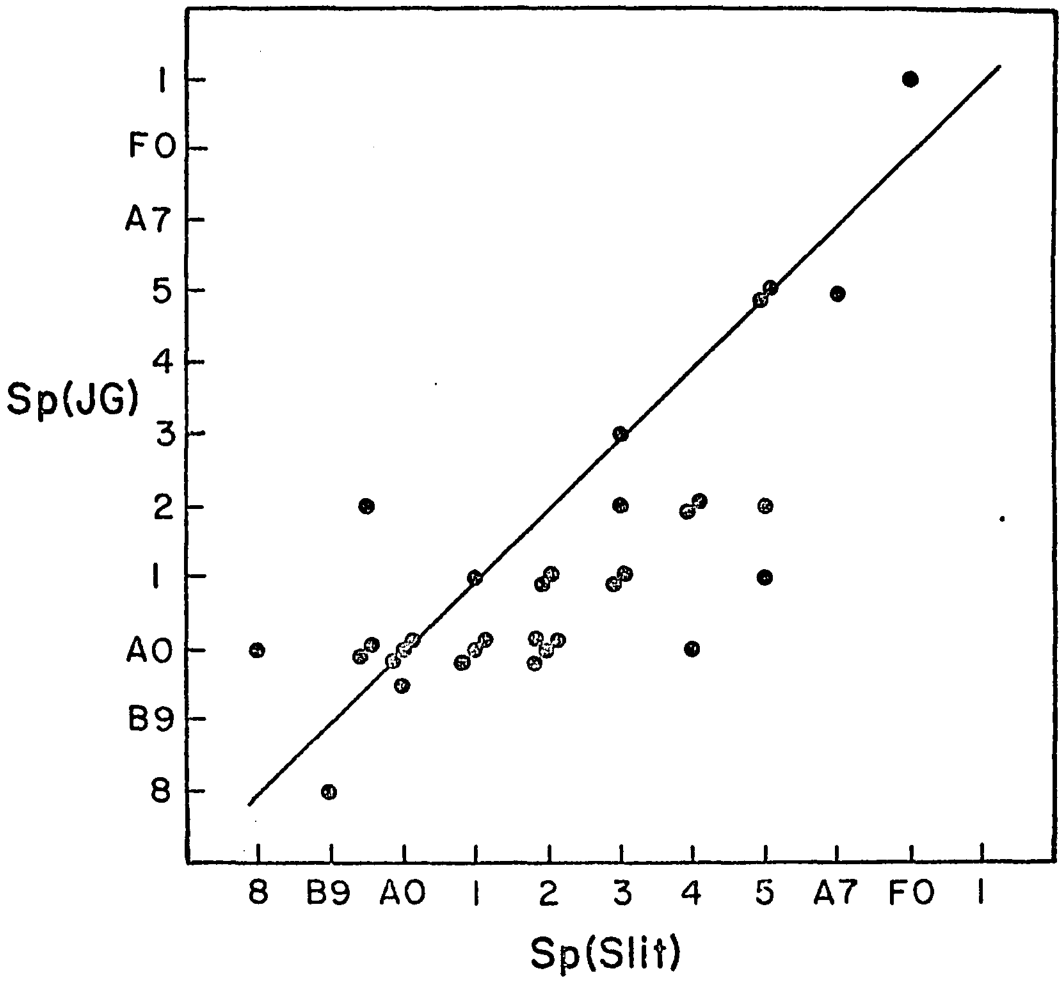

Figure 7. Comparison of Objective Prism Classifications with Slit-Spectra Classifications

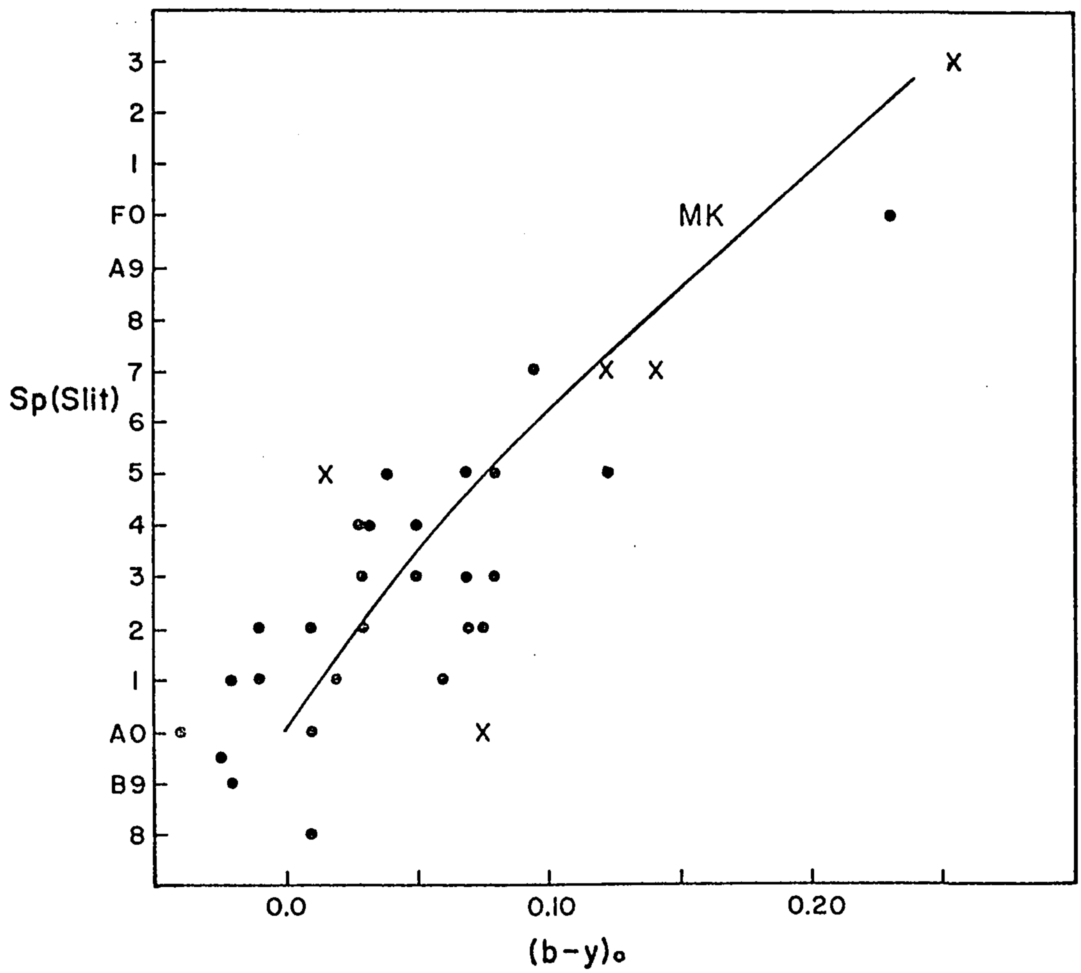

Figure 8. Comparison of Slit-Spectra Classifications with $(b-y)_o$ -- Filled circles represent stars observed in the present program; crosses, stars in Upper Scorpius observed by Garrison (1967).

available for comparison we do not feel justified in applying any corrections to the objective prism types.

uvby Photometric Reductions

Sixteen nights of uvby photoelectric photometry were available at the Cerro Tololo Inter-American Observatory (C. T. I. O.) during May 1968. Data were obtained with two 16-inch telescopes using Steward Observatory's No. 1 set of uvby filters. The transmission curves of these filters are compared in Figure 9 to the original filters used by B. Strömgren in setting up the four-color system.

Filters having rather narrow transmission curves such as those used for uvby photometry must be carefully matched in effective wavelength to assure a straightforward transformation from the instrumental to the standard system. It may be seen from Figure 9 that most of the filters satisfy this requirement with the possible exception of the v-filter. For this reason it is desirable to reduce the photometric data using the following relations, which include a color term in the transformations to compensate for the differences in filter sets:

$$V = A + y' - B \cdot (b-y)$$

$$(b-y) = C + D \cdot (b-y)'$$

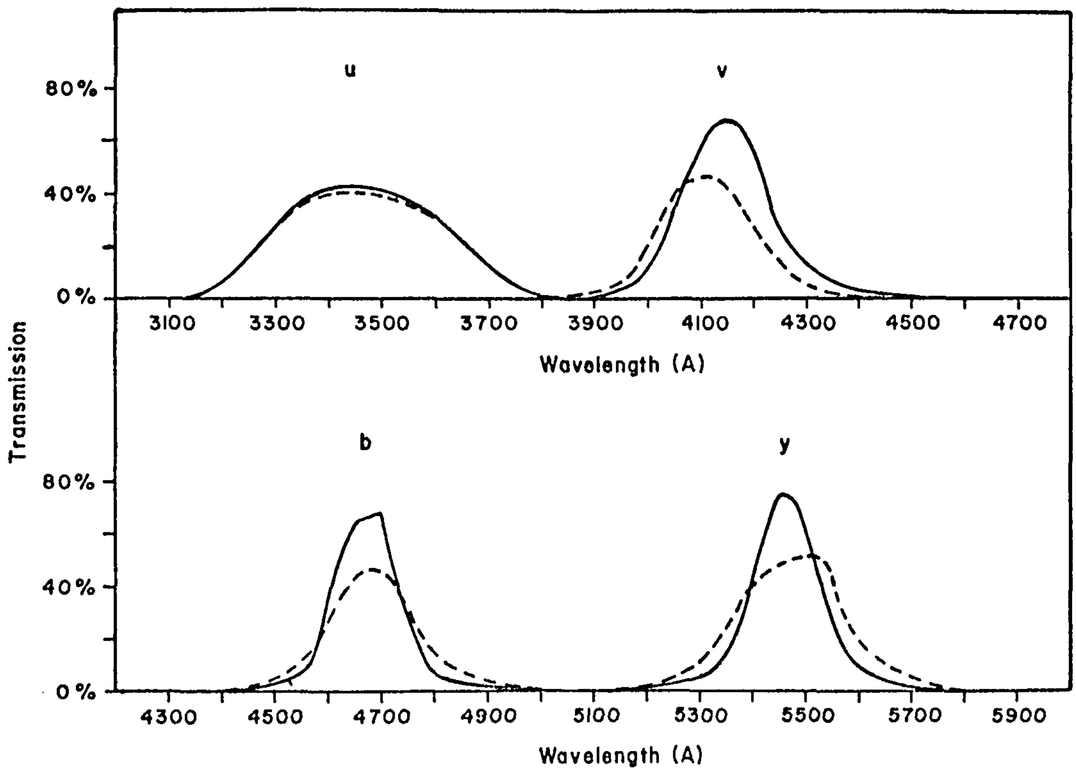

Figure 9. Four-Color Filter Transmission Curves -- Solid lines represent the Steward Observatory No. 1 set of uvby filters; broken lines, the Kitt Peak National Observatory No. 1 set.

$$m_1 = E + F \cdot m' + J \cdot (b-y)$$

$$c_1 = G + H \cdot c' + I \cdot (b-y)$$

(b-y)', m', c', and y' are the instrumental indices already corrected for atmospheric extinction.

In correcting the instrumental magnitudes for extinction, only the color-independent extinction coefficients are used, once again, because of the narrow bandpass of the filters. Individual coefficients computed on the basis of observing two or more stars through a large air mass are listed in Table 1. These coefficients are defined such that:

$$y = y'' - k \cdot X$$

$$(b-y)' = (b-y)'' - k_1 \cdot X$$

$$m' = m'' - k_2 \cdot X$$

$$c' = c'' - k_3 \cdot X$$

where X is the air mass at the time of observation, and the double primed (") quantities are the raw instrumental magnitudes. The average values of each of these coefficients did not differ appreciably from the mean values calculated for C. T. I. O. from a large number of well determined individual coefficients: $\overline{k} = 0.179$, $\overline{k}_1 = 0.068$, $\overline{k}_2 = 0.053$, and $\overline{k}_3 = 0.187$ (Barnes, 1970). These means were adopted during the data reduction.

Table 1. Four-Color Extinction Coefficients

Night	k	k_1	k_2	k_3	Wt.
May 2	0.230	0.051	0.063	0.184	1/2
6	0.190	0.070	0.035	0.198	1
20	0.192	0.036	0.066	0.200	1
22	0.215	0.043	0.066	0.193	1/2
29	0.121	0.055	0.036	0.183	1
June 1	0.163	0.041	0.044	0.194	1/2

Standard stars from the list of Crawford and Barnes (1970c) were observed each night, and the published values of the (b-y)-, m_1-, and c_1-indices allowed transformation from the instrumental to the standard system. After transforming each night's observations separately, it was obvious that the slopes in the transformation equations were constant, so averages were found for each coefficient. Some nights were assigned half weight according to the scatter of residuals in the standard star observations. The weighted averages and their standard deviations are: $B = -0.043 \pm 0.039$, $D = 1.004 \pm 0.012$, $F = 1.144 \pm 0.037$, $J = 0.087 \pm 0.018$, $H = 0.948 \pm 0.009$, and $I = -0.212 \pm 0.016$. The final data reductions were done using these mean coefficients, and the reduction program determined only the zero points for each transformation. Table 2 shows the root mean square errors determined from the standard star observations for each night. The nights of May 21 and May 24 were reduced in two parts because the transformation in the y-magnitude changed during the night.

An independent check on the consistency of the photometry is obtained by comparing the data to observations of eight of the program stars by Crawford and his associates. Mean differences and standard deviations in the (b-y)-, m_1-, and c_1-indices are, respectively, $+0^m.002 \pm 0^m.009$ (s.d.), $-0^m.003 \pm 0^m.017$, and $+0^m.003 \pm 0^m.018$. No corrections have been applied to the photometric indices determined in this program.

A similar comparison was made of the V-magnitudes on the Johnson-Morgan system, which was calculated using the above transformations from the y-magnitude to those found from UBV photometry of the same stars by Hardie and Crawford (1961), Guttierrez-Moreno and Moreno (1968), and Garrison (1967). In this case the mean differences between their photometry and mine are quite systematic, with an average difference of $-0^m.03 \pm 0^m.01$ (s.d.). This correction was applied to all of the Tololo observations, since the above mentioned authors did a more thorough analysis of the atmospheric extinction and the zero point of the V magnitude transformation than was possible in this uvby program.

Table 2. R.M.S. Errors from uvby Reductions

Night		V	(b-y)	m_1	c_1	n
May	2	$0\overset{m}{.}031$	$0\overset{m}{.}008$	$0\overset{m}{.}011$	$0\overset{m}{.}016$	16
	3	0.029	0.008	0.012	0.013	27
	4	0.027	0.007	0.012	0.013	26
	5	0.033	0.008	0.010	0.013	20
	6	0.024	0.006	0.012	0.014	20
	20	0.031	0.011	0.009	0.012	21
	21.1	0.026	0.009	0.015	0.014	10
	21.2	0.023	0.007	0.011	0.015	12
	22	0.037	0.014	0.014	0.017	21
	23	0.048	0.010	0.013	0.014	8
	24.1	0.019	0.004	0.012	0.012	7
	24.2	0.025	0.017	0.024	0.008	10
	25	0.028	0.010	0.012	0.012	12
	29	0.024	0.015	0.009	0.011	13
	30	0.026	0.013	0.020	0.013	12
June	1	0.031	0.015	0.012	0.013	16

In addition to the Tololo data described above, additional observations of a few stars were obtained on June 26 and June 27, 1969 using the K. P. N. O. No. 2 36-inch telescope with the K. P. N. O. No. 1 set of uvby filters. Transformation of the (b-y)-, m_1-, and c_1-indices was straightforward; however, four stars in common with the lists of Hardie and Crawford and the Morenos showed a systematic difference of $+0^{m}.08$ in the V-magnitude, probably caused by the fact that these stars were observed at low altitude and a mean extinction coefficient was used to reduce the observations. This correction was applied to each observation made on those two nights.

The final averaged data are listed in Table 3, along with the Hβ photometry described below.

Hβ Photometry Reductions

During May 1968 Hβ photometric data were obtained on nine nights for the Scorpio-Centaurus program stars using the C. T. I. O. 16-inch telescopes and filters Nos. 217 and 222 belonging to that observatory. The data were recorded on a strip chart recorder using a series of 10 second integrations with a charge integrator having $2^{m}.5$ and $0^{m}.5$ gain steps. The integrator gains were calibrated each night. The results were quite consistent, and during the data reductions mean gain calibrations were used for each integrator. One half-night (May 17.1) of observations was

Table 3. Photometry of Stars in Scorpius and Centaurus

HD No.	V	(b-y)	m_1	c_1	n	β	n
118060	$8^m.86$	$0^m.096$	$0^m.202$	$0^m.991$	3	$2^m.861$	3
118335	7.62	.015	.166	1.002	3	2.921	3
119103	7.11	-.018	.109	.941	3	2.774	3
119221	7.24	.086	.192	.924	3	2.879	2
119268	8.57	.040	.162	1.042	2-1/2	2.888	3
119361	5.94	-.024	.101	.760	2	2.711	3
119430	7.07	.003	.113	1.098	3	2.830	2-1/2
119674	9.00	.165	.257	.870	3	2.823	3
120487	8.96	.144	.197	.812	3	2.819	3
120959	8.70	.075	.172	1.113	3	2.848	3
120960	7.81	.207	.170	.687	3	2.745	3
121057	7.15	.091	.198	1.002	3	2.869	3
121226	7.41	.050	.164	1.071	3	2.893	3
121399	7.16	.269	.112	.943	3	2.741	2-1/2
121528	9.15	.218	.168	.815	3	2.747	3
121701	8.57	.084	.220	.931	3	2.875	3
122109	8.00	.028	.139	1.109	3	2.870	3
122664	8.35	.129	.170	.916	3	2.833	3
122705	7.62	.056	.204	.955	3	2.895	3
122756	8.64	.252	.137	.551	3	2.711	3
122757[a]	8.56	.084	.165	1.010	3	2.885	3
123021	8.32	.150	.177	.779:	3	2.786	3
123291	8.23	.024	.127	.949	2-1/2	2.836	3
123344	7.95	.017	.154	.986	3	2.880	3
123431	8.72	.003	.150	1.014	3	2.894	3
123635[b]	7.70	.026	.086	.616	3	2.714	3
123664	7.63	.067	.139	1.200	3	2.876	3
124228	7.85	.104	.162	1.059	3	2.854	3
124254	7.41	.119	.187	.895	3	2.818	3
124504	8.09	.133	.194	.905	3	2.844	3
124540	9.00	.084	.171	1.135	3	2.895	3
125253	7.08	.038	.193	1.021	3	2.921	3
125509	7.69	-.003	.130	.995	3	2.859	3
125541	8.84	.186	.193	.680	3	2.746	3
125718	9.23	.124	.177	.995	3	2.863	3
125937	8.08	.143	.178	.881	3	2.810	3
126062	7.44	.024	.187	.980	3	2.918	3
126110	7.90	.025	.125	.951	3	2.855	3
126135	6.98	-.019	.119	.725	2	2.788	3
126194	6.69	.063	.170	.885	2	2.873	3
126476	8.06	.089	.207	.982	3	2.860	3
126561	7.23	-.008	.172	.964	3	2.914	3
127716	6.61	.043	.141	1.283	3	2.843	3
127717	9.03	.192	.184	.741	3	2.742	3
127778	9.84	.277	.172	.678	3	2.700	2

Table 3.--Continued Photometry of Stars in Scorpius and Centaurus

HD No.	V	(b-y)	m_1	c_1	n	β	n
127879	7ᵐ83	0ᵐ143	0ᵐ190	0ᵐ828	2-1/2	2ᵐ812	3
128066	8.85	.223	.142	.659	3	2.716	3
128224	8.81	.054	.189	1.119	3	2.886	3
128344	6.63	.012	.104	.755	3	2.747	3
128532	6.78	.083	.194	1.018	3	2.872	3
128648	8.82:	.297	.159	.502	3	2.665	3
128788	8.27	.109	.190	.898	3	2.860	3
128819	6.64	-.025	.124	.756	2	2.800	3
128855	7.35	.041	.144	1.182	3	2.844	3
129791	6.89	.033	.140	.972	3	2.864	3
130133	8.44	.053	.194	1.044	3	2.884	3
130163	6.92	.007	.158	1.060	3	2.879	3
130388	7.61	.108	.174	.994	3	2.863	3
131399	7.04	.047	.197	.967	3	2.925	3
131460	8.95	.183	.202	.813	3	2.797	3
131461[c]	7.23	.031	.185	.964	3		
131503	7.99	.133	.188	.971	3	2.830	3
131518	9.12	.164	.199	.853	3	2.795	3
131752	6.37	.031	.156	.966	3	2.874	3
131777	8.13	.039	.174	1.014	3	2.896	3
131901	7.20	.051	.169	1.053	3	2.876	3
132080[d]	9.67	.179	.184	.846	3	2.801	4
132094	7.25	-.010	.133	.917	3	2.857	3
132761	7.72	.136	.180	.894	3	2.835	3
132851	5.82	.097	.183	1.058	3	2.841	3
133574	8.69	.196	.181	.734	3	2.762	3
133716	7.17	.031	.172	1.090	3	2.892	3
133750	7.18	.022	.172	1.032	3	2.905	3
133954	8.12	.073	.217	.924	2	2.891	2
133991	9.20	.400	.192	.749:	2	2.700	2
134055	7.23	.139	.213	.796	2	2.810	2
134518	9.25	.195	.187	.870	3	2.803	2-1/2
134685	7.66	.088	.146	1.002	3	2.885	2-1/2
134930	7.36	.084	.212	.923	1		
134950	8.32	.138	.192	1.007	3	2.874	3
134990	7.06	.054	.180	1.025	3	2.863	3
135454	6.75	-.019	.142	.952	3	2.854	2-1/2
135815[e]	9.31	.129	.167	1.053	3	2.844	2-1/2
135877	8.73	.105	.220	.993	2	2.795	2
136013	7.74	.055	.147	1.007	3	2.927	3
136164	7.78	.092	.193	.913	2	2.838	2
136334	6.19	.033	.166	1.056	3	2.892	2-1/2
136482	6.65	-.029	.121	.823	3	2.805	2-1/2
136483	8.99	.280	.143	.793:	2	2.635	2

Table 3.--Continued Photometry of Stars in Scorpius and Centaurus

HD No.	V	(b-y)	m_1	c_1	n	β	n
136961	$6^m.75$	$0^m.023$	$0^m.204$	$1^m.038$	2-1/2	$2^m.908$	3
137119	7.62	.039	.214	.963	2	2.908	1
137169	8.96	.076	.182	1.112	2	2.874	1
137193	7.38	-.014	.204	.721	3	2.783	3
137432	5.49	-.072	.115	.389	1	2.707	1
137499	9.47	.297	.153	.405	3	2.656	3
137785	7.62	.105	.184	.893	2	2.878	1
137957	9.44	.038	.143	1.115	2	2.878	1
138138	6.85	.080	.212	.887	2	2.863	2
138285	7.50	.007	.174	.966	3	2.925	3
138564	6.38	-.016	.150	.925	3	2.892	3
138940	7.63	-.014	.130	.914	3	2.845	2
139048	9.10	.191	.201	.773	3	2.759	2
139094	7.38	.077	.099	.600	2	2.747	2
139160	6.19	.014	.116	.464	3		
139233	6.60	-.040	.137	.846	3	2.841	3
139486	7.63	.031	.133	.899	3		
139524	8.07	.030	.091	.870	3	2.766	3
139883	8.37	.248	.153	.517	3	2.686	3
140475	7.72	.041	.205	.960	3	2.916	3
140817	6.83	.015	.153	.838	2	2.858	3
140958	8.06	.113	.197	.856	3	2.819	3
141404	7.73	.107	.096	1.097	3		
141518	8.56	.257	.171	.475	3	2.688	3
141774	7.72	.076	.100	.881	3		
141779	8.10	.103	.203	.855	3	2.851	3
141905	8.31	.137	.151	1.093	3	2.903	3
141939	8.24	.117	.197	.984	3	2.905	3
142096	5.05	.019	.093	.293	3		
142097	8.39	.238	.169	.884	3	2.851	3
142165	5.40	.020	.104	.496	3		
142184	5.43	.016	.087	.281	3		
142250	6.18	-.022	.116	.502	3		
142301	5.90	-.017	.118	.301	3		
142315	6.89	.047	.104	.746	3		
142378	5.96	.020	.094	.351	3		
142431	7.05	.051	.187	1.015	3	2.881	3
142990	5.44	-.030	.108	.251	3		
143567	7.20	.064	.131	.826	3		
143600	7.34	.076	.112	.887	3		
143692	7.95	.115	.178	1.010	3	2.868	3
144334	5.92	-.027	.121	.353	3		
144844	5.87	.026	.120	.594	3		
145353	6.95	.107	.097	.864	3		

Table 3.--Continued Photometry of Stars in Scorpius and Centaurus

HD No.	V	(b-y)	m_1	c_1	n	β	n
145468	$8^m.21$	$0^m.194$	$0^m.169$	$0^m.942$	3	$2^m.857$	3
145554	7.63	.111	.102	.815	3		
145631	7.56	.112	.100	.866	3		
145793	7.95	.139	.160	.934	3	2.842	3
146001	6.06	.058	.083	.509	3		
146029	7.38	.064	.116	.924	3		
146284	6.70	.132	.073	.763	3		
146285	7.91	.183	.058	.723	2		
146416	6.63	.030	.112	.832	3		
146606	7.09	-.011	.147	.949	3	2.897	3
146706	7.52	.086	.107	.854	3	2.832	1
146899	10.28	.393	.128	.952	3	2.786	1
146998	9.52	.413	.177	.745	3	2.796	1
147009	8.06	.206	.094	.996	3		
147010	7.41	.125	.112	.512	3		
147196	7.04	.157	.035	.760	2		
147343	9.34	.464	.064	.993	3	2.876	3
147384	8.61	.287	.066	.983	3	2.881	3
147432	7.54	.150	.171	.905	3	2.863	3
147592	8.91	.180	.155	.984	2	2.939	3
147703	7.51	.137	.087	.932	2		
147809	8.61	.274	.085	.985	3	2.923	3
147889	7.92	.643	-.112	.045	1		
147932	7.27	.240	.035	.288	1		
148352	7.52	.255	.156	.519	2	2.689	2
148562	7.84	.084	.185	.970	2	2.901	3
148563	8.61	.137	.153	.997	3	2.923	4
148579	7.34	.210	.059	.801	3		
148594	6.89	.116	.053	.659	2	2.720	1

[a]HD 122757: faint companion.

[b]HD 123635: double star λ198; $7^m.6$, $11^m.5$ at 8^{π} (Innes, Dawson, and van den Bos 1927).

[c]HD 131461: double star I84; 7.3, 9.9 at 4^{π} (Innes et al. 1927).

[d]HD 132080: faint companion.

[e]HD 135815: faint companion.

obtained using a D.C. amplifier, also calibrated in $2^{m}.5$ and $0^{m}.5$ gain steps.

Observations were made in the manner described by Crawford and Mander (1966). Average deflections of star+sky for each filter were determined visually using a measuring engine, and the sky deflections were automatically subtracted out. The results were punched onto computer cards and an initial reduction of the data was made using the K. P. N. O. Hβ reduction program on that observatory's CDC 6400 Computer. A number of photoelectric Hβ standard stars from the list of Crawford and Mander (1966) were observed each night, and the instrumental β" values for these stars were used to transform the observations to the standard system. In doing this, however, it is often preferable to first determine the natural β' system of the filter set, and to calculate the slope of the transformation from the β' to the β system. In this procedure B-type stars are treated separately from A- and F-type stars, referred to hereinafter as AF stars.

The procedure consists of picking one night that was of good quality and contained observations of a large list of standard stars. The night of May 18 was selected as the starting point of the β' system. Individual observations on both May 17.2 and May 19 were compared to the May 18 observations and average residuals were obtained for each night and applied in the form of a night correction to each observation. Then a new β' was found for each star by averaging the corrected β''s of the May 17.2 and 19 with the β'' of May 18. This gave a second approximation to the β' system. This procedure was repeated for the rest of the nights by finding individual residuals of each observation with the current β' adopted for each star, night corrections were calculated and applied, and a new average β' was calculated by averaging together all of the nights. One final round of calculations was then made for all nights, and the resulting β' values, the number of nights observed, and the standard β values are given in Table 4. The transformations determined by least squares solutions for the AF stars and the B stars are:

$$\text{AF stars:} \quad \beta_{AF} = 0.9809\beta' - 0.0193 \text{ (rms error } \pm 0^{m}.0041)$$

$$\text{B stars:} \quad \beta_{B} = 0.9543\beta' + 0.0563 \text{ (rms error } \pm 0^{m}.0056)$$

The final data reductions were done using only the slopes of these relations. The reduction program calculated the zero points separately for each night. The final rms errors derived for each night's standard star observations are given in Table 5, along with n, the number of standards observed.

Twenty-one stars in these observing lists having two or more observations also have been observed at least twice by D. L. Crawford and his associates during observing

Table 4. Hβ Standard Stars

B Stars				AF Stars			
HR	β	β'	n	HR	β	β'	n
3314	$2^{m}.897$	$2^{m}.985$	4	4405	$2^{m}.821$	$2^{m}.900$	7
3410	2.851	2.936	5	4540	2.628	2.700	7
3454	2.653	2.718	5	5270	2.540	2.605	8
4119	2.730	2.798	7	5531	2.863	2.940	1
4133	2.555	2.619	7	5997	2.579	2.653	9
5511	2.846	2.920	9	6355	2.878	2.956	7
5993	2.621	2.686	9	7069	2.903	2.973	2
6141	2.662	2.736	7	7377	2.739	2.809	8
6629	2.908	2.979	7				
6714	2.590	2.653	8				
7446	2.565	2.634	5				
7447	2.711	2.777	4				

Table 5. RMS Errors from Hβ Reductions

Night	AF Stars	n	B Stars	n
May 8	$0^m.0073$	7	$0^m.0057$	16
9	0.0097	7	0.0052	15
15	0.0082	7	0.0078	21
16	0.0075	6	0.0079	4
17.1	0.0036	2	0.0142	5
17.2	0.0042	8	0.0073	18
18	0.0065	13	0.0073	16
19	0.0042	10	0.0068	11
29	0.0107	7	0.0036	8
June 1	0.0040	7	0.0083	11

runs at C. T. I. O. The average difference between the two sets of observations was $-0\overset{m}{.}003 \pm 0\overset{m}{.}014$ (s.d.). It therefore may be concluded that the Hβ observations obtained in this program are on the standard system of Crawford and Mander (1966) and may be combined with the additional data obtained by Crawford and his associates without loss of accuracy.

The final averaged data are listed in Table 3, above, and Table 6, along with the uvby photometry.

Radial Velocity Summary

The plate material consisted of measurable spectra of four standard velocity stars and 44 measurable spectra of 26 program stars (mostly $m_{pg} = 9$ and fainter), obtained in May 1968 with the C. T. I. O. 60-inch spectrograph at 78 A/mm. Eleven measurable spectra of four standard velocity stars and 135 measurable spectra of 54 program stars (mostly brighter than $m_{pg} = 9$) were obtained at 62 A/mm with the C. T. I. O. 36-inch spectrograph in early June 1968. All measured spectra had iron-arc comparison lines and were measured on the Grant Comparator Engine of the K. P. N. O. Laboratory wavelengths were used to reduce the measurements using N. B. Sanwal's radial velocity program on the K. P. N. O. CDC 6400 computer. This program fits a polynomial equation to the observed positions of the comparison lines, giving a prediction of the observed

Table 6. Stars Having Only β Observations

HD	β	n
120307	$2^{m}.631$	3
120324	2.473	3
120908	2.685	3
120955	2.672	3
121743	2.641	3
125238	2.655	3
132955	2.704	2
133937	2.739	2
135814	2.766	2
136504	2.658	2
140008	2.733	2
140543	2.583	2
140602	2.882	2
143118 AB	2.622	3
143699	2.709	2
144294	2.674	2
147890	2.755	3
148321	2.880	3
148703	2.641	2
151346	2.706	3

wavelength as a function of the linear distance from some reference point. The maximum order of the polynomial depends on the size of the scatter on the data. Forward and reverse measurements are combined by taking weighted mean velocities for all stellar lines which were measured in both directions.

Both spectrographs apparently had mechanical problems during the observing period. The velocities obtained from the 60-inch spectrograph of the four standard velocity stars show a great deal of scatter and imply that the spectra were of poor quality. The velocities measured from the 36-inch spectra show a reasonably small scatter; however, too few plates were taken of too few standard stars to allow a proper determination of the external probable errors and the systematic errors. It seems likely, though, that any systematic error calculated from these data lies within the scatter in velocities.

As a check on the scatter in the data the range in velocities observed for each program star was determined and was used to construct a histogram (Figure 10) of the number of stars with velocity ranges ($\Delta V_r = V_{max} - V_{min}$) between 0-9, 10-19, ... km/sec. It should be noted that most of the stars observed with the 60-inch only had two spectra per star, whereas many of the stars observed with the 36-inch had three or four spectra, hence the first histogram, which has a larger statistical sample, is

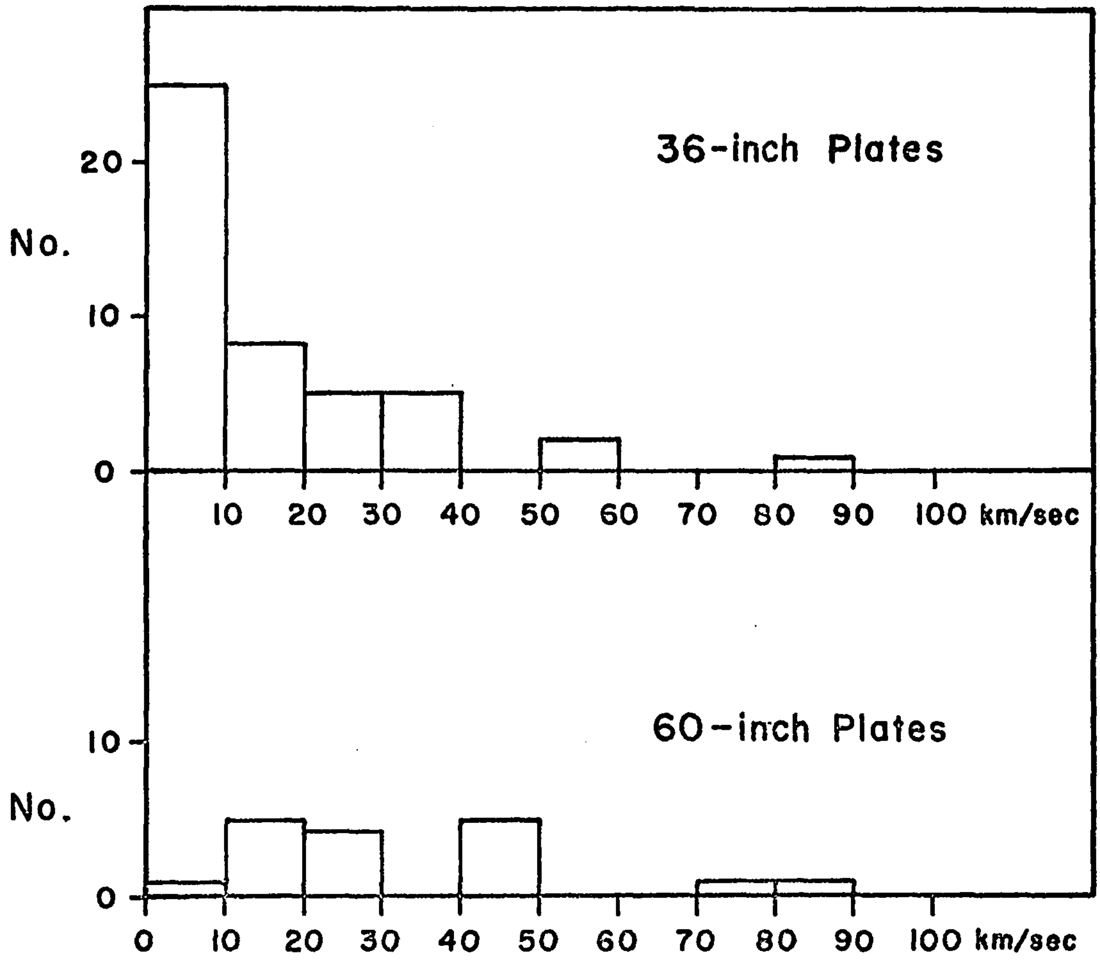

Figure 10. Frequencies of Radial Velocity Ranges, $(V_{max} - V_{min})$

actually biased towards showing larger ΔV_r's than the second. The interpretation of the first histogram is that there are a large number of constant velocity stars in the data, and that the dispersion in their velocities is less than 10 km/sec. The second histogram shows no such low velocity range peak, but there may be a peak at around 20 km/sec. If real, this would imply that the scatter of the measured velocities is much larger than it should be at this dispersion, and therefore that the velocities should not be trusted to indicate either spectroscopic binaries or single (constant velocity) stars. The very discrepant velocities obtained for the velocity standards α Hya and η Leo (see Table 7) would in themselves be sufficient to imply that the velocities obtained with the 60-inch are unreliable.

It is suggested, therefore, that (1) the 60-inch spectra be discarded from any further analysis, and (2) the spectra from the 36-inch be analyzed using 10-15 km/sec as an acceptable variation for a "constant" velocity star--keeping in mind that these spectra were all taken within a five day period. The final data are listed in Table 8.

Table 7. Radial Velocity Observations of Standard Velocity Stars

Name	Date J.D. 2439980+	Vel (km/sec)	N	p.e. (km/sec)	Tele	V_r (publ) (km/sec)
α Hya	8.471	+77.3	16	2.4	60 in	-4.4
η Leo	8.480	+217.4	10	2.8	60	+2.2
	32.458	+7.2	9	0.8	36	
β Vrr	8.490	+21.3	12	2.1	60	+5.0
	30.473	+1.9	9	2.0	36	
	30.477	+5.4	12	1.5	36	
β Crv	10.609	+12.9	16	1.8	60	-7.7
	30.488	-9.5	16	1.1	36	
	30.568	-4.7	17	1.4	36	
	31.483	+0.3	11	1.9	36	
	32.580	-8.2	15	1.4	36	
α TrA	29.894	+19.9	10	1.6	36	-3.7
	30.897	-2.0	16	0.8	36	
	31.810	+3.4	13	1.6	36	
	31.902	-1.8	12	1.5	36	

Table 8. Radial Velocity Observations of Stars in Scorpius and Centaurus

HD No.	Date J.D. 2440000+	Vel (km/sec)	N (lines)	p.e. (km/sec)	Sp
118335	9.560	-8.0	10	2.6	
	10.514	-8.2	9	4.6	
	12.473	-5.3	9	3.3	
		-7.2 (3)			A1 III:
119103	9.545	+13.4	8	2.6	
	10.528	-24.3	7	1.6	
	12.484	-18.4	9	3.7	
		var? (3)			B8: .
119361[a]	11.490	-23.3	9	3.6	B7 V
119430	9.514	+3.2	10	3.4	
	9.519	-0.6	9	2.2	
	11.497	+15.0	10	2.5	
	12.492	+6.1	9	1.5	
		+5.9 (4)			A0 III:
120959	9.573	+22.4	9	1.0	
	12.508	+19.6:	8	5.7	
		+21.0 (1-1/2)			A3 V
121399[b]	9.587	-14.9	11	3.2	
	11.504	+3.9:	10	5.0	
	12.520	-10.7	10	3.3	
		-9.4: (2-1/2)			Composite
121701	9.606	-3.8	9	3.4	A5 IV:
122109	9.620	-12.0	10	2.0	
	10.544	-12.2	10	3.6	
	12.620	-7.2	10	3.9	
		-9.3 (3)			A2 V
122705	9.631	+7.5	10	2.3	
	10.555	-1.5:	9	5.9	
	12.631	+6.5:	9	5.0	
		+5.0 (2)			A4 V
122756	9.645	-1.0	8	1.3	F0:

Table 8.--Continued Radial Velocity Observations of Stars in Scorpius and Centaurus

HD No.	Date J.D. 2440000+	Vel (km/sec)	N (lines)	p.e. (km/sec)	Sp
122757	9.672	-25.5	7	4.6	
	12.536	-20.0	9	4.8	
		-22.7 (2)			A4: V
123291	9.744	+3.2:	7	7.7	
	12.553	-30.8	10	2.1	
	12.643	-21.4	10	2.6	
		-20.2 (2-1/2)			A0 IV
123344	9.709	+25.9	10	1.8	
	10.577	+50.8	9	2.4	
	12.656	-4.6	10	3.7	
		var? (3)			A0 III:
123635	9.687	+7.0	10	2.4	
	10.589	+5.0	9	1.1	
	12.668	-2.0	9	2.1	
		+3.3 (3)			B8 III:
123664	9.700	-5.1	10	4.1	
	10.598	-9.0	10	2.8	
	12.679	-10.2	10	4.1	
		-8.1 (3)			A2 IV:
125509	10.607	-7.0	10	3.4	
	12.668	-1.7	9	4.4	
		-4.3			B9.5 III:
126110	9.768	-4.5	10	2.6	
	10.624	-6.0:	10	6.3	
	12.720	+1.2	9	4.7	
		-2.5 (2-1/2)			B9 IV
126135	9.781	+16.0:	9	5.3	
	10.635	+29.9:	5	2.6	
	12.569	+6.3	8	3.0	
	12.757	+24.9	9	2.7	
		+18.1 (3)			B8 V

Table 8.--Continued Radial Velocity Observations of Stars in Scorpius and Centaurus

HD No.	Date J.D. 2440000+	Vel (km/sec)	N (lines)	p.e. (km/sec)	Sp
126194	9.786	+75.9:	7	5.3	
	11.570	-7.1	10	3.2	
	12.586	-65.7	10	3.4	
		var? (2-1/2)			A2 V
127716	10.655	-27.9	9	3.0	
	11.579	-32.8	9	1.3	
	12.564	-33.8	9	2.6	
	12.614	-39.9	9	1.8	
		-33.8 (4)			A3 IV
127879	11.587	+2.7	9	4.1	
	12.746	+5.0	9	3.8	
		+3.8 (2)			A5 V
128344	9.799	+25.7	8	3.3	
	10.665	+16.9:	9	5.0	
	11.595	+7.3	9	3.8	
	12.592	+17.6	9	3.0	
		+16.9 (3-1/2)			B7 V
128819	9.804	+24.8	9	2.5	
	11.600	+19.0:	9	3.6	
		+22.8 (1-1/2)			B8 V
128855	10.696	-46.0	9	2.4	
	11.607	+6.6	10	3.0	
		var? (2)			A1 V
129791	9.811	-4.4	9	4.7	
	11.614	+11.1	9	3.9	
		+3.3 (2)			B9.5 V
130388	10.716	+12.1	8	3.4	
	11.621	+18.6	9	2.9	
		+15.4 (2)			B9.5 V
131399	10.728	-28.6	9	1.9	
	11.628	+4.3	9	1.1	
		var? (2)			A3 III:

Table 8.--Continued Radial Velocity Observations of Stars in Scorpius and Centaurus

HD No.	Date J.D. 2440000+	Vel (km/sec)	N (lines)	p.e. (km/sec)	Sp
131461	10.736	+7.6	10	1.7	
	11.637	+20.0	10	2.8	
	12.802	+22.8	9	4.5	
		+16.8 (3)			A1 IV:
132094	11.644	-26.4	9	3.5	
	12.810	-25.1:	8	5.6	
		-26.0 (1-1/2)			B9 IV
132851	9.819	+23.9	9	3.9	
	10.752	+20.7	9	3.9	
	11.650	+14.5	9	4.1	
	12.820	+12.8	8	4.1	
		+18.0 (4)			A5 V
133750	10.758	+15.0	9	2.6	
	11.654	-10.5	10	3.1	
	12.826	-7.2:	9	6.4	
		+0.3: (2-1/2)			B8 V
134685	10.767	-6.6	10	2.8	
	11.663	-18.2:	8	5.5	
		-7.8 (1-1/2)		9.0	A0 V
134930	11.671	-10.8:	8	6.7	
	12.848	+7.0:	7	5.9	
		-1.9 (1)			A5
135454	10.780	+21.3	9	1.7	
	11.678	+12.2	9	3.4	
	12.854	+11.4:	8	8.2	
		+15.7 (2-1/2)			B9 V
136013	12.599	+6.4:	10	3.0	A1 V
136334	10.798	-3.1	10	3.6	
	11.683	+1.8	10	3.8	
		-0.6 (2)			A2 V
136482	10.802	+10.1	7	4.4	
	11.715	+7.9	9	9.0	
		+9.0 (2)			B9 V

Table 8.--Continued Radial Velocity Observations of Stars in Scorpius and Centaurus

HD No.	Date J.D. 2440000+	Vel (km/sec)	N (lines)	p.e. (km/sec)	Sp
136961	10.807	+1.4	9	4.9	
	11.719	+2.1	10	2.8	
		+1.8 (2)			A4 IV
137193	10.814	-15.2:	7	6.3	
	11.725	-17.8	9	1.6	
	12.607	-17.2	10	1.9	
		-17.0 (2-1/2)			Ap
138285	10.821	+12.8:	9	6.3	
	11.735	+38.6	10	2.8	
		+30.0 (1-1/2)			A2 V
138564[c]	9.825	+21.3	9	3.0	
	10.826	+1.0	9	2.5	
	12.880	+35.4:	6	5.4	
		+16.0 (2-1/2)			B9 IV:
138940	10.834	-15.3	9	2.0	
	11.742	-12.7	10	3.0	
		-14.0 (2)			A0 IV
139233	9.829	+8.4	8	3.4	
	10.845	+16.4	10	2.6	
	11.750	+9.7	9	2.8	
	12.886	+16.5:	9	7.2	
		+12.2 (3-1/2)			B9 V
139524	11.760	-16.3:	8	3.9	B9 V
140475	11.775	+20.7	9	2.3	A5 III:
140817	9.834	+5.5	10	4.0	
	10.850	+4.5	9	4.5	
		+5.1 (2)			A0 V
141779	11.788	+6.2:	7	1.7	A7 V
145793	10.859	-5.3	11	4.1	
	11.801	+2.5:	10	5.4	
		-2.7 (1-1/2)			A3 V

Table 8.--Continued Radial Velocity Observations of Stars in Scorpius and Centaurus

HD No.	Date J.D. 2440000+	Vel (km/sec)	N (lines)	p.e. (km/ sec)	Sp
146606	9.844	+26.3	10	3.6	
	10.875	+12.8	10	3.4	
	11.832	+2.8	10	4.3	
	12.908	+7.5:	5	6.8	
		+13.0 (3-1/2)			A0 V
147010[d]	9.861	+3.7	9	2.9	
	11.862	-1.3	8	1.3	
		+1.2 (2)			Ap
147432	9.851	-18.6:	8	7.0	
	10.890	-10.2	9	3.4	
	11.845	-6.1:	7	5.5	
		-11.3 (2)			A2 V
147890[e]	11.876	+9.9:	8	6.2	B9.5p (St)
148562[f]	11.892	+2.8:	8	6.1	A3 V
148563[g]	9.876	-1.1	8	4.1	A2 V

[a]HD 119361: Spectral type from Hube (1970).

[b]HD 121399: Types A0: + G ?

[c]HD 138564: Spectral type from Hube (1970).

[d]HD 147010: Spectral type from Garrison (1967).

[e]HD 147890: Spectral type from Garrison (1967).

[f]HD 148562: Spectral type from Garrison (1967).

[g]HD 148563: Spectral type from Garrison (1967).

CHAPTER 3

B STAR ANALYSIS

In addition to the uvby and Hβ observations obtained in this program by the present author, a large number of B-type stars in Scorpio-Centaurus have been observed by D. L. Crawford and his co-workers (Crawford, Barnes, and Golson 1970, and Crawford 1970b). The data for the stars used in present discussion are listed in Tables 9, 10, 11, and 12, along with their photometric properties. For those stars observed by Crawford et al., Gutierrez-Moreno and Moreno (1968), and the present author, the data have been combined with equal weight in the following analysis.

Reddening Corrections

The stars selected to be analyzed as B-type stars had to satisfy the following criteria: (1) $2.550 \leq \beta \leq 2.880$ and (2) $c_1 \leq 0^m.95$. The intrinsic color of each star was computed using the equation $(b-y)_o = -0.116 + 0.097\ c_1$ given by Crawford, Glaspey, and Perry (1970) to estimate $(b-y)_o$, the $E(c_1) = 0.2\ E(b-y)$ (where E = observed minus intrinsic color) was computed and used to correct c_1 for reddening, and a new value of $(b-y)_o$ was calculated. For highly reddened stars this procedure had to be repeated one more time to correct completely for reddening. The

Table 9. Additional Photometric Data for B-Type Stars in Lower Centaurus

Name	HD No.	V	b-y	m_1	c_1	n	β^a	n
HR 4618	105382	4^m.45	-0^m.079	0^m.102	0^m.264	9	2^m.677	16
δ Cen	105435	2.51	-.016	.048	-.010	3	2.467	6
ρ Cen	105937	3.94	-.087	.114	.326	3	2.707	6
δ Cru	106490	2.78	-.113	.086	.043	3	2.619	6
ζ Cru	106983	4.05	-.089	.105	.259	3	2.680	6
σ Cen	108483	3.91	-.089	.092	.157	3-1/2	2.654	6
γ Mus	109026	3.85	-.077	.110	.346	3	2.695	6
α Mus	109668	2.69	-.104	.093	.112	3	2.649	6
HR 4848	110956	4.64	-.070	.096	.301	4	2.701	6
β Cru	111123	1.29	-.103	.061	-.041	3-1/2	2.597	6
λ Cru	112078	4.63	-.062	.086	.364	3	2.681	6
μ_1 Cru	112092	4.06:	-.082	.093	.179	4	2.664	6
HR 4940	113703	4.69	-.063	.099	.378	3	2.716	6
ξ_2 Cen	113791	4.30	-.085	.088	.163	3	2.657	6
HR 5035	116087	4.58:	-.069	.107	.350	3	2.700	6
ε Cen	118716	2.30	-.094	.058	.043	3	2.612	6

[a]The quoted value of β is a mean of the Crawford et al. and the Gutierrez-Moreno and Moreno values.

Table 10. Additional Photometric Data for B-Type Stars in Upper Centaurus

Name	HD No.	V	(b-y)	m_1	c_1	n	β	n
ν Cen	120307	$3^m.40$	$-0^m.102$	$0^m.076$	$0^m.084$	3	$2^m.626$[a]	9
μ Cen	120324	3.42v	-.051	.054	-.006	3	2.478[a]	9
3 Cen	120709	4.34	-.033	.104	.318	5-1/2	2.700	9
HR 5217	120908	5.89	.039	.074	.526	2-1/2	--	
4 Cen	120955	4.74	-.046	.081	.466	3	2.674[b]	6
Ø Cen	121743	3.81	-.105	.082	.145	3	2.646[a]	9
HR 5249	121790	3.85	-.101	.090	.162	3	2.642[b]	6
χ Cen	122980	4.34	-.095	.089	.179	9	2.651[b]	16
2 Lup	125238	3.54v?	-.082	.082	.258	3	2.656	3
a Cen	125823	4.40	-.086	.080	.211	3	2.656[b]	6
α Lup	129056	2.30	-.088	.058	.098	3	2.604[b]	6
HR 5471	129116	4.00	-.078	.091	.251	3	2.675[b]	6
o Lup	130807	4.33	-.077	.092	.358	3	2.693[b]	6
β Lup	132058	2.71	-.098	.064	.099	3	2.618[b]	6
κ Cen	132200	3.14	-.097	.080	.191	3	2.639[b]	6
HR 5595	132955	5.44	-.046	.094	.346	3	--	
HR 5625	133937	5.83	-.048	.103	.549	3	--	
λ Lup	133955	4.07	-.078	.098	.280	10	2.698[a]	16
δ Lup	136298	3.22	-.097	.067	.085	3	2.616[b]	6
ε Lup	136504	3.41	-.089	.088	.216	3	2.656[a]	9
$Ø_2$ Lup	136664	4.53	-.069	.092	.327	3	2.684[b]	6
γ Lup	138690	2.81	-.097	.082	.142	3	2.634[b]	6
d Lup	138769	4.54	-.088	.096	.271	3	2.684[b]	6
$Ψ_2$ Lup	140008	4.75	-.064	.100	.423	3	2.728[a]	9
HR 5873	141318	5.75	.081	.015	.122	2-1/2	--	
η Lup	143118	3.42	-.102	.077	.114	3	2.619[a]	9

Table 10.--Continued

HR 5967	143699	4.90	-.066	.094	.382	3	2.705	3
θ Lup	144294	5.92	-.084	.088	.261	3	2.671[a]	8

[a]The quoted value of β is a mean of the Crawford et al., Gutierrez-Moreno and Moreno, and Glaspey observations.

[b]The quoted value of β is a mean of the Crawford et al. and the Gutierrez-Moreno and Moreno values.

Table 11. Additional Photometric Data for B-Type Stars in Scorpius

Name	HD No.	V	(b-y)	m_1	c_1	n	β	n
τ Lib	139365	$3^{m}.68$	$-0^{m}.081$	$0^{m}.087$	$0^{m}.269$	3	$2^{m}.682$[a]	6
	140543	8.88	.065	.022	-.066	3	--	
1 Sco	141637	4.64	.003	.070	.130	8	2.640[a]	14
2 Sco	142114	4.60	-.003	.065	.246	3	2.678[a]	6
ρ ScoA	142669	3.88	-.089	.074	.165	3	2.645[a]	6
HR 5934	142883	5.86	.044	.095	.353	3-1/2	2.723	3
	142884	6.78	.058	.074	.387	3	2.725	4
HR 5941	142983	4.95	-.022	.083	.768	3-1/2	2.593	3
π Sco	143018	2.89	-.058	.045	.032	Std	2.614	Std
δ Sco	143275	2.31	-.019	.038	-.018	Std	2.602	Std
ω_2 Sco	144470	3.95	.031	.038	.022	Std	2.621	Std
	145102	6.60	.072	.093	.822	3	2.796	4
13 Sco	145482	4.58	-.070	.083	.200	3	2.652	3
ν Sco	145502	4.00	.072	.059	.150	6	2.674[b]	6
HR 6042	145792	6.40	.063	.075	.416	3	2.725	3
	146332	7.63	.188	.039	.472	2	2.668	2
σ ScoA	147165	2.88	.164	.002	.030	4	2.603	3
ρ OphD	147888	6.74	.260	.036	.289	3	2.713	2
	147889	7.89	.657	-.071	.050	3	2.664	8
	147890	7.66	.200	.047	.832	3	--	
χ Oph	148184	4.42	.254	-.054	-.147	5	2.380[a]	6
22 Sco	148605	4.77	-.047	.077	.220	Std	2.662	Std
HR 6143	148703	4.25	-.060	.069	.133	3	2.646[b]	9
τ Sco	149438	2.82	-.100	.051	-.065	8	2.605[a]	6
ζ Oph	149757	2.56	.085	.082	-.061	12	2.579	12
	151346	7.90	.361	-.013	.513	3	--	
	151865	8.85	.127	.090	.711	2	2.781	2
μ_1 Sco	151890	3.04	-.089	.078	.103	3	2.625[a]	6

Table 11.--Continued

μ_2 Sco	151985	3.56	-.090	.076	.103	5	2.620[a]	6
θ Oph	157056	3.26	-.092	.089	.104	4	2.622[a]	6

[a]The quoted value of β is a mean of the Crawford et al. and the Gutierrez-Moreno and Moreno values.

[b]The quoted value of β is a mean of the Crawford et al., Gutierrez-Moreno and Moreno, and Glaspey observations.

Table 12. Additional Hβ Photometric Data for B-Type Stars in Scorpius

Name	HD No.	β	n
HR 5801	139160	$2^{m}.748$	5
λ Lib	142096	2.709	5
HR 5906	142165	2.730	5
HR 5907	142184	2.657	4
HR 5910	142250	2.734	4
3 Sco	142301	2.682	3
	142315	2.803	3
47 Lib	142378	2.686	5
HR 5942	142990	2.678	6
	143567	2.846	3
	143600	2.857	3
HR 5988	144334	2.724	6
HR 6003	144844	2.793	3
	145353	2.816	3
	145554	2.836	3
	145631	2.857	3
HR 6054	146001	2.753	6
	146029	2.769	3
	146284	2.768	3
	146285	2.818	3
HR 6066	146416	2.830	12
	147010	2.769	3
	147196	2.726	3
	148579	2.831	3

distribution on the sky of color excesses for these stars is shown in Figure 11. Blaauw's Regions 2 and 3 are included to show the general outline of this section of the moving cluster. The unreddened photometric indices, quantities derived from them (and explained below) such as the distance modulus (d.m.), and other available information are listed in Tables 13, 14, and 15.

Comparison With Spectral Classification

Reliable spectral types are available from Garrison (1967) and Slettebak (1968) for many of the brighter B-type stars in the moving cluster. These spectral types are compared with the intrinsic indices c_o and m_o and the β-index in Figures 12, 13, and 14. The location of the points representing many of the peculiar stars in the first two diagrams shows the well-known tendency of these stars to have colors more representative of earlier spectral types. This trend is not as evident in Figure 14. Instead, there seems to be a slight tendency for the middle B-type stars in Upper Scorpio to have, on the average, higher values of m_o than the B-type stars in Upper Centaurus.

The m_1-Index Discrepancy

Figure 15 shows the c_o, m_o diagram for the Scorpio-Centaurus B-type stars. The different sequences for the Upper Scorpio and Upper Centaurus stars are clearly evident. The fact that the Centaurus sequence is narrow is also of

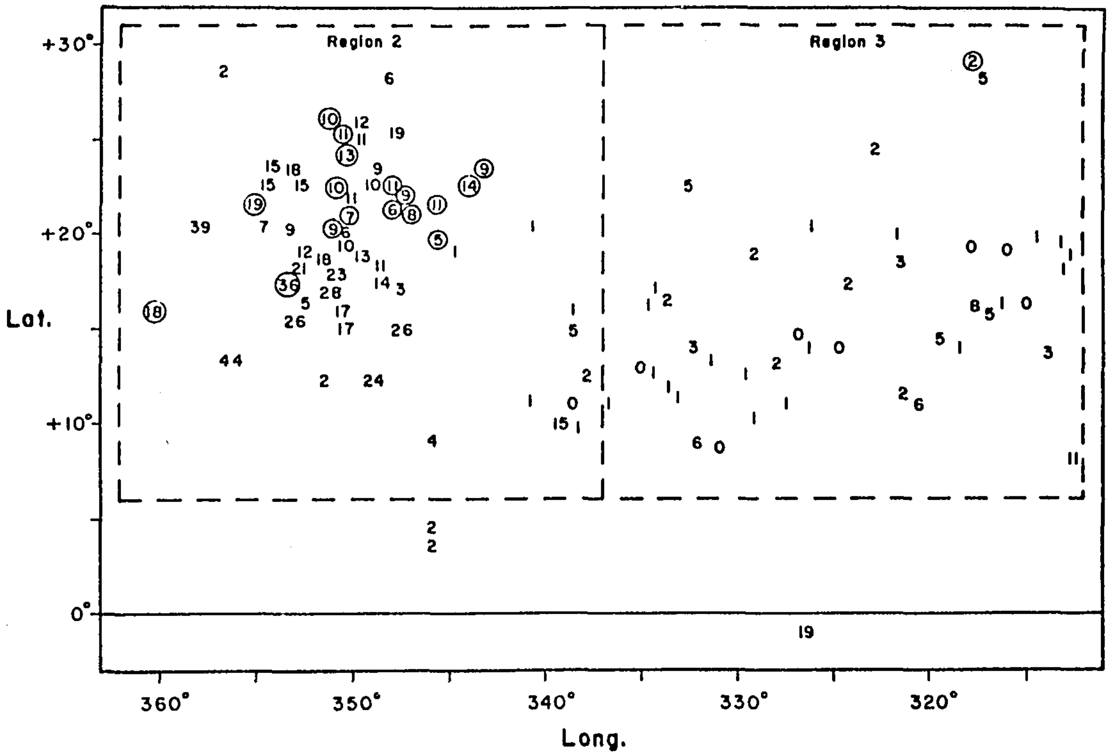

Figure 11. Areal Distribution of E(b-y) of B-Type Stars -- Numbers plotted at the galactic coordinates of the B-type stars represent the color excesses, in units of $0\overset{\text{m}}{.}01$. Broken lines indicate Blaauw's (1946) Regions 2 and 3; circled numbers, B-type stars with large m_1-indices.

Table 13. Unreddened Photometric Colors in Lower Centaurus

Name	HD No.	Sp	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o	$(u-b)_o$	d.m.(β)
HR 4618	105382	B2 IIIne	2.677	.011	4.44	-.090	.105	.262	.291	5.8 B
δ Cen	105435	B2 IVne	2.467	.103:	2.07	-.119	.079	-.031	-.121	-- B
ρ Cen	105937	B3 V	2.707	.000	3.94	-.087	.114	.325	.380	4.8 B
δ Cru	106490	B2 IV	2.619	.000	2.78	-.113	.086	.043	-.011	6.2 B
ζ Cru	106983	B2.5 V	2.680	.002	4.04	-.091	.106	.259	.288	5.3 B
σ Cen	108483	B2 V	2.654	.012	3.86	-.101	.096	.155	.143	5.9 B
γ Mus	109026	B5 V	2.695	.005	3.83	-.082	.112	.345	.405	5.9 B
α Mus	109668	B2 IV-V	2.649	.001	2.69	-.105	.093	.112	.088	5.0 B
HR 4848	110956	B3 V	2.701	.017	4.57	-.087	.101	.298	.324	5.6 B
β Cru	111123	B0.5 III	2.597	.017	1.22	-.120	.066	-.044	-.152	5.5 B
λ Cru	112078	B4 V	2.681	.019	4.55	-.081	.092	.360	.380	6.0 B
μ_1 Cru	112092	B2 IV-V	2.664	.017	3.99:	-.099	.098	.176	.172	5.8 B
HR 4940	113703	B5 V	2.716	.016	4.62	-.079	.104	.375	.423	5.4 B
ξ Cen	113791	B1.5 V	2.657	.015	4.24	-.100	.093	.160	.144	6.3 B
HR 5035	116087	B3 V	2.700	.013	4.52	-.082	.111	.347	.404	5.5 B
ε Cen	118716	B1 III	2.612	.018	2.22	-.112	.063	.039	.084	5.9 B

Table 14. Unreddened Photometric Colors of B-Type Stars in Upper Centaurus

Name	HD No.	Sp	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o	$(u-b)_o$	d.m.(β)
	119103	B8	2.774	.007	7.08	-.025	.111	.940	1.112	8.6 NM?
	119361	B6	2.724	.014	5.88	-.042	.113	.761	.902	6.4 NM?
ν Cen	120307	B2 IV	2.626	.006	3.37	-.108	.078	.083	.022	6.6 B
μ Cen	120324	B2 Ve	2.478	.069	3.12	-.120	.075	-.043	-.117	-- B
3 Cen	120709	B5 III	2.700	.053	4.11	-.086	.120	.307	.307	5.1BNM?
HR 5217	120908	B5 V	2.682	.106	5.43	-.067	.106	.505	.572	6.9BNM?
4 Cen	120955	B5 IVp	2.674	.025	4.63	-.071	.088	.461	.494	6.2 B
∅ Cen	121743	B2 IV	2.646	.000	3.81	-.105	.082	.145	.099	6.5 B
HR 5249	121790	B2 V	2.642	.000	3.85	-.101	.090	.162	.140	6.5 B
χ Cen	122980	B2 V	2.651	.004	4.34	-.099	.090	.175	.160	6.3 B
	123291	B9	2.836	.049	8.02	-.025	.142	.939	1.168	7.1 NM
	123635	B7	2.714	.084	7.34	-.058	.111	.599	.697	8.0 NM
2 Lup	125238	B2.5 IV	2.656	.009	3.50	-.091	.085	.256	.244	5.5 NM?
a Cen	125823	B3: p	2.656	.010	4.36	-.096	.083	.209	.182	6.1 B
	126110	B9	2.855	.050	7.69	-.025	.140	.941	1.166	6.7
	126135	B9	2.788	.028	6.86	-.047	.127	.719	.877	6.4
	128344	B8	2.747	.056	6.39	-.044	.121	.744	.892	6.5
	128819	B7	2.800	.019	6.56	-.044	.120	.752	.922	6.0
α Lup	129056	B1.5 III	2.604	.019	2.22	-.107	.064	.094	.006	6.1 B
HR 5471	129116	B2.5 V	2.675	.014	3.90	-.092	.093	.248	.201	5.5 B
o Lup	130807	B5 IV	2.693	.004	4.31	-.081	.093	.357	.381	5.3 B
β Lup	132058	B2 IV	2.618	.008	2.68	-.106	.066	.097	.017	5.9 B
	132094	B8	2.857	.017	7.18	-.027	.138	.914	1.134	6.2
κ Cen	132200	B2 V	2.639	.000	3.14	-.097	.080	.191	.157	5.4 B
HR 5595	132955	B3 V	2.705	.047	5.24	-.093	.108	.336	.361	6.1 B
HR 5625	133937	B7 V	2.739	.015	5.77	-.063	.107	.546	.634	6.0 B
λ Lup	133955	B3 V	2.698	.011	4.02	-.089	.101	.278	.301	5.3 B
δ Lup	136298	B2 IV	2.616	.011	3.17	-.108	.070	.083	.006	6.6 B
	136482	B8	2.805	.007	6.62	-.036	.123	.822	.995	6.0
ε Lup	136504	--	2.656	.006	3.38	-.095	.090	.215	.204	5.4

Table 14.--Continued

ϕ_2 Lup	136664	B3 V	2.684	.015	4.47	-.084	.097	.324	.358	6.0	B
	137193	B8p(Si)	2.783	.032	7.24	-.046	.214	.715	1.047	6.8	NM?
HR 5736	137432	B3 V	2.707:	.008	5.42	-.078	.095	.391	.436	6.3:	B
HR 5773	138564	B9	2.897	.007	6.35	-.023	.152	.925	1.183	5.1	NM
γ Lup	138690	B2 V	2.634	.005	2.79	-.102	.083	.141	.104	5.3	B
d Lup	138769	B3 IVp	2.684	.002	4.53	-.090	.097	.271	.284	5.8	B
	138940	B8	2.845	.013	7.57	-.027	.123	.911	1.124	7.1	NM
HR 5805	139233	B7	2.841	-.006	6.60	-.034	.135	.847	1.040	5.7	
	139524	B9	2.766	.063	7.80	-.033	.110	.857	1.005	7.6	NM
Ψ_2 Lup	140008	B6 V	2.728	.011	4.70	-.075	.103	.421	.476	5.1	BNM?
	140817	A0:	2.858	.051	6.61	-.036	.168	.828	1.087	5.6	
HR 5873	141318	B2 III	--	.189	4.94	-.108	.072	.084	-.007	--	
η Lup	143118	B2 V	2.619	.003	3.41	-.105	.078	.113	.059	6.6	B
HR 5967	143699	B6 V:	2.705	.012	4.84	-.078	.097	.380	.418	5.7	B
θ Lup	144294	B2.5 V	2.671	.007	5.89	-.091	.090	.260	.257	7.5	BNM

Table 15. Unreddened Photometric Colors of B-Type Stars in Upper Scorpius

Name	HD No.	Sp	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o	$(u-b)_o$	d.m.(β)
	139094	B7 V	2.747	.137	6.80	-.060	.140	.573	.719	6.9 NM
HR 5801	139160	B7 IV	2.748	.086	5.83	-.072	.142	.447	.578	5.8
τ Lib	139365	B2.5 V	2.682	.009	3.64	-.090	.090	.267	.267	4.9BNM?
	139486	B9.5 V	--	.061	7.37	-.030	.151	.887	1.123	--
	140543	B0.5 IIIn	2.572	.191	8.06	-.126	.079	-.104	-.216	13.6 NM
1 Sco	141637	B2 V	2.640	.111	4.16	-.106	.101	.105	.087	6.7 B
	141774	B9 V	--	.109	7.24	-.033	.133	.859	1.048	--
λ Lib	142096	B2.5 Vn	2.709	.107	4.58	-.089	.122	.277	.332	5.6
2 Sco	142114	B2.5 Vn	2.678	.097	4.18	-.094	.094	.227	.205	5.6
HR 5906	142165	B6 IVn	2.730	.090	5.01	-.070	.131	.478	.591	5.2 NM
HR 5907	142184	B2.5 Vn	2.657	.110	4.95	-.092	.111	.248	.275	6.7
HR 5910	142250	B6 Vp	2.734	.048	5.96	-.096	.129	.484	.600	6.4
3 Sco	142301	B8p	2.682	.078	5.55	-.088	.126	.555	.357	7.0 NM?
	142315	B8 V	2.803	.092	6.48	-.045	.132	.728	.892	5.9
47 Lib	142378	B3 V	2.686	.104	5.51	-.084	.125	.330	.399	6.4 B
ρ ScoA	142669	B2 IV-V	2.645	.011	3.83	-.100	.077	.163	.116	6.1 B
HR 5934	142883	B3 V	2.723	.129	5.31	-.084	.134	.327	.412	5.8
	142884	B9p(Si)	2.725	.139	6.18	-.081	.116	.359	.415	6.7 NM
HR 5941	142983	B3:e	2.593	.019	4.85	-.041	.089	.764	.615	-- B
HR 5942	142990	B5 IV	2.678	.063	5.17	-.093	.127	.238	.300	6.6
π Sco	143018	B1+B2	2.614	.055	2.65	-.114	.062	.022	-.087	6.2 B
δ Sco	143275	B0.5 IV	2.602	.100	1.88	-.119	.068	-.038	-.150	6.0 B
	143567	B9 V	2.846	.102	6.75	-.038	.161	.806	1.042	5.7
	143600	B9 V	2.857	.108	6.87	-.032	.144	.865	1.079	5.9
HR 5988	144334	B8p	2.722	.065	5.64	-.082	.140	.346	.455	6.1
ω_1 Sco	144470	B1 V	2.621	.148	3.31	-.117	.082	-.008	-.092	6.5 B
HR 6003	144844	B9 IV(p?)	2.793	.086	5.50	-.060	.149	.578	.747	5.0 NM
	145102	B9p(Si)	2.796	.110	6.13	-.038	.126	.800	.965	5.6
	145353	B9 IV	2.816	.142	6.35	-.035	.140	.836	1.031	5.7
13 Sco	145482	B2 V	2.652	.027	4.46	-.097	.091	.195	.180	6.6 B

Table 15.--Continued

ν Sco	145502	B2 IV	2.674	.177	3.2:	-.105	.112	.115	.111	4.8BNM?
	145554	B9 V	2.836	.151	6.99	-.040	.147	.785	.985	6.1
	145631	B9.5 Vn	2.857	.147	6.94	-.035	.144	.837	1.056	5.9
HR 6042	145792	B5 V	2.725	.098	5.98	-.035	.104	.398	.525	6.5
HR 6054	146001	B7 IV	2.753	.127	5.51	-.069	.121	.484	.587	5.5
	146029	B9 V	2.769	.092	6.98	-.028	.144	.906	1.145	5.9
	146284	B8 IV	2.768	.177	5.94	-.045	.126	.728	.863	5.7
	146285	B8 V	2.818	.232	6.92	-.049	.128	.677	.811	6.1
	146332	B5 II	2.668	.263	6.50	-.075	.118	.419	.479	8.2 NM
HR 6066	146416	B9 V	2.830	.067	6.34	-.037	.132	.819	1.002	5.5
	146706	B9 V	2.832:	.122	7.00	-.036	.144	.830	1.033	6.3
	147010	B9p	2.769	.195	6.56	-.070	.171	.473	.654	6.4
σ ScoA	147165	B1 III	2.605	.282	1.67	-.118	.087	-.026	-.117	5.7 B
	147196	B8 Vnnp	2.726	.207	6.16	-.046	.104	.720	.815	6.7
	147703	B9 Vn	--	.166	6.80	-.029	.137	.899	1.102	--
ρ OphD	147888	B5 V	2.713	.355:	5.21:	-.095:	.142:	.218:	.278:	5.9:B
	147889	B2 V	2.664	.783:	4.52:	-.126:	.144:	-.107:	-.090:	-- NM?
	147890	B9.5p(Si)	2.757	.241	6.62	-.041	.119	.784	.916	6.6
ρ OphC	147932	B5 V	--	.334:	5.83:	-.094:	.135:	.221:	.271:	--
χ Oph	148184	B2 IIIpe	2.380	.392:	2.73:	-.138:	.064:	-.225:	-.373:	--BNM?
	148579	B9 V	2.831:	.257	6.23	-.043	.140	.757	.927	5.3
	148594	B8 Vnn	2.720:	.171	6.15	-.055	.104	.625	.706	6.8:
22 Sco	148605	B2 V	2.662	.049	4.56	-.096	.092	.210	.197	6.5 B
HR 6143	148703	B2 IV	2.646	.044	4.06	-.104	.082	.124	.076	6.4 B
τ Sco	149438	B0 V	2.605	.022	2.73	-.122	.058	-.069	-.200	6.8:B
ζ Oph	149757	095 V	2.579	.211	1.65	-.126	.075	-.103	-.266	6.8:
	151346	B7p	2.709	.436	6.03	-.075	.118	.426	.469	6.8
	151865	B8 V	2.781	.178	8.08	-.051	.143	.676	.843	7.7 NM
μ_1 Sco	151890	B2 V	2.625	.017	2.94	-.106	.083	.100	.052	5.9 B
μ_2 Sco	151985	B2 IV	2.620	.016	3.49	-.106	.081	.100	.048	6.7 B
θ Oph	157056	B2 IV	2.622	.014	3.20	-.106	.093	.101	.074	6.1 B

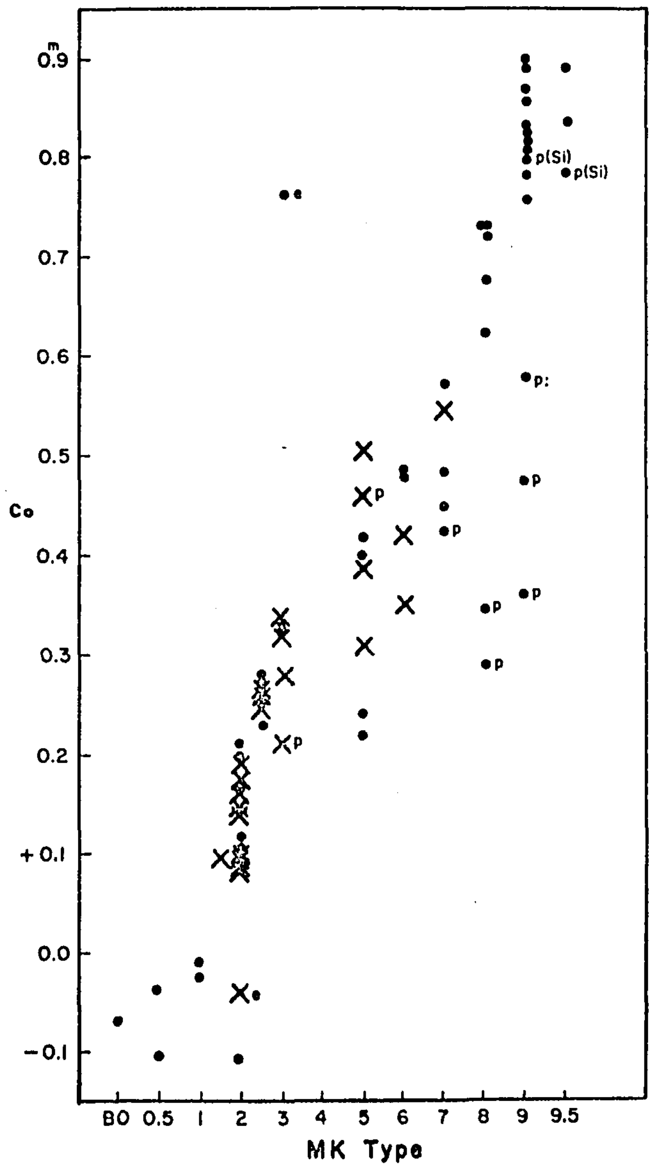

Figure 12. c_o, Sp(MK) Diagram for B-Type Stars -- Filled circles represent stars in Upper Scorpius; crosses, stars in Upper Centaurus. Peculiar stars are marked with the letter "p."

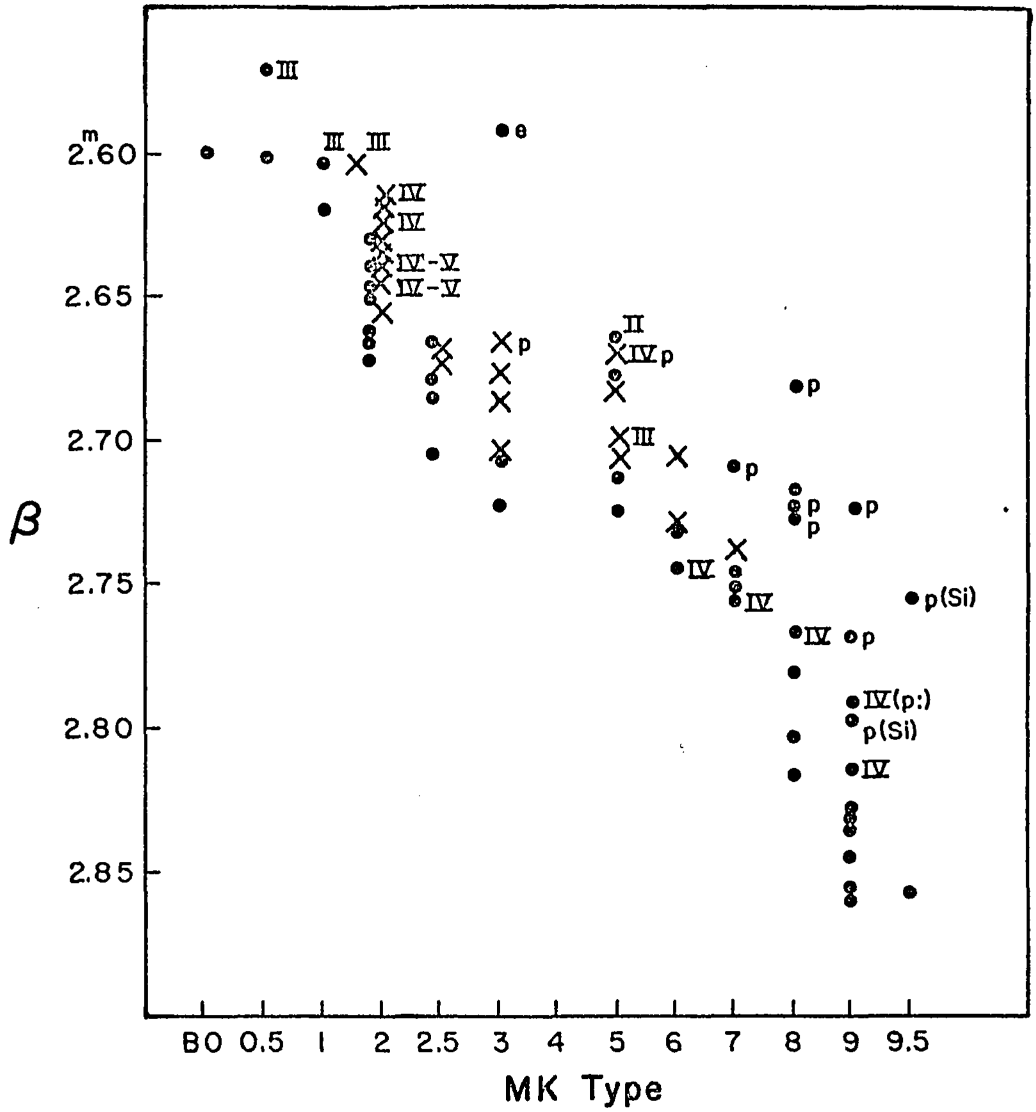

Figure 13. β, Sp(MK) Diagram for B-Type Stars -- Symbols are the same as in Figure 12. Luminosity classes for non-main sequence stars are labelled next to the appropriate symbols.

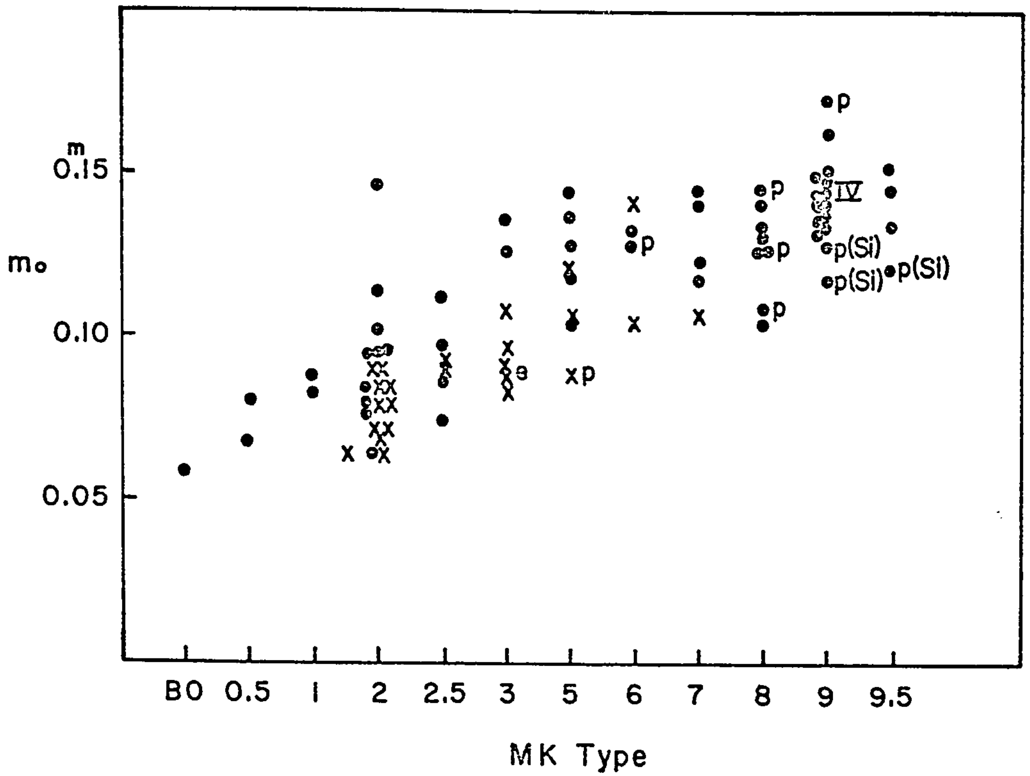

Figure 14. m_o, Sp(MK) Diagram for B-Type Stars -- Symbols are the same as in Figure 12.

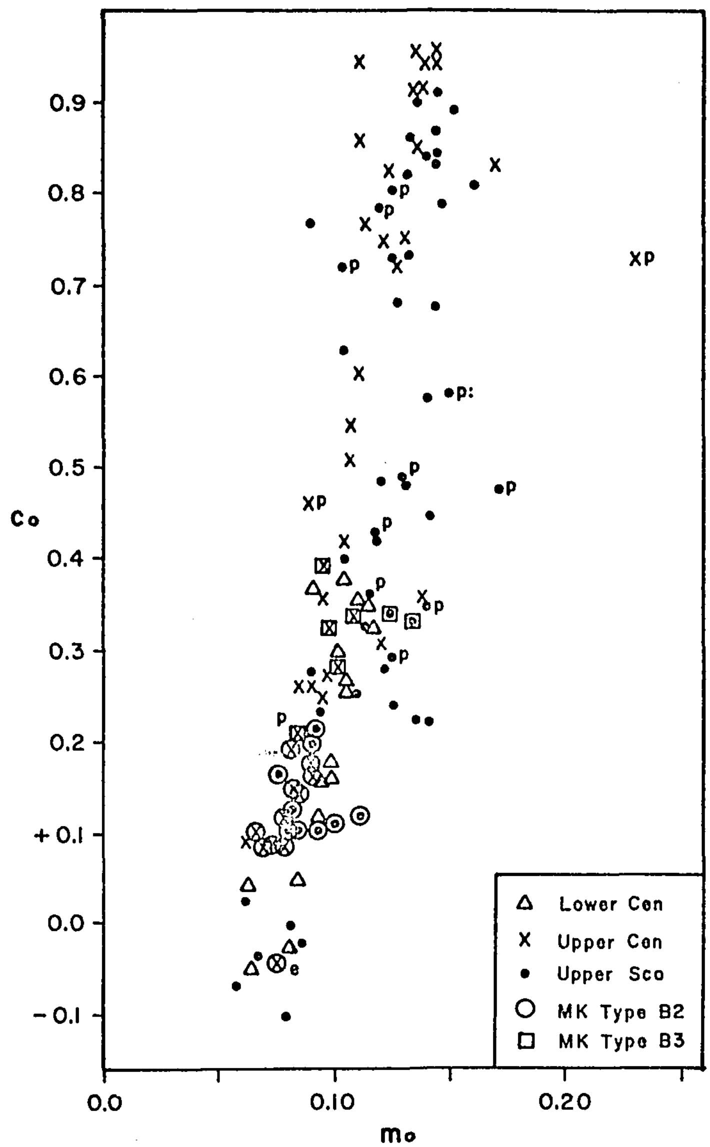

Figure 15. c_o, m_o Diagram for B-Type Stars -- Peculiar stars are marked with the letter "p."

interest, especially when compared with the broad Upper Scorpio sequence. This scatter in Scorpio could be partially due to the larger reddening applied to these stars, but this would not explain the average separation of the two sequences of $0^m.03$ in m_o.

It should also be clear that although data for the Bp-type stars share in the separation, excluding them would not reduce it. The location of indices of the B2- and B3-type stars in this diagram implies that most of the separation is along the m_o-axis. It is possible that the scatter is due to a combination of the large, variable reddening and the presence of a large number of peculiar B stars. This effect may be typical of a cluster containing a large number of Bp-type stars; or the explanation may lie in some as yet unknown cause.

Errors in the photometry do not seem to be the cause of this separation. When the best observed stars in Crawford's data are considered, the same effect is present. This is also true when only photometry of highest quality from the present investigation is used. The reason for being so cautious about the data is due to the possible differences in the various Strömgren v-filters used, and the resulting difficulties in transforming the observations to the standard uvby system.

To aid in separating the differences in the m_1-indices from those in the c_1-indices, the photometry was also corrected for interstellar reddening by using the (u-b), (b-y) diagram. An intrinsic, unreddened sequence was determined using four-color data on bright B-type stars observed from the southern hemisphere by Crawford and Barnes (1970b); then, plots of c_o vs. $(b-y)_o$ and m_o vs. $(b-y)_o$ were made for the Scorpio-Centaurus B stars. In each diagram two sequences were apparent for stars in the two regions. The differences were $0\overset{m}{.}04$ in c_o and $0\overset{m}{.}03$ in m_o, assuming that the $(b-y)_o$ values were correct. Returning to Figure 15 again we see that the separation between sequences may be interpreted as being either $0\overset{m}{.}02$-$0\overset{m}{.}03$ in m_o or several <u>tenths</u> of a magnitude in c_o. Apparently we should accept the first interpretation, that the difference between the sequences is due to the m_o-index.

A simple check on whether or not the separation between the two sequences is related to color excess may be made by plotting $\Delta m_1 = m_o - \overline{m_o}(\text{Cen})$ (at the same c_o) against the computed E(b-y) for the Upper Scorpius stars. Figure 16 shows that there is little or no dependence of Δm_1 on E(b-y). The color excesses corresponding to those stars for which $\Delta m_1 \leq 0\overset{m}{.}02$ were circled in Figure 11. Evidently these stars tend to lie at higher galactic latitudes than the stars with small Δm_1.

Another possibility would be to explain the different m_1-indices in the two regions as being due to

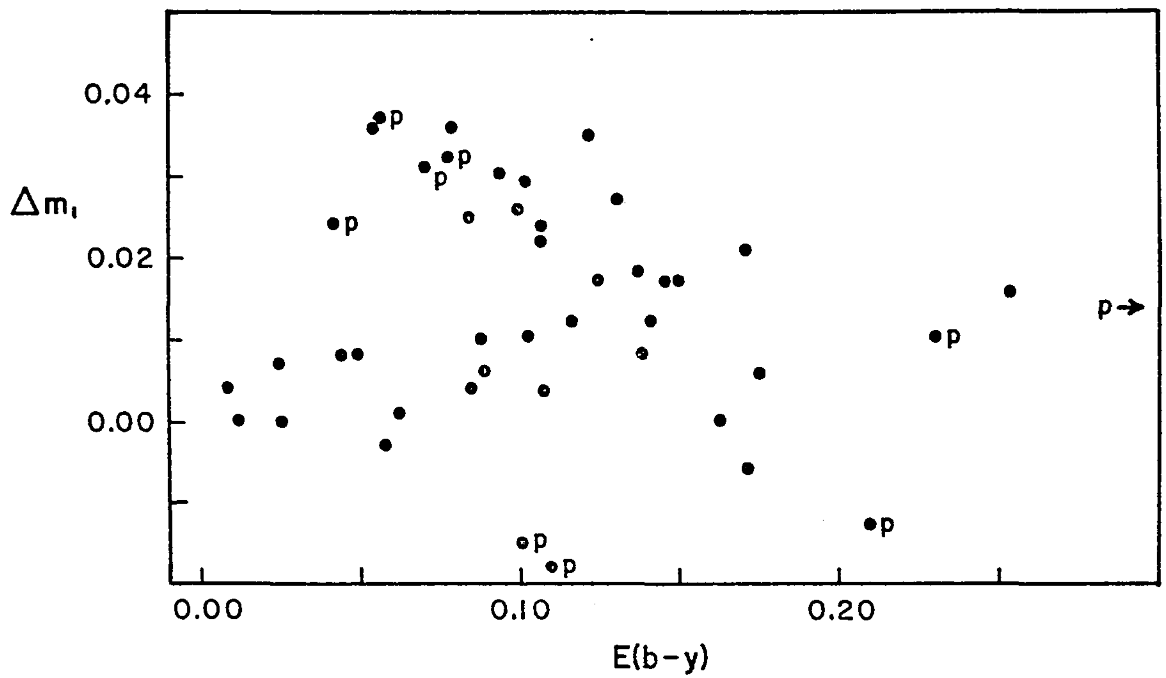

Figure 16. Δm_1, E(b-y) Diagram for B-Type Stars in Upper Scorpius

the differences in the strengths of the Balmer lines associated with the evolution of the stars. Since the v-filter is centered on Hδ, differences in the equivalent width of that line would affect the m_1-index. In that case there should be some correlation of Δm_1 with $\Delta\beta = \beta_{seq} - \beta_*$ (taken from the Zero-Age Main Sequence, or Z.A.M.S., in the β, c_1 diagram). A graph of Δm_1 vs. $\Delta\beta$ values for the bright northern B-type stars from the data of Crawford (1970b) shows a dependence of $\Delta m_1 = -0.60\Delta\beta + 0.022$ ($\pm 0^m.01$ in m_1). In other words, an unevolved ($\Delta\beta = 0$) star--or a sequence of stars--should lie $+0^m.022$ in m_1 above the reference line (which was taken to be the Centaurus sequence). Small values of Δm_1 would seem reasonable for the early end of an evolved cluster, however, we see that in the present situation the difference in m_1 between the two regions persists to considerably later spectral types. At these later types $\Delta\beta = 0$ for the Centaurus stars as well as for the Upper Scorpius stars, hence the Centaurus stars should have values of m_1 similar to those of the Scorpius stars, which is contrary to what is observed.

Another possible explanation for the differing sequences might be a higher incidence of binary stars in one region than in the other, which might systematically affect the photometric indices. To investigate this hypothesis it was decided to create numerically (b-y)-, m_1-, and c_1-indices of binary stars, the components of which have similar spectral types, by combining the observed photometric indices of pairs of program stars. The equations predicting the binary colors are:

$$(b-y)_{combo} = (b-y)_{star\ 1} - 2.5 \log (1 + 10^{0.4\Delta b})$$

$$+ 2.5 \log (1 + 10^{0.4\Delta y})$$

$$(m_1)_{combo} = (m_1)_{star\ 1} - 2.5 \log [(1 + 10^{0.4\Delta v})$$

$$(1 + 10^{0.4\Delta y})] + 5 \log (1 + 10^{0.4\Delta b})$$

$$(c_1)_{combo} = (c_1)_{star\ 1} - 2.5 \log [(1 + 10^{0.4\Delta u})$$

$$(1 + 10^{0.4\Delta b})] + 5 \log (1 + 10^{0.4\Delta v})$$

The terms on the right of each equation represent the changes in the indices of Star No. 1 if a companion is added to it. These changes seem to be small, as is shown in Table 16, where the results of some sample calculations are presented. The changes that do occur locate the combination along the line connecting the two points which represent the individual stars. Therefore the combination of two main sequence stars of somewhat similar spectral types lies along the main sequence. We do not investigate the case where the secondary may be a late type giant star, for this situation is less probable (see Murphy 1969) and would be distinguishable on the basis of its very peculiar photometric indices.

Table 16. Changes in m_1 and c_1 for Artificial Binaries

Combination	Sp.	Δm_1	Δc_1
HD 132200 + HD 129116	B2 IV + B3 V	$+0^m.005$	$+0^m.018$
HD 144470 + HD 141637	B1 V + B1.5 Vn	+0.005	+0.032
HD 144470 + HD 138285	B1 V + A0	+0.001	+0.008

In order to eliminate the possibility that stellar rotation differences between the two regions are having some effect on the m_1-indices, the rotational velocities of Slettebak (1968) are compared with the Δm_1 values in Figure 17. Considering only the Upper Scorpius stars, where Δm_1 varies from $0^m.0$ to $0^m.040$, no dependence of v sin i on Δm_1 is found.

It does not seem possible, then, to explain the discrepancy between the m_1-indices in the Scorpius and the Centaurus subgroups of B-type stars by any of the following ways: (1) systematic errors in the photometry, (2) reddening corrections, (3) different Hδ line strengths associated with evolutionary effects, (4) unresolved binary stars, and (5) effects related to different mean rotational velocities. One suggested explanation is that the v-filter in the m_1-index is detecting variations in the strengths of weak lines around Hδ, and that some of these stars are distinguishable spectroscopically as being

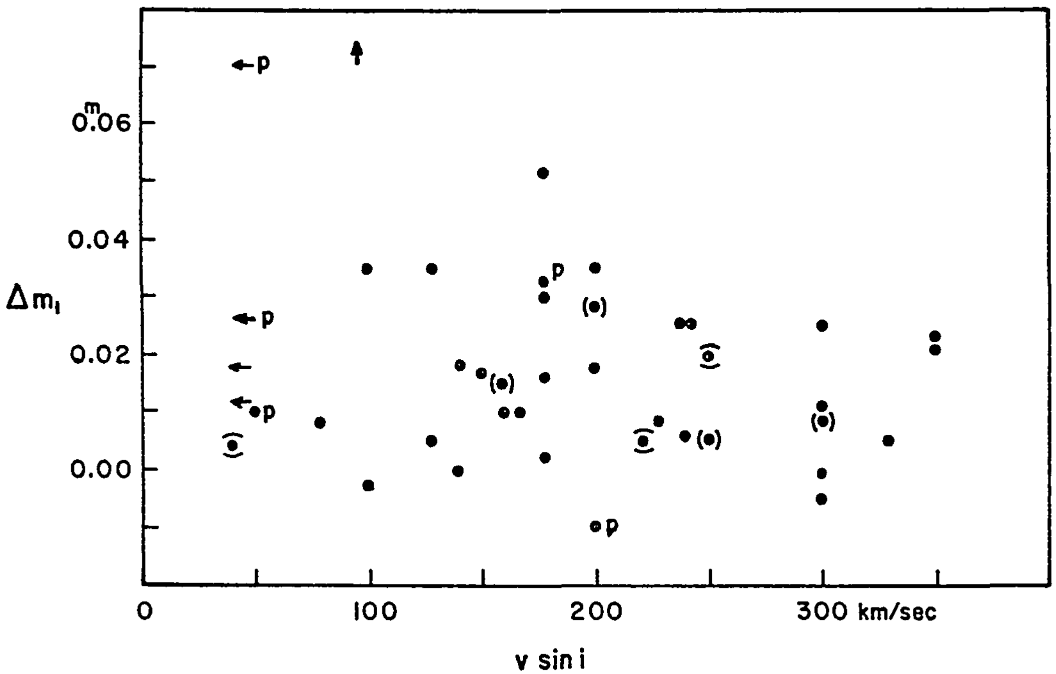

Figure 17. Δm_1, v sin i Diagram for B-Type Stars in Upper Scorpius

peculiar B stars. Unfortunately, the present data do not allow us to investigate this possibility.

Absolute Magnitude Calibration

D. L. Crawford and his associates are currently calibrating the β-index as a function of absolute magnitude for B-type stars by fitting together the main sequences of young cluster in the V_o, β diagram. Distances to the α Persei and Pleiades clusters determined by other means are then used to fix the zero point. An important check on this technique would be to use the resulting calibration on the Scorpio-Centaurus Moving Cluster, the distance of which has been determined dynamically and is, therefore, independent of the calibrations used above in finding distances to the calibration clusters.

Figure 18 shows the sequence obtained by plotting Bertiau's absolute magnitudes against β for those stars having an observed constant radial velocity. Crawford's Z.A.M.S., drawn in for comparison, fits the Scorpio-Centaurus sequence quite well. Figure 19 shows $M_v(\beta)$ plotted against M_v(Bertiau). $M_v(\beta)$ was calculated without using the correction of $\Delta M_v = -8\Delta\beta$ given by Crawford (1970a) for evolved stars at the bright end of the sequence. The two calibrations seem to agree within the scatter of the data, with the exception of the stars in

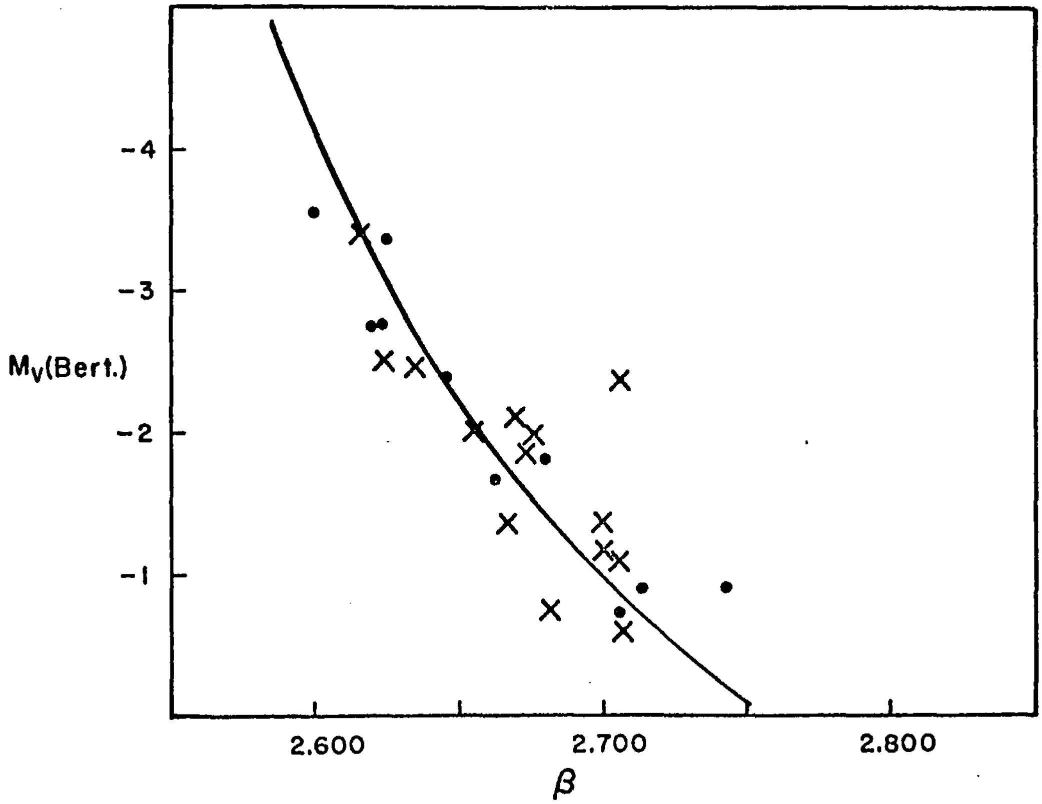

Figure 18. M_V(Bertiau), β Diagram for B-Type Stars -- Symbols are the same as in Figure 15. Only stars having a constant radial velocity are plotted. The solid line is Crawford's preliminary calibration curve.

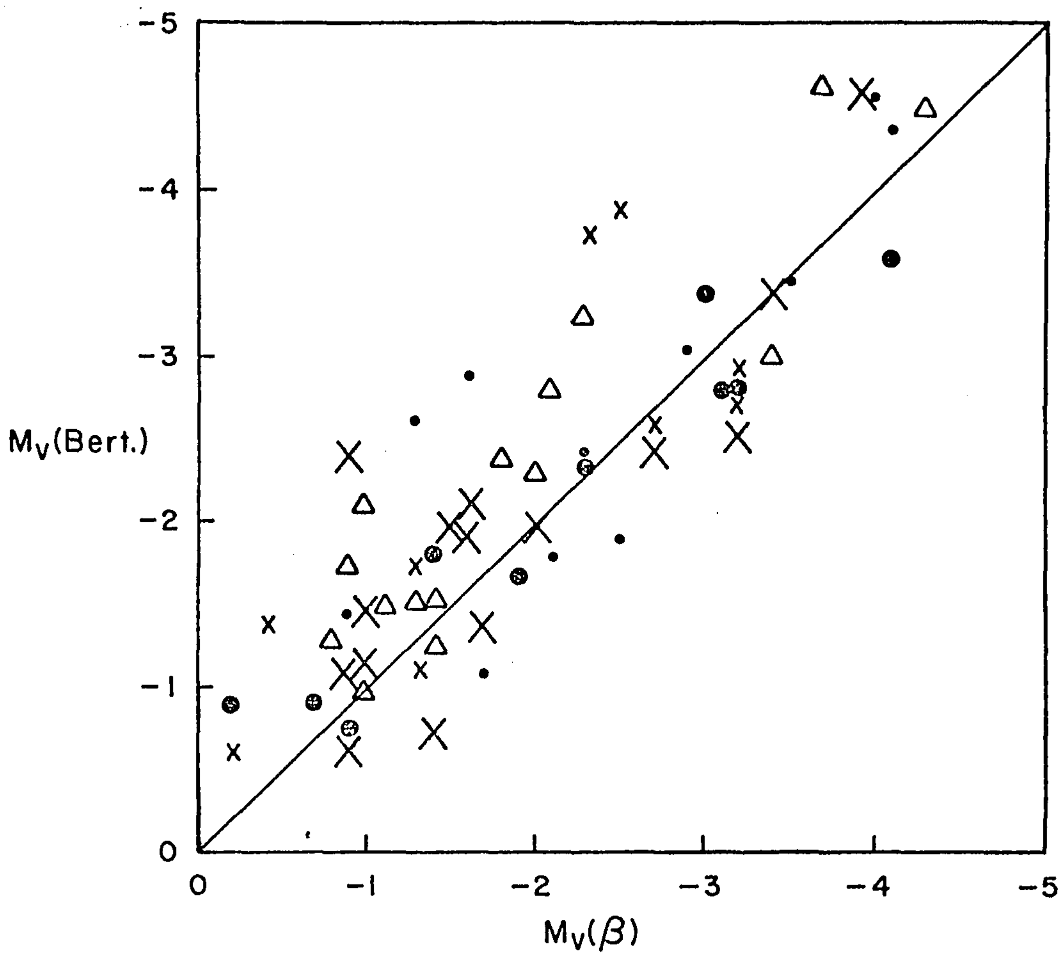

Figure 19. M_V(Bertiau), $M_V(\beta)$ Diagram for B-Type Stars -- Filled circles and crosses have the same meaning as in Figure 15; in addition, triangles represent B-type stars in Lower Centaurus; large symbols represent stars with constant radial velocity; small symbols, variable velocity stars.

Blaauw's Region 4. These latter stars are brighter in Bertiau's calibration by an average difference of $-0^{m}.4$.

To approach this calibration problem somewhat differently, in Figure 20 we plot V_o vs. β, again including Crawford's calibration curve shifted to Bertiau's adopted distance modulus of $6^{m}.2$. For normal, single B-type stars this curve should be identical with a mean curve drawn through the points. Most of the stars brighter than $V_o = 5^{m}.5$ were included in Bertiau's analysis. It is evident from the diagram that elimination of all stars suspected of being binary stars does not reduce the scatter in the lower end of the main sequence. The dashed line also does not represent the points plotted for the Lower Centaurus B-type stars.

A color-magnitude diagram is shown in Figure 21, in which V_o is plotted against $(u-b)_o$. Crawford's absolute magnitude calibration is again included at Bertiau's adopted distance modulus. A spread of 100 pc along the line of sight corresponds to a difference of $1^{m}.3$ in apparent magnitude at the distance of 170 pc adopted by Bertiau for the Association. The tendency for the stars in Upper Centaurus and in Lower Centaurus to fall above the calibration line could be explained (1) by an error in the calibrations of M_v vs. $(u-b)_o$ in the range $0.2 \leq (u-b)_o \leq 0.8$ or (2) because these stars are closer, and therefore brighter, than the Upper Scorpio stars.

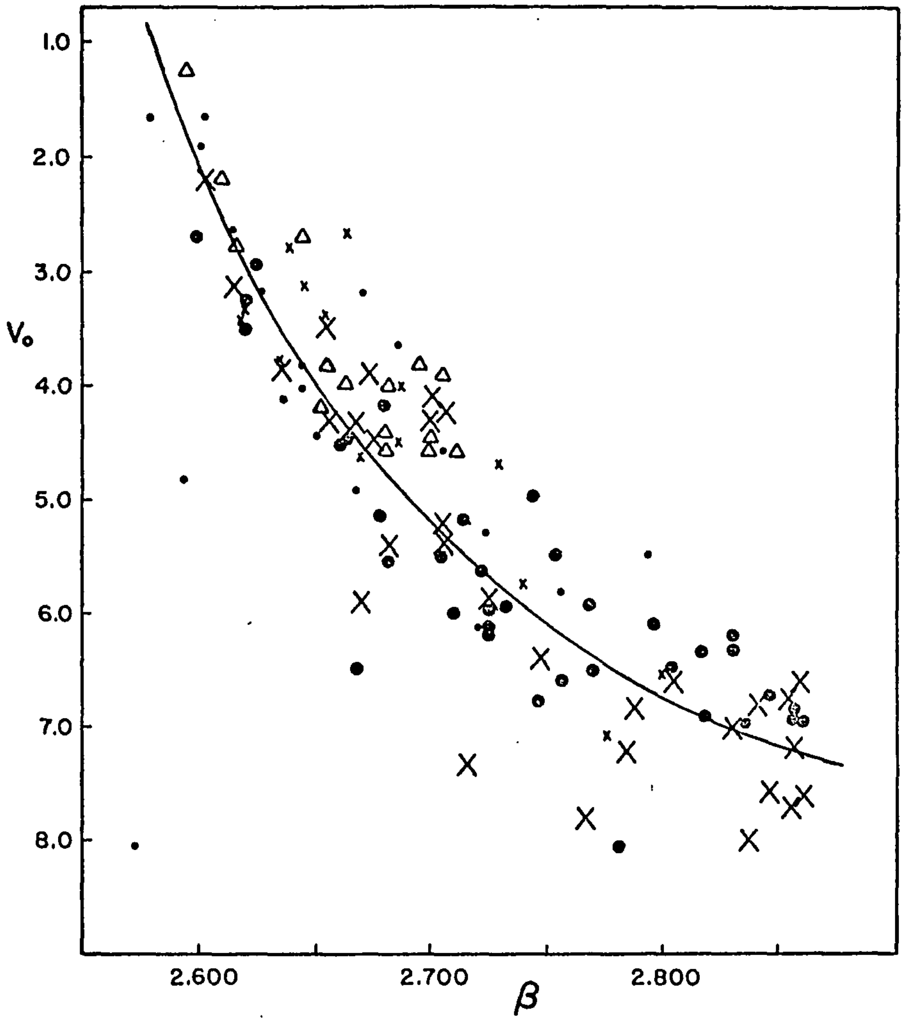

Figure 20. V_o, β Diagram for B-Type Stars -- Symbols have the same meaning as in Figure 19.

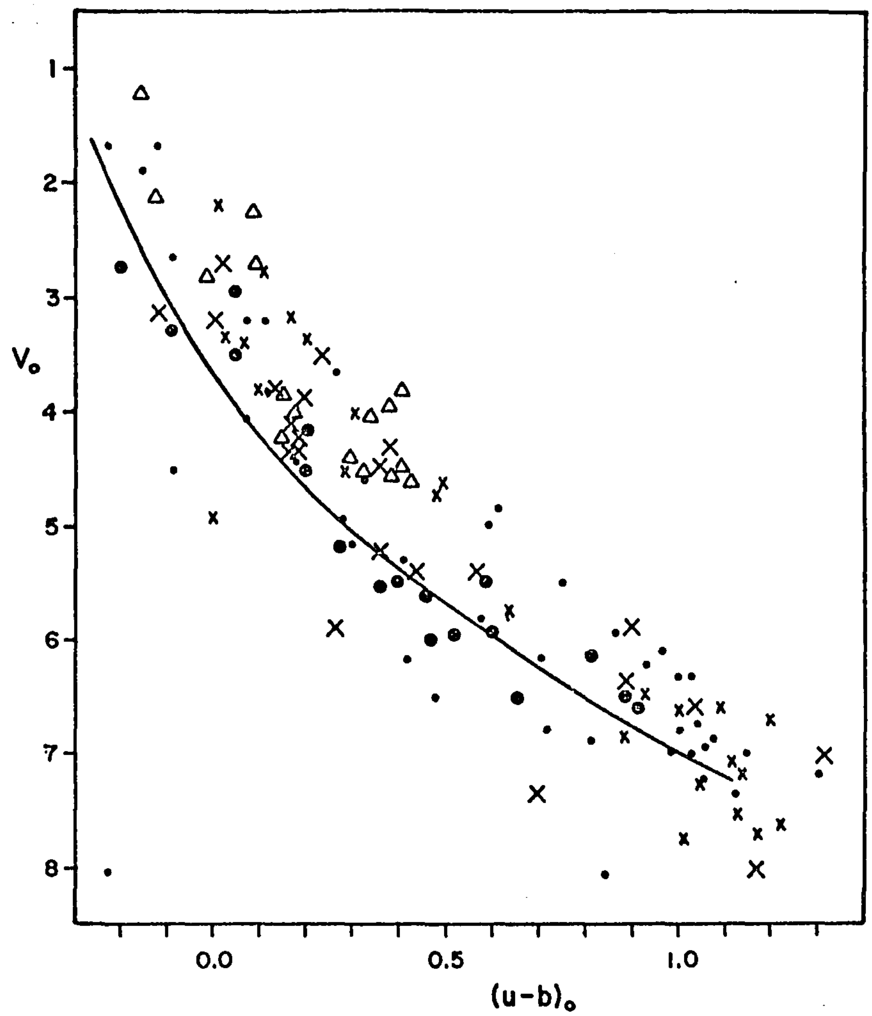

Figure 21. V_o, $(u-b)_o$ Diagram for B-Type Stars -- Symbols have the same meaning as in Figure 19; however, small symbols represent variable or low quality radial velocities; large symbols, well studied constant velocity stars.

The absolute magnitudes obtained from the β-index have been used to derive distance moduli for B-type stars in the Scorpio-Centaurus association. Figure 22 shows histograms of the number of stars having distance moduli in each interval of $0^m.4$. The first three of these are for stars in Bertiau's list in the Lower Centaurus, Upper Centaurus, and Upper Scorpius regions. The mean moduli for the three regions are $5^m.7$, $5^m.9$, and $6^m.1$, respectively. No allowances have been made for duplicity, however, so the means may be biased towards smaller moduli. We see that many of the stars in Lower Centaurus (Blaauw's Region 4) do appear to have slightly smaller moduli than the stars in the other regions, as was suggested in Figure 20. The final two histograms, Figure 22(d) and 22(e) indicate the frequencies of the distance moduli for the "non-Bertiau" B-type stars in the Upper Centaurus and Upper Scorpius regions. Several stars having rather large values of $\delta\beta$ above the Z.A.M.S. in a β, $(u-b)_o$-diagram have been excluded, since many of them appear to be distant evolved stars. The mean modulus for the twelve "non-Bertiau" late B-type stars in Upper Centaurus is $6^m.2$. Most of the late B-type stars in Upper Scorpius which were not listed by Bertiau are in Garrison's (1967) list, and the mean modulus for them is $6^m.1$, the same as for the early B-type stars.

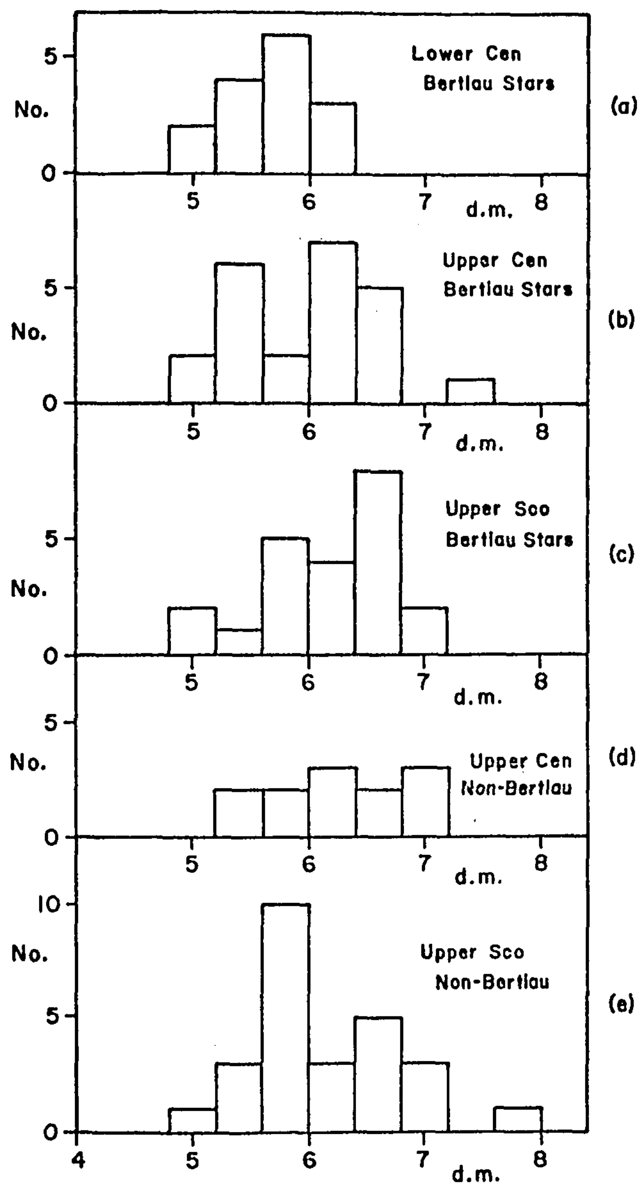

Figure 22. Frequencies of B Star Distance Moduli

The β, $(u-b)_o$ Diagrams

Because the β-index is sensitive to luminosity effects for the B-type stars, if we plot β versus some appropriate temperature indicator [in this case the (u-b) color], we then have essentially a Hertzsprung-Russell diagram which is independent of the relative distances of the stars being studied. In normal HR and color-magnitude diagrams allowances must also be made to correct apparent magnitudes for duplicity of the observed stars, otherwise the observed main sequence will show considerable scatter above the Z.A.M.S. Fortunately, differences in the β-indices and $(u-b)_o$-colors due to binary stars (for components with somewhat similar spectral types) are such as to place the combined indices along the line connecting the points that represent the individual components. No additional scatter should be introduced into the β, $(u-b)_o$ diagram, therefore, if a particular cluster happens to have a high frequency of binary stars. Rotational velocity effects can be important in the middle and late B-type star range, where rapid rotation causes both the β-index and $(u-b)_o$-color to change in a manner mimicking evolved stars.

One important goal of this research is to compare the Upper Centaurus region with the Upper Scorpius and, where possible, the Lower Centaurus regions. To study differences in the B stars in these regions, we plot in Figure 23 the separate β, $(u-b)_o$ diagrams for each group.

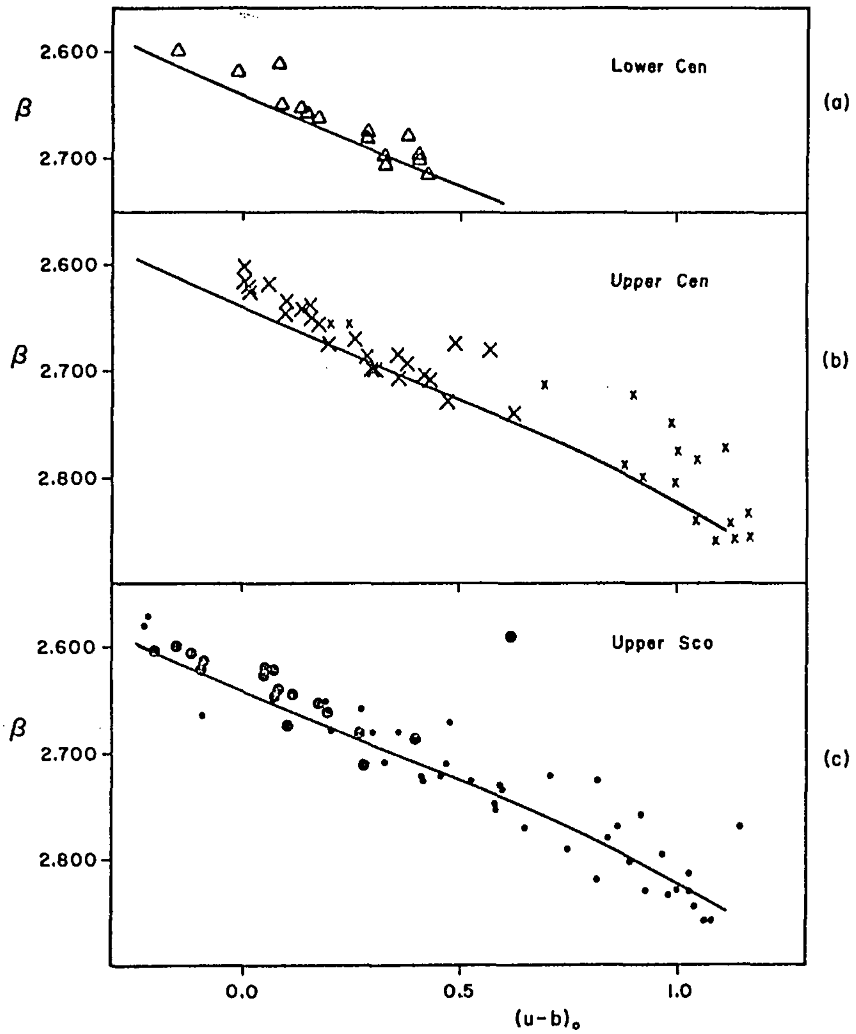

Figure 23. β, $(u-b)_o$ Diagrams for Subgroups in the Association -- Large symbols represent stars from Bertiau's (1958) list; small symbols, additional B-type stars. The solid line represents the Z.A.M.S.

These diagrams are used in Chapter 4 to estimate ages of the stars in each region; however, for the moment we wish only to make some qualitative comparisons.

Only those bright B-type stars in Lower Centaurus that were listed by Bertiau and that have published four-color photometry are plotted in Figure 23(a). Several of the earliest type stars lie above the Z.A.M.S.; however, the later types lie essentially on the Z.A.M.S. In Figure 23(b) we show the β, $(u-b)_o$ diagram for the B-type stars in Upper Centaurus, indicating the B-type stars on Bertiau's list by large crosses. With few exceptions these stars form a very narrow sequence, the faint end of which lies on the Z.A.M.S. The two points representing B-type stars from Bertiau's list that fall several hundredths of a magnitude in β above the Z.A.M.S. represent HD 120908 (MK class B5 V) and HD 120955 (B5 IVp). No rotational velocity has been measured for the former star; however, Slettebak (1968) found $v \sin i \leq 20$ km/sec for the latter. It appears, therefore, that HD 120955 has evolved away from the Z.A.M.S., but we may only conjecture that HD 120908 is rapidly rotating. For the rest of the points that fall appreciably above the Z.A.M.S. we are also unable to decide from this diagram whether the stars are evolved or are rapid rotators. In Chapter 7, when all of the membership and non-membership evidence is combined, we shall see that many of these stars are indeed background objects. We should note that in discussing the effects of rotational velocities within a cluster, it is essential to know which stars are members. The situation in Figure 23(c) for the Upper Scorpius stars is more straightforward, since most of the stars were taken from the study by Garrison (1967). The young main sequence is quite apparent from the large points representing stars from Bertiau's list. Also, most of the points falling well above the Z.A.M.S. are known to represent evolved or rapidly rotating stars. The large number of points falling below the Z.A.M.S. is interesting, for if we assume that the reddening has been properly taken into account in determining the intrinsic $(u-b)_o$ colors, then these large values of the β-index may confirm Garrison's comment that the hydrogen lines in the spectra of many of the B stars in Upper Scorpius are visibly stronger than the hydrogen lines in the field stars used as MK standards. This would again imply that the Upper Scorpius subgroup is quite young.

CHAPTER 4

AGE DETERMINATION

In this section we apply theoretical evolutionary models to the problem of determining the age of the Upper Centaurus association. To compare the models with observations, however, it is first necessary to calibrate the observed photometric indices in terms of the theoretical parameters.

Effective Temperature Calibration

To compare the observed photometric sequences to stellar age computations it is necessary to have a reliable calibration of the effective temperature (T_{eff}) in terms of one of the photometric indices. In the present study we have chosen to work with $(u-b) = c_1 + 2m_1 + 2(b-y)$ and $(u-b)_o$, the unreddened color-index, instead of the c_o-index, because (u-b) does not depend strongly on the possible differences in the v-filters belonging to different filter sets as discussed in Chapter 3. It also has a large range (approximately $1^{m}.5$) in possible values for the B-type stars, therefore results based on the (u-b)-index should be relatively insensitive to observational scatter.

There are several recent calibrations of effective temperatures of B-type stars which may be used to obtain the $(u-b)_o$-log T_{eff} transformation. Hayes (1970) has recently presented a temperature calibration of the B-type stars based on his determination of the Balmer and Paschen discontinuities of α Lyr using absolute spectrophotometry (see Figure 24). For this calibration he used Mihalas' (1966) unblanketed LTE models and corrected the effective temperature to correspond to that of a blanketed model. The uncertainty in the spectrophotometry is indicated by the fact that Oke and Schild (1970a, 1970b) have also carried out a recalibration of the absolute spectrophotometry of α Lyr, and they have found that the Balmer and Paschen discontinuities computed from the two calibrations still show some disagreement. The Hayes calibration also disagrees with the observations of Brown et al. (1967) for the early B-type stars; however, the difference is probably within the uncertainty due to the assumptions made in each procedure. Nonetheless, Hayes points out that his temperature calibration leads to better agreement for early B-type stars between far ultraviolet flux observations and the predicted fluxes from models. For this reason, and because he corrected his temperatures to agree with the blanketed model atmospheres published by Morton and his co-workers (see Morton and Adams 1968, and references cited therein), we prefer to work with this temperature calibration for the comparison of evolutionary tracks with observations. If at some later date the re-calibration

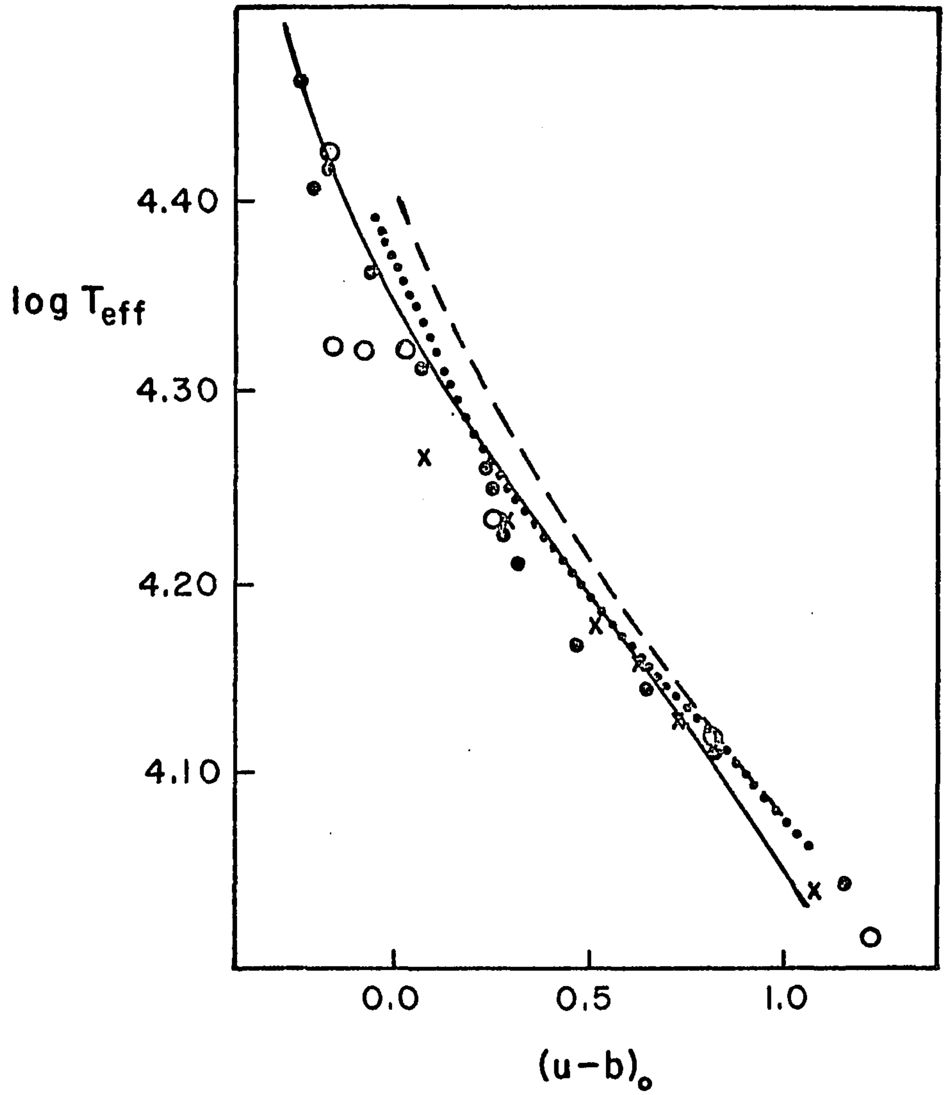

Figure 24. Temperature-Color Calibrations -- Open circles represent the data from Brown et al. (1967); filled circles, Heintze (1969); solid line, Morton and Adams (1968); crosses, Morton and Adams as revised by Strom and Peterson (1968); dashed line, Strömgren (1964); dotted line, Hayes (1970).

of α Lyr by Oke and Schild is shown to be preferable, the observed Balmer jump would be decreased somewhat, raising the temperature scale. The adopted calibration is given in Table 17, along with the bolometric corrections (discussed below) and approximate MK spectral types.

Table 17. Adopted Calibrations of log T_{eff} and B.C.

$(u-b)_o$	log T_{eff}	B.C.	Sp.
0.0	4.370	-2.4	B2
0.2	4.284	-1.9	B3
0.4	4.220	-1.6	B4
0.6	4.172	-1.3	B6
0.8	4.127	-1.1	B8

Strömgren (1964) also computed model atmospheres of B-type stars and predicted flux distributions, which he then used to compute (u-b)' and (b-y)' color-indices, and D, the Balmer discontinuity index. Observations of $(u-b)_o$ and D for B-type stars with little or no reddening were used to compare the computed (u-b)' with the observed $(u-b)_o$ and to determine the zero point corrections needed to transform the computed (u-b)' values to the observed system. Strömgren thereby calibrated the $(u-b)_o$ colors with the effective temperatures of the corresponding models. He also showed that the predicted (u-b)' was independent of the values of log g adopted for the models. In the final section of his paper Strömgren compared the predicted flux on the far (rocket) ultraviolet to the observed fluxes published by Chubb and Byram (1963). For each of seven stars, Strömgren found that his models predicted from $1^{m}.0$ to $2^{m}.0$ too much flux at 1314 A, relative to the y-filter. This may not in fact be too serious since many of the early far ultraviolet observations suffered from inaccurate calibrations. Figure 24 shows the run of log T_{eff} with $(u-b)_o$ for the zero-age relation adopted by Strömgren, as well as the other calibrations discussed below. We note that at a given $(u-b)_o$, Strömgren's calibration predicts considerably hotter temperatures than the other calibrations.

Morton and Adams (1968) used model atmosphere calculations for early-type stars to obtain an effective temperature scale and a bolometric correction scale. The calculated Balmer discontinuities were used to relate the models to observed spectral types and colors for the earliest type stars. For late B-type stars they used Mihalas' (1966) blanketed models, and used the (B-V) colors to relate to the temperatures. The individual models are discussed elsewhere (Hickok and Morton 1968; Mihalas and Morton 1965; Adams and Morton 1968; Mihalas 1966). A comparison of the predicted far-ultraviolet flux for a model equivalent to MK class B4 V with recent rocket observations shows fair agreement (Adams and Morton 1968) and a comparison of their temperature scale to the scale obtained from the stellar diameter observations of Brown et al. (1967) also shows good agreement (see Figure 24). The Strömgren (u-b) colors corresponding to each Johnson-Morgan (U-B) and the original calibration were obtained from the mean curve in a plot of (u-b) vs. (U-B) for stars listed by Heintze (1969). Bless (1970) points out that recent far ultraviolet observations from satellites suggest that for stars B5 and earlier the Morton and Adams temperatures appear to be too cool by 1000-2000 °K.

Part of the Morton and Adams calibration of B-type star temperatures was modified by Strom and Peterson (1968). They used the Balmer jump determined by Hayes (1967) to change the zero point of the grid of models and then applied mean corrections to account for stellar rotation effects. The range of temperatures covered by their re-calibration does not extend to hot enough temperatures to be useful in the present discussion; however, their temperature scale is included in Figure 24 for comparison. We see that it disagrees quite seriously with other calibrations at the hotter end of its range.

Another temperature scale for B-type stars was presented by Heintze (1969) using Balmer jumps derived from published spectral scans. The temperatures came from

Mihalas' (1965) models, and the Balmer jumps were scaled so that the value for Vega is $1^{m}.43$, as derived by Heintze (1968). Using $(u-b)_o$ colors of Heintze's stars calculated from photometric data of Crawford, we have plotted the temperatures and colors in Figure 24 along with the other calibrations. Heintze's data evidently agree very well with the Morton and Adams calibration.

Bolometric Corrections

In order to compare the theoretical Z.A.M.S. with the observed Z.A.M.S. we must not only choose an appropriate temperature calibration, but we also need a table of the corresponding bolometric corrections (abbreviated B.C.). Strömgren (1964) gives such a table based on his model atmosphere calculations. Morton and Adams (1968) also give B.C.'s; however, their values are approximately $0^{m}.3$ more positive than Strömgren's. According to Bradley and Morton (1969) a better choice of the effective temperature of the sun leads to bolometric corrections for stars of type B4 and earlier that are $0^{m}.25$ more negative than the B.C.'s originally given by Morton and Adams. This brings the two B.C. scales into almost exact agreement for the early B-type stars. Since the adjustment suggested by Bradley and Morton produces a discontinuous jump in the Morton and Adams scale at MK class B4, we conclude that the more uniform bolometric correction scale given by Strömgren is sufficient to use in the following discussion.

Zero Age Main Sequence

Kelsall and Strömgren (1966) present a series of stellar evolution computations for which they tabulate the temperature and bolometric magnitudes corresponding to the initial main sequences for each composition with which they computed models. In Figure 25 we compare the locations of three such sequences to the observed Z.A.M.S. in the β, $(u-b)_o$ diagram, using the Hayes, Morton and Adams, and Strömgren temperature calibrations, the Strömgren bolometric correction scale, and Crawford's β-M_V calibration. We note that the X = 0.70, Z = 0.03 models, with the Strömgren temperature calibration, fit the main sequence quite well, however the other sets of curves deviate strongly away from the early end of the observed sequence. This could indicate systematic errors in the models, the bolometric correction scale, the temperature scale, or the observed Z.A.M.S.

Since all of the models assumed no rotation, it would seem likely that adding corrections to the model sequences to take this into account would improve the agreement with the observed sequence. A detailed study of the effect of stellar rotation on the Hβ line and related quantities has been done by Collins and Harrington (1966). They tabulate the differences in the β-indices and

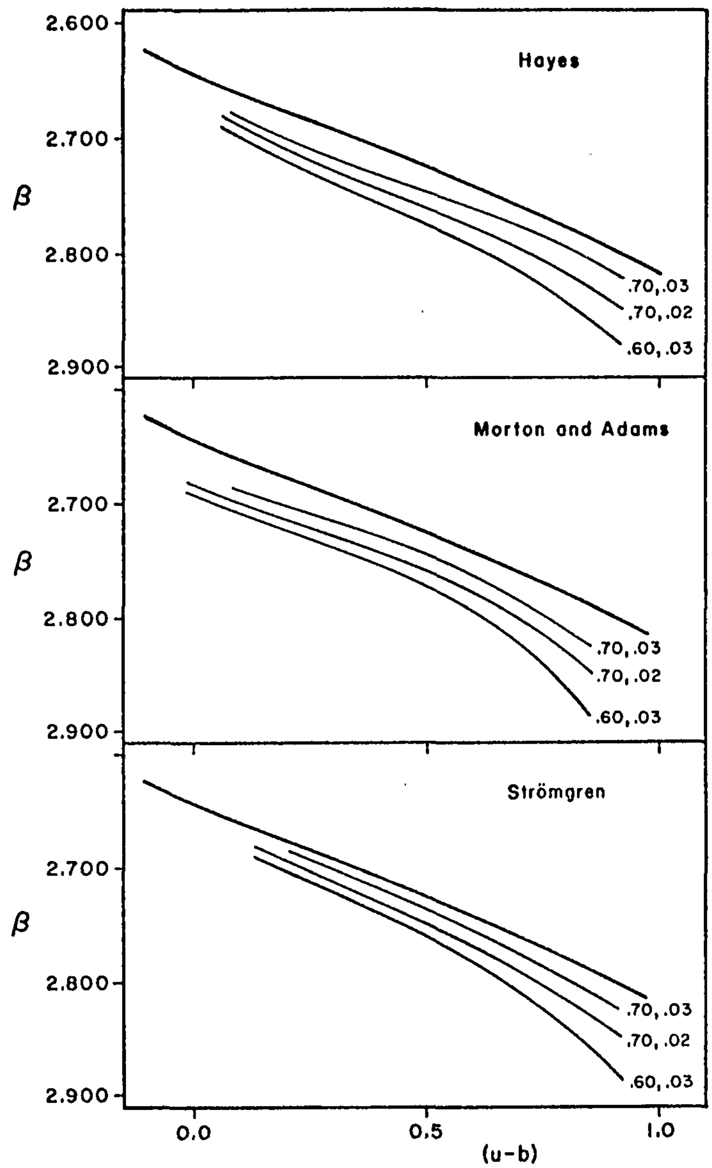

Figure 25. Main Sequence Relations in the β, $(u-b)_o$ Diagram -- Numbers at the ends of the sequences represent the compositions adopted by Kelsall and Strömgren (1966). The first number is the hydrogen mass fraction, X; the second number is the mass fraction of all elements heavier than helium. The heavy solid lines represent the Z.A.M.S.

(U-B)-colors for stars of different mass, angular momentum, and aspect angle. Their data show that the β-indices and colors of rotating stars will be located above and to the right of the non-rotating sequence in a β, (u-b) diagram, such as Figure 25. Average B-type stars, having v sin i between 150-250 km/sec would lie $0^{m}.01$-$0^{m}.02$ above the non-rotating sequence. This correction would bring the theoretical initial sequence into better agreement with the Z.A.M.S.

Conversion from ΔM_{bol} to β

To transfer the evolutionary track isochrones into β, (u-b) diagram we need both a T_{eff}-(u-b) calibration and a method for converting the published ΔM_{bol} (taken above the main sequence at the same temperature) to the appropriate value of the β-index. The calibration of the β-index in terms of absolute magnitude by Crawford may be used along with the observed Z.A.M.S. in the β, (u-b) diagram. For each computed point to be plotted, ΔM_{bol} is added to the absolute magnitude of the Z.A.M.S. at the (u-b), or T_{eff}, in question, and the resulting value of β is read off of the mean β-M_v relation. Implicit in this procedure is the assumption that the bolometric correction of an evolved star does not depend significantly on ΔM_{bol}, that is to say $\Delta M_{bol} = \Delta M_v$. Strömgren (1964) showed that the bolometric correction does not change appreciably as a function of log g, which is related to M_v, so the procedure described above should be valid.

Comparison of Models to Observations

Before directly comparing the series of theoretical evolutionary sequences to the observed sequences, it should be noted that the model computations by Iben (1965a, 1965b, 1966a, 1966b, 1966c, 1967) of the evolution of 5 and 2.25 $M_\odot$ stars do not agree with the corresponding Kelsall and Strömgren models. Figure 26 shows ΔM_{bol} vs. log T_{eff} for the X = 0.70, Z = 0.02 case of the Kelsall and Strömgren models, and the X = 0.708, Z = 0.02 case of Iben. The latter's models are plotted to the end of the main sequence lifetimes, the ages of which agree with the ages found by Kelsall and Strömgren. However, the values of ΔM_{bol} for Iben's models are less than ~ 2/3 ΔM_{bol}(KS). This would tend to make isochrones for Iben's models lie that much closer to the Z.A.M.S. As we shall see below, even the Kelsall and Strömgren models fail to approach the observed amount of turning-up apparent in the observations of clusters. Nonetheless, it seems preferable to use the Kelsall and Strömgren models. A similar judgment may be made against using the 5 $M_\odot$ model by Schlesinger (1969), which shows an even shorter evolutionary track than the corresponding Iben model.

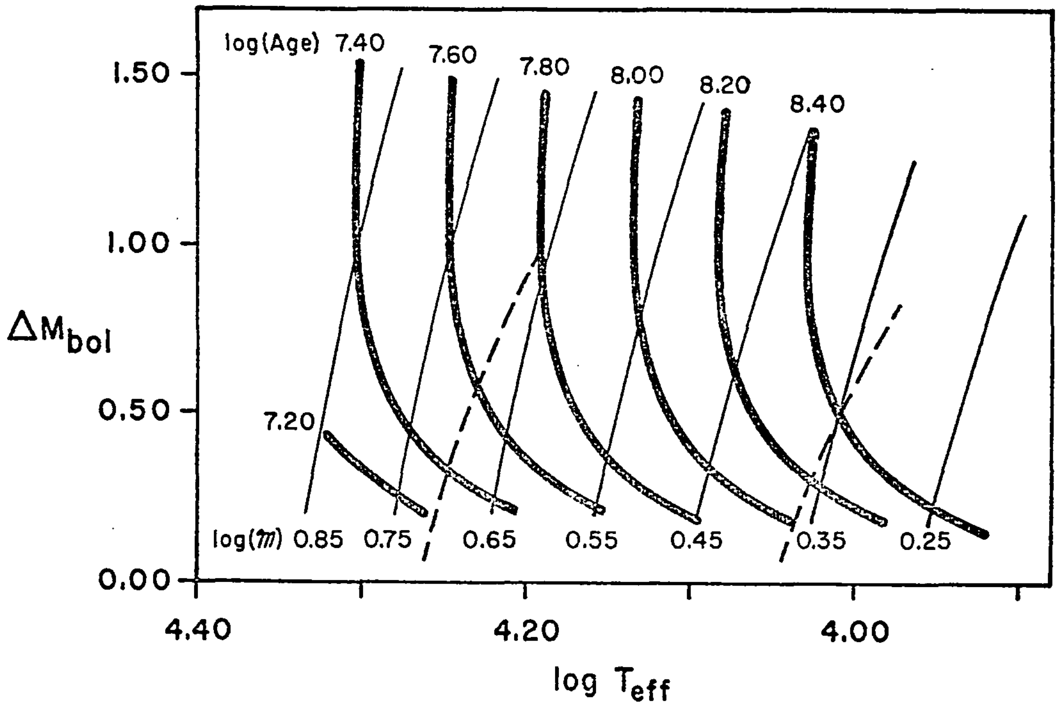

Figure 26. Evolutionary Tracks and Isochrones for $X = 0.70$, $Z = 0.02$ -- Model calculations from Kelsall and Strömgren (1966). Heavy solid lines are time-constant loci, labeled with the log(Age). Lighter solid lines represent evolutionary tracks for models corresponding to the labelled log($\mathfrak{M}$). Dashed lines represent Iben's (1966a, 1967) $5M_{\odot}$ and $2.25M_{\odot}$ model tracks for $X = 0.708$ and $Z = 0.02$. The ends of Iben's tracks correspond to ages of 65×10^6 and 480×10^6 years, respectively, for the $5M_{\odot}$ and $2.25M_{\odot}$ models.

The β, (u-b) diagrams in Figure 27 show the Kelsall-Strömgren isochrones for three compositions, using the Hayes temperature calibration. The equivalent diagrams using the Morton and Adams and the Strömgren calibrations are quite similar. To overlay the observed sequence, however, we should first choose the composition which seems most appropriate. Morton (1968) discussed the abundance of helium in A- and B-type stars and came to the conclusion that X = 0.70 and Z = 0.02-0.03 are the most appropriate values for the young Population I objects. Some caution must be exercised against the possibility of circular reasoning, however, since some of his evidence was based on a comparison of the theoretical mass-luminosity relation from the Kelsall-Strömgren models to the observed mass-luminosity relation.

The observed β, $(u-b)_o$ diagram for the Upper Scorpius, Upper Centaurus, and Lower Centaurus regions are shown in Figure 23. Overlaying the X = 0.70, Z = 0.02, and Z = 0.03 model diagrams on the Upper Centaurus data leads to ages between 16×10^6 and 12: $\times 10^6$ years, respectively, while the X = 0.60, Z = 0.03 models give an age of 12×10^6 years. Although the Upper Centaurus stars show what appears to be a smooth rise away from the main sequence for the earliest B-type stars, ending at $(u-b)_o = 0\overset{m}{.}0$, the Upper Scorpius stars show no such rise, the earliest stars being at $(u-b)_o = -0\overset{m}{.}2$. There appears to be a gap in the

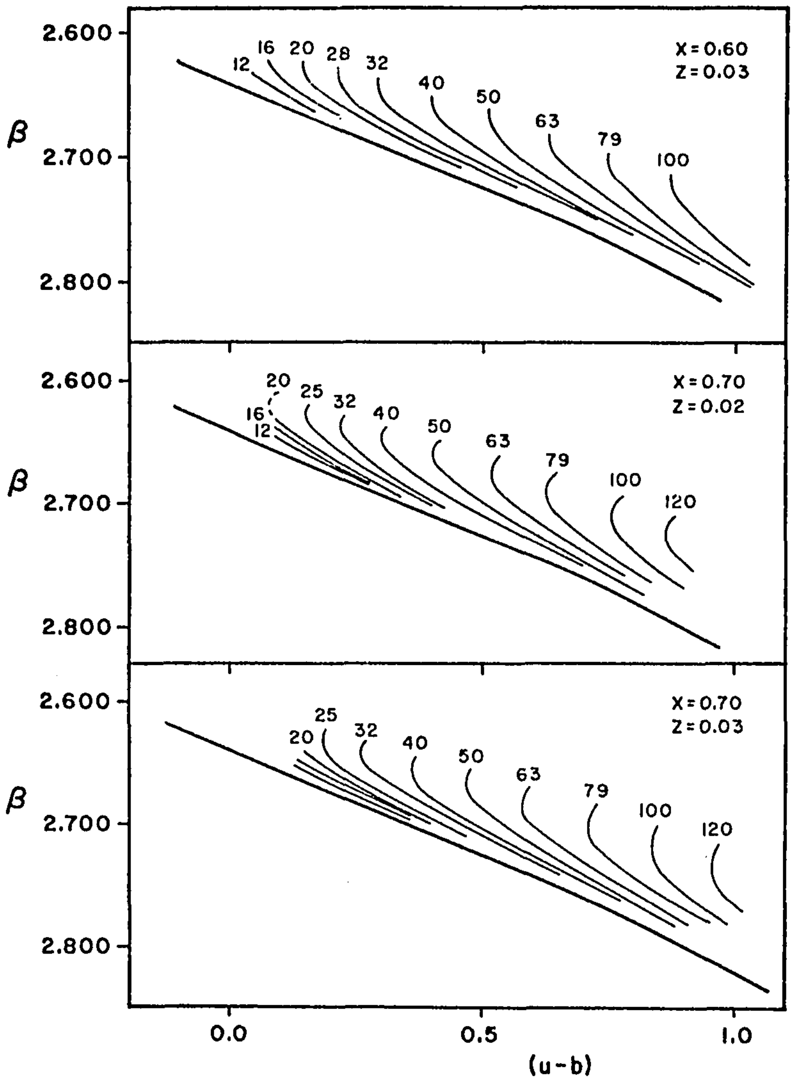

Figure 27. Isochrones for Different Compositions in the β, $(u-b)_o$ Diagram -- Ages in millions of years are labelled at the end of each track.

early main sequence for the Upper Scorpius stars, extending from $(u-b)_o = -0^m.09$ to $+0^m.05$. This is probably not significant, nonetheless it does appear weakly in the β, $(U-B)_o$ diagrams published by Hardie and Crawford (1961). It should also be pointed out that there is one early B star in the southern part of the Upper Centaurus region that shows Hβ in emission (HD 120324 = μ Cen), which seems to lie to the left of the hottest Centaurus stars in Figure 45. Similarly, HD 105435 = δ Cen in Lower Centaurus shows Balmer line emission, so its β- and $(u-b)_o$-indices are not plotted directly in Figure 23.

Another method for comparing the models to observations to determine the age of the group would be use a V_o, $(u-b)_o$ diagram. By locating the Z.A.M.S. at the appropriate distance modulus, isochrones could be drawn relative to this. The Scorpio-Centaurus stars, however, are so nearby, and their distribution across the sky is so large, as to create a larger than normal dispersion in the color-magnitude diagram which does not occur in the β, $(u-b)_o$ diagram. There also seems to be a rather high frequency of binary stars in Scorpio-Centaurus, adding to the dispersion in the V_o, $(u-b)_o$ diagram. The effect of the presence of a companion on the β- and $(u-b)_o$-indices, however, is such as to shift the binary along the main sequence. Therefore, the problem of a high binary frequency may be neglected.

<u>Summary</u>

We have calibrated the $(u-b)_o$ color-index with the effective temperature scale of Hayes (1970). Using the β-M_v calibration of Crawford (1970b) and the bolometric corrections from Strömgren (1964), the zero-age interior models of Kelsall and Strömgren (1966) agree reasonably well with the observational Z.A.M.S. The β-M_v and the β-$(u-b)_o$ calibrations were used to determine the relation between ΔM_v and β for stars evolving away from the Z.A.M.S. The Kelsall and Strömgren models were then transformed to a β, $(u-b)_o$ diagram for direct comparison with the observed sequence. The ages derived for different compositions lie between 12 and 16 million years for the Upper Centaurus B stars. The sequence of Upper Scorpio stars seems to exclude this old an age, and the Lower Centaurus stars may be intermediate in age between the two other regions.

CHAPTER 5

AO STAR ANALYSIS

Stars that have effective temperatures corresponding to the observed maximum in the strength of the hydrogen Balmer lines present considerable difficulties to photometrists who attempt to determine their intrinsic colors and absolute magnitudes. As has been mentioned before, for B-type stars the size of the Balmer jump correlates well with the intrinsic color and effective temperature, and the strength of the Balmer lines; for example, Hβ correlates with the absolute magnitude of the star. In the A and F star range the reverse situation is true; the β-index is strongly dependent on the effective temperature, while the c_1-index depends both on temperature and luminosity. Near spectral type AO, there occurs a reversal of the roles played by the photometric indices, with the result that the β- and c_1-indices depend on both temperature and luminosity. For unreddened stars and for members of open clusters this problem is unimportant, since for the former case the location of the (b-y)-, c_1-, and β-indices in the c_1, (b-y) plane and the β, (b-y) plane determines the effective temperature and luminosity, and for the latter case the B- or A-type members of the cluster may be used to eliminate any reddening. Difficulties obviously arise when we attempt to deal with faint field stars for which we have no knowledge of the interstellar reddening. This is the situation we encounter in studying the A0-type stars in the Scorpio-Centaurus region. Therefore, some procedure must be established to deal with these stars.

The Zero Age Main Sequence for A0 Stars

The first step in developing a calibration of the uvby and Hβ photometric systems for the A0 stars is to establish the location and dispersion of the Z.A.M.S. for the (b-y)-, m_1-, c_1-, and β-indices. The most effective way of doing this is to use observations of open clusters which have members extending throughout the spectral range of interest near A0. The available data consist of observations of the Pleiades (Crawford 1970b), IC 2931 (Perry and Hill 1969), IC 2602 (Hill and Perry 1969), and NGC 7243 (Hill and Barnes 1970). All of these clusters include B-type stars, and have main sequences that extend through the A0 range and well into the A star range. Mean reddening corrections appropriate to each cluster were determined from the B- and A-type stars. The resulting data, when combined with the existing calibrations for B- and A-type stars, yield the intrinsic colors for the Z.A.M.S. given in Table 18, where $[m_1]$ is defined as

Table 18. AO Calibration

(b-y)	(u-b)	[m_1]	c_1	β	M_V Z.A.M.S.
$-0^m.020$	$1^m.24$	$0^m.156$	$0^m.945$	$2^m.868$	$+1^m.1$
-0.015	1.30	.164	.965	2.890	1.2
-0.010	1.33	.171	.970	2.901	1.3
-0.005	1.35	.178	.975	2.907	1.4
0.000	1.37	.182	.980	2.909	1.5
+0.005	1.39	.186	.980	2.909	1.6
0.010	1.40	.190	.977	2.908	1.6
0.015	1.42	.193	.975	2.907	1.7
0.020	1.43	.197	.973	2.906	1.8
0.030	1.44	.203	.967	2.900	1.9
0.040	1.46	.210	.960	2.894	2.1
0.050	1.47	.216	.950	2.888	2.2
0.060	1.47	.222	.935	2.880	2.3

$[m_1] = m_1 + 0.3(b-y)$. The calibration has been smoothed to join with the endpoints of the B and A star calibrations.

The effects of luminosity differences near A0 are not as easily determined, since no cluster which has a turn-off at this spectral range has yet been observed with the four-color system. It is necessary, therefore, to use bright field stars which, hopefully, are unreddened, and which have accurate MK spectral classifications. We may then compare the locations of the photometric indices of stars with different luminosity classes in the c_1, (b-y) and β, (b-y) diagrams. Data for this comparison are taken from Jaschek, Conde, and de Sierra (1964), Crawford, Barnes, and Golson (1970), and an unpublished catalogue of four-color and Hβ data for bright A0-type stars by D. L. Crawford, Barnes, Gibson, Golson, and M. L. Crawford (1970). Figures 28 and 29 show β vs. (b-y) and c_1 vs. (b-y) for those stars brighter than $m_v = 4.5$. The Z.A.M.S., the width of the Z.A.M.S. (as indicated by the cluster data mentioned above), and the slopes of the reddening lines are drawn in for comparison. The distribution of the bright A0 stars shows considerable scatter above the Z.A.M.S., probably due to a combination of the effects of reddening and the spread of ages represented. In the sample of the brightest A0 stars, presumably unreddened, very few points actually fall on or near the indicated Z.A.M.S. in the c_1, (b-y) diagram.

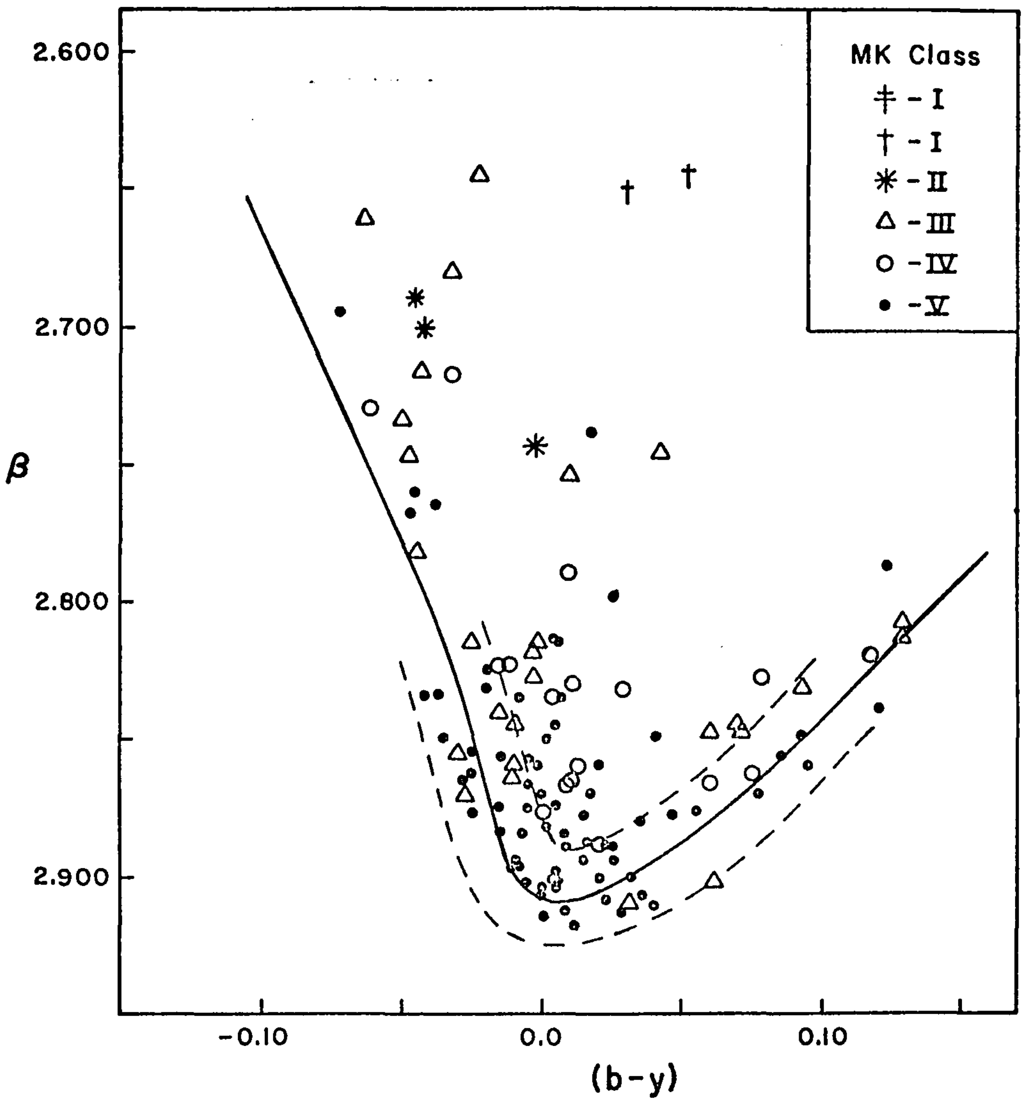

Figure 28. β, (b-y) Diagram for Bright A0 Stars -- The Z.A.M.S. and its width, as shown by young, open clusters are indicated by solid and broken lines, respectively.

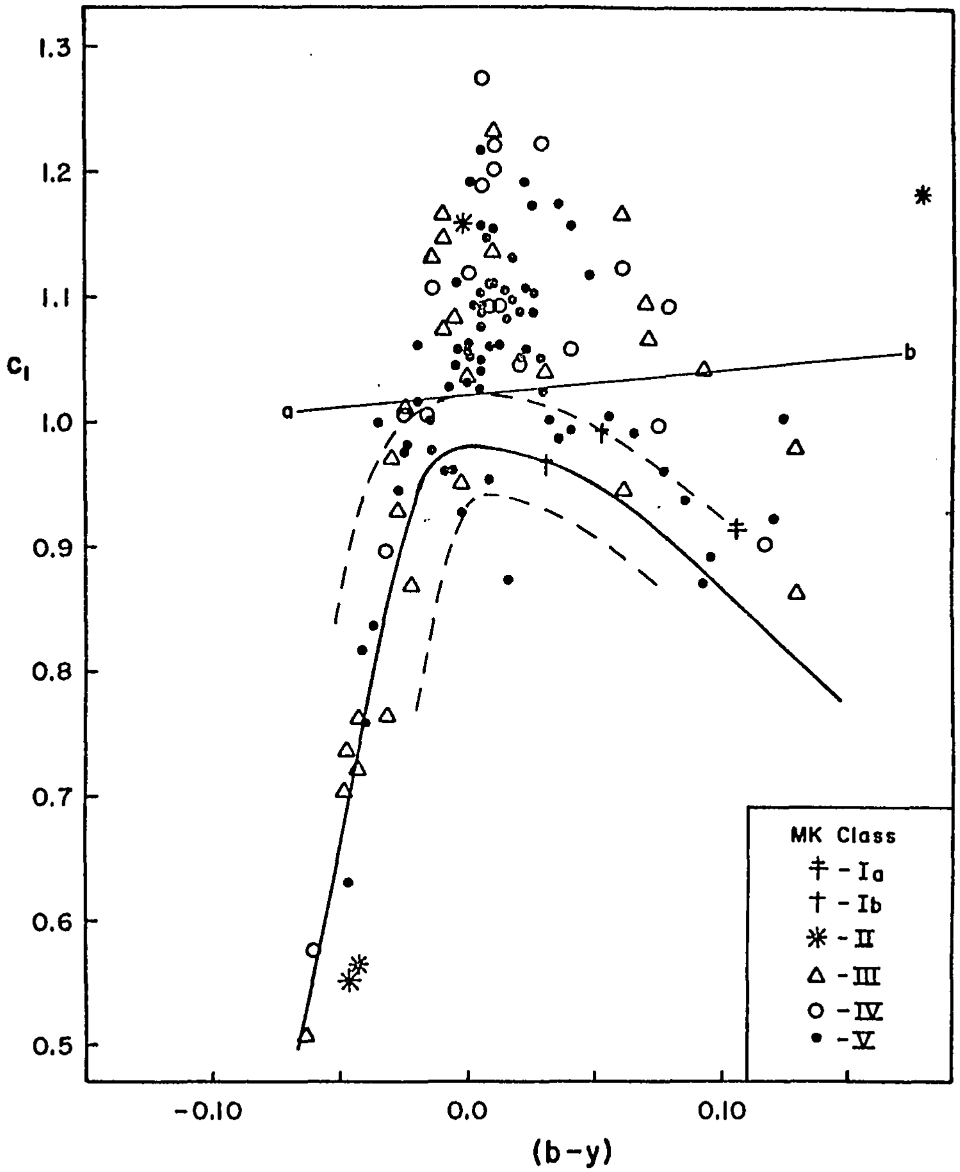

Figure 29. c_1, (b-y) Diagram for Bright A0 Stars -- All stars above the line "ab" are assumed to be evolved stars.

The narrow width of the cluster sequences in the c_1, (b-y) diagram and the large spread in c_1-values observed for the field stars suggest that an initial elimination of evolved stars from the Scorpio-Centaurus analysis can be made by simply excluding stars above the line ab in Figure 29.

Determination of Color Excesses

An estimation of the intrinsic (b-y) color, $(b-y)_o$, for each star can be made using the $[m_1]$-index, where $[m_1] = m_1 + 0.3(b-y)$ is, to a first approximation, independent of reddening. The cluster sequences in the $[m_1]$, $(b-y)_o$ diagram were again used to determine a mean relation, where the value of $(b-y)_o$ for each cluster member was calculated using the mean color excess for each cluster. Figure 30 shows the mean $[m_1]$, $(b-y)_o$ relation derived from the four clusters and the location of the indices for several bright stars having spectral types near A0 and luminosity classes ranging from IV to Ia. The mean relation apparently does not represent stars that have evolved above the main sequence, assuming that these stars are unreddened. Obviously, care should be taken to eliminate as many non-main sequence stars as is possible before using this technique to determine the color excess of field stars.

The avoid this problem Strömgren (1966) defined two new indices using linear combinations of the basic uvby

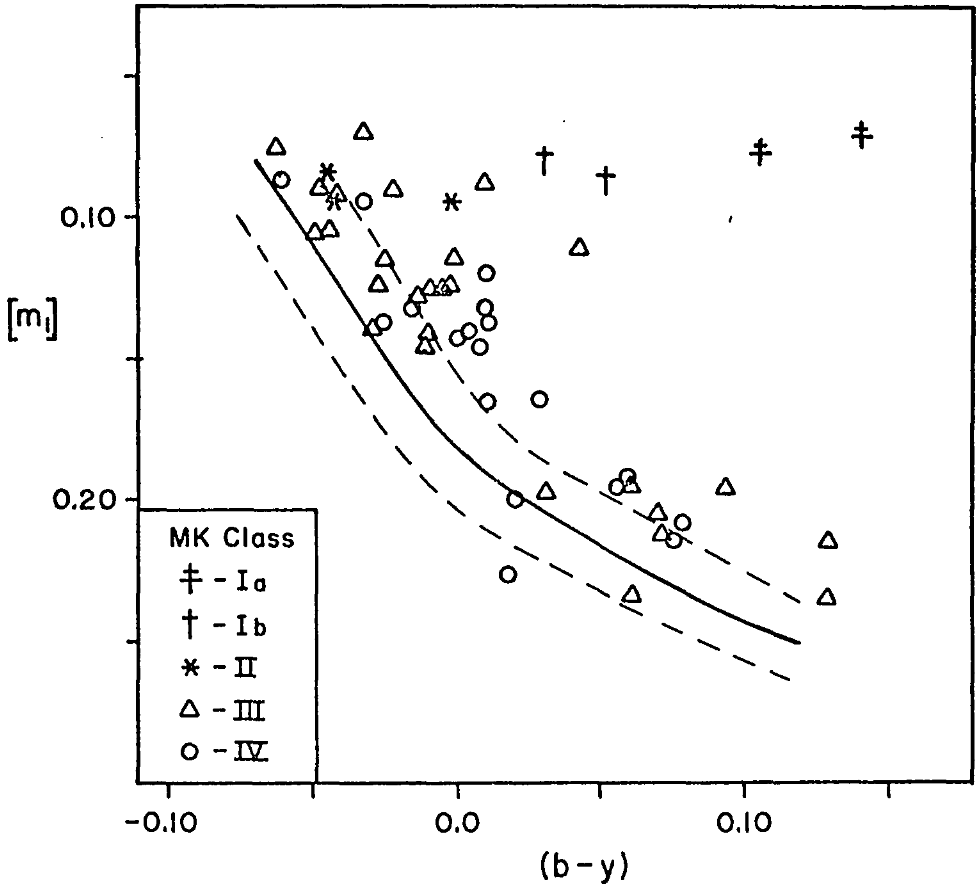

Figure 30. $[m_1]$, (b-y) Relation for Young A0 Stars

indices:

$$a = (b-y) + 0.18\{(u-b) - 1^m.36\} \quad \text{(temperature indicator)}$$

$$r = 0.35[c_1] - (\beta - 2.565) \quad \text{(luminosity indicator)}$$

where $[c_1] = c_1 - 0.2(b-y)$ is independent of reddening. The r-index is defined in such a way that it will be near zero along the main sequence. Membership in the group of A0 stars was to be determined by the exclusion of a star from either the B or AF groups. The first relation is sensitive to interstellar reddening, so it would be desirable to calibrate a_o, the unreddened a-index, in terms of some temperature dependent, reddening-free quantity. Strömgren found that normal stars would satisfy the following expression: $a_o = 2.0([m_1]_s - 0.179) + 0.80r$, where $[m_1]_s = m_1 + 0.18(b-y)$ is the reddening free index defined by Strömgren. A more recent determination of the slope of the reddening line in the m_1, (b-y)-diagram leads to the definition $[m_1] = m_1 + 0.30(b-y) = [m_1]_s + 0.12(b-y)$. This would change the above calibration of the a-index in terms of $[m_1]$ and r, but the difference in the value of the a-index determined from Strömgren's expression and a revised one would be equal to .24(b-y), i.e., $a_o' = 2([m_1] - .179) + .80r - .24(b-y)$. This in turn implies that for a reddened star the difference between the true, unreddened a_o and the predicted a_o' is $a_o - a_o' = .24E(b-y)$. From the definition of the a-index and knowing that the color excess $E(u-b) = 1.7E(b-y)$, we find that the excess

$E(a) = 1.31E(b-y)$. Therefore, using the observed index a_{obs} computed from (b-y) and (u-b), we find $a_{obs} - a_o' = a_{obs} - a_o + .24E(b-y) = E(a) + .24E(b-y) = 1.55E(b-y)$. We conclude that we can determine the color excess E(b-y) from the difference between the observed index a_{obs} and the a_o' predicted from $[m_1]$, r, and (b-y): $E(b-y) = 0.645(a_{obs} - a_o')$.

Color excesses have been calculated for the A0-type stars in the Scorpio-Centaurus region using both the mean $[m_1]$, $(b-y)_o$-relation and Strömgren's a,r technique. The color excesses computed by the two methods agree quite well, with a mean difference of $0^m.002$ for the twenty unevolved stars in Centaurus and $0^m.005$ for the stars in Scorpius. Because the $[m_1]$, $(b-y)_o$ relation does not take luminosity effects into account, color excesses of evolved stars cannot be determined by this method. The a, r technique includes a luminosity correction; therefore, it was decided to use the a, r method to determine the reddening for each A0-type star. (In either case, it should be noted that reddened Ap or Am stars having large m_o-values give color excesses that are either negative or are too small.) Figure 31 shows c_o vs. $(b-y)_o$ for the A0 stars in Scorpio-Centaurus. The filled circles and triangles represent the unevolved stars in Upper Centaurus and Upper Scorpio, respectively, and the open circles and open triangles represent the evolved stars. The location

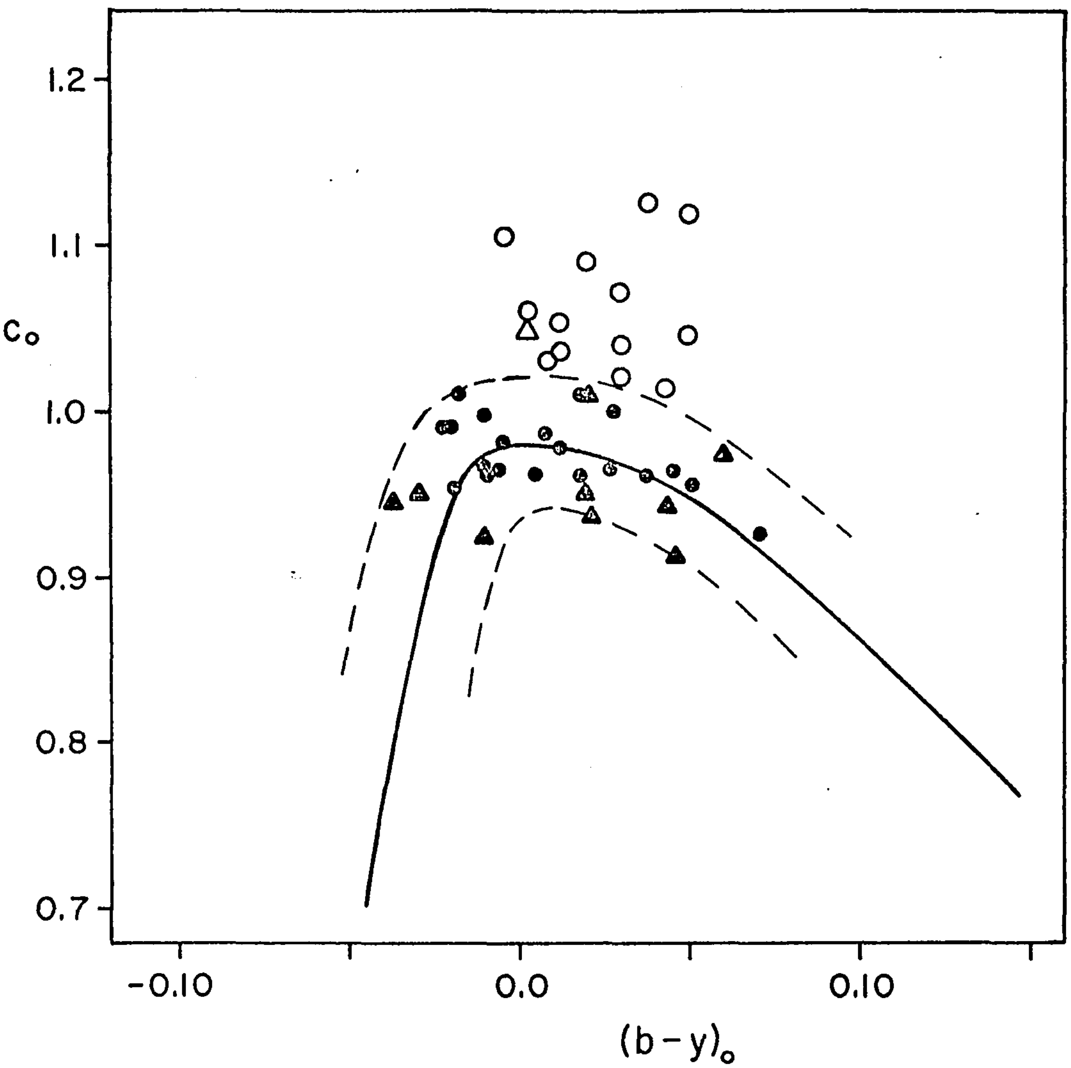

Figure 31. c_o, $(b-y)_o$ Diagram for A0 Stars in Scorpius and Centaurus -- Filled circles represent unevolved A0 stars in Upper Centaurus; open circles evolved stars; filled triangles, unevolved stars in Upper Scorpius; open triangles, evolved stars.

of the Z.A.M.S. and its expected width are indicated. The large number of apparent zero-age stars in the Scorpio-Centaurus sample contrasts sharply with the small number of zero-age stars present in the sample of stars brighter than $m_v = 4^m.5$ shown in Figure 29. Tables 19 and 20 list the Scorpio-Centaurus A0 stars, their color excesses, and unreddened photometric indices for the evolved and the unevolved stars, respectively. The color excess distribution across the sky is shown in Figure 32, which plots l vs. b. The color excesses are given in units of $0^m.01$, and circled numbers represent the unevolved A0 stars determined from the c_o, $(b-y)_o$ diagram.

By assuming that all of the A0 stars within the Z.A.M.S band shown in Figure 31 are indeed unevolved main sequence A0 stars, we may use the main sequence absolute magnitudes to calculate distance moduli. Figure 33 shows a histogram of the number of stars in each $0^m.4$ interval of distance modulus for the A0 stars. The open bars represent the A0 stars in Upper Centaurus, whereas the hatched bars added to these represent some of the A0 stars listed by Garrison (1967) as being members. The small cross at d.m. = $6^m.2$ indicates Bertiau's adopted modulus from his moving cluster analysis of the B-type stars. There appears to be a tendency for the A0 stars to fall at smaller moduli than $6^m.2$, but it is doubtful that this is significant. The mean photometric distance moduli for the Upper Centaurus

Table 19. Unreddened Photometric Indices for Unevolved A0 Stars

HD No.	Sp.	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o	d.m.
118335	A1 III	$2^{m}.921$	$0^{m}.026$	$7^{m}.51$	$-0^{m}.011$	$0^{m}.174$	$0^{m}.997$	6.2
122705	A4 V	2.895	.005	7.60	.051	.206	.954	5.4
122757AB	A4 V	2.885	.056	8.32	.028	.182	.999	6.4
123344	A0 III	2.880	.021	7.26	-.004	.160	.982	5.8
123431	A0	2.894	.021	8.63	-.018	.156	1.010	7.5
125509	B9.5 III	2.859	.023	7.59	-.026	.137	.990	6.6
126062	A1	2.918	.011	7.39	.013	.190	.978	5.8
126561	A0	2.914	.003	7.22	-.011	.173	.963	5.9
129791	B9.5 V	2.864	.039	6.72	-.006	.152	.964	5.3
131399	A3 III	2.925	.020	6.95	.027	.203	.963	5.1
131461AB[a]	A1 IV	--	.014	7.19	.017	.189	.961	5.5
131752	A0	2.874	.026	6.26	.005	.164	.961	4.8
131777	B9	2.896	.021	8.04	.018	.180	1.010	6.2
133954	A2	2.891	.002	8.11	.071	.218	.924	5.8
134685	A0 V	2.885	.080	7.32	.008	.170	.986	5.7
135454	B9 V	2.854	.014	6.75	-.019	.142	.952	5.6
136013	A1 V	2.927	.076	7.41	-.026	.170	.992	6.3
137119	A1	2.908	-.012	7.62	.045	.212	.963	5.5
138285	A2 V	2.925	.012	7.43	-.010	.178	.963	6.1
140475	A5 III	2.916	.004	7.70	.037	.206	.959	5.7
141939[b]	A2	2.905	.056	8.00	.061	.214	.973	5.7
146606[c]	A0 V	2.897	.026	6.98	-.037	.155	.944	6.3
147009[d]	B9.5 V	2.925	.235	7.04	-.029	.165	.949	6.1
147343[e]	A1 Vn	2.876	.418	7.54	-.046	.189	.909	5.3
147384[f]	B9.5 V	2.881	.298	7.33	-.011	.155	.923	6.0
147592[g]	A1 V	2.939	.161	8.22	.019	.203	.952	6.4

Table 19.--Continued

147809[h]	A1 V	$2\overset{m}{.}923$	$0\overset{m}{.}253$	$7\overset{m}{.}52$	$0\overset{m}{.}021$	$0\overset{m}{.}161$	$0\overset{m}{.}934$	$5\overset{m}{.}7$
148562[i]	A3 V	2.895	.045	7.64	.043	.200	.942	5.5
150035[j]	A5p(SrCr)	2.898	.152	8.00	.021	.181	1.009	6.2

[a]HD 131461: E(b-y) from $[m_1]$.

[b]HD 141939: In Upper Scorpius.

[c]HD 146606: In Upper Scorpius.

[d]HD 147009: In Upper Scorpius.

[e]HD 147343: In Upper Scorpius.

[f]HD 147384: In Upper Scorpius.

[g]HD 147592: In Upper Scorpius.

[h]HD 147809: In Upper Scorpius.

[i]HD 148562: In Upper Scorpius.

[j]HD 150035: In Upper Scorpius.

Table 20. Unreddened Photometric Indices for Evolved A0 Stars

HD No.	Sp.	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o
119268	gA1:	$2^m.888$	$0^m.028$	$8^m.45$	$0^m.012$	$0^m.170$	$1^m.036$
119430	A0 III	2.830	.022	6.98	-.019	.120	1.094
122109	A2 V	2.870	.032	7.86	-.004	.149	1.103
124540	A1	2.895	.048	8.80	.038	.185	1.126
125253	A1	2.921	.001	7.08	.030	.193	1.021
128224	A2	2.886	.004	8.79	.050	.190	1.118
130133	A1	2.884	.001	8.44	.052	.194	1.044
130163	B9.5 V	2.879	.004	6.90	.003	.159	1.059
133716	A1	2.892	.011	7.12	.020	.175	1.088
133750	B8 V	2.905	.014	7.12	.008	.176	1.029
135334	A2 V	2.892	.021	6.10	.012	.172	1.052
136761	A4 IV	2.908	-.017	6.75	.030	.202	1.038
141404[a]	B9.5 V	--	--	--	--	--	--
141905	A1	2.903	.108	7.85	.029	.183	1.071
142431	A2	2.881	.008	7.02	.043	.189	1.031
142805[b]	A0 III	2.830	.137	6.55	.003	.135	1.048

[a]HD 141404: Large c_1-index; observed by Garrison (1967) in Upper Scorpius.

[b]HD 142805: Observed by Garrison (1967) in Upper Scorpius.

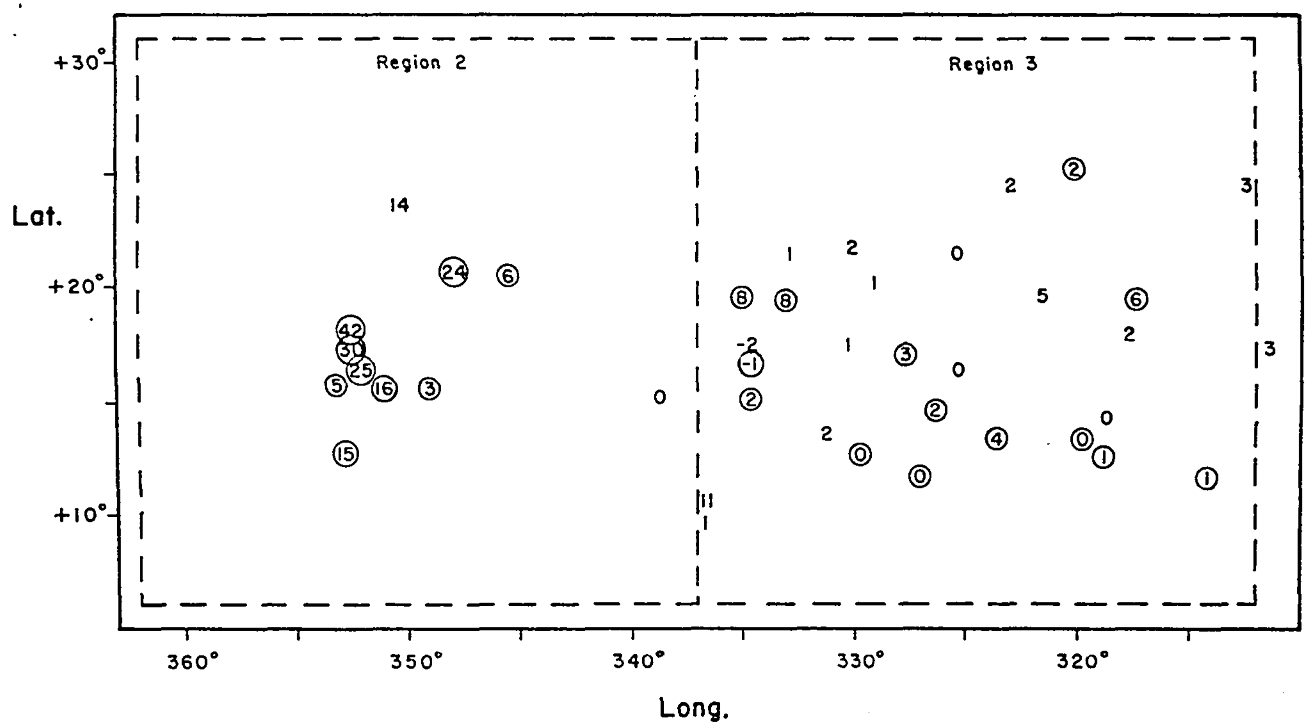

Figure 32. Areal Distribution of E(b-y) for A0 Stars -- Plotted numbers represent E(b-y) in units of $0^{m}.01$. Circled numbers represent unevolved stars.

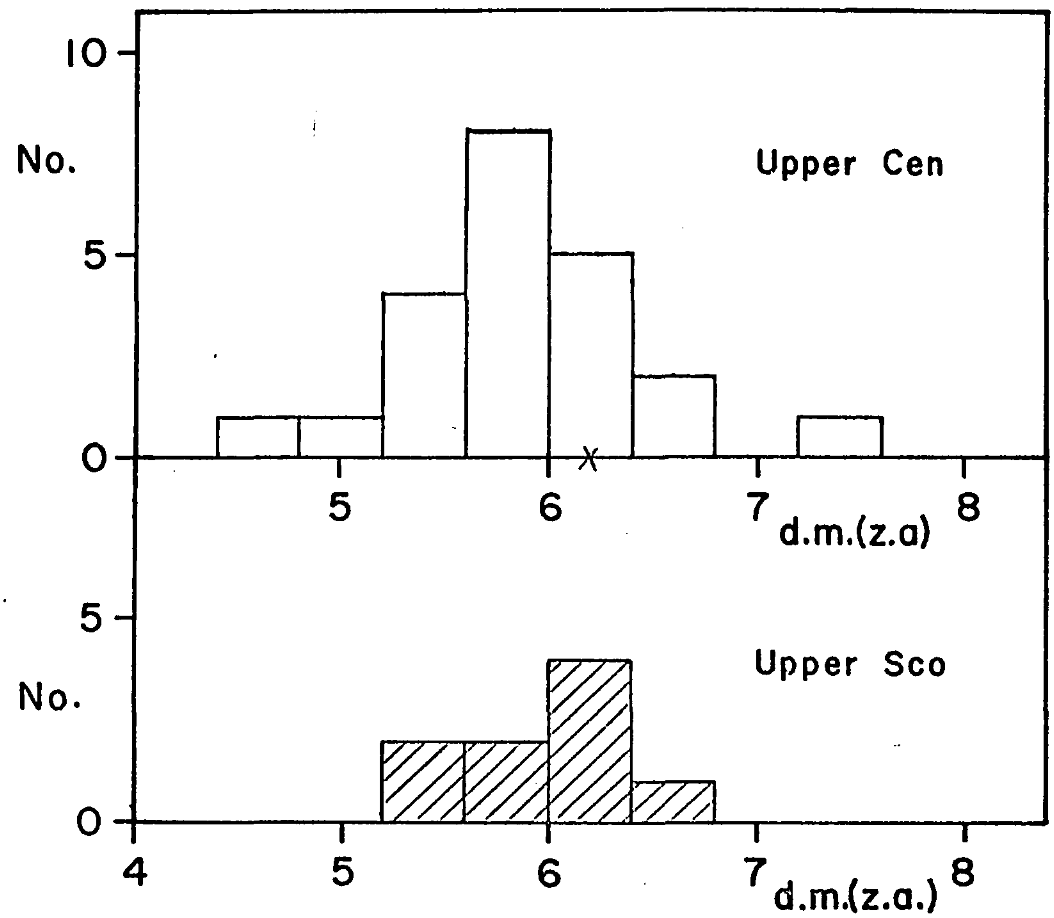

Figure 33. Frequencies of Distance Moduli for A0 Stars -- Only unevolved stars have been counted, using zero-age values of M_v.

A0 stars and the Upper Scorpius stars are, respectively, $6\overset{m}{.}0$ and $5\overset{m}{.}9$.

CHAPTER 6

A AND F STAR ANALYSIS

There are seventy-six stars in the current program having uvby and Hβ photometry which are considered to be A- and F-type stars on the basis of their spectral types and photometric indices. The criteria used have been that (1) each star have an objective prism spectral type of A0 or later, and (2) $\beta \leq 2.880$. Crawford (1970a) gives the standard relations between the quantities β, (b-y), m_1, c_1, and M_v. The absolute magnitude calibration was determined from observations of bright field A- and F-type stars having measured trigonometric parallaxes as well as A- and F-type stars in nearby open clusters. The Hyades cluster was excluded from the determination of the relations between β, (b-y), c_1, and M_v. The standard relation between m_1 and (b-y), however, is determined from the Hyades.

The intrinsic color $(b-y)_o$ may be calculated from the observed β-index, the difference between the observed c_1 and the zero-age value of c_1 at the same β, δc_1, and the difference between the Hyades sequence m_1 at the same β and the observed m_1, δm_1. The expression given by Crawford is: $(b-y)_o = 2.943 - \beta - 0.1\delta c_1 - 0.1\delta m_1$. The unreddened photometric indices determined in this way and related quantities for stars in the Scorpio-Centaurus association are listed in Table 21. The distribution of color excesses, E(b-y) (in units of $0^m.01$), on the sky is shown in Figure 34. The agreement with the equivalent diagrams for B-type stars (Figure 11) and for A0 stars (Figure 28) is good. The circled numbers represent (presumably) unevolved stars (having $\delta c_1 \leq 0^m.05$) which will be discussed below.

Evolutionary Effects

In the A and F star range differences in the Balmer jump are related to luminosity differences. Therefore, the c_1-index should help to identify evolved, more luminous stars. The quantity δc_1 indicates the difference between the observed c_1 and the c_1(Z.A.) for the same value of β. The β-index is well correlated with effective temperature in the AF star spectral range. To determine the appropriate upper limit to impose on the size of δc_1 that will exclude evolved (large δc_1) stars, we return to the discussion in Chapter 5 of the observed main sequences for the young open clusters. The extreme width of the observed sequences in c_1 is indicated by the dashed curves in Figure 29. The upper limit of the Z.A.M.S. in the c_1, (b-y) diagram lies no more than $0^m.05$ above the zero-age line. We therefore assume that A- and F-type stars in Scorpius and Centaurus

Table 21. Unreddened Photometric Colors for A and F Stars

HD No.	Sp.	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o	δc_1	d.m.
118060	A5	$2^m.861$	$0^m.026$	$8^m.75$	$0^m.070$	$0^m.210$	$0^m.986$	$0^m.09$	$7^m.1$
119221	A3	2.879	.023	7.14	.063	.199	.919	-.01	4.8[a]
119674	Am	2.823	.045	8.81	.120	.270	.861	.04	6.2[a]
120487	A7	2.819	.022	8.87	.122	.204	.808	.00	6.3[a]
120959	A3 V	2.848	.008	8.67	.067	.174	1.111	.24	--
120960	A7	2.745	.013	7.75	.194	.174	.684	.02	4.9[a]
121057	A7	2.869	.028	7.03	.063	.207	.997	.09	5.3
121226	A1	2.873	-.001	7.41	.050	.164	1.071	.15	5.7
121399[b]	Comp	2.741	.107:	6.70	.162	.144	.922	.26	--
121528	F0:	2.747	.039	8.98	.179	.180	.807	.13	7.3
121701	A5 IV:	2.875	.017	8.50	.069	.225	.928	.00	6.2[a]
122664	A5	2.833	.042	8.14	.086	.183	.908	.17	7.0
122756	F0:	2.711	.023	8.54	.229	.144	.546	-.02	5.2[a]
123021	A7	2.786	-.002	8.32	.152	.176	.779	.03	5.6[a]
123664	A2 IV:	2.876	.036	7.45	.031	.150	1.193	.27	7.4
124228	A3	2.854	.040	7.68	.064	.174	1.051	.17	6.9
124254	A3	2.818	.005	7.49	.114	.189	.894	.09	5.6
124504	A3	2.844	.042	7.91	.091	.207	.897	.04	5.4[a]
125541	F1	2.746	-.010	8.90	.196	.190	.682	.01	6.0[a]
125718	A5	2.863	.060	8.96	.064	.195	.983	.08	7.2
125937	A5	2.810	.034	7.93	.109	.188	.874	.18	--
126194	A2 V	2.873	-.006	6.69	.069	.170	.885	-.04	4.4[a]
126476	A5	2.860	.016	7.99	.073	.212	.979	.09	6.5
127716	A3 IV	2.843	-.008	6.61	.051	.139	1.285	.42	(6.8)
127717	F0	2.742	.009	8.99	.183	.187	.739	.08	6.8
127778	F1	2.700	.050	9.62	.227	.187	.668	.13	7.6
127879	A5 V	2.812	.018	7.75	.125	.195	.824	.03	5.1[a]
128066	F0	2.716	.006	8.82	.217	.144	.648	.07	6.3
128532	A3	2.872	.024	6.68	.059	.201	1.013	.10	5.2
128648	F5	2.860	.030	8.14	.079	.199	.892	.00	5.7[a]
128788	A5	2.665	.027	.870	.270	.167	.498	.05	5.1[a]

Table 21.--Continued Unreddened Photometric Colors for A and F Stars

HD No.	Sp.	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o	δc_1	d.m.
128855	A1 V	$2^{m}.844$	$-0^{m}.019$	$7^{m}.35$	$0^{m}.060$	$0^{m}.138$	$1^{m}.186$	$0^{m}.32$	--
130388	B9.5 V	2.863	.052	7.39	.056	.190	.984	.08	$5^{m}.6$
131460	A7	2.797	.043	8.77	.140	.215	.805	.03	6.1[a]
131503	A3	2.830	.048	7.78	.095	.202	.961	.13	6.3
131518	A7	2.795	.024	9.02	.140	.206	.848	.07	6.9
131901	A1	2.876	.001	7.20	.049	.169	1.053	.13	5.9
132080	A7	2.801	.048	9.46	.131	.198	.836	.06	7.3
132761	A5	2.835	.038	7.55	.098	.191	.886	.04	5.1[a]
132851	A5 V	2.841	.018	5.74	.079	.188	1.054	.20	5.0
133574	A7	2.762	.020	8.60	.176	.187	.730	.03	5.8[a]
133991	F3	2.700	.177	8.44	.223	.245	.714	.18	6.7
134055	A7	2.810	.005	7.21	.134	.214	.795	.00	4.5[a]
134518	A5	2.803	.068	8.96	.127	.207	.756	.07	6.9
134950	A5	2.874	.084	8.32	.054	.217	.990	.07	6.3
134990	A1	2.863	.001	7.06	.055	.180	1.025	.12	5.7
135815	A5	2.844	.056	9.07	.073	.184	1.042	.18	8.3
135877	A3	2.795	-.020	8.80	.125	.214:	.997	.18	7.5
136164	A3	2.838	-.005	7.66	.097	.191	.914	.07	5.8
136483	F2	2.635	.017	8.92	.263	.148	.790	.42	8.7
137169	A3	2.874:	.029:	8.84:	.047:	.191:	1.106:	.18:	7.9:
137499	F3	2.656	.012	9.42	.285	.157	.403	-.01	5.7[a]
137785	A2	2.878:	.040:	7.45:	.065:	.196:	.885:	-.04:	5.2:[a]
137957	A1	2.878:	-.003:	7.44:	.040:	.143:	1.115:	.18:	6.5
138138	A2	2.863	-.001	6.85	.080	.212	.887	-.01	4.4[a]
139048	A7	2.759	0.015	9.04	.176	.206	.770	.08	6.9
139883	F1	2.686	-.005	8.35	.253	.152	.518	.02	5.0[a]
140958	A5	2.819	-.005	8.04	.118	.196	.857	.05	5.4[a]
141518	F2	2.688	-.010	8.52	.267	.168	.477	-.03	5.1[a]
141779	A7 V	2.851	.009	8.06	.094	.206	.853	-.02	5.2[a]
142097[c]	A3	2.851	.159	7.71	.079	.207	.852	-.02	5.2[a]
143692[d]	A2	2.868	.051	7.73	.064	.193	1.000	.09	6.0

Table 21.--Continued Unreddened Photometric Colors for A and F Stars

HD No.	Sp.	β	E(b-y)	V_o	$(b-y)_o$	m_o	c_o	δc_1	d.m.
145468[e]	A3	$2^m.857$	$0^m.124$	$7^m.68$	$0^m.070$	$0^m.206$	$0^m.917$	$0^m.04$	$5^m.3$[a]
145793[f]	A3 V	2.842	.059	7.70	.080	.178	.922	.07	5.8
146899[g]	A7 V	(2.786)	.261:	9.16:	.122:	.206	.900	.15	--
146998[h]	A7p(SrCr)	(2.761)	.234	8.52	.179	.247	.698	--	5.6:
147084[i]	A5 II	2.788	.600	1.98	.016	.158	1.494	.76	--
147432[j]	A2 V	2.863	.078	7.20	.074	.194	.889	-.01	4.8[a]
148321[k]	A5mp(Sr)	2.881	.004	7.00	.084	.248	.850	-.18	4.5[a]
148352[l]	F3 V	2.687	.002	7.51	.253	.157	.519	.02	4.1[a]

[a] d.m. from M_V(Z.A.).

[b] HD 121399: Visual Binary.

[c] HD 142097: In Upper Scorpius.

[d] HD 143692: In Upper Scorpius.

[e] HD 145468: In Upper Scorpius.

[f] HD 145793: In Upper Scorpius.

[g] HD 146899: Observed by Garrison (1967).

[h] HD 146998: Observed by Garrison (1967).

[i] HD 147084: Observed by Garrison (1967).

[j] HD 147432: In Upper Scorpius; uvby data from Crawford (1970b).

[k] HD 148321: Observed by Garrison (1967).

[l] HD 148352: Observed by Garrison (1967).

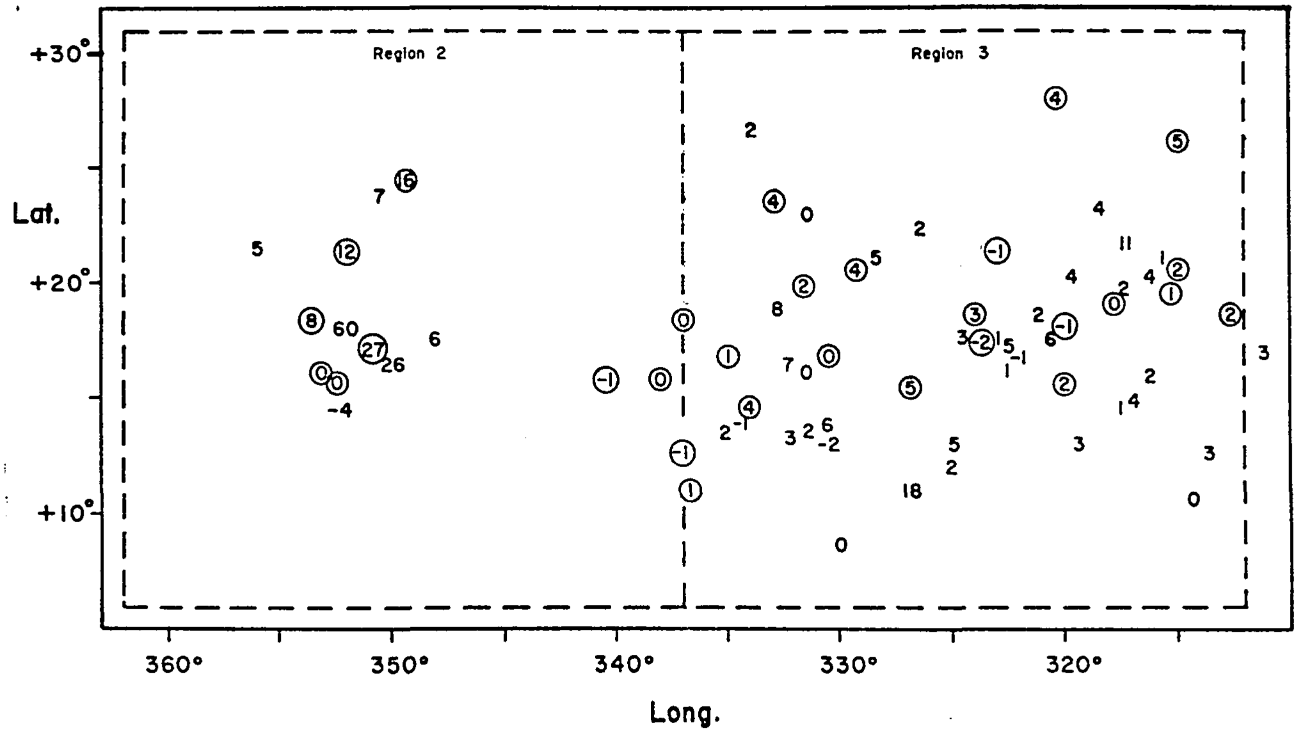

Figure 34. Areal Distribution of E(b-y) for AF Stars -- Plotted numbers represent E(b-y) in units of $0^{m}.01$. Circled numbers represent unevolved AF stars.

having $\delta c_1 \leq 0^m.05$ are young and are possible members of the Upper Centaurus B-type star association.

Figure 35 shows c_o, the intrinsic c_1 index, plotted against $(b-y)_o$ for the A- and F-type stars observed in the current program. The A0 stars observed are included for comparison. Crawford's Z.A.M.S. is also drawn in for reference, as is the upper limit of the Z.A.M.S. We should point out that the adopted upper limit is quite a generous one. However, there may be other intrinsic effects than age acting to change the photometric indices and broaden the observed sequence, such as different rotational velocities. This last effect has been shown to be rather small by Crawford (1970a), who found for A-type stars changes in c_1 of the order of $0^m.04$ for 100 km/sec difference in rotational velocity, and we do not anticipate any difference in the mean rotational velocities that is that large.

The points falling slightly below the zero-age line for $(b-y)_o \leq 0^m.100$ could be significant in terms of the evolution of low mass stars to the main sequence when compared with the small number of such stars for $(b-y)_o > 0^m.100$. The MK spectral type that corresponds to $(b-y)_o = 0^m.100$ is A7; however, the latest spectral type which could have contracted to the main sequence is approximately F2 if the earliest spectral type still observed to be within the main sequence is type B2 (see Murphy 1969). According to

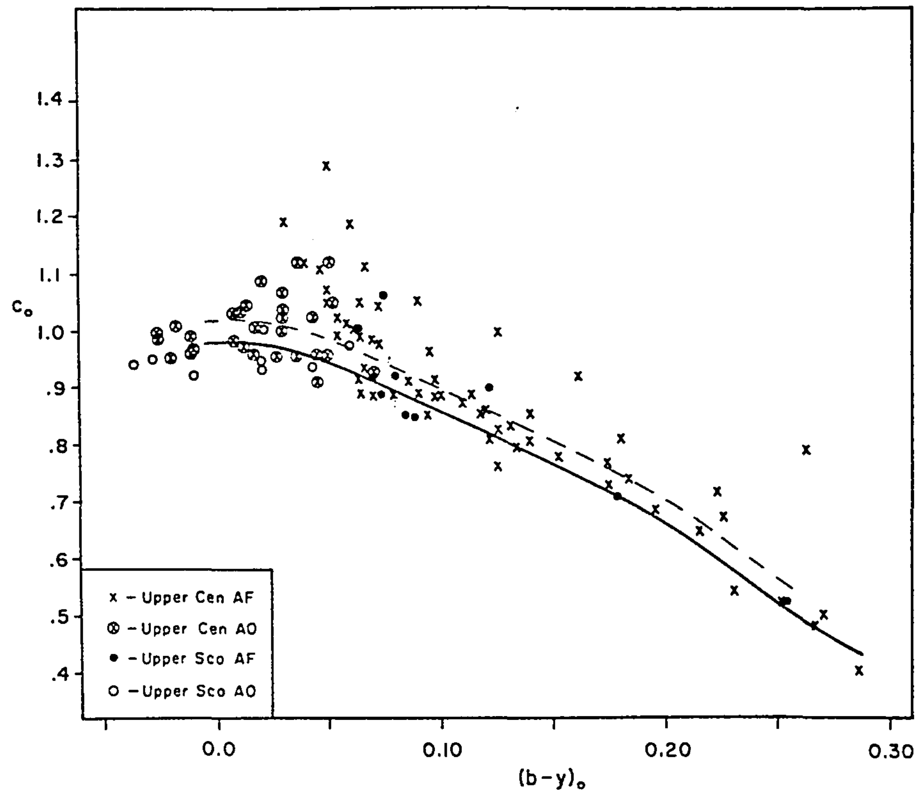

Figure 35. c_o, $(b-y)_o$ Diagram for AF Stars in Scorpius and Centaurus -- The solid line represents the Z.A.M.S.; the broken line, upper limit to the Z.A.M.S.

Murphy, who used Iben's (1965a, 1965b, 1966a, 1966b, 1966c) model calculations, if the earliest type is B2 and the latest type is F2, the age would be less than or equal to 20×10^6 years, whereas if the latest main sequence star observed is A7, the age would be greater than or equal to 10×10^6 years. There is obviously some difficulty present in comparing the observed c_o, $(b-y)_o$ diagram to Murphy's spectroscopic analysis, since an F2 type star corresponds to a color of $(b-y)_o = 0.200$. Most probably, the lack of stars with negative δc_1's does not signify the end of the main sequence, and may simply be caused by observational scatter. Also, with so few stars having values of $(b-y)_o$ greater than $0^m.200$, it would be difficult to draw any reliable conclusion about the presence of such late type stars on the Z.A.M.S. However, it is interesting to note that five out of six stars having $(b-y)_o \geq 0^m.250$ lie on or near the Z.A.M.S.

Absolute Magnitudes and Distance Moduli

According to Crawford (1970a), the absolute magnitude of each A-type star may be determined from $M_v = M_v(\text{Z.A.}) - 8\delta c_1$ with an r.m.s. scatter of $0^m.3$ for one star. The factor 8 comes from observations of evolved stars in open clusters plus trigonometric parallax stars, but the zero point for the calibration comes exclusively from trigonometric parallax stars. The computed absolute magnitude stars have been used to calculate the individual distance modulus for each AF star on our list. Figure 36 shows several histograms of the number of stars having moduli in the plotted $0^m.4$ intervals. It is clear from the first histogram, Figure 36(a), showing the frequency distribution with distance modulus for the stars having $\delta c_1 \leq 0^m.05$, that the mean distance modulus is at least half a magnitude less than the value of $6^m.2$ adopted by Bertiau as the mean modulus. The hatched bars in Figure 36(a), showing the frequency distribution of those stars having $\delta c_1 \leq 0^m.0$, were included to determine what contribution these particular stars make to the mean distance modulus. Evidently these stars have been assigned systematically smaller moduli. This could be explained by the fact that since these stars had $\delta c_1 \leq 0^m.0$, the correction to M_V(Z.A.) used to determine the true absolute magnitude was positive, thereby increasing M_V but decreasing d.m. = $V_o - M_V$ by a few tenths of a magnitude. Figure 36(b) shows the histogram obtained for stars having δc_1 = $0^m.05$ but with no correction applied to the absolute magnitudes. The hatched bars again represent the contribution made by stars having $\delta c_1 \leq 0^m.0$, and show that there is no significant difference in distance modulus between those stars having $\delta c_1 \leq 0^m.0$ and those having $0^m.0 \leq c_1 \leq 0^m.05$. The mean modulus for the $\delta c_1 \leq 0^m.05$ group, $5^m.3$, is rather

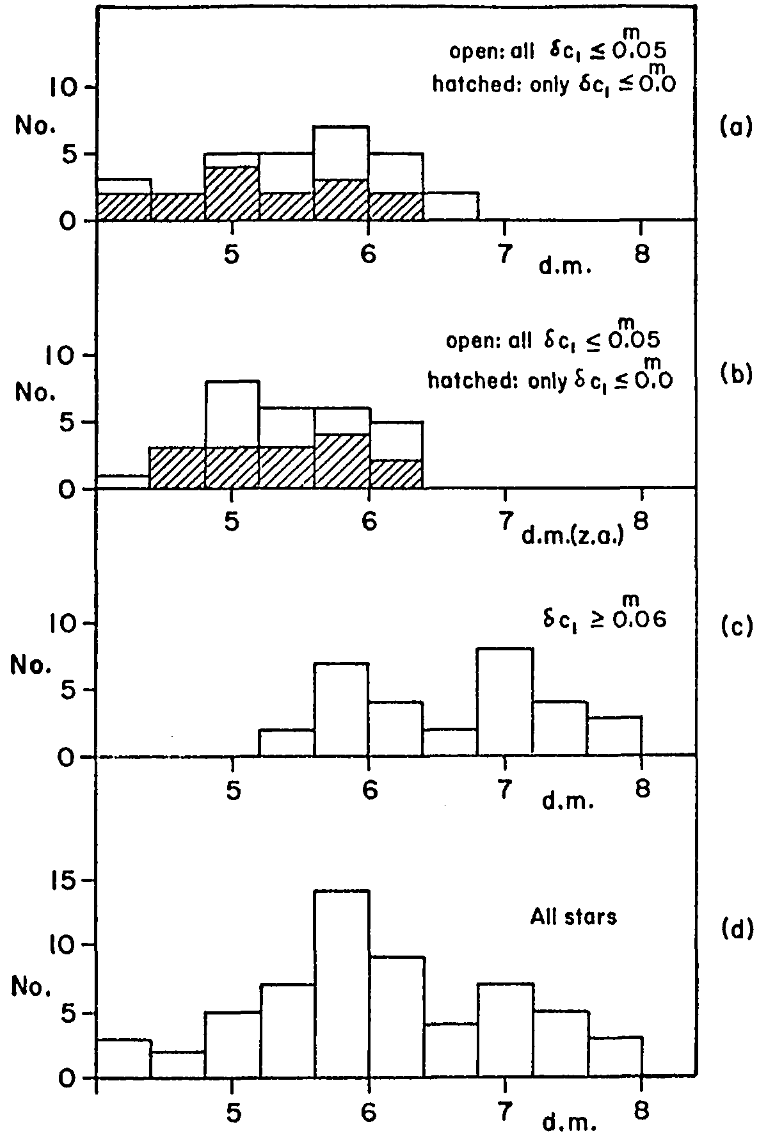

Figure 36. Frequencies of Distance Moduli for AF Stars

small and may indicate the presence of many nearby field stars remaining in the sample.

Figures 36(c) and 36(d) show, respectively, the histograms for the stars having $\delta c_1 > 0^m.05$ and for all of the observed A- and F-type stars in Scorpius and Centaurus. The large value for the mean distance modulus for the large δc_1 stars is probably due to a selection effect created by the way in which stars were chosen for the observing program, namely, by apparent magnitude.

The Metallicity Index

Another check on the uniformity of the sequence of A- and F-type stars chosen because of their $\delta c_1 \leq 0^m.05$ can be made using the m_o, $(b-y)_o$ diagram (see Figure 37). Because the m_o-indices of field stars show a wide range of values, this diagram may not be used to verify the similarities of members of a previously determined group. Previous comparisons of cluster sequences for nearby open clusters (see Crawford and Perry 1966; Crawford and Strömgren 1966; Crawford and Barnes 1969a, 1969b, 1970a) have shown that F- and late A-type stars in physical groups tend to form a fairly tight band in the m_o, $(b-y)_o$ diagram. The mean relation from cluster to cluster may vary, however, as shown by late A- and F-type stars in the Hyades (Crawford and Perry 1966) and Pleiades (Crawford 1970b). This point has been discussed by Chaffee, Carbon, and Strom (1971),

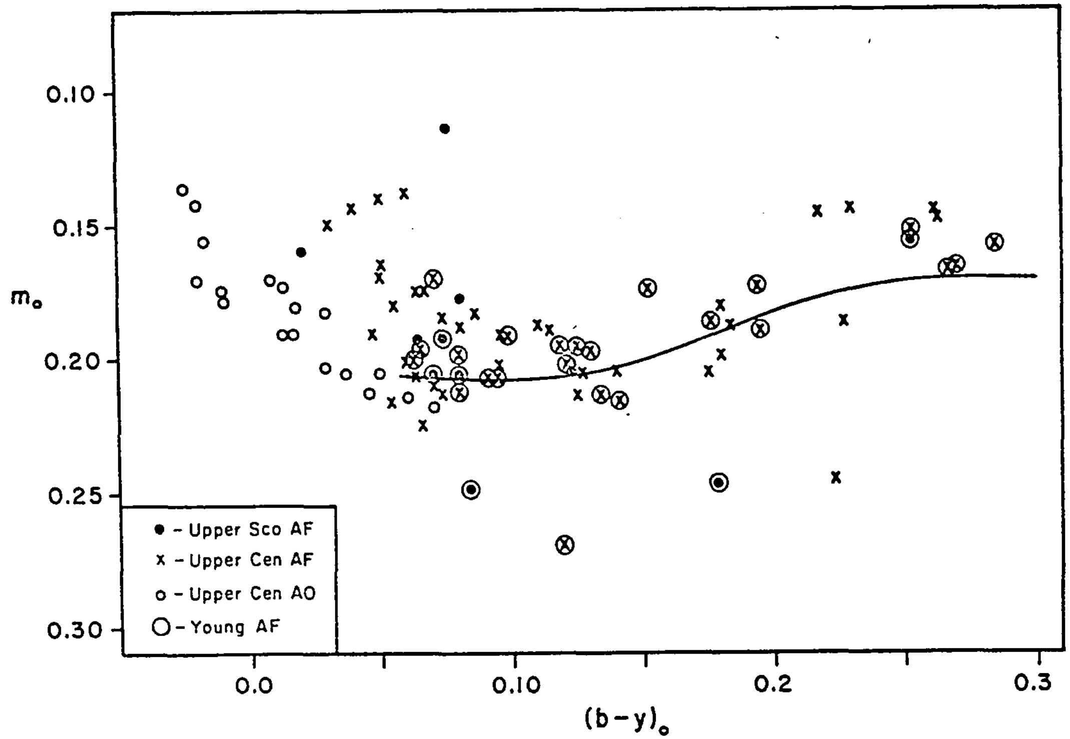

Figure 37. m_o, $(b-y)_o$ Diagram for AF Stars in Scorpius and Centaurus -- Filled circles represent Upper Scorpius stars; crosses, Upper Centaurus; open circles, AO stars in Upper Centaurus. Symbols enclosed in large circles represent unevolved AF stars.

who discuss different metal abundances, microturbulent velocities, ages, and helium abundances as possible causes for the observed photometric differences. We see from Figure 37 that with few exceptions the chosen A- and F-type stars (indicated by large circles) in Scorpius and Centaurus do indeed form a fairly narrow sequence. In the A star region it lies only slightly above the Hyades standard relation. In the F star region, $(b-y)_o > 0^m.160$, the few stars circled lie even farther above the standard relation. However, these stars are more doubtful as to their membership in the association, so little emphasis can be placed on their different values of m_1.

Several stars having large values of m_1 are apparent in Figure 37. Two stars observed by Garrison in Upper Scorpius, HD 146998 and 148321, were classified by him as A7p and A5mp, respectively, The position of HD 146998 is uncertain because it has only one observation in Hβ, therefore its color excess was determined by assuming that it lies along the Z.A.M.S. in the c_1, (b-y) diagram. We also see that HD 119674 and HD 133991, both of which are in the Upper Centaurus region, have large values of m_1. The former star appears to be an Am star from the available slit spectra, which agrees with the large m_1-index. No slit spectrogram is available for HD 133991; however, it has a rather large value of (b-y) relative to most Am stars, and it also has a large value of δc_1, suggesting that it may be a binary star.

CHAPTER 7

DISCUSSION AND CONCLUSIONS

In this final chapter we shall consolidate much of the information derived in the earlier chapters. We shall present here our final list of possible members of both the Upper Centaurus and the Upper Scorpius associations. A comparison will be made between the β, $(u-b)_o$ diagrams for the two regions and the equivalent diagrams for several other young clusters and associations. In addition, a brief summary will be presented concerning the problem of the peculiar stars in Upper Scorpius, and the possible memberships of two Am stars will be considered. Several suggestions for future work on the associations will also be offered.

Motions Analysis

It has been known for many years that the B-type stars in the Scorpio-Centaurus association share a common space motion. For this reason any discussion of possible additional members should normally include--or perhaps, consist of--a detailed analysis of the proper motions and radial velocities of the suspected members. In the present situation, however, the stars under investigation are not bright; well observed, northern hemisphere stars, but they are mostly between $m_V = 7^m.0$ and $m_V = 10^m.0$, and they can only be observed properly from southern hemisphere observatories. This means that the proper motions suffer from both larger internal scatter and from unknown systematic errors in the proper motions. The radial velocity information, on the other hand, is almost non-existent for most of the A- and F-type stars in the Scorpio-Centaurus region; therefore, a detailed study of the motions would involve obtaining and measuring large numbers of spectra for each of the many stars in question. We shall see in the following discussions that the available proper motions and radial velocity data did not offer reliable means for distinguishing individual possible member stars.

Proper Motions

One of the most serious problems encountered in dealing with a variety of proper motion lists is to determine the systematic corrections to be applied for the reduction of these proper motions to a common and reliable fundamental system. Fricke (1966) discussed the systematic errors in the FK3, FK4, N30, and GC systems. He showed that differences between the values of μ_δ in the FK4 and GC systems, for example, in the region of the Scorpio-Centaurus association can reach over 0".004 p.a. and 0".002 p.a. for $\mu_\alpha \cos\delta$. Fortunately, even if systematic errors of this order are still present in the data used here, we shall see that it would be too small to affect the present discussion, for the estimated systematic effects are considerably less than the observational errors in the proper motions.

The proper motions for all stars included in the current program have been obtained from the Smithsonian Star Catalog (Smithsonian Astrophysical Observatory 1966) which combines information from a large number of catalogues. The systematic differences between the different systems involved have already been taken into account, as well as can be done, in the preparation of the catalog itself. The identification numbers, proper motion components, accidental errors, and notes are listed in Table 22. Stars studied by Bertiau (1958) have a "B" in the Notes column; those studied by Garrison (1967) but not by Bertiau have a "G" in the notes.

The mean values of μ_δ and $\mu_\alpha \cos\delta$ for the bright B-type stars seem to remain fairly constant over the face of the cluster. For this reason we assume that we can plot in Figure 38 histograms of the frequency of μ_δ and $\mu_\alpha \cos\delta$ in Centaurus for different groups of stars. Figure 38(a) shows the frequency of μ_δ for the bright B-type stars from Bertiau's list; Figure 38(b) shows the corresponding histogram for the young late-B and AF stars considered to be possible members; and Figure 38(c), for those stars considered to be non-members from the current investigation.

Table 22. Proper Motions from the Smithsonian Catalog

HD No.	SAO cat	μ_δ "p.a.	$\sigma_{\mu\delta}$ 0.001 "p.a.	$\mu_\alpha \cos\delta$ "p.a.	$\sigma_{\mu\alpha}$ 0.001 "p.a.	Notes
118060	224263	-.023	12	-.029	12	
118335	204656	-.037	5	+.005	5	
119103	224349	-.009	11	-.035	15	
119221	224355	-.036	13	-.012	17	
119268	224361	-.002	12	-.038	12	
119361	224365	-.010	7	-.028	9	
119430	224377	+.004	12	+.026	12	
119674	204804	-.042	13	-.016	13	
120307	224469	-.025	4	-.024	5	B
120324	224471	-.026	2	-.022	3	B
120487	224479	-.021	12	-.006	12	
120709	204916	-.042	4	-.056	4	B
120908	241262	-.032	7	-.022	11	B
120955	204944	-.016	4	-.015	5	B
120959	204950	-.013	18	+.037	18	
120960	224511	-.020	13	+.023	16	
121057	224519	-.022	13	-.067	17	
121226	224534	-.030	12	-.053	16	
121399	204997	+.007	9	-.005	9	
121528	224563	-.017	12	-.017	12	
121701	224576	-.017	12	-.032	12	
121743	224577	-.025	4	-.026	4	B
121790	224585	-.024	4	-.026	4	B
122109	205084	-.016	5	-.007	5	
122664	205138	-.037	16	-.005	14	
122705	224654	-.046	12	-.031	12	
122756	224657	-.030	12	-.055	12	
122757	224659	-.013	12	-.035	12	
122980	224673	-.024	4	-.019	5	B
123021	224678	-.035	12	-.014	12	
123291	224711	+.003	12	-.002	12	
123344	205209	-.003	10	-.025	12	
123431	224719	-.031	11	+.023	12	
123635	224734	-.004	12	+.008	12	
123664	224737	-.024	10	+.002	14	
124228	205316	+.004	13	+.003	13	
124254	224774	+.019	10	+.027	15	
124504	205344	-.008	21	-.027	21	
125238	224833	-.001	4	-.014	5	
125253	224835	-.007	11	-.046	16	
125509	205456	-.008	10	-.011	12	
125541	224854	-.039	12	-.014	12	
125718	224869	-.015	12	-.001	12	

Table 22.--Continued Proper Motions from the Smithsonian Catalog

HD No.	SAO cat	μ_δ "p.a.	σ_{μ_δ} 0.001 "p.a.	$\mu_\alpha \cos\delta$ "p.a.	σ_{μ_α} 0.001 "p.a.	Notes
125823	205497	-.036	4	-.029	5	B
125937	224891	-.040	18	-.021	18	
126062	224901	-.038	12	-.022	13	
126110	224904	-.037	18	+.001	18	
126135	224905	-.021	8	-.034	9	
126194	205531	-.021	10	-.035	12	
126476	224926	-.020	12	-.021	16	
126561	224936	-.009	8	-.036	9	
127716	225027	-.033	6	-.018	8	
127717	225026	-.009	12	-.020	12	
127879	225038	-.034	12	-.019	12	
128066	225053	-.068	12	-.011	12	
128224	205754	-.005	6	+.010	6	
128344	225073	-.023	10	-.011	14	
128532	205789	-.037	10	-.039	12	
128648	225092	-.067	12	-.026	12	
128788	225101	-.039	12	-.018	12	
128819	225106	-.040	10	-.032	12	
128855	225111	-.010	8	+.008	10	
129116	205839	-.036	4	-.024	5	B
129791	225174	-.038	8	-.021	11	
130133	225187	-.024	12	-.005	12	
130163	205948	-.010	11	-.065	15	
130388	205974	-.022	11	+.017	16	
130807	225248	-.030	4	-.021	6	
131399	206071	-.037	11	-.030	12	
131460	206081	-.040	13	-.058	13	
131461	206083	-.028	12	-.019	15	
131503	225292	-.002	12	-.009	12	
131518	225294	-.012	12	-.012	12	
131752	206010	-.028	8	-.027	16	
131777	225315	-.028	12	-.029	12	
131901	206026	-.038	8	-.043	9	
132058	225335	-.043	2	-.037	2	B
132080	229337	-.009	12	-.024	12	
132094	206049	-.031	12	-.026	14	
132200	225344	-.027	2	-.019	2	B
132761	206222	-.042	21	-.012	21	
132851	183099	-.041	5	+.095	6	
132955	206239	-.030	5	-.022	6	B
133574	206294	-.040	13	-.062	13	
133716	206306	-.019	11	+.024	12	

Table 22.--Continued Proper Motions from the Smithsonian Catalog

HD No.	SAO cat	μ_δ "p.a.	σ_{μ_δ} 0.001 "p.a.	$\mu_\alpha \cos\delta$ "p.a.	σ_{μ_α} 0.001 "p.a.	Notes
133750	206315	-.013	8	-.019	9	
133937	225479	-.021	11	-.028	15	B
133954	225480	-.023	12	-.018	12	
133955	225483	-.022	6	-.016	7	B
133991	225488	-.005	12	-.005	12	
134055	206335	-.028	12	-.028	13	
134518	206375	-.054	13	-.072	13	
134685	206406	-.033	21	-.028	21	
134930	225554	+.003	12	-.039	12	
134950	206429	+.006	13	-.068	13	
134990	206436	-.029	12	-.014	13	
135454	225612	-.023	11	-0.26	16	
135815	225643	-.016	12	-.003	12	
135877	225649	-.003	12	+.007	12	
136013	206522	-.035	21	-.012	21	
136164	206531	-.026	11	-.005	14	
136298	225691	-.032	3	-.016	3	B
136334	225695	-.035	11	-.011	12	
136482	206559	-.028	12	-.027	12	
136483	225707	-.013	12	-.008	12	
136504	225712	-.015	4	-.019	6	
136664	206580	-.025	3	-.018	3	B
136961	206599	-.003	10	+.012	15	
137119	206625	-.032	11	-.040	13	
137169	225768	-.018	12	-.003	12	
137193	206637	-.012	10	-.014	13	
137432	206660	-.038	5	-.012	7	B
137499	206664	-.036	13	-.030	13	
137785	206695	-.089	9	-.046	12	
137957	225851	-.024	12	-.012	14	
138138	206720	-.018	10	-.024	12	
138285	206742	-.042	12	-.013	12	
138564	206769	-.050	11	-.026	13	
138690	225938	-.031	3	-.016	3	B
138769	225950	-.032	5	-.026	7	B
138940	225972	-.004	11	-.016	15	
139048	206809	-.051	13	-.008	13	
139094	183622	-.007	9	-.012	10	G
139160	183631	-.026	7	-.009	7	G
139233	206826	-.025	11	-.033	12	
139365	183649	-.033	3	-.014	3	B
139524	226048	-.005	15	-.008	17	

Table 22.--Continued Proper Motions from the Smithsonian Catalog

HD No.	SAO cat	μ_δ "p.a.	σ_{μ_δ} 0.001 "p.a.	$\mu_\alpha \cos\delta$ "p.a.	σ_{μ_α} 0.001 "p.a.	Notes
139883	206877	-.022	21	-.058	21	
140008	206889	-.032	5	-.021	5	B
140475	206931	+.003	13	-.025	14	
140543	183753	-.019	12	+.018	15	G(NM)
140817	206963	-.028	12	-.018	13	
140958	206984	-.015	18	-.008	18	
141318	243044	-.015	6	+.003	8	
141404	183833	-.014	13	-.041	17	G
141518	207034	-.070	21	-.006	21	
141637	183854	-.027	3	-.018	3	B
141774	183864	.000	12	+.010	15	G
141779	207062	+.010	13	-.023	13	
141905	207077	-.036	10	-.029	10	
141939	183884	-.031	15	-.032	15	
142096	183895	-.027	1	-.011	1	B
142097	183894	-.019	9	-.013	11	
142114	183896	-.028	3	-.015	3	G
142165	183900	-.026	4	-.021	4	B
142184	183901	-.028	5	-.015	5	B
142250	183907	-.026	8	-.024	10	G
142301	183914	-.025	4	-.012	5	G
142315	183916	-.010	14	+.036	16	G
142378	159572	-.025	5	-.017	4	B
142431	226375	-.032	12	-.043	12	
142669	183957	-.021	3	-.008	3	B
142805	183769	-.035	7	-.022	7	G
142883	183972	-.021	7	-.017	7	G
142884	183973	-.011	8	-.008	10	G
142983	159607	-.019	1	-.015	2	B
142990	183982	-.021	6	-.014	6	G
143018	183987	-.027	2	-.009	2	B
143118	207208	-.034	3	-.022	4	B
143275	184014	-.025	1	-.010	1	B
143567	184043	-.012	13	-.014	17	G
143600	184045	-.026	18	-.006	18	G
143692	184055	+.012	15	-.015	15	
143699	207276	-.034	6	-.042	6	B
144294	207332	-.033	2	-.019	3	B
144334	184113	-.031	5	-.012	6	G
144470	184123	-.024	2	-.010	3	B
144844	184164	-.025	6	-.012	6	G
145102	184184	-.031	9	+.007	12	G

Table 22.--Continued Proper Motions from the Smithsonian Catalog

HD No.	SAO cat	μ_δ "p.a.	σ_{μ_δ} 0.001 "p.a.	$\mu_\alpha \cos\delta$ "p.a.	σ_{μ_α} 0.001 "p.a.	Notes
145353	184205	-.017	8	-.019	10	G
145468	184211	-.006	18	-.011	18	
145482	184221	-.028	3	-.012	4	B
145502	159764	-.026	2	-.011	2	B
145554	159770	-.023	13	-.010	17	G
145631	159777	-.035	7	-.004	10	G
145792	184241	-.016	8	+.014	9	G
145793	184244	-.025	15	+.005	15	
146001	184258	-.022	7	+.008	8	G
146029	184259	-.012	9	-.003	13	G
146284	184278	-.011	9	-.004	10	G
146285	184277	-.025	20	-.011	20	G
146332	184280	-.020	10	+.012	11	G
146416	184285	-.019	9	-.015	9	G
146606	184300	-.035	9	.000	10	
146706	184305	-.029	18	-.028	18	G
146998	184319	-.043	18	-.028	18	G
147009	159858	-.026	8	.000	9	G
147010	159860	-.019	7	-.010	7	G
147084	184329	-.026	3	-.003	4	G
147165	184336	-.023	1	-.009	1	B
147196	184337	-.022	8	-.020	8	G
147343	184345	-.022	18	+.008	18	G
147384	189347	-.047	18	+.021	18	G
147432	184350	+.006	18	+.010	18	
147592	184356	-.024	12	-.009	12	G
147703	184365	-.030	7	-.074	10	G
147809	184372	-.019	12	-.015	12	G
147888	184377	-.040	7	-.010	8	B
147889	184376	-.027	18	-.014	18	G
147890	184380	-.005	7	+.004	9	G
147932	184383	-.032	7	+.007	7	G
148184	159918	-.029	3	-.011	3	B
148321	184403	+.014	11	+.019	13	G
148352	184405	-.056	18	-.049	18	G(NM)
148562	184424	-.019	18	-.001	18	G
148563	184423	-.035	20	-.036	20	G
148579	184425	-.033	7	-.033	9	G
148594	184428	-.006	7	-.009	9	G
148605	184429	-.024	4	-.007	3	B
148703	207732	-.017	2	-.010	2	B
149438	184481	-.025	2	-.008	1	B

Table 22.--Continued Proper Motions from the Smithsonian Catalog

HD No.	SAO cat	μ_δ "p.a.	σ_{μ_δ} 0.001 "p.a.	$\mu_\alpha \cos\delta$ "p.a.	σ_{μ_α} 0.001 "p.a.	Notes
149757	160006	+.023	1	+.012	1	ζ oph
150035	184527	-.027	12	+.008	12	G
151346	184646	-.002	15	-.010	15	G
151865	160126	-.022	12	-.011	17	G(NM)
151890	208102	-.029	2	-.012	2	B
151985	208116	-.025	3	-.011	5	B
157056	185320	-.021	1	-.003	1	B

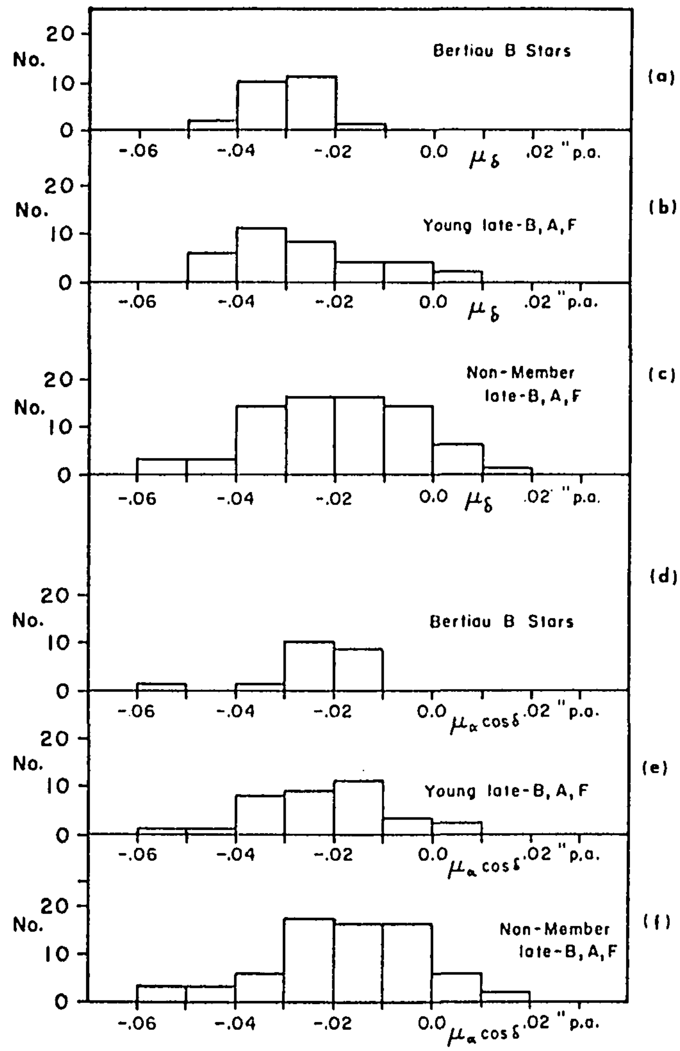

Figure 38. Frequencies of Proper Motions in Centaurus

The last histogram indicates the spread in proper motions expected from observational errors of about 0".010 p.a. and from the reflex solar motion present in a sample of field stars with a wide range of distances. A large percentage of the stars represented in Figure 38(b) seem to imply roughly the same distribution of μ_δ as is shown by the B-type stars in Bertiau's list, represented in Figure 38(a). Similar arguments can be made concerning the corresponding histograms for the $\mu_\alpha \cos\delta$ proper motions shown in Figures 38(d), (e), and (f).

Considering the distributions discussed above, and noting in addition that a typical value of $\sigma_\delta \approx \sigma_\alpha \approx$ 0".012 p.a. quoted in the catalogue for stars as faint as those considered here, it does not seem possible to make use of the observed proper motions to decide which of the new candidates for cluster membership actually share in the common stream motion of the bright B-type stars. However, we can tentatively conclude that a sizeable fraction of the apparently young B-, A-, and F-type stars which are suggested to be members on the basis of their photometric indices do seem to show proper motion distributions similar to the stars which participate in the stream motion.

We are able to eliminate several stars having proper motion components which differ too greatly from the distributions of B-type star motions. From μ_δ we shall exclude the following stars, which have values of

$\mu_\delta \geq -0\overset{''}{.}010$ p.a. or $\mu_\delta \leq -0\overset{''}{.}050$ p.a.: HD 125509, HD 126561, HD 140475, and HD 141779. Similarly, we exclude HD 118335, HD 126110, HD 131460, HD 133574, and HD 137119, all of which have values of $\mu_\alpha \cos\delta \geq 0\overset{''}{.}000$ p.a. or $\mu_\alpha \cos\delta \leq -0\overset{''}{.}040$ p.a.

Radial Velocity Analysis

A considerable amount of published radial velocity data for stars in Scorpio and Centaurus is available from the literature, mostly for the brighter B-type stars. Table 23 lists these velocity data, many of which were obtained from the catalogue of Evans (1970) at the University of Texas, and Abt (1970) at the Kitt Peak National Observatory. I wish to thank Dr. Evans, for supplying me with the data he had available, and Dr. Abt, for allowing me to examine his files. In the analysis that follows arithmetic means have been computed from different observers' values, which were weighted according to the number of plates each had used.

The distribution of radial velocities with respect to galactic longitude for the B-type stars in this program for which velocities are not known to be variable is shown in Figure 39. From the rather narrow distribution of the stars considered to be members by Bertiau, it seems reasonable to assume that most stars outside of the band

Table 23. Published Radial Velocities

Name	HD No.	V_r km/sec	n	Quality[a]
	119361	-21	5	3
μ Cen	120334	+10	23	1
3 Cen	120709	+11	16	1
HR 5217	120908	+8	15	1
HR 5249	121790	+6	15	3
χ Cen	122980	+10	20	1
	123021	+7	4	3
2 Lup	125238	+22	11	1
a Cen	125823	+8	25	1
	128344	+16	2	4
HR 5471	129116	+5	7	2
o Lup	130807	+7	16	2
β Lup	132058	-1	28	1
HR 5591	132851	+10	8	3
HR 5595	132955	+6	12	2
δ Lup	136298	+1	17	2
ϕ^2 Lup	136664	+3	9	2
HR 5736	137432	+5	14	2
HR 5773	138564	0	6	3
HR 5805	139233	+5	5	3
	140543	-6	6	3
HR 5873	141318	-1	13	2
2 Sco	142114	-10	12	2
HR 5906	142165	+1	12	3
HR 5910	142250	+6:	9	3
3 Sco	142301	-5	20	2
	142315	+3:	2	4
47 Lib	142378	-6	7	3
ρ ScoA	142669	0	11	2
HR 5934	142883	-17 v?	8	3
	142884	-12	2	4
HR 5942	142990	-11	4	3
	143567	-17	2	4
HR 5967	143699	-4	18	2
θ Lup	144294	+15	8	2
HR 5988	144334	-7	13	3
ω_1 Sco	144470	-5	32	2
	145102	+14	4	4
HR 6042	145792	+6	11	3
HR 6054	146001	-8	22	2
	146029	+16	2	4
	146284	-28	5	4
HR 6066	146416	-8	12	4
	147010	-9	3	4

Table 23.--Continued

19 o Sco	147084	-8	9	3
	147196	+4	4	4
ρ Oph D	147888	-9	7	3
	147889	-3	5	4
	147890	+7	1	4
ρ Oph C	147932	-19	4	4
	148321	+5	2	3
22 Sco	148605	-7	27	1
τ Sco	149438	+2	38	1
	151346	+24	2	4
HR 6247	151890	-19	3	4
μ_2 Sco	151985	+1	13	1

[a]The "Quality" listed for each star is defined such that 1 = excellent, 2 = good, 3 = fair, 4 = poor.

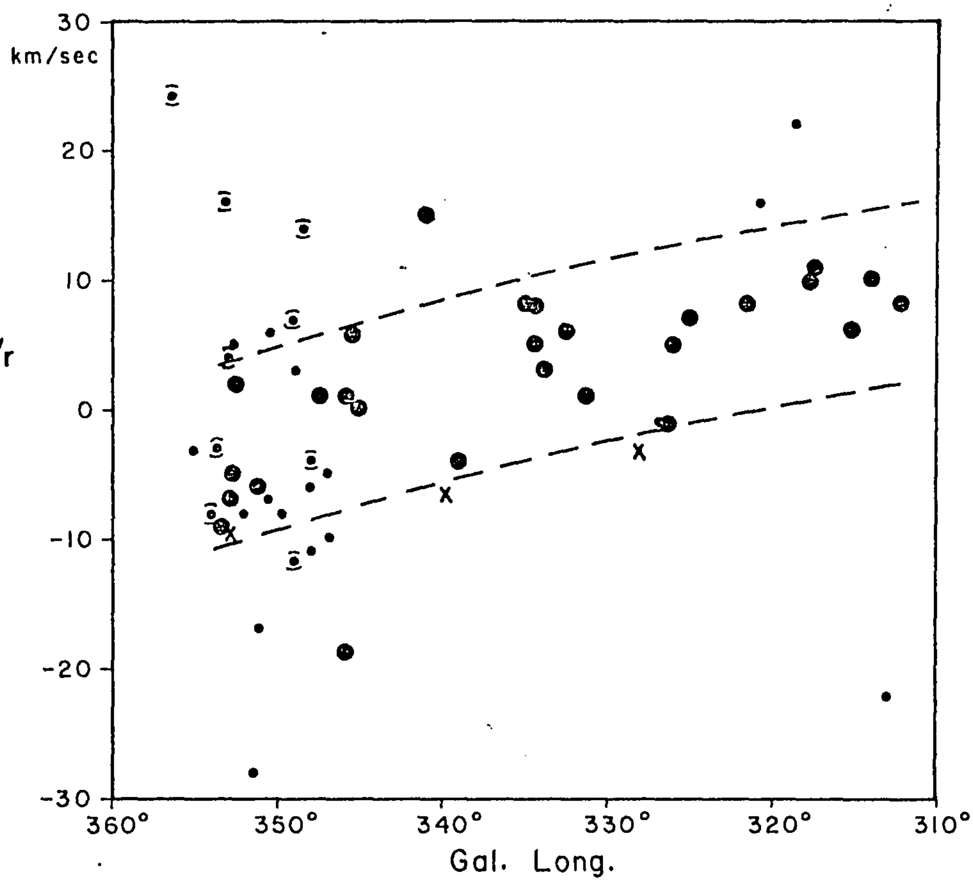

Figure 39. Radial Velocities Versus Galactic Longitude for B-Type Stars -- Large filled circles represent B-type stars from Bertiau's (1958) list; small filled circles, additional B-type stars; crosses, the reflex solar motion. The dashed band defines approximate limits to the B-type star velocity distribution.

defined by the dashed lines are not members of the moving cluster.

The distribution of radial velocity with respect to galactic longitude for the A- and F-type stars in the direction of the Scorpio-Centaurus cluster is shown in Figure 40. Most of the velocities used were obtained in the current program. The dashed curves represent the boundaries determined in Figure 39 of the B-type stars known to be members, assuming that there is no systematic difference between the AF stars and B-type star velocities. The crosses are located at the velocities and longitudes representing the reflex solar peculiar motion at several points in the Scorpio-Centaurus direction. The data show no obvious tendency towards common motion. Two-thirds of the A- and F-type stars for which some radial velocity data are available lie outside the indicated band that represents the B-type stars. Nevertheless, the fact that the average radial velocity with respect to the Local Standard of Rest is not the same for different longitude ranges is encouraging. Between l = 310° and 325° this differential velocity is near zero; however, between l = 325° and 355° the average is approximately 10 km/sec more positive than the reflex solar peculiar velocity. This is roughly the same as the velocity of the Scorpio-Centaurus B-type stars relative to the Local Standard of Rest; therefore, we might again conclude that some of the A- and F-type stars in the

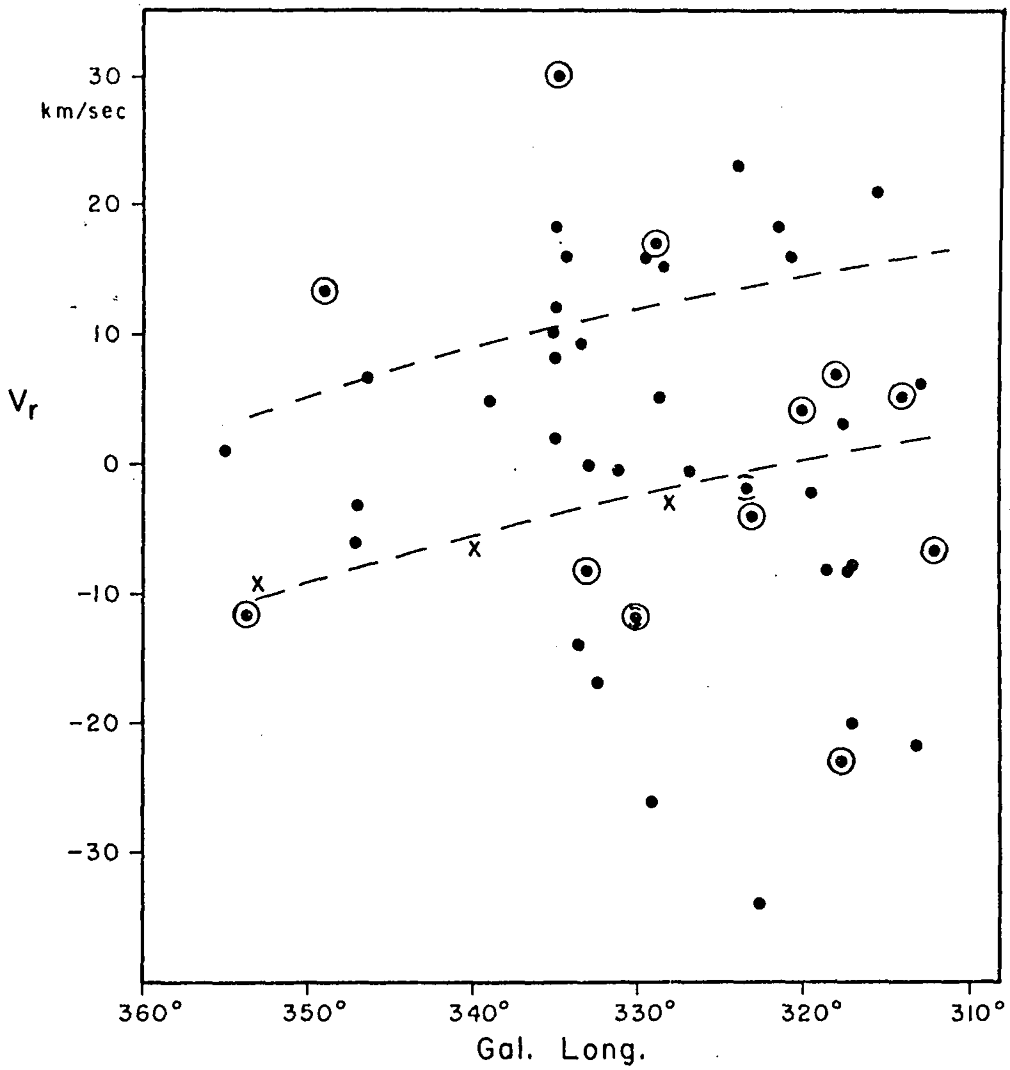

Figure 40. Radial Velocities Versus Galactic Longitude for A- and F-Type Stars -- Filled circles represent late B-, A-, and F-type stars; crosses and dashed lines have the same meaning as in Figure 39. Symbols enclosed in larger circles represent unevolved stars.

present sample, especially in the interval 355° < 1 < 325°, share in the motion of the Scorpio-Centaurus B-type stars. Unfortunately, by considering those stars to be members for which velocities lie within the limits indicated in Figure 40, we obviously would also include many non-member stars that happen to have a slightly positive radial velocity relative to the Local Standard of Rest. Returning to those stars in the longitude range 325° < 1 < 310° in Figure 40, we see that 14 out of 21 have velocities not significantly different from the reflex solar peculiar velocity. This would seem to suggest that many of the A- and F-type stars in this region are not members of the moving cluster. Better quality data than those now available in the entire Scorpio-Centaurus region would obviously be required for a complete analysis.

Since the proper motions and the radial velocity material available for the fainter stars do not seem to be of much use in deciding membership, we shall instead make use of the absolute magnitude calibrations to choose those stars which appear to fall at the proper distance.

Distance Modulus Criteria for Upper Scorpius Stars

We plot the values of V_o vs. M_v as determined from the four-color photometry in Figure 41. We see that the upper distance modulus limit fits the early B-type stars quite well; however, most points representing $M_v > 0$ lie

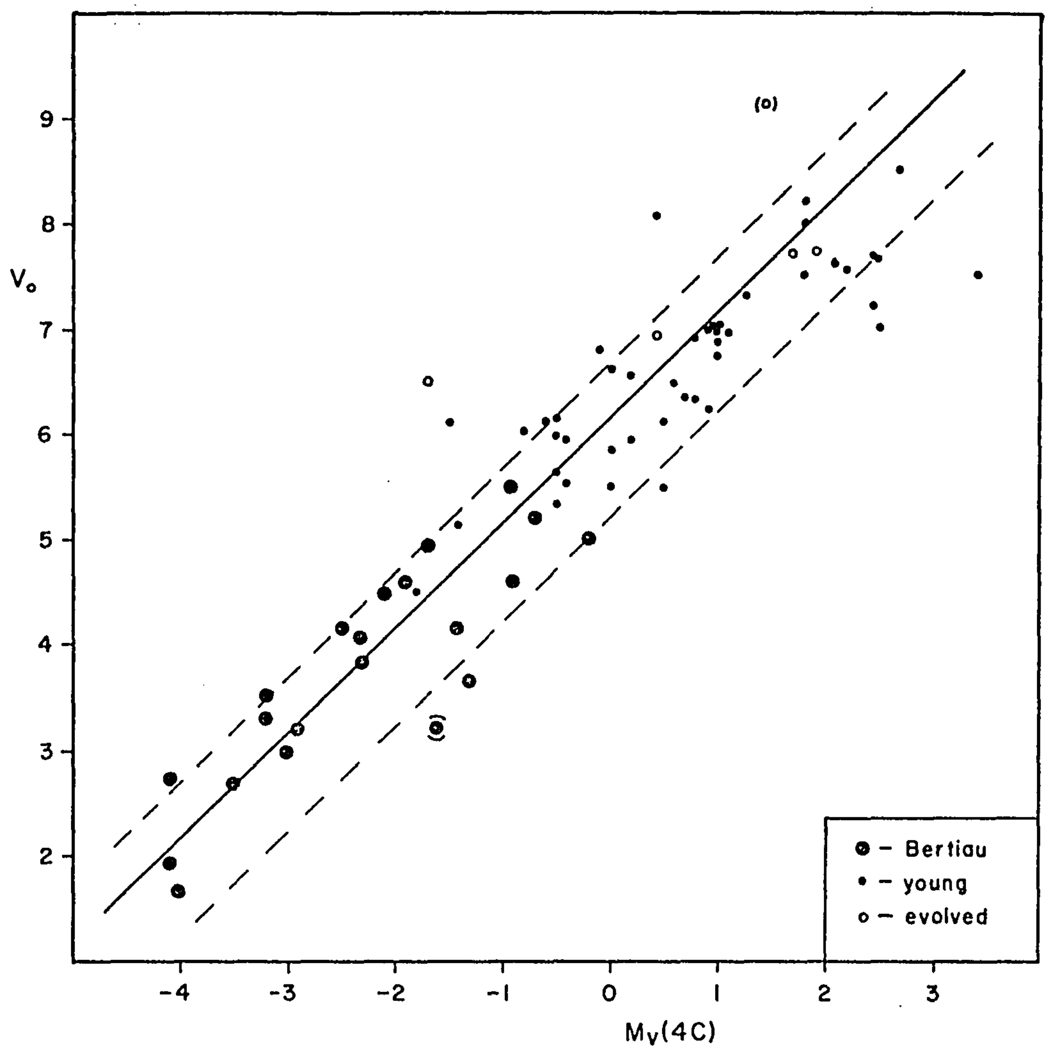

Figure 41. V_o, M_v Diagram for Upper Scorpius Stars -- The solid line represents a distance modulus of $6^m\!.2$; the dashed lines, the limits on d.m. of $5^m\!.25$ and $6^m\!.7$ adopted for the B-type stars.

between the limits $6^{m}.2 > d.m. > 5^{m}.25$. This might be the result if only the brightest stars at each spectral type were picked in the original process used to make up observing lists. This does not seem very likely for the Upper Scorpius stars, since Garrison (1967) observed most of the stars visible in a small area of the sky in Scorpius. A slight difference in the absolute magnitude calibration of the B-type stars relative to the A stars' calibration would cause this effect; however, many of the A-type stars lie above the Z.A.M.S. in the color-magnitude diagram described below. This also implies that they are slightly nearer, and therefore the brightest of these may not be members.

The Color-Magnitude Diagram for Upper Scorpius

In Figure 42 we plot V_o vs. $(b-y)_o$ for those stars in Upper Scorpius for which four-color photometry is available. We see that the sequence of B-type stars looks quite reasonable. Unfortunately, there are very few stars with $(b-y)_o > 0^{m}.0$ included in this sample. The fact that the stars fainter than $V_o = 7^{m}.0$ show considerable scatter is probably caused by the fact that these few stars are at the faint end of the observed sample.

The final list of suggested members for Upper Scorpius is given in Table 24. "G" denotes a star also considered to be a member by Garrison (1967). In

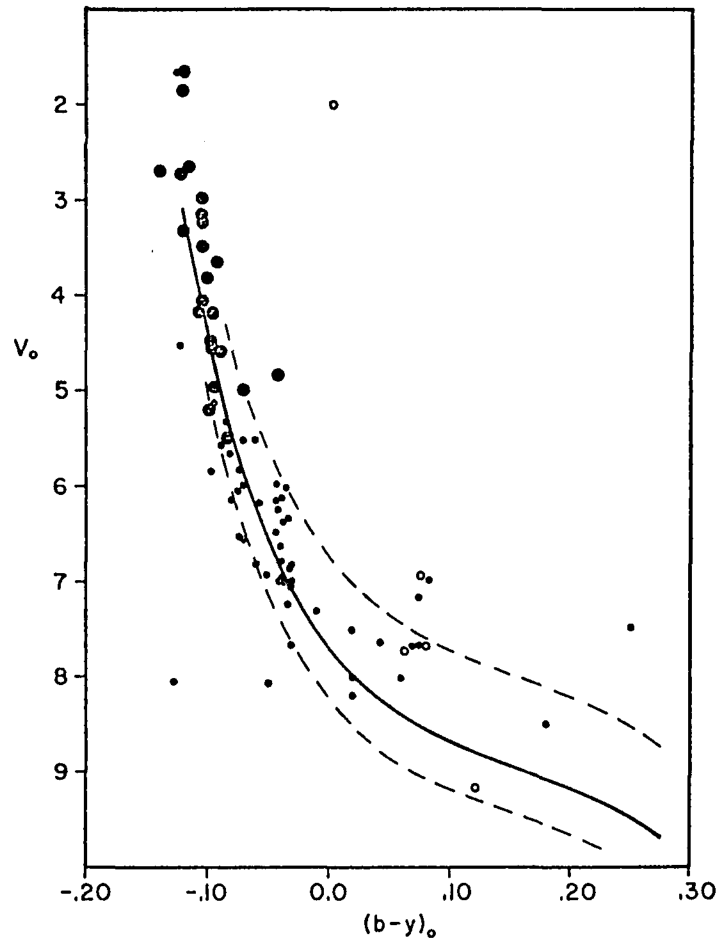

Figure 42. V_o, $(b-y)_o$ Diagram for Upper Scorpius Stars -- Symbols have the same meaning as in Figure 41.

Table 24. Possible Members in Upper Scorpius

B Stars	AO Stars	AF Stars
HD 139160 G	HD 141939	HD 145468
139486 G	146606	146998 G
141774 G	147009 G	(147084) G
142096 G	147343 G	
142117	147384 G	
142184 G	147592 G	
142250 G	147809 G	
142315 G	148562 G	
142883 G	150035 G	
142983		
143567 G		
143600 G		
144334 G		
145102 G		
145353 G		
145554 G		
145631 G		
145792 G		
146001 G		
146029 G		
146284 G		
146285 G		
146416 G		
146706 G		
147010 G		
147196 G		
147773 G		
147888 G		
147889 G		
147890 G		
147932 G		
148579 G		
148594 G		
149757 ζ Oph		
151346 G		

Table 25 we list those stars considered to be non-members in the present study, but which were considered to be members by Garrison (1967).

Table 25. Possible Non-Members Considered to be Members by Garrison

B Stars	AO Stars	AF Stars
HD 139094	HD 141404	HD 148321
140543	142805	
142165		
142301		
142884		
144844		
(147932)		

Distance Modulus Criteria for Centaurus Stars

Since the photometric indices used here provide an indication of the absolute magnitude for each star, one way to eliminate foreground and background stars from the observed sample of Centaurus stars is to plot the unreddened apparent magnitude, V_o, against the absolute visual magnitude. Figure 43 shows V_o vs. M_v for all of the B-type stars in the Centaurus program and the apparently young A- and F-type stars.

Each limit on the distance modulus excludes one of Bertiau's B-type stars, even though the fit along the envelope of the rest of the stars is quite good. We shall, therefore, exclude as non-members those stars having

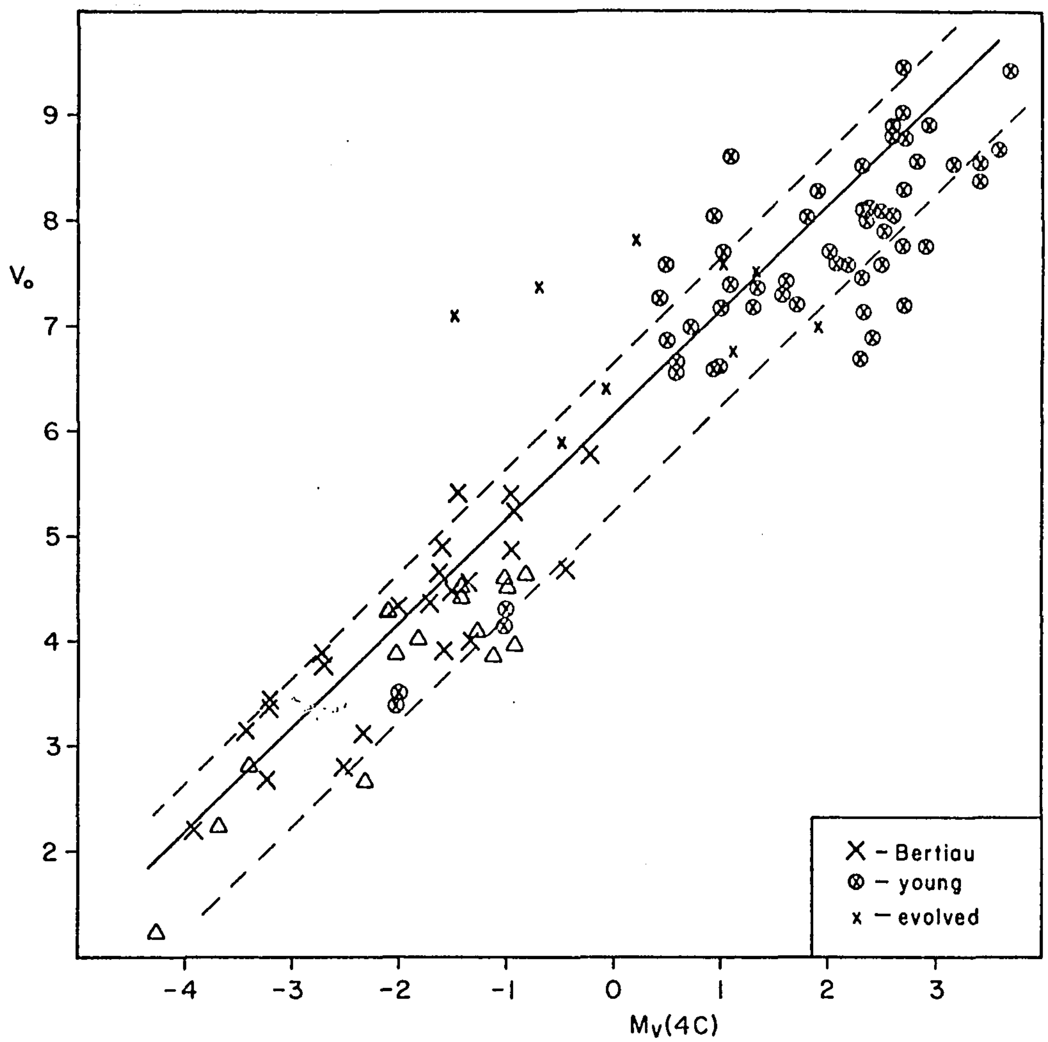

Figure 43. V_o, M_V Diagram for Centaurus Stars -- Triangles represent B-type stars in Lower Centaurus; large crosses, Bertiau's B-type stars in Upper Centaurus; circled small crosses, young late B-, A-, and F-type stars in Upper Centaurus; small crosses, evolved late B-, A-, and F-type stars in Upper Centaurus. The solid and dashed lines have the same meaning as in Figure 41.

distance moduli outside of the range $5^m.25 < d.m. \leq 6^m.7$. (The Lower Centaurus B-type stars show the same tendency to fall at smaller distance moduli that was referred to in Chapter 3, and we have excluded them from this discussion.)

It is obvious from this diagram that there are a large number of young stars present with $M_V \gtrsim 1^m.5$ and which appear to lie nearer than d.m. = $6^m.2$. There are also several stars with $M_V > 2^m.0$ which lie nearer than d.m. = $5^m.25$, but only one lies farther than d.m. = $6^m.7$. To discuss this effect further we should also plot the points representing the apparently evolved stars. In doing this the evolved A0 stars would have to be excluded, since the calibrations of absolute magnitude and intrinsic colors are not well determined for such stars. Also, the zero-age A-type stars have no δc_1 correction applied to the absolute magnitudes and we shall have to compare these stars to the evolved A-type stars, which require δc_1 corrections to determine M_V properly. For these regions we prefer to work with the color-magnitude diagram.

The Color-Magnitude Diagram for Upper Centaurus

It is now possible to plot V_o vs. $(b-y)_o$ for the stars in Upper Centaurus (see Figure 44). The Z.A.M.S. is drawn in at an apparent distance modulus of $6^m.2$. The tendency for the later type young stars to lie on and above Z.A.M.S. is clear; however, this effect only seems to set

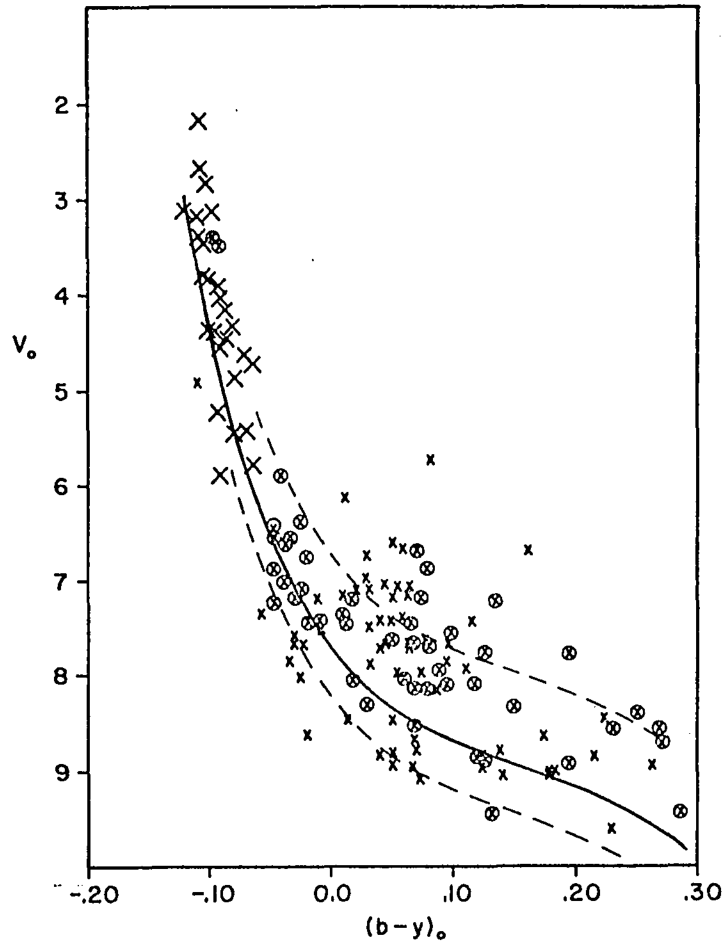

Figure 44. V_o, $(b-y)_o$ Diagram for Upper Centaurus Stars -- Symbols have the same meaning as in Figure 43.

in at $(b-y)_o = 0^m.06$ and then continues on into the later types. There is no corresponding excess in the number of apparently young stars falling below the Z.A.M.S. as it is drawn in this diagram. In fact, it seems remarkable that only one of the apparently young A-type stars falls below the Z.A.M.S. We also note that the distribution of points representing the apparently evolved A-type stars in the present sample shows much the same distribution above the Z.A.M.S. as the evolved sample, whereas below the Z.A.M.S. we get a quite distinct separation. Without additional observations of more stars at least one-half of a magnitude fainter than the present group, it does not seem possible to resolve the problem of having so many bright, young stars. Nonetheless, it still seems safe to conclude that those stars that appear to be unevolved and which fall in the distance modulus range $5^m.25 < \text{d.m.} \leq 6^m.7$ are probably associated with the bright B-type stars in the Scorpio-Centaurus association.

The final list of suggested new members of the Upper Centaurus association are listed in Table 26 by their HD numbers.

Discussion of Age Estimates

In Chapter 1 we described several attempts to determine the age of the Scorpio-Centaurus association through estimates of the time required for the association

Table 26. Possible Members in Upper Centaurus

B Stars	A0 Stars	AF Stars
HD 126135	HD 122705	HD 119674
128344	122757 AB	120487
128819	123344	121701
130094	126062	123021
136482	129791	124504
136504	131461 AB	125541
139233	131777	128648
140817	133954	137499
	134685	137785
	135454	140958
	136013	
	138285	

to expand from a small size to its present dimensions. Blaauw (1946) first assumed a model in which the original cluster size was too large for it to be gravitationally bounded and the present size and shape could be described as resulting from the perturbing action of the galactic tidal force. This model led to an age of approximately 10^8 years. In a revised analysis, Blaauw (1952) created a similar model, only this one assumed that the cluster was expanding at some prescribed rate. For this case he concluded that the best estimate of the age was 72×10^6 years. Some years later Bertiau's (1958) study of the proper motions and radial velocities of cluster members yielded an expansion rate appropriate to an age of 20×10^6 years. Shortly thereafter, Blaauw (1959) pointed out observational evidence for different evolutionary ages for the Upper Scorpius stars relative to the rest of the Association, and he suggested that Bertiau's expansion age actually applied to the older, southern regions. For Upper Scorpius he suggested that the age of 1.6×10^6 years appropriate to the runaway star ζ Oph be adopted. Blaauw (1964) has also quoted more recent values for the evolutionary ages derived from color-magnitude diagrams: 10×10^6 years for Upper Scorpius and 14×10^6 years for Upper Centaurus. The age of the Upper Centaurus region derived in Chapter 4, $12\text{-}16 \times 10^6$ years, compares quite favorably with the ages listed above, as does the upper limit of 10×10^6 years on the age of the Upper Scorpius region.

It may also be useful at this time to compare the four-color diagrams for the Scorpio-Centaurus association to other young groups. In Figures 45(a), (b), (c), (d), (e), (f), (g), and (h) we plot β vs. $(u-b)_o$ for the cluster NGC 6231, the associations I Sco (Crawford 1970b) and III Cep (Crawford and Barnes 1970a), and the clusters h and χ Persei (Crawford, Glaspey, and Perry 1970), IC 2602 (Hill and Perry 1969), IC 2391 (Perry and Hill 1969), NGC 7243 (Hill and Barnes 1970), and the Pleiades (Crawford 1970a), respectively. We have ordered this list approximately in order of increasing age. Table 27 lists these clusters again, plus the Upper Scorpius (II Sco) and the Upper

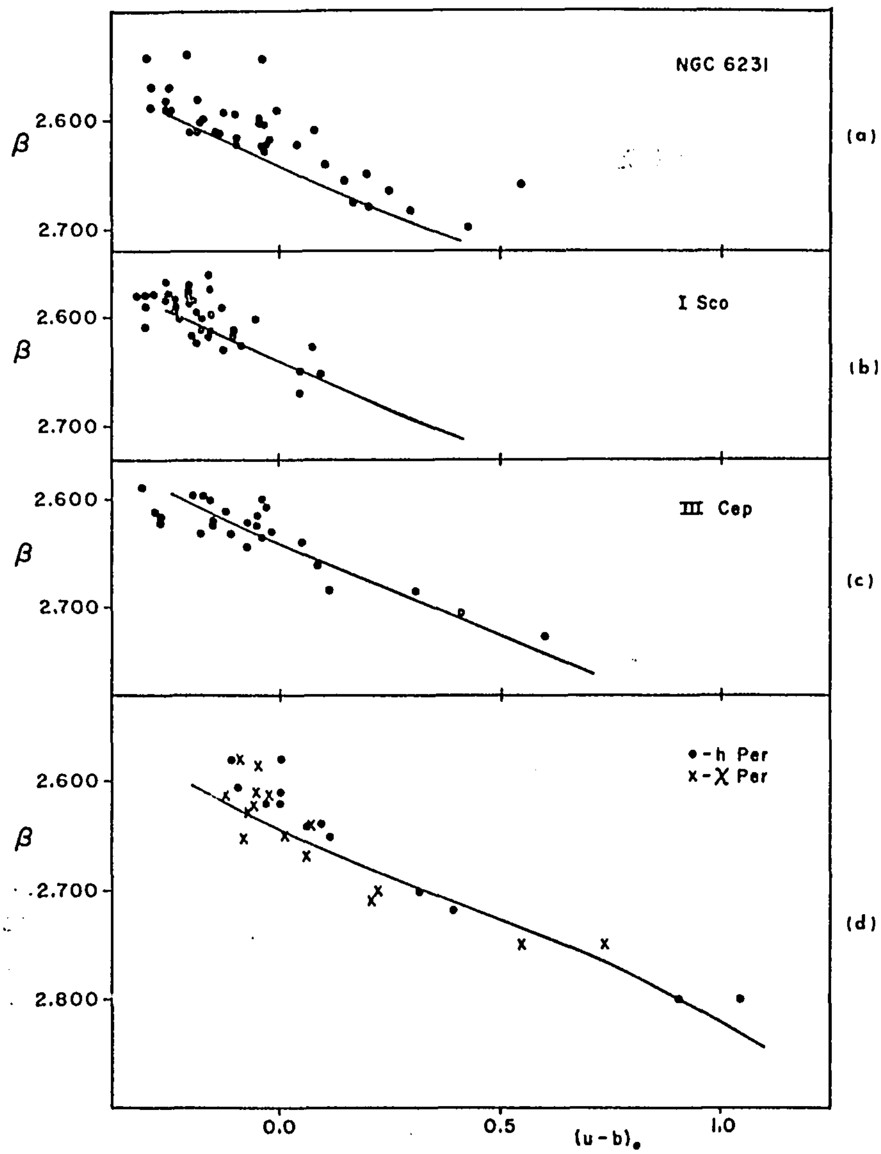

Figure 45. β, $(u-b)_o$ Diagrams for Young Open Clusters and Associations -- The solid lines represent the Z.A.M.S.

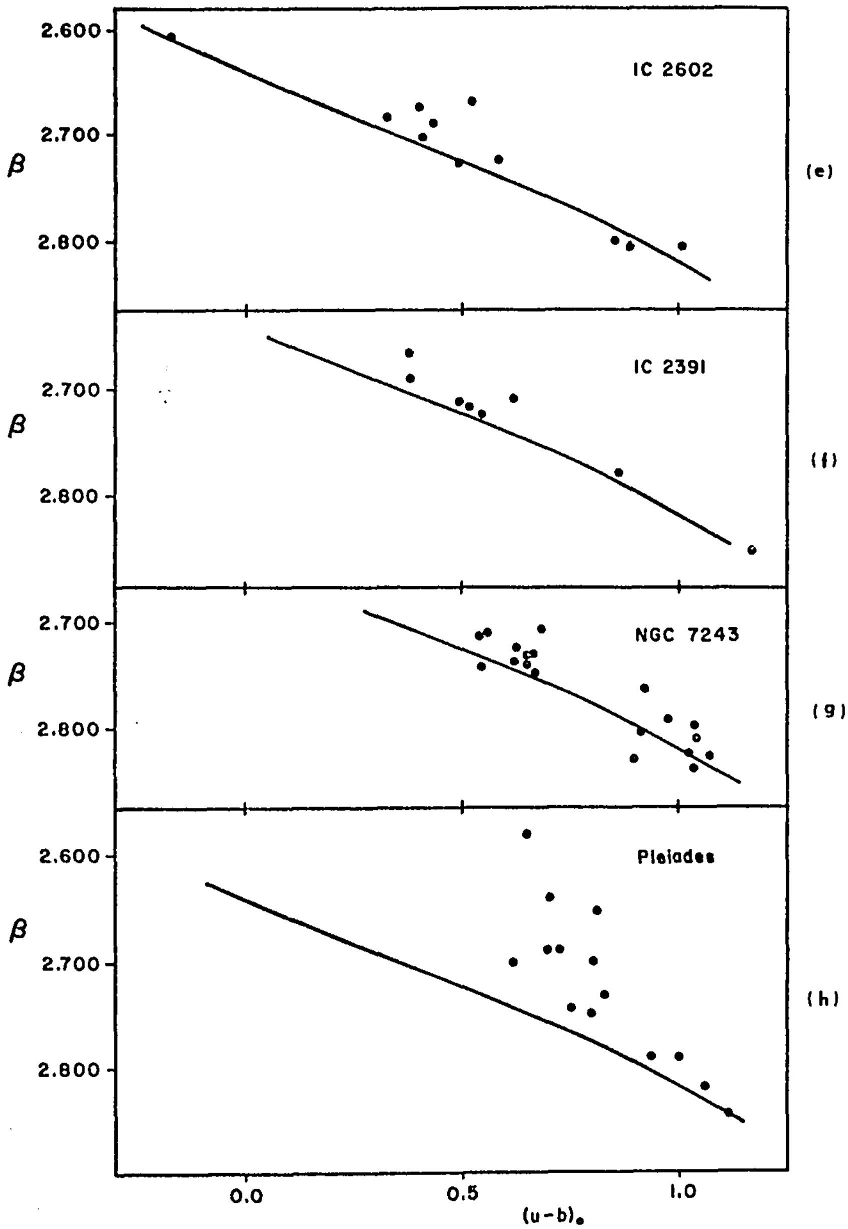

Figure 45.--Continued

Table 27. Cluster Age Estimates

Cluster	Age (4c)	Age (other)
NGC 6231 I Sco	Very young	10^6 yrs
III Cep	Very young	$4 - 8 \times 10^6$
Upper Sco	$\lesssim 10 \times 10^6$ yrs	10×10^6
h Per χ Per	$10 - 12 \times 10^6$	--
Upper Cen	$12 - 16 \times 10^6$	14×10^6
IC 2602	Young or 50×10^6	$4 - 20 \times 10^6$
IC 2391	50×10^6	--
NGC 7243	70×10^6	76×10^6
Pleiades	80×10^6	100×10^6

Centaurus association, with ages, when possible, as derived from the four-color data.

It should be pointed out that in IC 2602 there is one BO V type star, then a gap, and no more early B-type stars until spectral type B3. Hill and Perry (1969) agreed that star formation in IC 2602 was not coeval, based on the latest type stars considered to be members. The older age listed for this cluster corresponds to the B-type star age derived from the photometry, excluding the BO V star, HD 93030.

Peculiar Stars

In this section we wish to summarize the findings concerning the various peculiar stars in Scorpio-Centaurus. There are two reasons for placing special emphasis on these stars, the first being that there seems to be an unusually large number of B-type stars with peculiar spectra in Upper Scorpius. The second reason concerns the possible memberships of two Am stars in the two subgroups under consideration.

Garrison (1967) first noticed the high percentage of B-type stars in Upper Scorpius having peculiar spectra. The effective temperatures corresponding to the spectral classes assigned to these stars were, on the average, much cooler than those suggested by the (U-B) colors. We have seen in Chapter 3 that these stars generally fall along the main sequence in the β, $(u-b)_o$ diagram, implying normal luminosities, whereas these same stars seemed to lie above the main sequence in Garrison's HR diagrams. We interpret this last effect as being due to Garrison's assigning temperature classes on the basis of the apparent line strength, which places them at too cool a temperature compared to that implied by the Balmer discontinuity.

We also show that the m_1-indices of the B-type stars in Upper Scorpius tend to be a few hundredths of a magnitude larger than the m_1-indices of the stars in Upper Centaurus which have approximately the same c_1-indices. This difference between the two groups of stars is observed at least partially as a larger scatter in the Upper Scorpius sequence in an m_o, c_o diagram. I had hoped that the reality of this phenomenon could be discussed more fully if some comparisons could be made with the equivalent diagrams of other young clusters and associations. Unfortunately, no other young cluster or association has been studied in enough detail to provide a large enough sample of mid- and late B-type stars to search for this effect. (We should point out that the one very peculiar star in the Centaurus region, HD 137193, the spectrum of which is very similar to HD 147010 in Upper Scorpius, does not have a $(u-b)_o$ color indicative of an earlier spectral type. In the β, $(u-b)_o$ diagram, however, it seems to have large $\delta\beta$, whereas in the β, c_o diagram it does not.)

One additional example of a discrepancy between color and spectral type has been reported in the association III Cephei by Crawford and Barnes (1970a). Their uvby and Hβ photometry would indicate that the spectral type of star No. 19 (as numbered by Blaauw, Hiltner, and Johnson 1959) is approximately B3, whereas Garrison (1970) has classified the star as type B7 V (with Si II somewhat strong). The β-index of this star is also more typical of a star near type B3. Finally, the m_1-index of this star is the largest of any of the stars considered to be members of III Cep by Crawford and Barnes. An extension of the spectroscopic and photometric observations to fainter members of the association would be most interesting.

The second major point to be mentioned regarding peculiar stars concerns the possible membership of Am stars in young clusters or associations. Conti and van den Heuvel (1970) have reviewed the history of this aspect of Am stars. In brief, the membership of Am stars in young clusters was not accepted until Garrison (1967) reported the membership of HD 148321 in the Upper Scorpius Complex. Spectra for A-type stars in the clusters M7 and NGC 7160 have been obtained by Conti and van den Heuvel (1970). Two stars in M7 and one in NGC 7160 were classified as Am stars, although the membership of one of the Am stars in M7 is questionable. Hill and Barnes (1970) have studied the open cluster NGC 7243 both photometrically and spectroscopically and have reported one Am star as a possible member.

We should, therefore, examine the available information concerning Am stars in the Scorpio-Centaurus association. There are several difficulties with HD 148321 in Upper Scorpius, classified as A5mp (strong Sr) by Garrison (1967). It appears to have very little reddening, assuming that the calibration of the four-color system is applicable to Am stars, whereas the reddening for most of the stars in Upper Scorpius is $E(b-y) \approx 0^{m}.1$. Also the observed c_1-index for this star is small enough that it lies below the Z.A.M.S. in the c_1, $(b-y)$ diagram without making corrections for reddening. Assuming that the photometry is accurate, this implies that this star is a foreground star. From its calculated distance modulus of $4^{m}.5$ and the location of its values of V_o and $(b-y)_o$ above the Z.A.M.S. in Figure 42, we would also conclude that HD 148321 is a foreground star.

We seem to be more fortunate with HD 119674 in Upper Centaurus. It has a very large m_1-index; only $0^{m}.045$ of reddening in the $(b-y)$ color; and the value of δc_1 is only $0^{m}.04$, again quite acceptable. The adopted distance modulus is $6^{m}.2$, and its value of V_o and $(b-y)_o$ place it right on the main sequence in Figure 44. For these reasons we may consider it a possible member of the Upper Centaurus association.

<u>Summary</u>

We may now summarize the results of this dissertation. One of the primary objectives was to test the absolute magnitude calibration of the β-index for B-type stars by comparing the values of $M_v(\beta)$ for each star in the Scorpio-Centaurus association with the absolute magnitudes given by Bertiau (1958).

In Chapter 3 a direct comparison of the values of M_v (Bertiau) to the (unpublished) preliminary calibration of β in terms of M_v showed no systematic differences in the Upper Scorpius and Upper Centaurus regions; however, the Lower Centaurus B stars were $0^m.4$ brighter in Bertiau's calibration. We may, therefore, feel confident about the reliability of previous calibrations which had been based on the moving cluster analysis of the Scorpio-Centaurus association. Conversely, it is equally satisfying to find that the Hβ calibration agrees well with results from the independent approach of using the moving cluster method, uncertain though these results might have been.

The second point of interest centers on the phenomenon of different subgroups within associations. The fact that there is a measurable difference in the ages of the Upper Centaurus and the Upper Scorpius sections of the association appears to be well established by the β, $(u-b)_o$ diagrams given in Chapter 3. In Chapter 4, evolutionary tracks in the ΔM_{bol}, log T_{eff} plane have been transformed to the β, $(u-b)_o$ diagram, giving ages of 12-16 million years for the Upper Centaurus stars and of approximately 10 million years for the Upper Scorpius stars.

Another difference between the Upper Centaurus and the Upper Scorpius sections of the association is apparent in the m_o, c_o diagrams for the two groups of stars (see Figure 15). The m_o-indices of the B-type stars in Upper Scorpius had, on the average, values of m_o approximately $0^m.02$ larger than the B-type stars of similar spectral type in Upper Centaurus. This result was quite unexpected, for the m_1-index was not thought to be of any real value in the study of B-type stars. The explanation of this phenomenon is still not clear, although we have suggested that it may be related to the large number of peculiar B stars in Upper Scorpius which had been found (spectroscopically) by Garrison (1967). Further study of this phenomenon will be needed to solve this problem.

The final result of this investigation concerns the list of apparently young, late-B- and A-type stars in Centaurus which lie at approximately the same distance as the B star members (see Tables 24 and 26). We consider these fainter stars to be candidates for membership in the Upper Centaurus association. The most important criterion for membership should be that each star share in the common stream motion of the B-type stars. We have seen in this chapter that the available radial velocities and proper motions are not of high enough quality to be used for this purpose.

Suggestions for Future Work

The preceding discussions have, naturally, raised several questions for which further information will be required before they can be answered. With this in mind we would suggest certain observational projects which could add to our knowledge not only of the Scorpio-Centaurus association, but also to our knowledge of young groups of stars in general.

Crucial to the proper discussion of the possible membership of late B- and early A-type stars in the different subgroups is the lack of accurate proper motions. Besides our need to know with precision the systematic errors in the right ascension and declination components of the existing proper motions for this section of the sky, it would also be quite useful if we could improve the accuracy of the proper motions for the fainter stars of later spectral type which have been suggested as members. We therefore recommend that all of the stars listed by Garrison (1967) for Upper Scorpius and those listed as possible members in the present investigation for Upper Centaurus be included in programs of astrometric observations in the southern sky.

A program that could be carried out in a much shorter time scale is one to determine accurate radial velocities of all suggested new members. Blaauw (1946) had pointed out the differences between the radial velocities of the bright B-type stars in the Scorpio-Centaurus association and the distant field stars. We have seen from Figure 40, however, that observations consisting of only a few plates per star do not give us the same separation. More detailed studies are needed to determine the usefulness of radial velocities for confirming the membership of stars of later spectral types.

More extensive four-color photometric observations of the late B- and A-type stars suggested as new members by Garrison (1967) are also needed. These additional data would be useful in comparing the spectroscopic techniques used by Garrison to the photometric techniques used here an and for other associations and clusters. More four-color observations of B5-B9 stars in Upper Centaurus are also desirable, for this is one spectral range where the number of stars observed was unintentionally small.

The several peculiar B-type stars in Upper Scorpius (and one in Upper Centaurus) will undoubted need more study before we can understand their properties. This could mean that high dispersion spectra will eventually be required for analysis. Concerning the Am stars in both regions, it would be desirable to have confirmation of the four-color and Hβ photometric indices and further investigation into their possible membership.

Additional data which could provide more information on the differences between the Upper Scorpius and the Upper Centaurus stars would be (1) rotational velocities for more of the Upper Centaurus stars and more of the faint Upper Scorpius stars and (2) a study of the binary frequency in each region.

In the same spirit we especially urge that more young clusters and associations be studied thoroughly for membership to later spectral types, even though this will sometimes mean observing rather faint stars. Those clusters that have had such a detailed analysis have in some cases shown unusual properties, so it would not be too surprising if this were also the case for other groups of young stars.

REFERENCES

Abt, H. A. 1970, Kitt Peak National Observatory, private communication.

Adams, T., and Morton, D. 1968, Astrophys. J. 152, 195.

Ambartsumian, V. A. 1954, Trans. I.A.U. 8, 665.

Ambartsumian, V. A. 1955, Observatory 75, 72.

Ambartsumian, V. A. 1959, Endeavor 18, 45.

Barnes, J. V. 1970, Kitt Peak National Observatory, private communication.

Barry, D. C. 1967, Dissertation, The University of Arizona.

Bertiau, F. C. 1958, Astrophys. J. 128, 533.

Blaauw, A. 1946, Dissertation, University of Groningen.

Blaauw, A. 1952, Bull. Astron. Inst. Neth. 11, 414.

Blaauw, A. 1958, Astron. J. 63, 186.

Blaauw, A. 1959, I.A.U. Symp. No. 10, J. Greenstein, Ed., Suppl. Ann. d'Astrophys Fasc. No. 8, p. 105.

Blaauw, A. 1964, Ann. Rev. Astron. Astrophys. 2, 213.

Blaauw, A., Hiltner, W. A., and Johnson, H. C. 1959, Astrophys. J. 130, 69; Astrophys. J. 131, 527 [erratum].

Bless, R. C. 1970, I.A.U. Symp. No. 36, L. Houziaux and H. E. Butler, Eds. (D. Reidel, Publ., Dordrecht, Holland), p. 73.

Bok, B. J. 1937, The Distribution of Stars in Space (University of Chicago Press, Chicago), p. 97.

Bonneau, M. 1964, Dissertation, University of Besançon.

Borgman, J., and Blaauw, A. 1964, Bull. Astron. Inst. Neth. 17, 358.

Boss, B. 1937, General Catalogue of Proper Motions (Carnegie Inst. Washington, Washington, D. C.).

Bradley, P. T., and Morton, D. C. 1969, Astrophys. J. 156, 687.

Brown, R. Hanbury, Davis, J., Allen, L., and Rome, J. 1967, Mon. Not. Roy. Astron. Soc. 137, 393.

Cannon, A. J., and Pickering, E. C. 1918, Ann. Harvard College Obs. vols. 91-99.

Chaffee, F., Carbon, D., and Strom, S. 1971. Smithsonian Astrophys. Obs., unpublished manuscript.

Charlier, C. V. L. 1916, Astrophys. J. 49, 311.

Chubb, T., and Byram, E. 1963, Astrophys. J. 138, 617.

Clube, S. V. M. 1967a, Mon. Not. Roy. Astron. Soc. 137, 189.

Clube, S. V. M. 1967b, Observatory 88, 140.

Collins, G., and Harrington, J. 1966, Astrophys. J. 146, 152.

Conti, P., and van den Heuvel, E. P. J. 1970, Astron. Astrophys. 9, 466.

Crawford, D. L. 1958, Astrophys. J. 128, 185.

Crawford, D. L. 1970a, Stellar Rotation, A. Slettebak, Ed. (D. Reidel Publ. Co., Dordrecht, Holland), p. 114.

Crawford, D. L. 1970b, Kitt Peak National Observatory, private communication.

Crawford, D. L., and Barnes, J. V. 1969a, Astron. J. 74, 407.

Crawford, D. L., and Barnes, J. V. 1969b, Astron. J. 74, 818.

Crawford, D. L., and Barnes, J. V. 1970a, Astron. J. 75, 946.

Crawford, D. L., and Barnes, J. V. 1970b, Astron. J. 75, 952.

Crawford, D. L., and Barnes, J. V. 1970c, Astron. J. 75, 978.

Crawford, D. L., and Mander, J. 1966, Astron. J. 71, 114.

Crawford, D. L., and Perry, C. 1966, Astron. J. 71, 206.

Crawford, D. L., and Strömgren, B. 1966, Vistas in Astron, A. Beer, Ed., 8, 149.

Crawford, D. L., Barnes, J. V., Gibson, J., Golson, J. C., and Crawford, M. L. 1970, Kitt Peak National Observatory, unpublished manuscript.

Crawford, D. L., Barnes, J. V., and Golson, J. C. 1970, Astron. J. 75, 624.

Crawford, D. L., Glaspey, J. W., and Perry, C. 1970, Astron. J. 75, 822.

Davies, R. D. 1960, Mon. Not. Roy. Astron. Soc. 120, 483.

Eggen, O. J. 1961, Roy. Obs. Bull. No. 41.

Eggen, O. J. 1963, Astron. J. 68, 697.

Evans, D. S. 1970, University of Texas, private communication.

Fricke, W. 1966, Vistas in Astron, A. Beer, Ed., 8, 205.

Garrison, R. F. 1967, Astrophys. J. 147, 1003.

Garrison, R. F. 1970, Astron. J. 75, 1001.

Gould, B. A. 1879, Uranometria Argentina, p. 335.

Gutierrez-Moreno, A., and Moreno, H. 1968, Astrophys. J. Suppl. 15, 459.

Hardie, R., and Crawford, D. L. 1961, Astrophys. J. 133, 843.

Hayes, D. S. 1967, Dissertation, University of California at Los Angeles.

Hayes, D. S. 1970, I.A.U. Symp. No. 36, L. Houziaux and H. E. Butler, Eds. (D. Reidel Publ., Dordrecht, Holland), p. 13.

Heeschen, D., and Lilley, A. 1954, Proc. Nat. Acad. Sci. USA, 46, 1095.

Heintze, J. R. W. 1968, Bull. Astron. Inst. Neth. 20, 1.

Heintze, J. R. W. 1969, Bull. Astron. Inst. Neth. 20, 154.

Herschel, J. 1847, Cape Observations, p. 385.

Hickok, F., and Morton, D. 1968, Astrophys. J. 152, 203.

Hill, G., and Barnes, J. 1970, Dominion Astrophysical Laboratory, unpublished manuscript.

Hill, G., and Perry, C. 1969, Astron. J. 74, 1011.

Hube, D. P. 1970, Mem. Roy. Astron. Soc. 72, 233.

Iben, I. 1965a, Astrophys. J. 141, 993.

Iben, I. 1965b, Astrophys. J. 142, 1447.

Iben, I. 1966a, Astrophys. J. 143, 483.

Iben, I. 1966b, Astrophys. J. 143, 505.

Iben, I. 1966c, Astrophys. J. 143, 516.

Iben, I. 1967, Astrophys. J. 147, 650.

Innes, R. T. A., Dawson, B. H., and van den Bos, W. H. 1927, Southern Double Star Catalogue (Union Observ., South Africa).

Jaschek, C., Conde, H., and de Sierra, A. 1964, Publ. Astron. Obs. La Plata 28, No. 2.

Kapteyn, J. C. 1914, Astrophys. J. 40, 43.

Kelsall, T., and Strömgren, B. 1966, Vistas in Astron, A. Beer, Ed., 8, 159.

Kerr, F., and Westerhout, G. 1965, Galactic Structure, A. Blaauw and M. Schmidt, Eds. (University of Chicago Press, Chicago), p. 167.

Lesh, J. 1968, Astrophys. J. Suppl. 17, 371.

Mihalas, D. 1965, Astrophys. J. Suppl. 9, 321.

Mihalas, D. 1966, Astrophys. J. Suppl. 13, 1.

Mihalas, D., and Morton, D. 1965, Astrophys. J. 142, 253.

Morton, D. 1968, Astrophys. J. 151, 285.

Morton, D., and Adams, T. 1968, Astrophys. J., 151, 611.

Murphy, R. E. 1969, Astron. J. 74, 1082.

Norton, A. P. 1959, Star Atlas and Reference Handbook (Gall and Inglis, Edinburgh), 14th Edition.

Oke, J., and Schild, R. 1970a, I.A.U. Symp. No. 36, L. Houziaux and H. E. Butler, Eds. (D. Reidel Publ., Dordrecht, Holland), p. 13.

Oke, J., and Schild, R. 1970b, Astrophys. J. 161, 1015.

Perry, C. L., and Hill, G. 1969, Astron. J. 74, 899.

Petrie, R. 1962, Mon. Not. Roy. Astron. Soc. 123, 501.

Petrie, R. 1965, Publ. Dom. Astrophys. Obs. 12, No. 9.

Schlesinger, B. M. 1969, Astrophys. J. 158, 1059.

Shapley, H., and Cannon, A. J. 1921, Harvard Circulars No. 226.

Slettebak, A. 1968, Astrophys. J. 151, 1043.

Smart, W. M. 1939, Mon. Not. Roy. Astron. Soc. 100, 60.

Smithsonian Astrophysical Observatory 1966, Star Catalog, Smithsonian Publ. 4652 (Washington, D. C.).

Strom, S., and Peterson, D. 1968, Astrophys. J. 152, 859.

Strömgren, B. 1963, Quart. J. Roy. Astron. Soc. 4, 8.

Strömgren, B. 1964, Rev. Mod. Phys. 36, 532.

Strömgren, B. 1966, Ann. Rev. Astron. Astrophys. 4, 433.

Thackeray, A. D. 1967, I.A.U. Symp. No. 30, A. Batten and J. Heard, Eds. (Academic Press, New York), p. 163.

Walraven, Th., and Walraven, J. 1960, Bull. Astron. Inst. Neth. 15, 67.

Wesselius, P., and Sancisi, R. 1971, Kapteyn Astronomical Laboratory, Groningen, unpublished manuscript.