A study of the Scorpio-Centaurus cluster

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1. Introduction and Summary.

In the year 1914 KAPTEYN published a detailed study of the proper motions of the bright southern B stars and showed that the majority of these stars form an extended moving cluster, called the Scorpio-Centaurus cluster after the constellations which contain its most conspicuous part. The increasing amount and accuracy of the observational material of radial velocities and proper motions has led to many new investigations. Nevertheless we do not yet possess a satisfactory picture of the structure and the motion of the cluster. Smart denies the existence of the cluster, whereas other investigators do not question this existence and determine the shape and motion, but with diverging results. This variety of results presents the main motive for the new investigation of this paper. An additional reason is the recent discovery of large systematic errors in the system of proper motions in declination of Boss' *General Catalogue* at southern declinations. Further, the evolution of the cluster in connection with the theory of differential galactic rotation presents a problem which has not yet been considered seriously by other investigators, and the cluster forms a very suitable object for the determination of the luminosity law of the B stars.

Chapter I. In Chapter I the previous investigations of the motion of the cluster are summarized. Some points which are of importance for the explanation of the divergence of the previous results and which lead to the new investigations of Chapters II and III are discussed.

In *section 2* KAPTEYN's investigation is described and precessional and other corrections to the mean proper motions used by this author are computed. It appears that the systematic errors form a considerable fraction of the proper motions themselves so that it is necessary to revise KAPTEYN's conclusion as to the community of motion of nearly all the B stars in the region studied by him. Later investigators have taken into account part of these corrections, but they generally did not investigate the parallelism of the proper motions and the boundaries of the cluster as carefully as KAPTEYN did. In *section 3* RASMUSON's investigation of the proper motions is described.

In *section 4* the positive excesses in the radial velocities of the southern B stars are shown; they were found by PLASKETT and PEARCE, and identified by these authors with KAPTEYN's stream motion. In *section 5* the treatment of the stream motion by PLASKETT and PEARCE on the basis of the proper motions and the radial velocities is discussed. As a consequence of an erroneous apex of the stream motion, found from the proper motions and used in the treatment of the radial velocities, an unexpectedly large K term was found together with a small value of the stream velocity. From computations by SAMUELS LALL it follows that the radial velocities used by PLASKETT and PEARCE can be explained by values of the stream elements which agree fairly well with those found in Chapter II (see the last part of section 5).

SMART's investigations are discussed in *section 6*. SMART's conclusion that the Scorpio-Centaurus cluster must be removed from the list of moving clusters is based mainly on the large dispersion of the internal velocities found by this author from the radial velocities. However, it was noted already by PLASKETT and PEARCE that the excesses of the radial velocities are confined mainly to the brighter stars. SMART's value of the dispersion of the internal velocities decreases considerably if the apparently faintest stars are omitted from the list, and thus the main argument of this author against the existence of the cluster disappears if we assume that these faint stars do not belong to the cluster.

In *section 7* the contents of the investigations by CANAVAGGIA and FRIBOURG, BERTAUD, DOLEJSI, MILLER, and KULIKOVSKY are summarized. The main conclusions to which we are led in this chapter are given in *section 8,* together with a table of the elements of the stream motion and the dispersion of the internal velocities according to the various authors.

Chapter II. In Chapter II the motions of the southern B stars are investigated anew. We find that a moving cluster of apparently bright stars does exist, and an attempt is made to explain its motion and shape on the basis of the theory of differential galactic rotation.

The region studied and the observational data used are described in *sections 9* and *10*. The proper motions are taken from the *General Catalogue* but the components in declination are reduced to the system of the FK3. The investigation starts in *section 11* by studying the relation between the positive excesses in the radial velocities and the apparent visual magnitudes. The radial velocities after elimination of the solar motion with respect to the B stars in general (the elements of which are given on page 30) are denoted by R and plotted against the visual magnitude m in the (R, m) diagrams of Figures 1, 2, 3, 4 (pages 32 to 35), for different intervals of galactic longitude and for the subclasses B0 to B2, B3, and B5 separately. It appears that the brighter stars in the region $l = 240°$ to $340°$ show systematically positive values of R with a mean value of about $+10$ km/sec, whereas the effect of differential galactic rotation is negative for the greater part of this region. The positive values of R are confined mainly to the stars brighter than a well defined apparent magnitude m_c ($= 5.25$ for B0 to B2, 5.5 for B3 and 6.0 for B5), and the change from the positive to negative or zero values appears to take place rather abruptly. It is concluded provisionally that the bright B0 to B5 stars in the region $l = 240°$ to $340°$ form a group, moving with a positive radial component with respect to the centre of gravity of the stars in the neighbourhood of the sun. The radial velocities of the fainter stars probably show the normal effect of differential galactic rotation. In *section 12* it is shown that the group of bright stars can be traced also among the numbers of stars as a function of the apparent magnitude and the galactic latitude in the region $l = 270°$ to $340°$ (Table 8, page 39). In *section 13* the apparent distribution of the stars on the sky is studied separately for the stars brighter and fainter than the magnitudes m_c (Figures 5 and 6, page 41). A part of the group of bright stars, the existence of which appeared from the radial velocities, is shown to be identical with the well known conspicuous group of bright B stars at positive galactic latitude. A group of bright B stars at negative galactic latitude in the region $l = 300°$ to $330°$, which apparently is only loosely connected with the main body of the cluster, probably belongs to it (see Figure 5).

In *section 14* the mean space motions of the bright B0 to B3 stars are studied. The stars are divided into the areas 1 to 7 which cover the greater part of the region between galactic longitudes 200° and 340° (see Figure 5, page 41). For each area the mean space motion after elimination of the solar motion and the differential galactic rotation is computed for the B0 to B3 stars brighter than the limits (12) on page 40 which are approximately equal to the magnitudes m_e mentioned above. These mean space motions are the sum of the mean radial velocity and the mean tangential velocity both considered as vectors. In computing the latter the mean proper motion components in longitude and latitude are converted into linear tangential velocities with the mean parallaxes given in Table 9, column 9 (page 43). These mean parallaxes are based on the mean apparent magnitudes and the mean visual absolute magnitudes given in Table 11 (page 46), and on an assumed amount of the visual interstellar absorption (^{m}.9 per 1000 parsecs). The components of the mean space velocity perpendicular to the galactic plane are small. The amounts and directions of the total components in the galactic plane are represented by arrows in Figure 7 (page 54). We infer from this diagram that the stars in areas 1 to 5 possess a common stream motion, and that the stars in areas 6 and 7 do not share this motion. Thus the provisional limit of the cluster at longitude 240° found from the (R, m) diagrams is confirmed. The amount and direction of the common stream motion of areas 1 to 5 is determined in *section 15*. It is pointed out that no reliable determination can be based on the mean space velocities of section 14 as a consequence of the uncertainty in the mean parallaxes. The elements of the stream motion are first determined from the mean radial velocities (pages 59 and 60) and next from the mean proper motions (pages 61 and 62). The results are compared in section 15*c* (page 63). The difference between the two sets of coordinates of the apex of the stream motion is not incompatible with its probable error, and may be affected in addition by systematic errors in the proper motions or by errors in the ratios of the mean parallaxes of Table 9. In determining the final elements of the stream motion preference is given to the results from the radial velocities. The component in the galactic plane is the mean of the solution from the radial velocities of the B0 to B3 stars and an additional solution from the radial velocities of the B0 to B5 stars. The component perpendicular to the galactic plane which is not well determined from the radial velocities is taken from the solution of the proper motions. The final elements, given by (35) and (36) on page 64, are:

the stream velocity with respect to the sun after elimination of the differential galactic rotation is 25.9 km/sec ± .8 (p. e.) towards the point $l = 226°.9 \pm 1°.6$ (p. e.), $b = -13°.8 \pm 2°.1$ (p. e.); if the solar motion with respect to the B stars in general (page 30) is also eliminated we find 11.9 km/sec ± .5 (p. e.) towards $l = 271° \pm 5°$ (p. e.), $b = -11° \pm 5°$ (p. e.).

In the present investigation the radial velocities have *not* been corrected for a K term of unknown origin; only the gravitational red shift estimated by PLASKETT on the basis of the dimensions and masses of the B stars has been taken into account. It is believed that the evidence in favour of a K term of unknown origin, found by some investigators, is not strong enough to justify the *a priori* subtraction of such a term from the radial velocities. The present results do not involve a modification of this view.

In *section 16* the shape of the cluster is derived from the distribution of the distances of the B0 to B3 members of the cluster. The latter distribution is determined from the distribution of the components of proper motion in longitude; the method applied is outlined on pages 65 to 67. The dispersion of the values of $\mu_l \cos b$ is due to the accidental observational errors of the proper motions, to the peculiar velocities of the members and to the dispersion of the distances of the members. The distribution of the values of $\mu_\tau \cos b$ for each of the areas 1 to 5 is shown in Figure 10 (page 68). The diagram reveals immediatly the small dispersion of the values of $\bar{\mu}_\tau \cos b$ for the bright Bo to B3 stars compared with the mean value of $\mu_\tau \cos b$ in areas 2, 3 and 4. It follows that the dispersion of the distances must be small compared with the mean distance. The computations are based on the Bo to B3 stars and made in two steps. First the stars brighter than the limits (12), used also in the computation of the mean space velocities and forming the majority of the members, are considered and next the fainter ones. In order to correct the observed dispersion of the components $\mu_\tau \cos b$ for the peculiar motions of the members, the dispersion of the peculiar velocities is derived from the radial velocities with probable errors smaller than $\pm$ 3 km/sec. The dispersion found is, however, so large that it is incompatible with the small dispersion of the proper motion components after correction for the accidental observational errors of the proper motions. This discrepancy probably is due to an underestimate of the probable errors of the radial velocities in MOORE's catalogue which were used in the present computations in correcting the observed dispersion of the radial velocities for the observational accidental errors. A more satisfactory value is derived from the systemic velocities of spectroscopic binaries and from the radial velocities based on ten or more observations; the resulting value is $\pm$ 2.0 km/sec. The dispersion of the distances of the Bo to B3 stars brighter than the limits (12) in each of the areas 1 to 5 is given in the last line of Table 19 (page 69). The results are also shown in Figure 7 (page 54), where the straight lines, partly broken, mark the boundaries which include about two thirds of the group stars. It is shown on the basis of the numbers of stars as a function of the apparent magnitude, and by a comparison of the values of R and $\mu_\tau \cos b$ with those of the stars brighter than the limits (12), that the members fainter than the limits (12) form a small fraction of the total number of stars in the cluster. The dispersion of the distances derived from the bright Bo to B3 stars therefore will hold approximately for all Bo to B3 members. Figure 11 (page 79) gives a schematic picture of the projection on the galactic plane of the space distribution of the Bo to B3 stars in the main body of the cluster (*i. e.* in areas 2, 3, 4, 5 of Figure 5). The diagram reveals the elongated shape of the cluster, the distance between the extreme points in the direction of elongation being about three times its transverse section.

The B5 stars are considered in *section 17*; the dispersion of the peculiar radial velocities probably does not differ from that found from the Bo to B3 stars, whereas the dispersion with respect to the central line of the main body of the cluster seems to be somewhat larger than for Bo to B3. In *section 18* it is shown that the cluster probably does not contain any O star. Stars of spectral types later than B5 are considered briefly in *section 19*. It is shown on the basis of the distribution of the values of $\mu_\tau \cos b$ that the cluster contains B8 and B9 stars. Whether later spectral types occur among the members can be decided at present only on the basis of a study of the apparent distribution on the sky. In *section 20* the dispersion of the peculiar velocities is determined from the τ components of the proper motions in areas 2, 3, 4. The result is $\pm$ 1.4 km/sec.

In *section 21* an attempt is made to explain the motion and the shape of the cluster on the basis of a theory of the galactic orbits of single stars, due to LINDBLAD. It is assumed on the basis of various considerations (see pages 86 and 87) that the space density of the members of the cluster is small compared with the space density of the field stars in general, so that the motions of the members of the cluster are governed by the same forces as the field stars. On pages 87 to 93 the orbits of single stars are studied. Figure 13 (page 92) shows the relative orbits in a rotating co-ordinate system ξ, η (ξ being directed from the galactic centre outwards and η in the direction of rotation) with the origin O moving in a circular orbit. For some simplifying assumptions made in the computations see pages 87 and 94. Some special properties of the orbits discussed on page 93 are of importance for the explanation of the motion and the shape of the cluster. This explanation is given on pages 95 to 101; the result can be summarized as follows. Between $.4 \times 10^8$ and 1.5×10^8 years ago the cluster, which up to that time may have been spherical, was liable to a disturbing force which gave it a velocity between 9 and 18 km/sec relative to an imaginary star, moving in a circle around the galactic centre and coinciding with the centre of the cluster at the time of the disturbance. Differences occurred between the values of this relative velocity for different members of the cluster, equal to about 10 to 30 percent of the mean relative velocity; the directions of these relative velocities being the same. The present shape and motion of the cluster are explained by the evolution since this disturbance. The explanation is based mainly on the property that stars which move with different velocities but in the same direction relative to the imaginary star just mentioned, are situated permanently on a straight line through the imaginary star. We further find some evidence of a mean motion of the stars surrounding the sun in the direction from the galactic centre outwards (the Π direction) and amounting to between 0 and + 15 km/sec.

In *section 22* it is shown that KAPTEYN's Vela group must be struck off the list of moving clusters.

Chapter III. In Chapter III the luminosity law of the B0 to B5 stars in the cluster is determined. To that purpose the members of the cluster are discriminated from the field stars by means of accurately defined criteria based on the radial velocity and the τ component of the proper motion. The members are subdivided into certain members, probable members and doubtful members, and the field stars into probable field stars and certain field stars. Individual parallaxes are derived for the certain, probable and doubtful members; these parallaxes are the weighted mean of the parallax derived from the v component of the proper motion and the mean parallax of all group stars in the direction of the star considered (see page 105). From these individual parallaxes and the apparent visual magnitudes, values of the visual absolute magnitude increased by the visual interstellar absorption, M + abs, are computed.

In *section 23* the luminosity curve is derived from all certain, probable and doubtful members in areas 2, 3, 4 in which the discrimination of members and field stars is most reliable. The amount of the visual interstellar absorption is assumed to be $^m.15$ for each star. The numbers of stars with M between given limits are counted. As the criterion of membership is based mainly on the radial velocity, stars with unknown radial velocity are not included in the counts. The number of members among the latter stars is estimated by means of their values of the *v* component of proper motion compared with the distribution of the values of this component for the members and for the field stars with known radial velocity. It appears to be a small fraction of the total number of members; the corresponding members are represented in the luminosity curve by means of hypothetical absolute magnitudes. For the apparently faintest stars neither the radial velocity nor the proper motion is known. An upper limit of the contribution of these stars to the luminosity law is derived. The final luminosity law for *M* brighter than .0 is given in Table 26*a* for each of the HARVARD subclasses B0 to B5 and for the combined subclasses. Table 26*b* gives upper limits of the numbers for *M* between .0 and + 1.5 for which Table 26*a* is incomplete. Table 27 gives the luminosity law after arranging the stars of Table 26*a* according to the revised spectral types of PEARCE. Mean visual absolute magnitudes and average deviations with respect to these mean values, derived from the luminosity laws of Tables 26*a*, 26*b* and 27, are given in Table 28 for the separate and combined subclasses. Table 29 shows that the *n* and *nn* stars in PEARCE's classification generally are absolute brighter than the *s* stars or the stars without suffix. In *section 24* the new luminosity law is compared with previous results and the differences are explained. In Table 31 of *section 25* the criteria on the basis of which the stars are divided into the three classes of members and the two classes of field stars are given. Lists of the certain, the probable and the doubtful members are given in Table 33. Table 34 gives the probable field stars. Some desiderata for further observations of the southern B stars, especially with regard to the radial velocities, are given at the end of this section. These observations may lead to an improved determination of the shape and the motion of the cluster, to the discovery of members among the spectral types later than B9, and to an improved determination of the faint end of the luminosity law.

In this connection it should be mentioned that most of the astronomical papers published in the years 1942 to 1945 were not available in this country before the present investigation was finished.

Appendix A gives a comparison of the San Luis visual magnitudes, given for many stars in the GC, with the Harvard visual magnitudes. Smoothed differences as a function of the spectral type and the declination are given in Table 35.

Appendix B gives the relations between the mean distance, the mean parallax, and the logarithmic mean parallax of stars of a given apparent magnitude for SCHWARZSCHILD's and SEELIGER's density laws under some simplifying conditions.

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