THE EVOLUTION OF EXPANDING STELLAR ASSOCIATIONS; THE AGE AND ORIGIN OF THE SCORPIO-CENTAURUS GROUP

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The first and the second section deal with the change of the form and dimensions of a group of stars which originate with expanding motions in a small region of space, and the motions of which are governed bij the general galactic field of force. The evolution of the group, in case the initial velocity of expansion s_0 is 1 km.sec^{-1}, is shown in Figure 2. The dimensions of the configurations are proportional to s_0. The direction of the elongation changes with time according to formula (2), represented in Figure 3 and by the table on page 416.

In the third section the results of the second section are applied to the Scorpio-Centaurus group. From its form, dimensions and orientation as projected on the galactic plane and from its mean motion we find that the group must have been formed about 70 million years ago in a region about 2200 parsecs distant in the direction of galactic longitude 26° and that the mean initial velocity of expansion was 0.7 km.sec^{-1}.

The abnormal motion of the star ζ Ophiuchi may find an explanation if the star is genetically related to the Scorpio-Centaurus group but of more recent formation than the majority of its members.

1. *Introduction.*

The hypothesis of expanding motions in groups of stars of recent formation, introduced by AMBARZUMIAN in order to explain the forms and dimensions of the O-associations, has been confirmed for the case of the ζ Persei group of O- and B-type stars[1]). As expanding motions may thus be indeed a general property of such groups, it is important to consider the consequences of this property. At the earliest stages the shapes of the groups will be spherical if the motions of the individual stars are isotropic. Later on, however, the effect of differential galactic rotation will predominate; as a consequence the group will assume an elongated form and its main characteristics, such as its orientation and its dimensions, will be a function of its age and of the constants of differential galactic rotation, A and B, defined by the galactic field of force.

As the constants of differential galactic rotation are sufficiently well known for the region within 2000 parsecs from the sun, we can predict with a fair degree of certainty the properties of the groups that we should expect to observe. The dimensions and orientations of the groups in connection with their age and the initial velocity of expansion will be considered in the next section. In the last section it will be shown that the theory leads to a satisfactory understanding of the phenomenon of the Scorpio-Centaurus group, and to a determination of its age and of the amount of the initial velocity of expansion.

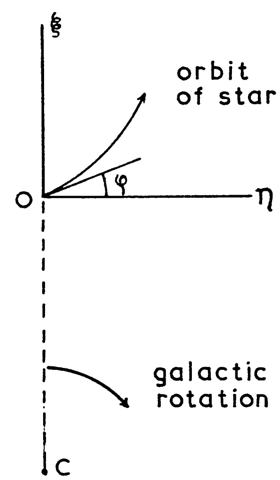
2. *The evolution of expanding associations.*

We assume the initial expanding motions with respect to the centre of the group to be uniform, i.e. not slowing down by the mutual attractions of the stars of the group. Except perhaps at the very first stage of their existence, this assumption will apply to most of the O-associations in view of their low mass density. In the course of time the motions will change as the stars are submitted to the galactic field of force.

[1]) See the preceding paper in this *Bulletin*.

In this section we shall consider only the components of the motions parallel to the galactic plane, and the form and dimensions of the group as projected on this plane. The third dimension of the form depends on the motions perpendicular to the galactic plane and these are in a first approximation independent of those parallel to the plane. They have to be considered in the discussion of individual cases like that of the Scorpio-Centaurus group in the next section.

FIGURE 1



For the description of the motions parallel to the galactic plane, we use the rotating co-ordinate system ξ, η, the origin O of which moves with the circular velocity on a circle around the galactic centre C (see Figure 1). The ξ-axis is in the direction CO, reckoned positive outwards from O, and the η-axis is perpendicular to CO and reckoned positive in the direction of galactic rotation. We consider a star which at the time $t = 0$ was at O and moved relative to the system ξ, η with the velocity s_0 in the direction φ (φ counted from the η-axis towards the ξ-axis). The components of velocity at $t = 0$ are

$$\dot{\xi}_0 = s_0 \sin\varphi \qquad \dot{\eta}_0 = s_0 \cos\varphi.$$

The equations of motion of the star are given, among others, in a previous paper on the Scorpio-Centaurus group[1]); that paper will be denoted in the following by *G.P.* 52. The special case of a star passing through the origin O, considered here, is treated on page 89 of that paper. After some modifications the equations for ξ and η can be written:

$$\xi = \frac{s_0}{\varkappa}\left[\sin\varkappa t \sin\varphi + \beta(1-\cos\varkappa t)\cos\varphi\right] \qquad (1)$$

$$\eta = \frac{s_0}{2B}\left[(1-\cos\varkappa t)\sin\varphi + (2At - \beta\sin\varkappa t)\cos\varphi\right],$$

where A and B are the constants of differential galactic rotation; for the numerical computations we adopt

$A = +\,0.020\,\text{km.sec}^{-1}.\,\text{parsec}^{-1} = +\,2.05 \times 10^{-8}\,\text{year}^{-1}$
$B = -\,0.007\,\text{km.sec}^{-1}.\,\text{parsec}^{-1} = -\,0.72 \times 10^{-8}\,\text{year}^{-1}$;

$$\beta = \sqrt{\frac{A-B}{-B}} = 1.965,$$
$$\varkappa = 2\sqrt{-B(A-B)} = 2.815 \times 10^{-8}\,\text{year}^{-1}.$$

Equations (1) are an approximation of the true orbit with respect to the system ξ, η, valid as long as the co-ordinates ξ and η are small compared with the distance OC. The orbit can be described as a motion in retrograde direction along an epicycle with the axes

$$\frac{s_0}{\varkappa}\sqrt{\sin^2\varphi + \beta^2\cos^2\varphi} \quad \text{and} \quad \frac{\beta s_0}{\varkappa}\sqrt{\sin^2\varphi + \beta^2\cos^2\varphi},$$

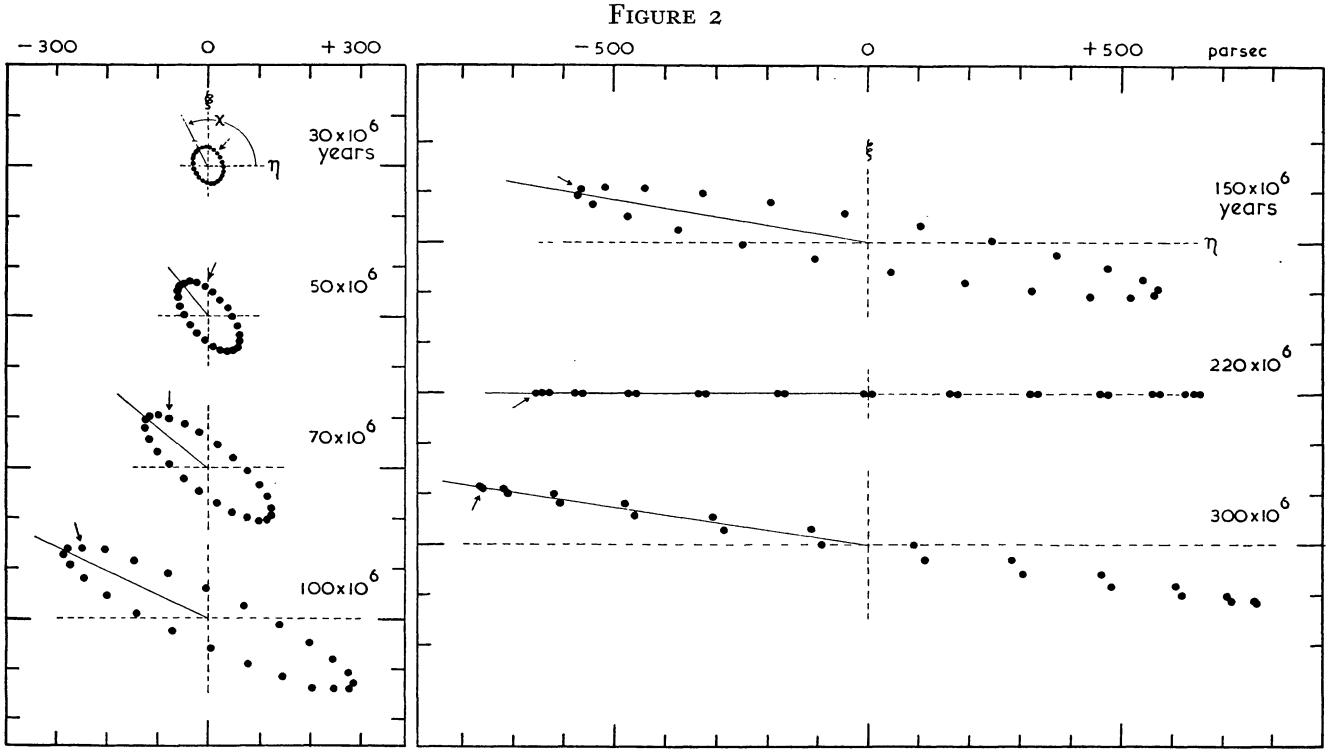
in the directions of ξ and η, respectively. The centre of the epicycle moves uniformly with the speed $s_0(A/B)\cos\varphi$ along a line parallel to the η-axis at the distance $\xi = -(s_0/2B)\cos\varphi$ from this axis.

The relative orbits are illustrated in Figure 13 (page 92) of *G.P.* 52 for various directions φ of the initial velocity s_0, for which a value of 5 km.sec^{-1} was assumed in that figure. As ξ and η are proportional to s_0 according to equations (1), the form of the relative orbit does not depend on s_0, but its dimensions are proportional to s_0. Thus, for $s_0 = 1$ km.sec^{-1}, the value used in the calculations described below, the relative orbits are five times smaller than those of Figure 13 of *G.P.* 52.

Instead of studying the orbits of individual stars for different values of φ, as was done in *G.P.* 52, we shall now study the change with time of the configuration of a group of stars, moving from O simultaneously with equal initial velocities s_0 in different directions φ. The calculations have been carried out for $s_0 = 1$ km.sec^{-1} $= 1.025 \times 10^{-6}$ parsec. year^{-1} and for the 24 directions $\varphi = 0°, 15°, 30°, 45°, 60° \ldots 345°$. The results are in Figure 2, for seven values of the time

[1]) *Publ. Kapteyn Astr. Lab. Groningen* No. 52 (1946).

FIGURE 2



Configurations of a group of stars at 30, 50, ... 300 million years after these stars started their expanding motions of 1 km.sec^{-1} at the origin of the system of co-ordinates ξ, η in the directions $\varphi = 0°, 15°, 30°, \ldots$ The star for which φ was 0° is marked with an arrow. The direction of the major axis of the elliptical configurations is also marked. The calculations are based on the constants A and B as found for the region around the sun.

elapsed since the motions started at O: $t = 30, 50, 70, 100, 150, 220$ and 300 million years, thus ranging from one eighth to nearly one and a half times the period of revolution around the galactic centre for the stars in the region near the sun (230 million years). The figure shows the configurations of the 24 hypothetical stars with respect to the ξ, η-axes. The arrow marks the position of the star whose initial velocity was in the direction $\varphi = 0°$. The scale of distances is given at the lower and at the upper side of the diagram.

It can be shown that the configurations are always ellipses whose dimensions are proportional to s_0 and with the centre at O. The direction of the major axis of the ellipse is given by

$$\mathrm{tg}\, 2\chi = -\frac{1 - \cos \varkappa t}{At - \dfrac{A - 2B}{\varkappa} \sin \varkappa t} , \qquad (2)$$

where χ is the position angle of the major axis reckoned from the η-axis in the same direction as φ . χ is independent of s_0. Figure 3 and the table below show χ as a function of t for the first 350 million years. It runs from 90° to 180°, the extreme direction, and next shows small oscillations, touching the direction of the negative η-axis toward which it approaches.

Figure 4 shows the values of $2a$ and $2b$, the major and minor axes, as a function of t and for $s_0 = 1$ km.sec^{-1}.

In the foregoing it has been assumed that the origin O of the expanding motions moves on a circular orbit around the galactic centre. It follows directly from the equations (1) that the relative orbits of the stars with respect to the centre of the group, and hence also the configurations of Figure 2, remain the same if the motion of the centre of the group is not circular. The formula for χ remains valid and so do the diagrams of Figure 2, if we define new axes ξ and η parallel to the original ones but with their origin in the centre of the group. It is assumed that the deviation of the orbit of the centre of the group from the circular motion is small compared with the distance to the galactic centre.

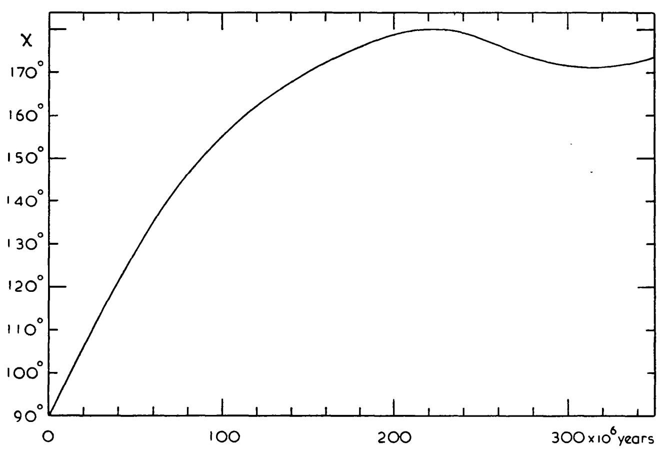
From the above consideration we infer that, whatever be the mean motion of the group as a whole (as long as this does not differ more than, say, 20 km.sec^{-1} from the circular velocity), the age of the group can be derived directly from its orientation. This age, which we may call the 'expansion age', is independent of the initial velocity of expansion s_0. Strictly, the determination of the expansion age from the angle χ is unambiguous only if χ is below 170°. χ, and hence t being known, the velocity s_0 can be derived from the dimensions of the group.

For $s_0 = 1$ km.sec^{-1}, the dimensions of the groups at ten to hundred million years after the beginning of the expansion are of the order of 20 to 600 parsecs. The detection among the stars of the galactic system of structures of these dimensions and forms may become possible as soon as more data are available about the distribution of the stars in space, especially for the

Direction of elongation, χ, and major axis of the elliptical configuration for $s_0 = 1$ km.sec^{-1}, as functions of the time t.

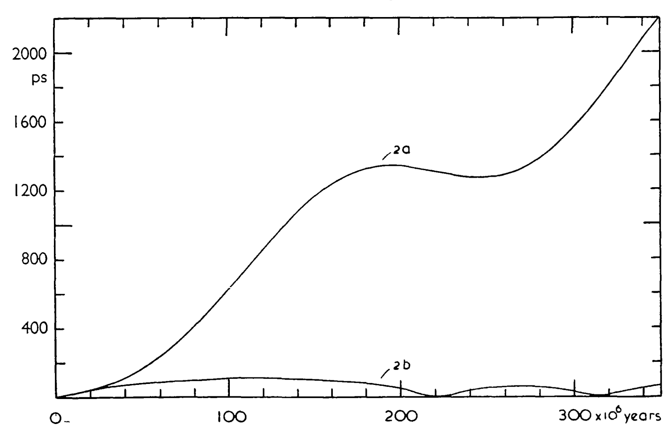
t (in millions of years)	χ	$2a$ (parsecs)	t (in millions of years)	χ	$2a$ (parsecs)
10	98°	20	190	178°	1340
30	114	76	210	180	1320
50	128	166	230	180	1280
70	140	320	250	178	1280
90	151	520	270	175	1320
110	159	740	290	172	1460
130	165	960	310	171	1680
150	170	1160	330	172	1940
170	174	1280	350	173	2200

FIGURE 3



The position angle χ of the major axis of the elliptical configuration as a function of time.

FIGURE 4



The major and minor axes of the elliptical configuration as a function of time for the initial velocity $s_0 = 1$ km.sec^{-1}.

early-type stars. Among the nearest stars the Scorpio-Centaurus group very probably is of this kind, as will be shown in the next section.

3. *The Scorpio-Centaurus group.*

As has been shown in *Groningen Publications* No. 52, the main body of the Scorpio-Centaurus group has an elongated shape with the dimensions, projected on the galactic plane, of about 290 × 100 parsecs (see *G.P.* 52, page 79). Figure 11 of *G.P.* 52 is reproduced in Figure 5a of the present paper. It is a schematic image of the distribution of the B0 — B3 stars of the group, representing the number of stars in its various parts and their concentration towards the central line of elongation. The axes in the diagram have the same directions as the axes ξ and η used in the preceding section but the origin of the co-ordinates is put at the sun. The direction of elongation corresponds to χ = 142° (see *G.P.* 52, page 95).

In *G.P.* 52 a theory of the evolution of the group was developed, which attempted to explain its shape, orientation and motion on the assumption that the group had been originally spherically shaped, but that it had been submitted to a disturbing force which caused the stars of the group to move with different velocities in one direction. We arrived at a value between 40 and 150 million years for the time elapsed since the disturbance.

The results of the preceding section render this theory somewhat doubtful. It appears that expanding motions of the stars at the time of their formation lead to structures which are very similar to that of the Scorpio-Centaurus group. As the hypothesis of expanding motions has been confirmed for the case of the ζ Persei group, whereas the assumption of a disturbing force in *G.P.* 52 was an *ad hoc* hypothesis, an explanation of the phenomenon of the Scorpio-Centaurus group on the basis of AMBARZUMIAN's principle of expansion is certainly to be preferred.

With $\chi = 142°$ and formula (2) or the table we find the expansion age

$$T_x = 72 \text{ million years.}$$

This age is not incompatible with the observed luminosities of the stars. There are no stars of spectral type earlier than B0 in the group and the visual absolute magnitude of the brightest ones is about −4.5. The maximum ages estimated on the basis of the chemical composition of the atmosphere[1]) are of the same order of magnitude as T_x. A possible exception may be the star ζ Ophiuchi (see below).

The theory applied here is based on the assumption that the initial motions were isotropic. We do not know whether this assumption is correct for the Scorpio-Centaurus group. A marked preferential direction for the largest initial velocities may lead to a direction of elongation different from the direction χ for the isotropic case. This possible difference introduces some uncertainty in connection with the above determination of T_x.

With this value of the time elapsed since the beginning of the expansion and with the dimensions of the group as represented in Figure 5a, we find that the

[1]) See A. UNSÖLD, *Z. f. Ap.* **24**, 278 (1944).

FIGURE 5a

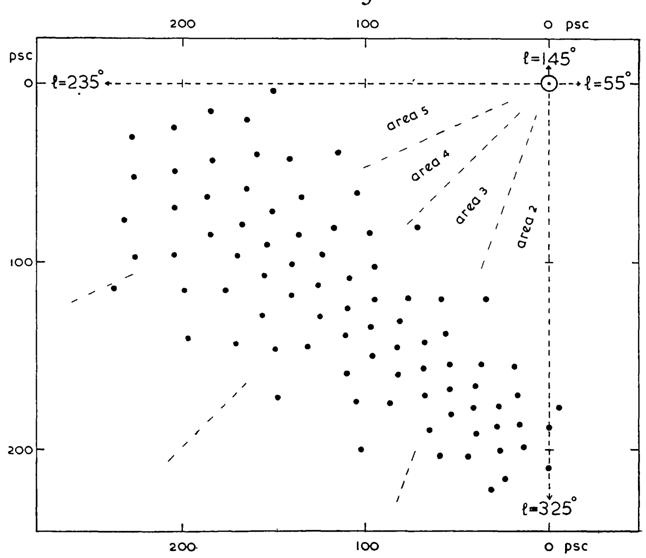


FIGURE 5b

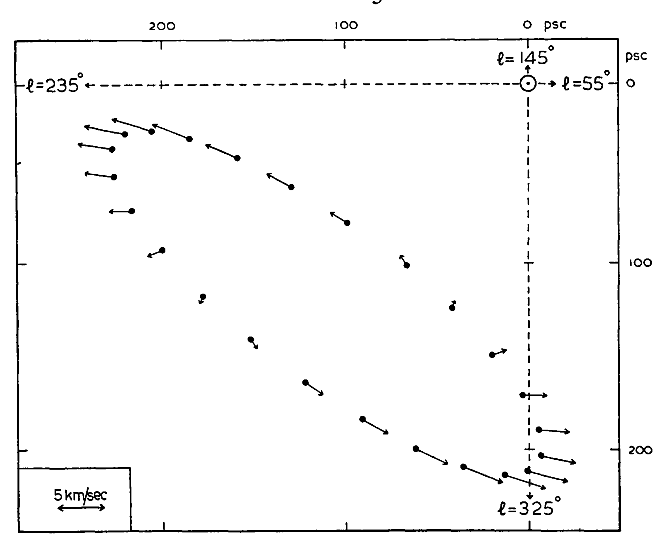


Fig. 5a: The main body of the Scorpio-Centaurus group projected on the galactic plane according to *Gron. Publ.* No. 52, page 79. The centre of the co-ordinates is at the sun. Fig. 5b: The elliptical configuration for the expansion age $T_x = 72$ million years and $s_0 = 1$ km.sec^{-1}, for which the orientation and dimensions resemble those of the Scorpio-Centaurus group. Arrows represent the relative internal velocities with respect to the centre of the configuration. The scale of the velocities is indicated at the lower left-hand corner.

initial velocity of expansion for the stars at the periphery must have been 1.0 km.sec^{-1}. The mean velocity of expansion parallel to the galactic plane must have been about

$$\bar{s}_0 = 0.7 \text{ km.sec}^{-1}.$$

Figure 5b represents the configuration of the 24 stars for $s_0 = 1.0$ km.sec^{-1} and $T_x = 72$ million years. The position of the centre of the group has been chosen to be the same as that in Figure 5a. With the adopted values of T_x and s_0 we can compute the relative velocities of the 24 stars with respect to this centre. These are represented by the arrows in Figure 5b. The scale of these velocities is indicated in the lower left-hand corner. The largest relative velocities are 4.9 km.sec^{-1}.

The character of these relative velocities is such, that there should be a noticeable mean motion of the extreme parts of the group relative to each other. This relative motion is mainly in the direction of elongation. Viewed from the sun the group may be divided into the four parts separated by the galactic longitudes 260°, 280°, and 305°; these four parts then correspond to the four areas 2, 3, 4, and 5 indicated in Figure 5 (page 41) of *G.P.* 52. The directions of these areas are also indicated in Figure 5a of the present paper. The component of the mean motion relative to the centre of the group in the direction of the line of sight as viewed from the sun is estimated to be about + 0.4, − 0.2, + 0.6 and + 3.1 km.sec^{-1} for areas 2, 3, 4 and 5, respectively. For the tangential components we find + ″/a.0033, + ″/a.0009, − ″/a.0007 and − ″/a.0015, respectively. The effect in the radial velocities should be observable, when comparing area 5 with the other areas, as soon as more accurate radial velocities are known and the separation of group- and field stars has been improved. The detection of the effect in the proper motions in galactic longitude is hampered by the possible presence of systematic errors in the proper motions, as the stars are scattered over a very large interval of right ascensions and declinations, and also by the uncertainty in the distances of the various parts of the group.

The internal motions within each of the areas will be hardly observable. The average residual radial velocity within an area on the assumption that the mean initial velocity $\bar{s}_0$ is 0.7 km.sec^{-1} should be about 0.4 km.sec^{-1} in areas 2 and 5, and about 0.1 km.sec^{-1} in areas 3 and 4. In *G.P.* 52, page 52, a value of 2 km.sec^{-1} was derived for the root mean square residual radial velocity. This is not incompatible with the above estimates, considering the large uncertainty inherent to the determination in *G.P.* 52.

The predicted average residual proper motion with respect to the mean as far as it is due to the internal motions in the tangential direction is at most ± ″/a.002 (in areas 2 and 3). It will be practically impossible to separate this from the dispersion in the proper motions due to the dispersion of the distances of the group stars in an area (see Table 19 of *G.P.* 52).

The region of the galaxy where the group was formed can be found from the observed mean motion of the group (which is the motion of its centre) and the expansion age T_x. For that purpose we introduce a rotating system of co-ordinates ξ, η with the centre at the point where the group originated. The components of the relative motion of the group with respect to the field stars in the region of the group are then

$$\dot{\xi}_{rel} = S_0 \left[\beta \cos \Phi \sin \varkappa T_x + \sin \Phi \cos \varkappa T_x\right]$$

$$\dot{\eta}_{rel} = \frac{S_0}{\beta} \left[\beta \cos \Phi \cos \varkappa T_x - \sin \Phi \sin \varkappa T_x\right],$$

where S_0 is the mean initial velocity of the group and Φ the direction of this velocity (see *G.P.* 52, p. 90). S_0 and Φ being found, we can compute the co-ordinates ξ and η of the centre of the group after the interval of time T_x and hence inversely compute the position of the point of origin with respect to the group and with respect to the sun. According to *G.P.* 52, page 65, we have

$$\dot{\xi}_{rel} = -\ 6.9 \text{ km.sec}^{-1} = -\ 7.1 \times 10^{-6} \text{ ps. year}^{-1}$$

$$\dot{\eta}_{rel} = -\ 9.5 \text{ km.sec}^{-1} = -\ 9.7 \times 10^{-6} \text{ ps. year}^{-1}.$$

We find that the group originated at the distance of 2200 parsecs from the present position of the sun in the direction of galactic longitude 26° (Vulpecula-Sagitta), and that its mean velocity S_0 at that time was 19 km.sec^{-1} in the direction $\Phi = 87°$, that is approximately in the direction outward from the galactic centre. In this computation a small correction has been applied in connection with the fact that the distance of 2200 parsecs is not sufficiently small compared with the distance of the galactic centre, to permit calculations based only on the first approximation theory of the relative orbits. The adopted correction takes into account the curvature of the η-axis along a circle around the galactic centre.

In the preceding computations we only considered the motions parallel to the galactic plane and the form of the group as projected on this plane. In the discussion of the third co-ordinate, z, two observations merit particular attention: the thickness of the group in the direction perpendicular to the galactic plane and the inclination of the group on this plane.

For a star moving with the velocity Z perpendicular to the galactic plane the amplitude of the oscillations with respect to this plane will depend on the value of Z for $z = 0$, denoted by Z_0, and on the force perpendicular to the galactic plane $K(z)$ as a function of z.

According to OORT's investigation[1]) of $K(z)$ in the region around the sun, the period of the oscillations for stars with Z_0 below 15 km.sec^{-1} is about 84 million years. The stars of the group accordingly have not yet completed one oscillation. The scattering of the stars in the z-direction will depend on the exact phase in the period of oscillation, and it would be premature to derive this from the still uncertain data about the period of oscillation and the time T_x. We estimate that for stars for which the initial velocities Z differ by 2 km.sec^{-1} (twice the maximum expansion velocity s_0) the maximum difference between the co-ordinates z must be of the order of 30 parsecs, which is not incompatible with the thickness of the group as judged from Figure 5 in *G.P.* 52.

The inclination of the group with respect to the galactic plane seems at first sight incompatible with the assumption of isotropic initial motions; the mean distances of the extreme parts of the group from the galactic plane being about + 60 and − 10 parsecs. However, as was pointed out to me by Dr J. H. OORT, this difference in the distances z may be due to a difference in phase in the oscillating z-motions arising from a difference in the function $K(z)$. For stars at the distance z from the galactic plane the force $K(z)$ is due for about two thirds to the matter within a cylinder perpendicular to this plane and with radius $2z$. Thus, the regions of the galaxy which determine the force $K(z)$ for the stars which at present are in the extreme parts of the group, practically do not overlap.

Small-scale irregularities in the density distribution of interstellar matter and other objects with strong galactic concentration therefore will highly influence the force $K(z)$ at the small distances z with which we deal here. If we assume the density to differ by, say, 30% for the extreme regions of the group, which are about 300 parsecs apart, the periods of oscillation will differ by about 15%. This may give rise to a difference in phase in the oscillations large enough to explain the observed differences in the mean distances from the galactic plane.

These small-scale irregularities in the density do not affect the motions in the ξ, η plane which, as is well known, are governed mainly by the forces due to the galaxy as a whole.

[1]) *B.A.N.* No. 238 (1932).

A rediscussion of the observational data based on the proper motions, the radial velocities, the spectroscopic and the colour data, which may lead to improved information about the properties of the Scorpio-Centaurus group, has not been attempted in the present paper, as various observational programmes supplying these data are at present being carried out at different observatories. A rediscussion of the individual stars is therefore also postponed, but an exception may be made for the star ζ Ophiuchi. This star (HD 149757 = GC 22332, $m = 2.70$, Sp O9.5, $E_1 = +{}^{m}.13$) which is situated at $l = 334°.1$, $b = +22°.1$ has the accurately determined proper motion $\mu_l \cos b = +{}^{''/a}.025$, $\mu_b = +{}^{''/a}.005$. Contrary to the proper motions of the early-type stars in general, this proper motion is opposite to the direction toward the solar anti-apex. The star apparently possesses a rather high peculiar velocity. If we assume $m_0 - M = 5.8$ (corresponding to the visual absolute magnitude $M_v = -4.0$), the velocity after elimination of the standard solar motion derived from the proper motion in galactic longitude amounts to + 31 km.sec^{-1}, and that from the proper motion in galactic latitude to + 6 km.sec^{-1}. The radial velocity is not well determined[1]); after elimination of the solar motion we find − 5 km.sec^{-1} ± 8 (p.e.). The position of the star on the sky is near the most northern end of the Scorpio-Centaurus group (see *G.P.* 52, Figure 5, page 41). From this position and the direction of its motion we infer that it is quite possible that this star also originated somewhere in the Scorpio-Centaurus group. If it was formed in the centre of the group, we find that its age should be of the order of 3 million years. An accurate determination of the star's radial velocity and hence of its space motion might help in deciding the question of its relation to the Scorpio-Centaurus group.

[1]) *Publ. Lick Obs.* XVIII (1932).

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