Stellar Motions (Council report on the progress of astronomy)

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STELLAR MOTIONS

The domain of stellar motions has not recently yielded striking new aspects. Nevertheless, important advances have been made, which, in the following, will be illustrated by some typical examples, while it will also be attempted to give a brief survey of present knowledge. The principal new data of observation which have become available in the last few years are summarized in the first section. It is to be noted that the present review is not, even approximately, to be considered as a complete report on the very great amount of work done in this field in recent years.

A very complete and welcome survey of the methods used in the discussion of stellar motions and the dynamics of star-systems has just become available in Smart's book on *Stellar Dynamics* (Cambridge, 1938). The same subject has likewise been treated in von der Pahlen's extensive *Lehrbuch der Stellarstatistik* (Leipzig, 1937), which also contains ample information on the results of observation.

I. *Observations*

By the preparation of the *Dritter Fundamentalkatalog des Berliner Astronomischen Jahrbuchs* * a considerable improvement has been achieved in the accuracy of fundamental proper motions.

A vast material of new data on proper motions has become available through the publication, in 1938, of the General Catalogue prepared at the Dudley Observatory, Albany, and containing the motions of 33,342 stars (among which are all those brighter than the seventh magnitude).

For fainter stars the material obtained by the re-observation of the *Astronomische Gesellschaft Catalogues* is gradually increasing. For the parts of the sky from $-2°$ to $+1°$, $+20°$ to $+30°$ and $+50°$ to $+60°$ declination the repetition has been completed and published by the Yale Observatory. These catalogues give proper motions of about 40,000 stars, complete to $9^{m}\cdot0$ BD, and with probable errors ranging from $\pm 0''\cdot005$ to about $\pm 0''\cdot010$ according to the declination zone. The Astronomische Gesellschaft, which has taken up the entire re-observation of the northern hemisphere, is making rapid progress; the Yale Observatory has completed the reductions for the zones between $-10°$ and $-20°$, and is working on the zones from $-2°$ to $-10°$ and $-20°$ to $-30°$. The part of the sky south of $-30°$ is being observed by the Cape Observatory, which has already published a catalogue of rather accurate proper motions for 20,000 stars down to $9^{m}\cdot5$ CPD and situated between $-40°$ and $-52°$ declination.† The whole

* I. Teil: *Veröff. Astr. Rechen-Inst.*, Nr. 54, 1937; II. Teil: *Abh. Preuss. Ak., Phys.-math. Klasse*, Nr. 3, 1938.

† *Proper Motions in Zone Catalogue*, Royal Observatory, Cape of Good Hope, 1936.

repetition, when finished, will yield the proper motions of some 200,000 stars.

A large amount of work has been done on the proper motions of still fainter stars. Van de Kamp and Vyssotsky* have determined proper motions of 18,000 stars in 341 small regions, down to an average limiting magnitude of 12·4 visual. The average probable error is $\pm 0''\cdot 0057$ for the relative motions. Each field was centred on a bright star, selected from Boss's P.G.C., and usually reduced to the tenth magnitude by a rotating sector; by the aid of the known proper motion of this star the motions of the faint stars were reduced directly to the system of the General Catalogue. A second, still considerably larger undertaking was that of the determination of about 33,000 proper motions at the Radcliffe Observatory,† started as part of Kapteyn's Plan of Selected Areas. The Radcliffe Catalogue contains very accurate motions (average probable error $\pm 0''\cdot 0037$) for stars down to $15^{m}\cdot 0$ to $15^{m}\cdot 5$ pg. In this case it is the *relative* motions to which the greatest importance should be attached.

Our knowledge of large proper motions has been very greatly enlarged by Luyten's exhaustive survey on the Harvard Bruce plates.‡ This survey, which covers almost the entire southern hemisphere, has yielded over 90,000 proper motion stars. The reductions have been completed for the declinations south of -55°, while in addition all motions in excess of $0''\cdot 45$ per annum have been reduced. The latter material is practically complete to $14^{m}\cdot 5$ pg.; part of the data are complete even to $16^{m}\cdot 5$. The individual data have not yet been published. For stars down to about $18^{m}\cdot 0$ Oosterhoff § has published a list of 651 proper motions found on Mt. Wilson plates of the Selected Areas.

Since the appearance of Moore's General Catalogue,|| radial velocities have been published for about 2000 stars not contained in that catalogue, in addition to duplicate observations for many other stars. The most interesting additions relate to special types of stars, such as δ Cephei and RR Lyrae variables, R- and N-type stars, early-type stars showing interstellar lines, and to the nebulæ.

The following list comprises, I hope, all the more extensive publications containing radial velocity data not included in Moore's catalogue.

R. O. Redman, "The galactic rotation effect in some late-type stars," *Publ. Dominion Obs. Victoria*, **6**, 27, 1931.

V. A. Albitsky and G. A. Shayn, "Radial velocities of 343 stars," *Publ. Poulkovo*, II/**43**, 1933.

W. E. Harper, "The radial velocities of 477 stars," *Publ. Dominion Obs. Victoria*, **6**, 151, 1933.

R. F. Sanford, "Radial velocities of the stars of spectral classes R and N," *Ap. J.*, **82**, 202, 1935; *Mt. Wilson Contr.*, No. 525.

* *Publ. McCormick Obs.*, **7**, 1937.
† *Radcliffe Catalogue of Proper Motions in Selected Areas*, 1934.
‡ *Publ. Obs. Minnesota*, **2**, No. 5, 1938.
§ *Ap. J.*, **83**, 340, 1936; *Mt. Wilson Contr.*, No. 542.
|| *Lick Publ.*, **18**, 1932.

F. K. Edmondson, "The motions of the globular clusters and the galactic rotation," *A.J.*, **45,** 1, 1935 (contains unpublished velocities for 8 globular clusters, measured by Humason and Slipher).

M. L. Humason, "The apparent radial velocities of 100 extra-galactic nebulæ," *Ap. J.*, **83,** 10, 1936; *Mt. Wilson Contr.*, No. 531.

W. E. Harper, "The radial velocities of 917 stars," *Publ. Dominion Obs. Victoria*, **7,** 1, 1937.

P. W. Merrill, R. F. Sanford, O. C. Wilson and Cora G. Burwell, "Intensities and displacements of interstellar lines," *Ap. J.*, **86,** 274, 1937; *Mt. Wilson Contr.*, No. 576.

A. H. Joy, "Radial velocities of Cepheid variable stars," *Ap. J.*, **86,** 363, 1937; *Mt. Wilson Contr.*, No. 578.

R. F. Sanford and P. W. Merrill, "Radial velocities of some early-type stars," *Ap. J.*, **87,** 517, 1938; *Mt. Wilson Contr.*, No. 591.

W. H. Christie and O. C. Wilson, "The radial velocities of 600 stars and measures of 69 spectroscopic binaries," *Ap. J.*, **88,** 34, 1938; *Mt. Wilson Contr.*, No. 593.

W. S. Adams and A. H. Joy, "A list of stars with unpublished radial velocities greater than 75 km./sec.," *P.A.S.P.*, **50,** 214, 1938.

A. H. Joy, "Radial velocities of 67 variable stars of the RR Lyræ type," *P.A.S.P.*, **50,** 302, 1938.

H. Mineur, "Sur la rotation galactique des amas ouverts, etc.," *Ann. d'Astrophysique*, **1**, 269, 1938 (contains some unpublished velocities of open clusters, measured by Trumpler).

At Harvard, Bok and McCuskey have given a new impetus to the determination of radial velocities of B-, A-, and F-type stars by means of objective prisms and neodymium screens.* They have succeeded in improving the accuracy of these velocities; their further development of this method, which may prove of much importance for the exploration of the galactic system, is awaited with considerable interest.

II. *Interpretation of Observations*

Solar Motion and Differential Motions.—The determination of the Sun's motion from radial velocities has been the object of numerous investigations. I will mention only the study by Nordström † as the most comprehensive work on this subject, in which much material has been added which was not available at the time when Mineur and his collaborators published similar investigations.‡ The motion of 20 km./sec. towards $\alpha = 18^h\ 0^m$, $\delta = +30°$, which has often been adopted as a standard, has been generally confirmed. The different types of stars show slightly varying values, but the deviations may well be of accidental character, except possibly for the bright B-stars, and also for dwarfs and special types of stars where the asymmetry of the high velocities causes systematic deviations.

* *H.A.*, **105,** 327, 1937.
† *Lund Meddel.* II, No. 79, 1936.
‡ *B.A.*, **6,** Fasc. 9, and **7,** Fasc. 8.

In studies of solar motion stars in different parts of space are now often studied separately, in order to determine the relative systematic motions of different parts of the galactic system. These systematic motions have usually been found consistent with a rotation of the galaxy around a centre in 325° longitude, though there are certainly some local deviations from this simple scheme. The most notable of the local deviations is perhaps that connected with the so-called K-term of the bright B-type stars. Nordström, for example, finds from 464 Oe5 to B5-stars K = 4·6 km./sec. ± 0·3 (p.e.).* According to Plaskett and Pearce † the systematic error due to relativity shift will be only + 1·3 km./sec., so that an unexplained motion of + 3·3 km./sec. remains. After correcting the B-star motions for the solar motion as usually adopted for the bright stars in general, Plaskett and Pearce noted that especially large positive deviations remained in the region of the great southern group of B-type stars between 210° and 330° longitude, which had previously been studied by Kapteyn. This group, which includes the so-called Scorpio-Centaurus cluster, would have a systematic motion of about 8 km./sec. with respect to the centroid of the bright stars, and this would be the main cause of the large K-effect and of the somewhat deviating solar motion found for the B-stars. The existence of local systematic motions differing slightly from the general average would not be surprising in view of the existence of the pronounced inequalities in the space distribution of these early-type stars. ‡ According to computations by Smart, Nordström and by Lall §, who remark that the vertex was not derived correctly, there would be a considerable difference between the group motion as indicated by the proper motions on one hand and the radial velocities on the other hand, so that they reject the stream. However, as it is well known that considerable systematic errors may exist in the southern proper motions, the objections made to Plaskett and Pearce's plausible explanation of the K-term may, after all, not be insuperable.

The investigations at Victoria on early-type stars and interstellar gas, which were concluded by the publication of the general study of the motions of O- and B-stars just quoted, constituted a very considerable gain in our knowledge of relative motions in the galaxy. The same can be said of Merrill and Sanford's || recent investigation of the interstellar gas, in which numerous new observations of distant stars have been added, the velocities being derived from the K-line of Ca^{+} as well as from the D-lines of sodium. The most distant group of stars included is at about 2000 parsecs (*cf.* fig. 3, *loc. cit.*).

The most important contribution has been made by Joy ¶ who has studied the velocities of 128 δ Cephei variables. In his most distant group

* *Loc. cit.*, p. 90. *Cf.* also Mineur and Guintini, *B.A.*, **8**, 255, 1934.

† *Publ. Dominion Obs. Victoria*, **5**, No. 4, p. 277, 1936.

‡ It is to be noted that the effect of this group would naturally divide itself over the solar motion and the K-term.

§ *M.N.*, **99**, 42, 1938.

|| *Ap. J.*, **87**, 118, 1938; *Mt. Wilson Contr.*, No. 585.

¶ *P.A.S.P.*, **45**, 202, 1933. Individual data in *Ap. J.*, **86**, 363, 1937; *Mt. Wilson Contr.*, No. 578. See also *Publ. Kapteyn Lab. Groningen*, No. 47, p. 3.

the systematic deviations from the motion of the stars near the Sun run up to values from 40 to 55 km./sec. Three out of the four longitudes with maximum deviation are covered by the observations; the variation with the longitude agrees very well with the double sine-curve of ordinary differential rotation.

The data of differential rotation so far available had mostly been derived from types of stars showing a strong concentration towards the galactic plane and having small peculiar motions; the only exceptions were formed by the planetary nebulæ and the N-type stars. The data available for the latter were, however, so meagre as to be of little significance. Quite recently these have been very considerably extended through the work of Sanford,* who finds good evidence of the galactic rotation among these rather distant stars.

Summarizing that part of our knowledge concerning the systematic motions in the galactic system which appears to be firmly established, we may state that up to the distances of the farthest Cepheids observed, that is, to an average distance of about 2500 parsecs in the galactic plane, the observed motions are well represented by the first order terms of the differential galactic rotation. Though the most southern part of the sky contains only few observations, the interval from 271° to 193° longitude, or nearly 80 per cent. of the galactic circle, including the four regions of maximum differential effect, is well covered.

From a purely kinematical point of view the observed differences in radial motion can, of course, be interpreted in different ways (see articles by Pilowski,† Mineur,‡ Ogrodnikoff§ and Milne‖). But, if the knowledge of these differential motions is combined with all other knowledge about the galactic system, the interpretation as the effects of a simple rotation around the centre of this system appears to be the most probable. But for some minor deviations which are plausibly described to local irregularities, all the facts observed are well represented by this model. So far as present observations of systematic motion go, there do not appear to be any well-defined effects for which a generalization of the simple representation would be required.

In this connection it should be mentioned that in discussions of radial velocities of bright stars Mineur and others have previously found evidence of a change of the systematic motion with the positions of the stars with respect to the galactic plane. The same phenomenon is found in Nordström's article, the apex derived from stars of northern and southern latitudes differing by about 14° (*loc. cit.*, Table 22 and p. 109). However, as no corresponding shift is found in the space velocities it is doubtful what significance can be attached to the phenomenon.

From a combination of existing data on rotation Plaskett and Pearce (*loc. cit.*, p. 281) derive $325°{\cdot}4 \pm 1{\cdot}1°$ (p.e.) for the *longitude* l_0 *of the centre* of rotation. Adding Joy's determination, $l_0 = 324°$, and the value $l_0 = 329°$

* *Ap. J.*, **82**, 202, 1935; *Mt. Wilson Contr.*, No. 525.

† *Zs. f. Ap.*, **3**, 53, 279, 291 and **4**, 396, 1931–32.

‡ Cf. *B.A.*, **5**, 505, 1929.

§ *Zs. f. Ap.*, **4**, 190, 1932.

‖ *M.N.*, **95**, 560, 1935.

found by Merrill and Sanford, to the list given by the Victoria observers, there appears to be very strong evidence for the identity of the rotational centre and the material centre of the galactic system. The longitude of the latter can be found in two entirely different ways: in the first place from the distribution of globular clusters, from which it is estimated as $325° \pm 2°$ (p.e.); in the second place from the distribution of faint stars at great distance from the galactic plane, which gives $324° \pm 3°$ (p.e.).* The close agreement is important, as it indicates that the systematic motions are perpendicular to the radius vector, and not inclined, as they would be in case they followed spiral orbits. The longitude derived also agrees with the direction perpendicular to the systematic motion of objects of high velocity, for which Strömberg † found 331°, and Oort 325°,‡ the p.e. being estimated at about $\pm 3°$ in each case.

The *distance to the centre*, R_0, can best be estimated from the distribution of globular clusters. If the effect of absorption is taken into account and the evidence is combined with that derivable from the motions of globular clusters, nebulæ and other high velocity objects, it may, in my opinion, be safely concluded that the distance is not less than 6000 and not more than 10,000 parsecs. Provisionally, we might adopt $R_0 = 8000$ parsecs.

As regards *the constant A*, various determinations yield considerably different results. The determination is complicated by the fact that fundamental distances are needed to find the constant. These distances can only be derived from proper motions, which are reliable only for the nearer groups of bright stars where the effect of the rotation is small and disturbed by local motions. The method followed, then, is to estimate mean distances of the fainter groups by assuming that the mean absolute brightness is the same as, or can be derived from, that of the bright groups. But here a new difficulty comes in, as the light of the distant stars is dimmed by absorption. In Plaskett and Pearce's work the absorption has been neglected. Introducing an average absorption of $1^{m}\cdot 0$ (visual) per 1000 parsecs between the bright and faint groups used by these authors, a weighted average $A = \cdot 0182$ km./sec. parsec is found from their Tables 21 and 22. This agrees closely enough with independent values derived from δ Cephei variables by Joy ($A = \cdot 0185$) and from *c*-stars brighter than $5^{m}\cdot 8$ ($A = \cdot 023$). Determinations from proper motions only, yield an uncertain, but entirely independent value of $0''\cdot 0026$ or 0·0123 km./sec. parsec.§ We may provisionally adopt $A = \cdot 018$.

For the constant *B* we might adopt $-0\cdot 013$ km./sec. parsec or $-0''\cdot 0027$, as derived directly from proper motions (see below) as well as from the ratio of the galactic axes of the velocity-ellipsoid.‖ The resulting angular velocity

* *B.A.N.*, **8**, 263, 1938.

† *Ap. J.*, **61**, 377, 1925; *Mt. Wilson Contr.*, No. 293.

‡ *B.A.N.*, **4**, 270, 271, 1928.

§ Average of determinations by Plaskett and Pearce, *loc. cit.*, Oort, *B.A.N.*, **4**, 86, and Wilson and Raymond, *A.J.*, **47**, 56, 1938.

‖ *Cf.* the complications in *B.A.N.*, **8**, 154, 1937, and in *A.J.*, **47**, 56 (Wilson and Raymond).

of rotation $B-A$ is $-0''\cdot 0065$, while the average rate of change of the circular velocity Θ_c with distance to the centre, $\partial\Theta_c/\partial R = -A-B$, is $-0\cdot 005$ km./sec. parsec.

The linear *velocity of rotation* is equally uncertain as the distance to the centre. With the angular velocity just adopted the value corresponding to $R_0 = 8000$ parsec would be 248 km./sec. The latest direct determination from 26 globular clusters by Edmondson* gives 274 km./sec. $\pm$ 40 (p.e.), while from the nearest extra-galactic nebulæ a value of 365 ± 70 (p.e.) has been derived. An entirely independent determination may be obtained from a combination of the rate of decrease of density with R in the system of globular clusters, and the average peculiar velocity of these objects. Using Edmondson's data for the average peculiar velocity and van de Kamp's data † for the density gradient the acceleration near the Sun may be estimated at $2\cdot 5 \times 10^{-8}$ cm./sec.², from which we derive $\Theta_c = 250$ km./sec. This estimate is admittedly uncertain, but the uncertainty is probably not larger than that of the more direct determinations.

The problem of *second-order terms* in the differential rotation has been discussed by several authors. It may be useful to make a distinction between two causes determining the appearance of these terms. In a system with rotational symmetry deviations from the simple double-harmonic formula will firstly occur for geometrical reasons, the zero-points of the differential velocity near 55° and 235° longitude being shifted in the direction of the centre of the system. If this shift is denoted by ϕ we have evidently $\sin\phi = r/R_0$, where r is the distance of the stars considered. The shift is, of course, independent of the way in which Θ_c varies with R. Deviations from linearity in the latter variation will show themselves primarily as differences in the amplitude of the rotational term between the quadrants near the centre and those near the anti-centre. It is not possible to predict in which direction the difference would go. Moreover, for the present, it seems a hopeless task to approach this latter effect from the observational side, as any observed asymmetry of the kind mentioned might as well be ascribed to a systematic difference in absorption between the centre and the anti-centre regions. As regards the shift ϕ, this would amount to about 9° for the most distant group of stars for which somewhat precise data are accessible (Joy's faintest Cepheids); a shift in the right direction seems indeed to be indicated in this case for the zero-point near 55° longitude, but the data are insufficient to make a significant estimate of the amount. We may conclude that, even for the Cepheid data, there is not much need for introducing second- or higher-order terms. For the open clusters the situation is decidedly less favourable for finding evidence of these higher-order terms.

It is possible that higher-order effects are present in the motions of the planetary nebulæ, but the interpretation of this case is still uncertain. Ogrodnikoff, treating all nebulæ together without separating them according to distance, finds evidence of fairly small second-order terms,‡ but as the

* *A.J.*, **45**, 2, 1935. † *A.J.*, **42**, 161, 1933.
‡ *Poulkovo Circ.*, No. 21, 1937.

individual velocities are large and the number of objects small, the determination is admittedly uncertain. Berman,* and more recently Camm,† have separated the nebulæ according to their distance. Berman derives distances which for many of these nebulæ are of the order of 10,000 parsecs or more, thus extending to the galactic centre and beyond. These large distances would be confirmed by the radial motions. It is clear that these results, if substantiated, might yield information of the greatest importance concerning the structure of the galactic system. Berman has taken pains to discuss very carefully all data at his disposal. However, the main argument leading to these very large distances, viz. the practical identity in absolute magnitude and dimensions of the faint and bright planetaries, combined with the assumption that the diameters are not influenced by galactic absorption, is not convincing. It may be remarked that the observed radial velocities for each of Berman's 4 groups can be practically equally well represented upon the assumption of much smaller distances, for which only first-order terms would be relevant. If, on this assumption, the mean distances are derived in the usual manner from the coefficient of $\sin 2(l-l_0)$, values of 1200, 1700, 1700 and 3700 parsecs are found for Berman's first 4 distance groups,‡ while Berman derives 854, 2638, 4722 and 9130 parsecs respectively. Similar objections may be made against Camm's discussion. There is also other evidence indicating that the distances assumed are too large. The case is evidently uncertain.

Motions of Objects of High Velocity.—Radial velocities for 67 RR Lyræ variables have been published by Joy §; by this publication the number of known velocities has been increased by 150 per cent. From the new data the following constants for the solar motion may be derived: 130 km./sec. ± 14 (p.e.) directed to $\alpha = 297°$, $\delta = +52°$ or $l = 53°$, $b = +12° \pm 8°$ (p.e.). The direction agrees well with that of the rotation. The average residual velocity of ± 69 km./sec. is nearly as large as that of the globular clusters. Some of the stars appear to possess exceptionally high velocities, ranging up to 400 km./sec. with respect to the galactic centre. With improved values for the proper motions, which will be available in the near future, these stars may give interesting information in yielding a lower limit for the velocity of escape from the galactic system.

* *Lick. Bull.*, **18**, 57, 1937. † *M.N.*, **99**, 71, 1938.

‡ The use of radial velocities for estimating the distances is criticized by Camm. We may note, however, that the values of the coefficient, $\bar{r}A$, are of the same order as those found by Joy for the faint δ Cep variables (see *Publ. Kapteyn Lab. Groningen*, No. 47, p. 3). The latter data, which are considerably more accurate than those for the planetaries (on account of the smaller peculiar velocities and the better knowledge of absolute magnitudes), indicate clearly that the corresponding distances are still small compared with the distance to the centre. Using a reasonable estimate of the absorption they also indicate that up to the $\bar{r}A$-values concerned this coefficient varies in an approximately linear way with the distance, and is, therefore, probably a reliable indicator of the mean distance.

In the case of the planetaries some uncertainty arises, however, from the circumstance that the peculiar velocities are fairly high, so that the systematic motions might differ somewhat from the circular motions.

§ *P.A.S.P.*, **50**, 302, 1938.

Distribution of Peculiar Motions.—The motions of the bright stars have been treated by various authors. Perhaps the most important fact, long known, but strongly confirmed by recent investigations, is the deviation of the major axis of the velocity-ellipsoid from the direction to the centre of the galactic system. From an investigation of the radial velocities of stars brighter than $6^{m}{\cdot}0$ Nordström, for instance, finds $340° \pm 3°$ (p.e.) for the longitude of the vertex. The earlier determinations from proper motions had given 346°, thus deviating still more from the adopted centre. There can be not much doubt that this deviation is real. There are indications, however, that the fainter dwarfs do not show it; according to an unpublished investigation by Veldt of the space motions of the nearest stars, the longitude for dwarfs fainter than $+5^{M}$ is found at $326° \pm 1°$ (p.e.). A similar direction seems to be indicated by the preferential motion among high-velocity objects.

The inequality in the distribution of the stars over the two streams, which was found by Eddington in his analysis of the Boss stars, has not been confirmed from radial velocities (see an article by Smart).* Nor has a similar inequality been found among fainter stars.

A new feature found in Nordström's paper is that the peculiar motions of faint O–B5-stars, contrary to those of bright stars of these types, show a decidedly ellipsoidal distribution, the ratio of the two galactic axes being 0·59, and the major axis pointing to 304° longitude. It should be noted, however, that the phenomenon is complicated, in this case, by the large effects of galactic rotation.

The most important advance has come from investigations of faint stars. Among other investigations we may mention Know-Shaw and Scott Barrett's discussion of the Radcliffe motions,† and van de Kamp and Vyssotsky's study of motions of stars on parallax-plates.‡ Smart and Tannahill § have added new material to the notable investigations in this direction published at the Cambridge Observatory in the past. Stenquist || has determined magnitudes, spectra and luminosities for faint stars in the Cambridge regions, and has discussed the motions in relation to these new data. Luyten has published an investigation of 85,000 faint southern stars with motions exceeding $0''{\cdot}050$ per annum.¶ Jackson ** has analysed a large material of proper motions down to $10^{m}{\cdot}5$ pg. in the zone $-40°$ to $-52°$.

From these investigations, in particular from that by Knox-Shaw, which extends to 15^{m}, it has become once more clear that the phenomenon of star-streaming extends unaltered up to large distances (up to 1500 parsecs for the Radcliffe data). The vertex derived from the faint stars shows a similar deviation from the direction of the centre as that from bright stars,

* *M.N.*, **96**, 165, 1936.

† *Radcliffe Catalogue of Proper Motions in the Selected Areas 1 to 115*, 1934.

‡ *Publ. McCormick Obs.*, **7**, 1937.

§ *M.N.*, **98**, 563, 1938.

|| *Upsala Meddel.*, No. 72, 1937.

¶ *H.A.*, **105**, 397, 1937.

** Proper Motions in the Zone Catalogue of 20,843 stars observed at the Royal Observatory, Cape of Good Hope, 1936.

though the amount of the difference becomes probably somewhat smaller. For stars from $9^{m}\cdot0$ to $14^{m}\cdot0$ the Radcliffe Catalogue gives a mean vertex at $l=336°$, $b=-4°$, for stars between $14^{m}\cdot1$ and $15^{m}\cdot0$, $l=332°$, $b=+1°$, with p.e.'s of not more than $\pm 2°$. Using mean proper motions instead of the distribution of position angles Blaauw * derived $l=322°\cdot7 \pm 2°\cdot3$ (p.e.) from the same material. Van de Kamp and Vyssotsky, with rather brighter stars, find, however, $l=346°$, $b=+4°$. From the Cambridge regions Smart and Tannahill find $l=337°$, $b=-1°$; the material extends perhaps to 12^{m} pg.

Van de Kamp and Vyssotsky, as well as Jackson, have found independently that the longitude of the vertex derived from stars at high galactic latitude is about 10° lower than that for stars near the galaxy.

The ratio of the axes of the velocity-ellipsoid has been found to be about the same as that determined from bright stars. After correcting roughly for the influence of accidental errors van de Kamp and Vyssotsky found 0·63 for the ratio of the major axis to the average of the two other axes. Similarly, from the Radcliffe material, Blaauw found 0·60 ±·03 (p.e.) for the ratio of the two galactic axes.

From the Radcliffe motions another new point of much interest for dynamical considerations may be inferred, namely, that for regions near the galactic plane the average peculiar velocity does not appear to vary in an important degree throughout the large part of the galactic system covered by these observations.†

Motions in Interstellar Gas.—It has been shown by Beals ‡ that the interstellar lines in ρ Leonis as well as in ϵ and ζ Orionis are double. The result holds both for sodium and calcium, which show identical values for the individual velocities of the two main clouds that are apparently involved, the difference in velocity between the two clouds being respectively 29, 14 and 26 km./sec. Similar differences, ranging up to values of 47 and in one case even 68 km./sec., have been reported by Sanford, Merrill and O. C. Wilson § for seven other stars. It was already known that in some cases the interstellar gas exhibits a peculiar velocity which cannot be due to galactic rotation. Also, this gas appears to extend to considerable distances on both sides of the galactic plane,|| differing in this respect rather radically from the early-type stars, and perhaps resembling more nearly the distribution of late-type giants. This also indicates that there must be fairly large peculiar velocities in the gas. The general existence of separate clouds with considerable peculiar motions may also be concluded from the fact that at greater distances the intensity-ratios in the doublets, D_2/D_1 and K/H, are much smaller than 2, while at the same time the absolute intensities appear to increase linearly with the distance, and show no variation with galactic longitude. The interpretation of these facts with the aid of separate clouds

* *B.A.N.*, **8**, 311, 1939.

† *B.A.N.*, **8**, 83, 1936.

‡ *M.N.*, **96**, 661, 1936; also *Ap. J.*, **87**, 568, 1938.

§ *P.A.S.P.*, **50**, 58, 1938, and *Report Mt. Wilson Obs.*, 1937–38, p. 26.

|| *Cf.* Sanford, *Ap. J.*, **86**, 136, 1937; *Mt. Wilson Contr.*, No. 573. Also Oort, *Annales d'Astrophysique*, **1**, 79, 1938.

has, I believe, first been suggested by Beals ; * it has been worked out in considerable detail by O. C. Wilson and Merrill.† The dimensions of the individual clouds may be of the order of 200 parsecs, but the evidence on this point is somewhat conflicting. No explanation has yet been offered for how the individual motions of these clouds could be maintained, notwithstanding the circumstance that they must be continually penetrating and dissolving into each other.

Internal Motions in Clusters.—From data derived from intercomparison of, on the average, 39 pairs of plates taken with Carte du Ciel instruments, Hertzsprung ‡ has succeeded in finding some evidence of internal motions among members of the Pleiades between $8^m{\cdot}3$ and $11^m{\cdot}6$ pg. Titus § has recently published results of still considerably higher accuracy for the brighter Pleiades. He finds a mean square internal motion of $\pm 0''{\cdot}00079$ per annum in one co-ordinate (the average mean error of his motions is $\pm 0''{\cdot}00046$). Assuming a parallax of $0''{\cdot}011$ the mean square velocity in one component is found to be $\pm 0{\cdot}34$ km./sec., and the total mass is estimated from this as 260 solar masses, of which approximately 200 can be accounted for by known stars in the cluster.

Schilt and Titus ‖ have likewise derived internal motions in Praesepe, for which van de Kamp ¶ had previously indicated the existence of such motions. In this case again, the results derived at the Rutherfurd Observatory, with the aid of plates taken by Rutherfurd as early as 1870, are of an unrivalled accuracy. The true mean square motion is found to be $\pm 0''{\cdot}00080$ or 0·53 km./sec. in each co-ordinate.

These are the first instances in which internal motions have been found in clusters. It is much to be hoped that it will be possible to add to this knowledge by spectroscopic measures of the presumably very much larger internal velocities in globular clusters, as these data, and the masses which might be derived from them, would evidently be of the greatest value in the study of the dynamics of these objects.

Mean Parallaxes of Faint Stars.—In addition to contributing to the knowledge of the velocity distribution at large distances, the great material of motions of faint stars has been of importance for the determination of the mean parallaxes of these distant stars. Van de Kamp and Vyssotsky ** on the one hand have mainly utilized the v-components for determining secular parallaxes. As their fields were centred on bright Boss stars, the brightness of which had been reduced by a rotating sector, the mean motions of the faint stars could be directly referred to the system of Boss's Catalogue. The Radcliffe material, on account of its small and well-determined accidental errors, lends itself extremely well to a determination of mean parallaxes

* *M.N.*, **96**, 661, 1936; also *Ap. J.*, **87**, 568, 1938.
† *Ap. J.*, **86**, 44, 1937; *Mt. Wilson Contr.*, No. 570.
‡ *B.A.N.*, **7**, 187, 1934.
§ *A.J.*, **47**, 25, 1938.
‖ *A.J.*, **46**, 197, 1938.
¶ *Ap. J.*, **81**, 297, 1935.
** *Publ. McCormick Obs.*, **7**, 1937.

from the dispersion of the proper motions; * all uncertainty arising from eventual systematic errors remaining in the fundamental motions is then avoided. An attempt has been made to determine also the distribution of the stars in space from the distribution of proper motions, but a still higher accuracy of the individual motions will be required for making much progress in this direction.

For details concerning this subject reference may be made to the articles mentioned.

Proper motions of bright stars have played an important part in deriving the distribution of their distances and absolute magnitudes. This subject, on which extensive investigations have been made by Strömberg, Gratton and several others, has, however, been considered to lie outside the domain which the present note was intended to cover.

Constant of Precession.—New determinations of the constant of precession and the constant B of galactic rotation have been made by Plaskett and Pearce, van de Kamp and Vyssotsky, Oort, and Raymond and Wilson. For the results the reader may be referred to the study by Wilson and Raymond,† which is the most recent one. All these investigations from proper motions indicate a correction of about $+0''\cdot010$ per annum to Newcomb's constant of precession and about $+0''\cdot011$ for the correction needed by the proper motions in right-ascension based on Newcomb's equinox. These corrections have not, however, been used in the new fundamental catalogues. Recent results for the constant B of galactic rotation obtained in these same investigations are fairly accordant, and indicate a mean value of approximately $-0''\cdot0027$.

III. *Dynamics of Stellar Systems*

On the theoretical side attention has been given mainly to the study of the spiral structure of extra-galactic nebulæ, while in our own system the deviation of the vertex has been a main incentive to further researches. There are, of course, several other observational phenomena which have not been satisfactorily explained, such as the fact that the system of globular clusters does not partake in the rotation of the galactic system, that massive objects like long-period and RR Lyræ variables show so large a dispersion in their velocities, and that a number of O-type stars show peculiar radial velocities between 40 and 70 km./sec. which, if real, must be almost exactly parallel to the galactic plane, etc. Though references have been made to the first-mentioned problems, *e.g.* by Strömberg ‡ and by Lindblad, § their theories, which tie up these questions with the birth of the galactic system, are of necessity vague and do not yet seem to permit much further progress.

* van Hoof, *B.A.N.*, **8**, 67, 1936; Oort, *B.A.N.*, **8**, 75, 1936.

† *A.J.*, **47**, 56, 1938.

‡ *Ap. J.*, **79**, 460 and **80**, 327, 1934; *Mt. Wilson Contr.*, Nos. 492 and 503. See also a criticism by Gustafson and Nordström, *Zs. f. Ap.*, **10**, 228, 1935, and the answer by Strömberg, *ibidem*, p. 234.

§ *M.N.*, **94**, 231, 1934.

The Galactic System.—In a rotating system in strict dynamical equilibrium the distribution of peculiar velocities at each point should show rotational symmetry around an axis coinciding with the velocity of rotation. In case of small peculiar motions the major axis of the section of the velocity-ellipsoid with the galactic plane should point to the centre of the system, and this axis should be equal to the axis perpendicular to the galactic plane. Neither of these conditions is fulfilled in the galactic system. The axis perpendicular to the galactic plane is considerably smaller than the major axis in the plane, the ratio between the two varying with the type of stars; and there is a considerable deviation between the galactic major axis and the direction to the centre. There appears to be no reason to worry much over the first-mentioned difference. Various authors have pointed out that, if the actual conditions in a very flat system like our own are examined more closely, it appears that in such a system an inequality between the two axes referred to is entirely compatible with the condition of approximate dynamical equilibrium.* Chandrasekhar has recently worked out this problem in some detail.†

The outstanding problem is the explanation of the deviation between the longitude of the principal vertex and that of the centre of the galactic system. While at first there seemed to be the possibility that the deviation might be only a local effect, the fact that almost all investigations of faint stars, even up to average distances of 1500 parsecs, showed a similar deviation made it evident that the deviation is a large-scale phenomenon. On the other hand it is well to remember that not all objects show the phenomenon in the same measure: the fainter dwarfs, the stars at high galactic latitude, and in general the objects of high velocity appear to give an approximately normal position for the vertex.

The observed deviation of the vertex-line proves that either the conditions in the galactic system differ considerably from that of dynamical equilibrium, or that there are large-scale deviations from rotational symmetry.

Various attempts have been made to gain an insight into the significance of the deviation. It is, of course, quite possible to construct a dynamical picture of the galactic system in which the vertex-deviation is represented, but the physical side of the problem, viz. finding a connection between this phenomenon and other data, and gaining an insight into its causes, proved to be considerably more difficult, and I think it cannot yet be said that an altogether satisfying explanation has been found. The analogy with spiral nebulæ and the appearance of the K-term in the radial velocities of bright B-stars have led some investigators to examine the properties of an expanding stellar system. It is easy to see that in an expanding system the direction of the centre as derived from the effects of differential motion will not coincide with that of the true centre, and that also other deviations from the steady-state conditions will arise. A discussion of the effects of such an expansion upon the rotation terms has been given in articles by Pilowski, Ogrodnikoff and Milne already referred to, while a similar generalization applicable to the distribution of peculiar motions, and thus

* See for instance Lindblad, *M.N.*, **96**, 71, 1935. † *M.N.*, **98**, 710, 1938.

also to our present problem, has been discussed by Shiveshwarkar.* It is difficult, however, to identify the models discussed with the galactic system, the principal objection being that, apart from the expansion shown by the bright B-stars (which is most likely due to slight group motions), the radial velocity observations, even of very distant stars, show no evidence of the existence of an expansion.

Recently, attempts in a somewhat different direction have been made by Lindblad,† which it may be of interest to examine in some detail, in connection with the possible existence of a spiral-like structure in the galactic system. Lindblad remarks that the process of condensation of gaseous and meteoric material into stars which probably takes place in a stellar system may give rise to the development of regions of instability, surrounding the much flattened inner parts of the system, so that stars moving in circular orbits near the outer edge of the flattened core will, by a slight disturbance, start off in spiral-like orbits lying outside the original core. The region where circular motions are unstable extends from the edge of the core to a certain distance R_1. The orbits corresponding to the disturbed circular motions in the unstable region may, however, extend to considerable distances beyond R_1, say to a maximum distance R_2, after reaching which they would gradually return to the edge of the core.

Lindblad has made the original suggestion that such a region of unstable circular motions might exist in the galactic system somewhat inside our distance from the centre, and that the Sun would be situated between R_1 and R_2, *i.e.* in a region where circular motions are stable, but which is traversed by the asymptotic orbits starting from the edge of the strongly flattened core. It would then be not unreasonable to suppose that, in addition to stars moving more or less at random, we should observe more or less parallel streams composed of stars emanating from the edge of the central core. There would be an in- and out-going stream of such stars, which would probably come from widely different points on the circumference of the core, so that it would be plausible to suppose that the two streams might have somewhat different moments of momentum and energies, thus causing a deviation of the vertex-line. In order that these streams, which would be composed of stars with more or less equal motions, be effective, they should comprise a considerable fraction, say half, of the stars in our neighbourhood. Lindblad notes that the moving clusters in Taurus and Ursa Major might be considered as the cores of such streams; it should, however, be remarked that the stars as a whole show little evidence of their belonging to two distinct streams of this kind. It is also to be noted that, in any simple model of the galactic system, the existence of an inner

* *M.N.*, **95**, 655, 1935. See also *M.N.*, **96**, 749, 1936. See also Heckmann, *M.N.*, **96**, 67, and Lindblad, *M.N.*, **96**, 71, 1935.

† *Stockholms Obs. Ann.*, **12**, No. 4, 1936; also an article in the *Östen Bergstrand Festskrift*, 1938. Both papers contain a review of Lindblad's recent work on the dynamics of stellar systems in general, together with extensive references to the recent work of others. I may refer the reader to the first-mentioned article for a great many details which cannot be treated in the present note.

region of unstable motions, from which the "asymptotic" orbits extend beyond the Sun, would appear to be accompanied, in our neighbourhood, by a fairly strong decrease of the circular velocity with R, which it seems difficult to reconcile with the very slight decrease, of about ·005 km./sec. parsec, actually observed.* It may be, however, as Lindblad has remarked, that the streams are but remnants of orbits originated from former unstable regions which at present are no longer important.

Perhaps the most plausible interpretation of the vertex-deviation might be obtained by dropping the idea that the galactic system has rotational symmetry. Recent investigation of the distribution of density in the galactic system has indicated large-scale unevenness in the distribution of stars. An intimate connection must necessarily exist between the characteristics of the distribution of density in the surrounding of the Sun and the characteristics of the distribution of peculiar motions (while, at the same time, the systematic motions of B-type stars, etc., need not be disturbed). From this point of view it is hardly surprising to find that the vertex deviates somewhat from the position it would have if the density distribution were entirely regular. The density data are, however, by no means sufficiently accurate to establish a correspondence with the observed vertex-deviation.

The occurrence in our neighbourhood of extensive local groups of early-type stars, which groups are of such loose structure that it seems unlikely that they could be held together against the disturbing influence of the galactic gravitational field, proves that the galactic system is in some respects still far from a steady state. From the known effects of differential rotation we can estimate that an agglomeration of the kind of the southern group of B-stars could not have existed in something like its present form during much more than 10^8 years, or half of a revolution of the galactic system. It is fairly certain that the age of the galactic system is much higher and we would have to conclude, therefore, that either the assumption that the wide B-star groups are not held together by gravitation is wrong or that these stars are of much more recent formation than the majority of the stars in the galactic system.

The problem of the stability of groups of stars and of open clusters has been fully discussed by Bok,† while more recently a mathematical treatment of the subject has been given by Mineur.‡ Bok concludes that groups become unstable if their density falls below about one-tenth of the mass of the Sun per cubic parsec; clusters of lower density are rapidly disrupted by the general gravitational field of the galactic system. Those of higher density will at first disintegrate much more slowly by the effect of encounters, as has already been pointed out in classical papers by

* Calculations based on simple schematic models give values of the order of ·015 to ·018 km./sec. parsec for this quantity. Lindblad now informs me that he has made calculations for a more complicated model, in which the core contains a ring-shaped formation; this model would give a better agreement with the observations.

† *H.C.*, No. 384, 1934.

‡ *Comptes Rendus*, May 31, 1937, p. 1620.

Jeans and Eddington. From the conditions of existing clusters Bok estimates that 2×10^{10} years represents a reasonable upper limit to the age of the galaxy.

Extra-galactic Nebulæ.—The deviations from a smooth state indicated in the preceding are by no means peculiar to the galactic system, but are found in the majority of extra-galactic systems; they are usually exhibited on a very large scale in the spiral structure of these systems.

It is not improbable that an insight into the cause and the dynamics of the spiral structure, which is probably shown by all systems of a flattening comparable to that of the galactic system, would at the same time enable us to a much better understanding of the dynamics of our own system, and *vice versa.* But at present this does not yet seem to be the case. Though a great deal of work has been done on the subject of spiral structure and some notable progress has been made (in recent years especially by Lindblad, Vogt, Lambrecht, Bucerius), the problem is of such complexity that it has not been possible, except in a few special cases, to deal with it in a quantitative manner. Apart from the intricacy of the problem and the circumstance that we know nothing of the initial conditions, there is the difficulty that except for the shape of the arms there are very few observational data to build on. The measures, recently made by Humason * on Mount Wilson and by Horace W. Babcock † at the Lick Observatory, of the rotational velocity in various regions of a few elliptical and spiral nebulæ are, therefore, of the greatest importance.

The lack of quantitative knowledge about the dynamics of spiral structure may typically be illustrated by the fact that it has not been possible to obtain agreement about the sense of the rotation of spiral nebulæ with respect to the direction in which the arms are wound. Nevertheless, the investigations carried out must certainly be considered to be of great value in preparing the way for a successful attack. An adequate discussion of the progress already made is, however, outside the scope of the present note.

J. H. OORT.

* *Report Mt. Wilson Obs.*, 1936–37, p. 31.

† *P.A.S.P.*, **50**, 174, 1938.