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VIII. GALACTIC DYNAMICS

Theoretical problems of galactic dynamics received much attention. The centre of interest was the question of the number of independent integrals of motion, in particular the form and properties of the third integral.

Lynden-Bell (1) has pointed out that only the obvious integrals of energy and angular momentum have been considered while there are five integrals in all. He has considered the role of the neglected integrals and showed that certain classes of integrals should indeed be omitted. He further (2) has devised a method for the discovery of models for unrelaxed, self-gravitating, axially-symmetrical, steady-state stellar systems and developed (3) the dynamical theory without the aid of the restrictive ellipsoidal hypothesis. For many forms of the potential the local integrals were derived and tabulated. Idlis (4) has shown that there exist three and only three independent integrals and (5) offered a new proof of the symmetry with regard to the equatorial plane of a system with a continuous phase density and with the third integral quadratic in velocities. Dynamics of a non-steady-state galaxy with a potential allowing the

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three-axial ellipsoidal velocity distribution of motion was developed by Genkin (**6**). Models of axially symmetrical self-gravitating systems for the case when the phase density is a function of the first two integrals of motion were constructed by Kuzmin and Kutuzov (**7**). The properties and applications of the third integral were discussed by Kuzmin (**8**), van de Hulst (**9**), Contopoulos and Barbanis (**10**), Contopoulos (**11**), Goudas and Barbanis (**12**) and Hori and Liu (**13**). Contopoulos reports on several papers in preparation concerning the commensurabilities of the oscillations in two perpendicular dimensions, the third integral in non-smooth potentials (together with Woltjer) and the tables of plane galactic orbits (together with Strömgren).

Methods developed for plasma physics were applied to stellar dynamics by Sweet (**14**). He treated the interstellar gas as a hydrodynamic fluid and the stars as a collisionless gas.

Kreiken (**15**, **16**) has represented stellar systems by polytropic gas spheres. The density distribution within the system of globular clusters was found to correspond to that of a polytropic sphere with $n = 5$. This index is assumed to hold for many stellar systems (**17**). The expressions for the effects of galactic rotation, derived by Kreiken, were generalized by Kizilirmak (**18**).

The influence of a slow change of the regular gravitational forces and of irregular forces on velocity dispersions was investigated by Kuzmin (**19**).

Vetesnik (**20**) discussed stars with known space velocities and found that the frequency distribution of the energy integral is of the Gaussian type with an insignificant asymmetry. Only RR Lyrae stars have a different distribution of the energy integral. About 20% of these stars may exceed the velocity of escape.

Some basic unsolved problems of galactic dynamics and possible methods of their solution were discussed by Ogorodnikov (**21**).

Galactic Orbits

Three-dimensional galactic orbits were investigated by Ollongren (**22**). The computations show that in the galactic field of force there is no conversion between the two meridional components of the motion. Empirical evidence is brought forward for the existence of a third integral of motion. In particular, the so-called box orbits were discussed which have the property that their meridional trajectory fills a region in the meridional plane having the shape of a box with rectangular corners.

Galactic orbits in the plane of symmetry and inside a spheroid with a Schmidt density-law were discussed analytically by Perek (**23**). The relation between the apsidal rotation and the stability of circular orbits was studied. Abalakin (**24**) has studied periodic orbits of stars inside a heterogeneous ellipsoidal stellar system with the density falling off from the centre along a parabola.

General behaviour of the motion of a star was discussed by Hori (**25**) in a model of the Galaxy which represents closely the Schmidt potential and admits a separability of the Hamilton-Jacobi equation. Expressing stellar motions by a generalized Keplerian motion, Hori and Liu (**26**) studied orbits with high eccentricity.

Woolley (**27**) has pointed out that if a group of stars is detected in the solar neighbourhood which had a common origin in time and in place, one would see a selection of the original group. The selection would be such that the stars had a common velocity component in the direction of galactic rotation. The older the group, the sharper the selection.

An expression giving zero for a circular orbit, a unity for a straight line orbit, and reducing to the usual definition of eccentricity e for a mass point attraction, was suggested by Lynden-Bell (**28**) as a definition of the invariant eccentricity of galactic orbits.

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Stellar motions perpendicular to the galactic plane were investigated by Shimizu (**29**). The orbits were classified into three classes, the first two corresponding to resonances. The resonances are made responsible for the development of the inner structure of a galaxy into a spiral or barred form. Contopoulos and Bozis (**30**) have considered perturbations due to the ellipticity of a galaxy. They found the perturbations in radius vector and position angle negligible for time intervals of 10^7 years.

The distribution function of the orbit elements based on the ellipsoidal velocity distribution and on Parenago's expression for the potential was tabulated by Dzigvashvili (**31**). The distribution of eccentricities was investigated by Bonnino and Missana (**32**), But (**33**) and Dziewulski (**34**). A strong correlation between the eccentricities and the observed ultra-violet excess was found by Eggen *et al* (**35**). Stars with the largest excess are invariably moving in highly elliptical orbits, whereas stars with little or no excess move in nearly circular orbits. The data require that the oldest stars were formed out of gas falling toward the galactic centre in the radial direction and collapsing from the halo onto the plane. The collapse was very rapid and only a few times 10^8 years were required for the gas to attain circular orbits in equilibrium. Shimizu and Takahashi (**36**) found an age effect in the parameters of galactic orbits.

Mass and Potential

A method for estimating surface densities from the observed rotation curve was suggested by Belton and Brandt (**37**). The discrepancies between the surface densities computed from the rotation curve and those computed from the z-force analysis were explained by insufficient knowledge of the rotation curve exterior to the Sun and by simplifying assumptions in the z-force analysis. A theory of the analysis of rotation curves by means of a series of spheroidal homoeoids compressed into a disk was developed by the same two authors (**38**).

The problem of the distribution of mass in stellar systems similar to the Galaxy was discussed by Perek (**39**). A survey of galactic models based on the distribution of either velocities or mass is given.

Lohmann (**40**) has applied the virial theorem to 70 globular clusters and derived the mass of the Galaxy of $2 \cdot 1 \times 10^{11}$ solar masses with an estimated accuracy of 20%. Brandt's (**41**) estimate is 4 to 7×10^{11} solar masses from the fact that the sizes of the nearby dwarf galaxies are determined by the tidal action of the Galaxy and 2 to 4×10^{11} solar masses from a comparison with other Sb galaxies. A distance $R_0 = 10 \cdot 5$ kpc follows from the above estimates.

Nahon (**42**) has devised a method for deriving the velocity of escape from the Galaxy based on the velocity distribution. Extremal values of the velocities lead, according to Massonie (**43**), to a difference between the velocity of escape and the circular velocity of 86 km $\sec^{-1}$.

In a discussion of the distribution of mass in the Galaxy Schmidt (**44**) arrived at the following values: $A = 15$ km $\sec^{-1}$ kpc^{-1}, $B = -10$ km $\sec^{-1}$ kpc^{-1}, $R_0 = 10$ kpc. The density of mass near the Sun falls off as R^{-4}. If this holds throughout the outer parts of the Galaxy, then the total mass becomes $1 \cdot 8 \times 10^{11}$ solar masses. The escape velocity near the Sun is 380 km $\sec^{-1}$, or 130 km $\sec^{-1}$ more than the local circular velocity, 250 km $\sec^{-1}$. The well-known high-velocity cut-off in the direction of rotation of 63 km $\sec^{-1}$ cannot correspond to the escape velocity.

Attraction Perpendicular to the Galactic Plane

Hill (**45**) determined K_z from K-type giants and derived a density at the Sun of 0·13 solar masses per pc^3. His values were made consistent with the Poisson equation by Oort (**46**) and the corrected density of 0·15 was derived. Eelsalu (**47**) drew attention to the effects of possible unreliability of the material underlying the above determinations. Yasuda (**48**) studied the kinematics of high-velocity stars at large distances from the galactic plane. He derived the

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force K_z and the density at the Sun of 0·15 solar masses per pc^3. Using a relation between the density, Oort's constants and the z-dispersion, Jones (**49**) discussed the distribution of A0 stars perpendicular to the galactic plane and derived a density of 0·14 in the same units. Sinzi (**50**) found from proper motions and the dispersion in radial velocities of the cepheids a density of 0·11.

Emoto (**51**) investigated the z-motion quite generally. He found that the motion of stars in nearly circular orbits is quite stable. On the other hand, the amplitude of the perpendicular motion of stars with small rotational velocities increases rapidly with time. A fairly great amount of stars with small rotation seem to have obtained large amplitude even if they were moving originally in the galactic plane.

The velocity distribution perpendicular to the galactic plane was studied by Rudnicki (**52**) and Kolkhidashvili (**53**) who found a non-gaussian distribution.

Dynamics of Spiral Structure

Spiral structure is closely connected with many other dynamical problems. In order to reconcile the spiral structure as derived from the Leiden and Sydney observations, Kerr (**54**) introduced an outward velocity component of 7 km sec^{-1} for the Sun and the local centre of rest. Genkin (**55**) obtained two almost symmetrical spiral arms for $K = -2$ km sec^{-1} kpc^{-1}. He showed that the galactic law of rotation permits a relatively long lifetime of the arms as logarithmic spirals. Schmidt-Kaler and van Schewick succeeded in separating the gas belonging to the spiral arms from that of the associations. Three definite spiral arms were located at 0·5, 1·6 and 2·9 to 3·6 kpc with a fourth dubious arm at a larger distance.

Rutgers (**56, 57**) applied Maxwell's criterion for the stability of Saturn's rings to the Galaxy. He found that stars oscillate around the centroid with increasing amplitudes. This leads to radial condensations and through the agency of the differential rotation to the formation of spiral arms.

Stability of elliptic rings, the influence of gas clouds and magnetic fields on the formation of spiral arms and the possibility of an approximately steady spiral structure in galaxies was investigated by Lindblad (**58, 59**). The theory points out the dynamical importance of matter returning towards the system in the outermost spiral arms and the capacity of a trailing arm to capture matter in its surroundings. Attention is directed especially to the anticentre direction where in-going motions are shown by various results for the 21 cm line. Höglund (**60**) traced branches of obvious deviations from circular motion. It seems possible that these may be proceeding inwards towards the Perseus arm. The possible presence in our neighbourhood of systematic motions outwards as well as inwards is of interest for the investigation of star streaming in our surroundings and for explaining the vertex deviation.

Gravitational instability is capable of explaining the origin of condensations which lead to the formation of spiral arms according to Pacholczyk (**61**). These considerations give also an upper limit of the magnetic field of 4×10^{-6} gauss (**62**). Stodolkiewicz (**63**) investigated the gravitational instability which limits the lifetime of the Perseus arm. The persistence of spiral structure was already discussed by Prendergast and Burbidge (**64**). They found that the present structure cannot last more than for two revolutions. A longer lifetime for spiral arms was derived by Fujimoto (**65**) who found an upper limit of $1{\cdot}5 \times 10^8$ years. Tassoul (**66**) has investigated the combined effects of the gravitational potential and a magnetic field on the dynamics of a galaxy. The differential rotation can be affected only by the component of the magnetic field in the direction of the axis of rotation. A transversal magnetic field parallel to the plane of symmetry of the system has no effect in this respect. A possible mechanism of spiral structure formation is suggested.

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Spiral structure is frequently brought into connection with the outward motion from the galactic centre. Oki *et al* (**67**) considered a gravitational Keplerian field and a magnetic field as the initial stage. If the magnetic field is homogeneous and parallel with the galactic plane, the gas condenses into trailing spiral arms and has a radial outward component of motion. Grzedzielski (**68**) proposed a model of the motion of the interstellar gas in the inner regions of the Galaxy and offered a possible explanation of the spiral structure by means of the mechanism of coronal instability and expansion in the hydrogen principal plane.

Greyber (**69**) assumed a general dipole magnetic field with an axis coinciding with the axis of the Galaxy. He predicted a very thin galactic disk and a sporadic but continuous production of spiral arms. Pismis (**70**) suggested the following theory: In an already existing galaxy of population II stars, similar to an E galaxy, the development of a gaseous component is postulated. The gaseous subsystem possesses, and is held together by, a magnetic field, roughly represented by a centrally located dipole having its axis coinciding with the axis of the galaxy. Since the gaseous bulge rotates as a rigid body no distortion of the dipole field should occur. The spheroid will gradually contract and carry along the magnetic lines of force. The only two regions from where matter may escape, leaking out from the shrinking nucleus, are the two magnetic poles. The escaping matter will stay behind and through the differential rotation will delineate spiral arms. Their lifetime was estimated as 3×10^9 years for M 31. Thus the differential rotation, far from being destructive, may be the very agent that produces spiral structure.

Hoyle and Ireland (**71**) have shown that the outward motion of gas cannot arise unless at a greater distance from the galactic centre there is a corresponding inward motion. Later (**72**) they suggested that the halo magnetic field is primary and the spiral arm field secondary. In a model in which the lines of force of the halo cross the interarm regions of the galactic plane, it is possible for the whole interstellar medium to gain angular momentum at a comparatively rapid rate. For a field intensity in the halo of 3×10^{-6} gauss the windings move out to the periphery of the galaxy in a time scale of the order of 5×10^8 years.

There are empirical as well as theoretical reasons for a large scale circulation of the interstellar gas and its angular momentum between the halo and the galactic plane according to Wentzel (**73**). This would explain the persistence of spiral structure.

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