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Numerical computations on the ejection of stars into spiral arms from gas rings containing magnetic fields

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With 6 figures in the text

Introduction

Recent studies of external galaxies give strong indications that the formation of spiral arms in such systems is intimately related to their content of interstellar gas. Thus according to radio measurements in the 21-cm line of neutral hydrogen the elliptical galaxies seem to contain a very small amount of interstellar gas, and the percentage of interstellar gas seems to increase with advancing Hubble-type (J. H. Oort 1957).

Radio observations in the 21-cm line also have shown that the cool interstellar gas in our Galaxy is concentrated to armlike structures in the galactic plane. This result has given strong support to the idea that the spiral arms are mainly arms of gas. We must not forget, however, that the spiral arms seen in external galaxies are always arms of bright stars and interstellar dust, and that we cannot determine the detailed distribution of gas in such systems because the gas itself is invisible, and the radio observations do not permit of the high resolution necessary for an investigation of fine details. The emission patches around some of the hot stars tell us only that these stars are surrounded by gas, which is also to be expected since the hot stars were probably newly born in complexes of gas clouds. Hot supergiants without any emission regions have also been observed in the Andromeda galaxy M 31 as well as in the Milky Way indicating that the spiral arms of stars are not always identical with the concentrations of gas clouds.

According to the hypothesis developed by one of us (A E) the visible spiral arms originate in the gas but do not coincide with the structures in the gas. The spiral arms are defined as the loci of bright stars formed during the time interval of the last half revolution of the galaxy.

Since the formation of spiral structure thus seems to be a problem of gas dynamics as well, and if magnetic forces are thought to play an important role in addition to the gravitational attraction, the problem of spiral formation ought to be treated with the methods of magneto-hydrodynamics. In years to come such methods will probably be used, but for the moment so many of the parameters involved in the problem are still unknown that it seems worth while to investigate some simplified models based on a preliminary solution of the problem with less elaborate methods.

If we admit that pure stellar systems (i.e. star systems without interstellar gas) cannot develop spiral arms but that the arms are formed from structures in the gas, we are forced to admit that the motion of the interstellar medium is in some way different from the motion of the stars, since stellar and interstellar matter moving in exactly the same way should be able to arrange itself in the same pattern. If the differences in the motions are due to magnetic forces of the kind assumed in our theory, the velocity of galactic rotation will not be the same for stars and gas. It is not easy to prove that such differences occur in our Galaxy, however, since it is very difficult to determine exactly the velocity of gas clouds relative to the velocity of stars in the same region because of the different methods used in the observations of these two kinds of objects. The main difficulty is the impossibility of determining the true distances of the clouds. The observations of large scale motions show that, at least in the neighbourhood of the sun, the velocity of galactic rotation is nearly the same for the gas as for the stars. Small differences, less than 10 per cent of the velocity, are indicated. Therefore, it seems justified to consider the motion of the gas as governed to a first approximation by the same laws as the motion of the stars and to treat the differences in the velocities as small disturbances. In some galaxies this method may not give reliable results but in our Galaxy or other galaxies of a similar type it will probably lead to a good estimate of the order of magnitude of the effects.

Theory

n our first approximation we will consider a model based on stellar dynamics. In this model the only force acting on a mass point (a star, a cluster of stars or a gas cloud) is the gravitational attraction from all other masses in the system. In a stellar system with rotational symmetry the gravitational force $F(R)$ in the equatorial plane is everywhere directed toward the centre and it is a function of the distance (R) from the centre only. The function $F(R)$ will depend on the distribution of mass in the system. Since we are interested here in the development of spiral structure which will be confined to a thin layer in and near the galactic plane we will treat two-dimensional problems only, neglecting all motions or forces perpendicular to the galactic plane. Small deviations from circular symmetry due to the concentration of matter in spiral arms or elliptic rings will cause local disturbances in the gravitation field in real galaxies. Such disturbances will also be considered in our models.

B. Lindblad has treated the dynamics of stellar systems in considerable detail. In our present paper we will in particular use some of his results concerning the "dispersion orbits", i.e. orbits in the galactic plane along which dissolving clouds of stars or gas tend to disperse as a consequence of the differential galactic rotation.

If ω be the angular velocity of circular motions at the distance R from the centre in the Galaxy and $\varkappa$ the frequency of oscillation in the radius vector for an orbit in the equatorial plane which differs slightly from a circular orbit, B. Lindblad (1955, 1956, 1958) has shown that, in a coordinate system of angular speed $\omega' = \omega - \frac{1}{2}\varkappa$, the orbit in a region within 10 kpc from the centre is a dispersion orbit. Its shape is a closed oval, in the first approximation an ellipse, with its centre in the centre of the Galaxy. The frequency $\varkappa$ is

$$\varkappa = 2\sqrt{\omega(\omega - A)}$$

where

$$A = -\tfrac{1}{2} R \frac{d\omega}{dR}.$$

It has also been pointed out by Lindblad that stars and interstellar matter may be concentrated to a number of elliptical rings of this kind in a galaxy, at least during a certain phase of the evolution of the galaxy. Ring structures are also often observed in galaxies. In order to investigate the interaction of such ring structures one of us (POL) has made extensive computations on the motions of ring formations in a typical stellar system, taking into account the disturbing forces due to the attraction from the matter distributed along the ring itself. Only gravitational forces were considered. A preliminary report was given at a symposium held in Dublin in 1955. (B. Lindblad and P. O. Lindblad 1955, P. O. Lindblad 1958.)

Recently the hypothesis has been developed (A. Elvius 1958) that such ring structures are mainly built up of gas clouds and that electromagnetic forces play an important role for the stabilization of the rings as well as for the formation of spiral arms of bright stars ejected from the gas rings. In the present paper we wish to make use of the formulae and computations already at hand from the work on moving ring structures to solve some problems concerning the relative orbits of stars ejected from the gas rings according to the new hypothesis.

As mentioned above the gas clouds in the galactic plane tend to disperse along certain elliptic orbits. Magnetic lines of force connected with the clouds will then be drawn out along the ring. It must be pointed out that though the ring itself remains almost fixed in a certain rotating coordinate system, the gas moves at a rather high speed along the ring, and there will be a considerable differential motion along the ring itself. When the magnetic lines of force are drawn out along the ring, the magnetic field becomes stronger and more regular. After some time a magnetic field may exist all along the ring in such a way that we may consider the ring of gas also as a ring of magnetic lines of force. (The lines of force certainly do not run smoothly everywhere along the ring. They may be curved or twisted in several places, but they are thought to run *mainly* parallel to the ring.)

As has been shown in a recent paper (A. Elvius and N. Herlofson, 1960), the magnetic forces will then cause the ring of gas to contract until a balance is set up between the centrifugal force acting outwards in the system and the gravitation and magnetic forces acting inwards in the system towards the centre. If the magnetic field is stable and strong enough, it will keep the gas in the ring since the magnetic lines of force are "frozen into the matter" under the conditions prevailing in interstellar space. Thus the gas can move freely along the ring but not so easily across the ring. The stars, on the other hand, are not influenced by the magnetic field, and their motion is determined by the gravitational field only. If stars and gas clouds move in circular orbits at the same distance from the centre, the gas clouds must have a higher velocity than the stars to compensate for the magnetic force. If stars are formed in the gas clouds in a ring and start their motion with the velocity of the clouds, the stars will be ejected from the ring because the centrifugal force is stronger than the attraction from the centre. Stars ejected from a circular gas ring of radius R will oscillate around a new equilibrium distance $R+d$ from the centre, reaching first a distance $R+2d$. The relative increase of the distance, d/R, will depend on the ratio of magnetic to gravitational force; to a first approximation

$$\frac{d}{R}=\frac{H^2}{4\pi\varrho\,\theta_c^2}$$

where H = magnetic field, θ_c = tangential velocity in a circular orbit, ϱ = density of matter (Elvius and Herlofson, 1960).

Usually the gas rings in a galaxy are not circular, however, but slightly elliptical. The stars ejected from such elliptical orbits will move in a similar way to stars ejected from circular orbits. The differences in velocity in different parts of an elliptic orbit will cause some complications, however, and we may also wish to include the disturbances from the massive gas ring in the computations of the orbits of the stars ejected from such a ring. Therefore, we have used a few simple models of a galactic system to compute the orbits of stars ejected from an elliptic ring, using for convenience the codes already worked out by P. O. Lindblad for the electronic computer BESK in Stockholm, and introducing in parameters or initial conditions small alterations corresponding to the assumed action of magnetic forces.

Model computations

In constructing the models we have started from models of balanced elliptical rings used by P. O. Lindblad in his work (to appear in Stockholms Observatoriums Annaler). These rings consist of a number of mass points (here 48 or 64) moving under the influence of the attraction of all the other mass points in the ring and the gravitational force from the whole galaxy according to the force function computed by M. Schmidt (1956) in his final model of the Galaxy. Such rings are rather stable and do not change their form considerably in several hundred million years. In a fixed coordinate system the apsidal line of the ellipse moves with the angular speed ω'. In order to account for the influence of magnetic forces we have introduced certain changes in the parameters of the above-mentioned models. As is shown in Table 1, which contains the data concerning the general construction of our models, the changes introduced in the different models are of quite different kinds and are chosen somewhat arbitrarily. In all cases the model galaxy consists of three main

Table 1. General properties of the models used in the computations.

Model POL dispersion ring	A II	B I	C I	D I	E I
Mean radius	6.0576 kpc	8.4553 kpc			
Major half-axis a	6.7000 kpc	9.3000 kpc			
Minor half-axis b	5.3468 kpc	7.4638 kpc			
b/a	0.8	0.8			
Number of points defining the ring	48	64	64	64	64
Mass of 1 point (when defining the ring)	$16 \cdot 10^6 M_\odot$	$16 \cdot 10^6 M_\odot$	0	$16 \cdot 10^6 M_\odot$	$16 \cdot 10^6 M_\odot$
ω'_{POL} km/sec·kpc	9.6	12.61	12.19	12.61	12.61
ω' (in model A)	12.22				
Changes from POL dispersion ring	ω' increased	velocity along ring increased 15 km/sec	velocity along ring increased 15 km/sec	velocity along ring increased 10 %	force function modified
Magn. field assumed (as estimated from ΔV or ΔF)	$3 \cdot 10^{-5}$ gauss	$3 \cdot 10^{-5}$ gauss	$3 \cdot 10^{-5}$ gauss	$(2-3) \cdot 10^{-5}$ gauss	$(2-3) \cdot 10^{-5}$ gauss

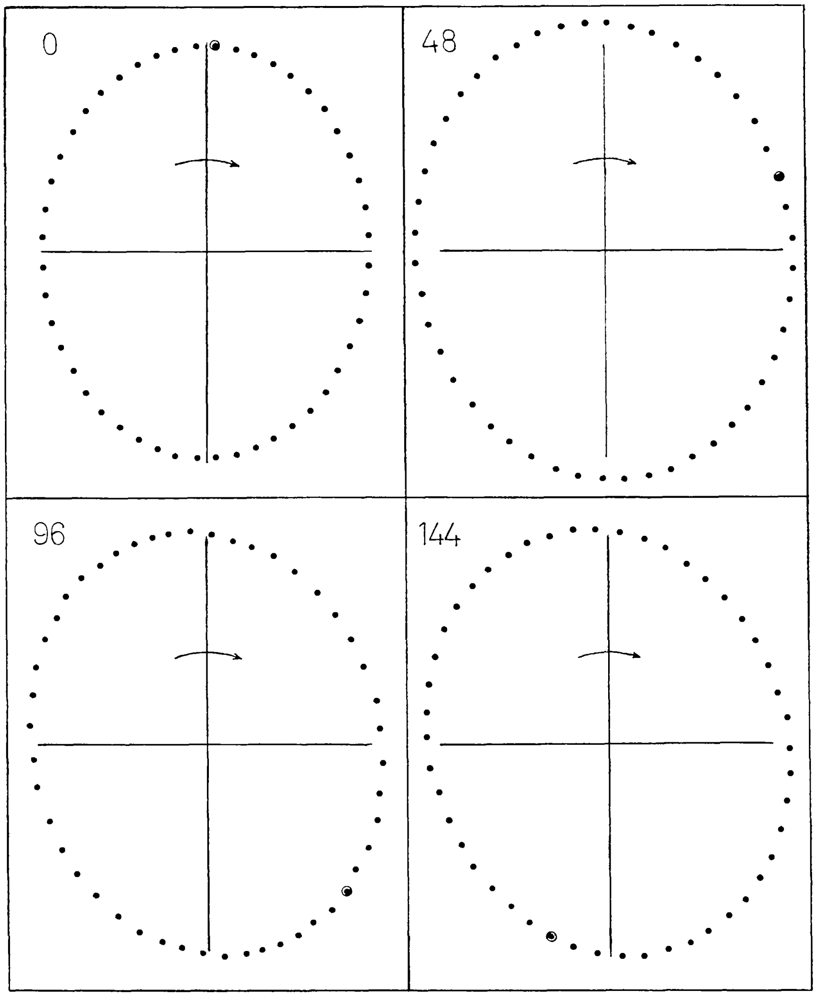

Fig. 1. Positions of the mass points of model A at the times $t=0$, 48, 96, and 144 million years in the coordinate system rotating with the angular speed 12.22 km/sec · kpc, in which the gas ring remains fixed. A point starting near the vertex is marked with a small ring to show the motion of this point.

parts: 1) the main mass of the system, represented by the force function in the computations, 2) mass points defining a massive gas ring that remains in equilibrium (i.e. the ring is fixed in the coordinate system rotating with the angular velocity ω'). In order to avoid singularities in the force function the mass points are surrounded by a zone in which the attraction increases from zero with the distance from the mass points as has been described by P. O. Lindblad in his work cited above. In all our models the radius of this zone was 1.133 kpc. 3) mass points representing stars or star clusters born in the gas ring, starting with the velocity of the gas and then moving under the influence of the general gravitation field and the attraction from the gas ring. The points representing stars (or clusters) are thought to have very small masses and do not attract each other. At $t=0$ they coincide with the mass points of the gas ring.

In the first four models we have used the above-mentioned force function given by Schmidt to define the general gravitation field in our model galaxy. The magnetic forces assumed to act on the gas ring in our model then have to be added in some way. This has not been done explicitly but in an indirect way as a certain increase in the

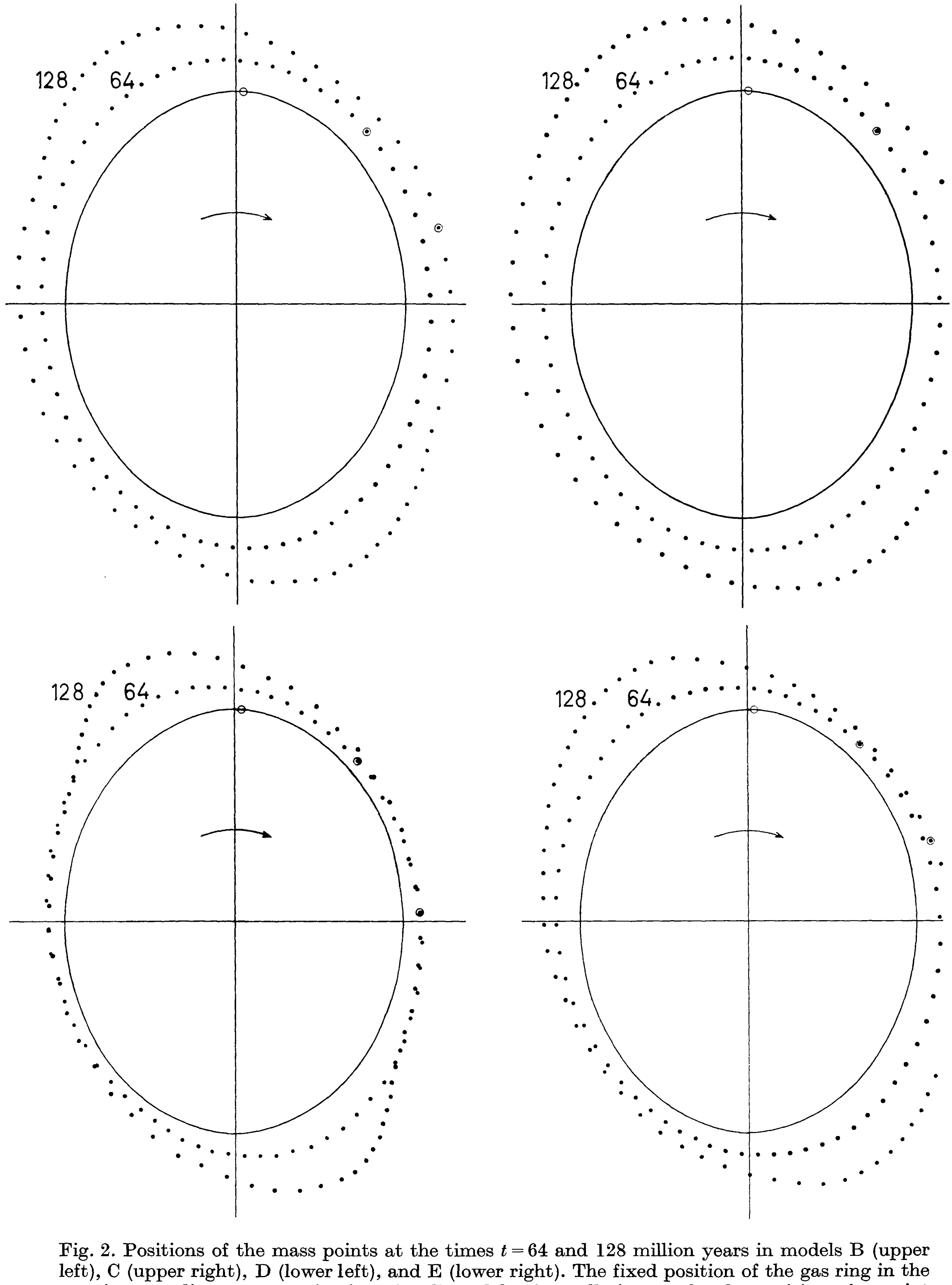

Fig. 2. Positions of the mass points at the times $t = 64$ and 128 million years in models B (upper left), C (upper right), D (lower left), and E (lower right). The fixed position of the gas ring in the rotating coordinate system is given in all models. A small ring marks the position of a point starting near the vertex.

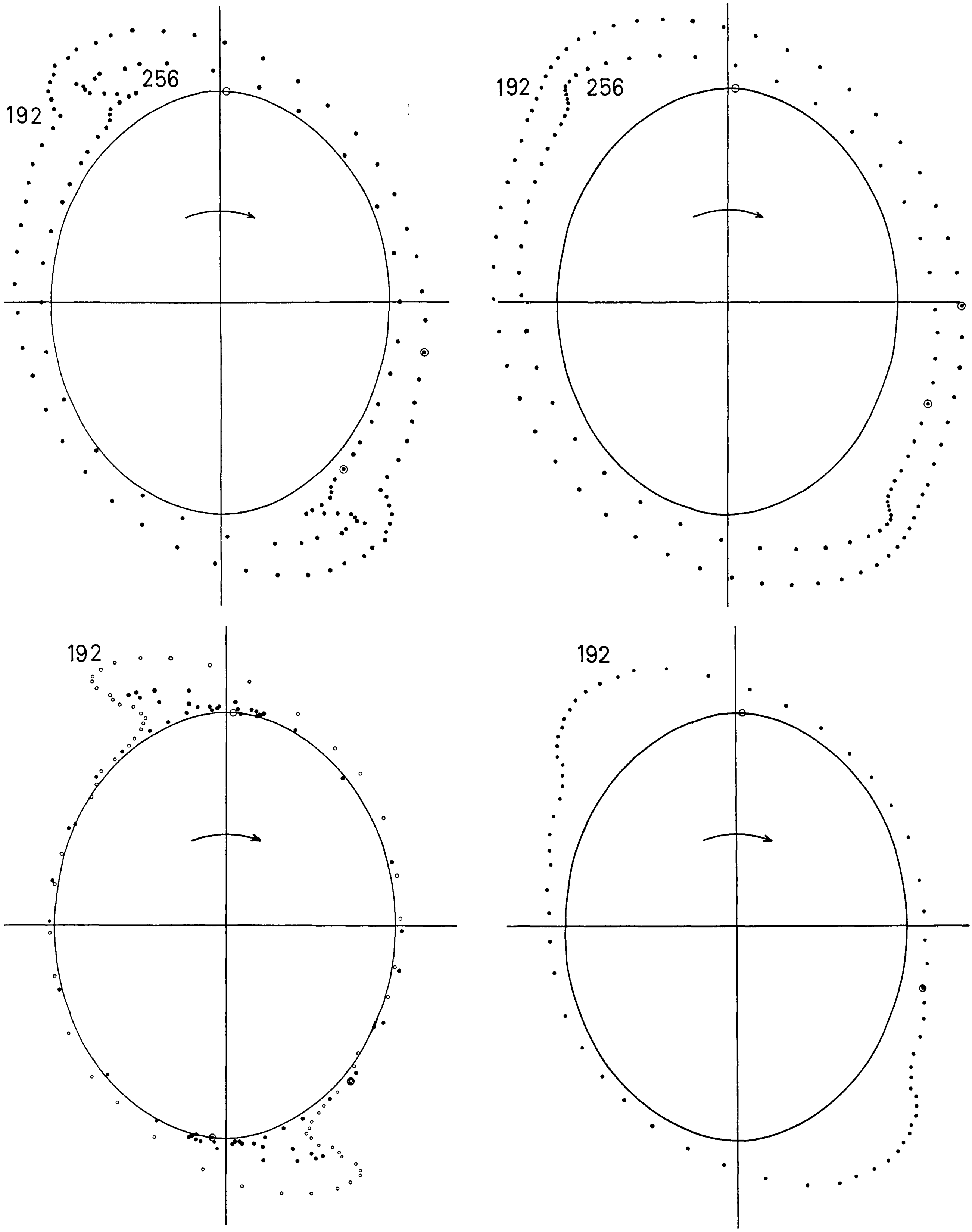

Fig. 3. Positions at $t = 192$ and 256 million years (256 not computed in model E). Models arranged as in Fig. 2.

velocity of the gas. In model A we have increased the angular speed of the rotating coordinate system, thus increasing the centrifugal force acting on all mass points. This increase of the force is proportional to the distance from the centre. In models B, C, D we have instead increased the velocity along the ellipse; in B and C a velocity of about 15 km/sec (1 kpc in 64 million years) was added to the velocity in the dispersion orbit. In model D the excess velocity is 10 per cent of the original velocity along the ellipse. (This corresponds to about 5 per cent of the velocity in a fixed coordinate system since the angular speed of rotation of the coordinate system ω' is approximately equal to $\omega/2$.) Since the velocity is considerably higher near the minor axis of the ellipse than near the vertex, the excess velocities in model D are also larger near the minor axis (cf. Table 3 giving the velocities in the rotating coordinate system at time $t = 0$). A comparison of the velocities in models B and D with the velocities in model E will show how models B and D differ from the original model of a dispersion orbit. In model C we have neglected the mass of the gas ring. Therefore the angular velocity ω' and the velocities of the points along the ring differ slightly from the corresponding values of model B. The velocities added in models A–D define the strength of the magnetic forces assumed to act in each case. Though the mapping of the exact form of the corresponding magnetic field would be complicated, we may estimate the order of magnitude of the magnetic field which is of interest here. Rough estimates of the magnetic field strengths assumed in different models are given in Table 1. In models A–D the magnetic field H is computed from $H^2 \approx 8\pi \varrho \theta_c \Delta V$, where ϱ = gas density, θ_c = circular velocity, ΔV = excess velocity. In model E we have $H^2 = 4\pi \varrho R \Delta F$, where ΔF is the difference between the force functions of Schmidt's model and model E.

Since the force function computed by Schmidt was based on the observed radial velocities of the interstellar hydrogen gas, the models A–D deviate somewhat from the conditions observed in our Galaxy but may still be appropriate in a typical spiral galaxy. In our last model E we have started with the observed velocities and used a modified function of the gravitational force. Though this method would seem to be the appropriate way to solve our problem, the present solution is only a preliminary one. The changes of the force function were made in a rather rough manner to simplify the computations, and we feel that our model ought to be based on a more far-reaching recomputation of the gravitation field to be assumed in our Galaxy if the motion of the interstellar gas is governed not only by the gravitation but also by magnetic forces. Part of the action of "unknown objects" in Schmidt's model may be interpreted as due to magnetic forces. The remaining part may be reduced by a revision of the assumed distance of the sun from the galactic centre. The possible need for such a revision has been pointed out by Schmidt himself (1958). The work on an entirely new model would be rather time-consuming, however, and must be based on further investigations into the possible strength of the magnetic forces. Therefore, we find it justified to publish these preliminary results now.

To illustrate the main results we have chosen the configuration after certain time intervals of the points representing stars born in the elliptic gas ring at time $t = 0$. Fig. 1 shows the expansion and contraction of the ring of stars in model A. The time scale is shorter in this model than in the other models because the ring is smaller. The stars will reach the maximum distance from the ring after some 50–60 million years in model A. In the other models the maximum distance is reached after 100–200 million years, the time depending on the position of the point of ejection in the ellipse. Therefore, longer time intervals have been used to illustrate the motions in models B–E in Fig. 2 and Fig. 3. The influence of different parameters may be traced by a comparison of the different models. The variation of excess velocities along the ring in model D causes a more rapid distortion of the ring of stars than is found in other models. A comparison between model C and model B shows the influence of the disturbing force due to the attraction from the points representing the massive gas ring in model B. Particularly in Fig. 3, showing the configurations after 192 and 256 million years respectively, the distortion of the star orbits is well marked in model B. The rings of stars in model B are also smaller than the corresponding rings in model C as must be expected because of the attraction from the gas ring in B. The mass of the gas ring in model B (and D, E) is probably overestimated. It is assumed to contain about 1.5 per cent of the total mass of the galaxy. The action of a less massive ring may be estimated by interpolation between the models B and C. In model E the massive ring has maximal influence because of the weakness of the general gravitation field assumed.

Even in model C where the motion of the stars is governed by the general galactic gravitation field only, the originally elliptical ring of stars will be somewhat distorted with time. In a real galaxy the motions of the stars will probably be influenced by disturbances from several spiral arms or other concentrations of matter making the orbits even more complicated than in our models. Thus the orbits of the stars ejected from one gas ring will ultimately fill a considerable space in the galactic plane (probably also above the plane in real galaxies) i.e. the aging stars will be lost in the general field of population II stars, hence the visible spiral arms are defined by the young stars only. Therefore, if we wish to use our model calculations to study some possible forms of spiral arms, we must follow the orbits of stars ejected from the gas ring during a certain time interval probably comparable in length with the time needed for half a revolution of the galaxy.

Formation of spiral arms

From an elliptical ring of gas the visible spiral arms of stars may be formed in different ways. Three main cases may be distinguished:

1. Stars may be formed simultaneously during a short time period along the whole ring or along some large parts of the ring. If the star formation takes place along two symmetric parts of the ring, these arcs may look like trailing or leading arms depending upon the position of the arcs in the ellipse. The parts of spiral arms formed in this way will move outwards in the system at the same time as they will proceed forwards in the rotation, as may be seen from the expanding and rotating rings of stars shown in Fig. 1 and Fig. 2.

2. Stars may be ejected from a special point (or two symmetrical points) in the elliptic ring during a long period of time (of the order of 100 million years or more). The spiral arms will then show the same form as the orbit of a single star ejected from this same point. The arm will usually not be trailing. This case is illustrated in Fig. 4 a, b and Fig. 5 a, b. The form of the arm will depend upon the position of the point of ejection in the ellipse.

3. Star formation may be started in certain points in the gas ring and then follow the motion of the gas along the ring, i.e. the point of ejection of stars from the ring moves along the ring at the same speed as the gas. In this case the arms will be trailing as is shown in Fig. 4 c, d and Fig. 5 c, d. At least in the examples we have studied

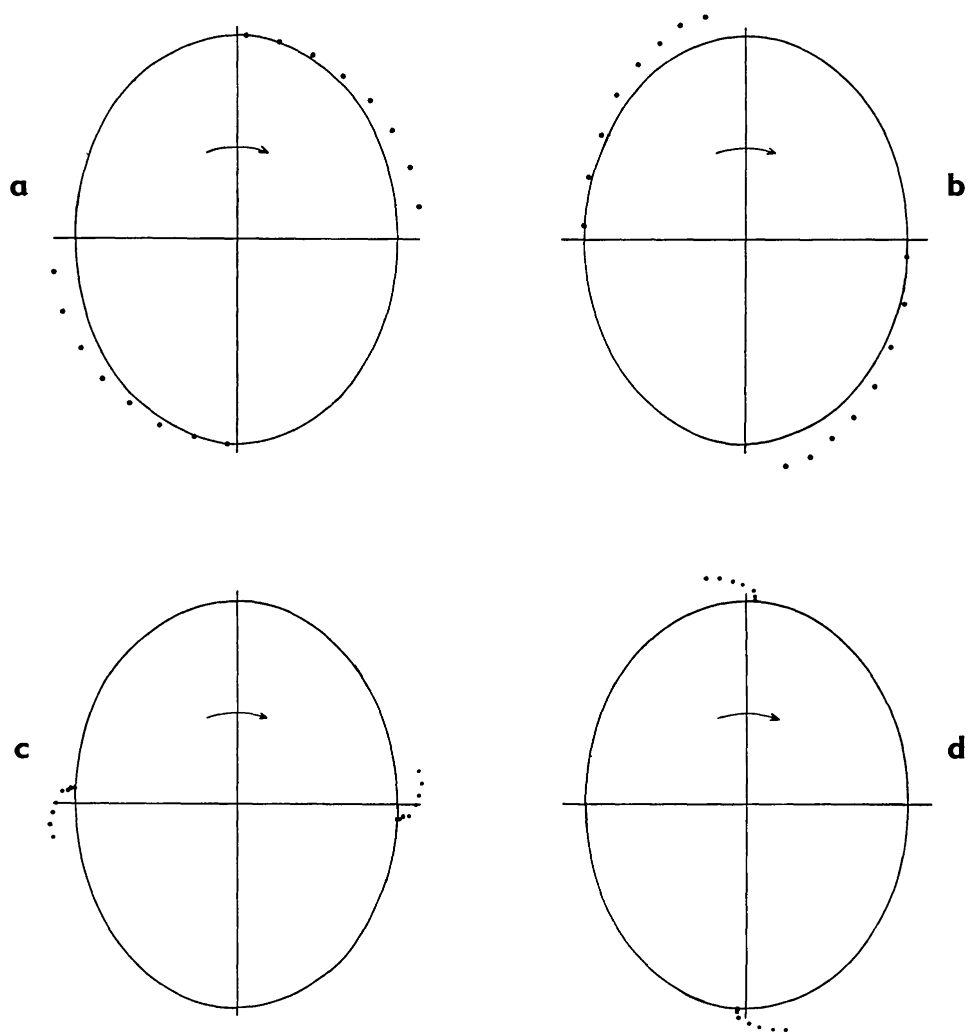

Fig. 4. Model A. Simplified spiral arms defined as the loci of stars ejected from certain points in the ellipse during 56 million years. Upper half: the points of ejection remain fixed in the ellipse. a—near the vertices, b—near the minor axis. Lower half: the points of ejection follow the motion of the gas, starting c—from the vertices, d—from the minor axis. The arms ejected from moving points are very short and almost perpendicular to the ring at the point of connection.

the form of the trailing arms found in case 3 seems to differ from the forms of spiral arms observed in real galaxies. From this point of view case 3 seems less probable than the other cases.

Our knowledge concerning the whole process of star formation is too incomplete to make possible any decision about the most probable way of spiral arm formation. According to M. Schmidt (1959), however, the rate of formation of stars from the gas is probably proportional to the square of the gas density. Since the dispersion rings have density maxima around the vertices (because of the law of areal velocity), the star formation may take place mainly in a region near each vertex. As the gas is streaming rapidly along the ring, the density at the vertex will not decrease markedly during some hundred million years, and the star formation in this region may continue over long periods of time. This case may be regarded as a combination of the much simplified cases 1 and 2 described above. It is illustrated by two models in Fig. 6. The arms will be leading in the rotation.

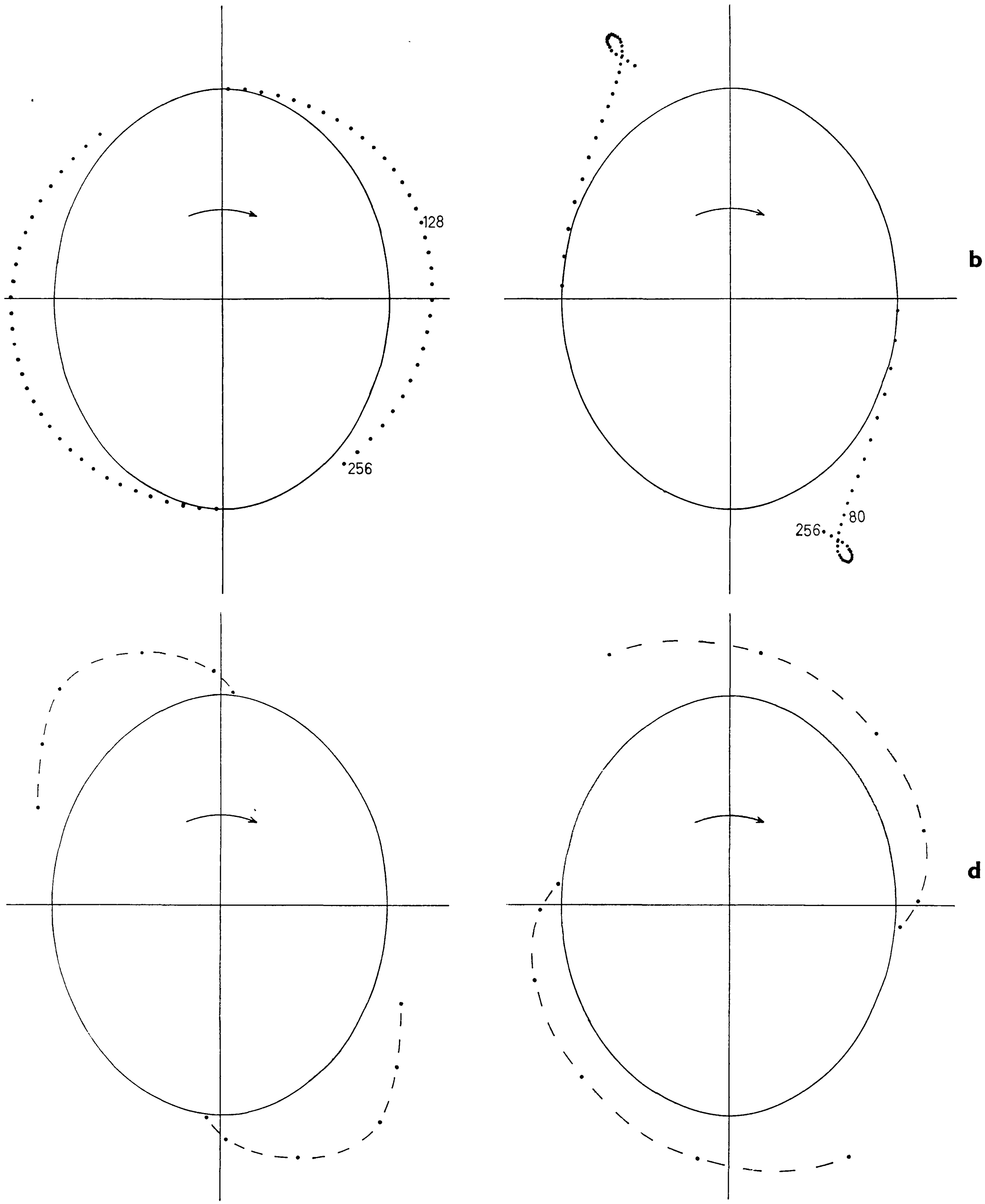

Fig. 5. Model B. Arms of the same kind as in Fig. 4. Age of the arms: 256 million years in a and b, 216 million years in c and d.

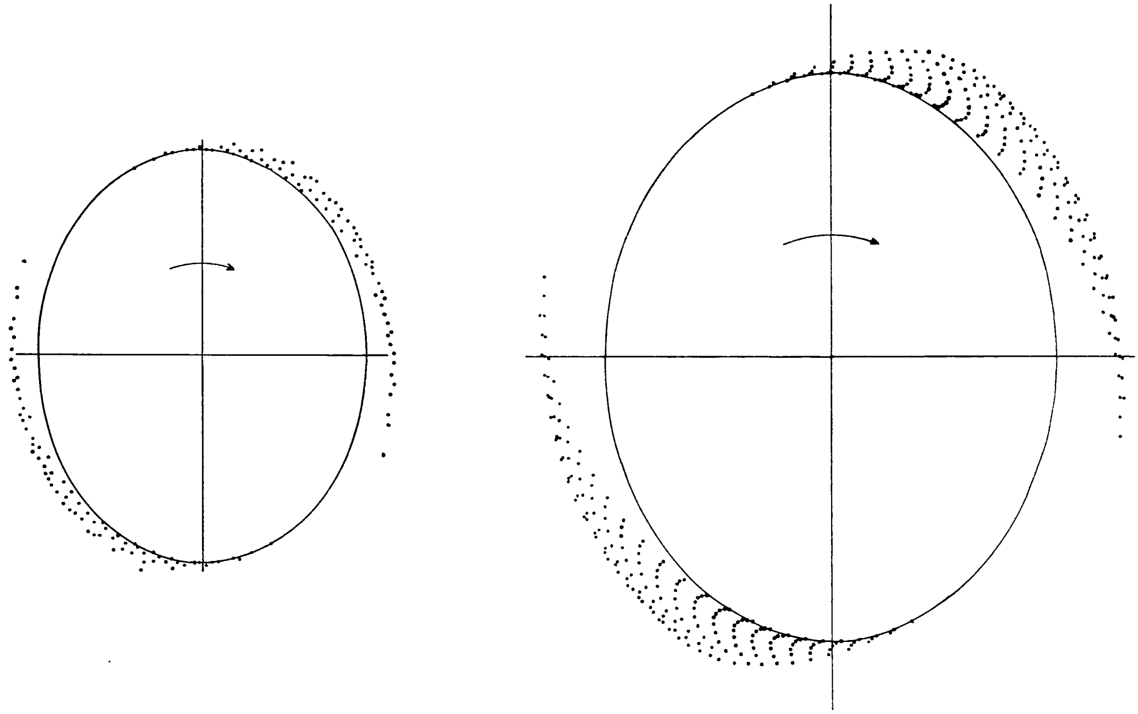

Fig. 6. Two models showing the shape of spiral arms when star formation is assumed to take place in extended regions around the vertices, where the gas density is high. In model A a region defined by 4 points at each side of the vertex is included and the age of the arms is 64 million years. In model B the region of star formation is defined by 5 points at each side of the vertex and the age of the arms is 136 million years.

In all the above-mentioned cases (with the exception of ring formation in case 1) only very limited parts of spiral arms are formed. In most galaxies, however, we observe rather long continuous arms. To explain this by the aid of our theory we assume the existence of several gas rings at different distances from the centre. Then the stars ejected from an inner gas ring may enter an outer ring. We do not yet know if anything special will happen in this case, but there is a slight possibility that the stars entering the outer gas ring will cause some disturbances resulting in the formation of new stars in this outer ring. If so, the stars formed in the outer ring will be ejected from this ring, and the loci of these stars will form a continuation of the inner spiral arm. In this way a continuous spiral arm of considerable length may be formed.

Hot supergiant stars may cause considerable disturbances in the interstellar medium surrounding them. If such disturbances lead to the formation of new stars, this process will be of great interest in our hypothesis concerning the repeated ejection of stars from several rings, provided that the stars entering an outer ring are still young and sufficiently luminous. Since the age of a star entering the outer ring is determined by the time it takes to move from one ring to the next one it will be of interest to study the time scale in our models. The distance between the rings is of the greatest importance. If this distance is too large the stars will not reach the outer ring. In the limiting case when the distance between two rings is about equal to the maximum distance reached by the stars from the inner ring the necessary time will be of the order of 50 million years in model A and 100–150 million years in the other models used here. With smaller distances between the rings the stars will need much shorter times to reach the outer ring since the star orbits are almost parallel to

Table 2. Coordinates (kpc) and velocities (kpc/10^6 years) in the rotating coordinate system of model A at the time $t=0$.

x	y	V_x	V_y
0.3221	6.6875	0.13936	−0.01083
0.9632	6.5874	0.13799	−0.03250
1.5946	6.3872	0.13517	−0.05421
2.2094	6.0867	0.13072	−0.07592
2.7993	5.6861	0.12441	−0.09748
3.3554	5.1868	0.11598	−0.11863
3.8670	4.5915	0.10513	−0.13895
4.3225	3.9053	0.09162	−0.15789
4.7091	3.1362	0.07530	−0.17469
5.0139	2.2962	0.05625	−0.18848
5.2250	1.4011	0.03484	−0.19835
5.3332	0.4710	0.01181	−0.20352

Table 3. Coordinates (kpc) and velocities (kpc/10^6 years) in the rotating coordinate systems of models B–E at $t=0$.

Models B–E		Model B		Model C		Model D		Model E	
x	y	V_x	V_y	V_x	V_y	V_x	V_y	V_x	V_y
0.2907	9.2921	0.09195	−0.00506	0.09478	−0.00512	0.08399	−0.00462	0.07635	−0.00420
0.8724	9.2291	0.09187	−0.01522	0.09472	−0.01541	0.08410	−0.01393	0.07645	−0.01267
1.4554	9.1023	0.09168	−0.02548	0.09457	−0.02581	0.08429	−0.02342	0.07663	−0.02129
2.0399	8.9098	0.09135	−0.03592	0.09428	−0.03643	0.08449	−0.03322	0.07681	−0.03020
2.6256	8.6491	0.09081	−0.04663	0.09374	−0.04733	0.08460	−0.04344	0.07691	−0.03949
3.2111	8.3168	0.08991	−0.05771	0.09282	−0.05863	0.08444	−0.05420	0.07676	−0.04927
3.7936	7.9091	0.08846	−0.06926	0.09131	−0.07041	0.08378	−0.06559	0.07616	−0.05963
4.3685	7.4214	0.08622	−0.08131	0.08894	−0.08269	0.08233	−0.07764	0.07485	−0.07059
4.9291	6.8496	0.08286	−0.09380	0.08542	−0.09543	0.07976	−0.09030	0.07251	−0.08209
5.4664	6.1900	0.07805	−0.10660	0.08039	−0.10845	0.07570	−0.10339	0.06882	−0.09399
5.9689	5.4410	0.07146	−0.11938	0.07354	−0.12145	0.06978	−0.11657	0.06343	−0.10597
6.4227	4.6037	0.06282	−0.13168	0.06459	−0.13394	0.06170	−0.12933	0.05609	−0.11757
6.8126	3.6832	0.05197	−0.14287	0.05340	−0.14530	0.05129	−0.14100	0.04663	−0.12818
7.1227	2.6896	0.03899	−0.15221	0.04004	−0.15478	0.03863	−0.15078	0.03512	−0.13707
7.3388	1.6384	0.02421	−0.15896	0.02485	−0.16162	0.02404	−0.15786	0.02186	−0.14351
7.4498	0.5504	0.00821	−0.16251	0.00843	−0.16522	0.00817	−0.16160	0.00743	−0.14691

Table 4. Modified force function used in model E.

Distance R from centre in kpc	Force $F(R)$ in units of 100 km^2/sec^2 kpc	Distance R from centre in kpc	Force $F(R)$ in units of 100 km^2/sec^2 kpc
7.0	65.4	10.5	30.48
7.5	59.0	11.0	27.77
8.0	52.5	12.0	23.33
8.5	46.5	13.0	19.88
9.0	41.5	14.0	17.14
9.5	37.23	15.0	14.93
10.0	33.60		

the rings. It must be pointed out here that the rings are not infinitely thin. They may be rather wide and in the determination of the minimum age of the stars the distance between the rings will be thought of as the distance from the outer edge of one ring to the inner edge of the next ring.

As has already been pointed out the time scale is much shorter in model A than in the other models because of the smaller mean distance from the centre in model A. Thus we may conclude that in the inner parts of a galaxy the stars may move very rapidly from one ring to the next whereas the motions in the outer parts of the galaxy are rather slow. This seems to favour our hypothesis, making the connection between spiral arms from the inner rings more probable. Stars ejected from the largest ring need not be young when reaching their greatest distance from the ring. It is more favourable to our theory if these stars have already evolved into fainter types when they begin to approach the gas ring, where they were born.

Two special remarks may be added here. Firstly, the great mass assumed to be concentrated in the gas rings in our models is rather unfavourable since it diminishes the effects considerably. If the mass now concentrated to one ring could have been distributed along several rings of different radii the effects would certainly have been more favourable to our theory. The codes at hand could not be used for this arrangement, however. Secondly, the time scale of evolution of the bright young stars also seems to be somewhat uncertain. Estimates of the possible luminosity of stars reaching an outer ring must therefore be postponed until further data are available.

The hypothesis concerning the ejection of stars from a series of gas rings still contains many loose assumptions and may need revision on several points. It should be regarded only as a rough outline of one possible way of explaining the spiral arm formation in a typical galaxy.

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