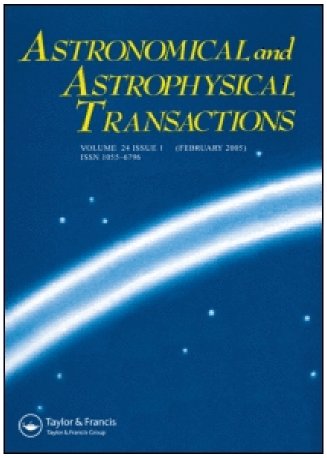

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STAR COMPLEXES AND EARLY DYNAMICS OF GALACTIC DISKS†

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Star complexes are considered as fundamental building blocks of the structure of spiral galaxies. These huge aggregates of stars and gas are the largest cells of star formation in the galaxies and are probably ubiquitous in all disk galaxies. A scenario for the formation and evolution of disk galaxies is considered with particular emphasis on the role of dark matter and star-gas complexes that may be the first structures arising in a galactic disk after its formation.

1 INTRODUCTION

A large majority of young disk stars in disk galaxies are gathered into huge star complexes (Efremov, 1978, 1988, 1989). The typical mass of an individual complex is 10 million solar masses which is summed up from the masses of its stars and also the masses of gas clouds in the same volume.

Star complexes seem to appear as a result of the evolution of gaseous "superclouds" which are the largest in size and mass entities (up to about ten million solar masses) of the diffuse matter distribution in the galactic disks (Elmegreen and Elmegreen, 1983; Efremov, 1988, 1989).

During the last years, the concept of star complexes – superclouds as a basic scale of star formation is becoming to be generally accepted (Larson, 1988; Alfaro, Delgado and Cabrera-Caño, 1992), so it is timely to consider the evolution of spiral galaxies within its frameworks.

One can assume that superclouds, progenitors of star complexes are characteristic not only of the present state of galactic disks, but also of the initial epoch of the formation of the disks when gravitational condensation of the protogalactic diffuse matter occurred and the gaseous material settled into centrifugal equilibrium near the central plane of the rotating protogalaxy. This is a plausible assumption because the time scale for the supercloud formation is much shorter than that for the disk formation. We assume also that a major part of the mass resides within the complexes from the very beginning of the disk formation.

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Basing on these assumption, one can suggest that the star complexes and their progenitors might play a crucial role in the formation of the disks and the large-scale structural patterns such as bars and the spiral grand design in them.

2 THE PROTOGALAXY: A SCENARIO OF EVOLUTION

Despite decades of effort there is still no consensus on a scenario for the formation of the Galaxy. Many theories are based on the classic paper by Eggen *et al.* (1962) describing a collapse of a smooth gaseous protogalactic cloud. The scenario we would like to discuss here is also based on this picture. The major new features of our scenario are the concept of star complexes as building blocks of the structure of the galactic disks and the galactic dark-matter corona.

In this scenario, three key evolutionary stages can be considered in the formation of a massive spiral galaxy. At the first of them, the spheroidal bulge/halo subsystem of the galaxy forms via the gravitational condensation and fragmentation of the central regions of the gaseous protogalaxy. At the second one, the major part of the gaseous material settles onto the rotating disk at the plane of symmetry of the galaxy. And at the third stage, fragmentation of the disk leads to the formation of gas- star complexes and the large-scale structure of the disk develops due to collective interaction of the complexes.

We can discuss the evolution of the internal structure of the protogalactic cloud using the cooling and free-fall time scales determined now not only for the cloud as a whole, but for any spherical layer within it. The time-scale arguments (Efremov and Chernin, 1994) suggests that a central part of the protogalactic cloud can undergo a free-fall collapse and fragmentation. A cascade of the fragmentation develops more rapidly than the whole contraction of the central mass, under the adopted condition. As a result, this central mass transforms rapidly into a collisionless system of dense gravitating fragments and soon can come into a virial equilibrium as a whole. In this way, the central condensation of the Galaxy, its bulge, can form. According to this cosmogonic picture, the bulge appears to be the oldest part of the Galaxy. Its geometrical form cannot be too flat, but rather spheroidal, because of the decreasing specific angular momentum in the central region of the initial protogalaxy.

The other element of the galactic spheroid, the halo, can start to form immediately after the collapse of the bulge. Concerning the space-scale of the system in this way, it might be, say, 2 or 3 times the size of the bulge. Its form should be fairly spherical owing to the same reasons as the ones that were mentioned for the bulge. The mass and characteristic radius of the observed galactic halo are close to these corresponding figures.

Both elements of spheroidal sub-system, the bulge and the halo, form at the time-scale which is less than the age of the Universe at the epoch of galaxy formation, and so this first stage of the evolution of the protogalaxy lasts for no more than about 1–3 Gyr.

3 THE GALACTIC DISK: FORMATION OF COMPLEXES AND BARS

The next stage of the evolution takes much more time. The major process of this stage is a slow contraction of the remaining gas cloud which involves up to 80–90% of the initial cloud material. The whole contraction of the material proceeds at the "global" time-scale, and cooling takes around 6 Gyr (Efremov and Chernin, 1994). This time is the measure of the time interval between the formation of the spheroidal bulge/halo structure and the formation of the galactic disk. Indeed, this interval is close to the observed one between two major star formation bursts in the spherical and disk sub-systems of the Galaxy (Barry, 1988; Marochnik and Suchkov, 1984).

After this time the disk is formed, the geometrical form of which should be fairly flattened because of its rapid rotation which gives rise to the centrifugal equilibrium. The gaseous disk starts soon to fragment since its radius drops, the typical mass of the gas fragment being determined by the temperature and the density of the disk and in that time (about 6 Gyr since the formation of the bulge and the halo) the Jeans mass in the disk is about 10 Million in the solar units (Efremov and Chernin, 1994).

We see that the first and largest fragments in the disk might have the typical masses of the superclouds that evolve into star complexes.

Judging on their masses, the total number of the superclouds is about 1000 for giant galaxies and 10 times less for typical spirals. Such a comparatively small number of the building blocks for the structure formation means that the random statistical fluctuations in their space distribution can be rather high in amplitude. These fluctuations are able to provide seed irregularities that are strong enough for the effective onset of collective instabilities in the ensembles of the clouds dominating the disk by their gravitation (see, for instance, Ivanov 1989).

The most recent analysis of one of such instabilities carried out by Ivanov (1992), shows that two-armed spirals can be excited intermittently in disk galaxies by small fluctuations in the state of "marginal stability".

Another effective process of the same nature is related to the well known bar instability. Numerical experiments demonstrate that selfgravitating disks transform rapidly into elongated ovals similar to the massive bars of SB-galaxies. Such a bar instability develops in a rotating disk in which gravitation of the matter is balanced by circular (or almost circular) motions. A factor which can act against this instability is the presence of a massive spherical sub-system which could make a significant contribution to the total gravitational field of the galaxy. The spheroidal halo of the galaxy with the mass of about 10% of the disk mass (as it is in our Galaxy) cannot play this role. The dark matter corona of the mass adopted in our model prevents the formation of the bar on the space-scale of the whole disk.

However, ongoing accretion of gas on the central part of the disk can stimulate the bar instability there. The accretion flow can be due to the ongoing gas settling on the disk and also to the fall of some gas-star complexes of the Jeans mass that form in the disk and experience a dynamical friction in it.

4 DYNAMICS OF THE GALACTIC DISK: FORMATION OF THE SPIRAL STRUCTURE

The bar (or mini-bar) formed in the central region of the galaxy can produce an important dynamical effect on the ensemble of gas-star complexes in the galactic disk. Basing on the results of analytical calculations for the linear response of a *disk to* the gravitational field of a rotating bar (Feldman and Lin, 1974; Efremov *et al.*, 1989), we can expect that the bar can perturb the initial axial symmetry of the disk, and a wave could arise in it because of this. The wave has the form of trailing spiral arms and the wave pattern rotates around the galactic center at the angular velocity of the bar.

As stressed by Efremov *et al.* (1989), even small deviations of the mass distribution in the central part of a galaxy from its axial symmetry, probably always observed in grand design spiral galaxies, can produce a regular two-armed spiral pattern. A majority of grand design spiral galaxies have a two-armed structure and it really may be a clue to the origin of the regular spirales (Efremov, 1989).

The spiral pattern developing in the disk is build up by the gas-star complexes whose life-time is rather short and much less than the age of the galactic disks. However, the same spiral wave that was triggered by the first complexes can in its turn stimulate formation of new complexes in the diffuse gas of the disk (a part of the gas may come to the gas background from the evolving complexes). In this way, the spiral structure composed of the complexes with their short life-time can occur as a stable and long-living feature in the galactic disks. Such a self-supporting collective process seems to be able to create a quasistationary dynamical state which is observed in the Milky Way and other disk galaxies.

5 A CONCLUDING REMARK

Within this scenario, the correlation of the mass of a disk galaxy with the prominence of its spiral structure can be explained as depending on the number of gas-star complexes within a galaxy and the ease to form them under a given shearing (Efremov, 1989, chapter 12.4). The absence of small-mass spiral galaxies is explained simply by a too small number of complexes in such a galaxy and its rigid-body rotation; the latter explanation was suggested by Baade (1963) many years ago.

With increasing the mass of a disk galaxy, the number of complexes there increases also, as well as the concentration of mass to the bulge. The resulting differential rotation leads to spreading the complexes into fragments of spiral arms. Thus a flocculent spiral structure arises within which the oldest star ages are no more than 100 Myr, the same as within star complexes. The grand-design galaxies have larger masses and matter distribution which is more concentrated to the center than the flocculent galaxies and therefore the former ones have larger shearing at similar distances from the center. Probably this is why, in the grand-design spiral galaxies, the complexes can arise mainly within the spiral density wave arms where shearing is lower than between the arms, as noted by Elmegreen (1987).

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DISCUSSION

Fridman: In one of the recent works of Leo Blitz and his collaborators there are given arguments that the Milky Way has a bar. But, on the other hand, according to Blitz, there are four spiral arms outside the solar ring and, according to Petrovskaya, inside the solar ring, there are four arms but not two.

Efremov: I do agree with the possibility of a bar existence in our Galaxy (if it ends at 3–4 kpc from the center). In barred galaxies, a two-armed spiral emerges often from the ends of the bar and our Galaxy would not to be exception. By the way, therefore we have no need in another (besides a bar) triggering mechanism for the arms. The brightest parts of the arms should be inside the molecular ring.

Petrovskaya: The results of Blitz and our results were obtained from the neutral hydrogen observations, and we found four arms not only for the solar vicinity but for all the Galaxy.

Efremov: I have no definite opinion on the grand-design spiral pattern of the Galaxy except that we certainly have a long (about 40 kpc) arm, a fragment of which in the solar neighborhood is known as the Car-Sgr arm.

Orlov: How many hierarchy levels of star formation are observed?

Efremov: The levels are as follows: a supercomplex, a complex, an aggregate, an association (or cluster), and a star. For more details see a table in my book "Centres of Star Formation", Moscow, 1989.

Seleznev: 1) In some cases cepheid complexes coincide with the complexes of young clusters, and in some cases they do not coincide. For one case (NGC 206), cepheids concentrate at the periphery of a complex of bright stars. What means this difference? 2) Was the star formation history different in these regions? (Regions with different mutual positions of cepheids and young star clusters).

Efremov: 1) This is a question of the age range inside a complex – if it is small we have only OB stars or only cepheids; if the range is large, we have both kinds of objects. But at a scale of order 100 pc the age dispersion is always under $1 \cdot 10^7$ years. Therefore, at this scale, cepheids and O stars avoid each other and the central part of OB 78 is totally filled in with O stars. 2) Some conditions for efficient star formation should exist to provide a small age range. There is the possibility of the alternation of young and older complexes along a spiral arm.