The modern view of the nature of the spiral structure of galaxies

Yu. N. Efremov, V. I. Korchagin, L. S. Marochnik, and A. A. Suchkov

The P. K. Shternberg State Astronomical Institute (Moscow State University); Rostov State University; and The Institute for Space Research, Academy of Sciences of the USSR, Moscow

Uspekhi Fiz. Nauk **157**, 599–629 (April 1989)

The current state of the Lin-Shu density wave theory is discussed in the light of modern observational data. Much attention is paid to the problem of wave excitation and to the response of the interstellar gas to the wave gravitational potential. It is noted that the major predictions of the density wave theory—the galactic shock waves, the spiral velocity field of stars, and the age gradient across the spiral arms—have become fundamental observational facts at present, so that the density wave theory now has no competition from alternative theories. The nature of flocculent spirals is also discussed since, unlike regular spirals, they are probably not connected with density waves but with the effects of induced star formation in differentially rotating galactic disks.

1. INTRODUCTION

Two of the present authors published a paper with a similar title in Usp. Fiz. Nauk in 1974.[1] The problem has not lost its timeliness in the fifteen years since the publication of this paper, although the "hot topics" have, of course, changed their positions. The essence of the problem is the following: approximately 80% of high luminosity galaxies are of spiral type (Fig. 1). The majority of spiral galaxies rotate differentially, i.e., the angular speed of their rotation is a function of galactocentric distance; consequently, any structural formation not gravitationally bound must be rapidly dissipated by the galaxy's differential rotation. Therefore, the theory must primarily explain two facts: 1) why disk galaxies, as a rule, have a symmetric spiral pattern which extends from their central regions to their edges, and 2) why this pattern exists over many revolutions of a galaxy, notwithstanding the fact that the system's differential rotation would seemingly have to "stretch it out" after at most two to three revolutions of the disk. This problem has already been excellently stated long ago by Oort.[2] He wrote: "In systems with strong differential rotation such as is observed in all spiral galaxies without bars, spiral features are perfectly natural. Any structural inhomogeneity is probably twisted, forming part of a spiral. But we must not consider this phenomenon. We must explain a spiral structure encompassing an entire galaxy from its nucleus to its outermost part, and which consists of two arms emerging from two diametrically opposite points. Although this structure is often hopelessly irregular and patchy, a general pattern of this large-scale phenomenon can be traced in many galaxies."

To the problems indicated above, the last 15 years have added at least four more fundamental facts which the theory must also explain: the existence of spiral structure for the velocity fields of stars and gas, the existence of spiral arms formed not only by young stars but also by old disk stars, an age gradient for objects across spiral arms, and the existence of a narrow zone of strongly compressed gas and dust along the inner edges of spiral arms (see Ref. 3).

There are serious reasons for thinking that the visible spirals in normal galaxies are spiral density waves which rotate with a constant angular speed around the system's center. The idea of density waves allowed one to explain all six facts mentioned above that are connected with disk galaxies and with the properties of their spiral structure. Furthermore, the last four facts were actually predicted by the density wave theory, and only then were they actually discovered by observations. There are not very many theories in astrophysics which would possess such a powerful predictive power! Only a few alternative theories of spiral structure have appeared recently (some of which have been briefly elucidated in the last section of this chapter); not one could explain the whole range of indicated facts, and furthermore, they could not predict any major new facts (in any case, facts that might be confirmed by observations).

There is one more important property of the wave theory of spiral structure which distinguishes it from other theories: it makes it possible to predict the geometry of the spiral pattern for a given galaxy if the galaxy's parameters are known. In turn, this allows one to compare quantitatively the theory's predictions with observations. Investigations of this kind were successfully carried out both for our Milky Way galaxy and also for a number of other spiral galaxies. The wave theory explains from a single point of view not only the existence of a regular spiral pattern but also the concentration of centers of star formation in the spiral arms.

The theory of waves in the rotating stellar disks of actual galaxies is complicated because of the need to allow for a large number of diverse physical factors. The properties of the waves are determined here in equal measure by the effects of inhomogeneity and of dispersion. Since a system is bounded, the boundary conditions turn out to be fundamental. The strongly nonlinear behavior of the interstellar gas in the gravitational fields of stellar density waves is a separate major problem.

This review is devoted to the current state of the problem of galactic spiral structure. In it, the most attention is paid to the orthodox theory of density waves, since the remaining hypotheses which have appeared recently are encountering difficulties in the interpretation of some observational data.

2. THEORIES OF SPIRAL STRUCTURE

The idea of stellar density waves as a mechanism for forming the spiral arms of galaxies was first expressed by Lindblad.[4]

The first step in the modern theory is connected with the paper of Lin and Shu.[5] In it the possibility of existence of

 0038-5670/89/040310-18$01.80

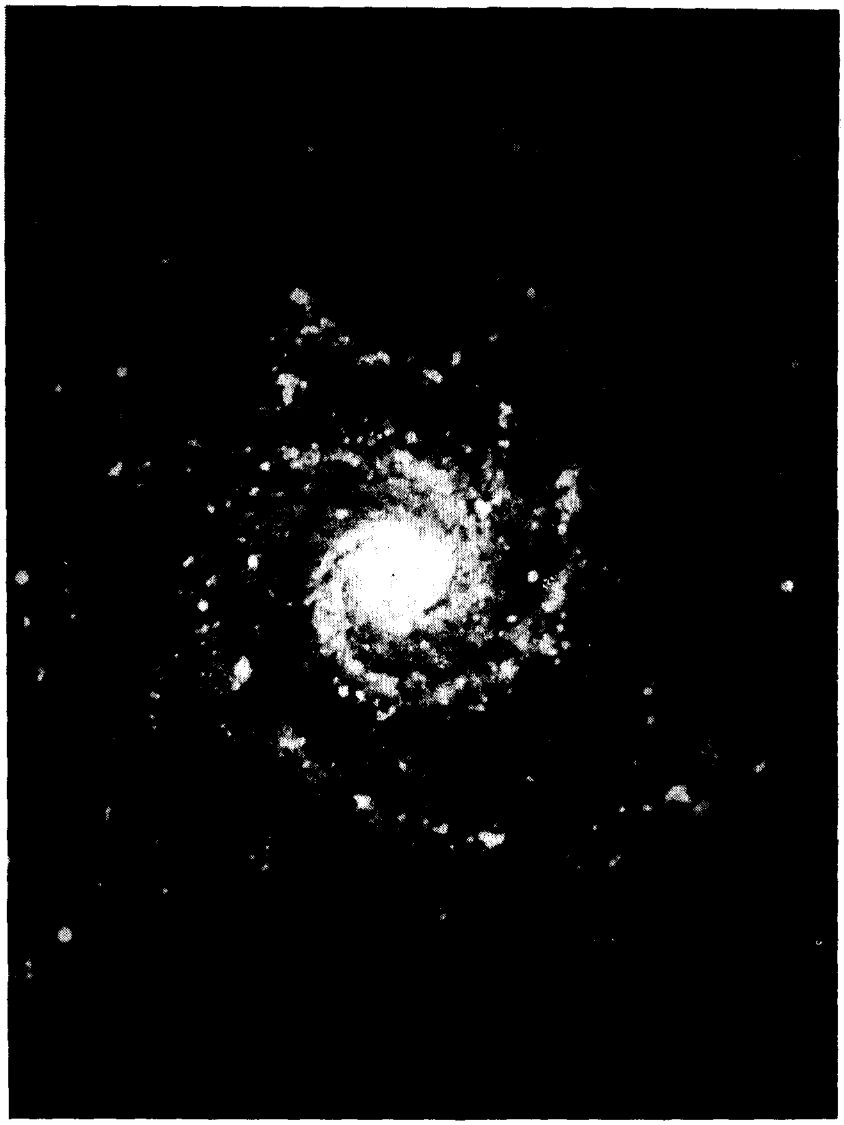

FIG. 1. The spiral galaxy NGC 628 with clearly pronounced, regular spiral arms. (The photograph was taken by N. A. Tikhonov with the six meter telescope of the Special Astrophysical Observatory, Academy of Sciences of the USSR.)

spiral waves was shown, and a dispersion relation was found which allows one to reproduce the geometry of a spiral pattern from a galaxy's known parameters and a known wave phase velocity. The wave property characteristics caused by a system's inhomogeneity (Lindblad resonances and corotation) were indicated.

However, it is not sufficient to prove that waves can exist. In order to understand and describe the spiral structure, one must know how these waves are excited and are maintained over a long time, since they operate in the conditions of a strongly inhomogeneous and bounded system. And although this problem has not yet been completely solved, a breakthrough in this direction was made at the end of the 1970s. We mean the theory of discrete spiral modes in which, by allowing for a particular but fairly realistic case, this problem was solved practically over its entire range. The theory elucidated the extremely complicated and interesting conditions with which the spiral waves in stellar disks of galaxies are connected. For example, it turned out that the angular speed of the spiral pattern's rotation Ω_p and the direction of twisting of the spiral arms (both parameters in this theory are known) are connected with the nature of the system's inhomogeneity and with the wave's behavior at the boundary of the disk. In order to see more clearly the possibilities of the wave theory and the difficulties which arise here by virtue of the system's complexity, let us consider the theory of discrete modes in more detail.

2.1. Theory of Discrete Modes

The theory was constructed both in the hydrodynamic approximation and also on the basis of the kinetic equation for a stellar disk. An asymptotic approximation to find the discrete spectrum of the spiral waves was developed in the hydrodynamic model.[6,7,8] Unstable spiral modes were investigated in Refs. 9 and 10 by the numerical integration of a system of dynamical equations without using an asymptotic approximation. An asymptotic theory of discrete spiral modes in a stellar disk was developed in Ref. 11. The idea of the discreteness of the spectrum of density waves in stellar disks and the conditions for their "quantization" were first formulated in Ref. 12 (also see Ref. 3).

A two-component model, which includes an "active" stellar or gas disk and a dynamically "inactive" spheroidal halo which makes a decisive contribution to the system's gravitational field, is considered as the basic state of the system in Refs. 6–11. Such a model was first suggested in Ref. 12, in which it was shown that only allowance for the existence of the dynamically differing stellar subsystems that are observed in actual galaxies leads to density waves with properties which correspond to the observational data.

An active disk is characterized by a surface density $\sigma(r)$, a stellar velocity dispersion $c(r)$, and by a rotation velocity $v(r) = \Omega(r)r$. The epicyclic frequency

$$\varkappa^2(r) = 4\Omega^2\left(1+\frac{1}{2}\frac{\mathrm{d}\ln\Omega}{\mathrm{d}\ln r}\right), \tag{1}$$

the characteristic length $\lambda^* = \pi G\sigma/\kappa\lambda^2$, and the dimensionless stellar velocity dispersion $Q = c/\kappa\lambda^*$ are the important parameters. A typical distribution of angular speed, of surface density, and of the velocity dispersion as measured by the dimensionless parameter Q in the models of flat subsystems of galaxies that are discussed in Refs. 6–11 is presented in Fig. 2.

Let us consider small perturbations of density, potential, and of velocities for an equilibrium model, selecting them in the form

$$f_1(r)\exp[i(\omega t - m\theta)]; \tag{2}$$

here r and θ are polar coordinates, m is the number of arms, and ω is the wave frequency, which can be represented in the form

$$\omega = m\Omega_p - i\gamma.$$

If one can represent $f_1(r)$ in the form

$$f_1(r) = \tilde{f}_1(r)\exp\left(i\int k(r)\,\mathrm{d}r\right), \tag{3}$$

then the perturbations have the form of spirals, the form of which at a fixed moment of time is determined by the expression

$$m(\theta-\theta_0) = \int_{r_0}^{r} k(r)\,\mathrm{d}r. \tag{4}$$

One can show that, in the hydrodynamic approximation, the perturbations are described by a second order differential equation which is obtained from linearized dynamical equations and the Poisson equation for the approximation of strongly "twisted" spirals[6,7,8]:

$$\frac{\mathrm{d}^2u}{\mathrm{d}r^2} + \hat{K}^2u = 0, \tag{5}$$

where

$$\hat{K}^2 = (\lambda^*Q)^{-2}\left(\frac{1}{Q^2} - s + \nu^2\right).$$

The function u is connected with the perturbation of surface density by the following relation

$$\sigma_1 = \sigma\left[\frac{\varkappa^2(1-\nu^2)}{\sigma r c^4}\right]^{1/2} u\exp\left(-i\int k_0\,\mathrm{d}r\right), \tag{6}$$

where

$$k_0 = \frac{\pi G\sigma}{c^2}, \quad \nu = \frac{1}{\varkappa}(\omega - m\Omega).$$

The dimensionless frequency ν has a simple meaning: Re ν is the frequency with which the material of a galaxy moving with an angular speed Ω passes into the arms of a spiral pattern rotating with the angular speed Ω_p.

A method for the approximate solution of the Poisson equation, which allows one to examine correctly spiral waves with large twists, up to angles of inclination $i\sim 45°$, was developed in the derivation of Eq. (5).[13] In the more general case, instead of Eq. (5), we have a more complicated equation with singular coefficients which go to infinity at the points $r = r_1$ (the inner Lindblad resonance, $\nu = -1$) and $r = r_2$ (the outer Lindblad resonance, $\nu = +1$).

Equation (5) describes the behavior of the solutions far from the Lindblad resonances. This is achieved by the choice of a fairly particular model, in which the index of stability Q equals 1 over the entire disk (also including the vicinity of corotation), and Q increases rapidly only in the central regions (presumably due to the contribution of the bulge stars; see Fig. 2). Such behavior of the equilibrium parameters of the disk leads to the situation that the coefficient $\hat{K}$ of Eq. (5) goes to zero at two points: far from the center at the corotation resonance r_c, and in the central regions of the disk (but without reaching the inner Lindblad resonance) at the point r_i, at which $Q = (1-\nu^2)^{-1/2}$. The coefficient $\hat{K}$ changes sign at the point $r = r_i$; therefore, one can set a boundary condition which consists of the exponential decrease of the wave in the region $r < r_i$. If one assumes that damping of the wave occurs fairly far from the point $r = r_c$, then one can choose the condition of radiation at infinity as the second boundary condition. The spiral wave problem in the theory of discrete modes was solved for just this formulation.

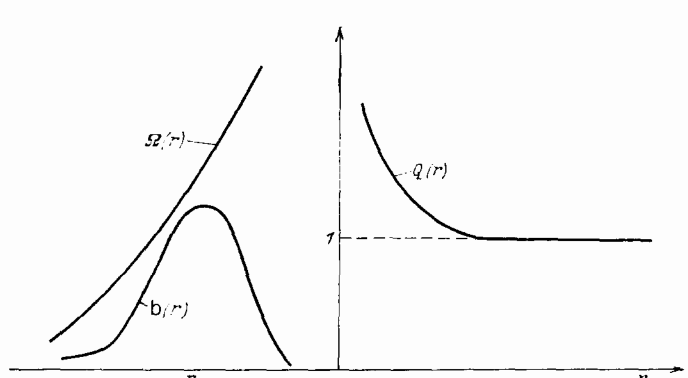

FIG. 2. A typical distribution of the rotation rate $\Omega(r)$, surface density $\sigma(r)$, and of the dispersion $Q(r)$ in the classes of models considered in Refs. 6–11.

The condition of radiation far from the corotational resonance is formulated for trailing spiral waves in Refs. 6–11. In a certain sense this actually postulates that the spiral waves transfer angular momentum and energy from the system's center to its edge. However, other boundary conditions are not excluded.

The continuous radiation of spiral waves in a bounded galactic disk is possible only in the case where the waves are absorbed at the edge of the galaxy. Therefore, the outer Lindblad resonance which, as expressed by Lin and Bertin,[14] "helps to excite discrete modes" by absorbing waves coming from the central regions by a resonance interaction with the stars that is analogous to Landau damping in a plasma, must play an important role in the physical justification of the model of discrete modes. But if there is no outer Lindblad resonance, or the density of resonance stars near it is so low that they cannot remove all of the wave's arriving energy, then the justification of the radiation condition becomes a more difficult matter. One must also notice that, during a fairly prolonged interaction of a wave with the resonance stars near the outer Lindblad resonance, one can expect nonlinear saturation during the interaction of the arriving wave with the stars: after absorbing a sufficient amount of the wave's energy, the stars leave the resonance. One must evidently expect different physical conditions at the boundary in these cases. At present, these major questions remain outside the scope of the theory of discrete modes.

The joining of the solutions of Eq. (5) in the regions $r < r_i$ and $r > r_c$ leads to conditions for the natural frequencies for discrete spiral modes:

$$\int_{r_i}^{r_c} K(\nu)\,dr = \left(n+\frac{1}{2}\right)\pi + \frac{1}{4}\,i\ln 2 \qquad (n=0,\ 1\ \ldots). \quad (7)$$

The imaginary part of the frequency in the dispersion Eq. (7) determines the growth rate of instability:

$$\gamma = \frac{1}{4\tau}\ln 2,$$

where

$$\tau = \int_{r_i}^{r_c} \frac{dr}{|\partial\omega/\partial k|}.$$

It is assumed that, of the set of spiral modes in galaxies [Eq. (7)], the fastest mode for which the value of γ is a maximum is realized. It explains the correct two-arm structure (for $m = 2$). The superposition of several modes makes it possible to explain more complicated structure, for example, branching of the spiral arms, etc. Calculations show that normal spiral arms of the type which are observed in Sa galaxies appear when the model of the galaxy includes a massive bulge with a high velocity dispersion, and the density of the "active" disk decreases towards the central regions.[6–10] When the model of the galaxy is a differentially rotating disk with no nuclear bulge or halo, the unstable discrete modes have features that are inherent to barred spiral galaxies (Type SB). In this case, the structure near the center can be represented as the superposition of leading and trailing spiral waves.[10] The spiral wave is trailing beyond the corotational resonance. Thus, by varying the basic parameters of the model—the density and velocity dispersion distributions along the radius, and also the rotation curve, one can explain the spiral structures of galaxies of different morphological types. This even includes such complicated systems in which independent spiral arms of inner and outer layers are visible (NGC 5364, NGC 210, and NGC 4314). Thus, if the dimensions of a bulge in a galaxy are especially large, then an ordinary trailing spiral is generated by the instability outside it, and the disk component inside the bulge can, for a sufficiently large mass, create a completely independent pattern.

However, we shall not forget that the theory of discrete modes most probably only demonstrates the possibility of the wave theory, and does not give a complete description of the physical situation. It has been constructed for a fairly specific model of a galaxy; there are problems in it with boundary conditions, etc. Therefore, we shall consider another approach to the problem of spiral waves in the following section.

2.2. The Generation of Spiral Waves by a Bar or a Satellite

The distribution of mass and, consequently, also of the gravitational field in the central regions of spiral galaxies are often not axisymmetric. Type SB galaxies with their thick, strongly elongated central bars demonstrate this most clearly. But an ovalness of the central part of their bulges (spheroids) is detected even for normal spiral galaxies. Probably there is such an oval for all galaxies with fairly regular spiral structure.[15] By the way, one must notice that it would be incorrect to consider the bars of Type SB galaxies as overgrown, elongated bulges. The high rotation rate of the bars is caused by the strong concentration of young stars of high luminosity in this region, and not at all by a strong concentration of mass. Here the departure from axial symmetry in the mass distribution is considerably less than in the luminosity distribution. An elongated nuclear bulge is itself an actual ellipsoidalness of a galaxy's entire central body. Observations in the infrared region show this.[15]

It is obvious that the gravitational field of a rotating bar or oval will perturb the fundamental axisymmetric state of the entire disk and will excite a wave in it. At present, this effect is considered by most authors as the most probable mechanism for generating spiral structure. Spiral waves can be excited in a similar way in galaxies with satellites by the satellite's tidal action. A very fundamental observational fact is that regular spiral structure is encountered practically only in those cases when there is a central bar or oval, and also when the galaxy has a satellite.[15–18]

One can pick out three parts in the problem of generating spiral structure with a bar or non-axisymmetric bulge: the origin of the bar itself, the response of a gas or stellar disk to the bar's gravitational field, and the establishment of a density wave and the effect of a spiral gravitational potential. Actually the generation of structure is a single dynamical process, and only the difficulties of describing it and also the wish for it to be broken up as details of the physical phenomena compel us to divide it into separate sections.

2.2.1. The bar-instability of a disk

One of the most fruitful methods for studying the dynamics of stellar systems is connected with the numerical integration of the equations of motion of a large number of particles ($N \sim 10^5$) interacting gravitationally. Even the first numerical expeirments of this kind, in which two-dimensional stellar disks were studies,[19,20,21] led to an unexpected result: the disks were transformed fairly rapidly into elongated ovals or ellipsoids similar to elongated elliptical galaxies or to the bars of Type SB galaxies. The same pattern was also discovered in the three-dimensional case.[22] Thus, a rotating disk in which gravitational attraction is balanced by circular (or almost circular) stellar motions turns out to be unstable with respect to the formation of a bar. Bar-instability did not arise in two cases. The first one is when the system's kinetic energy consisted mainly of stellar peculiar velocities and not of rotation (i.e., when noncircular motions were large). The second one is when there is another subsystem making a major contribution to the total gravitational field. A halo or a massive bulge may be such a subsystem in a galaxy. Ostriker and Peebles,[23] after summarizing the results of many numerical experiments, found that a disk is stable if the ratio of the kinetic energy of rotation to the system's potential energy is sufficiently small, $E_{rot}/|u| < 0.14$. Direct experiments with two-component systems (halo + disk) showed that the transformation of a disk into an ellipsoid does not occur only when more than 60% of the system's mass occurs as part of the halo, and moreover, spiral structure arises in the system in this case.[24]

There are now few doubts that the stellar disks of spiral galaxies exist thanks to massive haloes which suppress bar instability. By the way, the halo's visible mass is usually insufficient to stabilize the disk. It is therefore thought that, to a significant degree, the halo is formed by "hidden" mass. An axisymmetric configuration is unstable only in the central part of such systems, and an ellipsoidal configuration of stars, an oval or bar, arises here. It also generates a spiral wave in the disk. It is curious that the bar's rate of rotation is noticeably slower than that of the disk in the central region.[22] Since the spiral wave pattern's rate of rotation coincides with that of the bar, then the distance at which the pattern's and the disk's rates of rotation are equal (the point of corotation) is located fairly far from the center, but the bar can also extend out to the corotation point.[25,26]

2.2.2. The generation of spiral structure by a bar or central oval

Even the first analytical calculations of the linear response of a gas disk to the field of a bar[27,28] allowed one to draw the conclusion that it can lead to the formation of spiral structure. More detailed results were obtained by means of the numerical integration of the two-dimensional nonlinear equations of hydrodynamics, which describe an isothermal, differentially rotating thin disk that is held in equilibrium by a balance between rotation and gravitation. The isothermal equation of state approximation is used because the time for the radiative cooling of the gas is usually significantly shorter than the time for typical dynamical processes. However, a more realistic allowance for the thermal processes originating in the gas is necessary in a number of cases (see Sec. 3).

The numerical calculations showed that, with the inclusion of the bar's field, the initial axisymmetric state of such a system is perturbed and a wave arises in it. It has the form of trailing spiral arms and, moreover, the wave pattern rotates around the center with the bar's angular speed[29,30] (see Fig. 3). This wave is not self-consistent, since the intrinsic gravitation of the perturbations of the gas density is not allowed

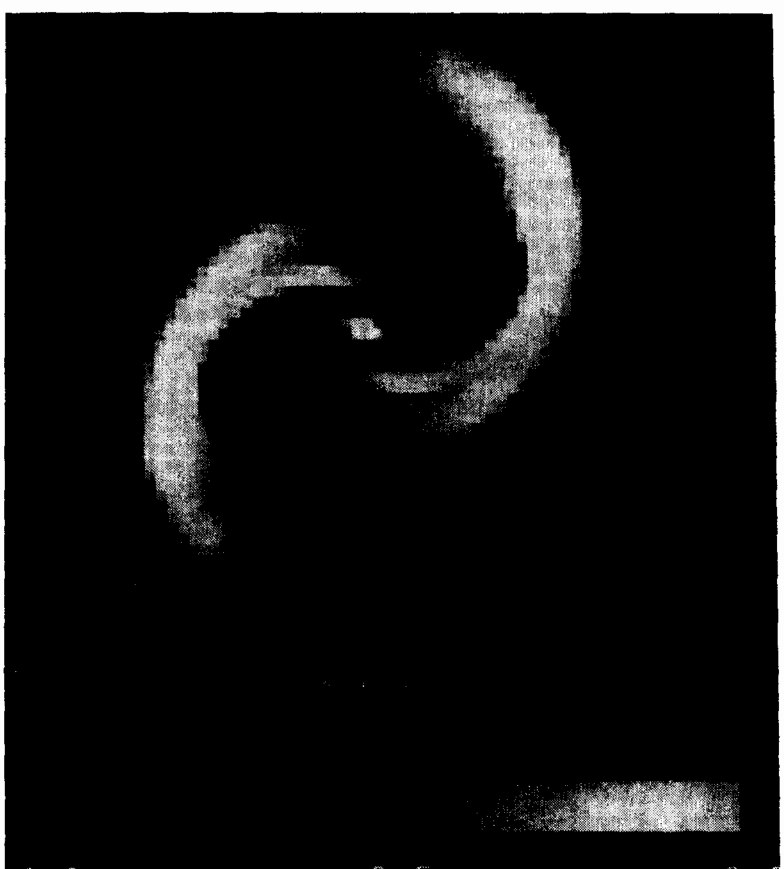

FIG. 3. Form of the spiral pattern initiated by a bar (according to the calculations in Ref. 29).

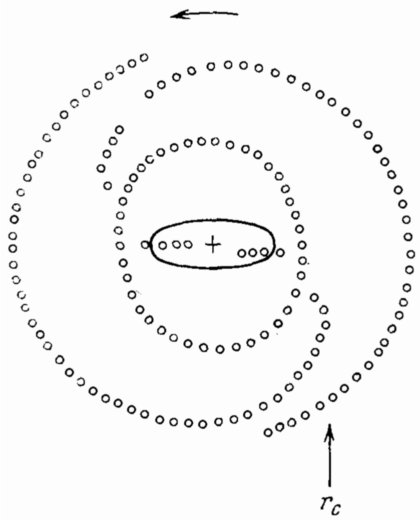

FIG. 4. The form of the spiral pattern excited by a bar in a differentially rotating disk.[38] A ring structure is excited near the region of corotation. The position of corotation is shown by an arrow.

for. But, as was shown later, allowance for self-gravitation does not fundamentally change the pattern.[31]

The calculations mentioned above allow one to discuss directly the behavior of the gas component of the disks of galaxies, and not only that. One can also describe the two-dimensional motions in the plane of a rotating stellar disk to a certain degree of approximation by gas dynamical equations. As was first shown in Ref. 32 (and later in other Refs. 33 and 34), in a plane perpendicular to the system's axis of rotation, the kinetic description of the "stellar gas" can be replaced by the equations of collisionless stellar hydrodynamics that are analogous to the hydrodynamic description of Chew, Goldberger, and Low[35] for a collisionless plasma in a magnetic field.

This makes it possible to extend the results of the gas dynamics calculations to the stellar component. Of course, the specific properties of the waves in the stellar and gas disks will be different because of the differences of the equations of state, the dispersion properties at the resonance points, etc. But the conclusion about exciting waves which form a spiral structure with trailing arms rotating at the bar's rate is obviously general. Reference 36, in which the response not of the gas, but of $\sim 10^4$ individual interacting particles, "stars," to a slowly increasing field of a bar was investigated, confirmed this directly. As was also expected, a long-lasting spiral density increase which rotates like a solid body around the center with the same angular velocity as the bar arose in the disk. The amplitude of this wave turns out to be comparatively small. This is understandable, since the effective adiabatic exponent for the "stellar gas" equals $\gamma = 2$, whereas the adiabatic exponent is usually taken as equal to $\gamma = 1$ for the gas.

It is interesting to note that the trailing arms do not owe their origin to the differential nature of the disk's rotation. They also arise in exactly the same way in disks rotating like solid bodies.[37] But on the whole, the specific geometry of a wave pattern and its thickness depend on the bar's characteristics, the disk's rotation curve, etc. By varying only the rates of rotation of the disk and the bar, one can obtain nearly all the morphological types of spiral patterns (see Figs. 4 and 5), including ring structures.[38]

The region of corotation plays an important role in the morphology of the spiral pattern. As has been shown in Ref. 39, the resonance behavior of the excited harmonics in the region of corotation leads to the situation that the response to the bar's potential has the form of a ring near the region of corotation. This result was confirmed in later calculations.[38,40]

Numerical integration of the equations of gas dynamics allowed one to discover interesting effects in the central region of the system, where the bar rotates more slowly than the rapidly rotating gas disk. One of them is the strong compression of gas at the bar's leading edge; this was already predicted in the 1960s.[41] It appears that we actually observe this effect in galaxies. It is revealed by a narrow dust belt extending along the leading edges of bars, and often it crosses from the ends of the bar to the trailing edges of the spiral arms (see Fig. 5). Let us recall that dust is associated

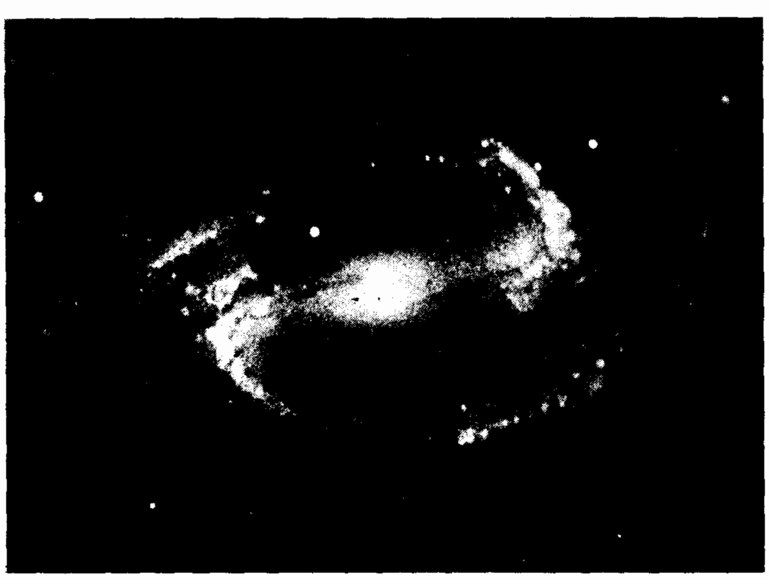

FIG. 5. A spiral galaxy with a bar (connector), NGC 1300.

with gas in galaxies, and dust belts indicate regions of strong gas compression. Here, as also in the calculation results, the region of compression is not quite parallel to the bar's axis; it lies closer to the bar far from the bar's center.[38,42]

Thus, central ovals and bars are capable of explaining not only the generation of spiral structure, but also the origin of a number of important structural features in the gas component of galaxies. As a spiral wave generator, a bar has obvious advantages over an instability mechanism in the theory of discrete global modes. Here there are no difficulties with boundary conditions, and the pattern of the nonlinear stage is clear. (All the same, this possibly only indicates the imperfection of the theory of discrete modes.) The appearance of spiral modes as responses to a nonaxisymmetric, rotating gravitational field appears to be physically perfectly natural. This, in combination with its great universality, allows one to consider it as one of the most reliably established mechanisms for generating the spiral arms of galaxies.

2.2.3. The excitation of spiral waves by the satellites of galaxies

The possibility of generating waves in a galaxy by the tidal action of its satellite is physically very obvious. The main results connected with this mechanism were also obtained by means of numerical integration of the nonlinear equations of gas dynamics. Calculations for fairly realistic models of galaxies showed that a satellite generates a spiral pattern in a disk both during a close flyby[43] and also during periodic motion along a closed orbit.[44] The main features of the observed pattern of gas distribution and of the velocity field are reproduced surprisingly well in the second case. Open spirals are formed in the disk of the galaxy, one of which goes over into a "bridge" joining the galaxy with its satellite. Part of the mass of the gas is captured by the satellite, and from it there extends a gas train, a "tail," etc. A two-arm pattern arises specifically in the first case[43]; this lasts over approximately ten revolutions of the disk and then, gradually twisting, it disappears.

It is curious to note the following. The hypothesis was expressed in Ref. 14 that a satellite revolving around a galaxy will not be able to generate a spiral structure effectively because of the significant difference between the time scales of the galaxy and of the galaxy-satellite system. Actually, this is probably not so. Such generation by a satellite revolving along an elongated, long-period orbit was investigated in Ref. 45. It turned out that a spiral pattern also arises in this case; it rotates slowly, "following" the motion of its satellite generator.

In conclusion, let us make a comment of a general nature. As Lin and Bertin emhasized,[14] the mechanism for the generation of spiral arms by the gravitational fields of bars or satellites is connected in a certain sense with an approach based on the internal dynamics of discrete spiral modes. If a galactic disk finds itself with conditions which exclude strong instabilities and only slightly increasing or damping modes are possible, the gravitational field of a satellite or bar amplifies some of them and maintains them over a long time. However, calculations demonstrating a mechanism for selecting discrete spiral modes have not yet been made.

2.3. Stochastic star formation

Starting from the end of the 1970s, a series of papers was written in which spiral structure was considered as the result of the effect of a galaxy's differential rotation on extensive regions of star formation that are randomly scattered through its disk.[46,47,48] The differential rotation twists these regions into spiral segments and, on the whole, a visible pattern of spiral vorticity is created in the system. Of course, this pattern is changing and irregular, i.e., it cannot explain the regular, symmetric, two-arm structure of galaxies like M51. But there are enough systems where regular structure is actually not visible, and an impression of spiral structure arises from numerous small breaks and fragments of spiral arms (fragmentary or patchy spiral structure; see Sec. 4).

On the whole, this idea is, of course, not new. For example, Goldreich and Lynden-Bell developed such a mechanism for the generation of spirals in a specific form.[49] The new point consisted of the fact that, in the framework of a completely determined pattern of star formation ("induced," propagating star formation which arises stochastically in different parts of the galaxy), one succeeded in numerically tracing the evolution of regions of star formation

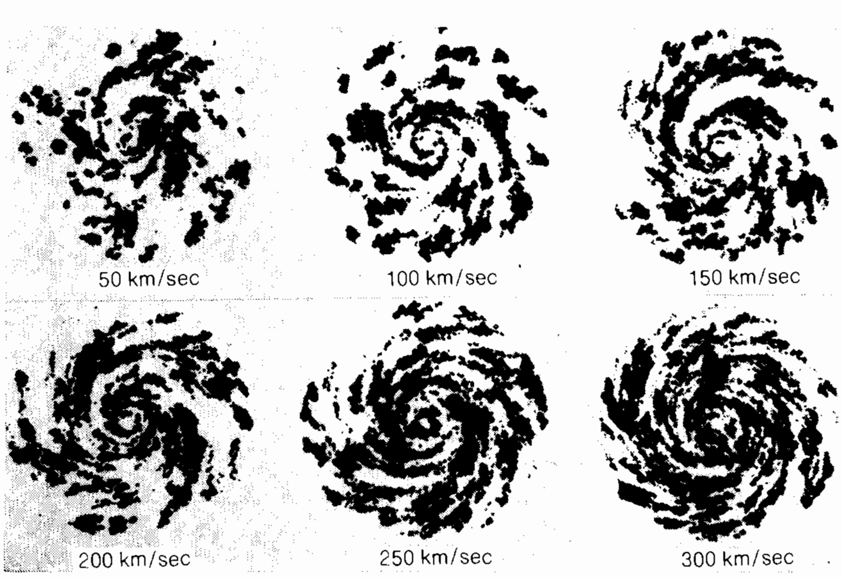

FIG. 6. Models of the spiral structure arising during self-propagating, stochastic star formation and of the flat rotation curve with the velocities (in km/sec) indicated on the figure (from the paper of Gerola and Seiden,[60] 1979).

in a differentially rotating disk and in reproducing the patterns which are obtained here. Undoubtedly they make a great impression (see Fig. 6). Of course this drew much attention to papers on the formation of spiral structure as a result of stochastic star formation.

It is obvious that the possibilities of the idea under discussion are fairly limited. One cannot explain in its framework such fundamental facts as the existence of a galactic shock wave at the inner edges of spiral arms, the gradient of star ages across the spiral arms, and the spiral field of star velocities in the disk. Nevertheless, effects of stochastic star formation definitely operate in galaxies. This is beautifully evident for the example of irregular galaxies, for example, in the Large Magellanic Cloud and, with differential rotation present, they definitely add an element of spiral structure to the spatial distribution of the bright regions associated with star formation. If the regions of star formation are arranged in space by some external factor, then even a regular two-arm spiral can arise. The plane of the "hypergalaxy" (or of a polar ring), at the site of whose interaction with the disk of the galaxy regions of star formation are formed, is considered as such a factor in Ref. 50.

The possibility for forming some kind of structure in the distribution of the bright regions of star formation is strongly connected with the nature of the star formation process itself. It may propagate like a wave in the galaxy and may be self-sustaining.[51,52,53] This interesting property is explained by the action of already existing stars on the interstellar medium from which new stars are generated. Thus, a whole series of factors can initiate star formation: shock waves from supernova explosions interacting with interstellar clouds,[54] ionization fronts around massive O and B stars,[55] and a stellar wind at the different stages of the evolution of stars.[56] On the other hand, supernova explosions can, by heating and making turbulent the interstellar medium, suppress star formation.[57,58] Thus, in a star and gas subsystem of a galaxy, various nonlinear feedback mechanisms operate which, in principle, can lead to spontaneous self-organization in space and time in a galaxy. Similar examples are well known in biology, hydrodynamics, and chemistry.[59]

Gerola and Seiden[48] numerically modeled a process for the propagation of star formation in a galactic disk in the following manner. The disk was divided into elementary cells containing gas in an "active" phase, i.e., capable of star formation, and in an inactive phase. The cells rotate around the disk's center according to a law typical for actual galaxies: the velocity increases rapidly from the center according to the law of solid body rotation, and then remains constant in the rest of the disk. "Young star clusters" which, with probability $P_{\rm eff}$ "induce" generation of stars in neighboring cells, are placed in approximately 1% of the cells at the start of the calculation. It was assumed that the probability of star formation depends on the amount of "active" gas in the cell:

$$P_{\rm eff} = P_{\rm st} D_{\rm a}^{n}. \tag{8}$$

The fact that, in a region where star formation recently occurred, material cannot generate new stars for a certain time, is allowed for. This is modeled by introducing a restoration time τ during which the gas in a cell goes from an inactive to an active phase. In addition to induced star formation, spontaneous generation of stars is allowed for, but with approximately 100 times lower probability.

The calculation results showed that a spiral structure that is multi-arm in most cases and is outlined by very young stars appears in the system (see Fig. 6). It is formed by sections of spiral arms, and moreover, the individual sections twist up and disappear, but other sections appear to replace them, so it turns out that a spiral pattern exists the entire time of the calculation.

The global spiral patterns of galaxies are undoubtedly caused by a spiral density wave. However, stochastic star formation may operate in parallel, introducing its contribution to the observed pattern. Gerola and Seiden[60] investigated the combined effect of the two mechanisms of star formation, the stochastic one and that connected with a wave. They introduced a new parameter $P_{\rm sdw}$, which describes an additional probability of generating stars in a spiral density wave, in their theory. If the efficiency of generating young stellar groupings in a wave is high, then the spiral pattern is well outlined, but the branchings and secondary details of the global pattern caused by self-propagating star formation look very realistic.

Roberts and Hausman[61] investigated in their more complicated model the question of the interaction of a spiral density wave and of stochastic star formation. They considered the dynamics of giant molecular clouds and of young stars moving along ballistic orbits in the fields of a spiral density wave and of the galaxy's axisymmetric potential. Part of the stars explode as "supernovae" at the end of their evolution. The star formation process can be started in a cloud either by the effect of a collision with another cloud or as the result of the action of the envelope of a nearby exploding supernova. It turned out that a spiral pattern arises in such a system, but it is not as regular as those in actual galaxies, which are well outlined by young stars and clouds.

The possibility of coherent oscillations in the rate of star formation, which can be related to bursts of star formation in galaxies and to the development of the ordering of star formation in space and time, is interesting. Oscillations were discovered both in numerical experiments[47,48] and also in analytical models with induced star generation.[62] The transition to oscillations of star formation in the experiments of Seiden, Schulman, and Feitzinger[47] depends on the restoration time τ during which the gas goes from an inactive to an active phase; they only appear for a fairly large value of τ.

In general, one can consider the development of oscillations in the rate of star formation as a sign of instability of the system. As has been shown in Refs. 62 and 63, a similar instability can also arise in a three-component system consisting of atomic gas, molecular clouds, and massive stars, and it leads to a regime of nonlinear periodic oscillations. The loss of stability by the system is connected with the complicated nature of the formation of molecular hydrogen from the atomic phase, when the rate of molecule formation depends nonlinearly on the mass of matter which already exists in molecular form.

It is interesting that very smooth and well outlined spiral patterns similar to the patterns of galaxies with two-arm structure were discovered simultaneously with undamped oscillations in the rate of star formation in the models of Gerola and Seiden (Fig. 7). The loss of stability of dynamical equilibrium in a nonlinear star-cloud system allows one to interpret the appearance of regular spiral structure in the numerical experiments as an example of spatial selforganiza-

FIG. 7. An example of a two-arm spiral pattern which arises upon modeling an oscillating mode of star formation [Ref. 47 (1982)]. The luminosities of the stars in the V band are represented.

tion so that, in principle, nonlinear selforganization can be the mechanism for creating large-scale spiral patterns in galaxies. However, there is an entirely different question: is this mechanism actually responsible for the formation of such structure in galaxies? As certain data show, the efficiency of spontaneous star formation can be significantly higher than that of induced star formation. This causes one to doubt the very posssibility of propagating star formation from one complex to another through space with a low gas density. The stretching of fairly large young star complexes by differential rotation gives a pattern of a fragmentary spiral pattern even without invoking induced star formation.[64,65,111]

2.4. Other models for the origin of spiral structure

It has been suggested in a number of papers (for example, see Ref. 66) to consider spiral structure as the result of the development of Kelvin-Helmholtz type instability in a galaxy's gas disk. Such instabilities arise in fluids with flows that are layer-inhomogeneous. It is assumed that the necessary gas flow inhomogeneity in galaxies is created in some region near the center where, as one goes out from the center, the rate of rotation decreases rapidly by a fairly large value. There are several problems with this approach from an observational point of view. In particular, typical variations of galactic star disk densities connected with spirals amount to from 20% to 40%. It is clear that even strongly nonlinear perturbations in the gas subsystem cannot redistribute to such a degree the material of a star disk possessing a large velocity dispersion and the overwhelming part of the mass (the mass of the stardisk usually exceeds the gas mass by an order of magnitude and more). Kennicutt and Edgar[67] strikingly demonstrate for the example of the galaxies NGC 7743 and NGC 495, in which there is no gas at all but which nevertheless have spiral structure with regular and smooth arms, that spiral structure is determined by the stars and not by the gas (see Fig. 8). The data on NGC 2566,[111] contrary to Ref. 66, agree with the theory of Ref. 5.

The special variety of the spiral structure for certain galaxies is probably connected with the eruption of gas from their centers. The galaxy NGC 4258, which van der Kruit, Oort, and Mathewson[68] investigated, is an example. A radio survey of this galaxy revealed two thick gas spiral arms which are displaced by almost 90° with respect to the spirals visible in the optical region, i.e., the ordinary stellar arms. The gas in the arms moves with a significant outward velocity. This tells us that it was ejected comparatively recently from the galaxy's nucleus. In Ref. 68 a mechanism has been suggested, according to which such arms are formed during the eruption of gas clouds with a total mass of the order of

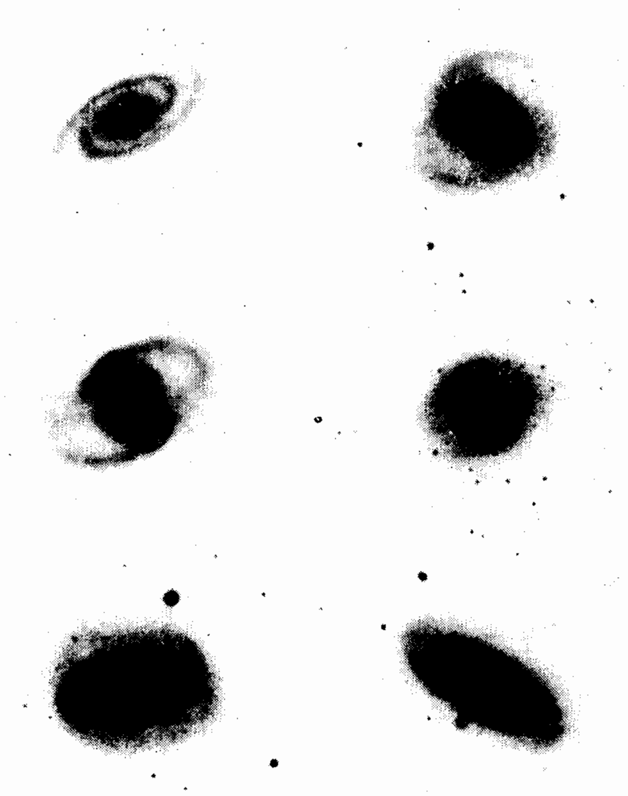

FIG. 8. Galaxies with smooth spiral arms consisting of old stars. [From a paper by Sandage, Ref. 112 (1983)].

$10^8 M_\odot$ from the galaxy's nucleus. The authors of Ref. 68 assume that ordinary arms also arise in a similar manner. As was noticed in Ref. 1, however, the mass of the gas arms is so small that it certainly cannot explain the observed stellar arms. There are also other objections to this idea, but we shall not discuss them, since the idea itself is now only of historical interest.

3. GALACTIC SHOCK WAVES AND GAS DYNAMICS WITH PHASE TRANSITIONS

3.1. Physics of the Interstellar Gas

From a physical point of view, if you like, the most interesting aspects of the wave theory of spiral structure are connected with the perfectly unusual gas dynamics of the interstellar medium. They are no less interesting from an astronomical point of view, since the most effective manifestations of spiral waves are connected with them; these are the processes which become more important during the motion of the interstellar gas in the gravitational fields of the spiral waves and are responsible, in the final analysis, for the extremely high luminosity of the spiral arms, for the strong synchrotron radio radiation and gamma radiation of the spiral arms, for the cloud structure of the interstellar medium, etc.

In what way is the gas dynamics of the interstellar medium unusual? The answer lies in the features of the thermal processes originating in it: three-dimensional heat losses (radiative cooling) and heating by external sources (by cosmic rays) play a decisive role in its dynamics.

The cooling mechanism is primarily connected with the

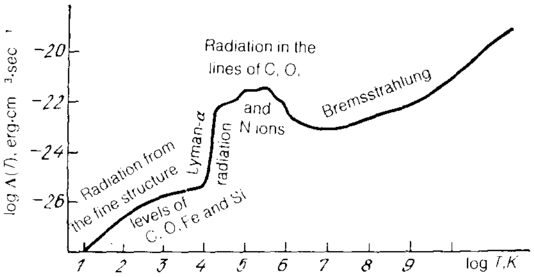

FIG. 9. The cooling function for the interstellar medium. The processes which make the main contributions to cooling at the different temperature ranges are indicated.

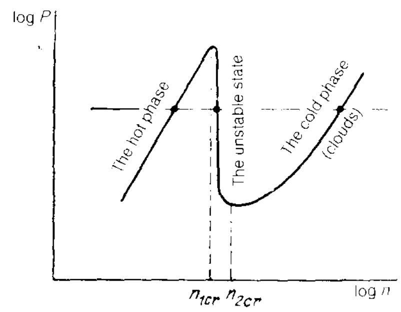

FIG. 10. The relation between pressure and density in a steady-state interstellar medium that is heated by cosmic rays and cooled by radiation.

excitation of atoms, ions, and molecules of the gas during inelastic collisions with free thermal electrons. Electromagnetic quanta are emitted as they go into the unexcited ground state and, since the interstellar gas is optically transparent, in the final analysis, thermal energy is carried away from the system by radiation. The rate of this process is proportional to the frequency of pair collisions and consequently, to the square of the particle number density n^2. Its efficiency depends on the temperature, the degree of ionization, and on chemical composition. The interstellar gas in the Milky Way consists of approximately 98% hydrogen and helium and 2% of all the remaining elements of the periodic table. It is ionized by cosmic rays and x-radiation, and therefore there are always free electrons in it. Under these conditions, electron impact excitation of the fine structure levels of carbon, silicon, and iron, and also of the vibrational and rotational levels of the H_2 molecule (if hydrogen is in the molecular form) plays the main role in cooling at temperatures up to 10^4 K. Starting from a temperature $T \approx 10^4$ K, the main process is connected with the excitation of atomic hydrogen, and "cooling by Lyman-α quanta" becomes dominant. At temperatures of the order of $2 \cdot 10^4$ K to 10^6 K, oxygen, nitrogen, and other elements make a large contribution to the cooling, and bremsstrahlung losses in Coulomb collisions are dominant at $T \approx 4 \cdot 10^7$ K. All this determines a complicated structure for the efficiency of cooling as a function of temperature. This function, $\Lambda(T)$, is often called the cooling function (see Fig. 9).

Heating of the gas occurs in the following manner. Cosmic ray protons ($E \sim 1$ MeV) knock electrons out of hydrogen atoms, transferring part of their energies, $\Delta E \sim 50$ eV, to the electrons. These electrons are thermalized in elastic collisions with neutral atoms, transferring their excess energy to the atoms. As a result, the internal energy of the gas is increased. The rate of this process is obviously proportional to the gas density n, and its efficiency Γ depends on the cosmic ray intensity. The change of the density of internal energy in the interstellar gas as a consequence of the cooling and heating processes is described by the equation

$$\frac{3}{2}\,\frac{\partial}{\partial t}(nkT) = \Gamma n - \Lambda n^2.$$

In the steady state when $\Lambda n^2 = \Gamma n$, a relation is found between the density n and temperature T, which one can obviously transform to the relation $P = nkT$ between density and pressure. One can call this relation $P = P(n)$, which is determined by the form of the function $\Lambda(T)$ and by the value of Γ, the equation of state of the interstellar gas. As is evident from Fig. 10, the relation $P(n)$ is nonmonotonic, and there exists a range of parameter values in which three values of density correspond to the same pressure. Therefore, in principle, three different states of gas, which are called phases of the interstellar medium, can be achieved at the same pressure in an equilibrium interstellar medium [the $P(n)$ relation in Fig. 10 is very similar to the liquid-vapor phase equilibrium curve that is described by the van der Waals equation].

The intermediate phase, where $\partial P/\partial n < 0$, is unstable; therefore, only the two extreme phases can actually be achieved; the hot one ($T > T_{1cr}$) and the cold one ($T < T_{2cr}$). And they are actually observed in the Milky Way in the form of cold, dense clouds and of the hot, tenuous interstellar gas.

The parameters of the interstellar gas in spiral galaxies, apparently not by chance, very often lie near the non-monotonic part of the equilibrium curve $P(n)$. Just this circumstance leads to a very nontrivial gas dynamics.

In many dynamical processes in the interstellar medium, the characteristic times of cooling $t_c \sim kT/\Lambda n$ and of heating $t_h \sim kT/\Gamma$ are significantly shorter than characteristic dynamical times. The values of P and n in these cases will not differ too strongly from the equilibrium values. Let us imagine that, upon the passage of a compression wave, the density of some element of a mass of gas in the hot phase increases to the value $n = n_{1cr}$ corresponding to a maximum of the equilibrium curve. Further compression leads to a sharp decrease of temperature and pressure. As a result, the density starts to increase catastrophically and will increase as long as the pressure in this element of mass and in the surrounding hot medium is not equalized. The density and temperature in the new state correspond to the stable cold phase and differ by approximately two orders of magnitude from the density and temperature of the surrounding hot phase. Thus, an originally slightly inhomogeneous gas flow can go over to a state with strong discontinuities. In essence, the formation of structure and of a multiphase medium with sudden changes of the parameters at a phase boundary occur. Just this distinguishes the dynamics of the interstellar gas from "classical" gas dynamics.

The nature of the possible types of flows, discontinuities, and of structures in the interstellar medium is extremely diverse; we encounter a whole series of such "non-classical" flows in the analysis of gas motion in the gravitational fields of spiral waves.

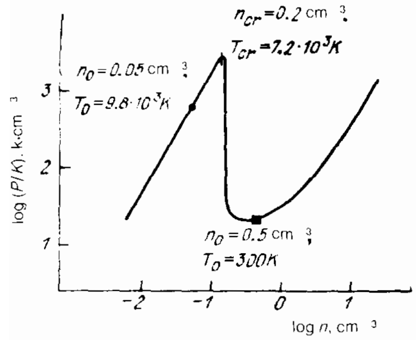

FIG. 11. Dependence of the pressure of the interstellar medium on density for a rate of primary ionization $\zeta = 10^{-15}$ sec^{-1}. The parameters of the initial state from which the development of the flow shown in Fig. 12 starts are marked by a dot, and those of the initial state for the flow shown in Fig. 14 are marked by a small square. The critical parameters are indicated.

3.2. The shock wave, the accretion wave, and three-phase flow

In a spiral galaxy, the gas moves under the action of a gravitational field φ which is made up of the regular axisymmetric field of the entire galaxy φ_G and of the spiral wave field φ_S. If $\varphi_S = 0$, then purely circular motion with the angular speed $\Omega = \Omega(R)$ is possible, so that $\Omega^2(R)R = \partial\varphi_G/\partial R$, where R is the distance from the system's center.

Let us assume that the spiral perturbation of the gravitational potential φ_S which rotates with angular speed Ω_p is superimposed on a state with circular gas motion; this leads to additional motions, mainly in the plane of the disk.

The gas flow was investigated numerically in Refs. 69–72 by using parameters that are typical for our Milky Way. And extremely unusual solutions from the point of view of "classical" gas dynamics were discovered even in a fairly simplified formulation of the problem.

3.2.1. A Galactic Shock Wave. Phase Transitions

When an initial homogeneous state corresponds to the hot phase (this is marked in Fig. 11 by a dot on the phase equilibrium curve), then the following pattern arises with inclusion of the spiral field φ_S (see Fig. 12). In a coordinate system rotating at the rate Ω_p (in which the spiral field is at rest), for supersonic gas flow through a potential well, a sudden change of density at which the normal velocity component undergoes a discontinuity is formed in the region in front of the well's minimum. A shock wave arises which is fixed with respect to the field φ_S and which one calls a galactic shock wave. Two situations are possible next. First, a case is possible where a steady-state flow is established for which the shock wave amplitude and the entire flow profile do not change with time. This case is achieved when the density at the shock wave front does not reach the critical value $n = n_{1cr}$ (see Fig. 11). If the compression in the wave is so large that the density reaches the level $n = n_{1cr}$, then the following occurs. For further compression at the wave front, the temperature decreases sharply and the density increases in some element of volume of gas. This element is, after some time, completely carried out of the region of the front in the form of a dense, cold cloud (of course, the cloud is one-dimensional in this calculation). The density at the front decreases below the critical level and then gradually in-

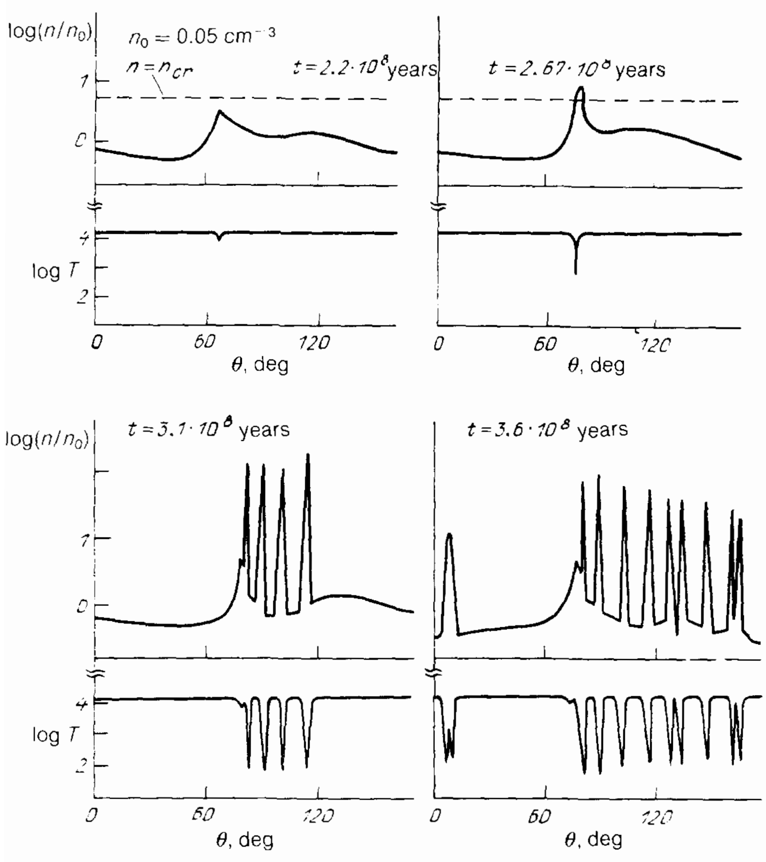

FIG. 12. The formation of a galactic shock wave and of gas clouds at a front. Profiles of density and temperature are shown for different times as functions of galactocentric angle for a two-arm spiral case. The position of the center of a spiral arm corresponds to $\theta = 90°$, and the position between the arms corresponds to the angles $\theta = 0°$ and 180°. The sizes of the clouds (the peaks on the density profiles) are shown to scale. The initial state is shown by the dashed line.

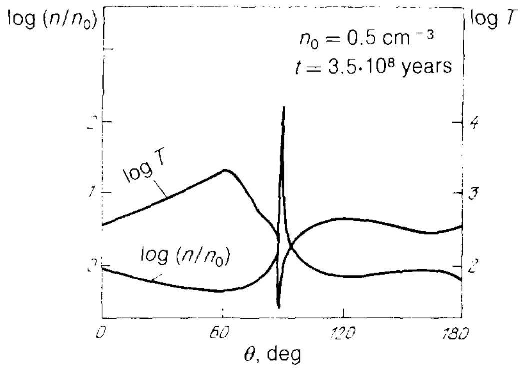

FIG. 13. An accretion wave. The initial state is shown by a dashed-dotted line. The wave becomes quasi-steady-state after a time $t \chi 3 \cdot 10^8$ years.

creases again, and the process is repeated. As a result, the wave front operates as a "mechanism" which continuously produces cold clouds of interstellar gas, creating a two-phase medium. This case is shown in Fig. 13.

It is curious that the removal of cold phase clouds from the region of the front is connected with the curvilinearity of the motion, with the action of the Coriolis force. A solution of the problem for the same parameters but in a rectilinear geometry showed that an unlimited increase of density with no removal of elements of cold matter outwards occurs in the region of the front.[72]

3.2.2. The accretion wave

A completely different pattern arises for the same parameters but for an initial combination of them which corresponds to the cold phase (this is marked by a small square in Fig. 11). A wave of unusually large amplitude ($n/n_0 \sim 100$) arises in the center of the potential well of φ_3 in this case. Large gas masses are delayed for a long time in a narrow region of the wave front, the gas velocity decreases to extremely low values and, moreover, there are cases when the velocity beyond the front generally changes sign and gas will flow into the region of the front from both directions. This type of gas flow discovered in Ref. 71 was called an accretion wave.

3.2.3. Three-phase flow

Calculation of this same variant, but with the value $R = 100$ kpc instead of $R = 5$ kpc, revealed one more type of motion in the gas; it was called three-phase flow.[71] The change of R is reflected most significantly in the unperturbed velocity of the gas with respect to the spiral potential: it decreases strongly and becomes comparable with the initial speed of sound (it was approximately six times faster than the speed of sound in the previous case). This circumstance radically changes the nature of the gas motion in comparison with the previous case: instead of an accretion wave, a flow is developed here that has been called three-phase in Ref. 71. The following is its peculiarity. The gas density near the center of the potential well at first increases smoothly by approximately a factor of two. Far from the center, the density decreases by approximately the same factor, but here this decrease is accompanied by a transition of the density from $n > n_{2cr}$ to $n < n_{1cr}$. At $n < n_{1cr}$ the gas is very rapidly heated to temperatures $T > T_{1cr}$. As a result, an enormous region arises in which the density is only half its initial value, whereas the temperature increases to about 30 times its initial value. In essence, two phases arise with a sharp, abrupt temperature change at their boundary; the density is discontinuous at the phase separation boundary and generally changes oly slightly in space.

An abrupt pressure change obviously arises at the phase boundary. Then it compresses the layers of the practically original cold phase that are adjacent to the boundary; as a result a narow region of strongly compressed, cold gas (a cold cloud) is formed. The abrupt temperature change at this boundary increases, but the abrupt pressure change decreases due to the formation of an abrupt density change. There are now already three strongly differing states, three "phases" with abrupt parameter changes at their boundaries. First, there is a phase where the parameters are close to their original values. Second, there is a phase with a high temperature ($T \sim 10^4$ K) and a fairly high density (there is a large, abrupt presure change at its boundary). Third, there is a phase in which the density is almost an order of magnitude higher than its original value at practically the original temperature (there are abrupt changes of density and pressure at its boundary; see Fig. 14).

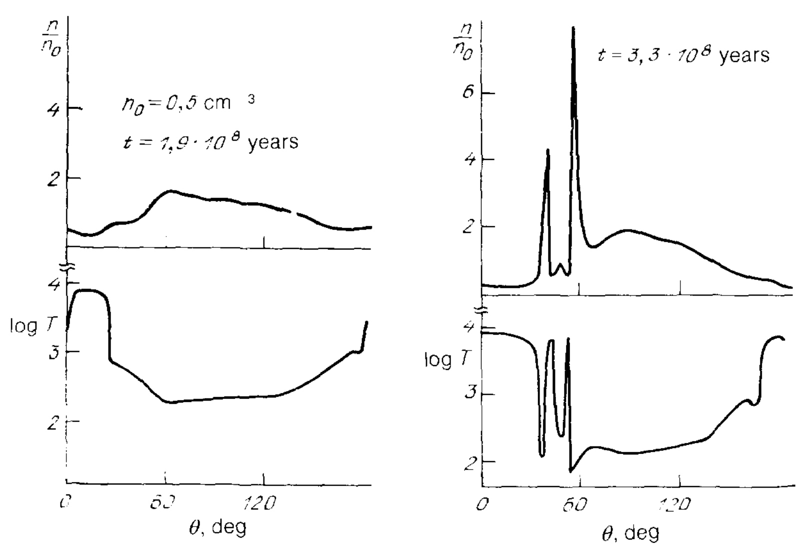

FIG. 14. The development of three-phase flow. A third phase, cold clouds with densities much less than the density of the original cold phase, arises after a time $t = 2 \cdot 10^8$ years.

The hot phase is close to the upper critical point; therefore, fluctuations of density in it caused by dynamical processes in turn lead to phase transitions. Those elements of volume in which the density turns out to be higher than the critical density are rapidly cooled, forming new cold phase clouds.

In conclusion, we note that one can divide the structural elements arising during the flow of interstellar gas in the field of a spiral wave into two types. First, there are strongly nonlinear waves, for example, galactic shock and accretion waves. Here the characteristic regions of parameter change (let us say a shock wave front) move through the gas; each element of a mass of gas enters into and exits from such a region. Second, there are regions of different phases that are connected with given elements of gas and which move together with them (cold phase clouds and intercloud gas). "Clouds" which are generated at a shock wave front belong to this second group in our examples.

3.3. Galactic Shock waves

Regions of strongly compressed interstellar gas extending in narrow bands along the spiral arms are clearly revealed in many galaxies. A perfectly natural and essentially the only interpretation of this is that galactic shock waves are observed as regions of increased density of gas and dust, and therefore the existence of such regions is considered as an unambiguous indication that spiral structure is caused by a gravitational potential wave moving through a galaxy's gas disk. Obviously, one may not expect anything like this if one assumes that the phenomenon of spiral structure is caused by nongravitational or non-wave processes that are proposed as alternatives to the spiral wave theory (see Sec. 2).

The galactic shock waves in external galaxies are revealed especially clearly in two phenomena. The first is a narrow dust band which sometimes extends over several kiloparsecs (see Fig. 1), usually along the inner edge of a spiral arm. They are visible on photographs of galaxies as a black band on the bright background of an arm and, moreover, its width is many times smaller than the width of the arm itself. A dust band is an optical indicator of a region of high gas density, since the gas carries dust along with it as it moves.[79,83]

The second is that a narrow region along the spiral arms turned out to be a strong source of synchrotron radiaiton. The connection here with a shock wave is the following. Along with the gas, a magnetic field frozen into it is compressed in a shock wave. Cosmic rays are also compressed with the magnetic field, and their energies are simultaneously increased. All these factors lead to a powerful amplification of the synchrotron radiation arising during the motions of relativistic cosmic ray electrons in the magnetic fields of galaxies.

A shock wave was also discovered in our Milky Way by the amplification of synchrotron radiation from a region of spiral arms (for example, see Ref. 73). It is revealed by peaks in the distribution of the radiation intensity over galactic longitude: the peaks were discovered in those directions where a significant part of the spiral arms in located on the line of sight (directions that are tangential to a spiral).

Analogous peaks in the longitude distribution of the gamma radiation intensity are one more effect. In particular, gamma radiation in the Milky Way arises in collisions of cosmic ray protons with interstellar hydrogen. The collisions generate π^0-mesons whose decay gives gamma quanta. Obviously, the intensity of the flux of such quanta will again be higher in directions where the line of sight goes along a region of high density of gas and cosmic rays. An analysis of the longitude distribution showed that one can explain the peaks of intensity if the gas density in these directions is ten times higher than the average density (for example, see Ref. 74).

At present, the data on galactic shock waves are so numerous and convincing that consideration of questions of the nature, origin, and maintenance of spiral structure without taking them into account may be of only abstract theoretical interest, not having relevance to the nature of the astronomical phenomenon which is called the "spiral structure of galaxies."

4. THE PROBLEM OF SPIRAL STRUCTURE FROM THE OBSERVATIOAL POINT OF VIEW

4.1. The Classification of Galaxies by the Degree of Regularity of the Spiral Pattern

The spiral structure of the galaxies and the structure of the arms themselves are externally so diverse that *a priori* there are no grounds to extend the regularities obtained from individual, even from very well studied systems, to the entire class of spiral galaxies. However the point of view according to which the spiral structure is reduced to two basic types has become more and more popular recently. The first type is characterized by regular arms that are symmetric with respect to the center, and which are traced over a complete rotation and further. Galaxies with a large number of breaks in the spiral arms, which are scattered over the disk of the galaxy and are not arranged along an overall spiral curve, represent the second type, the "fragmentary" spiral pattern. The presence of two types of spiral arms was first noted by Sandage,[75] who picked out a number of systems in the Hubble Atlas of Galaxies that are similar to NGC 2841 with clearly expressed fragmentary arms. The structure of the arms was investigated later by Kormendy and Norman[16] and by Elmegreen and Elmegreen.[18,77] The authors of Ref. 77 divided the spiral galaxies into 12 classes according to the nature of their arms. Membership of galaxies in the first classes signifies the predominance of unsymmetrical, fragmentary spiral patterns. The systems for which two long, symmetric arms are dominant belong to the last classes. This classification is convenient in many respects since now, in discussing the spiral structure details, it is sufficient only to indicate the spiral arm class. All the same, one must notice that it needs more precision and the introduction of quantitative criteria. For example, the angular lengths of the largest sections of arms can be taken as its basis, similar to the way the lengths of the dust bands along the spiral arms serve as the basis for classifying galaxies "by dust class." [78] Since dust bands always accompany spiral arms (and sometimes they are the main manifestation of them in the inner regions of galaxies), then the dust classes must correlate with the arm classes. Fig. 15 shows that such a correlation actually occurs. The data on H II regions in two galaxies which fall outside the correlation relation (NGC 3646 and NGC 4736) show that the dust class is a more accurate indicator of the degree of regularity of the spiral pattern, since the distribu-

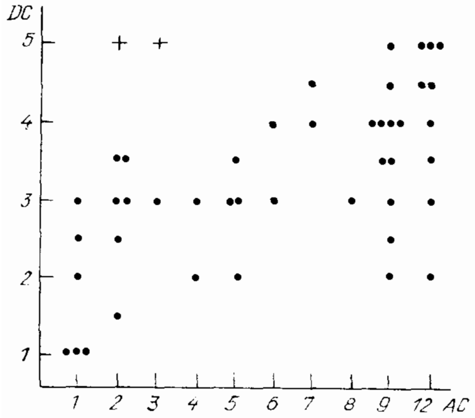

FIG. 15. Correlation between the dust class (DC) and the arm class (AC) of galaxies. NGC 3646 and NGC 4736 (marked by small crosses) deviate.

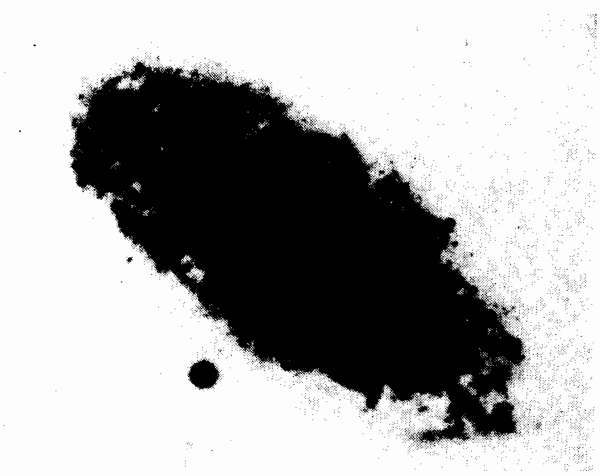

FIG. 16. The spiral galaxy NGC 2976 with a fragmentary spiral pattern (AC 3).

tion of H II regions indicates the correct spiral structure of these galaxies.[111]

The division of the spiral galaxies into regular galaxies (see Fig. 1) and fragmentary pattern ones (Fig. 16) apparently reflects a significantly different nature for the arms. The spiral arms of regular galaxies are from a spiral wave of increased star and gas density which encompasses an entire galaxy.[5] The nature of fragmentary arms (see Fig. 16) may be connected with stochastic star formation in combination with differential galactic rotation.[46–48] As was already noted in Sec. 2.3, these mechanisms are not mutually exclusive. More likely, they operate simultaneously, causing a complicated structure of spiral arms (see Fig. 17). Stars which were generated in a spiral wave can stimulate further star formation and the appearance of secondary fragmentary arms. At the same time, the secondary details of the spiral arms, which add a fragmentary appearance to the structure, may also have a wave nature; they may be caused by bifurcation effects, nonlinear wave interaction effect, etc.[80]

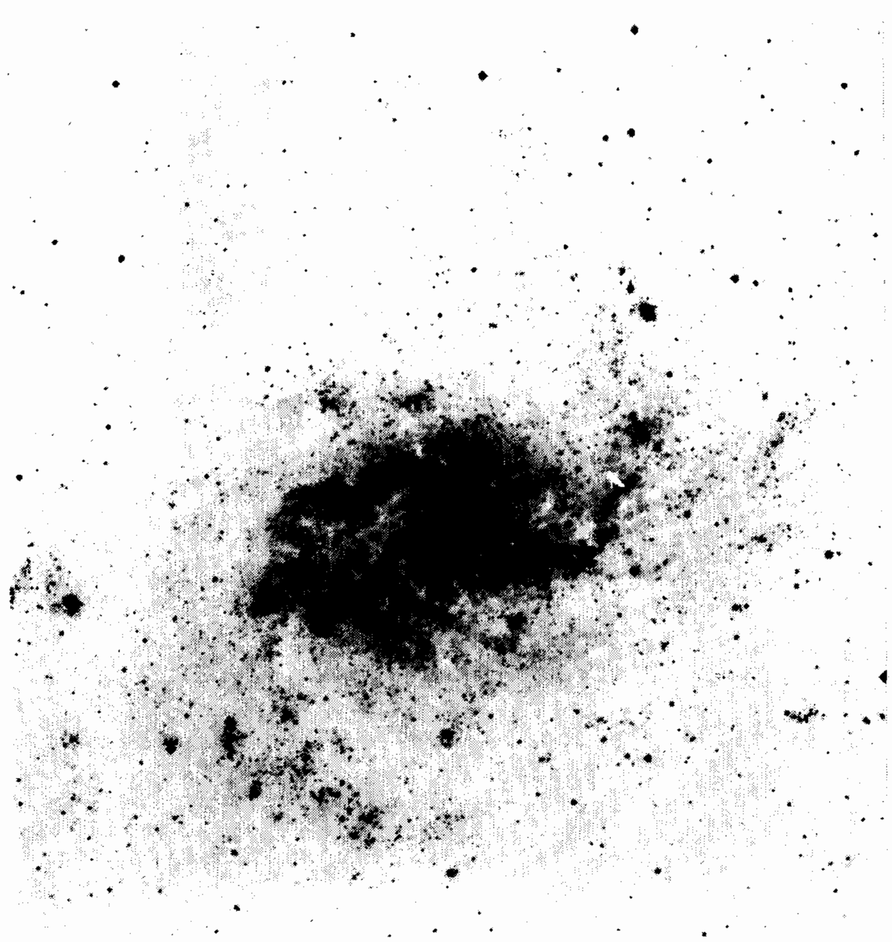

FIG. 17. A spiral galaxy in Triangulum (M33) which combines signs of the regular and fragmentary spiral patterns (AC 5).

4.2. The appearance of spiral waves

As was already noted, the wave theory predicted three effects on the scale of a whole galaxy that were unknown earlier: the galactic shock wave, the spiral perturbation of the velocity fields of stars and gas, and the gradient of star ages across the spiral arms. All these were confirmed by subsequent investigations of different galaxies, which led to extensive recognition of the wave theory of spiral structure.

4.2.1. Gas, dust, synchrotron radiation, and gamma radiation

Long dust bands situated, as a rule, along the inner edges of the stellar arms are observed in galaxies with regular spiral patterns,[75,81] and moreover, the more regular the stellar arms are, the longer and more continuous are the dust bands. Atomic and molecular hydrogen are also concentrated in the spiral arms. It is clearly evident in nearby galaxies such as the Andromeda Nebula that the maximum hydrogen density is reached just in the dust bands in front of the stellar arms.[82,83] All these properties of the distribution of gas and dust are determined by a galactic shock wave which arises in a gas which periodically passes into the wave's potential well. Clear confirmation of large-scale compression of gas in spiral arms was found in the investigation of the continuous radio radiation from the galaxy M51.[84] The amplification of synchrotron radio radiation during compression of the gas is connected with the freezing-in of the interstellar magnetic field and of cosmic rays, and was discovered in the form of bright spiral ridges on the map of the radio radiation from M51.

The increase of the densities of gas and cosmic rays in a galactic shock wave also leads to the amplification of gamma radiation from the spiral arms. From data on the gamma radiation of our Milky Way, one succeeds in constructing the detailed pattern of its spiral structure, and moreover, these data indicate that the gamma radiation is connected specifically with a galactic shock wave.[74]

The correlation of the radio luminosities of the arms of spiral galaxies with the type of spiral pattern is evidence for large-scale compression in spiral waves.[85] Strong radio radiation from the spiral arms is observed in galaxies with regular patterns, whereas the arms do not radiate noticeably in the radio range in galaxies with fragmentary patterns.

4.2.2. Departure from circular effects

The wave theory not only explains the spiral distribution of the densities of stars and gas, but also predicts a spiral velocity field which must be superimposed on a general circular motion in the disk. Such systematic departures from purely circular motion for stars and gas actually were found. They are now known from data obtained from observations of neutral, ionized, and molecular hydrogen in the Andromeda Nebula,[83,86,87] from observations of molecular hydrogen in M51,[79,88] from data for H I in the galaxy M81;[89,90] they have been detected recently from H I in the galaxy NGC 4946.[91]

Departures of velocity from circular motions have been detected for high luminosity stars in the Milky Way[92,93] which, by the way, is one of the reasons for classifying it as a system with regular spiral structure. The velocity field geometry turned out to coincide with the geometry of spiral arms that were already known long ago from the data of optical and radio observations. The amplitude of the spiral velocity component was also determined along with the geometry of the field. Overall, these characteristics allow one to calculate the most important parameters of the spiral wave in the Milky Way: the amplitudes of its density and gravitational potential, and also the rate of rotation of the spiral pattern Ω_p, which agreed with the value predicted in Ref. 1, $\Omega_p \approx 23$ km/sec·kpc.

4.2.3. The age gradient across the spiral arms

The discovery of an age gradient for young stars across the spiral arms is direct evidence for the existence of global spiral density waves and for the triggered nature of star formation in the spiral arms. One must keep in mind here that a number of processes in the spiral arms blur the pattern of the age gradient. For example, stars which were generated by the action of a spiral wave can then themselves stimulate star formation. The distribution of stars in space by their ages is changed here, and the age gradient across the arm becomes less noticeable. This may be one of the reasons for the slightly noticeable age gradient or even its absence in a number of cases noted in Refs. 94, 95, and 96. Nevertheless, an age gradient was found both in the Milky Way in the Sagittarius-Carina arm[97,98] and also in the S4 arm in the Andromeda Nebula.[99]

It is much more difficult to detect it in other galaxies because of the effect of absorption of light, insufficient spatial resolution, and other reasons. Both in the Carina arm and also in the S4 arm we encounter a case of intense star formation, and evidently little gas remains for secondary star formation. There is a direct indication of this in the S4 arm of the Andromeda Nebula; a record high gas density (H I and H II) in front of the inner edge of the stellar arm, and no bright H II regions further than 200 pc from this edge.[99] On the whole, one can explain the transverse structure of an arm by the presence of stars which were generated both from already existing clouds and also from clouds which were generated in the wave[111] (Fig. 18).

Contrary to Traat's comment,[100] one may not explain the asymmetry of the S4 stellar arm only by the absorption of light in a band of gas and dust in front of its inner edge: as is evident from Fig. 18, this band is two to three times narrower than the stellar arm, and besides, it follows from much data that star formation is still absent in the dust bands associated with the spiral arms. On the whole, a clear stratification of H I and H II regions across an arm is observed just in those cases when there is a dense and continuous dust band in front of the edge of the arm, indicating a high degree of gas compression in a galactic shock wave and a high rate of star formation initiated by it. This is explained for the S4 arm in M31 by its anomalously large angle of twist for M31.[99,111]

4.2.4. Other manifestations of spiral waves

New data have been obtained recently which confirm that the regular spiral patterns of galaxies are caused by density waves. Surface photometry of 34 galaxies was carried out in Ref. 101 in blue (B) wavelengths and in the near infrared (I) region (8250 Å), and it was shown that, upon going over to the infrared range, the spiral arms in galaxies with regular structure remain sharply delineated but become smoother and more continuous, whereas a global pattern

FIG. 18. A section of the S4 spiral arm in the Andromeda Nebula (M31). Isodensity curves of H I are shown; the small crosses show the brightest H II regions. The youngest stars are concentrated between the two dashed lines on the figure near the inner (left) edge of the arm, the H II regions are located on its boundary, and the periods of the Cepheids increase towards the same edge, i.e., their ages decrease.

does not appear in the infrared range for galaxies with fragmentary structure. This means that the density of old stars is higher only in regular spiral arms. From the brightness ratio of the arms in the B and I ranges, it was found in Ref. 101 that the density of old stars in regular arms is significantly higher (by 40% to 60%) than in the average over the disk. This eliminates the possibility of explaining the origin of regular spiral arms as the result of twisting of star formation regions by galactic rotation, and tells us that the regular spiral arms in galaxies reflect wave processes that include the stars of old subsystems. As the authors of Ref. 101 think, the fragmentary arms are regions of propagating star formation stretched into fragments of the spirals by the differential rotation of the galactic disk. According to their estimates, the ages of these spirals do not exceed $3\cdot10^8$ years.

The result of Lord and Young[102] is another confirmation of the wave nature of global spiral paterns. They found that, in the galaxy M51, the ratio of the emission intensities in the H_α and $\lambda = 2.6$ mm CO molecule lines in the interarm space is half that in the arms. Contrary to Ref. 103, this indicates an increased efficiency of star formation in a spiral density wave: two times more stars are generated here per unit mass of gas in the form of molecular hydrogen (let us recall that the amount of carbon monoxide CO is proportional to the amount of molecular hydrogen H_2 in the interstellar medium). The data of Ref. 79 also tell us this.

The formation of gigantic gas complexes is made much easier in spiral density waves, where the gas density is higher and there is less differential rotation.[103] These giant H I clouds then generate gigantic star complexes,[76,103,104] which are concentrated in the arms in galaxies with regular spiral structure. One can hypothesize that rotation closer to that of a solid body for galaxies in which fragmentary spiral structure is observed makes possible the formation of gravitationally weakly bound star complexes even without a density wave; these complexes are then stretched into sections of spiral arms fairly slowly.[111]

4.3. Observations relevant to the mechanisms of generation of spiral wave

4.3.1. Generation by the fields of bars and satellites

The existing data tell us that, in galaxies with regular structure, there are, as a rule and possibly even necessarily, either departures from axial symmetry in the central regions, or they have close satellites whose gravitational potentials cause the appearance of density waves in a disk of gas and stars. Even long ago Kormendy and Norman[16] arrived at the same conclusion from data on 54 galaxies, and it was confirmed for considerably more material in Refs. 18 and 77. It was shown in Refs. 18 and 77 that no less than 70% of the galaxies with regular spiral patterns either are located in dense groups or have a bar or satellite. Recent research shows that even those galaxies in which a bar is not visible on ordinary photographs have in their central regions departures from circular symmetry sufficient to excite spiral density waves. By studying the central regions of 11 spiral galaxies in the near infrared range ($\lambda = 0.8\ \mu$m), Zaritsky and Lo[15] found that all 11 galaxies possess elliptical nuclear bulges. As a result, they arrived at the conclusion that this phenomenon must be widespread. According to the conclusion of these authors, an oval gravitational potential may explain the noncircular motions of the gas in the central regions of galaxies and may generate spiral density waves. Let us recall that there are significant departures from circular symmetry near the center both in the Milky Way and in the Andromeda Nebula; they are especially clearly expressed in IC 342 (see Ref. 111).

4.3.2. Stochastic star formation and the spiral structure of galaxies

If young stars stimulate the formation of successive generations of stars, then, as was said above, the differential rotation of the galactic disk will stretch regions of propagating star formation into fragments of the spiral arms. Propagating star formation may be connected with other processes, for example, with a shock wave moving from the collision boundary of gas clouds. Thus, propagating star formation may be an effective mechanism for generating the spiral arms of fragmentary galaxies.

The existence of propagating star formation has extensive confirmation. Thus, Blaauw already showed[105] that, in stellar associations, the stars are organized into subgroups of different ages that are ordered in space. Later many regions were found both in the Milky Way and in other galaxies where sequential generation of stars occurs. Among them are the complexes S156, S157, S158, and S159,[106] and the complex W51 in the Sagittarius arm,[107] in which the H II regions are clearly ordered in space according to their ages. The Shapley III "constellation" of young stars in the Large Magellanic Cloud is one of the clear examples of induced star formation. A wave of star formation propagating with a

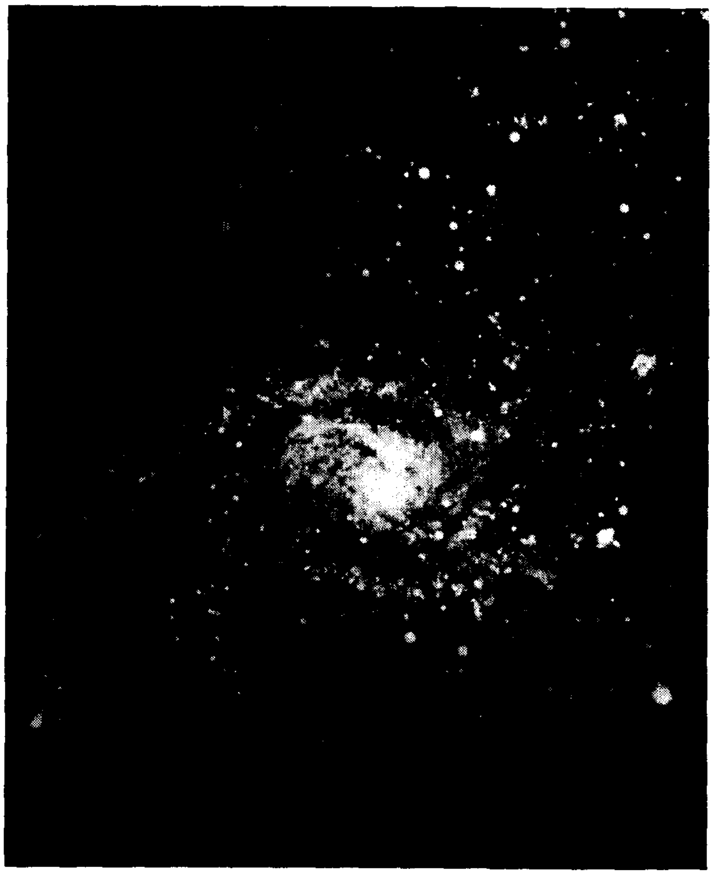

FIG. 19. The spiral galaxy NGC 6946, which is distinguished by active star formation which resulted in the outbursts of five supernovas. Arm class 9. (The photograph has been obtained by I. D. Karachentsev with the 6-meter telescope.)

velocity ~ 36 km/sec is observed in it.[108] However, there are data that a density of H I $> 10^{21}$ atoms/cm^2 is sufficient to form massive stars, and there is no need for an external trigger.[109,111]

One must emphasize that the nature of fragmentary arms cannot yet be considered to be reliably established. These arms also exist in some galaxies which, according to the data of Zeritsky and Lo,[15] have a nonaxisymmetric nuclear bulge, so that their wave nature cannot be excluded. Arms of a wave and shear nature can coexist, and then the resulting appearance of the spiral pattern will have a complicated character (see Fig. 19). On the whole, there are as yet no sufficiently convincing observational facts, such as in the case of the wave theory, which would speak in favor of the formation of fragmentary spirals as a result of propagating star star formation.

5. CONCLUSION

The quarter century that the Lin-Shu density wave theory has existed has demonstrated its extreme fruitfulness. It stimulated a large number of theoretical and observational papers, which led to the formation of qualitatively new views about the physical processes in star systems. Its predictions for galaxies with regular spiral structure were confirmed brilliantly. The most important of them were galactic shock waves and the synchrotron and gamma radiation connected with them, the spiral nature of the star velocity field, and the age gradient across spiral arms; from predictions, they passed into the category of observational facts, which significantly expanded the "bank" of fundamental properties of spiral galaxies. In summary, in spite of the problems which exist in the theory and which yield with difficulty to the efforts of the theoreticians, the gravitational theory of density waves remains without competition from alternative theories.

1 L. S. Marochnik and A. A. Suchkov, Usp. Fiz. Nauk **112**, 275 (1974); [Sov. Fiz. Usp. **17**, 85 (1974)].
2 J. Oort, *Interstellar Matter in Galaxies* (L. Woltjer, editor), Benjamin, N.Y., 1962.
3 L. S. Marochnik and A. A. Suchkov, *The Galaxy* (in Russian), Nauka, M., 1984.
4 B. Lindblad, Stockholm Observatory Ann. **22**, 3 (1963).
5 C. C. Lin and F. H. Shu, Astrophys. J. **140**, 646 (1964).
6 C. C. Lin and Y. Y. Lau, SIAM J. App. Math **29**, 352 (1975).
7 T. Nishimoto, Stud. Appl. Math. **60**, 11 (1979).
8 Y. Y. Lau and G. Bertin, Astrophys. J. **226**, 508 (1978).
9 R. F. Pannatoni and Y. Y. Lau, Proc. Natl. Acad. Sci. U.S.A. **76**, 4 (1979).
10 J. Haas, G. Bertin and C. C. Lin, Proc. Natl. Acad. Sci. U.S.A. **79**, 3908 (1982).
11 G. Bertin and W. K. Mark, Astron. Astrophys. **64**, 389 (1978).
12 L. S. Marochnik and A. A. Suchkov, Astron. Zh. **46**, 319 (1969); [Sov. Astron. **13**, 252 (1969)].
13 G. Bertin, Phys. Rep. **61**, 3 (1980).
14 C. C. Lin and G. Bertin, Adv. Appl. Mech. **24**, 155 (1984).
15 D. Zaritsky and K. Y. Lo, Astrophys. J. **300**, 66 (1986).
16 J. Kormendy and C. N. Norman, Astrophys. J. **233**, 539 (1979).
17 V. C. Rubin, W. K. Ford, and N. Thonnard, Astrophys. J. **238**, 47 (1980).
18 D. M. Elmegreen and B. G. Elmegreen, Astrophys. J. **267**, 31 (1983).
19 R. H. Miller, K. H. Prendergast, and W. J. Quirk, Astrophys. J. **161**, 903 (1970).
20 B. M. Dzyuba and V. B. Yakubov, Astron. Zh. **47**, 3 (1970) [Sov. Astron. **14**, 1 (1970)].
21 F. Hohl, Astrophys. J. **168**, 343 (1971).
22 R. H. Miller and B. F. Smith, Astrophys. J. **227**, 407, 785 (1979).

[23]J. P. Ostriker and P. J. E. Peebles, Astrophys. J. **186**, 467 (1973).
[24]F. Hohl, Astron. J. **81**, 30 (1976).
[25]G. Contopoulos, Astron. Astrophys. **96**, 164 (1980).
[26]J. A. Sellwood, Astron. Astrophys. **99**, 362 (1981).
[27]S. I. Feldman and C. C. Lin, Stud. Appl. Math. **52**, 1, (1973).
[28]V. I. Korchagin and L. S. Marochnik, Astron. Tsirk, No. 700 (1973); Astron. Zh. **52**, 700 (1975) [Sov. Astron. **19**, 428 (1975)].
[29]R. H. Sanders and J. M. Huntley, Astrophys. J. **209**, 53 (1976).
[30]S. A. Sorensen, T. Matsuda, and M. Fujimoto, Astrophys. Space Sci. **43**, 491 (1976).
[31]R. H. Berman, D. J. Pollard, and R. W. Hockney, Astron. Astrophys. **78**, 133 (1979).
[32]L. S. Marochnik, Astron. Zh. **41**, 264 (1964) [Sov. Astron. **8**, 202 (1964)].
[33]S. Kato, Publ. Astron. Soc. Japan **22**, 285 (1970).
[34]C. Hunter, Astrophys. J. **227**, 73 (1979).
[35]G. F. Chew, M. L. Goldberger, and F. E. Low, Proc. R. Soc. London Ser A **236**, 112 (1956).
[36]K. O. Thielheim and H. Wolff, Mon. Not. R. Astron. Soc. **199**, 151 (1982).
[37]V. I. Korchagin and Yu. G. Shevelev, Astrofizika **16**, 757 (1980); [Astrophysics **16**, 433 (1980)].
[38]V. I. Korchagin and Yu. G. Shevelev, Astrofizika **17**, 455 (1981); [Astrophysics **17**, 254 (1981)].
[39]V. I. Korchagin, Astron. Zh. **53**, 260 (1976); [Sov. Astron. **20**, 148 (1976)].
[40]M. P. Schwarz, Proc. ASA **5**, 4 (1984).
[41]K. H. Prendergast, *International Astron. Union Symposium No. 38*, D. Reidel, Dordrecht, Holland, 1970, p. 303.
[42]M. P. Schwarz, Mon. Not. R. Astron. Soc. **212**, 677 (1985).
[43]S. A. Sorensen, Mon. Not. R. Astron. Soc. **212**, 723 (1985).
[44]V. I. Korchagin and Yu. G. Shevelev, Astrofizika **18**, 589 (1982); [Astrophysics **18**, 337 (1982)].
[45]V. I. Korchagin, Ye. A. Langueva, and N. A. Prokhovnik, Astron. Tsirk., No. 1482 (1987); V. I. Korchagin, Ye. A. Langueva, and N. A. Prokhovnik, Astron. Zh. **65**, (1988) [Sov. Astron. **32**, (1988)].
[46]H. Gerola and P. E. Seiden, Astrophys. J. **223**, 129 (1978).
[47]P. E. Seiden, L. S. Schulman, and J. V. Feitzinger, Astrophys. J. **253**, 91 (1982).
[48]P. E. Seiden and H. Gerola, Fundam. Cosmic Phys. **7**, 241 (1982).
[49]P. Goldreich and D. Lynden-Bell, Mon. Not. R. Astron. Soc. **130**, 97 (1965).
[50]J. A. Jaaniste and E. M. Saar, Pis'ma Astron. Zh. **3**, 9 (1977) [Sov. Astron. Lett. **3**, 4 (1977)].
[51]Yu. A. Shchekinov, Pis'ma Astron. Zh. **13**, 862 (1987) [Sov. Astron. Lett. **13**, 361 (1987)].
[52]V. I. Korchagin, V. A. Krol', and A. D. Ryabtsev, Preprint ITP-87-91P [In Russian] Kiev, 1987.
[53]I. G. Kolesnik and S. A. Silich, Preprint ITP-87-59E, Kiev, 1987.
[54]E. Öpik, Irish Astron. J. **2**, 219 (1953).
[55]C. J. Lada, L. Blitz, and B. G. Elmegreen, in *Protostars and Planets* (T. Gehrels, editor), University of Arizona Press, Tucson, 1978, p. 341.
[56]C. Norman and J. Silk, Astrophys. J. **238**, 158 (1980).
[57]P. Goldreich and D. Lynden-Bell, Mon. Not. R. Astron. Soc. **130**, 125 (1965).
[58]A. A. Suchkov and Yu. A. Shchenikov, Astron. Zh. **56**, 1179 (1979) [Sov. Astron. **23**, 665 (1979)].
[59]H. Haken, *Introduction to Synergetics*, Springer-Verlag, N.Y. 1977 [Russ. transl., Mir, M., 1980.]
[60]H. Gerola and P. E. Seiden, in: *Photometry, Kinematics, and Dynamics of Galaxies* (D. S. Evans, editor), University of Texas Press, Austin, 1979, p. 475.
[61]W. W. Roberts and M. A. Hausman, Astrophys. J. **277**, 744 (1984).
[62]V. I. Korchagin, P. I. Korchagin, and A. D. Ryabtsev, Astrophys. Space Sci. **141**, 55 (1988).
[63]G. Bodifee and C. de Loore, Astron. Astrophys. **142**, 297 (1985).
[64]W. H. Waller, D. P. Clemens, D. B. Sanders, and N. Z. Scoville, Astrophys. J. **314**, 397 (1987).
[65]G. Smith, B. G. Elmegreen, and D. M. Elmegreen, Mon. Not. R. Astron. Soc. **210**, 399 (1984).
[66]A. M. Fridman, Astron. Zh. **63**, 884 (1986) [Sov. Astron. **30**, 525 (1986).
[67]R. C. Kennicutt, Jr. and B. K. Edgar, Astrophys. J. **300**, 132 (1986).
[68]P. S. van der Kruit, J. H. Oort, and D. S. Mathewson, Astron. Astrophys. **21**, 169 (1972).
[69]A. D. Tubbs, Astrophys. J. **239**, 892 (1980).
[70]V. G. Berman, L. S. Marochnik, Yu. N. Mishurov, and A. A. Suchkov, Institute for Space Research, Academy of Sciences of the USSR, Preprint No. 717 (In Russian), Moscow (1982).
[71]L. S. Marochnik, V. G. Berman, Yu. N. Mishurov, and A. A. Suchkov, Astrophys. Space Sci. **89**, 177 (1983).
[72]V. G. Berman, L. S. Marochnik, Yu. N. Mishurov, A. A. Suchkov, and P. N. Timonin, Astron. Zh. **63**, 31 (1986) [Sov. Astron. **30**, 20 (1986)].
[73]S. Phillips, S. Kearsey, J. L. Osborne, C. G. T. Haslam, and H. Stoffel, Astron. Astrophys. **98**, 286 (1981).
[74]V. I. Korchagin, P. I. Korchagin, and A. A. Suchkov, Astron. Zh. **60**, 478 (1983) [Sov. Astron. **27**, 277 (1983)].
[75]A. R. Sandage, *The Hubble Atlas of Galaxies*, The Carnegie Institution of Washington, Washington, D.C., 1961.
[76]B. G. Elmegreen and D. M. Elmegreen, Mon. Not. R. Astron. Soc. **203**, 31 (1983).
[77]B. G. Elmegreen and D. M. Elmegreen, Astrophys. J. **314**, 3 (1987).
[78]B. T. Lynds, Astrophys. J. **238**, 17 (1980).
[79]S. N. Vogel, S. R. Kulkarni, and N. Z. Scoville, Nature **334**, 402 (1988).
[80]Yu. N. Mishurov and A. A. Suchkov, Astron. Zh. **53**, 206 (1976) [Sov. Astron. **20**, 112 (1976)]. S. M. Churilov and I. G. Shukhman, Astron. Zh. **58**, 260 (1981) [Sov. Astron. **25**, 147 (1981)]. V. I. Korchagin and P. I. Korchagin, Pis'ma Astron. Zh. **10**, 14 (1984) [Sov. Astron. Lett. **10**, 5 (1984)].
[81]B. T. Lynds, Astrophys. J. Suppl. **28**, 391 (1974).
[82]S. C. Unwin, Mon. Not. R. Astron. Soc. **190**, 551 (1980).
[83]M. Nakano, T. Ichikawa, Y. D. Tanaka, N. Nakai, and Y. Sofue, Proc. Astron. Soc. Japan **39**, 57 (1987).
[84]D. S. Mathewson, P. S. van der Kruit, and W. N. Brown, Astron. Astrophys. **17**, 468 (1972).
[85]V. I. Korchagin, Astron. Tsirk., No. 1221 (1982).
[86]E. Brinks and W. W. Shane, Astron. Astrophys. Suppl. **55**, 179 (1984).
[87]J. M. Deharveng and A. Pellet, Astron. Astrophys. **38**, 15 (1975).
[88]G. Rydbeck, A. Hjamarson, and O. E. H. Rydbeck, Astron. Astrophys. **144**, 282 (1985).
[89]A. H. Rots and W. W. Shane, Astron. Astrophys. **45**, 25 (1975).
[90]H. C. D. Visser, Astron. Astrophys. **88**, 159 (1980).
[91]L. I. Tacconi and J. S. Young, Astrophys. J. **308**, 600 (1986).
[92]Yu. N. Mishurov, Ye. D. Pavlovskaya, and A. A. Suchkov, Astron. Zh. **56**, 268 (1979) [Sov. Astron. **23**, 147 (1979)].
[93]R. M. Humphreys, Astron. J. **75**, 602 (1970); R. M. Humphreys, Astron. Astrophys. **20**, 29 (1972).
[94]F. Schweitzer, Astrophys. J. Suppl. **31**, 313 (1976).
[95]J. R. Talbot, E. B. Jensen, and R. J. Dufour, Astrophys. J. **229**, 91 (1979).
[96]U. Guidoni, R. Messi, and G. Natali, Astron. Astrophys. **96**, 215 (1981).
[97]Ye. D. Pavlovskaya and A. A. Suchkov, Astron. Zh. **61**, 665 (1984); [Sov. Astron. **28**, 389 (1984)].
[98]L. N. Berdnikov, Pis'ma Astron. Zh. **13**, 110 (1987) [Sov. Astron. Lett. **13**, 45 (1987)].
[99]Yu. N. Efremov, Pis'ma Astron. Zh. **11**, 69 (1985) [Sov. Astron. Lett. **11**, XXX (1985)].
[100]P. Traat, Tartu Publ. **51**, 181 (1986).
[101]B. G. Elmegreen and D. M. Elmegreen, Astrophys. J. Suppl. **54**, 127 (1984).
[102]S. Lord, S. E. Strom, and J. S. Young, *Star Formation in Galaxies* (C. Person, editor) (1987), p. 303.
[103]B. G. Elmegreen, *International Astron. Union Symposium No. 115*, D. Reidel, Dordrecht, Holland, 1987, p. 457.
[104]Yu. N. Efremov, Vestnik, Akad. Nauk SSSR, No. 12, 56 (1984).
[105]A. Blaauw, Ann. Rev. Astron. Astrophys. **2**, 313 (1964).
[106]P. T. P. Ho, A. D. Haschick, and F. P. Israel, Astrophys. J. **243**, 526 (1981).
[107]J. F. Lightfoot, W. Cudlip, I. Furniss, W. M. Glencross, R. E. Jennings, K. J. King, and G. Poulter, Mon. Not. R. Astron. Soc. **205**, 653 (1983).
[108]M. A. Dopita, D. S. Mathewson, and V. L. Ford, Astrophys. J. **297**, 599 (1985).
[109]E. D. Skillman, Bull. Am. Astron. Soc. **18**, 691 (1986).
[110]J. E. Beckman, S. G. Bransgrove, and J. P. Phillips, Astron. Astrophys. **157**, 49 (1986).
[111]Yu. N. Efremov, Centers of Star Formation in Galaxies [in Russian], Nauka, M., 1989.
[112]A. R. Sandage, *International Astron. Union Symposium No. 100*, D. Reidel, Dordrecht, Holland (1983), p. 367.

Translated by Frederick R. West