**A. M. Fridman**, *Origin of the spiral structure of galaxies*. The problem of the origin of the spiral structure of galaxies can be formulated as follows: How can condensations of stars and gas in the form of spiral arms exist in a stationary manner in the flat subsystem of a spiral galaxy?

The problem would seem at first to be very simple. Indeed, let us suppose that there is an initial condensation $AB$ (Fig. 1a). Then because of the differential rotation of the galactic disk, the initial condensation $AB$ begins to stretch and becomes deformed into a segment $A'B'$ of the lagging spiral (Fig. 1b). Obviously, however, the spiral arm will be stretched further and further with each rotation of the galaxy, so that it will become more and more tenuous until it finally dissolves in the galactic disk. This means that a generating mechanism is necessary in order to maintain the spiral pattern. This generating mechanism must be powerful enough to fully regenerate the spiral pattern in a single revolution of the galactic disk. In that case, however, the spiral arms should consist entirely of young stars with ages comparable with the galactic rotation period (~$10^8$ years), and this is in conflict with observation. This "material" regenerative hypotheses of spirals, originated by Goldreich and Lynden-Bell[1] and presented briefly above, has no adherents at present.

The idea advanced by Lindblad[2] and developed by Lin and Shu[3] that the spiral arms are to be identified with density waves in the stellar "gas" in considerably more popular. Since there are dissipative forces in any real system and, in addition, wave packets may spread in the radial direction,[4] a generator of spiral density waves is necessary in order to maintain the spiral pattern. The mechanisms for generating density waves proposed by Lin and other authors are discussed in detail in Ref. 5: the Jeans instability at the periphery[6] and in the central part of the galactic disk,[3] and the rotating bar at the center of the galaxy.[7] An attempt to explain the multiarm and multistage structures (Fig. 2) in terms of these mechanisms, however, encounters serious difficulties.

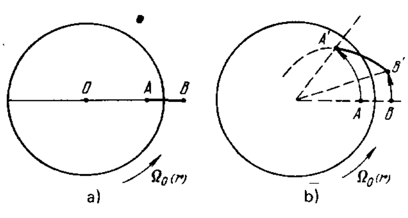


FIG. 1.

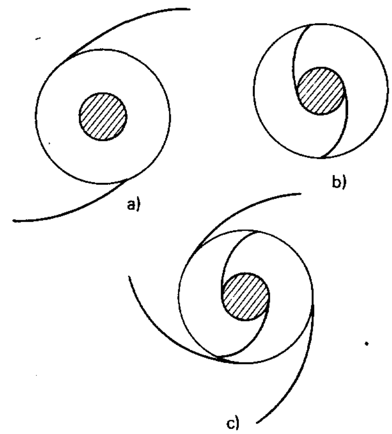


FIG. 2.

In the central region of the galaxy there can develop not only the Jeans instability, but also another kind of gravitational instability—flute instability[8]—the necessary condition for which is satisfied because of the bell-shaped distribution of hydrogen in the galactic plane (Fig. 3). The velocity distribution of stars in the vicinity of the sun, shown in Fig. 4, is of the "beam" type, and may therefore give rise to the development of gravitational instabilities of still another type—beam instabilities.[9]

In analyzing the various mechanisms for the generation of density waves one cannot fail to note that the formation of spirals in rotating media is not a specific property of gravitating media alone and is therefore not necessarily associated only with the Jeans instability and the gravitational interaction. Indeed, in daily life we frequently observe the formation of spirals in a rotating liquid, and satellite photographs provide beautiful pictures of the formation of spirals in a gas (cyclones and anticyclones).

The distribution of the basic parameters of spiral galaxies is such as to admit the generation of the same hydrodynamic instabilities as can arise in rotating *non-gravitating* continuous media.

Thus, Rubin and Ford[10] noted a segment on the rotation curve of the Andromeda nebula (Fig. 5) on which the rotational velocity falls sharply with increasing radius, and which may be due to a sharp edge of the plane bulge.


FIG. 3.

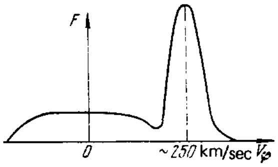


FIG. 4.

A Kelvin–Helmholtz instability might develop in such a region.[8]

It follows from a series of our studies that the non-Jeans instabilities have two important advantages over the Jeans instabilities as generators of spiral structure.

1) The discrepancy between the Jeans wavelength and the distance between the spiral arms is automatically removed, since now the minimum wavelength of a perturbation is determined by the thickness of the galactic disk alone.

2) The upper bound on the magnitude of the velocity dispersion of the stars and gas clouds is lifted; moreover, as the velocity dispersion increases, the logarithmic increments of the hydrodynamic instabilities also increase, for as the velocity dispersion increases the properties of the medium tend to those of an incompressible liquid (in which the dispersion is infinite).

In principle, the hydrodynamic mechanism for generating spiral arms enables us to model the process of spiral production in a rotating medium that does not interact gravitationally, for it has been shown[8] that the gravitational effects are small of the order of $(\lambda/\lambda_J)^2$ as compared with the hydrodynamic effects (here $\lambda$ is the wavelength of the disturbance and $\lambda_J$ is the Jeans wavelength). With the VP-1 rotating plasma device we obtain pictures showing two, three, four, and five spiral arms.[11]

The explanation for the multistage spiral structure of galaxies may be that the conditions in regions of the disk at different distances $r$ from the center are such as to favor a preferential development of some particular instabilities. Each of the instabilities is characterized by its own dependence of the maximum logarithmic increment on the azimuthal mode number $m$, and this leads to the development of different forms of spiral structure in different regions of the system.

Lin, Yuan, and Shu[12] maintain that the dispersion characteristics of a spiral density wave are determined equally by the gaseous and the stellar components. However, the gas in the spiral arms is several times denser than the background gas, and this means that one must resort to a nonlinear theory—at least as far as the gaseous component is concerned.

A nonlinear theory of density waves in the gaseous component has been developed in Refs. 5, 13, and 14. In the same papers (also see Ref. 15) the hypothesis

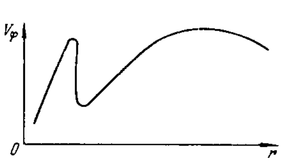

FIG. 5.

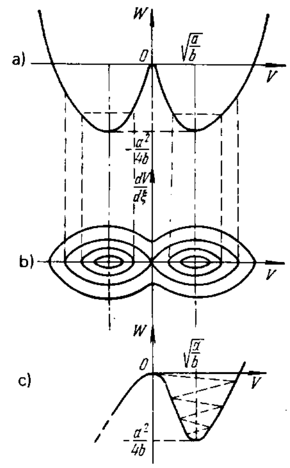


FIG. 6.

was advanced that the spiral density waves can be represented as moving solitons. By definition a soliton is a nonlinear stationary density wave. On the basis of observations we visualize a spiral arm to be precisely of this nature.

As it turned out,[13] the equation for finite-amplitude density waves in a gravitating disk is of the same type as the Duffing equation for a nonlinear oscillator.[16] The effective potential energy $W(V)$ and the phase plane for the Duffing equation in the absence of dissipation are shown in Fig. 6a and 6b. To the soliton (Fig. 7a) there corresponds a separatrix (see Fig. 6b) that separates two types of periodic solutions. In Fig. 6a the soliton corresponds to a "vibrational energy level" situated at $V=0$. Now if we take dissipation into account we find that the soliton transforms into a shock wave with an oscillating front (Fig. 7b and 7c).[17] In Fig. 7c, this solution corresponds to "particles falling into the well." Intense formation of stars from the compressed gas takes place at the shock front. Stellar formation may be stimulated, in particular, by shock instability.[4]

The problem of nonlinear waves in the stellar ellipsoid[18] can be reduced to the above mentioned problem[5,13,14] of nonlinear waves in the gaseous disk by the method of Chew, Goldberger, and Low for a magnetized plasma.[19] In the drift approximation we obtain the equations of anisotropic hydrodynamics for the model of a

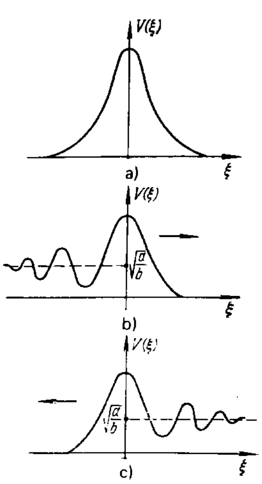


FIG. 7.

collisionless stellar ellipsoid, and on solving these equations in analogy with Refs. 5, 13, and 14, we find that solitons, shock instability, and collisionless shock waves are present in the stellar ellipsoid.[18] The results of Refs. 17 and 18 (unlike those of Ref. 20) show that shock waves exist in the gaseous disk and the collisionless stellar ellipsoid in the form of self-consistent solutions of the initial set of equations.

The existence in spiral galaxies of solitons moving outward from the center in the form of ring structures is predicted in Ref. 21. At present such ring structures have been found in nine of the nearest spiral galaxies.[22]


[1]B. Goldreich and D. Lynden-Bell, Mon. Not. Roy. Astron. Soc. **130**, 125 (1965).

[2]B. Lindblad, Stockholm Obsy. Ann. **20**, (6) (1958); **22**, 3 (1963).

[3]C. C. Lin and F. H. Shu, Astrophys. J. **140**, 646 (1964); Proc. Natl. Acad. Sci. USA **55**, 229 (1966). C. C. Lin, SIAM J. Appl. Math. **14**, 876 (1966).

[4]A. Toomre, Astrophys. J. **158**, 899 (1969).

[5]V. L. Polyachenko and A. M. Fridman, Ravnovesie i ustoichivost' gravitiruyushchikh sistem (Equilibrium and Stability of Gravitating Systems), "Nauka", Moscow, 1976.

[6]C. C. Lin, in IAU Symposium No. 38, Dordrecht, D. Reidel, 1970.

[7]S. I. Feldman and C. C. Lin, Stud. Appl. Math. **52**, 1 (1973).

[8]A. G. Morozov and A. M. Fridman, in Dinamika i evolutsiya zvezdnykh sistem (Dynamics and Evolution of Stellar Systems), VAGO, M.—L. 1975, p. 238. A. G. Morozov, V. L. Polyachenko, V. G. Faĭnshteĭn, and A. M. Fridman, Astron. Zh. **53**, 735 (1976). [*sic*]. A.G. Morozov, V.G. Faĭnsteĭn, and A. M. Fridman, Dokl. Akad. Nauk SSSR **228**, 1072 (1976). [*sic*].

[9]A. B. Mikhaĭlovskiĭ and A. M. Fridman, Zh. Eksp. Teor. Fiz. **61**, 457 (1971) [Sov. Phys.-JETP **34**, 243 (1972)].

[10]V. C. Rubin and W. K. Ford Jr., Astrophys. J. **159**, 457 (1971).

[11]A. G. Morozov, V. G. Faĭnshteĭn, and A. M. Fridman, Zh. Eksp. Teor. Fiz. **72**, 1249 (1976) [Sov. Phys.-JETP **44**, 653 (1976)].

[12]C. C. Lin, C. Yuan, and F. H. Shu, Astrophys. J. **155**, 721 (1969).

[13]A. M. Fridman, Diklad na Vsesoyuznoĭ konferentsiĭ po plazmennoĭ astrofizike (Report at the All-Union conference on plasma astrophysics), Irkutsk, 1976. A. B. Mikhailovskiĭ, V.I. Petviashvili, and A.M. Fridman, Astron. Zh. (1977) [*sic*]; Pis'ma Zh. Eksp. Teor. Fiz. **26**, 129 (1977) [JETP Lett. **26**, 121 (2977)].

[14]A. B. Mikhaĭlovskiĭ, V. I. Petviashvili, and A. M. Fridman, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 341 (1977) [JETP Lett. **26**, 241 (1977)].

[15]S. A. Kaplan, K. V. Khodataev, and V. N. Tsytovich, Pis'ma Astron. Zh. **3**, 13 (1977) [Sov. Astron. Lett. **3**, 7 (1977)].

[16]N. N. Moiseev, Asimptoticheskie metody nelineĭnoĭ mekhaniki (Asymptotic Methods in Nonlinear Mechanics), "Nauka", Moscow, 1969.

[17]A. M. Fridman, Pis'ma Astron. Zh. (1977) (in press).

[18]A. M. Fridman, Pis'ma Astron. Zh. (1978) [Sov. Astron. Lett. (in press)].

[19]G. Chew, M. Goldberger and F. Low, Proc. R. Soc. **A236**, 112 (1956).

[20]W. W. Roberts, Astrophys. J. **158**, 123 (1969).

[21]A. M. Fridman, Pis'ma Astron. Zh. (1978) [Sov. Astron. Lett. (in press)]. A.M. Fridman, in: IAU Symposium No. 79, Tallinn, 1977.

[22]M. A. Smirnov and B. V. Komberg, Pis'ma Astron. Zh. (1977). [Sov. Astron. Lett. (in press)]. S. Hayakawa, K. Ito, T. Matsumoto, and K. Uyama, Astron. and Astrophys. **58**, 325 (1977).