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ROTATING GALACTIC ARMS AND LEADING-EDGE SHOCK WAVES IN H III

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SHOCK WAVES IN H III

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SUMMARY

A steady-state galactic-structure theory based on magnetohydrodynamic principles has been developed. Quasi-steady states, however, are not excluded. The theory provides an energy source for the coronal heating called for in the theories of Pickelner and Spitzer. The magnitude of the energy source can be calculated and appears adequate for Spitzer's theory and possibly is adequate for Pickelner's theory. In order to agree with other aspects of our knowledge of spiral galaxies, barred spirals in particular, it is necessary to assume that spiral arms are shaped by supersonic drag with attendant shocks. The angular motion of the galactic arms through the gas in the disk produces a flow over the arms which is subsonic within a certain distance of the galactic center and is supersonic outside it. From resulting aerodynamic effects an explanation of important galactic phenomena can be made.

INTRODUCTION

The theory in this paper proposes that galactic arms are spiral shaped because the arms are rotating in a gas and encountering supersonic drag which would tend to force the arms into a spiral shape. In fact, some spiral-shape propeller blades have been designed for this very purpose of eliminating supersonic drag; the underlying principle is much the same as that of sweepback in airplane wing theory. However, for a rotating blade, or arm, the sweepback has to be increased progressively outward toward the end of the arm with a resulting spiral shape. The purpose of the spiral shape is to limit the component of velocity normal to the arm or blade axis to subsonic velocity. The present theory assumes that these ideas might be applicable to galaxies. Furthermore, if the rotational speed of the arm were somewhat slow so that only an outward portion of the arm were supersonic, then it might be that only the outward portion would be spiral shaped and thus barred spirals would be accounted for. The investigation of these notions applied to galaxies has led to the present theory.

In this theory, the arms are assumed to rotate through the interstellar, intercloud continuum gas of the disk, which may be regarded as simply the continuation of the halo through the disk; this continuum gas (hydrogen) is hereinafter referred to as H III[1]. The motion of the arms through the halo would create much "debris" and it is presumed herein that this debris is what is observed to be the "disk." The disk material would be accelerated by the arms so that there would be a complicated state of motion: a rigid body motion for the arms, the observed differential rotation for the disk, and a relatively stationary state for the halo outside the disk. The arms are viewed as plasma-magnetic structures and it is further assumed that the arms exclude H III already external because of the magnetic fields frozen into the gas of the arms (ref. 2, pp. 4 to 7). Therefore, the arms are taken to be like the impermeable bodies dealt with in aerodynamics. The arms are thought to be formed by an outflowing of ionized and neutral gas from the nucleus with a consequent stretching of magnetic lines out along the arms from the nucleus. A conceptual drawing illustrating the point of view of the present theory for a typical galaxy is shown in figure 1. The velocity of the arms relative to the H III gas might equal the speed of sound at some radius. Outside the sonic radius supersonic flow prevails; inside, the relative speed of the arms is subsonic. Supersonic flow and subsonic flow can be distinguished by observing that the former produces much higher drags than the latter. Therefore, it is expected that the arms, in order to be relieved of the supersonic drag, would be bent back into a spiral form, which would require the arms to take a spiral shape outside the sonic radius. Inside the sonic radius the arm shape would not be governed by drag but by other considerations so that the shape inside the sonic radius would be different in character from the shape outside; this suggests a cause for the formation of barred spirals. Furthermore, it is not difficult to include normal spirals also because it is only necessary to assume that the flow is supersonic all along the arm and that the sonic radius is less than the radius of the galactic nucleus.

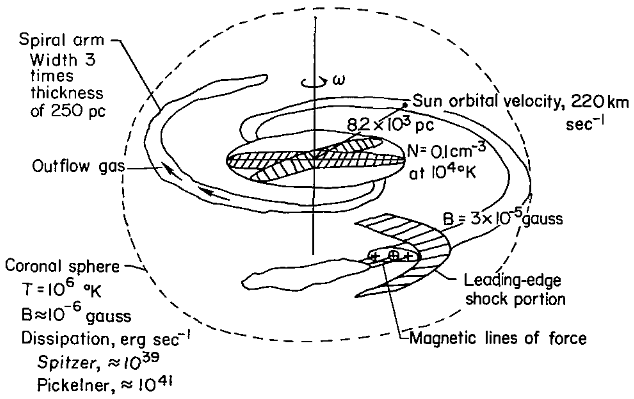

Figure 1.- Galaxy model.

Since the phenomena under consideration involve supersonic velocities, it is inevitable that shock waves will be involved. There is some encouragement that these shocks may offer an explanation of the heating of the galactic halo. Such shock waves would easily propagate up into the halo and thus be efficient in providing a heating mechanism throughout the halo.

The theory as presented herein is for the steady state. However, this does not mean that quasi-steady states are excluded. Therefore, it is envisioned that the theory would apply to galaxies that were slowly evolving from one type to another.

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[1]H III is admittedly a misnomer, as is mentioned in reference 1 (p. 1108); however, the same admission applies to H II. The use of H III seems preferable to choosing a new word.

SYMBOLS

B	magnetic field strength, gauss
b	nominal galactic arm length, parsec
c	speed of sound, centimeters per second
D	aerodynamic drag, dynes
$\overline{F}$	force, dynes
h	nominal galactic arm thickness, parsec
k	Boltzmann's constant, 1.38×10^{-16} erg per degree
M	Mach number, V/c
m	proton mass, approximately 1.67×10^{-24} gram
N	particle (hydrogen) concentration, per cubic centimeter
p	pressure, dynes per square centimeter
r,θ,z	cylindrical coordinates
T	temperature, degrees Kelvin
t	time, seconds
V	velocity, centimeters per second
x,y,z	rectangular Cartesian coordinates
ω	angular velocity, radians per second
Λ	angle by which the axis of a cylindrical element is swept back from the stream direction
φ	velocity potential function

Subscripts:

a	axial
p	perpendicular
1	upstream from shock
2	downstream from shock

A prime to a symbol indicates corotating or moving reference system.

The symbols ⊕ and + denote magnetic-field vectors perpendicular to the surface of the page.

The unit parsec (or pc) is approximately equal to 3.084×10^{18} centimeters.

REVIEW OF OBSERVATIONAL DATA PERTAINING TO GALAXIES

About 40 years ago, Edwin Hubble first discerned that many objects in the sky which had, prior to that time, been regarded as diffuse clouds within our own galactic system were themselves galaxies so distant that the individual stars could not be resolved. Hubble classified these galaxies by means of the now familiar "tuning fork diagram" shown in figure 2 (from ref. 3, p. 276). About 20 percent of all galaxies are spheroidal in form, their elliptical cross sections ranging from almost circular (E0) to highly elongated (E7). Two to three percent of the galaxies show an almost complete lack of form and are classified as irregulars. The rest, about 80 percent of the total number, are spiral galaxies which are of specific concern in this report. When looked at through an optical telescope, spiral galaxies appear as thin disks, their thickness at the center being only about 1 to 2 percent of the over-all diameter. When viewed perpendicularly to the plane of the disk, the galaxies display a wide diversity of spiral structure. The normal spirals, designated S in the Hubble classification, have spiral arms emerging directly from the central nucleus. The barred spirals, denoted SB, consist of a nucleus with a bar through it, the spiral arms extending from the extremities of the bar. The letters a, b, c define the degree of tightness of winding of the spiral arms. Thus, a galaxy which is given a classification Sa is a normal spiral galaxy with tightly wound arms; an SBc galaxy, on the other hand, is a barred spiral with loosely wound arms.

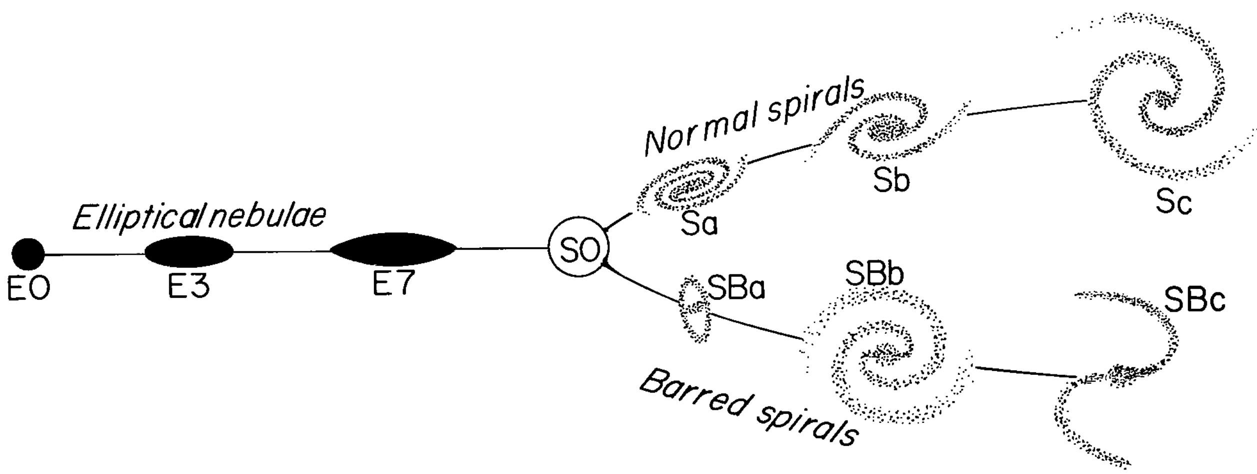


Figure 2.- Standard classification according to Hubble's tuning fork diagram (1925).

The arms of a spiral galaxy glow brightly, illuminated by the supergiant O and B stars which populate them. It is generally believed that much of the gas and dust which make up a spiral galaxy is concentrated along the spiral arms (ref. 4, pp. 86-87). This circumstance has provided a means for mapping the arms of the Galaxy by observing the 21-cm line of neutral hydrogen.

Within the past 15 years some extremely significant observations have been made pertaining to the structure of the Galaxy. It has been recently established (ref. 5, pp. 126-127) that the Galaxy is surrounded by a tenuous, roughly spherical halo of hydrogen gas, the halo being at a temperature as high as 10^6 °K and permeated by magnetic fields of the order of 10^{-6} gauss. Some years ago, following the discovery of polarization of starlight, it was deduced that the spiral arms were permeated by magnetic fields having a strength which is currently estimated to be about 3×10^{-5} gauss, the field lines being roughly alined along the spiral arms. (For discussions of arm magnetic-field strengths, see refs. 6 to 9.) More recently, surging of hydrogen outwards along bars, and presumably the spiral arms, has been observed (ref. 10). This outflow of partially ionized hydrogen is believed to be guided and constrained by the field lines embedded within it. Whether this outward streaming hydrogen exhausts at the extremities of the arms to intergalactic space or whether it is returned to the halo remains for the present an unanswered question.

The distribution of hydrogen within the galactic arms exhibits a surprising range of density variation (ref. 1, p. 1108). There are the cool clouds of neutral hydrogen, designated H I region, which measure about 10 pc across on the average and with a particle density of approximately 10 H atoms per cc have an estimated temperature of about 100° K. Most of the supergiant O and B stars are enveloped in hot and dense clouds of ionized hydrogen at a temperature of about 10 000° K, designated H II region, the particle density being approximately 10 H ions per cc. The H I and H II cloud regions occupy about 10 percent by volume of interstellar space. The remaining 90 percent of space is occupied by hydrogen in a state designated H III or intercloud region by Minnaert (ref. 1, p. 1108). It is a prevalent belief (ref. 11), though not shared by everyone, that in this intercloud region the temperature is about 10 000° K but the concentration is only about 0.1 particle per cc. This concentration would ensure pressure equilibrium with the H I clouds which are immersed in the H III region.

For conditions prevailing throughout the halo and in the space between the galactic arms, the data are sparse and indirect and one has to fall back on what at best is described as inspired guesswork. Spitzer (ref. 11) has argued that the temperature in the halo far removed from the galactic plane is of the order of 10^6 °K. He believes that, if the halo temperature were much higher than this, the halo could not be held captive by the galactic gravitational field and would rapidly boil away. If the halo were colder, on the other hand, it could not remain as distended as it is. Münch has recently established that there are H I clouds dispersed throughout the galactic halo and presumably then between the galactic arms (ref. 11, p. 21 and ref. 12, p. 64). If such clouds are to have other than a very transitory existence, they must be at the same pressure as the surrounding halo gas. Using this fact and the assumption of hydrostatic equilibrium throughout the halo, Spitzer (ref. 11) has computed the distribution of temperature and particle density as a function of distance from the galactic plane. Within the galactic plane itself he estimates the halo temperature to be about 10 000° K and the number density to be 0.1 particle per cc. These conditions are then considered to be representative of the state of the gas between the spiral arms.

It is to be emphasized that the values quoted for the halo are indeed inferential and are by no means generally accepted. Pickelner (ref. 1, pp. 935-939) has proposed a markedly different model of the galactic halo in which the gas is much cooler and more dense, the distension being maintained by rapidly moving H I clouds. Recent books giving background material for the present theory are references 6 and 13 which contain articles by leading authorities on galaxies. Especially noteworthy journal articles for the aerodynamic point of view in astrophysics are references 1 and 14.

BASIC AERODYNAMIC CONCEPTS

Consider the motion of a small point disturbance through a spatially homogeneous gaseous medium. The simplest case of all is that in which the disturbance moves in a straight line with constant speed V. The perturbation to the flow field is given by the following equation:

$$\frac{1}{c^2}\frac{\partial^2 \varphi}{\partial t^2} = \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2}$$

where c is the acoustic speed in the medium. If transfer is made to a frame of reference moving with the disturbance,

$$x' = x - Vt$$

$$y' = y$$

$$z' = z$$

$$t' = t$$

The field perturbation ceases to be time dependent and assumes the form

$$\left(1 - \frac{V^2}{c^2}\right)\frac{\partial^2 \varphi}{\partial x'^2} + \frac{\partial^2 \varphi}{\partial y'^2} + \frac{\partial^2 \varphi}{\partial z'^2} = 0$$

Note that there is a distinct difference in the nature of the field perturbation depending on whether the acoustic source is moving with subsonic speed or supersonic speed. At subsonic speeds the equation is of elliptic type and the disturbance remains more or less localized. At supersonic speeds, however, the equation is of hyperbolic type and a wave pattern appears. A more graphic presentation of the two flow regimes is given in figures 3(a) and 3(b). At each point along the path of the disturbance a wavelet orginates and spreads with acoustic velocity. At subsonic speeds there is no piling up of the individual wavelets, no formation of wave fronts, and no wave drag. At supersonic speeds the situation is entirely changed. Wave fronts do develop; there is continual outpouring of energy to infinity, and this manifests itself as wave drag. In figure 3(b) the wave front propagates perpendicular to itself with velocity c.

Consider now the motion of a point disturbance in a circular path. This problem has been considered in references 15 and 16. In this problem it is convenient to express the perturbation equation in cylindrical coordinates:

$$\frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2} = \frac{\partial^2\varphi}{\partial r^2} + \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\varphi}{\partial\theta^2} + \frac{\partial^2\varphi}{\partial z^2}$$

For a transfer to a frame of reference which is rotating at the same angular speed ω as the point disturbance,

$$r' = r$$

$$\theta' = \theta + \omega t$$

$$z' = z$$

$$t' = t$$

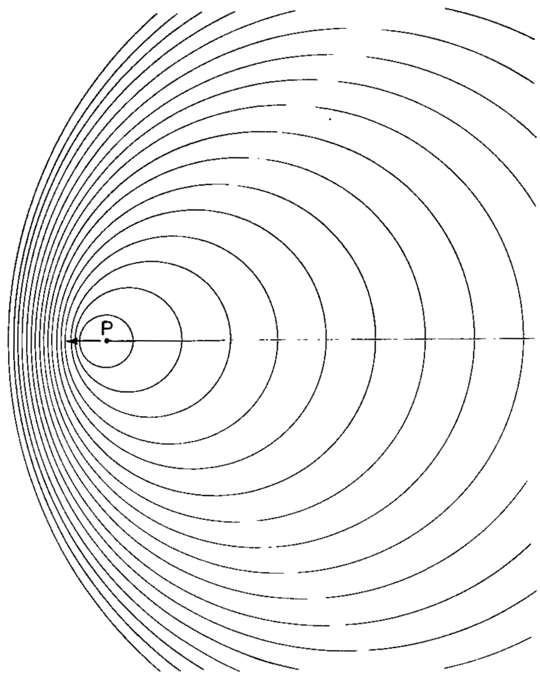
The equation once again loses its time dependence and assumes the form

$$\frac{\partial^2\varphi}{\partial r'^2} + \frac{1}{r'}\frac{\partial\varphi}{\partial r'} + \frac{1}{r'^2}\left(1 - \frac{\omega^2 r'^2}{c^2}\right)\frac{\partial^2\varphi}{\partial\theta'^2} + \frac{\partial^2\varphi}{\partial z'^2} = 0$$

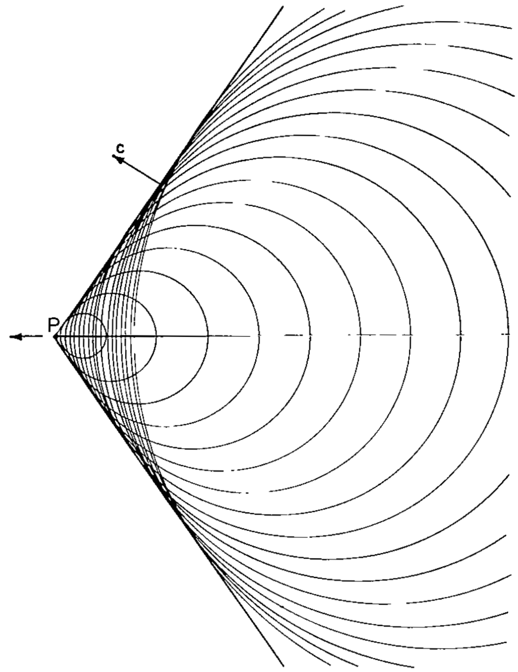
Irrespective of the peripheral speed of the disturbance field, inboard of the circle $r' = c/\omega$ the equation is of the elliptic type. Outboard of this circle the equation is of the hyperbolic type and wave patterns appear. The flow pattern in which the point disturbance is moving at sonic speed is shown in figure 3(c).

If a normal is drawn to the wave front at a point R, the component or velocity of the wave front along the normal is c. This normal is clearly tangential to the sonic circle because of the similarity of the triangles ORS and RQC. Thus, the wave front is an involute generated conceptually by the unwinding of a string from the sonic circle. A point disturbance moving at subsonic velocity produces no wave fronts. The wave front formed by a point disturbance moving at supersonic velocity is shown in figure 3(d). Note that the incoming wave is reflected at the sonic circle - that is, spiral wave fronts are formed only outside the sonic circle.

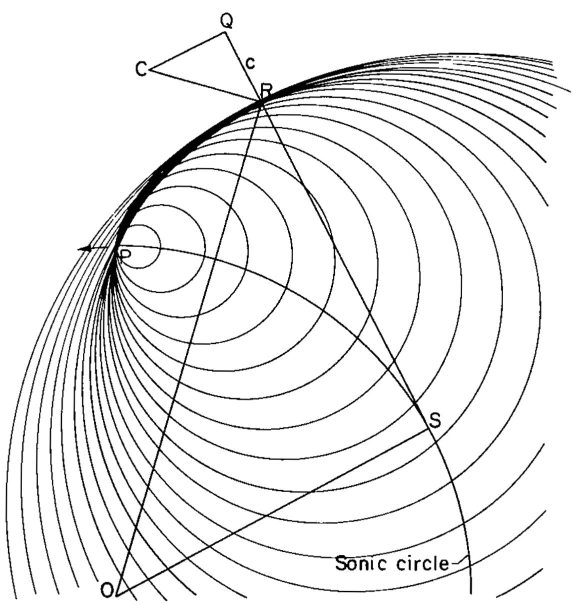
A slender body can be treated as a superposition of point disturbances (sources and sinks in aerodynamic theory). A cylinder of slender cross section moving in an inviscid fluid perpendicular to the cylinder axis at subsonic



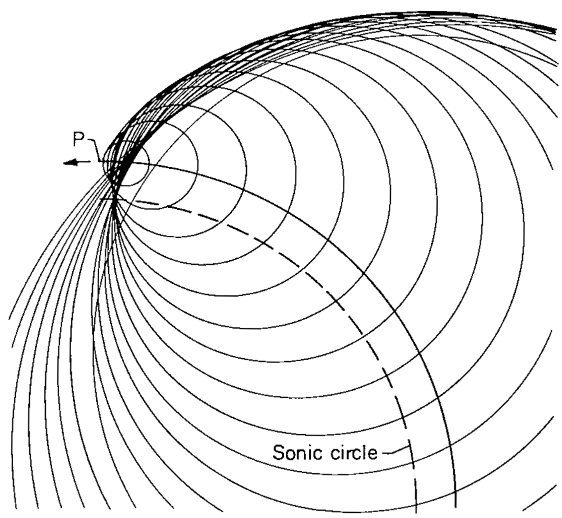
(a) Subsonic, translating.



(b) Supersonic, translating.



(c) Sonic, circular.

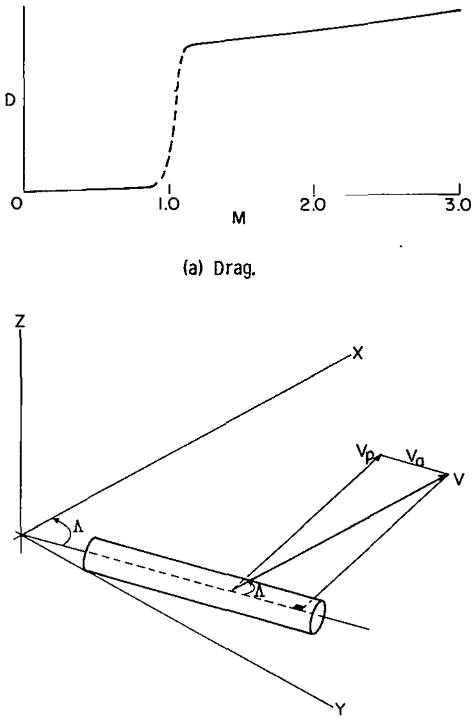


(d) Supersonic, circular.

Figure 3.- Wave flow patterns due to translating and circling motions of a point disturbance P in a compressible medium.

speeds is not subject to any drag force. Only when the cylinder speed exceeds sonic speed do drag forces appear. The drag force on a slender cylinder as a function of speed is shown in figure 4(a).

Finally, consider the alleviation effects of sweepback. Assume that the cylinder is moving in the x-direction with speed V and that the angle between the velocity vector and the axis of the cylinder in the XY-plane is defined as Λ. The motion of the cylinder relative to the fluid medium is shown in figure 4(b); the actual cylinder velocity V is resolved into components perpendicular to the cylinder axis V_p and along the cylinder axis V_a. Since effects of viscosity are not considered, the axial velocity component V_a will not modify the flow field. Clearly then, the force acting on the cylinder in a direction perpendicular to the axis corresponds to the velocity V_p. Moreover, the actual drag force is the component of this force in the direction of motion. By sweeping back the cylinder a marked reduction in drag force can thus be achieved. This well-known principle is used in designing supersonic aircraft.



(a) Drag.

(b) Sweepback.

Figure 4.- Drag and sweepback effects.

SHAPING OF SPIRAL ARMS BY AERODYNAMIC FORCES

As mentioned previously, recent observational data suggest an outflowing of partially ionized hydrogen guided by magnetic field lines embedded within and alined along the spiral arms of a galaxy. It is assumed in the present paper that these arms are rotating within a relatively stationary halo. It has been inferred by Spitzer that the space within the galactic disk and between the spiral arms is occupied by a tenuous distribution of hydrogen having a mean density of 0.1 particle per cc and a temperature of about 10 000° K. Such a gas may plausibly be assumed to have a sufficiently high electrical conductivity so that, with the large cosmic dimensions, magnetic fields will be "frozen" into the gas (ref. 2, pp. 4 to 7). Furthermore, since the mean free path is much smaller than the cross section of a spiral arm (thickness, typically, about 250 pc and breadth about 1000 pc), the gaseous medium between the spiral arms can be regarded as a continuum and in considering motion of spiral arms through it aerodynamic concepts are applicable (ref. 14, p. 36). The "fluid," being a conductor, cannot penetrate the magnetic field entrained in the spiral arm but flows around the arm in much the same way as air flows around the wing of an airplane.

Consider first that the sonic circle (the circle at which the peripheral speed is equal to the local speed of sound) lies within the galactic nucleus. The entire arm is therefore subject to supersonic drag. If no other forces were operative, the arm would be swept back until it assumed the form of an involute with respect to the sonic circle. Actually, the other forces which are operative - for example, gravitation, magnetic stresses within the arm itself, and centrifugal force (this force obviously opposes any tendency to bending of the arm) - limit the extent of sweeping back of the arm. Clearly, however, the equilibrium configuration might be expected in this instance to resemble a normal spiral galaxy.

Now consider that the sonic circle is external to the galactic nucleus. The circumferential motion of the arm inboard of the sonic circle is subsonic and hence subject to no drag, provided viscous forces are assumed to be entirely negligible. Only outboard of the sonic circle is the arm subject to aerodynamic drag forces. The arm itself is envisioned as a very pliant structure having virtually no bending stiffness. The arm may therefore, in this respect, be likened to a rope; it would yield at the point of onset of the applied load and an abrupt bending of the arm would be expected at the sonic circle. Thus, the kink (or knee) of a barred spiral arm would occur at the sonic circle. As the outflowing plasma negotiates this sharp turn, it would give rise to a force on the arm (see fig. 5) which would serve to oppose the action of Coriolis force and tend to keep the inner portion of the arm straight. The configuration expected in this instance would resemble that of a barred spiral galaxy.

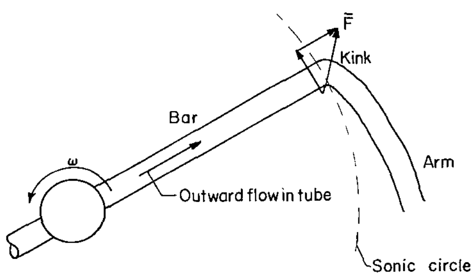


Figure 5.- One arm of barred spiral with force $\bar{F}$ due to effect of kink on outflow.

Therefore, the distinction between normal and barred spiral galaxies is made on the basis of whether the sonic circle lies within or external to the galactic nucleus.

HEATING OF THE GALACTIC HALO

Spitzer has estimated the temperature of the galactic halo to be about 10^6 °K. To maintain such a hot halo an energy input of about 10^{39} ergs/sec is needed. He has speculated that such an energy input might be provided by compressional waves produced by moving clouds in the galactic plane being converted to shock waves in the rarefied gas above this plane which, in turn, would convert their energy into heat. In the model of the halo favored by Pickelner, an energy input of about 10^{41} ergs/sec is demanded. Pickelner, however, is less specific in describing the source of such an energy input.

In the previous section it has been proposed that aerodynamic drag forces play a dominant role in shaping the galactic arms. It is the contention here that the dissipation associated with these drag forces is adequate to provide the heating of the halo.

The peripheral speed of the arm in the proximity of the sun is about 220 km/sec. This speed is much greater than the speed of sound in the relatively static medium between the arms of about 20 km/sec (corresponding to the estimated temperature of about 10 000° K); this great difference in speed suggests that strong shocks will form along the leading edges of the arms. A sketch of the flow normal to the arm is given in figure 6.

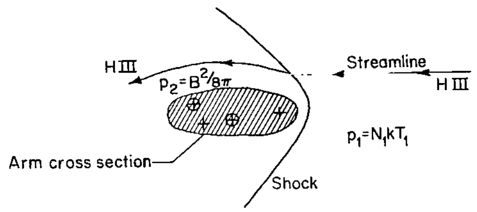


Figure 6.- Magnetic plasma arm and leading-edge-shock concept.

Again, assume that the kinetic pressure within the arm just suffices to balance out the gravitational forces (Spitzer, ref. 11). The additional magnetic pressure p_2 of about 3.6×10^{-11} dyne/cm^2 (corresponding to a magnetic field strength of 3×10^{-5} gauss) is balanced by gas pressure immediately external to the arm and defines, therefore, the pressure immediately downstream from the shock. It has already been assumed that between the spiral arms the concentration is 0.1 particle per cc and temperature is 10 000° K; this condition corresponds to a pressure of about 1.4×10^{-13} dyne/cm^2 upstream from the bow shock. Thus, the pressure ratio across the shock could be 250. This high pressure ratio provides additional confirmation of the existence of extremely strong bow shocks and hypersonic flow about the arms. In very high Mach number flow it is known that the pressure distribution on the forward portion of a body closely resembles that given by Newtonian flow in which the entire component of flow momentum normal to the body surface is destroyed on impact (the so-called Newtonian approximation for hypersonic drag). By invoking this approximation, the drag of an unswept body of thickness h and length b, with stream proton density N, proton mass m, and velocity V will be $NmhbV^2$. Thus, for two arms the rate of energy dissipation in overcoming drag is given by $2NmhbV^3$. If the following characteristics are assumed for a typical galaxy:

- thickness of galactic arm, h, ≈250 pc
- radial extension of galactic arm, b, $\approx 6 \times 10^3$ pc
- particle density, N, ≈0.1/cc
- peripheral speed of spiral arm, V, ≈220 km/sec
- proton mass, m, $\approx 1.67 \times 10^{-24}$ gram

the rate of energy dissipation is found to be about 10^{41} ergs/sec. This rate appears adequate to provide the energy input for the Spitzer model and possibly for the Pickelner model of the halo. In view of the evident roughness of the calculation the number cannot be regarded as admitting one model in preference to the other.

ADDITIONAL EVIDENCE SUPPORTING THE PROPOSED THEORY

Spiral galaxies exhibit wide diversity in the degree of tightness of winding of the galactic arms, such diversity being recognized in the Hubble classification. It is suggested that in those galaxies in which the spiral arms are the most open the outflow of plasma along the arm is greatest, and vice versa. Imagine the progressive throttling back of the outflow in a normal spiral. If the arms are assumed to be open at first, the galaxy would then be expected to evolve through the sequence Sc, Sb, and Sa until eventually, when the outflow has ceased, the arms are so tightly wrapped that they become an integral part of a nucleus and the result would be a galaxy of SO type. Thus, the SO type becomes understandable in terms of degeneration of normal spirals. For barred spirals a reduction of outflow would not modify the position of the sonic circle but lead to a progressively tighter wrapping of the arms at the extremities of the bar. The evolution would now be through the sequence SBc, SBb, and SBa. With complete cessation of the outflow the bar might plausibly be expected to disappear, and the final result would be a ring galaxy which, though it does not appear as an entity in the original Hubble classification, is recognized in the recent, more complete classification of De Vaucouleurs (ref. 3).

Barred spirals in the present theory have been defined as those galaxies in which the sonic circle has relatively large radius which suggests that barred spirals have slow rotational speeds. There appears to be a certain amount of observational data in support of this contention (Von Weizsäcker, ref. 17, footnote on p. 168).

Finally, it is expected that the drag forces would be greatest in galaxies in which the spiral arms have the most open structure. Hence, it is in these galaxies that dissipation and heating of the halo would be greatest. It has already been observed by radio astronomers (ref. 18, p. 256) that there is no discernible synchrotron radiation from the early-type (SO, Sa, or SBa) galaxies, whereas the late-type galaxies do emit in this way; this, therefore, is entirely consistent with the implications of the present theory. It would be interesting to establish whether, as the present theory suggests, the general level of synchrotron radiation from Sc (and SBc) galaxies exceeds that from Sb (and SBb) galaxies.

CONCLUDING REMARKS

The theory presented suggests that studies of galactic structure should consider the possibility that important galactic phenomena are due to essentially aerodynamic effects attendant on rotation of the arms through a background continuum gas. This suggestion is supported in two ways: (a) order of magnitude calculations show that an explanation of halo heating becomes possible when the suggestion is used, and (b) a plausible and internally consistent accounting results for the various types of galaxies which make up the Hubble classification.

The theory provides an explanation of why late-type galaxies emit synchrotron radiation and the early-type galaxies do not. It is simply that the late-type spirals have arms that are more open (not so much sweep back) and effective in producing shocks which heat the halo, whereas the early-type spirals do not.

It appears that in observations of galactic rotation, an attempt should be made to distinguish between the motion of the plasma-magnetic arms and the other matter in the disk.

Presenting more than just a bare outline of the theory has been beyond the scope of this paper. As a suggestion for further work, an attempt could be made to observe and distinguish the motion of the arms, the outflow of gas within the arms, and the gas flow around the arms. A more detailed magnetohydrodynamic theory should be developed for which the present theory could perhaps serve as a basis.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 23, 1965.

REFERENCES

1. Burgers, J. M.; and Thomas, R. N., eds.: Proceedings of the Third Symposium on Cosmical Gas Dynamics. Rev. Mod. Phys., vol. 30, no. 3, July 1958, pp. 905-1108.

2. Cowling, T. G: Magnetohydrodynamics. Interscience Publ., Inc., 1957.

3. De Vaucouleurs, G.: Classification and Morphology of External Galaxies. Encyclopedia Phys., vol. LIII, Astrophysics IV: Stellar Systems, S. Flügge, ed., Springer-Verlag (Berlin), 1959, pp. 275-310.

4. Lindblad, Bertil: Galactic Dynamics. Encyclopedia Phys., vol. LIII, Astrophysics IV: Stellar Systems, S. Flügge, ed., Springer-Verlag (Berlin), 1959, pp. 21-99.

5. Oort, J. H.: Radio-Frequency Studies of Galactic Structure. Encyclopedia Phys., vol. LIII, Astrophysics IV: Stellar Systems, S. Flügge, ed., Springer-Verlag (Berlin), 1959, pp. 100-128.

6. Woltjer, L.: Magnetic Fields in Galaxies. Problems of Extra-Galactic Research, G. C. McVittie, ed., The Macmillan Co., c.1962, pp. 166-169.

7. Sciama, D. W.: Consequences of an Open Model of the Galactic Magnetic Field. Monthly Notices, Roy. Astron. Soc., vol. 123, no. 4, 1962, pp. 317-325.

8. Elvius, A.; and Herlofson, N.: On the Dynamics of Galaxies With Large-Scale Magnetic Fields. Astrophys. J., vol. 131, no. 2, Mar. 1960, pp. 304-309.

9. Wentzel, Donat G.: Magnetic Fields and Spiral Structure. Ann. Rev. Astronomy Astrophys., vol. 1, Leo Goldberg, Armin J. Deutsch, and David Layzer, eds., 1963, pp. 195-218.

10. De Vaucouleurs, Gerard; and De Vaucouleurs, Antoinette: Rotation and Mass of the Magellanic-Type Galaxy NGC 4631. Astrophys. J., vol. 137, no. 2, Feb. 15, 1963, pp. 363-375.

11. Spitzer, Lyman, Jr.: On a Possible Interstellar Galactic Corona. Astrophys. J., vol. 124, no. 1, July 1956, pp. 20-34.

12. Münch, Guido: Interstellar Absorption Lines in Distant Stars. I. Northern Milky Way. Astrophys. J., vol. 125, no. 1, Jan. 1957, pp. 42-65.

13. McVittie, G. C.: Galaxies as Members of the Universe: Summary. Problems of Extra-Galactic Research, G. C. McVittie, ed., The Macmillan Co., c.1962, pp. 441-450.

14. Anon.: Problems of Cosmical Aerodynamics. ATI 103347, Central Air Doc. Office, 1951.

15. Busemann, A.: Zur Gasdynamik des drehenden Schaufelsterns. Z. Angew. Math. Mech., Bd. 18, Heft 1, Feb. 1938, pp. 31-38.

16. Davidson, Robert E.: Linearized Potential Theory of Propeller Induction in a Compressible Flow. NACA TN 2983, 1953.

17. Von Weizsäcker, C. F.: Problems Connected With the Origin of Spiral Arms. Gas Dynamics of Cosmic Clouds, Interscience Publ., Inc., 1955, pp. 167-171.

18. Mills, B. Y.: Radio Frequency Radiation From External Galaxies. Encyclopedia Phys., vol. LIII, Astrophysics IV: Stellar Systems, S. Flügge, ed., Springer-Verlag (Berlin), 1959, pp. 239-274.

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