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ABSTRACT

It is demonstrated that a magnetic gas cloud confined by gravity has no equilibrium configuration if cosmic rays are generated within it. Applying the theorem to the galaxy, it is shown that cosmic rays lead to inflation of the galactic magnetic fields, producing a halo of cosmic rays and field around the galaxy. Present observational estimates of cosmic ray life, magnetic field strength, etc. indicate an outward inflation rate of the order of 10^2 km/sec, though this number may be revised with improved observations. This cosmic ray halo extends far out from the disk and nucleus of the galaxy, presumably limited only by instabilities which must eventually free the cosmic rays and fields at a great distance.

The field inflation acts as a pressure regulator on the cosmic rays generated in the galactic disk and nucleus, so that the life of a cosmic ray particle in the disk of the galaxy is determined mainly by the rate of generation of cosmic rays.

Present estimates of the cosmic ray life are based on the rather uncertain value of the interstellar gas density. The gas is intimately associated with the dynamics of the galactic fields and with the rate of cosmic ray production.

Author

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I. INTRODUCTION

At the present time observations (Davis and Greenstein, 1951; Morris and Berge, 1964) do not show the general strength and configuration of the magnetic field of the galaxy in an unambiguous way. Consequently there are a number of different ideas on both the strength and the configuration (see for instance Chandrasekhar and Fermi, 1953a; Biermann and Davis, 1960; Hoyle and Ireland 1960, 1961; Ireland, 1961; Sciama, 1962; Wentzel, 1963; Woltjer, 1965). Certain general conditions, such as the virial theorem (Chandrasekhar and Fermi, 1953b) and the tensor virial equations (Parker, 1954, 1957; Chandrasekhar, 1961), are applicable to the dynamics of the galactic field, giving general conditions for the apparent quasi-equilibrium of the galaxy in each of the three dimensions, without requiring a detailed knowledge of the field configuration.

It is the purpose of the present paper to demonstrate another general theorem of the quasi-equilibrium of the galactic field which makes it possible to proceed further than the virial conditions, still without being dependent upon a knowledge of the general galactic field configuration. Application of the theorem to the galaxy depends upon the conditions that (a) intergalactic space is essentially a vacuum, so that the galactic magnetic field is confined to the galaxy only by the weight of the interstellar gas embedded in it, and (b) cosmic rays are continually generated in the galaxy. Given these conditions it follows that the galactic field has no static equilibrium. A halo-like structure of fields and cosmic rays is inflated around the galaxy as a consequence. The general situation will be illustrated with some hypothetical examples based on present estimates of the interstellar fields and cosmic ray life. It is to be hoped that observations will supply sufficient information before long to permit a model of the actual situation to be worked out from the general principles pointed out here.

To explain the physical basis for the formal dynamical theorem and its application to the galaxy, note that cosmic rays form a relativistic gas throughout interstellar space. In the presence of the interstellar magnetic field the cosmic ray gas has the large-scale properties of a conventional fluid.* The pressure of the cosmic ray gas is approximately isotropic and the cosmic ray gas tends toward a uniform distribution along the magnetic lines of force, etc. (This is discussed further in Appendix I).

Thus the galactic magnetic field together with the interstellar gas and the cosmic ray gas makes up a composite stress system, or fluid, extending throughout the galaxy. <u>All three constituents</u> - the field, the interstellar gas, and the <u>cosmic ray gas</u> - are important in determining the dynamical properties of the composite interstellar fluid. The magnetic field ties the constituents together and, by its effects, causes the cosmic rays to behave as a fluid on any scale of 10^{12} cm or more. The interstellar gas contributes inertia, and hence the weight by which the gravitational field confines the composite fluid to the galaxy (Appendix IV). The cosmic ray gas contributes energy and pressure, with relatively little rest mass.

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* This applies to all but the very highest energy cosmic rays, say up to 10^{16} ev/nucleon. The very high energy particles, whose radius of gyration is so large that they do <u>not</u> behave as a fluid over scales of 100 psc, have so little of the total cosmic ray energy that they can be ignored in the present discussion. They are themselves an interesting, but separate, problem.

The speed of sound in the interstellar gas alone would be 1 – 2 km/sec typically, and in the cosmic ray gas alone the speed of sound would be comparable to the speed of light. The speed of sound in the composite fluid is of the order of 10 km/sec (Parker, 1958a), which must be combined with the comparable Alfven speed to compute the usual hydromagnetic velocities.

As a consequence of its greater mobility and speed of sound, and its lack of weight, the cosmic ray gas presumably is spread more or less uniformly along the galactic magnetic field. . The energy density (pressure) of the cosmic ray gas is observed to be about 10^{12} ergs/cm^3, which is comparable to the energy density $B^2/8\pi$ of an interstellar field of 0.5×10^{-5} gauss. The life of the individual cosmic ray particles in the disk of the galaxy is estimated (Appendix III) to be of the order of 10^6 years. Evidence from meteorites indicates that the cosmic ray intensity has been approximately steady over at least the past 10^9 years (Lipschutz, Signer, and Anders, 1965). Thus the cosmic ray gas appears to be in a quasi-steady state in the galaxy. To maintain the steady state cosmic rays must be generated at an average rate of 2×10^{-26} ergs/cm^3. The total production is then 0.5×10^{41} ergs/sec throughout the galactic disk of some 200 psc. thickness* (Schmidt, 1965) and 10^4 psc radius. The origin of cosmic rays is believed to lie in the violent plasma phenomena which occur in the galaxy, such as novae, supernovae, the galactic nucleus, etc. (see discussion in Ginsburg and Syrovatskii, 1964).

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*The recent observation of a few gas clouds far out from the plane of the galaxy (Münch and Zirin, 1961; Muller, Berkhuijsen, Brouw, and Tinbergen, 1963) are of great interest and importance, and not a little puzzling, but they do not alter the situation under discussion here.

II. Non-equilibrium of a Gas Cloud

A. Simple Magnetic Gas Cloud

Consider a gas cloud (or star) confined within a finite region of space by the gravitational field of the mass distributed throughout the interior of the cloud. Suppose that the cloud is surrounded by vacuum. Let the cloud be filled with a magnetic field $\mathbf{B}$, the field initially confined wholly to the interior of the cloud. The electrical conductivity of the gas is presumed to be so high that the magnetic lines of force are "frozen" into the gas.

The first point to note is that the magnetic lines of force circle incommensurably throughout the interior of the cloud.* Starting at any point in the cloud it is possible, by following a magnetic line of force sufficiently far, to come arbitrarily close to any other point in the cloud.

Second, note that the force $(\nabla \times \mathbf{B}) \times \mathbf{B} / 4\pi$ exerted by the field on the gas has no component parallel to the field, so the gas flows freely along the magnetic lines of force. It follows that gas may be transported freely along the field from any point in the cloud to any other point in the cloud.**

Finally, then, it is possible to cause the gas to flow slowly but freely along the lines of force in such a way as to be placed in a region of arbitrarily small size at any given point in the field. Assume that the field remains unchanged during this operation. The work done is that required to compress the gas into the small

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*It is possible to conceive of a magnetic field in which the magnetic lines of force form simple closed curves, or in which the lines of force circle incommensurably throughout several limited regions with no connection between regions. But such configurations are apriori improbable.

** The energy dissipated by the transfer of gas can be made arbitrarily small if the rate of flow is sufficiently small.

volume. Concentration of the gas into the arbitrarily small region frees the rest of the field from the encumbrance of the gas, permitting the field to expand without limit. Suppose, then, that the field expands and that the arbitrarily small region occupied by the gas expands along with it. When the arbitrarily small region has expanded to the size of the initial gas cloud, the gravitational energy of the gas is restored to its initial value. Supposing that the compression and expansion was done reversibly, the energy initially put into compression of the gas is fully recovered on expansion. The magnetic field energy falls to zero as a consequence of expansion to an arbitrarily large volume. The net result of this hypothetical operation is to reduce the total energy of the system by an amount equal to the initial energy of the magnetic field.

It is evident that the entire process could have been carried out in such a way that the field was expanded everywhere only by the scale factor $1 + \epsilon$ $(\epsilon << 1)$ when the gas was restored to its initial configuration. The total field energy would then be reduced by the factor $1 - \epsilon$, with all other energies returning to their initial values. But a necessary condition for a static equilibrium is that there be no displacement of the system which leads to a first order decrease in total energy. Hence, <u>there is no static equilibrium of a gas cloud confined by gravity and containing an ergodic internal magnetic field</u>. A magnetic gas cloud left to itself develops a continuous flow of material along its lines of force such that portions of the field are progressively drained of gas and permitted to expand outward from the cloud.* This progressive disengagement

*It was noted by Hoyle and Ireland (1960) that the magnetic lines of force passing near the surface of the galaxy are subject to outward expansion, forming magnetic bubbles extending outward from the disk of the galaxy into the halo.

of the field from the cloud proceeds without limit.

The rate at which the field can disengage from the cloud is determined solely by the rate of redistribution of gas along the lines of force, and this is limited principally by the low density at the top of the various loops in the lines of force. The gas is presumably not far from hydrostatic equilibrium along the lines of force, so the density may decline exponentially outward from the cloud.* The flow velocity presumably does not exceed the speed of sound. Simple order of magnitude considerations show that an initial partial disengagement proceeds at some small fraction of the Alfven speed (of the order of a few km/sec in the solar photosphere** and in the galaxy). But complete disengagement of the field probably never occurs, because the rate of disengagement declines rapidly as the re-entrant loops of field (round which the gas is flowing) extend farther out to progressively lower gas densities.

B. Magnetic Gas Cloud with Cosmic Ray Gas

Consider, then, a magnetic gas cloud after a sufficient period of time has elapsed as to permit at least some slight penetration of the magnetic lines of force through the "surface" of the cloud. Suppose that a very hot gas, such as cosmic rays, is generated throughout the cloud*** up to some limiting pressure p_o which is

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* Polytropic gases, or cases where the temperature declines outward from the cloud more rapidly than $1/r$, might lead to zero gas density above a certain height, thereby shutting off the flow of gas, and the disengagement of the magnetic field, altogether. Such situations appear to be sufficiently unlikely, however, that they do not constitute a serious exception to the considerations here.

** Disengagement of the magnetic lines of force in a star is assisted by the effect of magnetic bouyancy and plays an intimate role in the formation of sunspots (Parker, 1955).

*** Generation at a single point in the cloud is sufficient, in view of the ergodic lines of force.

very small* compared to the characteristic magnetic pressure $B^2/8\pi$ in the cloud. The very hot gas communicates quickly along the field everywhere throughout the cloud, including those re-entrant loops which penetrate through the "surface" of the cloud. It will now be shown that the very hot gas, generated up to a pressure p_0 in the cloud, progressively inflates the protruding re-entrant loops of field, extending them outward without limit from the cloud as time progresses. This occurs for any nonvanishing p_0, no matter how small.

Inflation of the protruding loops of field is irresistible no matter how small the very hot gas pressure p_0 because the protruding fields must fall off to zero with increasing distance from the "surface" of the cloud. Where the field is sufficiently weak, the lines of force cannot contain the nonvanishing pressure p_0. All those lines of force passing far enough out that $B^2/8\pi$ falls below p_0 must be steadily inflated there by the very hot gas, and consequently extended farther and farther out from the cloud with the passage of time. The more feeble is the pressure p_0, the fewer will be the lines of force extending sufficiently far out to suffer the unlimited inflation, of course, but no matter how small is p_0 the inflating lines of force occupy all of space beyond where $B^2/8\pi$ falls to p_0.

The inflation may be illustrated by a simple formal example of a periodic two dimensional field extending upward from a plane cloud surface $y = 0$. The x and y components of the field are $\sin kx \exp(-ky)$ and $\cos kx \exp(-ky)$ before inflation and are illustrated in Fig. 1. The magnetic energy density declines upward as $\exp(-2ky)$ and falls below p_0

* The smallness of the limiting pressure p_0 is not necessary; it is for simplicity and generality in the exposition and will be dropped in application to the galaxy.

at some height y_1 . Above y_1 the very hot gas distorts the field outward, with the lines of force shown in Fig. 2 for progressively increasing pressure ϵp_0 $(\epsilon < 1)$ The details of the calculation are given in Appendix II.

The characteristic rate of extension of the protruding magnetic fields depends upon the rate of generation of the very hot gas up to the limiting pressure p_0 The extension may proceed rapidly if a copious supply of very hot gas is present.

In the simple quasi-equilibrium treatment given here, the extension of the magnetic fields proceeds without limit. In the actual case, however, it is to be expected that an instability must eventually develop which releases the very hot gas from the outer ends of the loops, thereby limiting the extension. Treatment of the limiting instability is beyond the scope of the present paper. The onset of the hose instability, which may not be the most effective one, is illustrated briefly in Appendix I.

III. Inflation of Galactic Fields

Consider the interstellar medium. Altogether the interstellar field, gas, and cosmic rays form a system which is confined to the galaxy by the weight of the interstellar gas (see discussion in Appendix IV). The cosmic rays represent a hot gas generated in the galaxy up to a pressure $p_0 \cong 10^{-12}$ $dynes/cm^2$. It follows, from the arguments of the preceding section, that the cosmic ray gas must inflate the magnetic fields outward from the galaxy, at a rate depending upon the rate of generation of cosmic rays. Present observations suggest that the galactic field is of the order of 0.5 - 1 x 10^{-5} gauss, suggesting that p_0 is not much less than $B^2/8\pi$, suggesting that inflation begins near the "surface" of the galactic disk.* The rate of inflation of the magnetic fields outward from the surface of the disk** can be computed from the estimated 10^6 year life of the individual cosmic ray particles in the galaxy. From the fact that the net outward streaming of cosmic rays must take them the 100 psc half-thickness of the disk in 10^6 years, the rate of outward inflation of the galactic fields must be of the general order of magnitude of 10^2 km/sec, subject, of course, to revision when improved observational estimates of the cosmic ray life, etc. are available (see discussion in Appendix III).***

Thus, present observational estimates of the interstellar magnetic field strength, the thickness of the gas in the galactic disk, and the rate of generation of cosmic rays lead to the conclusion, when applied to the dynamical theorem of the previous section, that the galactic magnetic fields are extended outward by cosmic rays at the rate of 10^2 km/sec to form a halo of field and cosmic ray particles around the galaxy. This effect does not deny the possibility that other processes may con-

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* Subject to revision if improved observations should show B to be greater.

** Cosmic rays undoubtedly inflate fields outward from the nucleus of the galaxy, but no estimate of conditions there is available.

*** It follows at once from energy considerations that the inflating fields do not carry a gas density in excess of 10^{-2} hydrogen atoms/cm^3 upward with them. Otherwise the 10^{-12} dynes/cm^2 cosmic ray pressure would not be sufficient to impart the 100 km/sec outward streaming velocity inferred from observations; the cosmic rays would then not escape so quickly and the cosmic ray energy density would increase above the observed level. There is no reason to expect that gas could be carried upward by inflating fields, of which Fig. 2 is an example, because the lines of force are stretched vertically. So there is no evident objection to 10^{-2}/cm^3 or less. Estimates of the halo density usually tend to be rather lower than this (see, for instance, Woltjer, 1965), though of course they are based on rather different concepts of the halo than presented here.

tribute to halo formation, too. It asserts only that cosmic rays create an extensive galactic halo by themselves.

It is not possible to state how far the cosmic ray halo may extend. It is suggested that the extension of the fields is limited only by some ultimate instability of the fields and cosmic rays.

It is evident that our theorem on inflation of galactic fields is applicable to galaxies other than our own, such as radio galaxies and other active structures. Only a lack of observational values for the relevant physical quantities prevents application here.

IV. Discussion

The formation of a halo of fields and cosmic rays around the galaxy is a question of broader interest than the simple dynamical theorem on which the present development is based. Not only do the special assumptions on which application of the theorem was based need careful consideration, but a galactic halo has been postulated and discussed for ten years from entirely different considerations than given here so far. Consideration of these diverse points is outlined in this section and discussed at greater length in the Appendices referred to earlier in the text.

To begin, the assumption was made that intergalactic space is a vacuum, i.e. the total pressure there is small compared to the 10^{-12} dynes/cm^2 of the interstellar fluid in the galaxy. This is the most conservative assumption that can be made on intergalactic conditions. There is no observation, or theoretical principle, which requires more. Some authors, notably Hoyle and Sciama, have assumed otherwise. In Appendix I their proposals are reviewed and the simple reasons for their rejection given.

It was asserted in the text that the cosmic ray gas behaves as a fluid with the conventional properties of an approximately isotropic pressure tensor, etc. in spite of the lack of collisions between cosmic ray particles. The basis for this assertion is the usual argument from the dynamics of collisionless plasmas, that any large deviation from fluid behavior, such as a strong anisotropy, leads to powerful instabilities which rapidly disorder the field and the motions of the particles of the fluid, restoring immediately an approximation to isotropy (see discussion in Parker, 1963). A specific example of conditions leading to the onset of the hose instability is presented as part of the discussion in Appendix I. It is shown how cosmic rays streaming along the lines of force toward decreasing field strength are subject to the "hose" instability which scatters the particles away from their small pitch angles, thereby tending toward isotropy and uniform density along the magnetic lines of force. The example illustrates how the cosmic rays inflating a protruding loop of field from the galaxy may accumulate in the outer end of the loop.

Finally, there is the problem raised by present observations of cosmic rays indicating that cosmic rays have a short life (10^6 years) in the disk of the galaxy and yet are remarkably isotropic here. This important question has been a strong argument for believing that cosmic rays circulate freely through some kind of large galactic halo region (Biermann and Davis, 1958, 1960; Ginsburg and Syrovatskii, 1964). Various possible structures for a galactic halo have been pointed out (Spitzer, 1956; Pikelner and Shkloviskii, 1957, 1959; Pickelner, 1957; Field, 1963; Woltjer, 1965). If the idea put forth in the present paper is correct, the origin of the galactic halo is specified: The cosmic rays affect the galactic magnetic field in such a way as to manufacture a halo and automatically produce cosmic ray isotropy in the galactic disk. Inflation of the surface fields of the galaxy acts as a crude pressure regulator on the cosmic rays generated in the galaxy itself. A copious supply of cosmic rays increases the cosmic ray pressure up to $B^2/8\pi$ and no more. Increased cosmic ray generation in the galaxy would not increase the cosmic ray pressure much. It would instead increase the rate of inflation of the surface fields and lead to a shorter life in the disk of the galaxy (appearing as a decreased Li, Be, B abundance). On the other hand, greatly reducing the rate of generation of cosmic rays would lower their pressure somewhat below $B^2/8\pi$ so that only a fraction of the magnetic lines of force crossing the surface would be subject to inflation. A cosmic ray particle would then have to circle several times before getting out into an inflating field. The cosmic ray life would be considerably increased. Cosmic ray anisotropy would appear in the galaxy as a consequence of some of the long escape paths.

Present observational evidence suggests that cosmic ray generation in the galaxy is sufficiently copious that the cosmic ray pressure is near $B^2/8\pi$ Most of the surface fields are subject to inflation, the cosmic ray life in the disk is relatively short, and cosmic rays are statistically isotropic.

The old cosmic ray problem of isotropy in combination with a short life is discussed in Appendix III. In Appendix IV some questions concerning the mean interstellar density in the disk are considered from the point of view of the dynamics of the interstellar gas, on the one hand, and the effect on cosmic ray generation, on the other hand.

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Appendix I. Ideas on Cosmic Rays and the Fluid Nature of the Cosmic Ray Gas

Gold and Hoyle (1959) have proposed that the cosmic rays observed at the solar system extend not only throughout the galaxy, but in fact fill the entire universe. The universe is in a state of expansion, of course, which dilutes and decellerates the cosmic rays in a characteristic time of the order of 10^{10} years. The necessary energy input to maintain the cosmic rays at the observed 10^{-12} ergs/cm^3 is then 3×10^{-30} ergs/cm^3 sec. There are about 10^{74} - 10^{75} cm^3 per large galaxy, requiring 3×10^{44} - 3×10^{45} ergs/sec per large galaxy. The total luminosity of a large galaxy is of the order of 3×10^{44} ergs/sec, most of which is electromagnetic radiation in the 1 volt region. There is no evidence that galaxies generate cosmic rays as fast as 3×10^{44} ergs/sec. Our own galaxy appears to be generating them at a rate of only 10^{41} ergs/sec. Thus in this view it is necessary to avoid the problem of cosmic ray generation either by stating that the universal cosmic rays are an intrinsic property of space (Burbidge, Burbidge, and Hoyle, 1963) or by stating that they originate in some mysterious phenomenon such as the quasar (Hoyle, 1964).

The objection to the idea, that cosmic rays fill the entire universe, is philosophical. The idea proposes a new and independent fundamental property of all space without in fact solving the cosmic ray problem. Universal cosmic rays may perhaps explain the cosmic rays in our own galaxy, but then they cannot explain the enormously more intense cosmic rays in radio galaxies, etc. The radio galaxy must be explained by "conventional" means. But if in principle it is possible to explain the radio galaxy by "conventional" processes, surely the feeble cosmic rays of our own galaxy can be explained by a conventional process, too. There is at present no evident need for the sweeping assertion that cosmic rays are universal.

Sciama (1962) has proposed the idea that cosmic rays extend throughout the galaxy and the Local Group of galaxies, confined there by intergalactic fields extending throughout the Local Group. An essential part of the idea is that the weak intergalactic fields are so smooth that the magnetic moment of each cosmic ray particle is preserved when the particle leaves the strong field of a galaxy, in order that the particle may return freely to the strong field of the galaxy and not suffer trapping in intergalactic space. For if significant trapping should occur in the presence of free circulation of cosmic rays in and out of the local galaxies, the cosmic ray energy density throughout the Local Group would increase toward the value 10^{-12} ergs/cm^3 which it has within the galaxy. The virial theorem shows that if this should occur, there is not sufficient gravitational potential energy (about 3×10^{-14} ergs/cm^3, Kahn and Woltjer, 1959) to contain the Local Group.

The simplest objection to the idea of free circulation of cosmic rays throughout the galaxies of the Local Group is that the intergalactic fields can hardly be sufficiently free of shock waves and other irregularities, in view of the motion of the individual galaxies and the halo activity around each galaxy. Another objection is based on the instabilities and disorder which the cosmic rays would produce in the intergalactic fields. The instabilities are of such a nature that a cosmic ray particle, leaving the relatively strong field B_o ($\sim 10^{-5}$ gauss) of a galaxy and moving along a magnetic line of force into intergalactic space where the field B is small compared to B_o, undergoes scattering to larger pitch angles with the consequence that it becomes trapped in the intergalactic field. The same effects occur in cosmic ray inflation of the halo, pointed out in the text.

The general rule is that, as a consequence of small-scale dynamical instabilities, the flow of cosmic rays along magnetic lines of force is like the flow of an ionized gas with collisions: The gas density tends to become uniform everywhere along the lines of force regardless of the strength or weakness of the field. The thermal velocities tend toward isotropy everywhere along the field.

Consider, then, an isotropic distribution of cosmic rays of N particles/cm^3 in a field B_0 within a galaxy. Suppose that the magnetic lines of force pass smoothly out of the galaxy and expand to make a weak smooth field B in intergalactic space. Then for stationary conditions the pitch angle θ of a particle varies such that $\sin^2\theta / B$ = constant. The largest pitch angle θ_m at any point in intergalactic space, where the field is B, is given by

$$\sin^2\theta_m = \frac{B}{B_0}$$

corresponding to a pitch angle of $\pi/2$ in the galactic field B. It follows from Liouville's theorem that the number density n of the particles streaming outward at some point in the intergalactic field is proportional to the solid angle in θ_m,

$$n(B) = \frac{N}{2}\int_0^{\theta_m} d\theta \sin\theta = \frac{N}{2}\left[1 - \left(1 - \frac{B}{B_0}\right)^{1/2}\right].$$

Presumably under steady conditions there is an equal density streaming inward toward the galaxy. The outward kinetic energy density, in terms of the individual particle energy $\frac{1}{2}Mw^2$, is

$$E(B) = \frac{1}{2} n(B) M w^2 = \frac{1}{4} N M w^2 \left[1 - \left(1 - \frac{B}{B_0} \right)^{1/2} \right] .$$

The pressure parallel to the field is

$$p_{\parallel} = n(B) M w^2 \cos^2\theta = \frac{1}{2} N M w^2 \left(1 - \frac{B}{B_0} \right) \left[1 - \left(1 - \frac{B}{B_0} \right)^{1/2} \right] .$$

and the pressure perpendicular to the field is

$$p_{\perp} = \frac{1}{2} n(B) M w^2 \sin^2\theta = \frac{1}{4} N M w^2 \frac{B}{B_0} \left[1 - \left(1 - \frac{B}{B_0} \right)^{1/2} \right] .$$

There is an equal contribution from the inward streaming particles.

When $B << B_0$,

$$E(B) \cong \frac{1}{8} N M w^2 \frac{B}{B_0} ,$$

$$p_{\parallel}(B) = \frac{1}{4} N M w^2 \frac{B}{B_0} ,$$

$$p_{\perp}(B) = \frac{1}{8} N M w^2 \frac{B^2}{B_0^2} .$$

Compare these quantities with the energy density and pressure $B^2/8\pi$ of the magnetic field. It is evident at once that the kinetic energy of the particles decreases only as the first power of B, so that the kinetic energy completely overpowers the field when the field is weak. Going further, $p_{\parallel}$ dominates both $p_{\perp}$ and $B^2/8\pi$. The hose instability results (Parker, 1958b). Disorder grows in the field at the expense of $p_{\parallel} - p_{\perp}$ with a characteristic time of the order of a few cyclotron periods and characteristic scales of a few radii of gyration.

It is evident, then, that cosmic rays cannot pass adiabatically out of a strong field B_0 into an empty weak field B without (a) having a kinetic energy density in excess of $B^2/8\pi$ as B becomes small, and (b) without strong disorder and scattering in the weak field B. The result is that a particle, having once left the strong field B_0, has little chance of returning to B_0. The particles leaving the strong field are trapped in the weak field where they accumulate up to the density in the strong field. Thus, dynamical instabilities in the collisionless cosmic ray gas have essentially the same effect as collisions in an ordinary dense gas, rendering the collisionless gas a fluid with approximately isotropic "thermal" motions, tending toward a uniform density distribution along the magnetic field.

Sciama's suggestion, that the cosmic rays observed in the galaxy circulate freely throughout the Local Group while maintaining a density between the galaxies small compared to the cosmic ray density within the galaxy is untenable. The cosmic ray density in intergalactic space would tend toward that in the galaxy, and could not be contained by the magnetic and gravitational field inferred from the motions of the members of the Local Group.

Appendix II. Inflation of a Two Dimensional Field

The condition for hydrostatic equilibrium of a very hot tenuous gas with pressure p in a two dimensional (x, y) magnetic field $\mathbf{B}$ is

$$0 = -4\pi \nabla p + (\nabla \times \mathbf{B}) \times \mathbf{B} . \tag{A1}$$

Writing $\mathbf{B} = \nabla \times [\mathbf{e}_z A(x, y)]$ it is readily shown that the equation becomes

$$0 = +4\pi \nabla p + \nabla^2 A \, \nabla A , \tag{A2}$$

where $\mathbf{e}_z$ is a unit vector perpendicular to the xy plane. It is necessary and sufficient to put $p = F(A)$, which states merely that the gas pressure is constant along each line of force, A = constant. Then $\nabla p = F'(A) \nabla A$ and if $\nabla A \neq 0$, it follows that

$$\nabla^2 A + 4\pi F'(A) = 0 . \tag{A3}$$

If the pressure is uniform, or negligible, then, of course, $\nabla^2 A = 0$ and the field is undistorted.

Consider the case that the pressure is proportional to the minimum $B^2/8\pi$ along each line of force. Then

$$p = \frac{\epsilon k^2}{8\pi} A^2(x, y) \tag{A4}$$

and

$$\nabla^2 A + \epsilon k^2 A = 0, \tag{A5}$$

where ϵ is a constant. A simple example of a solution of this wave equation is

$$A(x,y) = C \sin kx \, \exp\left[-(1-\epsilon)^{1/2} ky\right] \tag{A6}$$

where C is an arbitrary constant, with $0 \leq \epsilon \leq 1$. Increasing ϵ represents progressive inflation of the undistorted field

$$A = C \sin kx \, \exp(-ky) \tag{A7}$$

(illustrate in Fig. 1) with the condition that the y - component of the field remained fixed in the form $kC \sin kx$ at $y = 0$. In the limit as $\epsilon \rightarrow 1$, the field extends all the way to infinity, with $B_x = 0$, $B_y = kC \cos kx$. The field energy in $y > 0$, $0 \leq x \leq \pi/k$ is

$$\mathcal{E}_B = \int_0^{\pi/k} dx \int_0^{\infty} dy \, \frac{B^2}{8\pi}$$

$$= \frac{C^2}{16} \frac{(1-\epsilon/2)}{(1-\epsilon)^{1/2}} \cong \frac{C^2}{16}\left(1 + \frac{3}{8}\epsilon^2 + O(\epsilon^3)\right). \tag{A8}$$

The energy of the gas is

$$\mathcal{E}_G = \int_0^{\pi/k} dx \int_0^{\infty} dy \, \frac{3}{2} p = \frac{3C^2}{64} \frac{\epsilon}{(1-\epsilon)^{1/2}} . \tag{A9}$$

The energy of the gas lying above the line of force through $x = \pi/2k, y = y_0$ is

$$\mathcal{E}_G(y_0) = \frac{3C^2}{32} \frac{\epsilon}{(1-\epsilon)^{1/2}} \exp(-2ky_0) . \tag{A10}$$

Now, suppose that the inflation of the field (A7) extending beyond the cloud surface $y = 0$ is brought about by the generation of a very hot gas up to a small pressure p_0 at the cloud surface. The gas pressure has little effect on the field where $B^2/8\pi >> p_0$, and hence has little effect for $y < y_1$, where

$$k y_1 = \ln \frac{k^2 C^2}{8\pi p_0} \tag{A11}$$

Beyond y_1, however, the field cannot resist the gas pressure and inflation occurs. The gas pressure does not rise to p_0 on the lines of force extending beyond y_1 because the field cannot contain this gas pressure. Instead the field expands farther and farther with the steady generation of hot gas. To take a simple example, then, suppose that p rises to p_0 along the lines which do not reach to y_1, with little effect, whereas on the lines passing beyond y_1, p is of the form (A9) with ϵ increasing slowly with time. The field extends farther and farther with the continuing generation of hot gas. Far beyond y_1 the field is given by (A6). The lines of force of this inflated portion of the field are shown in Fig. 2 for progressively larger values of ϵ up to the maximum value $\epsilon = 1$, at which time the lines of force are extended parallel to the y-axis all the way to $y = \infty$. The energy of the gas beyond the line of force which reaches as far as $y = y_0$ ($> y_1$) is given by (A10). Note that the gas energy increases without limit as $\epsilon \to 1$.

Appendix III. The Problem of Cosmic Ray Isotropy

Cosmic rays consist principally of hydrogen nuclei and a smaller proportion of heavier nuclei, with average kinetic energies of the same order as their rest mass. There are about 10^{-9} cosmic ray particles per cm^3, giving a mean interparticle distance of 10^3 cm and a mean energy density of 10^{-12} $ergs/cm^3$. The radius of gyration of a typical cosmic ray particle in an interstellar magnetic field of 10^{-5} gauss is less than one a.u. and hence very small compared to galactic dimensions. Consequently cosmic ray particles are more or less constrained to move along the galactic magnetic line of force on which they were started, and the cosmic rays as a whole behave as a fluid -- a very hot, very tenuous gas. The pressure exerted by the cosmic ray gas is comparable to the energy density, 10^{-12} $dynes/cm^2$ and is comparable to both the energy density of the observed interstellar magnetic fields of $0.5 - 1.0 \times 10^{-5}$ gauss and to the kinetic energy density (turbulent pressure) of an interstellar medium of one hydrogen atom per cm^3 and an rms velocity of 10 km/sec.

The average cosmic ray intensity at the solar system appears to have been within a factor of 1.5 of the present value over the past 10^9 years, as determined from studies of radioactive nuclei (with half lives of $10^5 - 10^9$ years) produced in meteorites by cosmic ray bombardment (Lipshutz, Signer, and Anders, 1965). It is generally assumed that the cosmic ray gas is a permanent feature of the galaxy.

The age of cosmic ray particles can be deduced from the amount of fragmentation that has occurred in collision with stationary nuclei. It is observed that Li, Be, B nuclei are present among the cosmic ray particles with an abundance of about 0.2 the abundance of heavier nuclei (of which there is one for every 150 protons) (Waddington, 1960; Aizu, Fujimoto, Hasegawa, Koshiba, Mito, Nishimura, Yokoi, and Schein, 1959, 1961; O'Dell, Shapiro and Stiller, 1962; Daniel and Durgaprasad, 1962). The only known source of Li, Be, B is the collision of heavier cosmic ray nuclei with nuclei of interstellar material, leaving fragments of the heavier nuclei which have essentially the same velocity as before collision. With the assumptions that (a) cosmic rays are presently in a steady state, and that (b) those observed now at the solar system are typical of cosmic rays throughout the galaxy, the observed abundance of Li, Be, and B indicates that the cosmic ray heavier nuclei have passed through 3-7 gm/cm^2 of interstellar matter. If the heavier nuclei had passed through more material than this, there would be more fragments of Li, Be, B. Similar estimates have been obtained recently from the ratio of He^3 and He^4 (Hildebrand, O'Dell, Shapiro, Silberberg, and Stiller, 1963; Appa Rao, Dahanayake, Kaplon, and Lavakare, 1963). The median value 5 gm/cm^2 indicates a path length of $1 \times 10^6/N$ psc where N is the average number density along the path. It is usually assumed that only a very little material is traversed in the cosmic ray sources (novae, supernovae, etc.) so N is presumably some kind of mean interstellar density. It is also assumed that the cosmic ray protons are produced in the same sources as the heavy nuclei, so that $1 \times 10^6/N$ psc. is presumably the mean path length traversed by most cosmic ray particles.

Now the interstellar gas has a characteristic thickness of about 200 psc across the disk of the galaxy. The mean density of atomic hydrogen is 1/cm^3, observed at 21 cm. It has been suggested that the total interstellar density is about $5/cm^3$ as a consequence of molecular hydrogen (Gould, Gold, and Salpeter, 1963), based on estimates of the total amount of mass in the disk deduced from motions of K giant stars. Unfortunately it is not possible to observe molecular hydrogen directly at the present time. So the mean interstellar density must be regarded as somewhat uncertain. The lower density $1/cm^3$ gives a cosmic ray life of 3×10^6 years in the disk of the galaxy. The higher density of $5/cm^3$ gives 0.6×10^6 years in the disk. We are not able to resolve the question of the cosmic ray life here. The value of $1/cm^3$ appears to be inadequate to hold down the galactic field. The density of $5/cm^3$ gives so short a cosmic ray life that cosmic rays must be generated at an extraordinary rate, some 10^{41} ergs/sec. This is discussed in Appendix IV. For the present considerations it is sufficient to take a middle value of 10^6 years for the mean cosmic ray life in the disk*, remembering the present uncertainty in this life and in the inflation rate derived from it.

The life of 10^6 years requires cosmic ray generation at an average rate of 3×10^{-26} ergs/cm^3 sec throughout the disk, or a total of 6×10^{40} ergs throughout a disk of 200 psc thickness and 10^4 psc radius. The total energy output of novae and supernovae is estimated to be 10^{40} - 10^{41} ergs/sec. It is an open question whether novae and supernovae supply more than a fraction of the observed cosmic rays.

Now the short cosmic ray life of 10^6 years raises some serious questions when combined with the high degree of statistical isotropy of the cosmic rays.

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* The total life of a cosmic ray particle in the galaxy as a whole may be much longer than 10^6 years if the particles spend a large portion of their time in a galactic halo where the gas density is very low. The 10^6 years is the time spent in the disk during the longer life in the galaxy and the halo.

The escape of cosmic rays from the galaxy after a mean life of only 10^6 years in the disk is conventionally ascribed to the open nature of the galactic field. Either the galactic arms are open at their ends, or the cosmic rays pass freely back and forth along the magnetic lines of force from the disk of the galaxy to a supposed galactic halo.

To explore these possibilities consider first the idea that the ends of the galactic arms are "open". The essential point here is that the radius of gyration of most cosmic ray particles in a field of 10^{-5} gauss is only about 10^{12} cm. This radius is so small compared to the scale of the expected gradients in the galactic magnetic field that the particle drift velocity u across the field is very small compared to the particle velocity, of the order of c. For instance, a scale of 3 psc. gives $u = 10^3 \text{ cm/sec}$ and $u/c \cong 3 \times 10^{-8}$. Thus the cosmic ray particle is essentially confined to motion along a single line of force. But a line of force never ends because $\nabla \cdot \mathbf{B} = 0$. So a cosmic ray particle can escape from the galaxy only if the lines of force escape. A galactic arm can be open at its end only if the lines of force connect from there directly into intergalactic space, i.e. only if the galactic magnetic field is really only a constriction in a large-scale intergalactic field. But in view of the fact that the galaxy has rotated some 50 times in the past 10^{10} years it is difficult to understand how so complete and direct a connection between the galactic and intergalactic field could be maintained.

There is a more immediate problem, however, with the idea that cosmic rays escape out the ends of the galactic arms. The cosmic ray isotropy has been studied up to energies of at least 10^{16} ev/nucleon. No detectable anisotropy has yet been established.* Define the anisotropy δ as the difference between the maximum and minimum cosmic ray intensities observed in their respective directions divided by the average intensity

$$\delta \equiv \frac{I_{max} - I_{min}}{\frac{1}{2}(I_{max} + I_{min})}$$

Observations show (Greisen, 1956) that $\delta < 10^{-2}$ up to about 10^{16} ev/nucleon. Now suppose that cosmic rays are produced at various points scattered over a distance L along a galactic arm. The cosmic ray particle life in the arm is t. It follows that to pass out along the distance L in time t the cosmic rays must have a streaming velocity L/t. But it is readily shown (Compton and Getting, 1935; Parker, 1964) that streaming with a velocity v yields an anisotropy $\delta \cong 6v/c$. It follows that, if $\delta < 10^{-2}$, then

$$L \lesssim \frac{ct}{600}$$

But the path length ct of the individual particle in the disk is estimated at about 3×10^5 psc (10^6 lt. yrs.), yielding $L \lesssim 500\,psc$. The sources which generate the cosmic rays presently observed at the solar system cannot be far off! The galactic arms are so long, $L = 5 \times 10^4$ psc, that if the cosmic rays were channelled from sources along the arms the streaming velocity would have to be of the order of $0.2\,c$, yielding an enormous anisotropy.

The distance L, 500 psc, is comparable to the thickness of the galaxy, suggesting that the cosmic rays are generated throughout the disk of the

*Except for the diurnal effect, which is obviously of local origin in the solar system (Parker, 1964).

galaxy, and escape directly out the sides of the disk. If they did not escape out the sides, then they would generally be streaming past the solar system from distances very much in excess of 500 psc.

But now, if the cosmic ray particles escape directly out the sides of the galaxy a new difficulty appears. For if it is supposed that the cosmic rays are generated in supernovae, etc. then the cosmic rays observed at the solar system must have come from supernovae, etc. within a few hundred psc of the solar system. It is difficult to see how cosmic rays occasionally injected onto the lines of force of the galactic magnetic field at a few separate points in this small region could lead to the steady uniform cosmic ray distribution customarily assumed.

So with these questions in mind consider the ideas concerning a galactic halo. The general concept of a galactic halo is usually combined with the idea that the cosmic ray particles circulate freely around the halo and across the disk. (See, for instance; Bierman and Davis, 1958, 1960; Ginsburg and Syrovotskii, 1964) The halo has perhaps 10^2 times the volume of the disk so that the individual cosmic ray particles spend only 10^{-2} of their time in the disk. The gas density in the halo is presumably $10^{-2}/cm^3$ or less so that little matter is traversed in the halo. Hence the particle life in the halo and disk together is 10^2 times the life of 10^6 years in the disk, or 10^8 years altogether.

It is evident that such a picture can satisfy the requirement on the anisotropy. The path length ct before escape is 10^2 times longer, so L can be 10^2 times larger, $L \lesssim 5 \times 10^4$ psc. Thus cosmic rays produced anywhere in the galaxy may contribute to the cosmic rays observed at the solar system. Hence, with the possibility of such broad mixing it is easy to understand how the cosmic ray intensity is more or less steady in time, as seems to be required by the meteorite studies, and as is assumed in deducing the cosmic ray life from the Li, Be, B abundance. Altogether, then, the idea that cosmic rays circulate freely through a galactic halo (Biermann and Davis, 1958) is necessary to account for the isotropy and uniformity.

Various dynamical pictures of the galactic halo have been presented based on 10^6 °K gas (Spitzer, 1956), based on 10^2 km/sec turbulent gas motions (Pickelner, 1957; Pickelner and Shklovskii, 1957,1959) and based on explosions of the galactic nucleus (Burbidge and Hoyle, 1963). The present views give a somewhat different view of the dynamical origin of the halo. The halo is inflated by cosmic rays. The halo acts as a pressure regulator on the cosmic rays generated in the disk.

Appendix IV. Remarks on the Interstellar Gas Density and Quasi-Equilibrium of the Interstellar Fluid

The interstellar magnetic field and cosmic ray gas would expand outward and be lost immediately to the galaxy were it not for the weight of the interstellar gas which holds the field down in the disk and nucleus of the galaxy. The virial theorem can be written (Chandrasekhar and Fermi, 1953b)

$$2T + E_M = -U$$

where the kinetic energy T of all internal motions and the magnetic energy E_M are opposed by the gravitational potential energy U of the interstellar gas.

It is readily seen that the interstellar gas density cannot be too low if it is to perform this confining function properly. As an example, suppose that the mean interstellar density is one hydrogen atom/cm^3, as indicated by observations of atomic hydrogen. The 10 km/sec motions of the gas, the energy density of a 5×10^{-6} gauss interstellar magnetic field, and the cosmic ray gas, each contribute about 10^{-12} ergs/cm^3, giving a total of not less than 3×10^{-12} ergs/cm^3, or 2×10^{12} ergs/gm. Such an energy corresponds roughly to an equivalent velocity of 20 km/sec, comparable to the random velocity of the stars in the disk. Since both the stars and the interstellar gas move in the same total gravitational field, it would be expected that each should extend about equally far up out of the plane of the galaxy. As a matter of fact the gas has a characteristic extension of about 100 psc each way from the plane of the galaxy (Schmidt, 1956)* whereas

*It is not clear to what extent the recent observations of gas clouds far above the galactic disk (Münch and Zirin, 1951; Muller, Berkhuijsen, Broun, and Tinbergen, 1963) may alter the older estimate of 100 psc.

only the youngest stars are so closely confined. The stars generally extend two or three times as far from the plane.

The numbers used in this calculation are crude, but conservative. The point is that the interstellar gas must be rather denser than $1/cm^3$ if it is to be confined by gravity to the restricted domain observed. A gas density of $5/cm^3$, suggested by similar dynamical considerations of the K giants (Gould, Gold, and Salpeter, 1963) would appear to be adequate. Though of course a really accurate estimate can be made only when better observations are available.

Incidentally, these remarks would appear to favor the idea that the galactic field is less than 1×10^{-5} gauss rather than the stronger field, of the order of a few times 10^{-5} gauss, sometimes proposed (see Woltjer, 1963, 1965), though this was not intended as the main point of the remarks. The stronger field is difficult not only because its pressure tends to increase further the scale height of the gas distribution in the disk, but also because it has been necessary to assume in the strong field case that the gas and field are to a large extent mutually exclusive in order to explain the observed track of Zeeman splitting. Whereas the gas can hold down the field in the disk only if fully threaded with field: A cloud of field-free gas can slip in any direction between the lines of force; there is the additional difficulty, too, that a field free cloud is subject to Taylor or fluting instability, which would rapidly disperse the gas into the surrounding field (Parker, 1957).

An alternative view for the strong field might be the assumption that the galactic field is approximately force-free throughout the galactic disk and is held down at the galactic nucleus. None of the above objections apply then.

But there would be an increase of the field toward the galactic nucleus at least as fast as $1/r^2$ in order to contain the stresses of the field (Lüst and Schlüter, 1954; Chandrasekhar, 1956). It is not obvious that a $1/r^2$ increase toward the nucleus can be reconciled with the observed galactic structure and nonthermal radio emission.

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Figure Captions

Fig. 1. Magnetic lines of force of the undistorted two dimensional periodic field $B_x = \sin kx \exp(-ky)$, $B_y = \cos kx \exp(-ky)$ extending through the plane cloud surface $y=0$.

Fig. 2. A. magnetic line of force of the two dimensional periodic field of Fig. 1 above the level $y = y_1$ where the gas pressure, as measured by ϵ in equation (A4), inflates the field.

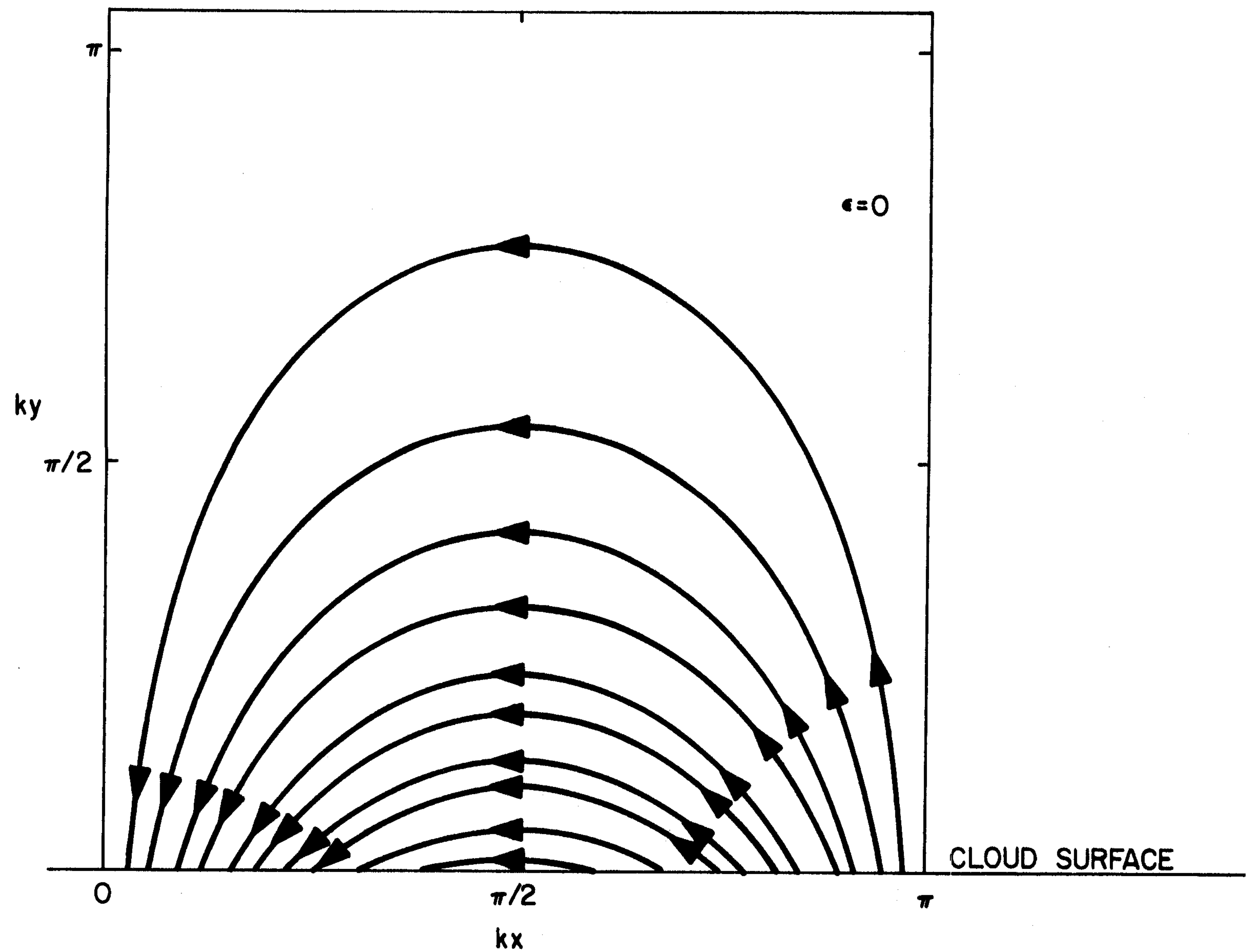

Fig. 1

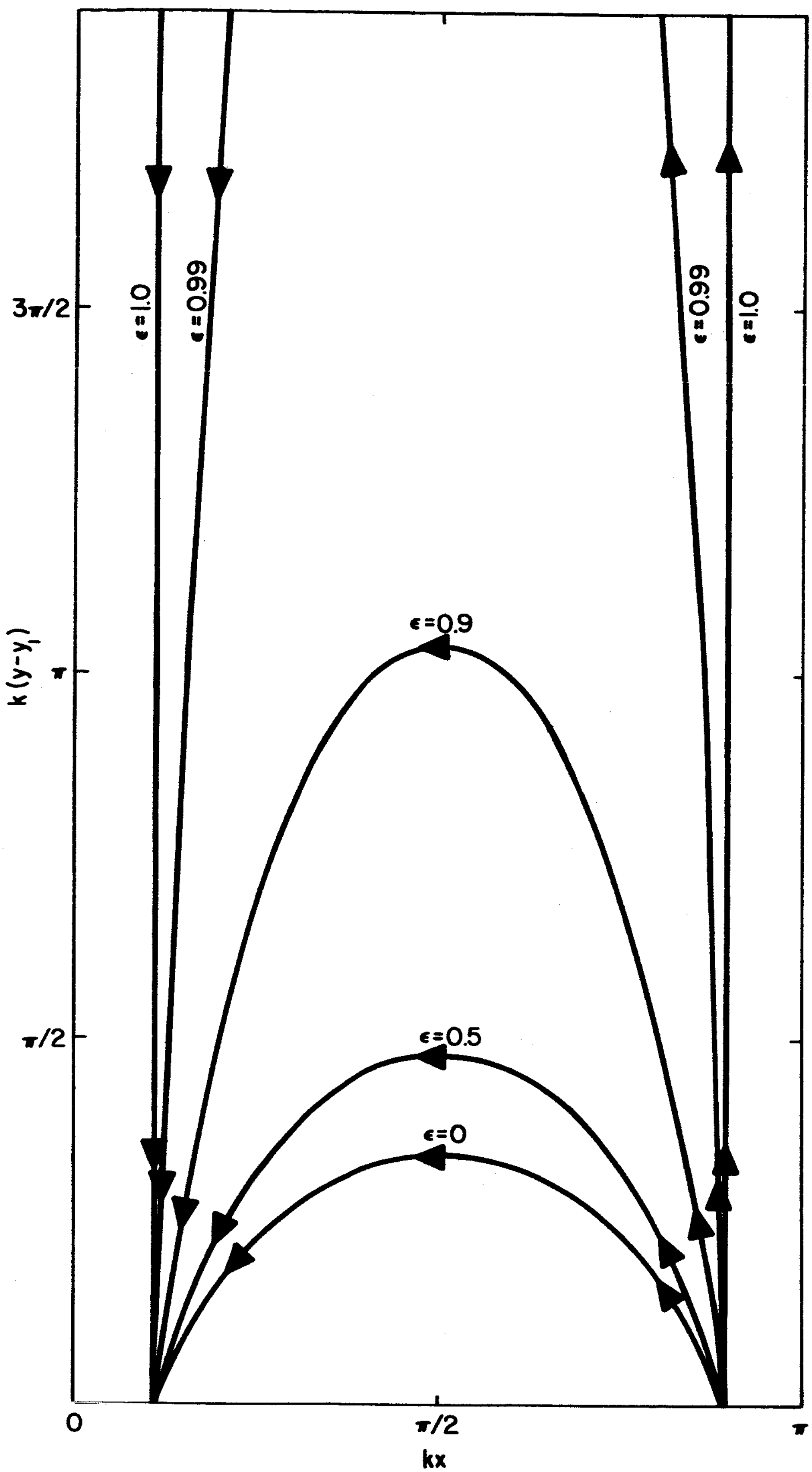

Fig. 2

EARLY ELECTROSTATIC PROBE RESULTS FROM EXPLORER XXII

by

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and

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INTRODUCTION

On October 9, 1964, Explorer XXII, the ionosphere beacon satellite,[1,2] was launched into an 80° inclination direct orbit which is nearly circular at an altitude of 1000 kilometers. The primary mission of the satellite is to permit radio propagation studies of the ionosphere on a global scale. The beacon experiment, radiating at 20, 40 and 41 megacycles, permits determination of the total electron content in the region between the satellite and an observing station on the ground. Knowledge of the electron density (N_e) at the satellite is very useful in the interpretation of beacon data, and for this reason two cylindrical electrostatic probes are employed to permit direct "in situ" measurements of the local plasma. It is the purpose of this paper to describe the probe experiment, report some of the early results, and suggest their possible implications.

THE EXPERIMENT

Figure 1 shows the mounting position of the probes and the electrical system employed. The satellite is stabilized by a passive magnetic system which

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