10. THE ORIGIN AND DYNAMICAL EFFECTS OF THE MAGNETIC FIELDS AND COSMIC RAYS IN THE DISK OF THE GALAXY

Introductory Report

(Friday, September 12, 1969)

E. N. PARKER

Dept. of Physics, University of Chicago, Chicago, Ill., U.S.A.

1. Introduction

The topic of this presentation is the origin and dynamical behavior of the magnetic field and cosmic-ray gas in the disk of the Galaxy. In the space available I can do no more than mention the ideas that have been developed, with but little explanation and discussion. To make up for this inadequacy I have tried to give a complete list of references in the written text, so that the interested reader can pursue the points in depth (in particular see the review articles Parker, 1968a, 1969a, 1970). My purpose here is twofold, to outline for you the calculations and ideas that have developed thus far, and to indicate the uncertainties that remain. The basic ideas are sound, I think, but, when we come to the details, there are so many theoretical alternatives that need yet to be explored and so much that is not yet made clear by observations.

2. The Galactic Field

Consider first what is presently known about the magnetic field in the disk of the Galaxy. (See Verschuur, this Volume, p. 150.) Observations of the polarization of starlight (Hiltner, 1956) indicate that the magnetic field in the disk of the Galaxy is oriented generally in the azimuthal direction around the disk. Observations of Faraday rotation of distant polarized radio sources indicate that the sense of the field may be in either direction at various places in the disk (Morris and Berge, 1964; Davis and Berge, 1968). In addition to the changes in sign of the field, there are large local fluctuations in direction and in magnitude (Hiltner, 1956; Jokipii and Lerche 1969; Jokipii *et al.*, 1969) so that if we write the field as the sum of the mean field $\mathbf{B}_0$ plus a fluctuating component $\Delta\mathbf{B}$,

$$\mathbf{B} = \mathbf{B}_0 + \Delta\mathbf{B}, \tag{1}$$

we have

$$\langle \Delta\mathbf{B}^2 \rangle = O(\mathbf{B}_0^2). \tag{2}$$

The mean strength of the field is subject to some uncertainty, but a few μG is suggested by Faraday rotation measurements of polarized radio signals from both extragalactic sources and from pulsars (Davis and Berge, 1968; Jokipii and Lerche, 1969) and appears not to be contradicted by measurements of Zeeman splitting in the dense cold H I regions where the effect is observable. What is more, the observed

Habing (ed.), Interstellar Gas Dynamics, 168–183. *All Rights Reserved. Copyright* © 1970 *by IAU*

dynamical behavior of the gas and field in the galactic disk suggests a strength of a few μG, on which we will have more to say below.

The galactic field is 'frozen' into the gas in the disk of the Galaxy. In H II regions the electrical conductivity σ is about 10^{13} e.s.u. so that the resistive diffusion time over small dimensions of 1 pc is large compared to the age of the Galaxy. In H I regions the field is frozen to the electrons and ions, which have densities of 10^{-2} cm^{-3}. The neutral gas is tied to the electrons and ions by collisions, so that the characteristic (ambipolar) diffusion coefficient is of the general order of magnitude of 10^{21} cm^2 sec^{-1} or less. Diffusion over dimensions of 1 pc requires 3×10^8 yr or more. Thus the field is frozen into the H I regions for most purposes even on scales as small as 1 pc.

The cosmic rays, which we consider to be a gas when viewed on a galactic scale, are tied to the magnetic field. Altogether, then, the interstellar medium is a composite fluid, made up of a thermal gas and a cosmic-ray gas, bound to the lines of force of the galactic field. Each of the three constituents has about the same energy density and pressure. The energy density of a field of 5 μG is 1.0×10^{-12} erg cm^{-3}, and the pressure is the same, in dyne cm^{-2}. This is to be compared with the energy density 1.5×10^{-12} erg cm^{-3} and pressure of 0.5×10^{-12} dyne cm^{-2} of the cosmic rays in the disk (Parker, 1966a), and the energy density 1.0×10^{-12} erg cm^{-3} and turbulent pressure of 0.7×10^{-12} dyne cm^{-2} of the interstellar gas (assuming a mean density of two hydrogen atoms cm^{-3} and an r.m.s. small-scale velocity of 7 km sec^{-1}).

The first question we might ask is what is the origin of the magnetic field. There are three possibilities that spring to mind. For instance, the field may be primordial, trapped in the original matter in the universe, and carried along with the matter into the present form of the Galaxy. The non-uniform rotation of the Galaxy would stretch the field out in the azimuthal direction, whatever the cause of the field, and it is an easy matter to show that the field is trapped in the gas in the disk for periods in excess of 10^{10} yr. I can think of no fundamental objection to this idea except, perhaps, that the field would be wound too tightly by galactic rotation.

We note, however, that the primordial field would be irrelevant if there were active generation of magnetic flux at the present time, which would simply obliterate the initial primordial field, replacing it with fields of more recent origin.

Turning then to active generation of magnetic flux, we might conjecture that the field has been generated by the observed random turbulent motions of the interstellar gas. It has been speculated (Alfvén, 1947; Biermann and Schlüter, 1951) that turbulence in a highly conducting fluid will build up any initial magnetic fields to a level where the field energy is comparable to the kinetic energy of the turbulence

$$\langle B^2/(8\pi)\rangle \approx \langle \tfrac{1}{2}\varrho v^2\rangle . \qquad (3)$$

The other possibility, that the magnetic energy does not build up to the kinetic energy, based on the similarity of the vorticity equation and the hydromagnetic equation for the field (Batchelor, 1950) has been suggested, too. In this case the galactic field would *not* be the result of random turbulence because the field energy builds up until it is equal to the kinetic energy in the small eddies, which possesses only a tiny fraction of the total kinetic energy density, $\langle \frac{1}{2}\varrho v^2 \rangle$ of the turbulence. Recently Kraichnan and Nagarajan (1967) have examined in detail the dynamical equations for a turbulent conducting fluid in the presence of magnetic fields. They point out that the generation of magnetic field by a turbulent flow depends upon several terms in the equation, all of the same order of magnitude. They show that the question of whether the field does, or does not, build up to equipartition of energy with the velocity field, depends upon the mean values (over wave number) of the various terms, which can be determined only by formal solution of the equations, and cannot be determined by any of the qualitative physical arguments proposed so far. Thus the question of the magnetic fields in a turbulent fluid is still an open question, after almost twenty years of debate.

It is possible to make a formal calculation of the magnetic field in a turbulent flow if the magnetic field, produced by the turbulence up to the time t, is statistically independent of the turbulent velocity at time t (Parker, 1969b). This condition is satisfied so long as (a) the field is too weak to affect the velocity significantly and (b) the correlation time of the turbulent flow is very short. In real turbulence the correlation time of the motion v on a scale l is of the order l/v i.e., during its lifetime an eddy turns through an angle of the order of one radian, giving a change $\delta\mathbf{B}$ in the field, which is comparable to $\mathbf{B}$, and hence is strongly correlated with the final field $\mathbf{B}+\delta\mathbf{B}$. Only if the correlation time is very short compared to l/v is $\delta\mathbf{B}$ so small that it is essentially uncorrelated with $\mathbf{B}+\delta\mathbf{B}$. On the other hand if (a) and (b) are satisfied, the field $\mathbf{B}$ and the velocity $\mathbf{v}$ can be treated as independent random variables. It can then be shown, by applying the theory of random functions to the hydromagnetic equations, that the magnetic field grows at all wave numbers. If dissipation destroys the field at large wave numbers, the net result of the turbulence is the generation of field at small wave numbers (large scale). One could imagine, then, that at some time in the distant past, turbulence in the interstellar gas may have generated a weak magnetic field (perhaps some fraction of a μG) which was then sheared by the non-uniform rotation of the galaxy into the presently observed field of several μG with the lines of force predominantly in the azimuthal direction (Parker, 1969c). It must be kept in mind, however, that application of the formal theory for short correlation times to real turbulence, in which the correlation time is l/v, is a conjecture of the same order as the earlier equipartition conjecture and the analogy with vorticity.

Observations give no particular support for any of the theoretical ideas. For instance, the solar photosphere is turbulent, as a consequence of the convective zone beneath, with a kinetic energy density of the order of 10^2 erg cm^{-3}, corresponding to the energy density of a field of 50 G. But the magnetic fields in the solar photosphere are observed to range from 1 G in very extensive regions, to 3000 G in sunspots. One may note the approximate equality of the energy density of the interstellar (galactic) field and the interstellar turbulence. But, of course, this example begs the question, because we are concerned with the problem of whether the interstellar field is, in fact, the result of the interstellar turbulence. And, in any case, it must be remembered that the interstellar field is dominated by the non-uniform rotation of the Galaxy rather than by the local turbulence. It is the non-uniform rotation which stretches the field into the observed azimuthal orientation and greatly intensifies the field in the process. We shall argue later on that the magnetic field strength is controlled by the cosmic-ray production rate.

It seems to me, therefore, that the source of the galactic field need not be very strong. Any mechanism which can produce a field of 1μG is entirely adequate. Non-uniform rotation does the rest. The approximate equality between $B^2/(8\pi)$ and the kinetic energy density of the interstellar gas is to be understood, it seems to me, from the dynamical instability of the gas-field-cosmic ray system, in which the energy of the field and cosmic rays is converted into kinetic energy of the gas. The gas is driven into clouds, leading to star formation, and then the clouds are disrupted to newly formed hot stars (Oort, 1952, 1954; Oort and Spitzer, 1955; Savedoff, 1956; Spitzer, 1968; Parker, 1967b). The equality of field energy and turbulent energy is then only a very loose relation. So, altogether, it cannot be shown yet whether the magnetic field in the disk of the Galaxy owes its origin to the turbulence there.

Consider, then, the third possibility, that the galactic field has been generated by motions which contain some order, such as might result from the Coriolis forces of galactic rotation. It was pointed out many years ago that cyclonic convective motions, together with non-uniform rotation (both the result of convection and Coriolis forces) are able to regenerate the dipole field of the Earth (Parker, 1955) and to produce the migratory fields which lead to the sunspots on the Sun (Parker, 1955, 1957; Leighton, 1969). What might such motions generate in the Galaxy? As in the Sun and Earth, the non-uniform rotation of the Galaxy stretches out the magnetic fields so that the dominant component is in the azimuthal direction. In the Sun and Earth the cyclonic convective motions move upward across the azimuthal field, locally lifting and twisting the lines of force into loops with non-vanishing projection on the plane perpendicular to the azimuthal field (i.e., with non-vanishing projection on the meridional planes). These loops coalesce to give large-scale loops of field in the meridional planes. For the Earth this leads to the observed dipole field. The question is whether some similar process might be operative in the Galaxy. The general idea of a galactic dynamo would begin with the non-uniform rotation. The non-uniform rotation of the Galaxy generates a toroidal field – presumably the observed azimuthal field – from whatever poloidal fields are present. The missing link is the generation of the poloidal fields from the existing toroidal fields. There is considerable turbulence and convection in the disk, and there are the Coriolis forces due to galactic rotation, so the turbulence must be slightly cyclonic. If cyclonic turbulence produces loops of flux in meridional planes with predominantly one sense, then the loops coalesce to give an overall poloidal field. For a given sense of rotation, rising and sinking cells produce loops of opposite sense, so that if rising and sinking cells occur in equal numbers, there is no net production of poloidal field. In the core of the Earth we believe that rising cells dominate. The sinking fluid is spread out over the broad regions between and has but little cyclonic rotation. Hence there is net production of poloidal field in the core

https://doi.org/10.1017/S0074180900004873 Published online by Cambridge University Press

of the Earth. There may be some such concentration of rising or sinking cells in the galactic disk. If there is, then the gas operates as a dynamo and we have the explanation for the galactic magnetic field. Indeed, we might point to the preponderance of negative radial velocities of interstellar gas at high latitudes and consider the matter resolved. But there is another possibility. Steenbeck *et al.* (1966) have made the general point that if fluid motions extend over one or more scale heights in an atmosphere, then rising cells of fluid are diverging laterally and sinking cells are converging laterally. Hence the Coriolis force produces retrograde rotation in the rising cells and direct rotation in the sinking cells (contrary to rising and sinking cells in an incompressible fluid such as the core of the Earth where both undergo direct rotation). The sense of the loop of field produced (in the meridional plane) by the cyclonic cells of fluid is determined by the product of the vertical motion and the rotation. Hence rising and falling cells extending over a scale height or more produce meridional loops with the same sense. If we apply this point to the Galaxy it raises the possibility that the galactic field is generated by the combination of non-uniform rotation and the cyclonic gas motions perpendicular to the disk. On the other hand, we must not be too hasty in asserting that this is the explanation of the galactic field, because a simple sketch of the cyclonic rotation, the non-uniform rotation, etc. shows that the basic dynamo mode is migratory, as in the Sun, with the direction of migration perpendicular to the disk (and, incidentally, in the direction opposite to the direction of progress of a right-hand thread turning with the Galaxy i.e., in the direction of the galactic North Pole). Such migration is blocked by the boundary of the disk. The question is whether there are higher modes of the dynamo which can regenerate the galactic field. I do not know the answer to this question yet. The origin of the galactic field is still a matter of speculation.

3. Equilibrium in the Galactic Disk

Whatever may be the origin of the galactic magnetic field, consider the conditions necessary for the dynamical equilibrium state in which we find the field today. It is readily shown from the virial equations that a magnetic field tends to expand (Chandrasekhar and Fermi, 1953). So the first question is what keeps the galactic field confined to the disk of the Galaxy? We showed some time ago (Parker, 1966b) that the field cannot be confined by the galactic nucleus (with a force-free configuration in the disk) unless the field increases at least as fast as r^{-3} toward the center of the Galaxy. This seems to be contrary to observation. So the only theoretical possibility remaining is that the field is confined to the disk of the Galaxy by the weight of the gas in the disk. The field necessarily penetrates through the gas if the gas is to hold down the field. This is just what observations would suggest, of course. There is a horizontal magnetic field (in the mean) through interstellar space, and the interstellar gas is distributed along and across the field. The scale height Λ of the gas is observed to be of the order of 100 to 200 pc (Schmidt, 1956; see also the remark by van Woerden, p. 184). Equilibrium in the vertical direction (the z-direction perpendicular to the disk) requires that

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(p + \frac{B^2}{8\pi}\right) = -\varrho g \tag{4}$$

where g is the gravitational acceleration perpendicular to the disk, ϱ is the gas density, and p the gas pressure. We use smeared-out average values of ϱ, p and B here, because both the gas and the field are subject to small-scale fluctuations which are not of interest to the large-scale equilibrium.

At this point we recall that the cosmic-ray pressure P is comparable to both $B^2/(8\pi)$ and the turbulent pressure of the gas, so it too should be included in the equation for equilibrium,

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{B^2}{8\pi} + P + p\right) = -\varrho g\,. \tag{5}$$

Now write $p=\varrho u^2$ where u^2 is the mean-square small-scale gas velocity (thermal plus turbulent) in the vertical direction. The mean-square velocity must be suitably averaged over both H I and H II regions, which we do not distinguish in this large-scale consideration of equilibrium. Then if the total pressure in intergalactic space is small compared to the total pressure within the disk, it is evident that $B^2/(8\pi)$ and P must vanish with z at least as rapidly as the density ϱ. For if they do not decrease with height as fast as ϱ, then above some height there is not sufficient weight $\int \varrho g\, \mathrm{d}p$ to confine the pressure $P+B^2/(8\pi)$ at that height. For simplicity suppose that $B^2/(8\pi)$, P and $p=\varrho u^2$ all decrease in proportion, so that

$$\frac{B^2}{8\pi} = \alpha\varrho u^2\,, \qquad P = \beta\varrho u^2\,, \tag{6}$$

where α and β are constants. Suppose too that u^2 is independent of z. Then Equation (5) can be written

$$\frac{1}{\varrho u^2}\frac{\mathrm{d}}{\mathrm{d}z}\varrho u^2 = -\frac{g}{u^2(1+\alpha+\beta)}\,. \tag{7}$$

The scale height Λ is, accordingly,

$$\Lambda = \frac{u^2(1+\alpha+\beta)}{\langle g\rangle_\Lambda} \tag{8}$$

where $\langle g\rangle_\Lambda$ denotes the mean value of $g(z)$ over the scale height. If we take $\Lambda=160$ pc, then $\langle g\rangle_\Lambda \cong 2\times10^{-9}$ cm sec^{-2}. Observation suggests that the small scale r.m.s. velocity u is of the order of 7 km sec^{-1}, from which we conclude that $\alpha+\beta\cong 1$. The reader may use his own favorite numbers for Λ, g, and u if he wishes. The point here is that with $\alpha+\beta$ of the order of unity, as suggested by observations, there is no reason to doubt that the distribution of gas and field in the disk is in large-scale hydrostatic equilibrium. The gas density necessary to confine the

https://doi.org/10.1017/S0074180900004873 Published online by Cambridge University Press

field and cosmic rays follows from

$$\frac{B^2}{8\pi} + P \equiv \varrho u^2 (\alpha + \beta). \tag{9}$$

The cosmic-ray pressure is one-third the energy density, or 0.5×10^{-12} dyne cm^{-2}. A field of 3.5 μG has the same pressure, so that with $\alpha + \beta = 1$ and $u = 7$ km sec^{-1}, we find $\varrho = 2 \times 10^{-24}$ gm cm^{-3}. Thus the weight of one or two hydrogen atoms cm^{-3} is required to confine a galactic field of 3 to 4 μG to the galactic disk. The mean hydrogen density in the disk appears to be about two atoms cm^{-3}, or even a little more (Schmidt, 1956, 1963), though both higher and lower figures are sometimes quoted. We note that again observation is not inconsistent with the simple equilibrium condition of Equation (5). And inasmuch as the gas and field appear to be in a quasi-steady equilibrium, we shall assume that Equation (5) is satisfied whatever varieties of u, Λ and ϱ may be suggested by various observations.

It is important to note that, unless $\Lambda \varrho g$ is much larger than present observations suggest, the Galaxy cannot accommodate a galactic field in excess of about 5 μG. There simply would not be enough gas to confine a stronger field to the disk. We suggest, then, that the r.m.s. magnetic field in the disk of the Galaxy is bounded by

$$\langle B^2 \rangle^{1/2} \lesssim 5 \mu G. \tag{10}$$

4. Internal Dynamics of the Galactic Disk

Before we inquire into the dynamical behavior of the magnetic field in the disk of the Galaxy, a few words should be said on the properties of cosmic rays, whose pressure P plays a role in shaping the dynamics. As already noted, the energy density of the cosmic rays is $U \approx 1.5 \times 10^{-12}$ erg cm^{-3} (1 eV cm^{-3}), half of which is carried by particles above 10 GeV per nucleon. The cosmic rays are highly relativistic, forming a gas with pressure

$$P \approx \tfrac{1}{3} U. \tag{11}$$

The number density of relativistic particles is $n \approx 10^{-10}$ cm^{-3}. The cyclotron radius R of a typical 10 GeV proton in a field of 3 μG is 10^{13} cm. This is a small fraction 3×10^{-8}, of the thickness of the galactic disk. Thus the average cosmic-ray particle is tightly bound to the lines of force of the galactic field and can drift across the lines of force only at a very slow rate as a result of field gradients or scattering. (For a detailed discussion of the kinetic properties of the cosmic-ray gas see Lerche and Parker, 1966; Lerche, 1967c; Scargle, 1968.)

The cosmic-ray gas is isotropic to better than one percent at the present time in the neighborhood of the Sun. Lerche has shown that anisotropies in which the cosmic-ray pressure parallel to the field differs from the perpendicular pressure are rapidly destroyed by unstable collective plasma interactions with the thermal gas and magnetic field. When $P_{\parallel} > P_{\perp}$, an unstable magnetosonic mode is excited (Lerche, 1967a).

When $P_{\perp} > P_{\parallel}$, the cosmic-ray electrons are unstable, producing a transverse mode propagating perpendicular to the field (Lerche, 1966, 1968; see Kadomtsev and Tsytovich, this volume, p. 108). These instabilities play the role of collisions, maintaining isotropy and permitting the cosmic-ray gas to be treated as a hydrodynamic fluid in many cases where the changes are slow (the fluid equation overlooks Landau damping and resonances). The bulk cosmic-ray streaming velocity follows as

$$\left(\delta + \frac{P}{c^2}\right)\frac{\mathrm{d}\mathbf{w}}{\mathrm{d}t} \cong \nabla P \tag{12}$$

where δ is the cosmic-ray gas density (n multiplied by the relativistic mass of the particles, see Tolman, 1946; Lerche and Parker, 1966; Lerche, 1967b; Scargle, 1968). If magnetic fields and a thermal gas are present too, the equations of motion become

$$\left(\delta + \frac{P}{c^2}\right)\frac{\mathrm{d}\mathbf{w}_{\parallel}}{\mathrm{d}t} = -\nabla_{\parallel} P \tag{13}$$

for the cosmic rays and

$$\varrho\frac{\mathrm{d}\mathbf{v}_{\parallel}}{\mathrm{d}t} = -\nabla_{\parallel} p_{\parallel} + \varrho\mathbf{g}_{\parallel} \tag{14}$$

for the thermal-gas motion parallel to the field (neglecting the gravitational forces on the cosmic-ray gas) and

$$\varrho\frac{\mathrm{d}\mathbf{v}_{\perp}}{\mathrm{d}t} = -\nabla_{\perp}(p + P) + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} + \varrho\mathbf{g}_{\perp} \tag{15}$$

for the perpendicular thermal-gas motion. Since both the cosmic-ray gas and the thermal gas are tied to the lines of force, we have $\mathbf{w}_{\perp} = \mathbf{v}_{\perp}$. We neglect the inertia of the cosmic-ray gas. The hydromagnetic equation for the magnetic field can be written

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla \times (\mathbf{v}_{\perp} \times \mathbf{B}). \tag{16}$$

The equations of continuity are

$$\frac{\partial\varrho}{\partial t} + \nabla\cdot(\varrho\mathbf{v}) = 0, \tag{17}$$

$$\frac{\partial\delta}{\partial t} + \mathbf{w}\cdot\nabla\delta + \left(\delta + \frac{P}{c^2}\right)\nabla\cdot\mathbf{w} = 0. \tag{18}$$

For small variations the pressure and density in each gas are related by the effective speed of sound in that gas. It is readily shown from these equations that there is an additional hydromagnetic wave mode as a consequence of the cosmic-ray gas. There is also some modification of the familiar fast mode (Parker, 1958, 1965b).

It has been shown recently (Wentzel, 1968, 1969; Kulsrud and Pearce, 1969; see Kadomtsev and Tsytovich, this volume, p. 108) that plasma turbulence is generated if the cosmic-ray gas streams along the magnetic field with a velocity relative to the thermal gas which is greatly in excess of the Alfvén speed in the thermal gas. The instability producing the turbulence involves scales of the same order as the cyclotron radius of the cosmic-ray particles, which is, in most cases, small compared to the collision mean-free path of the ions in the thermal gas. Thus the neutral atoms do not usually participate directly and the Alfvén speed is to be computed for the ionized component of the thermal gas alone, and may be 50 to 200 km $\sec^{-1}$ in typical H I regions. The net effect of the plasma turbulence is to introduce a frictional coupling between $\mathbf{w}_{\parallel}$ and $\mathbf{v}_{\parallel}$. Suitable friction terms should be introduced on the right-hand sides of Equations (13) and (14) to take account of this coupling when $|\mathbf{w}_{\parallel}-\mathbf{v}_{\parallel}|$ exceeds the critical value. The existence of such coupling was first suggested by Ginzburg (1965), who stressed its importance in regulating and controlling the escape of cosmic rays from the disk of the Galaxy, on which we will say more later.

Now consider the stability of the simple hydrostatic equilibrium described in the previous section. Let $p=\varrho u^2$ in the equilibrium state again and write

$$\delta p = \gamma u^2 \, \delta\varrho \tag{19}$$

for small variations in density and pressure. The coefficient γ can be as high as $\frac{5}{3}$ for rapid variations in which radiative transfer and thermal conduction are negligible. For the long term variations (10^7 to 10^8 yr) with which we shall be concerned, it is well known (Savedoff and Spitzer, 1950) that radiative transfer causes the temperature to decline with increasing density, so that $\gamma<1$, and in some cases $\gamma<0$ (see the recent work by Pikel'ner, 1967; Spitzer, 1968; Spitzer and Tomasko, 1968; Field *et al.*, 1969; Goldsmith *et al.*, 1969 and the references therein).

Now it is well known that a uniform thermal gas in free space is subject to instability if $\gamma<0$. In this case the pressure decreases with increasing density, so that a slight compression leads to collapse as a consequence of the pressure of the surrounding gas. It is also well known that an isothermal atmosphere in equilibrium in a uniform gravitational field is unstable provided only that $\gamma<1$. In this case the temperature and the scale height decline with increasing density so that a slight compression tends to collapse as a consequence of the weight of the overlying gas. Some of the thermal effects are discussed in detail by Field at this Symposium (see p. 51), who considers not only small perturbations to the equilibrium, but treats the final highly inhomogeneous equilibrium state of the gas. For the present discussion, illustrating the dynamical properties of the magnetic field and cosmic rays, it is sufficient to continue with the crude representation of the thermal effects in terms of γ.

The perturbation of an equilibrium atmosphere of thermal gas, horizontal magnetic field, and cosmic-ray gas in a gravitational field g, representing large-scale conditions in the disk of the Galaxy, can be carried out in a straightforward manner from Equations (13) through (19). We note that the inertia of the cosmic-ray gas is negligible so that Equation (12) contributes nothing. The cosmic-ray pressure remains uniform along each line of force and the volume of each tube of flux remains contant to first order. Hence

$$\frac{\mathrm{d}P}{\mathrm{d}t} \equiv \frac{\partial P}{\partial t} + v_z \frac{\mathrm{d}P}{\mathrm{d}z} = 0 . \tag{20}$$

We suppose that α and β are constant in the initial equilibrium. A simple normal mode analysis, with solutions of the form exp $(t/\tau + i\mathbf{k}\cdot\mathbf{r})$ leads to an adequate instability criterion. It is sufficient for the present discussion to restrict attention to perturbations involving variations and motions in the vertical z-direction and in the horizontal y-direction along the magnetic field. Then instability occurs for

$$\gamma < \frac{(1+\alpha+\beta)^2}{1+\beta+\alpha\left[\frac{3}{2}+8(k_y^2+k_z^2)\Lambda^2\right]} . \tag{21}$$

For long wavelengths and $\alpha = \beta = 0.5$, this criterion is $\gamma < \frac{16}{9}$, which is to be compared with the criterion $\gamma < 1$ in the absence of magnetic field and cosmic rays. The characteristic growth times are of the order of the free-fall time over one scale height, or the time in which the speed of sound or Alfvén speed traverses one scale height, typically (1 to 3) $\times 10^7$ yr. This is of the same order as the thermal instability time in the absence of field and cosmic rays. The characteristic scale of the instability is comparable to Λ, say 200 pc.

The magnetic field and cosmic rays both enhance the instability, each contributing about equally, as may be seen from Equation (21) above. The unstable effect of the magnetic field can be understood if we remember that the thermal gas is constrained to motion along the lines of force, like beads on a string. Then if the horizontal lines of force are perturbed, by raising them in some places and lowering them elsewhere, the gas tends to slide from the high places along the lines into the low places, further burdening down the low places, and unloading the high places where the field is then free to expand upward. The cosmic-ray gas contributes to the instability because its pressure remains constant along the perturbed line of force. Hence the cosmic-ray pressure is higher than the surrounding pressure on the raised portions of a line of force, tending to inflate and buoy up the raised portion further. On the depressed portions the cosmic-ray pressure is below the surrounding pressure, thereby permitting compression and sinking. Altogether the effects are much like the well-known Rayleigh-Taylor instability, in which the light fluids – the field and cosmic rays – try to bubble up through the heavy thermal gas.

The pressure of the thermal gas resists the accumulation of gas in the low places, but unless γ is larger than the value given by Equation (21), the resistance is ineffectual and the gas clumps into clouds.

We have explored the dynamical behavior of the interstellar gas-field-cosmic ray system in some detail (Parker, 1966b, 1967a, b, 1968b, c, d, e, 1969a; Lerche and Parker, 1967; Lerche, 1967c, d) carrying through calculations with the boundary conditions appropriate to the disk of the Galaxy, etc. The calculations show that introduction of the third dimension, with wave number k_x, enhances the instability somewhat. The most unstable modes have $k_x^2 \gg k_y^2, k_z^2$, suggesting a tendency for the interstellar gas to break up into relatively thin vertical sheets lying along the field. There appears to be no final inhomogeneous equilibrium state into which the gas can settle, suggesting that the gas clouds are shifting forms, rather than stable entities. It is, then, the combined effects of the cosmic rays, the galactic magnetic field, and the small γ (thermal instability, see Field, this volume, p. 51) which are responsible for clumping the interstellar gas into clouds and compressing those clouds toward compact masses in which star formation occurs. The overall dynamical picture of the interstellar gas which emerges from these theoretical considerations is one in which there is continual and vigorous competition between the dynamical instability, which tends to form the gas into shifting patterns of concentration, and the usual disruptive effects of hot stars and local cosmic-ray production, which tend to disperse the concentrations (Parker, 1968e). Self-gravitation (which we have omitted from the equations to keep the algebra as simple as possible) is relatively unimportant in most cases until the individual gas clouds become very dense and massive. The scale along the field is typically a few hundred pc, though the gas from such a region may then collapse into a much smaller volume. The scale across the field may be only a few pc, according to our simple linearized calculations. It will be interesting to see what turns up in future detailed observations of cloud structure. And of course it would be desirable to carry out more detailed and complete theoretical calculations of the behavior of the gas when the perturbations have grown to large amplitude and the cloud structure really begins to take shape. Some attempts have been made in these directions in the references cited above, but only restricted examples have been dealt with and the problem is still relatively unexplored.

5. The Role of Cosmic Rays in the Galactic Disk

It is interesting to inquire into the origin and evolution of the cosmic-ray gas in the context of the above dynamical considerations. It is generally presumed that the cosmic rays are generated by energetic phenomena in the galactic disk, such as novae, supernovae, pulsars, etc. There are more extravagant ideas available, of course, such as universal cosmic rays, originating in radio galaxies, quasars, etc. But for the present we pursue the conservative idea that most of the cosmic rays in the disk of the Galaxy are generated somewhere in the disk (see the general discussion of Ginzburg and Syrovat-skii, 1964; Parker, 1968a).

It is known from studies of radioactive nuclei in meteoritic material that the cosmic-ray density has been approximately steady over the past 10^5, 10^7 and 10^9 yr (see discussion and references in Parker, 1968a). The mean density over these periods has not varied significantly. So presumably the cosmic rays are in an overall steady state in the disk (apart from local outbursts and instabilities).

Studies of the abundances of such rare nuclei as Li, Be, B, He^3, etc. indicate that the heavier cosmic-ray nuclei have passed through a significant amount of matter,

https://doi.org/10.1017/S0074180900004873 Published online by Cambridge University Press

approximately 3 g cm^{-2}. It is the breakup of the more common heavier nuclei in passage through matter that produces the rare nuclei. Translated into distance through interstellar space, 3 g cm^{-2} is about $2 \times 10^{24}/n$ cm. A mean interstellar density of $n=2$ atoms cm^{-3} gives 3×10^5 pc or 10^6 light-years, suggesting that the cosmic-ray particles which are observed today have spent about 10^6 yr in the disk of the Galaxy. It appears, then, that cosmic rays escape from the Galaxy after having spent about 10^6 yr in interstellar space.*

Now if cosmic rays are generated within the disk and escape out of the disk after a residence of $t=10^6$ yr, then the cosmic rays have a mean streaming velocity S of the order of L/t where L is the mean distance from the source to the exit. A streaming velocity S leads to an anisotropy such that an observer looking upstream sees a cosmic-ray intensity (measured at a particular particle energy) which is $1+\Delta$ times the mean, where

$$\Delta = (2 + \Gamma)\, S/c \tag{22}$$

where $\Gamma \approx 2.6$ is the exponent of the differential cosmic-ray energy spectrum, $E^{-\Gamma}$. Hence there is a cosmic-ray anisotropy which is a direct measure of the streaming of cosmic rays. If the mean distance for escape is $L=10^4$ pc or more, corresponding to distances along the galactic arm, or to distances to and from the nucleus of the Galaxy, we have $S \approx 10^9$ cm sec^{-1} and $\Delta \approx 10^{-1}$. But, as we have already noted, plasma turbulence prevents streaming of cosmic rays in excess of a few hundred km sec^{-1}, and observations indicate that Δ is very small, probably $\Delta < 10^{-3}$ ($S \leqslant 60$ km sec^{-1}) in the neighborhood of the Sun at the present time, showing that the cosmic rays in the vicinity of the Sun today are streaming at a very leisurely pace. Of course we are near the central plane of the Galaxy, which, as a plane of symmetry, may be a stagnation surface. And the streaming velocity may be larger nearer the surface of the disk. But whatever the situation, it appears that the cosmic rays do not escape along the length of the magnetic field, but must escape out the surface of the disk within a few hundred pc of their place of origin.

We suggest that the large-scale dynamical instability of the interstellar gas-field-cosmic ray system discussed in the section above, is essential to the escape of cosmic rays from the disk. The only means by which cosmic rays can escape is by inflation of the raised portions of the galactic field (Parker, 1965a). They must literally push their way out. The cosmic-ray pressure observed at the position of the Sun is 0.5×10^{-12} dyne cm^{-2}, equal to the pressure of a magnetic field of 3.5 μG. So there should be no difficulty for the cosmic rays to push their way out from some region where the field is raised and expanded to values well below 5 μG, the r.m.s. field strength given by Equation (10). This argument puts an upper limit on the field strength. But the field cannot be much smaller either, for if it were less than 3 μG deep in the disk, the raised portions of the field would offer no resistance whatever to the cosmic-ray gas. The

* It is conjectured by some that the cosmic rays may spend up to 10^8 yr in a galactic halo during which time they make occasional brief excursions into the disk where they accumulate 10^6 yr of residence before escaping from the Galaxy altogether. This idea does not affect the present discussion.

only limitation would then be the 'friction' of the plasma turbulence with the thermal gas when the streaming exceeds a few hundred km sec^{-1}. (Parenthetically we remark that indeed this offers the fascinating prospect of pushing interstellar gas to positions high above the disk ($z \gg \Lambda$) from where it falls back in clumps and is observed with high negative velocity at high galactic latitudes (see van de Hulst, this volume, p. 3). For instance, we might then expect to see a larger anisotropy in the cosmic rays here at the position of the Sun. We would also have some difficulty in explaining the storage of cosmic rays for 10^6 yr in the disk, unless, of course, the sources are quite densely distributed through the disk, because the cosmic rays would tend to burst directly out of the disk wherever they are produced, rather than spreading out along the field through the disk before escape. Finally, if the field is weak, then $B^2/(8\pi) \ll \frac{1}{2}\varrho v^2$ and the field would be completely disrupted and distorted by the turbulent motions of the interstellar gas. As pointed out by Pikel'ner, one could not then understand the large-scale order of the galactic field, with a well-defined reversal of sign across the galactic plane. Hence, all things taken together, it appears that

$$B \gtrsim 3\mu\mathrm{G}\,. \tag{23}$$

This lower limit, together with the upper limit given by Equation (10) confine the field strength rather closely if we are to understand the dynamical behavior of the interstellar gas-field-cosmic ray system in a simple way in terms of the present observational estimates of the gas density, turbulent velocity, scale height, etc.

To pursue the problem of escape of the cosmic rays a little further, recent theoretical considerations, together with observational studies of solar fields, indicate that the lines of force of the magnetic fields in nature are stochastic (Jokipii and Parker, 1969a, b). Pick any two lines of force which are neighbors, with separation $h(0)$ at some position along the field. Following along the lines of force a distance s we find that their separation $h(s)$ undergoes a random walk, so that on the average $h(s)$ is larger than $h(0)$.

The observed dispersion in the direction of the galactic field (Hiltner, 1956; Jokipii *et al.*, 1969) indicates that the lines of force random walk to the surface of the galactic disk (say to $z = 150$ pc) in distances of only 500 pc (Jokipii and Parker, 1969b). This stochastic property of the galactic field, in which each line of force comes close to the surface at various places, appears to be an essential property of the field accounting for the 10^6 yr cosmic-ray life in the disk. Were the field not stochastic, the cosmic-ray pressures in the disk would increase the scale height Λ a little, and would produce more violent instabilities of the interstellar gas-field-cosmic ray system.

We should not fail to note that the escape of cosmic rays through inflation of the fields at the surface of the disk must extend inflated bubbles of field out from the disk for some distance, producing a thick boundary layer of field and cosmic rays over the surface of the disk (Parker, 1965a). Presumably the inflated bubbles of field eventually free themselves from the Galaxy through the diffusive and dissipative effects of plasma turbulence. We have no way of computing how far out they extend before this occurs.

In summary, then, the escape of cosmic rays from the disk of the Galaxy appears to be from the surface of the disk. The streaming of cosmic rays along the field as they move toward escape is limited to speeds of a few hundred km sec^{-1}, or less, by the friction of plasma turbulence in the interstellar gas. Access to the surface of the disk is facilitated by the stochastic character of the lines of force of the field. The ultimate escape from the surface of the disk involves disengaging the cosmic-ray particles from the lines of force of the field of the disk. We have suggested that the particles disengage by inflating the field at the surface to form bubbles of extended field and cosmic rays, which presumably are eventually freed from the Galaxy by the dissipative effects of plasma turbulence. The cosmic rays which inflate them are then free of the Galaxy.

Now to comment in a broader context; the mechanism by which cosmic rays escape from the Galaxy is one which has been treated lightly for too long. I have proposed that cosmic rays escape by inflating the field and pushing their way out because I can think of no alternative mechanism. There may be alternatives. And if there are, they should be formulated and explored. Scattering out of the galactic field by plasma turbulence has been suggested as the means of escape, but upon close examination it does not seem adequate. As was already mentioned the cyclotron radius R of a 10 GeV proton in a field of 3 μG is 10^{13} cm. The cyclotron period is 2×10^3 sec. If we suppose that the 10 GeV proton is scattered n times through a large angle, the proton may random walk a distance of the order of $n^{1/2}R$ across the field. Escape from the disk implies diffusion across the field for some 100 pc, requiring $n = 10^{15}$. Even if the proton were scattered through a large angle as often as once each cyclotron period, the escape time is 2×10^{18} sec or 0.7×10^{11} yr!

The problem of escape becomes particularly acute in the universal theory of cosmic rays, which explains cosmic rays in the Galaxy by supposing them to be the dominating phenomenon of the universe, filling all space to the high density which we observe in the disk, and originating in colossal releases of energy in distant galaxies. In this theory the cosmic-ray density is more or less uniform throughout all space, with cosmic rays entering the disk of the Galaxy from outside, remaining for not longer than 10^6 yr, and departing. The uniform cosmic-ray pressure precludes cosmic rays pushing their way either in or out. And it has not yet been shown how they can penetrate across the fields of the disk of the Galaxy and back out again in only 10^6 yr. It has been suggested instead that the galactic fields lie 'open' to the outside in some way, with the lines of force in the rotating disk maintaining a direct connection into the intergalactic field. The proposal is contrary to the usual ideas of hydromagnetism, that lines of force move with the background plasma and can break and reconnect in a changing pattern only in the characteristic dissipative diffusion time. On the other hand, it cannot be ruled out that sufficient plasma turbulence is present to maintain connection of the galactic field with an intergalactic field. The problem is one of fundamental importance to the universal theory and merits serious inquiry.

The problem of cosmic-ray escape is of particular interest too when we consider the strength of the galactic field under the assumption that cosmic rays are generated within the disk of the Galaxy. We have indicated in the discussion (Parker, 1965a) that the cosmic-ray gas inflates the interstellar gas-field system until the cosmic-ray pressure becomes comparable to the magnetic pressure, whereupon the cosmic rays begin to escape by inflating the surface fields. Now suppose for the moment that there is some easier means of escape, such as direct connection into the intergalactic field. Then it is only plasma turbulence which limits the escape along the lines of force. If, as we have supposed, this is an easier escape than inflation of the fields, then the cosmic-ray pressure does not build up to the magnetic pressure. But observations suggest that the cosmic-ray pressure is, in fact, comparable to the magnetic pressure. The rough equality of the cosmic-ray pressure and magnetic pressure suggested by observations can be interpreted, then, as an indication that there is not, in fact, an easier way out than inflation of the fields. But, as noted above, there is still considerable uncertainty in the mean field strength in the disk, so this conclusion must be considered tentative for the time being.

It is evident from these qualitative considerations that our understanding of cosmic-ray escape would be greatly increased theoretically if a quantitative treatment of the limitations on cosmic-ray streaming by plasma turbulence could be applied to the dynamics of the inflation of a bubble of field from the surface of the disk, with the simultaneous downward streaming of the thermal gas and upward streaming of the cosmic rays.

Acknowledgement

This work was supported by the National Aeronautics and Space Administration under grant NASA-96-60.

References

Alfvén, H.: 1947, *Monthly Notices Roy. Astron. Soc.* **107**, 211.
Batchelor, G. K.: 1950, *Proc. Roy. Soc. London* **A201**, 405.
Biermann, L. and Schlüter, A.: 1951, *Phys. Rev.* **82**, 863.
Chandrasekhar, S. and Fermi, E.: 1953, *Astrophys. J.* **118**, 116.
Davis, L. and Berge, G. L.: 1968, *Nebulae and Interstellar Matter* (ed. by L. Aller and B. Middlehurst), University of Chicago Press, Chicago, Ch. 15.
Field, G. B., Goldsmith, D. W., and Habing, H. J.: 1969, *Astrophys. J. Lett.* **155**, L149.
Ginzburg, V. L.: 1965, *Astron. Zh.* **42**, 1129 (translation: 1966, *Soviet Astron.* **9**, 877).
Ginzburg, V. L. and Syrovat-skii, S. I.: 1964, *Origin of Cosmic Rays*, Pergamon Press, New York.
Goldsmith, D. W., Habing, H. J., and Field, G. B.: 1969, *Astrophys. J.* **158**, 173.
Hiltner, W. A.: 1956, *Astrophys. J. Suppl.* **2**, 389.
Jokipii, J. R. and Lerche, I.: 1969, *Astrophys. J.* **157**, 1137.
Jokipii, J. R. and Parker, E. N.: 1969a, *Astrophys. J.* **155**, 777.
Jokipii, J. R. and Parker, E. N.: 1969b, *Astrophys. J.* **155**, 799.
Jokipii, J. R., Lerche, I., and Schommer, R. A. 1969, *Astrophys. J. Letters* **157**, L119.
Kraichnan, R. H. and Nagarajan, S.: 1967, *Phys. Fluids* **10**, 859.
Kulsrud, R. and Pearce, W. P.: 1969, *Astrophys. J.* **156**, 445.
Leighton, R. B.: 1969, *Astrophys. J.* **156**, 1.
Lerche, I.: 1966, *Phys. Fluids* **9**, 1073.
Lerche, I.: 1967a, *Astrophys. J.* **147**, 681.
Lerche, I.: 1967b, *Astrophys. J.* **147**, 689.
Lerche, I.: 1967c, *Astrophys. J.* **149**, 395, 553.
Lerche, I.: 1967d, *Astrophys. J.* **150**, 651.
Lerche, I.: 1968, *Phys. Fluids* **11**, 1720.
Lerche, I. and Parker, E. N.: 1966, *Astrophys. J.* **135**, 106.

Lerche, I. and Parker, E. N.: 1967, *Astrophys. J.* **149**, 559.
Morris, D. and Berge, G. L.: 1964, *Astrophys. J.* **139**, 1388.
Oort, J. H.: 1952, *Astrophys. J.* **116**, 233.
Oort, J. H.: 1954, *Bull. Astron. Inst. Netherl.* **12**, 177.
Oort, J. H. and Spitzer, L.: 1955, *Astrophys. J.* **121**, 6.
Parker, E. N.: 1955, *Astrophys. J.* **122**, 293.
Parker, E. N.: 1957, *Proc. Nat. Acad. Sci. Am.* **43**, 8.
Parker, E. N.: 1958, *Phys. Rev.* **109**, 1328.
Parker, E. N.: 1965a, *Astrophys. J.* **142**, 584.
Parker, E. N.: 1965b, *Astrophys. J.* **142**, 1086.
Parker, E. N.: 1966a, *Astrophys. J.* **144**, 916.
Parker, E. N.: 1966b, *Astrophys. J.* **145**, 811.
Parker, E. N.: 1967a, *Astrophys. J.* **149**, 517.
Parker, E. N.: 1967b, *Astrophys. J.* **149**, 535.
Parker, E. N.: 1968a, *Nebulae and Interstellar Matter* (ed. by L. Aller and B. Middlehurst), University of Chicago Press, Chicago, Ch. 16.
Parker, E. N.: 1968b, *Astrophys. J.* **154**, 49.
Parker, E. N.: 1968c, *Astrophys. J.* **154**, 57.
Parker, E. N.: 1968d, *Astrophys. J.* **154**, 515.
Parker, E. N.: 1968e, *Astrophys. J.* **154**, 875.
Parker, E. N.: 1969a, *Space Sci. Rev.* **9**, 651.
Parker, E. N.: 1969b, *Astrophys. J.* **157**, 1119.
Parker, E. N.: 1969c, *Astrophys. J.* **157**, 1129.
Parker, E. N.: 1970, *Astrophys. J.* **160**, 383.
Pikel'ner, S. B.: 1967, *Astron. Zh.* **44**, 1915.
Savedoff, M. P.: 1956, *Astrophys. J.* **124**, 533.
Savedoff, M. and Spitzer, L.: 1950, *Astrophys. J.* **111**, 593.
Scargle, J. D.: 1968, *Astrophys. J.* **151**, 791.
Schmidt, M.: 1956, *Bull. Astron. Inst. Netherl.* **13**, 247.
Schmidt, M.: 1963, *Astrophys. J.* **137**, 758.
Spitzer, L.: 1968, *Nebulae and Interstellar Matter* (ed. by L. Aller and B. Middlehurst), University of Chicago Press, Chicago, Ch. 1.
Spitzer, L. and Tomasko, M. G.: 1968, *Astrophys. J.* **152**, 971.
Steenbeck, M., Krause, F., and Radler, K. H.: 1966, *Z. Naturforsch.* **21**, 369.
Tolman, R. C.: 1946, *Relativity, Thermodynamics, and Cosmology,* Clarendon Press, Oxford.
Wentzel, D.: 1968, *Astrophys. J.* **152**, 987.
Wentzel, D.: 1969, *Astrophys. J.* **156**, 303.