Part II: Theoretical Considerations on the Production and Dissipation of Velocity Fields in the Interstellar Medium

Gross Dynamics of the Interstellar Medium

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I. INTRODUCTION

THIS paper reviews the many, by now familiar, processes that have at various times been attributed to the interstellar motions, in an effort to piece together some over-all picture of the grosser dynamical relations which might be expected to apply to the motions of the material and electromagnetic fields between the stars. We are interested in numerical values for the material densities, velocity fields, magnetic fields, etc., and we should also like to know to what extent the observed properties of the different fields are dependent upon each other.

Most of the interesting theoretical problems in interstellar dynamics are entirely nonlinear, involving the simultaneous and coordinated functioning of several physical processes. Hence we cannot construct a rigorous, general, quantitative theoretical treatment of the interstellar problem. Therefore, we often find ourselves interpreting interstellar phenomena by constructing analogies to simpler individual processes which have been treated more or less completely and which we think we understand. Someday our understanding of compressible, radiating, supersonic, hydromagnetic motions in a tenuous gas may develop to the point where most of the contemporary uncertainties can be decided on a more rigorous basis.

For the present we treat the interstellar medium as a compressible, viscous, electrically conducting fluid, neglecting all phenomena, such as shock waves, which have scales as small as the mean free path of the individual gas molecules. We do not feel that shock waves, etc. are unimportant,—indeed, quite the contrary—but we suggest that their presence or absence does not greatly alter the gross dynamical features to be considered. We do not elaborate the development of individual topics which are discussed at length in the literature or which are treated extensively in the Symposium.

The theoretical researches of Spitzer and Savedoff[1] and Spitzer[2] suggest that in HI regions of interstellar space the kinetic temperature of the gas is of the order of 100°K, and in HII regions, 10^4°K. From these temperatures we may compute the viscosity η from the elementary formula for an un-ionized gas,

$$\eta=(mkT/36\pi^3r^4)^{\frac{1}{2}}\cong 0.5\times 10^{-5}T^{\frac{1}{2}} \text{ g/cm sec}, \qquad (1)$$

in the absence of magnetic fields. Here r is the effective collision radius for hydrogen atoms, of mass m, and has been taken equal to 10^{-8} cm. More comprehensive discussions may be found in the literature.[3]

The electrical conductivity of the completely ionized gas[4,5] may be computed from Cowling's approximate formula[6] or from Spitzer's discussion[7]

$$\sigma\sim 10^7\cdot T^{\frac{3}{2}}/Z \text{ esu}, \qquad (2)$$

where Z is the mean charge per ion.

The mean free path of a hydrogen atom, for which $r\cong 10^{-8}$ cm, in hydrogen gas consisting of N atoms per cubic cm is for an un-ionized gas,

$$\lambda\cong 1/r^2N=10^{16}/N \text{ cm}, \qquad (3)$$

and less for an ionized gas. We consider dynamical features of the interstellar medium which have a scale rather in excess of λ, so that the conventional use of pressure, viscosity, etc., is valid. Since N is of the order of unity, for which $\lambda\cong 10^{-2}$ pc, we do not deal with scales of less than about one parsec. On the other hand, since we do not concern ourselves with galactic dynamics, we limit the discussion to scales with an upper limit of, say, 200 pc; this being small compared to the

[1] L. Spitzer and M. P. Savedoff, Astrophys. J. **111**, 593 (1950).
[2] L. Spitzer, Astrophys. J. **120**, 1 (1954).
[3] S. Chapman, Astrophys. J. **120**, 151 (1954).
[4] A. Schlüter, Z. Naturforsch. **5a**, 72 (1950).
[5] T. G. Cowling, Proc. Roy. Soc. (London) **A183**, 453 (1945).
[6] T. G. Cowling in *The Sun*, edited by G. P. Kuiper (University of Chicago Press, Chicago, 1953).
[7] L. Spitzer, *The Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956).

galactic dimensions, we do not need to consider galactic rotation and shear explicitly.

II. INTERSTELLAR ELECTROMAGNETIC FIELDS

In his theory of the origin of cosmic rays, Fermi speculated[8,9] that there might be a large-scale interstellar magnetic field intimately associated with the dynamics of the interstellar medium. Theoretical interpretation[10,11] of the observations[12,13] of the polarization of the light of distant stars* has given substance to Fermi's original hypothesis, and it now appears reasonable to assume[14–16] that there is a general magnetic field of about 10^{-5} gauss lying in and along the galactic arms. There seems to be no indication of a general galactic dipole field with its axis parallel to the axis of galactic rotations.

If we suppose that there is a galactic magnetic field, the question arises as to what field equations it satisfies. In view of the enormous linear dimensions, the electrical conductivities computed from (2) are so high that electric fields in the interstellar medium are negligible. The electric field $\mathbf{E}'$ in the frame of reference moving with the medium is related to the electric field $\mathbf{E}$, magnetic field $\mathbf{B}$, and velocity field $\mathbf{v}$ in the fixed frame of reference by the Lorentz transformation

$$\mathbf{E}'=\mathbf{E}+(\mathbf{v}/c)\times\mathbf{B}$$

for velocities small compared to the speed of light. If we require that $\mathbf{E}'=0$ as a consequence of high electrical conductivity, we obtain the well-known[17,18] fundamental hydromagnetic relation

$$\mathbf{E}=-(\mathbf{v}/c)\times\mathbf{B}. \tag{4}$$

If the magnetic field is so strong that the cyclotron frequency of the free conduction electrons exceeds their collision frequency, (2) is no longer applicable. Instead of an electric field $\mathbf{E}$ resulting in a current $\sigma\mathbf{E}$, there results the mass motion

$$\mathbf{u}=c\mathbf{E}\times\mathbf{B}/B^2 \tag{5}$$

perpendicular to $\mathbf{B}$. There may be motion along $\mathbf{B}$, but the high electrical conductivity parallel to $\mathbf{B}$ means $\mathbf{E}\cdot\mathbf{B}=0$. Thus $\mathbf{E}=-\mathbf{u}\times\mathbf{B}/c$ and only $\mathbf{u}$ appears in the equation for $\partial B/\partial t$.

If the scale L of the electromagnetic field is large compared to the radius of gyration of the individual electron and ion motions in the magnetic field $\mathbf{B}$, as is usually the case, then $\mathbf{u}$ is the principle mass motion; $\mathbf{u}\cong\mathbf{v}$, and if we form the vector product of Eq. (5) with $\mathbf{B}$ we obtain (4). We might say, in this case, that the gas, realizing its inability to conduct electricity, is clever enough to hide its embarrassment by moving in such a way that the electric field which it experiences is zero.

Upon neglecting the displacement currents we have the electromagnetic field equation

$$c\nabla\times\mathbf{B}=4\pi\mathbf{j},$$

where $\mathbf{j}$ is the current density.

Substituting (4) into

$$\partial\mathbf{B}/\partial t=-c\nabla\times\mathbf{E},$$

we obtain the usual hydromagnetic equation

$$\partial\mathbf{B}/\partial t=\nabla\times(\mathbf{v}\times\mathbf{B}), \tag{6}$$

regardless of whether the collision frequency of the free electrons is large or small compared to their cyclotron frequency; the lines of force of $\mathbf{B}$ are "frozen" into the fluid.

The equation of motion of the fluid is approximately of the familiar form

$$\rho d\mathbf{v}/dt=-\nabla p+(\mathbf{B}\cdot\nabla)\mathbf{B}/4\pi-\nabla(\mathbf{B}^2/8\pi) \tag{7}$$

even when the collision frequency is extremely small, though in that case one may have a somewhat different pressure perpendicular than parallel to $\mathbf{B}$. These problems are developed at greater length in the literature.[6,19–23]

Substituting (4) into the equation of motion for a particle of mass m, charge q, and velocity $\mathbf{w}$,

$$d\mathbf{w}/dt=(q/m)[\mathbf{E}+(\mathbf{w}/c)\times\mathbf{B}],$$

and forming the scalar product with $\mathbf{w}$, we obtain

$$(d/dt)(mw^2/2)=q\mathbf{w}\cdot(\mathbf{w}\times\mathbf{B}/c).$$

This relation shows[24] that charged particles can be accelerated only when the mass motions of the fluid work against the Lorentz force $\mathbf{w}\times\mathbf{B}$ exerted on the particle by $\mathbf{B}$; thus, for instance, the mechanisms by which cosmic-ray particles can be accelerated are limited to the betatron effect and the Fermi mechanism.

III. FIELD DENSITIES

We now consider the relative proportions of the various fields and their dynamical effects.

[8] E. Fermi, Phys. Rev. **75**, 1169 (1949).
[9] E. Fermi, Astrophys. J. **119**, 1 (1954).
[10] L. Davis and J. Greenstein, Astrophys. J. **114**, 206 (1951).
[11] L. Spitzer and J. W. Tukey, Astrophys. J. **114**, 186 (1951).
[12] W. A. Hiltner, Astrophys. J. **109**, 471 (1949).
[13] W. A. Hiltner, Astrophys. J. **114**, 241 (1951).
* The interpretation of Davis and Greenstein[10] seems to be in better accord with the facts than that of Spitzer and Tukey.[11]
[14] L. Davis, Jr., Phys. Rev. **81**, 890 (1951).
[15] S. Chandrasekhar and E. Fermi, Astrophys. J. **118**, 113 (1953).
[16] S. B. Pickelner, Uspekhi Fiz. Nauk. **58**, 285 (1956).
[17] W. M. Elsasser, Phys. Rev. **95**, 1 (1954).
[18] T. G. Cowling, *Magnetohydrodynamics* (Interscience Publishers, Inc., New York, 1957).
[19] L. Spitzer, Astrophys. J. **116**, 299 (1952).
[20] Chew, Goldberger, and Low, Proc. Roy. Soc. (London) **A236**, 112 (1956).
[21] K. M. Watson, Phys. Rev. **102**, 12 (1956).
[22] K. A. Brueckner and K. M. Watson, Phys. Rev. **102**, 19 (1956).
[23] E. N. Parker, Phys. Rev. **107**, 924 (1957).
[24] E. N. Parker, Phys. Rev. **109**, 1328 (1958).

A. Magnetic Field

The galactic magnetic field is now believed to lie along the galactic arm and have a density of the order of 10^{-5} gauss. It is believed that it is the galactic field which is responsible for aligning the interstellar dust grains that polarize the starlight. Davis[14] was the first to suggest that the variations in the plane of polarization of the light of distant stars gives an estimate of the extent to which the interstellar motions are able to distort the galactic magnetic field. We let α be the observed root-mean-square angular deviation of the planes of polarization. Then it can be shown[14–16] that the inertia of interstellar motions $\mathbf{v}$ in a conducting fluid of density ρ is capable of distorting a large-scale magnetic field $\mathbf{B}$ through an angle α where

$$B = (4\pi\rho/3)^{\frac{1}{2}} v/\alpha. \tag{8}$$

With the observed deviation,[13] $\alpha \cong 0.2$, Davis assumed that $\rho \geq 10^{-23}$ g/cm^3, $v \cong 20$ km/sec, obtaining $B \cong 10^{-4}$ gauss. Chandrasekhar and Fermi[15] later repeated the calculation using the values $N \cong 1$, $\rho \cong 2\times10^{-24}$ g/cm, based on observations[25] of the interstellar 21-cm line, and the revised value[26] $v=5$ km/sec; they obtained $B \cong 0.7\times10^{-5}$ gauss.

Further estimates of the galactic arm field may be had from the equation for static equilibrium of a cylindrical galactic arm: The contracting influence of self-gravitation must be balanced by the expanding effect of thermal and turbulent motions, and lateral magnetic pressure. With a galactic arm radius of 250 pc, $N \cong 1$, and small scale motions of 5 km/sec, Chandrasekhar and Fermi[15] estimated that a galactic arm field of 0.6×10^{-5} gauss is necessary to make up the balance. Unfortunately N and v are sufficiently uncertain that acceptable values may give imaginary field densities.

Estimates of the galactic field density based on considerations of the interstellar dust gains yield values of the galactic arm field density: Davis and Greenstein[10] estimate that a galactic arm field of the order of 10^{-4} gauss is necessary to account for the aligning of the interstellar dust grains responsible for the observed polarization of starlight. The observation of thin curved dust filaments† in the Pleiades can apparently be explained only by the presence of a magnetic field not less than 0.25×10^{-5} gauss. It is quite possible that these filaments represent streaks of dust blown along by the motion of interstellar gas—an interstellar wind. The filaments are observed to be curved—the curvature presumably reflects the direction of the gas motion—but one asks why the centrifugal force does not spread the dust out. Inhibition of the spreading by gas resistance requires excessively large gas densities; but magnetic fields of the above size, acting on the excess negative charge (of one or two electrons) that each gain is estimated to possess[27–30,2], may be effective.

For, if $\mathbf{u}$ is the velocity of a dust gain of radius b and mass M in the presence of interstellar winds with velocity $\mathbf{v}$, then[31]

$$d\mathbf{u}/dt = \Gamma(\mathbf{v}-\mathbf{u}), \tag{9}$$

where

$$\Gamma = \pi b^2 N \langle u^2\rangle^{\frac{1}{2}} m/M. \tag{10}$$

N is the number of atoms per unit volume of interstellar medium, $\langle u^2\rangle$ is the mean square thermal velocity, and m is the mass of an individual atom. If an interstellar wind of velocity $v \cong \langle u^2\rangle^{\frac{1}{2}}$ were suddenly to strike a dust grain at rest, the particle would slip relative to the wind a distance of the order of v/Γ before being accelerated to steady motion v. If $b \cong 10^{-5}$, $N \cong 1$, and if the grain density is 1 g/cm^3, so that $M \cong 4\times10^{-15}$ g, then $v/\Gamma \cong 3$ pc, v/Γ varies with grain size as b, and we see that a dust globule may be tremendously smeared in a wind, with the larger grains following the curvature of the wind much less closely than the fine grains; each filament will spill over into its neighbor.

In the Pleiades one observes filaments with widths as small as $l \sim 0.01$ light year, and radii of curvature of the order of $R \sim 1$ parsec. Equating the centrifugal acceleration of a wind moving in a curved path of radius R to the gas resistance given by Eq. (9) we obtain the condition that gas resistance inhibit the smearing. The velocity difference between the grain and the wind is

$$\Delta v \cong v^2/\Gamma R.$$

In the time R/v that the region rotates one radian, the differential motion amounts to a distance

$$h \cong \Delta v(R/v) = v/\Gamma \text{ cm}. \tag{11}$$

In order to preserve the identity of two curved neighboring filaments, h must be less than one half their separation l. If $l=0.01$ light years, then we must have $N \gtrsim 1600/\text{cm}^3$. This is rather denser than one expects in most interstellar regions.

On the other hand, we may take advantage of the excess negative charge of each grain and thereby tie the grains to a magnetic field. A force F (in this case the centrifugal force Mv^2/R) exerted perpendicular to a magnetic field B on a grain of mass M and charge q causes the grain to drift perpendicular to both F and B with a velocity of Fc/qB. In the time that the region revolves one radian the drift amounts to Mvc/qB. Requiring that this be less than half the filament width means that B must be not less than 0.25×10^{-5} gauss

[25] J. H. Oort, Astrophys. J. **116**, 233 (1952).
[26] A. Blaauw, Bull. Astron. Soc. Neth. **11**, 405 (1952).
† For a discussion of the dynamical properties of dust grains *per se*, see the basic works of Spitzer[2,27–30] and Whipple.[31] We mention the dust striations here only as a means toward estimating the galactic field.

[27] L. Spitzer, Astrophys. J. **93**, 369 (1941).
[28] L. Spitzer, Astrophys. J. **94**, 232 (1941).
[29] L. Spitzer, Harvard Observatory Monograph No. 7, Centennial Symposia.
[30] L. Spitzer, Astrophys. J. **111**, 593 (1950).
[31] F. L. Whipple, Astrophys. J. **104**, 1 (1946).

with g equal to one electronic charge. Thus again we arrive in the vicinity of 10^{-5} gauss.

Finally, we note that it might be difficult to contain the observed cosmic-ray field, of density 10^{-12} erg/cm^3, in a magnetic field of lesser energy density, requiring that $B \cong 0.5 \times 10^{-5}$ gauss: though Schlüter has pointed out that it might be possible to contain cosmic-ray particles with a weaker field which merely couples them to the massive ion field of the interstellar medium.

B. Velocity Field

The interstellar velocity field is observed[32,25,26] to be irregular and of the order of 5 km/sec. The scale of the irregularities is of the order of 10 or 20 pc and Blaauw[26] estimates that about 0.1 or 0.05 of interstellar space is occupied by gas somewhat denser than the mean of 1 hydrogen atom per cm^3. Since the irregular motions of 5 km/sec are generally several times greater than the thermal velocity, one might guess that collisions between denser regions would be rather inelastic. Oort[33] estimates a mean decay time of the interstellar motions of 7×10^6 years (the time between inelastic head-on collisions of individual clouds). A mean interstellar velocity of 5 km/sec and a density of one hydrogen atom/cm^3 suggests an energy dissipation of the order of 10^{-27} erg cm^{-3} sec^{-1}.

Consider the source of energy maintaining the interstellar motions. Gravitational instability, which may result in the cellular collapse of the interstellar medium according to Jeans' criterion, is probably not very effective in agitating the interstellar medium. It results in implosions, not explosions, and involves velocities probably no higher than about 10 km/sec. Such objects as novae and supernovae may be much more effective; in each explosion an expanding shell of gas is ejected with a velocity of the order of 1500 km/sec. Let us suppose that a mass of gas M is ejected into interstellar space with a velocity V. The ejected mass, being of the nature of a spherical shell, sweeps the interstellar medium before it (providing it is one mean free path or more thick) and is slowed down until ultimately we have a much larger mass M' moving with a much lower velocity V'. Conservation of momentum requires that $MV = M'V'$. Thus the final kinetic energy is smaller than the initial by the factor M/M' or V'/V. If the initial velocity is 1500 km/sec, and the final velocity is the observed mean of 5 km/sec, a nova or supernova is able to convert about 3×10^{-3} of its initial kinetic energy into motion of the interstellar medium.

A supernova ejects a sizeable portion of its mass, say $M = 0.1\ M_\odot$ g; hence the kinetic energy of the expanding shell is about 2×10^{48} ergs. This is to be compared with the energy expended as visible radiation: A supernova near an absolute magnitude of -16 for twenty days expends about 2×10^{48} ergs. Taking the volume of the disk of the galaxy, where the interstellar gas appears, to be that of a disk of radius 10^4 pc and thickness 500 pc, *viz.* 4×10^{66} cm^3, and assuming that there is one supernova every 30 years, means a gross energy source of 0.5×10^{-27} erg/cm^3 sec, of which 3×10^{-3}, or 1.5×10^{-30} erg/cm^3 sec is available to the interstellar motions. Some estimates[34–37] indicate that, on the average, novae may expend 300 times as much energy as supernovae. Thus we might guess that 5×10^{-28} erg/cm^3 sec are available to the interstellar motions. However, it is not clear that the extremely small masses, ejected at random by novae ($10^{-3} - 10^{-4}$ $M_\odot$), can contribute effectively to producing the observed relatively ponderous interstellar motions. The total momentum in the shell of a nova is only about 10^{38} g cm/sec; whereas the momentum of a mass of interstellar gas of diameter of 10 pc and density $N = 10$ is 10^{41} g cm/sec at 5 km/sec. The tiny impulses of exploding stars would be applied in a random way with little effect by each impulse; the net effect on the massive interstellar motions of many small random impulses would not be significant. We suggest, therefore, that exploding stars do not contribute significantly to the over-all interstellar motions, though they may of course be of considerable local interest in the acceleration of high-speed particles, etc.[38]

Oort has suggested that the bursting apart of dense interstellar gas clouds by newly formed early type stars may introduce sizeable quantities of kinetic energy into the observed interstellar motions. The estimates [33,39,40] of the net input vary widely, however, and the actual energy balance is not entirely clear. Biermann and Schlüter have counted the number of early type stars enmeshed in nebulosity per kpc^3, estimated the ultraviolet output of these stars, and guessed that the ultraviolet might be of the order of one percent efficient in exploding the associated nebulosity. On this basis they arrive at the estimate that the energy input to the interstellar motions may be 10^{-1} or 10^{-2} erg/g sec, or 10^{-25} to 10^{-26} erg/cm^3 sec. Savedoff[41] on the other hand, considering the details of an O star bursting apart the surrounding nebulosity, estimates that 7×10^{-28} erg/cm^3 might be available. We feel that

[32] W. S. Adams, Astrophys. J. **97**, 105 (1943).
[33] J. H. Oort, Bull. Astron. Soc. Neth. **12**, 177 (1954).

[34] V. L. Ginzburg, Uspekhi Fiz. Nauk. **51**, 343 (1953).
[35] V. L. Ginzburg, Fortschr. Physik (Berlin) **1**, 659 (1954).
[36] V. L. Ginzburg, Doklady Akad. Nauk S.S.S.R. **99**, 703 (1954).
[37] V. L. Ginzburg, Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **20**, 5 (1956).
[38] H. Alfvén and N. Herlofson, Phys. Rev. **78**, 616 (1950); K. O. Kiepenheuer, Phys. Rev. **79**, 738 (1950); I. S. Shklovsky, Doklady Akad. Nauk S.S.S.R. **90**, 983 (1953); V. A. Dombrosvsky, *ibid.* **94**, 1021 (1953); J. H. Oort and J. H. Walraven, Bull. Astron. Soc. Neth. No. 462 (1956); J. E. Baldwin, Nature **174**, 320 (1954); A. Unsöld, Phys. Rev. **82**, 357 (1951); V. L. Ginzburg, Doklady Akad. Nauk S.S.S.R. **76**, 377 (1951); I. S. Shklovsky, International Conference on Nuclear Astrophysics, Liège (1953); M. A. Vashakidae, Abastumani Astron. Circ. No. **147**, 11 (1954).
[39] F. D. Kahn, Bull. Astron. Soc. Neth. **12**, 187 (1954).
[40] J. H. Oort and L. Spitzer, Jr., Astrophys. J. **121**, 6 (1955).
[41] M. P. Savedoff, Astrophys. J. **124**, 533 (1956).

there is an intrinsic difficulty with such calculations because it is not clear to what extent the exploding fragments of the nebulosity around an early type star can convey their kinetic energy to the more massive HI interstellar clouds, just as in the case of the novae shells discussed earlier.

On the other hand, Oort's original estimate[33] of the available energy avoids these difficulties, being based on counting the observed number of exploding *massive* nebulae. Oort's estimate constitutes a lower limit on the energy input. Within 1500 pc of the sun he estimates that there might be available $12\times10^6 M_\odot$ (km/sec)^2 per million years, or 8×10^{36} ergs per sec. If we suppose that this energy is liberated in the 500 pc thickness of the galactic disk within 1500 parsecs of the sun, a volume of 0.9×10^{65} cm^3, then we have an energy input of 10^{-28} erg/cm^3/sec.

The truth probably lies somewhere between the 10^{-26} of Biermann and Schlüter and the lower limit of 10^{-28} given by Oort. Seaton estimates that a mean dissipation of the order of 10^{-27} erg/cm$^3\cdot$sec is necessary to maintain the observed 120°K of HI regions if the heating is by collisions of clouds (say every 7×10^6 years) which abruptly raise the temperature to a few thousand degrees, followed by cooling to 120°K; he estimates 10^{-28} if the temperature is maintained uniformly at 120°K. Presumably energy dissipation by the interstellar motions larger than 10^{-28} or 10^{-27} would lead to interstellar temperatures in excess of what is observed.

IV. INTERSTELLAR TURBULENCE

It is often assumed that the interstellar medium may be in a state of hydrodynamic turbulence, because if one computes a characteristic Reynolds number, $LvNm/\eta$ for interstellar motions of scale $L=10$ parsecs, velocity $v=5$ km/sec, density $N=1$/cm^3, and viscosity 0.5×10^{-4} g/cm sec (corresponding to 100°K), he obtains a result of the order of 0.5×10^6. Such a Reynolds number is seemingly large enough to make turbulence more or less unavoidable.

There are certain attractions of a turbulent model of the interstellar medium. For instance, if we ignore the fact that the observed 5 km/sec is rather supersonic in 100°K hydrogen and assume that with a Reynolds number as large as 0.5×10^6, we should obtain the familiar hierarchy of eddies described by the Kolmogoroff spectrum; then we would write that the motions of scale L have velocities proportional to $L^{\frac{1}{3}}$. If we look upon the shearing in the disk of the galaxy [as a result of nonuniform rotation] as the largest eddy, of scale $L=10^4$ parsecs and velocity $v=50$ km/sec, then

$$v=v_0(L/L_0)^{\frac{1}{3}} \tag{12}$$

yields 5 km/sec on a scale of 10 parsecs, in complete agreement with observation.

But on pursuing the matter further, we encounter grave difficulties. Continuing to ignore the supersonic nature of the interstellar motions, let us compute the dissipation which we might expect in such a field of turbulence. If the eddies of scale L have a characteristic velocity v, then the energy transferred out of the scale L by the eddy viscosity of all smaller scale motions is of the order of v^3/L ergs/g sec. We note from (12) that v^3/L is independent of the scale, provided of course that we do not consider eddies so small as to be near the viscous cutoff. With $L\cong10$ pc, and $v\cong5$ km/sec, the dissipation is 4×10^{-3} erg/g sec, or 4×10^{-27} erg/cm^3 sec, which is perhaps a little larger than the observed heating will permit in view of Seaton's conclusions.

If the interstellar motions were merely eddies of scales in a hierarchy, of which the nonuniform rotation of the galaxy was to be regarded as the largest eddy, then the above dissipation would drain energy from the nonuniform motion. A difference in rotational velocity of 50 km/sec, and $N=1$, represents 2×10^{-11} erg/cm^3. Thus we estimate that out to the vicinity of the sun the galaxy might rotate rigidly after only 2 $\times10^8$ years, or one rotation of the galaxy. We suggest that this is not the case, and therefore that, in spite of the immense Reynolds numbers, the interstellar motions are not part of a general galactic hierarchy of eddies.

V. GRAVITATIONAL EFFECTS

Consider Jeans' gravitational instability criterion,[42,43]

$$\Lambda^2-\pi\gamma\langle u^2\rangle/3GNm, \tag{13}$$

without the complication of nonuniform galactic rotation. Λ is the scale beyond which gravitational instability may occur; $\langle u^2\rangle$ is the mean square velocity of all motions of smaller scale than Λ; γ is the exponent in the relation of $\langle u^2\rangle$ to N,

$$\langle u^2\rangle=\langle u_0^2\rangle(N/N_0)^{\gamma-1}, \tag{14}$$

assuming the usual polytrope law.[42,43] In the interstellar medium where $N\cong1$, $\gamma\cong1$,[1] and $\langle u^2\rangle^{\frac{1}{2}}\cong5$ km/sec, we have $\Lambda\cong500$ pc. Thus gravitational collapse in the interstellar medium is not completely unexpected, but, on the other hand, 500 pc is equal to the thickness of the galactic disk, or a spiral arm, and is not easily exceeded to produce collapse.

Chandrasekhar[44] has shown that the presence of a large scale magnetic field does not alter (14).

Suppose that somehow we formed an isolated self-gravitating interstellar gas cloud. For simplicity we regard the cloud as a homogeneous sphere of radius a. Then the virial differential equation[45] reduces to

$$\frac{d^2a}{dt^2}=(5/3)\langle u_0^2\rangle\frac{a_0^{3\gamma-3}}{a^{3\gamma-2}}-\frac{GM}{a^2}, \tag{15}$$

[42] S. Chandrasekhar, Proc. Roy. Soc. (London) **210**, 18, 26 (1951).
[43] E. N. Parker, Nature **170**, 1030 (1952).
[44] S. Chandrasekhar, Astrophys. J. **119**, 7 (1954).
[45] E. N. Parker, Phys. Rev. **96**, 1686 (1954).

where a_0 is the cloud radius when $\langle u^2\rangle$ has the value $\langle u_0^2\rangle$, and M is the cloud mass $(4\pi/3)Nma^3$. If $a=a_1$ is an equilibrium radius, then we have the usual virial condition:

$$(5/3)\langle u_0^2\rangle(a_0/a_1)^{3(\gamma-1)}=GM/a_1,$$

or with $\gamma=1$,

$$N=5\langle u^2\rangle/4\pi Gma_1^2. \qquad (16)$$

Letting $a_1=5$ pc, and if $\langle u^2\rangle^{\frac{1}{2}}$ has just the thermal value of 1.6 km/sec (100°K), then N must be of the order of 500 hydrogen atoms per cm^3. $\langle u^2\rangle^{\frac{1}{2}}\cong 5$ km/sec, corresponding to collision of such clouds, means that 5000 atoms/cm^3 are necessary for equilibrium. For a cloud with a diameter of 20 pc ($a_1=10$ pc) the corresponding densities are $\frac{1}{4}$ the above.

The cloud density usually mentioned, is $N\cong 10$ though there are well-known exceptions such as the Orion nebula.[46] We conclude, therefore, that most HI clouds are not self-gravitating, suggesting that they are held together by tenuous, hot HII gases in the regions between; the reader is referred to the original suggestion of Spitzer and Savedoff.[1] Suppose, after Blaauw,[26] that 1/20 of space is occupied by HI clouds of mean density $N=10$, and that the mean density over all space is about $N=1$. If follows that between the clouds $N\cong 0.5$. A temperature of a few thousand degrees where $N=0.5$ yields sufficient pressure to confine the HI clouds, in which $N\cong 10$ and $T\cong 100$°K.

Now consider an object such as the Orion Nebula,[46] or perhaps the galactic arm, where self-gravitation is certainly important and perhaps dominant. Equilibria follow from (15) or (16) for a spherical cloud, and from

$$a\frac{d^2a}{dt^2}=2\langle u^2\rangle+2GN\pi a^2$$

for a cylinder.[14,15] But what about the stability of these equilibria? We let a_1 represent the equilibrium radius of either the sphere or cylinder. Then, with $a=a_1(1+\epsilon)$ for small radial perturbations about the equilibrium, we find that the effective exponent γ must be larger than $\frac{4}{3}$ if the equilibrium of the sphere is to be stable, and larger than 1.0 for the cylinder.

Theoretical calculations of Spitzer and Savedoff[1] indicate that for variations in density with periods of 10^6 years or more (in excess of the relaxation time of the thermal state of the gas) the effective γ lies between 0.4 and 0.98 in HI regions, and between 1.00 and 1.04 in HII regions. Therefore, a self-gravitating HI or HII cloud possesses no stable equilibrium. An over-all rotation of a gas cloud can provide only temporary stability.[47]

A cylindrical model of the galactic arm is perhaps barely stable because most of its volume may be tenuous HII gas, for which $\gamma\geq 1.00$. But if there is any clumping of gas along the arm (as Jeans' gravitational instability suggests there would be), so that the gas is in three- rather than two-dimensional masses, then no stable equilibrium exists. We consider in the next section how a general galactic magnetic field might conceivably alter these circumstances.

VI. MAGNETIC EFFECTS

Thus far we have discussed the dynamical properties of the interstellar gas clouds without explicit mention of a galactic magnetic field. The observation that the plane of polarization of the light of distant stars varies along the galactic arm by only about 0.2 radian indicates that the galactic magnetic field, whatever may be its absolute density, is a strong field; its energy density is rather larger than the kinetic energy density of the motions of the interstellar medium. Local active regions may introduce exceptions to this condition, but we shall suppose that in general $B^2/8\pi\gg\rho v^2/2$. Several interesting effects result.

A. Turbulence

In the presence of a strong large-scale magnetic field the hydromagnetic equations (6) and (7) can be shown[17,18,48] to reduce to

$$\frac{\partial^2\mathbf{v}}{\partial t^2}-C^2\frac{\partial^2\mathbf{v}}{\partial x_1^2}=\frac{\eta}{Nm}\frac{\partial^3\mathbf{v}}{\partial t\partial x_1^2} \qquad (17)$$

for the velocity field in an incompressible fluid of density Nm and viscosity η. C is the hydromagnetic velocity $B_0/(4\pi Nm)^{\frac{1}{2}}$, x_1 is the space coordinate in the direction of the large-scale field $\mathbf{B}_0$, and $\mathbf{v}$ is transverse to $\mathbf{B}_0$. The total magnetic field is $\mathbf{B}_0+\mathbf{b}$, where $\mathbf{b}=\pm\mathbf{v}(4\pi Nm)^{\frac{1}{2}}$. Since $B_0^2/8\pi\gg\rho v^2/2$, it follows that $B_0^2\gg b^2$, and all motions are hydromagnetic waves of small amplitude. There are no nonlinear terms in (17), and so we expect no turbulence; a strong, large-scale field is too stiff to allow eddies.

In the galactic magnetic field the actual situation is more complicated than in (17) because of compressibility effects. The transverse component of $\mathbf{v}$, satisfying (17) when there is no compressibility, is coupled to the compressible longitudinal component, and so may be rather more complicated than transverse hydromagnetic waves of small amplitude. However, except across such discontinuities as shock fronts, the nonlinear term $(\mathbf{v}\cdot\nabla)\mathbf{v}$ in the equations of fluid motion, (7), remains small compared to the interaction with the magnetic field, $(\mathbf{v}\cdot\nabla)\mathbf{B}$, $(\mathbf{b}\cdot\nabla)\mathbf{B}$, etc. Since $(\mathbf{v}\cdot\nabla)\mathbf{v}$ plays a basic role in hydrodynamic turbulence, coupling together the Fourier components of different wave number, we suggest that, as in the incompressible case,

[46] D. E. Osterbrock, Astrophys. J. **122**, 235 (1955).
[47] E. N. Parker, Astrophys. J. **117**, 169 (1953).
[48] E. N. Parker, Phys. Rev. **99**, 241 (1955).

the galactic magnetic field probably plays a major role in suppressing large-scale galactic turbulence.

The galactic arm field exists independently of the interstellar motions and, being dominant, modifies the nature of those motions. We argue that there is not a basic relation, such as energy equipartition, between the galactic arm field and the interstellar motions. The galactic-arm field density is determined by gravitational effects in the arm[16,49] and by the drawing out of the arm by the nonuniform rotation of the galaxy; the interstellar motions presumably are maintained by some form of stellar agitation, such as Oort's mechanism. Thus the magnetic field density depends upon over-all galactic dynamics, and the interstellar velocity fluctuations upon local stellar activity.

B. Gravitational Stability

The conditions necessary for static equilibrium of a self-gravitating interstellar cloud will be essentially unaltered by a strong galactic arm magnetic field since the gas is free to move along the lines of force; even the classical Bernoulli law holds for such motion. But the *stability* of the clouds is profoundly altered by the constraint to one-dimensional motion. Instead of the gravitational potential energy varying inversely with the scale of the cloud, as in three dimensions, it becomes directly proportional to the scale in the direction of $\mathbf{B}_0$ (the scale perpendicular to $\mathbf{B}_0$ is held more or less constant by B_0). Stability, which required $\gamma > \frac{4}{3}$ in three dimensions and $\gamma > 1$ in two, now requires only that $\gamma > 0$, which so far as we know[1] is satisfied everywhere throughout interstellar space. The effective γ for the lateral compression of a galactic arm field is 2 ($\frac{4}{3}$ for isotropic compression). Thus the over-all stability of a cylindrical, self-gravitating model of the galactic arm is ensured.[49]

Thus again we see how a strong galactic arm magnetic field introduces a stabilizing and ordering influence on interstellar dynamics.

The effect of a self-contained, internal magnetic field on an interstellar gas cloud which is not threaded by the galactic field is discussed in the literature.[49–51] An internal magnetic field cannot confine a cloud which would otherwise expand; the net effect of an internal magnetic field is expansive.

C. Cosmic Rays

Hydromagnetic waves of large wavelength, $\lambda \cong 10$ pc, are not very effective in the initial acceleration of cosmic-ray particles.[24] And in the presence of a dense large-scale field there is no known way to develop small-scale motions of large amplitude which might be effective.[48] Therefore, our present knowledge of the interstellar medium suggests that cosmic rays are not originated throughout interstellar space. One looks to regions where the magnetic field is not stronger than the fluid motions, such as in the vicinity of active star[52–55] or in the galactic halo.[56] In such regions an initially weak magnetic field, $B^2/8\pi \ll \rho v^2/2$, presumably is twisted and sheared until some sort of approach to equipartition with the velocity field is achieved. The motions may then be thought of as strongly interacting hydromagnetic waves of large amplitude which may give efficient acceleration of particles by Fermi's mechanism up from thermal energies.[55] With this initial injection,[8,9] the acceleration then proceeds in interstellar space.[24]

VII. GENERAL COSMOLOGICAL CONSIDERATIONS

[added by the editors from tape recording of Parker's talk]

In the preceding, I suggest two things about the general galactic magnetic field: (i) there is no basic relation, in origin, between the galactic field in the arms and the random velocities in the interstellar medium; (ii) the general magnetic field gives stability to the gas clouds, cuts down energy dissipation, etc. It is interesting to look at what one might expect to occur in a galaxy which is somehow formed without magnetic fields, or with negligible magnetic fields. Let me take just the grossest background for forming this galaxy. Suppose that out of some primordial medium there is gravitational collapse, and a dense body of gas is formed which one might call a protogalaxy. How does this galaxy condense into stars? As this is discussed later in the Symposium let me be very general. Suppose that most of the stars have collapsed and there is still some interstellar medium remaining, the interstellar medium that we see today, for instance. The dissipation in that interstellar medium in the absence of a magnetic field is going to be large. If there are any turbulent motions they will, in at least a half a billion years or so, come to rest. And that means, when one writes down Jeans' instability criterion, that this instability size will become rather small, it will become 100 pc or less, and certainly we expect to see this medium collapsing into rather dense interstellar gas clouds. But, these clouds have no stable equilibrium because γ is actually less than $\frac{4}{3}$ and so there is nothing to prevent them from continuing their collapse, and forming stars immediately. I suggest that under these circumstances, one would not, 5 billion years after the formation of the galaxy, which is approximately when we are living, see much of an interstellar medium, certainly not as much as we apparently see today. So, in a nonmag-

[49] S. Chandrasekhar and E. Fermi, Astrophys. J. **118**, 116 (1953).
[50] S. Chandrasekhar and N. Limber, Astrophys. J. **119**, 110 (1954).
[51] E. N. Parker, Astrophys. J. Suppl. **3**, 51 (1957).
[52] V. L. Ginzburg, Doklady Akad. Nauk S.S.S.R. **92**, 727 (1953).
[53] V. L. Ginzburg, Nuovo cimento Suppl. **3**, 38 (1956).
[54] S. Hayakawa, Progr. Theoret. Phys. **15**, 111 (1956).
[55] E. N. Parker, Phys. Rev. **107**, 830 (1957).
[56] G. R. Burbidge, Phys. Rev. **101**, 907 (1956).

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netic galaxy, I would suggest that you would not find population I stars—hot supergiants—at any great time after the galaxy was formed. This may perhaps be some sort of explanation for the difference between certain of the stellar populations that are actually observed. I mention this not only to point out that interesting possibility, but also to emphasize how basically important a galactic arm magnetic field is for the interstellar medium that we observe today in our own galaxy.

DISCUSSION

F. D. KAHN, *Manchester University, Manchester, England:* If the magnetic field is as important as it seems to be, it should be possible to find some difference in the random motions of the clouds when looking along the field and looking across the field. Are there such observations? Secondly, I wonder whether the dissipation in the presence of the magnetic field can be reduced by such a large factor, because the motion of clouds along the magnetic field is not inhibited, and therefore if you get any appreciable velocity in that direction the clouds will collide, and you will again have shock waves. Even if there is only thermal motion, the cloud will expand and hit another cloud somewhere, and you will still get dissipation. Is there any answer to that?

G. MÜNCH, *Department of Astrophysics, Calfornia Institute of Technology, Pasadena, California:* I looked for a difference between the velocity dispersion at right angles to the Perseus arm and along the Orion arm, but no difference larger than 20% seems to be present.

E. N. PARKER, *Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois:* From a discussion with Pickelner, I understand that he may have some results on the question about the velocities perpendicular and parallel to the arm. Concerning your question about the dissipation for motions in the direction along the magnetic field, if there is motion along the spiral arm (along the magnetic field) you are entirely right. The dissipation in that case may be rather large, and that is why I say my estimate is probably rather less than what actually occurs. However, I think that the problem which the magnetic field does solve, is the question of the high dissipation computed from turbulent dissipation by using the eddy viscosity. It turned out to be 10^{-26} erg/cm^3/sec, instead of 10^{-27} or 10^{-28}, which one gets from bumping individual clouds together once in a while. The magnetic fields inhibit the decay into turbulence.

G. K. BATCHELOR, *Trinity College, Cambridge, England:* Parker discussed the possibility that turbulent motions arise from galactic rotation. He attacked that as a tenable theory by showing that the rate of dissipation to which it leads is much too high. If this is right, his studies have saved us a lot of trouble. But exactly what is the evidence for the belief that the rate of dissipation is not such as to reduce the galaxy to rest in 2 or 3 revolutions?

E. N. PARKER: It is observed that today the galaxy is not in rigid rotation, and yet the rate of rotation leads to 20 or 30 rotations in the 5×10^9 years or so given as the age of the earth. I take that to mean that we do not have the tremendous dissipation which my turbulence computation indicated.

J. M. BURGERS, *University of Maryland, College Park, Maryland:* When you speak about dissipation, what do you really mean? Viscous dissipation means a redistribution of energy. Differences of rotation become so redistributed that they are transformed into thermal motion, and one could expect that the galaxy would ultimately rotate as a solid body, with a higher temperature than it had originally. Or do you add to this the additional requirement that most of the thermal motion be radiated away into space?

E. N. PARKER: I had not concerned myself with what happens to the energy once it is out of the largest motions. What I meant by dissipation was a transfer of energy from the large scale motion, such as nonuniform rotation of the galaxy or the motion of individual interstellar clouds, into some smaller scale motions and therefore presumably fairly quickly into thermal motions. Now it is an excellent question, of course, what would happen if you feed too much energy into the thermal motions. I do not know the answer to that.

J. M. BURGERS: You were speaking about the magnetic field along the spiral arms. Evidently you meant lines of force along the spiral arms. Where do they go to form the ends of the arms?

E. N. PARKER: Since the divergence of a magnetic field is zero, the lines of force never end. But how they are connected, I do not know.

W. H. BOSTICK, *Stevens Institute of Technology, Hoboken, New Jersey:* The magnetic field exists in something like a material filament. Presumably that filament must be twisted somewhat in the manner of a force-free filament; otherwise, we do not know how the filament could exist. A force-free filament has a magnetic field as shown in Fig. 1. Experimentally such force-free filaments have been observed in the laboratory and,

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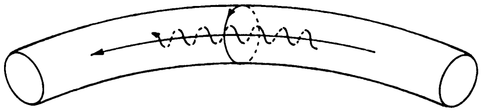

FIG. 1.

theoretically, it is obvious why they come into existence. If there is such a force-free filament, and there is a velocity of the ionized gas within the filament, the velocity must conform with the direction of the magnetic field. In the center of the cross section of the arm, this would give a velocity along the axis of the arms. The velocity at the periphery of the arm would, however, be largely transverse to the axis of the arm. Are the astronomical measurements on the velocities precise enough so that it would be possible to isolate various radial portions of the arm and determine whether the velocities would conform with the direction of a force-free field?

E. N. PARKER: I disagree with your statement that you must have a force-free field. In fact, I think the contrary: it can be shown that one cannot have a force-free field in a galactic arm, because there are forces that need to be balanced by the magnetic stresses. The hydromagnetic equation for the static case gives something of this form:

$$0=-\nabla\left(p+\frac{\mathbf{B}^2}{8\pi}\right)+\frac{(\mathbf{B}\nabla)\mathbf{B}}{4\pi}+\rho\nabla\psi.$$

The potential ψ of the gravitation forces is not negligible, nor is the pressure of the gas negligible. Therefore, I think that one cannot say that the magnetic terms should be negligible. Chandrasekhar and Fermi showed that one needs very strong magnetic stresses in order to balance the gravitational force.

As regards stability, one need not restrict himself to force-free fields. Consider a situation where $\mathbf{W}=[\pm\mathbf{B}/(4\pi\rho)^{\frac{1}{2}}]$. Any incompressible motion in which this is true is not only in equilibrium, it is stable. This is not necessarily a force-free field; it can have any sort of contortions one wishes.

One may look in the observations to see if there are reasons to believe that a galactic arm is a force-free field, but I think there are no *a priori* theoretical grounds to expect this. As the simplest model, one thinks of a uniform tube of flux for the galactic arm. It is suggested by the polarization of starlight.

J. M. BURGERS: In Bostick's case one has lines of force along the axis of the tube and lines encircling it on the outside. But one of the points Parker brought forth was that there is only a fluctuation of 0.2 radian in the direction of the polarization. Bostick's picture apparently leads to a much larger fluctuation of direction. Further, Bostick's experimental filaments start from two electrodes, but Parker's galactic filaments must end somewhere. How are the two cases to be related to each other?

W. H. BOSTICK: I actually do not believe that the galactic arm is formed of a single force-free filament. There is the possibility of one filament doubled on itself. I threw in the force-free filament to see what you thought.

E. C. BULLARD, *Cambridge University, Cambridge, England:* I was interested to hear Parker say he does not believe the kinetic and the magnetic energies have to be equal. One gets them equal by equating the nonlinear inertial terms to the magnetic terms, but there seems to be no particular reason to do this unless one constructs some special model in which the field is distorted by the turbulence. If you no longer consider the turbulence as a primary part of the process, but distort the field by large scale motions, the reason for putting these two equal no longer holds. In the only fields of which we have detailed knowledge, the equality is certainly not found. Both in the earth's core and in the sun the magnetic energy is many orders of magnitude greater than the kinetic energy, and I am rather relieved to hear that Parker does not need even a rough equality.

M. MINNAERT, *Sterrewacht Sonnenburg, Utrecht, Netherlands:* Parker's discussion was centered about the determination of the dissipation. But what is the amount of certainty about the figure 10^{-27} erg/cm^3 sec, essentially based upon the age of these clouds estimated to be 7×10^6 years? Any uncertainty about this age will affect the amount of the dissipation, which is important when we look for the source of the dissipation.

H. C. VAN DE HULST, *Leiden Observatory, Leiden, Netherlands:* The accuracy of the estimate of the mean free time between collisions of clouds ($=7\times10^6$ yr) is probably better than would follow from the uncertainty in the separate estimates of sizes and numbers of the clouds. If the line of sight cuts so many clouds per kiloparsec, any small cloud pursuing the same path will also cut so many clouds per kiloparsec. This means that the required mean lifetime is the observed number of clouds per kiloparsec divided by the average velocity of those clouds, and both of these data cannot be far wrong, say by a factor of 5 or so.

E. N. PARKER: The dissipation which I discussed was due to two causes. In the first place, if one estimates the size of a gas cloud and the number of gas clouds per cubic kiloparsec, one can make some guess as to how far a cloud will move before it bumps into another cloud: simply by computing a sort of collision cross section as indicated by van de Hulst. The other problem was how to prevent turbulence in the presence of such huge Reynolds' numbers. That does not really deal

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with a lifetime in the above sense. I merely thought of a large eddy, which is a nonuniform rotation, and that gave me the even larger figure of 10^{-26} erg/cm^3 sec. I claim no accuracy for these figures: they are extremely rough, but they seem always to be a hundred times larger than anything I can justify and so I went ahead with them, even though I doubt that they are accurate.

M. MINNAERT: Will collision mean that a cloud disappears?

H. C. VAN DE HULST: That depends on the magnetic field.

E. N. PARKER: One can say that clouds will lose the major portion of their kinetic energy, whatever happens to them, unless they contain a strong internal magnetic field. In general, collisions will not be elastic.

M. P. SAVEDOFF, *Department of Astronomy, University of Rochester, Rochester, New York:* About the dissipation there are some observational data. Recent 21-cm observations—λ Orionis by Wade and Barnards Loop by Menon—show high energy in directed motion. Münch's data for interstellar lines show that in the northern Milky Way there is a preponderance of velocities away from the stars. These directed motions may perhaps be the energy sources we are talking about and in the next few years we should estimate exactly how much energy is available in these sources.

M. J. SEATON, *Department of Physics, University College of London, London, England:* A point I would like to make (I hope that later on we can go into more detail) is the question of the cooling process, i.e., the degradation of thermal energy into low-energy quanta. When one considers the temperature deduced from 21-cm observations and considers known cooling mechanisms, one finds that a rate of input of thermal energy of order 10^{-27} erg cm^{-3} sec^{-1} is required. If the rate of input of energy is assumed to be much smaller than this, it will be difficult to explain why the temperature from 21-cm observations is not much lower than 125°K.

F. D. KAHN: To come back to an earlier point: the galaxy would need to be rotating uniformly now, if all the differential rotational energy had been degraded into thermal energy. Now there is a part of the galaxy which does seem to rotate, more or less, with uniform angular velocity. Drawing the curve of rotational velocity θ against distance R, one sees that the angular velocity is uniform in the inner parts of the galaxy where the curves of Θ against R is straight.

R. W. STEWART, *Department of Physics, University of British Columbia, Vancouver, B. C., Canada:* I would question the estimate that has been made of the rate of turbulent energy dissipation. It seems to me that if Parker calculates that all the turbulent energy has disappeared in two revolutions of the galaxy he must have grossly overestimated the rate of dissipation. Admittedly, this is what happens with what we call a turbulent eddy in laboratory turbulence. But an eddy in laboratory turbulence does not look a bit like a galaxy. For a structure that has anything like the organization or stability of a galaxy, e.g., a smoke ring or a whirl in the surface of water, the energy involved in the nonrigid rotation will last for many more rotations than one or two.

E. N. PARKER: It is true that the galaxy does not look like an eddy and that was, of course, my main point. In the galaxy we have the case where the interior portions rotate more rapidly than the outer portions and it is well known that this is unstable. If someone can show how the galaxy can be stable against hydrodynamic turbulence in view of its large shearing motions, then of course, the statement that I made is incorrect. But until that time I fail to see how one can really avoid these large dissipations.

R. W. STEWART: In van de Hulst's diagram showing velocity as a function of radius, referred to by Kahn in the foregoing, there is a plateau where shear must be small. Further, I think one should calculate Reynolds numbers in a situation like this, not by over-all scale and over-all velocity, but from something involving mean velocity gradients.

E. N. PARKER: In the first place, the thing that van de Hulst was pointing out is that there is a plateau of constant *velocity*; so there is immense shearing. Since I used the figure of only 50 km/sec instead of 250, I think I have more than allowed for that. As to your second statement, I computed the Reynolds number very conservatively. I did not use the large galactic rotational velocity of 250 km/sec, which would have given me $R_e \sim 10^8$. I stayed with small clouds and used 5 km/sec over 10 pc and that gave me 10^6.

J. M. BURGERS: Is there really a theory for the viscous dissipation in a rotating mass of gas, subjected to gravitational forces? Can one assume that a state with uniform angular velocity must be the ultimate result? I cannot believe it.

R. W. STEWART: That cannot possibly be right.

E. N. PARKER: As you say, it cannot possibly be right. But on the other hand, how can the shear be maintained if there is turbulence?

J. M. BURGERS: That will depend on the interaction between the parts. With separate clouds, one

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mechanism of dissipation is collisions between clouds. But clouds will move more or less like planets, so that constant angular momentum should be expected rather than uniform rotational velocity.

E. N. PARKER: The point is that in this case one cannot have clouds which are in stable equilibrium without a magnetic field. Spitzer's calculations show that one expects γ to be less than $\frac{4}{3}$, whereas γ must be greater than $\frac{4}{3}$ for stability. Hence the whole idea of isolated clouds is not correct.

J. M. BURGERS: What happens if the effective γ is less than $\frac{4}{3}$? Do the clouds blow up or contract?

E. N. PARKER: They will do both. If they contract, they will form stars: they will no longer be clouds, but we observe clouds. If they blow up it is just a matter of time before gravitational collapse will try again, and let us say there is a 50–50 probability each time that they get into stars. That was my point; I don't understand how the interstellar medium could survive 5 billion years without a magnetic field. It might survive half a billion years.

L. MESTEL, *19 Orchard Avenue, Cambridge, England:* I want to question the efficiency of a straight magnetic field that you put into a cloud in being able to hold the cloud up. I can see how initially you get just longitudinal motion along the lines of force. But that sends up the density while not changing the outward magnetic force. Therefore, the gravitational force across the field increases and will tend to pull the whole thing in. I should have thought that the cloud would tend to take a shape roughly like a spheroid oblate to the direction of the field, and one would get a roughly uniform contraction of the whole cloud. This is quite different from the effect of the centrifugal field in a cloud conserving its angular momentum. Centrifugal force then increases more rapidly than gravitation and you will presumably get a stable disk formed.

The other point is that in computing dissipation you seem to make use of ordinary Joule conductivity. In several recent papers, first Piddington and Cowling, then independently Spitzer and I have pointed out the very much greater dissipation of magnetic energy when the plasma density is a small fraction of the total density. The effect is due to the magnetic field, which is tied to the plasma, pushing the plasma through the neutral gas. The energy dissipation comes then from collisions, not between ions and electrons, but between plasma ions and neutral atoms.

E. N. PARKER: In interstellar space, the dissipation is primarily due to the viscosity and not due to the Joule losses. Does that answer your second question?

L. MESTEL: Not if one has a large magnetic field, because this extra dissipation is enormously larger than the ordinary Joule losses. I think Cowling gave as an example a factor of 10^{18} or 10^{19}. My point is that the plasma ion-neutral atom collisions, when we have a large magnetic field, much exceed the ordinary Joule electron-ion collisional dissipation.

E. N. PARKER (*added later by letter*): In the HI interstellar medium, the Joule losses are about 10^{-15} times the viscous losses. Therefore, the dissipation would have to be increased by a factor 10^{15} in consequence of the presence of neutral atoms in order to alter the energy balance significantly. I suggest that the presence of neutral atoms does not increase the Joule dissipation by as much as this factor, because Spitzer observes that everywhere outside the localized HI clouds the gas is fully ionized, so that neutral atoms are found in only 5–10% of space. I adopt the view that the HI regions do not form continuously connected masses along the spiral arm, but are isolated clouds with HII gas enclosing each cloud. It follows that the general HII matrix, which contains no neutral atoms, will prevent decay of a general galactic arm field in the HI regions simply because $\nabla \cdot B=0$. Any line of force going into an HI cloud on one side must come out somewhere else. The field inside the HI cloud will decay at most until B becomes the gradient of a scalar there. It can decay no further.

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