"The peanut-shape that you see in these edge-on bulges has never been modelled successfully, as far as I know. People have tried. We have tried it, but the guy who was doing it decided that he didn't want to do astronomy after trying this."

K.C. Freeman in Discussion I.1

GLOBAL DYNAMICS OF THE INTERSTELLAR GAS, MAGNETIC FIELD, AND COSMIC RAYS

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I have been asked to review the physical principles which underlie the dynamical equilibrium and stability of a composite system of gas, magnetic field, and cosmic rays. What is of particular concern here are those aspects which control the distribution of magnetic field and cosmic rays, and thus influence the morphology of galaxies as seen in nonthermal radio emission.

The salient features of the nonthermal spiral galaxy radio emission which are relevant to this discussion can be summarized briefly. Several of the observational data are ambiguous because of the difficulty of uniquely disentangling the nonthermal emission from the thermal emission of hot regions. It appears possible that nonthermal disk emission has a brightness variation which follows the general distribution of galactic mass, suggesting that cosmic rays are generated by some process which occurs in the overall stellar population (Van der Kruit et al. 1977). Away from the plane, spiral galaxies show nonthermal radio emission from thick disks or limited halos extending of the order of 1 to about 10 kiloparsecs from the galactic plane. Spectral indices of the observed radiation generally fall in the range -0.7 to -0.9 which suggests energetic electron spectra similar to what is observed in our own galaxy.

For our present purposes we will assume that galactic cosmic rays are produced in and largely confined to galaxies. This conservative assumption is consistent with the known properties of cosmic rays. The alternate possibility, that cosmic rays fill large regions of the universe, has been discussed extensively elsewhere (Brecher and Burbidge 1972). (Particles having energies above about 10^{17} eV/nucleon are likely to fill large regions of the universe, as these cannot be confined to galaxies. These particles possess a negligible fraction of the total cosmic-ray energy density in galaxies, and thus have no effect on the dynamics of galactic material.) The cosmic rays can be thought to comprise a high temperature, low density gas. In a typical galaxy the thermal energy of the cosmic-ray gas is more than 10^7 times greater than its binding energy in the galaxy's gravitational field. Thus

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cosmic rays remain in galaxies only insofar as they are constrained by other agencies. It can be shown through use of the virial equation that the net magnetic field stress is purely expansive, no matter how complicated and contrived the field morphology may be (Parker 1954). Thus a galactic magnetic field will expand away to infinity unless anchored by some other force. By virtue of the gas' electrical conductivity and the cosmic rays' relatively small gyration radii, the cosmic rays, gas, and magnetic field are constrained to move together as a single, composite medium. Taking interstellar conditions in our own galaxy to be representative, the composite medium can be visualized as a single fluid for spatial scales greater than about one parsec and time scales longer than some 10^4 years. Such a composite interstellar medium is confined to a galaxy by the gravitational force which acts predominantly on the gas. In our own galaxy the electron component of the cosmic rays contains only a small fraction, about one percent, of the total particle energy. Thus while the electrons provide only a small part of the total interstellar pressure, they are tied to the composite medium and their distribution is controlled by the dynamics of the composite medium. Thus galactic nonthermal radio morphology traces the gross dynamics of the complete system of gas, field and particles.

The physical character of the equilibrium of an interstellar medium can be pictured by concentrating on the force balance in the z-direction, perpendicular to a galactic disk. For simplicity suppose that the z-component of the gravitational force (due almost entirely to the stars) is a given constant, $-g\underline{e}_z$, above the galactic plane. If $\underline{B} = (B_x, B_y, B_z)$ is the magnetic field, if P is the cosmic-ray pressure, and if p is the gas pressure, then the condition for hydrostatic equilibrium in the z-direction is

$$\frac{d}{dz}\left[P + p + \frac{B_x^2 + B_y^2 - B_z^2}{8\pi}\right] = -\rho g \ , \qquad (1)$$

where ρ is the gas density. First consider a stratified interstellar medium (Parker 1966) in which $B_z^2 << B_x^2 + B_y^2 \equiv B^2$ and in which the cosmic ray and magnetic field pressures are proportional to the gas pressure. Writing $P = \beta\rho u^2 = \beta p$ and $B^2/8\pi = \alpha\rho u^2$, the solution of equation (1) is

$$\rho(z) = \rho(0)e^{-\Lambda/2} \ , \qquad (2)$$

where Λ is the characteristic scale height of the gaseous disk and is defined by

$$\frac{\Lambda}{2} = \frac{u^2(1 + \alpha + \beta)}{g} = \frac{p + P + B^2/8\pi}{<\rho>g} \qquad (3)$$

where $<\rho>$ is the average gas density in the disk. Equation (3) then relates the gas density and pressure, cosmic ray pressure and magnetic field strength to the thickness of the gaseous disk. Equation (3) offers a consistent description of the known properties of the gaseous disk of our own galaxy. But, as we will see below, equation (3) only applies in a crude way because the stratification assumptions are inevitably unrealistic. Parker (1966) showed that such a stratified interstellar medium is dynamically unstable in a Rayleigh-Taylor sense. The equilibrium in which a heavy interstellar gas confines buoyant cosmic rays and magnetic field against their expansionary tendencies is similar to the equilibrium of a light fluid overlain by a heavy fluid in a gravitational field. Each system is unstable to sinking of the heavy fluid through the light.

In galaxies the instability evolves to the form shown in Figure 1. Large gas complexes accumulate at localized regions as material slides along the field lines to gather in troughs of the magnetic field. In the spaces between the gas accumulations the magnetic field is relieved of its overburden of gas. Thus freed of the confining gravitational stress, the combined pressures of cosmic rays and magnetic field inflate the field to produce a system of magnetic arches extending to large distances above and below the galactic plane. The modes of this instability have been investigated in some detail (Parker 1967a,b, 1968a,b; Lerche and Parker 1967, 1968; Shu 1974). The growth time for the instability is a few times 10^7 years and the characteristic scale lengths along the magnetic field are several hundred parsecs to a kiloparsec.

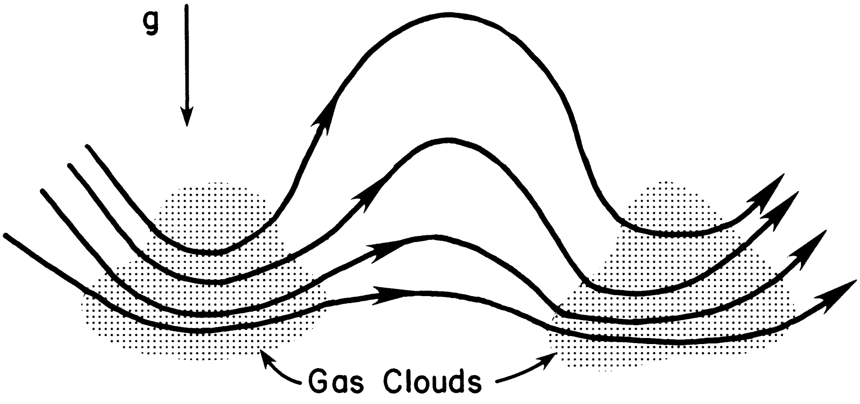

FIGURE 1

Dynamical instability of a composite interstellar medium produces large gas accumulations and an extensive system of arching magnetic loops.

Mouschovias (1974, 1975) has explored numerical models of the stationary equilibrium end states that result from the fully developed instability. He showed that in the absence of significant cosmic ray sources the stationary equilibrium has magnetic arches extending above and below the galactic plane to distances approximately equal to the separation of the gas complexes. Such an equilibrium would account for thick radio disks of nonthermal emission extending on the order of a half to one kiloparsec on either side of a galactic disk.

Now the equilibrium shown in Figure 1 is not stationary in real galaxies. Star formation, supernovae, galactic differential rotation, cloud motion, etc. act to continually disrupt the equilibrium states; at the same time the magnetic field is continually regenerated by dynamo action of the fluid motions in the differentially rotating gaseous disk (Parker 1971; Vainshtein and Ruzmaiken 1972). Furthermore cosmic rays are generated continually in galaxies, and this continual supply of cosmic ray energy has important dynamical consequences. The pressure of the cosmic ray gas inflates the magnetic field lines which protrude through the surface of the disk (Parker 1965). The field line inflation proceeds until the cosmic ray stresses completely overwhelm the field stresses in the inflated magnetic arch. At this point the cosmic rays escape the hold of the magnetic field. The further inflation of the field lines may produce a substantially more extensive halo than that which results from the equilibrium magnetic field arches. This inflation process constitutes, in essence, a pressure relief valve which enforces the approximate equality of the magnetic and cosmic ray energy densities. Such an approximate equipartition is observed in our own galaxy. Equipartition is generally presumed applicable to cosmic radio sources; field line inflation provides a dynamical basis for it.

The global dynamics of a system of magnetic field, gas, and cosmic rays which we have reviewed provides a dynamical basis for understanding the distribution of magnetic field and energetic particles which produces the radio morphology of galaxies. The following picture emerges from these considerations. Cosmic rays are generated broadly throughout the disks of galaxies. Since the nonthermal radio emission profile seems to match the disk mass profile, it is evident that cosmic rays are not well mixed throughout the disk, otherwise their distribution would smear substantially more than seems to be the case. Thus the weight of the evidence suggests that cosmic rays escape predominantly through the faces of galactic disks rather than by streaming along spiral magnetic fields to the peripheries of galaxies. The mechanism for particle escape perpendicular to the disk evidently is provided by the dynamical instability of the composite system of field, gas, and cosmic rays and by the further inflation of the field by cosmic ray pressure. These combine to produce an extended distribution of field and particles which may be observed in nonthermal emission as a thick disk or halo. As we will mention presently cosmic rays seem to pass freely between the disk and halo. However, the particles do not seem to mix freely throughout the halo as this also would smear the distribution more than is observed.

It is worth mentioning that several of the directly observed properties of cosmic rays in our own galaxy provide insight into these problems. It is well known on the one hand that the relative abundance of Li, Be, B, and C, N, O in Galactic cosmic rays implies that the average cosmic ray particle passes through 5 gm/cm^2 of matter during its life in the Galaxy. If the mean density of gas in the disk is one hydrogen atom per cm^3, then the disk residence time is about 3×10^6 years (cf. Meyer 1969). On the other hand the cosmic ray abundance of the radioactive isotope ^{10}Be, with a half-life of 1.5×10^6 years, provides a direct measure of the total cosmic ray residence time in the Galaxy. The most recent measurements (Garcia-Munoz et al. 1975; Webber et al. 1977) suggest total residence times of the order of 2×10^7 years. The most straightforward interpretation of the discrepancy is that these cosmic rays spend the largest part of their Galactic residence time in a halo where they encounter little matter and that the particles pass relatively freely between the disk and the halo. In the simplest case of a stationary halo, the above lifetimes suggest a halo volume perhaps five times as large as the disk volume. This would correspond to a "thick disk" extending about half a kiloparsec above and below the galactic plane.

A further point is that the small value of the observed cosmic-ray anisotropy in the Galaxy, combined with the short residence times, indicates that cosmic rays have only enough time to escape in the direction perpendicular to the galactic disk. This supports the idea that cosmic rays do not spread freely through large regions of the disk.

Note that consistent with the fabric of dynamical behavior which we have reviewed here are many possibilities for the detailed motion of the cosmic-ray particles. Each model has specific implications which can be compared with observations, but unique interpretations of the observations are not yet possible. A number of the specialized models of cosmic ray motion have been reviewed in detail recently by Ginzberg and Ptuskin (1976) and we refer the interested reader to their article.

The ideas described here lead naturally to the notion of expanding galactic halos (Ipavich 1975). Models of dynamical halos have been constructed recently by Owens and Jokipii (1977a,b) with which they have explored the consequences for radio emission from energetic electrons. The models are complicated by a number of free parameters and by the fact that the electrons suffer energy loss through adiabatic deceleration as well as through radiation. One significant point that emerges from their calculations is that electrons near the peripheries of the halo have on the average suffered the greatest energy loss. This results in a frequency dependence of the halo morphology which is equivalent to a steepening of the emission spectrum with increasing distance from the galaxy.

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DISCUSSION FOLLOWING REVIEW I.6 GIVEN BY E.H. LEVY

BURKE: What density did you assume for the local interstellar matter?

LEVY: About 0.1 to 0.3 cm^{-3}.

BURKE: Such a density is entirely acceptable for the sun's neighborhood, and then there is no discrepancy between the spallation lifetime and the Be^{10} lifetime for cosmic rays.

ALLEN: What is the variation of the magnetic field in Mouschovias calculations?

SHU: I don't remember the exact numbers, but the scale height for the magnetic field in the raised portions (where most of the cosmic rays are) is much larger than the scale height of the gas. In any case, I would stress again that the original stratified state is a physical artifact in that such an equilibrium, even if artificially created initially, cannot be stable.

ALLEN: COMMENTS ON THE RADIO CONTINUUM EMISSION FROM NORMAL DISK GALAXIES

The fine review by Dr. Levy on the theoretical situation has promted me to draw your attention to some features in the high-resolution radio aperture synthesis observations which are perhaps not easily explained by the existing models for the cosmic-ray origin and diffusion in galaxies. These features are:

(1) In normal flattened galaxies which show relatively bright radio disks ($\langle T_b \rangle \gtrsim 1$ K at 21 cm) the radio and optical surface brightnesses correlate well over the main parts of the disks. This has been shown for the ring-averaged radial distributions in the face-on galaxies NGC 6946 (van der Kruit et al. 1977, A.A. 55, 421) and M51 (van der Kruit 1977, A.A. 59, 359), and may also occur in the z distribution of NGC 891 from about 20" to 60" above the plane (unpublished work by Allen, Spinrad and Bruzual).

(2) The variations in the radio spectral index are rather small over the main parts of the disks for both the face-on galaxies referenced above (after removal of the thermal component), and for the edge-on system NGC 891 (Allen et al. 1977, A.A., in press, Figure 5) up to a distance of about 2.5 kpc above the plane. The frequently-noted steepening of the spectral index in fact begins to be incontrovertible only at the extremities in r and z.

(3) The morphology of the HI distribution differs substantially from that of the radio continuum in these bright-radio-disk systems both in r and in z; the latter is dramatically illustrated for NGC 891 in Figs 1 and 2 of Sancisi et al. (1975, La Dynamique des Galaxies spirales, ed. L. Weliachew, p. 295). The radio emission can apparently be strong in places where the HI is faint (central regions of the disk in e.g. M51 and NGC 6946, and at high z distances from the plane in e.g. NGC 891) and vice versa (large radial distances from the center). Note that there are obviously other components which contribute to the nonthermal radio continuum emission such as supernova remnants and the possible compression in a density wave shock. These components appear superposed on the disks referred to above. They apparently dominate in galaxies like M81 and M31 which have only relatively faint radio disks. My concern here is with galaxies which have bright radio disks.

These features in the observations suggest at least two inferences:
A. Any model in which the synchrotron radio volume emissivity is a monotonic function of the local gas density would seem to be too simple.
B. There may be a more intimate relationship between the electron component of the cosmic rays and an older stellar population than has hitherto been assumed.

Point A above may of course be circumvented if the distribution of ionized gas is substantially different from that of the HI. Although this situation may not yet be entirely excluded by observations, another hypothesis which has the possible virtue of corroborating all the known features is the following: Energetic electrons are produced not only by explosions of type II SN near spiral arms, but also by some other sources which are distributed throughout a galaxy more-or-less as an older stellar population. The electrons lose essentially all of their relativistic energy by synchrotron emission within one kpc or so of their sources; this requires magnetic fields stronger than about 10^{-5} gauss for electrons radiating mainly at 1500 MHz. Under these assumptions it is clear that the total observed synchrotron radio emission integrated over frequency must be independent of the magnetic field strength. From the standard formulae in e.g. Moffet (1975, Galaxies and the Universe, ed. A. Sandage, M. Sandage, J. Kristian, p. 211) it is easy to show that the synchrotron volume emissivity goes like $\varepsilon_\nu \propto Q_0 B^{\alpha-1} \nu^{-\alpha}$, i.e. linear in the density of sources of relativistic electrons, and as $B^{-0.3}$ for $\alpha = 0.7$. The required value of $\geq 10^{-5}$ gauss is roughly that which is found from equipartition arguments in e.g. NGC 891 (Allen et al. 1977, A.A., in press). The sources could be things like pulsars, flare stars, magnetic white dwarfs, X and γ-ray bursters, Type I supernovae, etc. etc. Note that one Type I SN per 30 years in a typical disk galaxy would result in more than 100 sources in a 1 kpc^3 volume of the disk in the $\sim 10^7$ year lifetime of the relativistic electrons. The steepening of the radio spectral index at the extremities in r and z would then be associated with the rapid decrease of B in these regions and with the subsequent breakdown of the "total confinement" model sketched above.

WAXMAN: ON THE NATURE OF A GALACTIC BOUNDARY LAYER FLOW

In studying fluid dynamical interactions between a galactic disk and a surrounding gaseous halo, two physical conditions are necessary for the existence of a boundary layer circulation. The first concerns the presence of a vertical shear in the azimuthal flow of gas, and the localization of this shear to the vicinity of the disk. If one treats the disk as a density enhancement in the equatorial plane of the halo, then this shear is due to the inclination between the equidensity surfaces of this enhancement and the equipressure surfaces of the background halo gas. That is, the vertical shear is a manifestation of the baroclinicity inherent to disk-halo systems. The second condition is that there must be an effective viscous coupling of the disk to the halo, localized to the disk region as well. This viscous coupling is provided by the stochastic momentum transport of interstellar gas clouds colliding with each other and their interaction with the intercloud medium.

In this work the fluid dynamical equations, for the case of a density enhancement which is small compared to the gas density in the halo, are solved by the method of matched asymptotic expansions. The result is a circulation of gas in the meridional plane extending over several disk scale heights from the galactic plane. Radial flows, inward in the disk and outward in the halo, should be of the order of 20 km/s. The vertical flows, of the order of 0.5 km/s are upward within about 10 kpc of the rotation axis and downward beyond this point. It is tempting to identify this weak downflow of gas with the low velocity "galactic infall" observed in the solar neighborhood. In addition, this circulation implies a thorough mixing of the metal-enriched disk gas with the overlying halo gas on a timescale of about a billion years. Density enhancements which simulate a significant decrease in the gas density near the central region of the disk give rise to new features in the flow pattern which are suggestive of a "3-kpc arm". A thorough stability analysis of this boundary layer circulation is presently under way.

The details of this analysis are to appear in the Astrophysical Journal in the near future.

ELVIUS: OPTICAL POLARIZATION IN GALAXIES

During several visits to the Lowell Observatory, Flagstaff, Arizona, USA, I have made observations of the polarization of light in galaxies. The latest results were obtained in early 1977. A scanning dual-beam polarimeter was used together with a computorized data acquisition system. Some results will be mentioned here. Details will be published elsewhere.

In the Seyfert galaxy NGC 1068 polarization of light has now been found also in regions outside the nucleus. About 10 seconds of arc to the north-east of the nucleus 4 percent of polarization in P.A. 135° indicates the presence of large clouds of scattering particles.

Polarization effects analogous to the 'interstellar polarization' in the Milky Way have been found in dark regions of many spiral galaxies like NGC 3190, 3623, 4216, 4565, 4594, 4826 and 5005. These observations indicate large-scale magnetic fields along the spiral arms. Similar polarization effects along dark features were also found in the barred spiral NGC 5383, in the nucleus of the peculiar galaxy NGC 3718 and in the filaments seen in absorption against the main body of NGC 2685.

Polarization due to the scattering of light has previously been observed in M82 and was mentioned above for NGC 1068. It was also observed in filaments outside the main body of NGC 2685, where the direction of the electric vector indicates that the light from the nucleus of NGC 2685 is scattered by non-spherical particles aligned in a magnetic field along the filament.

If the polarization observed on the brighter side of some galaxies like NGC 3623, 4216 and 7331 is also interpreted as due to scattering of light from the nucleus in clouds of aligned particles in the spiral arms, we are led to the controversial conclusion that the brighter side of the galaxy is the nearer one and that the arms are leading.