COSMIC-RAY TRANSPORT IN THE GALACTIC MAGNETOSPHERE

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ABSTRACT

It is advantageous to regard cosmic rays as the constituent particles of the Galactic radiation belts and cosmic ray energization as a consequence of inward radial diffusion in the quasi-dipolar Galactic magnetosphere. This process occurs in addition to Fermi acceleration.

1. Introduction. The purpose of this work is to explore a magnetospheric explanation for the elevation of Galactic charged particles to cosmic ray energies. The magnetosphere that is of interest in this context is not a planetary magnetosphere but a galactic magnetosphere entirely analogous to those inferred [1-3] from radio observations [4-6] of distant galaxies. It is the magnetosphere of the Milky Way. Cosmic rays are (by this interpretation) the charged particles that constitute the radiation belts of the Galactic magnetosphere. Thus, the mechanism by which charged particles attain cosmic-ray energies is presumably the mechanism by which radiation-belt particles attain high energies in more familiar magnetospheres, i.e., the radial diffusion associated with magnetic disturbances that contain spectral power resonant with the azimuthal drift of the particles [7].

The existence of galactic radiation belts has been proposed [3] as a means of explaining the similarity of decimetric (~ 3-GHz) radio-emission patterns from various galaxies to that from Jupiter's magnetosphere [8]. Such radio patterns are believed to result from the synchrotron emissions of relativistic electrons, but it is clear that galaxies might (by analogy with Jupiter) have ionic radiation belts (which would not be remotely observable) as well as electron radiation belts (which are). Indeed, it is logical to identify the Galactic cosmic rays routinely observed in the heliosphere with the constituent ions and electrons of the Galactic radiation belts. This identification is supported (for electrons at least) by comparisons [9,10] between the energy spectrum of cosmic-ray electrons observed at the top of the atmosphere and the frequency spectrum of radio emissions from the disk of the Galaxy.

2. Field Model. An immediate corollary of this line of thought is that cosmic-ray energization must be considered within the context of a specific model for the Galactic magnetic field. A dipolar model [11] is convenient and (in view of the radio observations cited above) at least topologically realistic. The analytical representation of the adopted field model is

$$\underset{\sim}{B}(r,\theta) = \begin{cases} (r_c^3/2r^3)(2\,\hat{\underset{\sim}{r}}\cos\theta + \hat{\underset{\sim}{\theta}}\sin\theta)B_c, & r > r_c \\ \hat{\underset{\sim}{z}}\,B_c = (\hat{\underset{\sim}{r}}\cos\theta - \hat{\underset{\sim}{\theta}}\sin\theta)B_c, & r < r_c \end{cases} \tag{1}$$

where r is the radial coordinate, θ is the colatitude, $z = r\cos\theta$, r_c is the radius of the Galactic core, and B_c (~ 25 nT) is the magnitude of the (ideally uniform) magnetic field within. The emitting electrons in this model [3] reside mainly near the magnetic equator ($\cos\theta = 0$) and not near the magnetic axis ($\sin\theta = 0$), in contrast with the assumption of other investigators [11,12]. It is convenient to define the (dimensionless) magnetic-shell parameter

$$L = \begin{cases} (r/r_c)\csc^2\theta, & r \geq r_c \sim 2 \text{ kpc} \\ (r_c/r)^2\csc^2\theta, & r \leq r_c \sim 2 \text{ kpc} \end{cases} \tag{2}$$

in analogy with the L parameter encountered in the study of planetary magnetospheres. It follows from (2) that $L \geq 1$. A more realistic model of the Galactic $\underset{\sim}{B}$ field would entail a more widely distributed azimuthal current, which in (1) is confined to the sphere $r = r_c$. The dynamo current of a real galaxy would presumably involve the entire core, as well as a major part of the disk. The disk current would tend to distort magnetic shells by analogy with the "magnetodisk" model [13] of Jupiter's outer magnetosphere. This distortion would account for observations [10] that suggest a $\underset{\sim}{B}$ field parallel to the disk itself, while preserving the generally poloidal form [11,14] of the large-scale Galactic magnetic field. Moreover, energy-density considerations [10] suggest that cosmic-ray ions themselves must generate (through gyration and adiabatic charged-particle drifts) a Galactic ring current that significantly distorts magnetic shells from dipolar form even beyond the disk. It is convenient nevertheless to adopt a dipolar model of the Galactic $\underset{\sim}{B}$ field in order to discuss a first approximation of cosmic-ray kinematics and transport in the Galactic magnetosphere, just as it is customary to adopt dipolar models of planetary magnetic fields in order to study radiation belt dynamics for the earth and Jupiter.

3. Kinematics. The adiabatic theory of charged-particle motion therefore provides a kinematical framework for understanding the transport of cosmic-ray ions and electrons in the Galactic magnetosphere, just as it does for radiation-belt particles in planetary magnetospheres. Adiabatic theory is based on quasi-conservation of the three invariant quantities M, J, and Φ, which are proportional (respectively) to the action integrals J_i associated with gyration (i=1), bounce motion (i=2), and azimuthal drift (i=3). The corresponding frequencies $\Omega_i/2\pi$ associated with adiabatic charged-particle motion are supposed to satisfy the inequalities $\Omega_1 \gg \Omega_2 \gg \Omega_3$, and so it follows that the adiabatic theory holds only for particle energies $E \lesssim 10^{18}$ eV/charge on the drift shell ($L = L_\odot \sim 5$; see below) that supplies Galactic cosmic rays to our heliosphere. The bounce period for a very relativistic particle trapped on this drift shell, which has a radius ~ 10 kpc ($\sim 5\, r_c$; see above) is $2\pi/\Omega_2 \sim 10^5$ yr in the dipolar model. Gyration and drift periods are of this order for particle energies $E \sim 7 \times 10^{18}$ eV/charge if the Galactic magnetic field has a local magnitude $B \sim 0.1$ nT here, and so the adia-

batic theory of charged-particle motion applies only to particle energies $E \ll 7 \times 10^{18}$ eV/charge in our part of the Galaxy.

4. Transport and Energization. Adiabatic motion impels a charged particle to remain attached to its original magnetic shell, i.e., to retain its original value of L. The usual mechanisms for radial transport of energetic charged particles in planetary magnetospheres involve time-dependent disturbances having azimuthal asymmetry. Such disturbances typically conserve the first two adiabatic invariants M and J while violating the third invariant Φ. The result is a diffusion of the guiding center with respect to L and a corresponding change in the energy of the particle. The change in particle energy for $L \gg 1$ is conveniently expressed by the relationship

$$-3/2 \leq (\partial \ln p/\partial \ln L)_{M,J} \lesssim -1, \tag{3}$$

where p is the scalar momentum of the particle. The precise value of $(\partial \ln p/\partial \ln L)_{M,J}$ depends upon the L value and equatorial pitch angle α_0 [15], but the limiting values -3/2 and -1 in (3) are attained for $\alpha_0 = \pi/2$ and $\alpha_0 = 0$, respectively.

The observed isotropy of cosmic-ray ion distributions in momentum space [10] is presumably a consequence of anisotropy-destroying plasma instabilities [16-19]. The mean value of $(\partial \ln p/\partial \ln L)_{M,J}$ for a fully isotropic distribution of charged particles trapped in a dipolar magnetic flux tube is found [20] to be

$$\langle(\partial \ln p/\partial \ln L)_{M,J}\rangle \approx -4/3 \tag{4}$$

for $L \gg 1$. This result suggests the utility of a quasi-invariant object

$$\Lambda \equiv (p^2/m_0 B_c) L^{8/3} \tag{5}$$

for the treatment of radial transport in the presence of strong pitch-angle diffusion, in preference to the "invariant" $\tilde{\Lambda} \equiv (p^2/m_0 B_c) L^3$ implicitly proposed by Walt [21] for a similar purpose. Indeed, the appropriate exponent for L in (5) is a function of the anisotropy of the pitch-angle distribution, the values 8/3 and 3 being appropriate to isotropy and to extreme anisotropy ($\alpha_0 = \pi/2$ for all particles), respectively. The essential point is that particles in a galactic radiation belt gain (lose) energy by diffusing inward (outward) in L.

The particle energization implicit in (5) corresponds to the mechanism [22,23] typically invoked for radial transport of the highest-energy particles in the earth's radiation belts. It is separate and distinct from the well-known mechanism of Fermi [24], which requires the violation of J for the energization of particles [25] in a dipolar $\underset{\sim}{B}$ field. Both energization mechanisms must rely (in this context) on pitch-angle diffusion (implicitly at nearly fixed p) to maintain the desired pitch-angle isotropy. Both energization mechanisms are multiplicative in the sense that a particle's rate-of-change of p is proportional to p itself, among other factors.

5. Source Distribution. Cosmic rays are presumed to originate in (e.g.,

supernova) events distributed with uniform probability density throughout the core of the Galaxy. In this model the rate-of-production of cosmic rays per unit volume of magnetosphere turns out to be proportional to L^{-4} for $L \gg 1$. However, if the differential energy spectrum is proportional to $p^{-2.6}$ [10], then it follows (assuming immediate isotropization) that the source of phase-space density (differential flux divided by p^2) at fixed Λ varies as $L^{-4}(p^{-2.6}/p^2)$, i.e., as $L^{32/15}$, for $L \gg 1$. This is a monotonically increasing function of L, and so it seems that the net result of radial diffusion in the Galactic magnetosphere can be an inward transport of phase-space density, which corresponds via (5) to a net energization of particles subsequently observed as cosmic rays at $L = L_{\odot} \sim 5$.

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