THE ASTROPHYSICAL JOURNAL, 228:576–581, 1979 March 1

PARTICLE STREAMING: IS THE ALFVÉN VELOCITY THE ULTIMATE SPEED LIMIT?

GORDON D. HOLMAN,* JAMES A. IONSON, AND JOHN S. SCOTT
Department of Physics and Astronomy, University of Maryland
Received 1977 November 10; accepted 1978 September 18

ABSTRACT

We show that, because of the resonant damping of waves by thermal protons, nonthermal particles in a hot plasma can in fact stream at a speed which is on the order of or greater than the ion sound speed in the background plasma. This result is in contradiction with previous results which had indicated that in all cases the particle streaming speed is limited to the Alfvén velocity due to particle scattering by self-generated hydromagnetic waves. We consider in particular the propagation of relativistic electrons in the Coma cluster of galaxies and within the supernova remnant Cas A. Our results also have implications for the viability of some recently discovered cosmic-ray acceleration mechanisms. Finally, observational studies indicate that a significant fraction of interstellar space is occupied by a hot ($T = 10^6$ K), tenuous gas. If this is so, the considerations discussed here lead to a solution to the often discussed problem of cosmic-ray escape from supernova remnants.

Subject headings: cosmic rays: general — hydromagnetics — interstellar: matter — plasmas

I. INTRODUCTION

A thorough understanding of the physical processes which affect the streaming of high-energy electrons or protons through a magnetized, thermal plasma is of considerable importance for a number of astrophysical problems. The need for such understanding has become more apparent in recent years, as our observational knowledge of astrophysical situations where particle streaming is important has increased. A number of authors (see Wentzel 1974) have suggested that energetic particles cannot stream freely along a magnetic field in a plasma, but will be limited to a mean parallel propagation velocity, $\langle v_{\parallel} \rangle$, on the order of the Alfvén speed, v_A. This occurs because the streaming particles amplify the preexisting thermal level of Alfvén and magnetosonic waves, which in turn resonantly scatter the particles and reduce their streaming velocity. On the other hand, observations pertaining to a number of astrophysical plasmas (i.e., in supernova remnants, clusters of galaxies, solar flare regions, etc.) strongly indicate that particles do, in fact, propagate at speeds significantly greater than v_A. In this paper we present a resolution of this paradox for those cases which have $\beta \gtrsim 1$, where β is the ratio of the thermal pressure of the plasma to its magnetic pressure, $nkT/(B^2/8\pi)$. Two specific examples which we consider here are (1) clusters of galaxies, and (2) the supernova remnant Cas A. We also discuss briefly the origin and propagation of galactic cosmic rays.

Rich clusters of galaxies such as the Coma and the Perseus clusters are observed to contain extended regions of X-ray emission. If this emission is produced by the thermal bremsstrahlung process, the presence of a hot, intergalactic gas with a temperature on the order of 10^8 K is implied. These clusters are also observed to contain extended regions of radio emission with diameters which are on the order of or less than the X-ray source diameters. The radiofrequency emitting electrons ($\gamma \sim 10^4$) are understood to be diffusing from one or more of the galaxies in the cluster.

Jaffe (1977) has argued, however, that such diffusion cannot supply the entire radio halo in the Coma cluster with the requisite number of relativistic electrons if the particle propagation velocity is indeed limited to the Alfvén speed. This is because electrons diffusing at such a slow rate would radiate away their energy long before reaching the outer portions of the halo. Similar problems occur in other detailed models of cluster X-ray and radio emission (Holman 1977; Lea and Holman 1978; Rephaeli 1977). These problems are alleviated if the electrons are able to drift at a speed which is at least as large as the ion sound speed.

There seems to be ample evidence that in situ particle acceleration occurs in the supernova remnant Cas A (see Dent, Aller, and Olsen 1974; Erickson and Perley 1975; Read 1977). Indeed, a number of theories have been proposed to explain this phenomenon (see Ginzburg 1953; Gull 1973; Scott and Chevalier 1975). It is clear, however, that plasma conditions (e.g., field strength, turbulent motions, scale sizes, etc.) vary significantly throughout the remnant (Bell, Gull, and Kenderdine 1975; Bell 1978). The acceleration of the relativistic particles by any of the suggested plasma processes would therefore be expected to produce different relativistic particle energy spectra in the various sections of the remnant.

The accelerated particles would canonically be expected to stream at a speed v_A. However, hydrodynamic expansion of the remnant is known to occur

* Center for Theoretical Physics Postdoctoral Fellow.

at speeds $\sim 10 v_A$, and the relativistic electrons (which produce the observed synchrotron emission) accelerated in a given region of the remnant would therefore be unable to mix with particles produced in other parts of the remnant. Thus one might expect to observe significant variations of the synchrotron spectral index (a quantity which is directly related to the energy spectrum of the accelerated particles) between the different regions of the remnant.

Such variations in the spectral index are observed *not* to exist—the spectrum is remarkably constant through the remnant (see Bell *et al.*). Therefore, unless the particle spectrum produced by the acceleration mechanism is independent of the widely diverse conditions mentioned above, this fact implies that the different populations of relativistic electrons *are* thoroughly mixed together throughout the remnant. The actual required streaming velocity must be on the order of or greater than the sound speed.

In the next section we show that in a plasma with $\beta > 1$, the average streaming speed of energetic particles will not be limited to v_A; rather, particles can travel with bulk speeds at least as large as and probably significantly greater than the ion sound speed, v_i. This is due to the fact that resonant particle pitch angle scattering will not occur for particles with $v_\parallel \lesssim v_i$, since waves which are capable of causing such scattering will not be present in a hot plasma. These waves are not produced because they are also resonant with the thermal background protons and are therefore strongly damped. Thus resonant particle pitch angle scattering cannot reduce the parallel streaming speed of the individual particles below a value which is on the order of the ion sound speed. In § III we discuss some astrophysical implications of this result.

II. PLASMA THEORY

As discussed above, a distribution of energetic particles which originally has a large measure of momentum parallel to the field (i.e., a "stream") will tend to relax in such a way as to equilibrate its total perpendicular and parallel energies. This process, which occurs because of particle pitch angle scattering, increases the average particle pitch angle and thereby reduces the average parallel velocity of the distribution. This increase of particle pitch angle cannot occur indefinitely, however, since there is a lower limit on the wavelength of the resonant Alfvén waves which will be present. In a cold background plasma ($T = 0$) this minimum wavelength, λ_{min}, of turbulence which is excited by the particle distribution reduces to zero and the pitch angle distribution will tend to be isotropized in the frame of the Alfvén waves. Hence, when completely isotropized in the wave frame, the particles will be streaming through the plasma with a mean velocity near the Alfvén speed. In a hot ($\beta \gtrsim 1$) background plasma λ_{min} can be much greater than zero since short-wavelength waves (i.e., those resonant with the thermal gas ions) will be suppressed because of ion cyclotron damping. Just as waves are amplified when they become resonant with particles in an anisotropic distribution of cosmic rays, these same waves will be rapidly damped if they have short enough wavelengths that they are resonant with a significant number of the highly isotropic thermal protons. This occurs because the waves will lose momentum and hence energy to the thermal protons as they attempt to reisotropize these particles in the moving frame of the waves. Thus, for the case of a hot plasma, a stream of low pitch angle (i.e., high $v_\parallel$) particles will on the average increase their pitch angles only until the scattered particles are resonant with waves which have $\lambda \sim \lambda_{min}$. Since waves with smaller wavelengths are not present, the particles' parallel velocities will be reduced no further, and the mean particle streaming speed can be considerably greater than that which would occur in the absence of ion cyclotron damping. Turbulence of a given wavelength λ such that $\lambda < \lambda_{min}$ will not be amplified above the thermal level if the growth rate (due to the instability), Γ_g, is exceeded by the damping rate, Γ_d. The value of λ_{min} is thus determined by the condition (see Fig. 1)

$$\Gamma_g(\lambda_{min}) = \Gamma_d(\lambda_{min}) . \quad (1)$$

Due to the approximations used by previous authors in the derivation of Γ_g, we will not be able to solve equation (1) exactly. However, by taking the *maximum* value of Γ_g and by calculating the wavelength at which Γ_d has this same value, we are able to derive a very strong lower limit to λ_{min}. We show that, even under these, the most conservative limiting assumptions possible, the ion cyclotron damping results in a mean particle streaming speed which is at least as large as the ion sound velocity.

The rate at which Alfvén waves are damped due to ion cyclotron damping is given by the following expression (Krall and Trivelpiece 1973, p. 416):

$$\Gamma_d \approx \frac{\omega_{pi}^2}{|k_\parallel| v_i} \left(\frac{v_A}{c}\right)^2 \exp\left(\frac{-1}{\beta}\frac{\Omega_i^2}{\omega^2}\right) , \quad (2)$$

where ω_{pi} is the ion plasma frequency in the thermal gas, $k_\parallel$ is the wavenumber parallel to the ambient magnetic field, v_i is the ion sound speed, ω is the wave frequency, and Ω_i is the ion cyclotron frequency. For Alfvén waves $\omega = k_\parallel v_A$ and the condition for resonant scattering is

$$k_\parallel \approx \Omega_\alpha / \gamma v_\parallel , \quad (3)$$

where Ω_α is the Larmor frequency for the species of cosmic ray of interest, γ is its Lorentz factor, $E_\alpha / m_\alpha c^2$, where $v_\parallel$ is the component of the particle's velocity parallel to the ambient magnetic field. The damping rate (2) reaches a maximum value, Γ_d^{max}, at the wavelength

$$\lambda_d = \frac{2\pi v_i}{\Omega_i} .$$

Using the resonance condition (3), this corresponds to

$$v_\parallel / v_i = (m_i / m_\alpha)\gamma^{-1} \approx 0.18$$

for electrons with $\gamma = 10^4$ (the highest energy of interest here).

For particles with a power-law energy distribution, $N(E) = KE^{-s}$, the growth rate is given by the following expression:

$$\Gamma_g = \frac{\pi}{4}\frac{s-1}{s}\,\Omega_i\,\frac{N(\gamma > \Omega_\alpha/k_\parallel c)}{n}\left(\frac{\langle v\rangle}{v_A} - 1\right), \quad (4)$$

where $N(\gamma > \Omega_\alpha/k_\parallel c)$ is the number density of nonthermal particles which is resonant with the wavelength of interest, n is the number density of thermal protons, and $\langle v\rangle$ is the average streaming speed of the particle distribution (see Kulsrud and Cesarsky 1971). This expression implicitly assumes a pitch angle distribution of the form $f(\mu) \propto (1 + \delta\mu)$, where μ is the cosine of the particle pitch angle ($v_\parallel = c\mu$) and $\delta \approx \langle v\rangle/c$. Note that if the particle energy distribution contains a low-energy cutoff $\gamma_{\rm min}$, this expression for Γ_g is not valid for $\lambda \lesssim 2\pi\gamma_{\rm min}/\Omega_\alpha$. However, for the purposes of determining the minimum streaming velocity of the particle distribution, we only need to derive a lower limit for $\lambda_{\rm min}$. Even without precise knowledge of the form of Γ_g for $\lambda \lesssim 2\pi c\gamma_{\rm min}/\Omega_\alpha$, we may still obtain this limit on $\lambda_{\rm min}$. This is due to the fact that we know the growth rate will reach a maximum value

$$\Gamma_g^{\rm max} \approx \Omega_i\,\frac{N_{\rm total}}{n}\left(\frac{\langle v\rangle}{v_A} - 1\right) \quad \text{at} \quad \lambda_g \approx 2\pi c\gamma_{\rm min}/\Omega_\alpha\,,$$

where $N_{\rm total}$ is the total density of nonthermal particles (Ginzburg, Ptuskin, and Tsytovich 1973). The growth and damping rates are shown schematically in Figure 1. The growth rate is being studied in more detail by Morrison *et al.* (1979).

With the resonance condition (3), solving equation (1) for $\lambda_{\rm min}$ is equivalent to solving for the minimum possible steady-state streaming velocity of the cosmic rays, $v_\parallel^{\rm min}$. While explicit values of $\gamma_{\rm min}$ are not known for most astrophysical situations, a lower limit on $\gamma_{\rm min}$ can be obtained from the requirement that the total energy density of cosmic rays not exceed that of the thermal gas. (If this condition does not hold, the cosmic-ray pressure dominates the gas pressure and the local gravitational field and any discussion of quasi-linear particle diffusion is irrelevant.) Considering only the cosmic-ray component of interest, it is therefore easily found that

$$\gamma_{\rm min} m_\alpha c^2 > \left(\frac{s-2}{K}\,U_{\rm th}\right)^{1/(2-s)} \quad (s > 2) \quad (5)$$

and

$$N_{\rm total} < \frac{K}{s-1}\left(\frac{s-2}{K}\,U_{\rm th}\right)^{s-1/s-2}, \quad (6)$$

where $U_{\rm th} \approx \frac{3}{2}nkT$. (Note that the inclusion of pressure from other cosmic-ray species only increases $\gamma_{\rm min}$ and hence our derived value for $\lambda_{\rm min}$ will be a firm lower limit.) A lower limit on $v_\parallel^{\rm min}$ can be obtained by solving the following equation for λ_*:

$$\Gamma_g^{\rm max} = \Gamma_d(\lambda_*)\,. \quad (7)$$

Note that, because of the Gaussian form of the damping rate for $\lambda > \lambda_d$, a large change in the growth rate will have only a small effect upon the value which is obtained for λ_* and, similarly, for $\lambda_{\rm min}$. In all cases $\lambda_{\rm min}$ will be greater than λ_* and, correspondingly, $v_\parallel^{\rm min} > \Omega_\alpha\lambda_*/2\pi\gamma$. The growth rate for $\lambda > 2\pi c\gamma_{\rm min}/\Omega_\alpha$, equation (4), can of course be used to determine $v_\parallel^{\rm min}$ if $\lambda_g \ll \lambda_d$. We find that, in general, this is not the situation for the specific cases considered here and, therefore, in § III we use equation (7) to obtain lower limits on $v_\parallel^{\rm min}$.

We wish to emphasize again that $v_\parallel^{\rm min}$ is the *minimum* parallel velocity for a given particle energy which is resonant with the unsuppressed Alfvén waves and does not necessarily represent the average streaming speed of the distribution, $\langle v_\parallel\rangle$. Pitch angle scattering will tend to distribute the parallel velocities of the particles over the full range of values for which resonant waves are present. Hence the particles will be distributed along the locus of diffusion and the mean streaming speed of the distribution will be at least as great as $v_\parallel^{\rm min}$. The isotropization of the particles to $\langle v_\parallel\rangle = v_A$ in fact requires that the particles be repeatedly turned around so that they spend part of their time with pitch angles which are greater than 90° (i.e., $v_\parallel < 0$). In order for such backscattering to

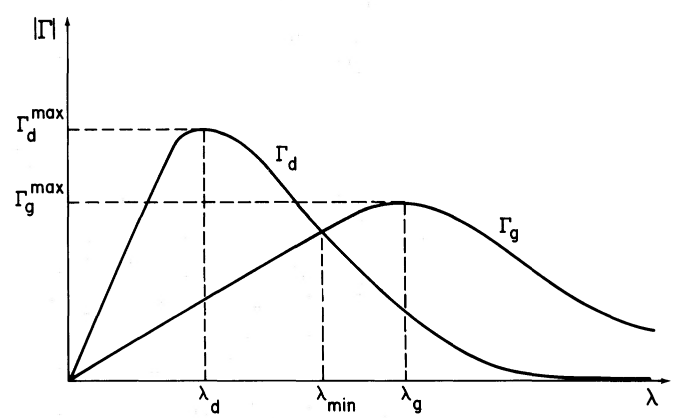

FIG. 1.—The growth and damping rates are shown as a function of wavelength for $\lambda_g > \lambda_d$ and $\Gamma_g^{\rm max} < \Gamma_d^{\rm max}$. The minimum wavelength of turbulence which is amplified by the streaming particles, $\lambda_{\rm min}$, is also shown.

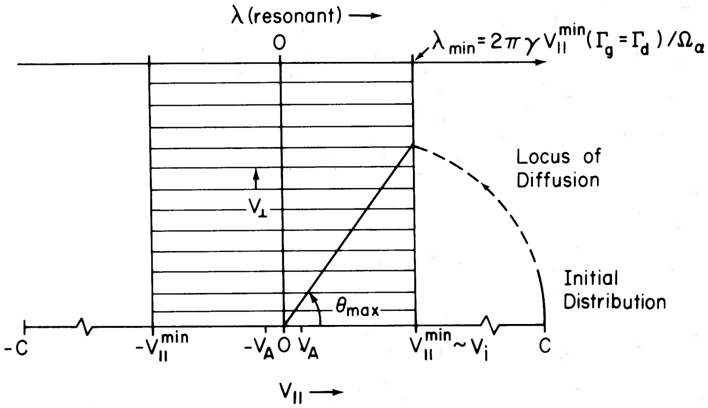

FIG. 2.—The pitch angle diffusion of a streaming distribution of relativistic particles is represented. The quantities $v_\|$ and $v_\perp$ are the components of a particle's velocity parallel and perpendicular to the ambient magnetic field. The crosshatched region is devoid of Alfvén waves and θ_{max} is the largest pitch angle for which resonant waves (i.e., those capable of scattering the particles) are present, and therefore the largest particle pitch angle (smallest $v_\|$) which will be present in the particle distribution.

occur, however, these particles must be turned through an angle of

$$\Delta\theta \geq 2\left(\frac{\pi}{2} - \theta_{max}\right) \approx 2\frac{v_\|^{min}}{c} \sim 2\frac{v_i}{c}$$

(see Fig. 2) in order to cross the region of the $v_\|$ versus $v_\perp$ plane which is devoid of resonant Alfvén waves. This cannot be accomplished by resonant pitch angle scattering and, when the particles are uniformly distributed over all pitch angles for which resonant waves are present, the mean streaming speed will in fact be on the order of the speed of light. This situation is summarized in Figure 2 and discussed in further detail in § III.

III. DISCUSSION

The density and temperature of thermal gas in the Coma cluster of galaxies are deduced from X-ray observations to be $n \approx 10^{-3}$ cm^{-3} and $T \approx 10^8$ K (Mushotzky *et al.* 1977) (we assume here that the electron and ion temperatures are roughly equal). Likewise, the energy distribution of relativistic electrons can be deduced from radio observations of synchrotron emission from the cluster, giving $N(E) \approx 5 \times 10^{-19} B_{\mu G}^{-2.2} E^{-3.4}$ cm^{-3} erg^{-1}, where $B_{\mu G}$ is in units of 10^{-6} gauss. Using equation (5), we obtain $\gamma_{min} > 3B_{\mu G}^{-1.57}$. Using equations (6) and (7) we find that $\lambda_{min} > 1.5 \times 10^{11}$ cm and $v_\|^{min} > 0.5v_i$ for $\gamma \approx 10^4$, $B \leq 10^{-6}$ gauss, and $\langle v \rangle \approx v_i$. Hence self-induced turbulence will in *no* case be able to reduce the mean streaming speed to a value significantly less than that of the ion sound speed, v_i. Energetic electrons which are streaming at this speed will produce a radio source with a size which is consistent with the observationally determined value for the Coma radio halo.

The magnetic field strength and thermal proton temperature and density in Cas A are, as summarized by Scott and Chevalier (1975), $B \approx 3 \times 10^{-4}$ gauss, $T \approx 5 \times 10^8$ K, and $n \approx 2$ cm^{-3}. The energy spectrum of relativistic electrons is deduced from radio observations to be $N(E) \approx 5 \times 10^{-12} E^{-2.5}$ cm^{-3} erg^{-1}. Taking $\gamma_{min} \geq 1$ and using equation (7) with $\langle v \rangle \approx v_i$, we find that $\lambda_{min} > 1.5 \times 10^9$ cm and, for $\gamma \approx 10^4$, $v_\|^{min} > 0.8v_i$. It is evident from this that cosmic-ray electrons accelerated in different parts of a supernova remnant can readily mix, since the mean drift speed of the cosmic rays will always exceed the hydrodynamic expansion rate.

We have shown that, because of the damping of short-wavelength waves, resonant scattering cannot transfer particles to pitch angles greater than $\sim 90°$, but we have not yet discussed the possibility that the longer wavelengths which are generated by the streaming particles can turn them around via magnetic mirroring. Since mirroring can occur only if the perturbation field strength in the wave, δB, is sufficiently large to increase a particle's pitch angle to 90°, we can derive a simple inequality which must be satisfied if mirroring is to occur. Remembering that for an Alfvén wave $\delta\boldsymbol{B}$ is pendicular to $\boldsymbol{B}$, and, hence that the change in the magnetic field *strength* is second order in δB, the constancy of the adiabatic invariant, $P_\perp^2/B$, yields the following condition for mirroring to occur:

$$\frac{\delta B}{B} > \frac{v_\|}{c}. \tag{8}$$

The *maximum* momentum which can be transferred to the waves is that of the streaming particles, ϵ_{cr}/c, where ϵ_{cr} is the cosmic-ray energy density. Since the ratio of the energy to the momentum in an Alfvén wave is v_A, $(\delta B^2/8\pi) < \epsilon_{cr}(v_A/c)$ and

$$\left(\frac{\delta B}{B}\right)^2 < \left(\frac{\epsilon_{cr}}{B^2/8\pi}\right)\frac{v_A}{c}. \tag{9}$$

Hence, since $v_\|^{min} \sim v_i$, mirroring may be important if

$$\frac{\epsilon_{cr}}{B^2/8\pi} > \frac{c}{v_A}\left(\frac{v_i}{c}\right)^2. \tag{10}$$

Taking $v_i \sim 10^3$ km s^{-1} and $v_A \sim 10$ km s^{-1}, parameters which are typical of the systems being considered here, mirroring need be considered only if the energy density in cosmic rays is greater than $\sim 0.1(B^2/8\pi)$. However, when the cosmic-ray energy density becomes comparable to the magnetic field energy density, both the real and imaginary parts of the dispersion relation change and Alfvén waves are no longer even normal modes of the system (Morrison *et al.* 1979). This is equivalent to violating the assumption that the growth rate, Γ_g, be much less than the wave frequency, ω (see Ginzburg *et al.*). Calculations bear out what would be intuitively expected—i.e., as the contribution to the pressure comes more and more from the cosmic rays, the normal modes look more and more like normal modes of the streaming cosmic-ray gas. Therefore the normal mode phase velocity approaches $\langle v_\parallel \rangle$. Clearly the idea of trapping at the Alfvén speed is meaningless in such a situation.

The results of § II also have implications for models involving the acceleration of cosmic rays in collisionless shock waves (Jokipii 1966; Fisk 1971; Bell 1978). In these models particles are accelerated through a first-order Fermi type mechanism engendered by repeated crossings of the shock front. The crossings from shock upstream to shock downstream are caused by scattering of the particles by turbulence which is generated by particles streaming away from the shock front. In these models the turbulence which backscatters the particles (and thereby allows particles to repeatedly cross the shock front) inhibits the upstream motion of the particles and thus allows the acceleration to be efficient. If, however, this turbulence is taken to be produced by the cosmic rays themselves (Bell 1978), our results show that for plasmas where $\beta \gtrsim 1$ particles will propagate upstream at a velocity which is at least as large as the ion sound speed (but may be $\sim c$). This will affect the number of particles which are overtaken by the shock wave and the time it takes for the shock to catch up to a given particle. An increase in catch-up time will of course reduce the maximum energy to which particles can be accelerated in a given period of time by this mechanism. The calculated results of application of the Bell mechanism will thus be affected for cases such as supernova remnants and extragalactic radio sources.

The fact that a negligible level of waves with wavelengths smaller than $\lambda_{\min}$ will be present in the plasma leads to a more fundamental difficulty for this type of acceleration mechanism. The acceleration scheme requires that the particles be repeatedly turned around so that they spend part of their time with pitch angles which are greater than 90°. As is discussed at the end of § II, however, this cannot be accomplished by resonant pitch angle scattering and the Bell mechanism per se is rendered inoperable. Therefore if acceleration models which involve particle turnaround are to remain viable, mechanisms other than resonant particle scattering must be invoked.

The fact that particle turnaround may be inhibited in a hot plasma should also be considered in halo models of cosmic-ray propagation such as those of Jokipii (1976) and Owens and Jokipii (1977*a*, *b*). Soft X-ray observations of the hot gas in the region above the galactic disk (Felten 1973) and radio observations of synchrotron emission in this halo (Webster 1975) imply $\beta \sim 1$–10 and, again, resonant scattering may not be able to turn the particles around. The simple halo diffusion models provide for a low density region of space where cosmic rays spend much of their lifetime. In order to agree with experimental determinations of this lifetime (Garcia-Munoz, Mason, and Simpson 1975), a low density propagation medium is required; one may need to postulate an ad hoc source of turbulence in the halo (one which is unconnected with the particles themselves). Otherwise the cosmic rays must spend time in some very low density region of the galactic plane (Scott 1975) such as "tunnels" of connected supernova remnants (Cox and Smith 1974).

We also wish to point out that the increased streaming speed in $\beta > 1$ plasmas may offer an answer to the problems (Kulsrud and Zweibel 1977) of cosmic-ray escape from supernova remnants. Cosmic rays which stream away from the supernova remnants where they are accelerated cannot escape without experiencing disastrous energy losses if their streaming speed is limited to the Alfvén speed in the warm (10,000 K) interstellar medium. This is because the rate at which the supernova remnant expands is highly super-Alfvénic and the cosmic rays are overtaken by the expanding remnant; this eventually causes the particles to experience unacceptable adiabatic expansion losses. On the other hand, recent evidence seems to indicate that 20%–80% of the interstellar medium is in a hot ($T = 10^6$ K) $\beta > 1$ phase (Jenkins 1977; Jones 1975; Scott, Jensen, and Roberts 1977; Smith 1977). When a supernova encounters a region of hot gas, the cosmic rays in the remnant may therefore be able to escape through the hot gas at a rate which can exceed the expansion rate of the remnant. If a large fraction of supernova do occur in or near the $\beta \gg 1$ plasma found in the hot, interstellar tunnels discussed by Cox and Smith (1974), this problem (along with the cosmic-ray lifetime problem discussed above) may be relieved. Further study of this general question is under way.

Finally, our discussion does not necessarily change the canonical objections (cf. Pacholczyk and Scott 1976) to the magnetospheric model (Jaffe and Perola 1973) of radio tails, since in this model the plasma is assumed to have $\beta < 1$.

The authors would like to thank S. M. Lea, P. Morrison, and D. Wentzel for helpful discussions. J. A. I. acknowledges partial support from the NSF Atmospheric Research Section.

REFERENCES

Bell, A. R. 1978, *M.N.R.A.S.*, **182**, 147.
Bell, A. R., Gull, S. F., and Kenderdine, S. 1975, *Nature*, **257**, 463.
Cox, D. P., and Smith, B. W. 1974, *Ap. J.* (*Letters*), **182**, L105.
Dent, W. A., Aller, H. D., and Olsen, E. T. 1974, *Ap. J.* (*Letters*), **188**, L11.

Erickson, W. C., and Perley, R. A. 1975, *Ap. J. (Letters)*, **200**, L83.
Felten, J. 1973, in *IAU Symposium No. 55, X- and Gamma-Ray Astronomy*, ed. H. Bradt and R. Giacconi (Dordrecht: Reidel), p. 258.
Fisk, L. R. 1971, *J. Geophys. Res.*, **76**, 1662.
Garcia-Munoz, M., Mason, G. M., and Simpson, J. A. 1975, *Ap. J. (Letters)*, **201**, L141.
Ginzburg, V. L. 1953, *Dokl. Akad. Nauk SSR*, **92**, 1133.
Ginzburg, V. L., Ptuskin, V. S., and Tsytovich, V. N. 1973, *Ap. Space Sci.*, **21**, 13.
Gull, S. F. 1973, *M.N.R.A.S.*, **161**, 47.
Holman, G. D. 1977, Ph.D. thesis, University of North Carolina–Chapel Hill.
Jaffe, W. J. 1977, *Ap. J.*, **212**, 1.
Jaffe, W. J., and Perola, G. C. 1973, *Astr. Ap.*, **26**, 423.
Jenkins, E. B. 1977, preprint.
Jokipii, J. R. 1966, *Ap. J.*, **143**, 961.
———. 1976, *Ap. J.*, **208**, 900.
Jones, E. M. 1975, *Ap. J.*, **201**, 377.
Krall, N. A., and Trivelpiece, A. W. 1973, *Principles of Plasma Physics* (New York: McGraw-Hill).
Kulsrud, R. M., and Cesarsky, C. J. 1971, *Ap. Letters*, **8**, 189.
Kulsrud, R. M., and Zweibel, E. 1977, private communication.
Lea, S. M., and Holman, G. D. 1978, *Ap. J.*, **222**, 29.
Morrison, P. J., Holman, G. D., Ionson, J. A., and Scott, J. S. 1979, in preparation.
Mushotzky, R. F., Smith, B. W., Serlemitsos, P. J., Bolt, B. A., and Holt, S. F. 1977, preprint.
Owens, A. J., and Jokipii, J. R. 1977*a*, *Ap. J.*, **215**, 677.
———. 1977*b*, *Ap. J.*, **215**, 685.
Pacholczyk, A. G., and Scott, J. S. 1976, *Ap. J.*, **203**, 313.
Read, P. L. 1977, *M.N.R.A.S.*, **178**, 259.
Rephaeli, Y. 1977, *Ap. J.*, **212**, 608.
Scott, J. S. 1975, *Nature*, **258**, 58.
Scott, J. S., and Chevalier, R. A. 1975, *Ap. J. (Letters)*, **197**, L5.
Scott, J. S., Jensen, E. B., and Roberts, W. W. 1977, *Nature*, **265**, 123.
Smith, B. W. 1977, *Ap. J.*, **211**, 404.
Webster, A. 1975, *M.N.R.A.S.*, **171**, 243.
Wentzel, D. G. 1974, *Ann. Rev. Astr. Ap.*, **12**, 71.

GORDON D. HOLMAN and JOHN S. SCOTT: Astronomy Program, University of Maryland, College Park, MD 20742

JAMES A. IONSON: NASA Goddard Space Flight Center, Code 682, Laboratory for Astronomy and Solar Physics, Greenbelt, MD 20771