SELF-CONFINED COSMIC RAYS

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Cosmic rays do not stream freely through the galaxy, contrary to earlier expectations. Streaming cosmic rays are slowed down by the emission of resonant Alfven waves that scatter the cosmic rays. The theory of self-confinement explains the isotropy of the bulk of the cosmic rays but not of cosmic rays above 10^3 Gev; it has been a stimulus to the theory for cosmic-ray acceleration at supernova shocks; and, on inclusion of diffusion in a galactic wind, it may explain the uniform cosmic-ray density out to 18 kpc in our galaxy. Rapidly streaming electrons in clusters of galaxies, in supernova remnants, and near solar flares are accomodated by the theory when it is expanded to include the effects of hot plasmas and other wave modes. A "resonance gap" may prevent the turning backwards of streaming particles and thus allow streaming near the particle speed.

INTRODUCTION

We have become used to measuring electric currents in the magnetosphere of the Earth, and even elsewhere in the solar system. However, the only electrical current that we can measure from beyond the solar system is a current of cosmic rays. All other astrophysical currents are merely inferred indirectly from observations of electromagnetic radiation.

Why should one expect cosmic rays to stream past the Earth? By about 1950 astronomers were fairly confident that the magnetic field in interstellar space is somewhere between 1 and 10 microgauss. In such a magnetic field, a typical cosmic ray at an energy of a few Gev has a gyroradius of the order of 10^7 km. This scale is some five orders of magnitude smaller than any interstellar structure that could then be observed. One deduced that cosmic rays should have constant magnetic moments as they propagate through the galaxy. They should be tied to the field lines and propagate along the magnetic field. If they are accelerated at supernovae, then the cosmic rays should be streaming away from these sources at roughly the speed of light. The cosmic rays would not actually provide a net electrical

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current, because a return current is very easily carried by thermal electrons. Nevertheless, the cosmic rays constitute a large fraction of the interstellar energy density, and therefore their rapid streaming would have been very important.

COSMIC-RAY ISOTROPY

The observations indicate that most cosmic rays are nearly isotropic. They stream past us at mean velocities less than a few 10^2 km/sec. For a few years, one could explain the isotropy by invoking cosmic rays permanently trapped on closed magnetic field lines, so that cosmic rays would reach us equally from all directions. Since then, the age of the cosmic rays has been measured. Most cosmic rays are merely some 10^7 years old (Stephens 1981). Therefore, there must be field lines along which cosmic rays can escape from the disk of our galaxy. We must conclude that some phenomenon makes the cosmic rays escape slowly.

Today we recognize that cosmic rays are scattered by Alfven waves with wavelengths comparable to the cosmic-ray gyroradii. The fundamentally new aspect recognized in the 1960's is that these Alfven waves can be generated by the cosmic rays themselves. The strongest original impact on cosmic-ray physics was a paper by Kennel and Petschek (1966) on the scattering of protons and electrons in the van Allen belts. In the same year, Tidman (1966) pointed out that suitable Alfven waves could scatter cosmic rays and influence their streaming. Lerche (1967) showed that streaming cosmic rays would generate resonant Alfven waves in a very short time. These ideas were then combined in papers by Kulsrud and Pearce (1969) and by myself (Wentzel 1969). We estimated the damping of the Alfven waves and we asked how rapidly the cosmic rays stream if the cosmic rays generate the waves as rapidly as the waves are damped. We found that the bulk of the cosmic rays can stream only barely more rapidly than the Alfven speed in the interstellar medium. This speed is between 10 and 10^2 km/sec in much of interstellar space, and it matches satisfactorily the slowest streaming rate that has been measured for the cosmic rays. Some places in the galaxy might permit much faster streaming, but the migration of cosmic rays through the galaxy is totally controlled by those places with the slowest streaming speed. The interpretation of this work is that cosmic rays cannot stream freely out of our galaxy but they are essentially self-confined to the interstellar medium. (See review by Wentzel 1974).

Have these ideas withstood the test of time? In the following I wish to outline two applications in which self-confinement is at least qualitatively important, namely the acceleration of cosmic rays and their dispersal in a galactic wind. Then I wish to stress a failure, in that observations of high-energy cosmic rays require more scattering than theory provides. Finally, I review the observations which require much less scattering than the standard theory provides, and the extensions of the theory that accomodate the observations.

ACCELERATION OF COSMIC RAYS

One success relates to the acceleration of cosmic rays. Supernovae are the most likely source of energy for the cosmic rays. One needs roughly 1% of supernova energy transferred to cosmic rays. Until a few years ago, 1% seemed like a rather large efficiency, theoretically. Yet the observers discovered ever more places in the universe where the acceleration efficiency seemed to be well above 1%. To my knowledge, the solution was first indicated by Schatzman (1963). He showed that particles could be accelerated very efficiently at hydromagnetic shocks if these particles could be made to cross the shock a large number of times. Bell (1977, 1978) pointed out that the cosmic rays near shocks would create Alfven waves that would scatter the cosmic rays back into the shock. The result is efficient acceleration. Blandford and Ostriker (1978, 1980) worked out enough details to show that this scheme is basically correct.

The cause of acceleration can be seen rather simply. Imagine a shock that is much faster than the Alfven speed. Therefore, any Alfven waves that exist are effectively moving with the gas. The increase in density across the shock requires a convergence in the velocity field, and therefore a convergence of the Alfven waves. If these waves scatter cosmic rays, then the cosmic rays find themselves in a converging set of scattering centers. Cosmic rays reflected from these centers many times experience what is called first-order Fermi acceleration. Moreover, the accelerated cosmic rays tend to diffuse away from the shock and, therefore, they will actually produce the Alfven waves that are needed.

The rate at which any one cosmic ray is accelerated depends on the frequency with which it crosses the shock; that is, the acceleration rate is proportional to the scattering rate caused by the Alfven waves. The duration of acceleration is limited by the distance beyond the shock from which the cosmic ray can still be scattered back to the shock; this duration depends inversely on the scattering rate. The product is significant acceleration largely independent of the scattering rate. Supernova shocks can easily replenish the cosmic rays that leave the galaxy. The concept of self-confined cosmic rays has increased the theoretical efficiency of acceleration from something like 1% to the order of unity. One presumes that this kind of efficiency also works for other astrophysical energetic phenomena. In fact, one sometimes hears the view that the acceleration problem is solved. I think such optimism is not yet justified (cf. Casse 1981, Volk 1981).

In the case of the cosmic rays, we have many observations concerning energy spectra, anisotropy, and the composition and ages of secondaries at various energies. Any detailed theory of cosmic-ray acceleration can be severely tested against these observations.

The theory cannot yet be this precise because of primarily three rather basic problems.

First, the cosmic rays are compressed and accelerated in the shock, but later they participate in the re-expansion of the gas and then they are adiabatically decelerated. They lose much of the energy gained by acceleration, but not all. The difference between gain and loss depends significantly on the shock strength, on the dynamics of the gas expansion, and on the relatively reduced scattering efficiency in the surrounding plasma (see discussion of the resonance gap below). Therefore, the net energy gain from a supernova is still quite uncertain (Blandford and Ostriker 1980).

Second, the accelerated cosmic rays must themselves influence the shock structure. One must therefore solve a highly nonlinear problem that involves not only shock dynamics but also the details of the acceleration process and the (possibly nonlinear) waves that are consistent with it. We are still far from such a solution (see Axford 1981, McKenzie and Volk 1982).

Third, we cannot measure interstellar cosmic rays below roughly 100 Mev, and interstellar electrons only indirectly down to 10 Mev (Bertsch and Kniffen 1983). We must depend largely on theory to explain how thermal particles can be selected to become cosmic rays. The observations of cosmic ray abundances and isotopes have not restricted these theories very much. (See Casse 1981). It is possible that cosmic rays come from ambient thermal interstellar material overrun by the supernova shock. Eichler (1980) has emphasized that a small number of particles must be accelerated out of the thermal distribution; the mere re-acceleration of existing cosmic rays would result in a spectrum of secondaries different from that observed. Eichler (1979) suggested how particles in the ambient gas may be selected and accelerated self-consistently with their resonant waves.

Despite all these difficulties, the theory is probably on the right track. When the solar wind impinges on the Earth's bowshock with the magnetic field sufficiently parallel to the wind velocity, then observations can be compared in detail with the theory for acceleration (Eichler 1981, Lee 1982). Observed details concerning waves, particles anistropy, and dependence on magnetic direction are reproduced by theory with essentially only one free parameter, namely the number of particles accelerated. The maximum energies of 100 Kev obtained in the bowshock are due to its finite extent. Much higher energies can be obtained in the much larger astrophysical shocks.

DISTRIBUTION OF COSMIC RAYS FAR FROM THE SUN

A very recent observation provides a new challenge to the theory for self-confined cosmic rays. The observation of gamma rays can tell us the density of cosmic rays in distant portions of the galactic disk. If you believe in self-confined cosmic rays, which cannot migrate very far in the galactic disk, then you expect a higher density of cosmic rays nearer the galactic center from the Sun, because supernovae are more frequent there and the cosmic rays are more easily confined to the galactic disk. You would expect a rather low density of cosmic rays well beyond the Sun's position in our galaxy. My colleague Leo Blitz and his collaborators at Leiden have recently compared the gamma-ray observations with maps of neutral hydrogen observed in 21-cm radiation. They find that the density of cosmic rays is remarkably uniform as far as 18 kpc from the center. Beyond that distance there is not enough gas to analyze the resulting gamma rays. Why should the density be so uniform where there is relatively little gas to confine cosmic rays and where there are rather few supernovae to make them? One might argue about details such as more efficient acceleration and fewer collisional losses where there is less gas, but the many possible factors are not likely to result in a uniform density.

Probably one has to relax self-confinement and incorporate it in a theory for the convection of cosmic rays. This can be done quite naturally for a galactic wind. Perhaps the wind is driven by the self-confined cosmic rays (Ipavich 1975), perhaps by the dynamics due to supernovae (galactic fountains). Owens and Jokipii (1977, see also Jokipii and Higdon 1979) have argued that a wind naturally explains why cosmic-rays are about ten times older than the time cosmic rays spend in the galactic disk. If a wind convects the cosmic rays away from the disk, individual cosmic rays may well be scattered back into the disk, but only if they have not been convected too far away. The maximum distance from which they can return determines the age of the oldest cosmic rays and also the mean age we observe at Earth. Owens and Jokipii (1977) modeled a wind moving perpendicular to the disk. At the other extreme, Ipavich (1975) and Axford (1981, Fig. 3) modeled a spherically symmetric

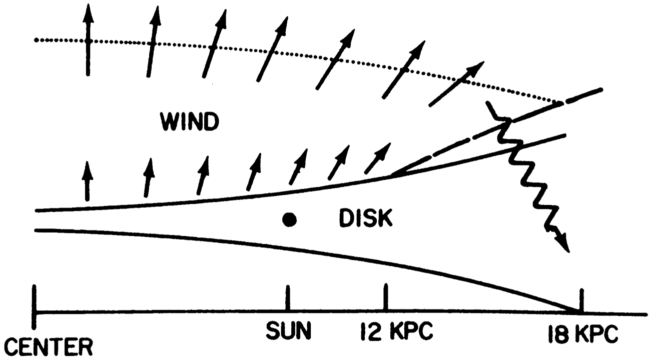

Figure 1. Cosmic rays may diffuse from the galactic wind back into the outer portions of the galactic disk.

wind. The reality is likely to be in between. In Figure 1, I assume a wind is driven from those portions of the disk where supernovae are frequent, say out to 12 kpc. Part of this wind becomes nearly radial. Because of this wind, cosmic rays can reach distant parts of the galaxy, even those rather close to the galactic disk. If one selects a fairly large but still reasonable diffusion coefficient, the cosmic rays are diffusion dominated out to the dotted line and they have a nearly uniform density out to there. If one now postulates at least a weak magnetic connection between the wind and the distant disk, perhaps caused by the equalizing of angular momenta in disk and wind, then cosmic rays can easily diffuse from the wind into the distant disk. The density of cosmic rays in the distant disk will simply mimic the density in the wind. If the density in the wind is nearly uniform, so is the density in the disk, as observed. The modeling for this kind of wind is only beginning. It presents a challenge to the concept of self-confined cosmic rays.

FAILURE: ISOTROPY OF COSMIC RAYS ABOVE 10^3 GEV

One major problem with cosmic-ray self-confinement is its energy dependence. Self-confinement is based on a balance between wave damping in the ambient medium and wave growth due to cosmic-ray streaming. The Alfven resonance requires that the Alfven wavelengths are similar to the gyroradii. The more energetic cosmic rays make longer wavelengths. The growth rate is proportional to n(c.r.) <v> where n(c.r.) is the integral number of cosmic rays able to resonate with the wavelength of interest. The damping by almost any nonlinear mechanism is proportional to the wave amplitude squared, thus to the scattering rate and to 1/<v>. (An efficient degradation of Alfven waves applicable to the 10^6K gas in the galactic disk and halo is derived by Shukla and Dawson 1983). In balance, <v> increases with energy roughly in proportion to $n(c.r.)^{-1/2}$. Cosmic rays above 10^3 Gev would stream faster than observations allow.

Resonant waves can grow appreciably faster if they grow by a coherent process at a shock front (Wentzel 1977). One may imagine that a shock surrounds the corona of our galaxy and that the cosmic rays are scattered at this shock. The isotropy near Earth might then merely be due to our location in the plane of symmetry of such a shock. Such a model would imply a different energy dependence in the escape rate of cosmic rays below and above roughly 10^3 Gev, but no model exists to evaluate this difference.

Two external sources of scattering have been suggested. First, there might be a cascade of eddies from large-scale interstellar turbulence down to the required small scales. This is improbable in detail (Cesarsky 1980). Second, Hall (1980, 1981) has argued that interstellar supersonic turbulence causes pressure anisotropies, and these anisotropies cause the firehose and mirror hydromagnetic instabilities. These instabilities are quite attractive for explaining the pulsar scintillations, because the scintillations are due to density fluctuations and these are not due to ordinary Alfven waves. However, the fluctuations have very short wavelength. The bulk of the cosmic rays must resonate with the magnetic fluctuations at the hundredth gyroharmonic, and the energetic cosmic rays at the millionth harmonic. Whether these fluctuations can confine cosmic rays is still somewhat uncertain.

Altogether then there is a fundamental problem with high-energy cosmic rays: no existing theory adequately explains their confinement to the galaxy.

OBSERVATIONS OF RAPIDLY STREAMING PARTICLES

Non-relativistic particles from solar flares show that the scattering theory I have outlined is substantially incomplete. One knows the magnetic fluctuations and Alfven waves in the solar wind, and therefore one can compute a scattering mean free path according to scattering theory (Jokipii 1971). This mean free path should become very small at low energies. Observations of flare protons show that the mean free path decreases to about 0.3 A.U. and stays at that value for non-relativistic protons (see Figure 1 in Goldstein 1980). A similar behavior occurs for flare electrons (Ma Sung and Earl 1978). In addition, one observes scatter-free events for non-relativistic particles from flares (McDonald, Fichtel and Fisk 1974). Clearly these observations indicate some rather fundamental omission in the scattering theory.

There also exist disquieting observations in astrophysics. The Coma cluster of galaxies is one of the few clusters that has a diffuse radio emission from the entire cluster. We know that the radiating electrons lose energy to inverse-Compton interactions on the cosmic background radiation. That gives us a maximum lifetime for the electrons of about 10^8 years. If we now suppose that the electrons are accelerated at the active galaxies near the center of the cluster and also that they travel to all parts of the cluster within their maximum lifetime, then we find that these electrons must stream at about 10^4 km/sec. However, if these electrons were self-confined to the Alfven speed, they should stream only at about 10 km/sec. There is a clear contradiction. One possible resolution (Dennison 1980, Vestrand 1982) is that the electrons are secondaries produced locally throughout the cluster by collisions of primary protons. The protons have very long lifetimes. They can reach all parts of the cluster during their lifetimes even when streaming merely at the Alfven speed. The other likely resolution is to admit very rapid streaming of electrons. Then one must seek a change in scattering theory.

A third suggestion of very rapid streaming arises for all sources of cosmic rays. It has long been stressed that self-confined cosmic rays are adiabatically decelerated while they try to travel away from their sources (Wentzel 1973, Kulsrud and Zweibel 1975).

The more compact the source, the greater the adiabatic deceleration before cosmic rays reach normal interstellar space. For acceleration very near a supernova, cosmic rays escape with merely one per cent of their original energy. For acceleration at a shock surrounding a supernova remnant, they may escape with less than half the original energy. This problem has led to suggestions that self-confinement breaks down near supernova shocks, perhaps once the shock has slowed down sufficiently.

CORRECTIONS TO SIGNAL SPEED

The Alfven speed $v_A = B/(4\pi\rho)^{1/2}$ is appropriate for a cold and isotropic plasma with negligible numbers of cosmic rays. Particles can stream more rapidly if the signal speed is faster.

Hall (1981) emphasized the turbulence of the 10^6K interstellar gas. The turbulence leads to an anisotropic gas pressure. For one sense of the anisotropy, the signal speed might be as high as the sound speed. But for the other sense of the anisotropy, one obtains the firehose instability. As long as both anisotropies are equally probable, the cosmic rays are still scattered by the firehose instability and stream slowly.

Cosmic rays may also increase the signal speed. Since cosmic rays have high magnetic rigidity, they should impart extra rigidity to the medium, and this increases the signal speed. The increase can be significant where (cosmic-ray pressure)x(streaming speed/c) > $B^2/8\pi$ (Morrison 1979). This may well be important in the Coma cluster of galaxies where the field is relatively weak, especially if one assumes rapid streaming to begin with (see also Spangler 1979). For supernova remnants, the signal speed increases only by a modest factor (Axford 1981) unless the accumulation of self-confined cosmic rays is substantial. All that is needed is a signal speed that is faster than the speed of the supernova shock.

THE RESONANCE GAP

It has been known since the beginning of self-confinement theory, first, that the simple Alfven self-confinement theory breaks down when $v_\parallel < v_A$, and second, that it is crucial for standard diffusion theory that particles can cross the state $v_\parallel = 0$ (Wentzel 1969). However, it was normally assumed that this range in velocity, now called the resonance gap, was small and easily bridged. Holman, Ionson and Scott (1979) outlined the observations suggesting rapidly streaming particles and argued that the resonance gap is indeed important in these situations. Considerable work has followed from their paper. Therefore, I first review why this gap is so important. When Alfven waves cause diffusion in pitch-angle, an individual particle undergoes many <u>small</u> changes in its pitch-angle. It continues to move in the same direction along the magnetic field until many of these small changes cause the pitch-angle to change past 90^o and the velocity along the field $v_\parallel$ reverses. We consider the particle to diffuse through space if it executes many such reversals in $v_\parallel$. Indeed, when we deduce a diffusion coefficient for particles observed in the solar wind, we compute the mean free path between reversals in $v_\parallel$ and we tend to ignore the many small changes in pitch-angle between the reversals. However, if for any reason the small pitch-angle changes cannot reach $v_\parallel = 0$, but they cease acting at some finite $v_\parallel = v_g$, then the particle continues to move in the same direction in which it started. Resonances can scatter the particles and make them nearly isotropic outside the gap, $v_\parallel > v_g$. If this gap is small, then the streaming speed is 0.5v (v = particle speed).

Nonresonant processes may "fill in" the resonance gap. The most widely considered process is mirroring from long-wavelength fluctuations in magnetic field strength. These may be caused by local gas dynamics or by the particle themselves. The minimum needed fluctuation is of order $\delta B/B \simeq (v_g/v)^2$. Alternatively (Fedorenko 1982), nonlinear processes may reverse the directions of the Alfven waves (cf. Shukla and Dawson 1983). Cosmic rays can be scattered by absorbing these re-directed Alfven waves. No resonance gap occurs. In either case, when the transfer of the particles through the resonance gap is slow, this process will determine the mean free path and the spatial diffusion rate. Meanwhile, resonant scattering may be quite rapid outside the gap. Therefore, the particle velocity distribution may frequently look as shown in Figure 2. In general, the mean free path is determined by the slower of the resonant scattering and the process causing particles to cross the resonance gap.

One must, therefore, ask two questions: how large is the resonance gap, and can any other phenomenon bridge the gap?

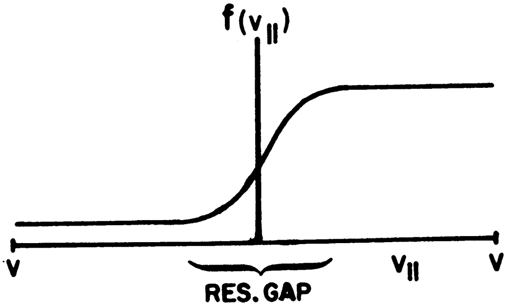

Figure 2. Velocity distribution when the transfer of particles through the resonance gap is slow compared to resonant scattering outside the gap.

We have the best chance to answer this question for solar particles in the solar wind. Goldstein (1980) suggested that the measured mean free path could be explained if the mean free path is controlled by mirroring of particles. Davila (1982) has computed the situation in considerable detail. For electrons, he finds that the gap has a width (γ = relativity factor) $v_g = 1.2\ c/\gamma$. Electrons below 300 Kev have $v < v_g$. They are not resonant with any waves in the wind, and they form the scatter-free events. Electrons above about 2 Mev have a small enough v_g such that the known field strength fluctuations in the wind can mirror the electrons. The mean free path is then just the wavelength of the waves carrying the field fluctuations, $\lambda \simeq 0.04$ A.U. This estimate fits the observations reasonably well. At still higher energies, mirroring is more rapid than resonance scattering. Then the standard resonance scattering theory again applies.

For protons, Davila finds $v_g = 2.5\ v_A$. The scattering time is λ/v_A and the mean free path is $\lambda(v_w/v_A) \simeq 0.3$ A.U., again in reasonable agreement with observations.

In many cosmic objects, the gas pressure exceeds the magnetic pressure (high-β plasma) and the ion thermal speed v_{Ti} exceeds the Alfven speed. Holman, Ionson and Scott (1979) pointed out that the resonance gap then is comparable to v_{Ti} and that such a large gap could allow streaming speeds much faster than v_A. Basically, the gap occurs because particles with $p_{\parallel} < m_i v_{Ti}$ could resonate only with waves that are highly damped and are effectively absent. The computation of the resonance gap is greatly simplified by the fact that all waves not traveling along the magnetic field are heavily damped; one need consider only waves along the field (Foote and Kulsrud 1979). Davila (1982) considered the gap in detail and found for supernova conditions

$$v_g(\text{protons}) = v_{Ti}\ (0.16 + 12/\gamma),$$

$$v_g(\text{electrons}) = v_{Ti}\ (0.06 + 8\text{x}10^3/\gamma),\ \gamma < 10^5.$$

The first term in each equation is appropriate for high-β plasma and is roughly independent of $\beta \gtrsim 10$; the second term depends only logarithmically on the density of the fast particles, as long as these are not so numerous as to affect the dispersion relation.

Davila concludes that electrons with $\gamma > 10^5$ are self-confined. The confinement of the other particles depends on how they might cross the gap. In the surroundings of a supernova shock, fluctuations in field strength of order $(v_{Ti}/c)^2 \simeq 10^{-6}$ seem quite probable, but it is unknown whether they are sufficiently numerous to mirror the particles as many times as is needed for acceleration. Achterberg (1981) estimated the field fluctuations due to streaming particles when the wave energy generated by the particles is limited by nonlinear damping. Since all waves are nearly transverse, the fluctuation in field strength is proportional to the square of the wave amplitude. Achterberg found that electrons with $\gamma < 200$ would be able to escape supernova remnants, and that most electrons and non-relativistic protons would also be able to stream through and escape from any surrounding hot plasma. It is possible, however, that confinement is better if field fluctuations are higher than computed. We should remember that the field fluctuations in the solar wind are substantially larger than had been anticipated.

In any case, when particles are accelerated at a supernova shock and are once self-confined, their acceleration makes them even more thoroughly self-confined (until their gyroradius becomes too large). This is rather contrary to the hopes of people worrying about adiabatic deceleration. It appears that particle escape will occur only when the shock slows down sufficiently.

The suggestion by Holman, Ionson and Scott (1979) is attractive for clusters of galaxies because electrons streaming at a few times v_{Ti} could indeed cross the radius of the Coma cluster within their lifetimes. However, the actual streaming speed again depends on the processes that allow the electrons to turn past $v_{\parallel} = 0$. If the medium is very quiescent, then the electrons stream at 0.5c.

If there are merely a few field fluctuations with amplitudes of at least $(v_{Ti}/c)^2 \simeq 10^{-5}$, they already slow the streaming speed down to the minimum needed for the electrons to traverse the cluster. The separations between mirrors can be no less than about 3% of the cluster radius. The galaxies moving within the cluster may well produce turbulence on such a scale.

SUMMARY

The original theory of self-confinement by Alfven waves has had to be extended to include convection, more details on the ambient plasma, and more details concerning the resonant waves, but basically the theory has fared quite well. It appears that electrical currents due to cosmic rays may alter the medium at supernova shocks, but even this is not established yet.

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DISCUSSION

Kennel: Aren't your two examples of non-confined cosmic rays different? In the solar wind you actually do see scatter-free propagation. But is it necessary for the Coma cluster? Why can't you have particles bound to the gas by wave-particle interactions and then have the gas expand?

Norman: The Coma cluster may not be a good example to emphasize since this phenomenon of an extended diffuse source is not at all a common phenomenon. The Coma cluster may in fact be made up of old radio sources where the transport of electrons is in energetic collimated jet flows at roughly 10^4 km/sec; these then shock and produce the acceleration at distances of 100 kpc to 1 Mpc from the source.

Bridle: There are clusters other than Coma which have diffuse steep-spectrum radio emission. An example is Abell 2256, which has a group of tailed radio sources and a steep-spectrum diffuse source which does not appear to be the integrated emission of discrete sources associated with individual galaxies.

Cowie: A third possible explanation of the electron lifetime would seem to be re-acceleration in turbulent shocks within the hot diffuse gas or in the bowshocks of galaxies. Can this be easily ruled out?

Norman: Bow shocks would have a very small filling factor, and there is no observational evidence for shocks in the general intracluster medium.

Wentzel: Certainly there are many sources where acceleration or re-acceleration throughout the source is required; some are mentioned in this Symposium. The question is: are there sites where apparent fast streaming cannot be explained by convective motions or acceleration? The arguments excluding fast convection and acceleration for the Coma cluster rest on its apparent homogeneity, including the broad, rather smooth X-ray distribution (Vestrand 1982). W. Jaffe (Astrophys. J. 212, 1, 1977) argued against convection of particles and acceleration by shocks in terms of excessive dissipation of kinetic energy, but his argument is weak if shock acceleration is efficient.

Dum: I thought the resonance gap at $v_{\parallel} = 0$ ($\theta = 90°$) that you mentioned arises only in quasilinear theory and that it is bridged by nonlinear orbit modification (resonance broadening). There were several papers by F. Jones, T. Birmingham and M. Goldstein that include numerical experiments demonstrating this effect.

Davila: If the scattering waves have a power at all k, as assumed in standard scattering theory, then the resonance gap is infinitessimal and resonance broadening effects can effectively cause particles to scatter across it. But when the maximum value of k is limited by ion-cyclotron damping, as assumed in resonance gap theories, the gap is too wide for resonance broadening to bridge the gap.

Wentzel: The work of Davila emphasizes the sensitive dependance of the gap on the dispersion relations of the relevant plasma modes. The nonlinear work (see M. Goldstein, Astrophys. J. 204, 900, 1976 and references therein) assumes magnetostatic turbulence.

Henriksen: Can the mirrors required for filling the resonance gap be due to the non-linear end of the resonant Alfvén wave spectrum?

Wentzel: The Alfvén waves may certainly become strong enough to interact nonlinearly, especially for k just somewhat below the resonant gap, and their degradation may fill in the gap to some degree. In fact, Achterberg shows that the mirroring is quite effective, even when the waves generated by the cosmic rays are kept fairly weak by nonlinear damping processes.

Mullan: Do particles from solar flares have time to excite Alfvén waves during their flight from the Sun to the Earth?

Wentzel: No, they are scattered by pre-existing turbulence. I used flare particles to demonstrate the importance of mirroring rather than self-confinement.