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INTERSTELLAR PROPAGATION OF LOW ENERGY COSMIC RAYS

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Wave particles interactions prevent low energy cosmic rays from propagating at velocities much faster than the Alfven velocity, reducing their range by a factor of order 50. Therefore, supernovae remnants cannot fill the neutral portions of the interstellar medium with 2 MeV cosmic rays.

1. Introduction. Several authors (Spitzer and Tomasko, 1969, hereafter referred to as ST, Spitzer and Scott, 1969, Field et al., 1969, Goldsmith et al., 1969) have assumed that low energy cosmic rays (of energy less than 10 MeV) are responsible for heating and ionizing the interstellar medium.

ST proposed that type I supernova remnants could establish the required density of low energy cosmic rays in the interstellar space. Their suggestion was principally based on energy considerations, plus the fact that the velocity of expansion of type I supernova shells is that of 2 MeV protons. ST further argued that, since a 2 MeV proton can travel several hundreds parsecs in interstellar medium before losing its energy, cosmic rays would spread throughout space.

In this communication, we point out that when the effect of the galactic magnetic field on the propagation of the cosmic rays is considered, the effective range of these particles is reduced from ST's estimate by a factor of order 50. Therefore, supernovae cannot fill the interstellar medium with 2 MeV cosmic rays. The relation of this result to light element nucleosynthesis in the galaxy, as well as other possibilities for cosmic ray heating of the interstellar medium, are discussed in section IV.

2. Streaming instability. Cosmic rays which stream through a magnetoplasma faster than the Alfven velocity, generate hydromagnetic waves of wavelength comparable to their Larmor radii. These waves in turn scatter the cosmic rays in pitch angle, and reduce their bulk velocity to a few times the Alfven velocity (Kulsrud and Pearce, 1969, hereafter referred as KP, Wentzel, 1969).

Even if the cosmic rays were ejected from their sources at greater speeds, they would slow down to $\sim$ the Alfven velocity in a very short time. To demonstrate this, let us consider a simple one-dimensional model. We assume a uniform field $B = 3.10^{-6}$ gauss. Since the growth rate is maximum for waves propagating parallel to the magnetic field, we only take those into account.

Following Kulsrud and Cesarsky (1971), we consider a cosmic ray beam streaming along field, with a momentum distribution

$$F = F_o p^{-q} \quad \text{for } p > P_1$$

where P_1 is the momentum of a 2 MeV proton. The cosmic rays are isotropic in a frame moving at a velocity V_R with respect to the ambient medium. The growth rate of the waves interacting with 2 MeV cosmic rays is given by

$$\Gamma_{CR} = \frac{\pi}{4} \, C \, \Omega_o \, \frac{N_{CR}}{n^*} \left(-1 + \frac{|V_R|}{V_A} \right)$$

where N_{CR} = number of cosmic rays with energy above 2 MeV/cm^3

$\Omega_o = e \, B_o / mc$

B_o is the strength of the magnetic field, and

m the mass of a proton ;

n^* the density of ionized particles,

$C = \frac{q-3}{q-2}$, and

V_A is the Alfven velocity.

We take $N_{CR} = 10^{-7} cm^{-3}$, corresponding to a hydrogen ionization rate of of $\zeta = 2.10^{-15}$ sec^{-1} in the interstellar medium. We also take $n^* = 0.03$ cm^{-3}, $q = 4.5$ and $B_o = 3$ μG ; then, $V_A = 37.8$ km/sec.

We estimate the time scale for decreasing the bulk velocity of the cosmic rays, by equating the momentum lost by the cosmic rays to that gained by the waves. The momentum associated with the streaming of the cosmic rays is equal to $N_{c.r.} \, mV_S$; the momentum of the waves resonating with them is equal to the energy density in waves. W, divided by V_A. So :

$$\frac{1}{V_A} \frac{\partial W}{\partial t} + m \, N_{CR} \, \frac{\partial V_S}{\partial t} = 0$$

and since

$$\frac{\partial W}{\partial t} = 2 \, \Gamma_{CR} \, W \equiv V_R \, W \, \eta$$

we obtain

$$\frac{\partial V_R}{\partial t} = \frac{\partial V_S}{\partial t} = - \frac{2 \Gamma_{CR} \, W}{V_A \cdot N_{CR} m} - \alpha V_R W$$

where

$$\eta = \frac{2 \, \pi^2 N_{CR} V_A C e}{B_o c} \; ; \; \alpha = \frac{2 \cdot \pi^2 \, \Omega_o \, C}{B_o^{\,2}}$$

If, at $t = 0$, $V = V_i$ and $W = W_i$, at a time t we have :

$$W = - V_A \, N_{C.R.} \, m \, V_R + W_o$$

and :

$$V_R(t) = \frac{V_i \, \frac{W_o}{W_i} \, \exp(-\alpha W_{ot})}{1 + \left(\frac{W_o}{W_i} - 1\right) \exp(-\alpha \, W_{ot})}$$

W_o is determined by the initial conditions :

$$W_o = W_i + N_{CR} \quad V_A \quad V_i \quad m$$

Take $V_i = 10^9$ cm/sec. A lower limit to W_i would be the energy of waves in thermal equilibrium with the background medium :

$$W_i = \frac{4\pi}{3} \; KT \quad k^3$$

where the wave number $k = 1.5 \; 10^{-11} \; cm^{-1}$ for waves interacting with particles of 2 MeV. If $KT = 1$ eV, the time for V_R to become equal to 1/10 of V_A is :

$$t \cong - \frac{1}{\alpha W_o} \left(\frac{W_i \frac{V_A}{10}}{W_o \; V_i} \right) = 3.10^6 \text{ sec.}$$

Therefore, even if the initial bulk velocity is large, it will decrease to nearly the neutral velocity in a tenth of a year.

3. <u>Range of a 2 MeV cosmic ray.</u> We want to evaluate the distance at which a 2 MeV cosmic ray will propagate from its source before losing its energy to the medium.

It turns out that in the model considered here, damping has a negligible effect on the steady streaming velocity. Waves are dissipated principally by the collisions between neutral and charged particles in the interstellar medium (KP). If the ionized part of the interstellar medium is mostly hydrogen, the damping rate is $\Gamma^* = 1.53 \times 10^{-9} \; n_H \; sec^{-1}$ if the temperature is $T = 100°K$, it increases slowly with T up to $8.4.10^{-9} \; n_H \; sec^{-1}$ for $T = 10^4 °K$ (Kulsrud and Cesarsky 1971). In a steady state, if $n_H = 1 \; cm^{-3}$, $\left(\frac{V_R}{V_A} - 1\right) = 0.015$ to 0.085 ; thus, the relative velocity between the medium and the cosmic rays is almost equal to V_A.

Since the rate of diffusion is much faster along the line of force than perpendicular to them, we can treat the problem in one dimension. Let be the life time of a 2 MeV cosmic ray in the medium considered. In first approximation, we can write the diffusion equation for the cosmic rays as :

$$\pm V_A \frac{\partial F}{\partial z} = \frac{\partial}{\partial z} \; D \frac{F}{z} + S_o \; \delta(z) - \frac{F}{\tau}$$

where z is the distance to the source along a tube of force, and S is the strength of the source.

We have :

$$D \frac{\partial F}{\partial z} = \mp F \cdot V_A$$

consequently

$$F = \frac{S_o}{4 \; V_A} \; e^{- |z| / 2 V_A \tau}$$

The mean range of the particles is

$$L_1 = 2 \; V_A \; \tau = 2 \; L_o \frac{V_A}{V} = 8.55 \text{ pc}$$

where L_o is the stopping length due to ionization losses in a gas of density $n = 1\ cm^{-3}$: L_o: 570 pc (Dalgarno and Mc Cray 1972) and V is the velocity of a 2 MeV proton : 2×10^9 cm/sec.

This calculation assumed that the spectrum of the particles is independent of z. In fact, because of the energy dependence of the ionization losses, the spectrum will flatten as one gets away from the source. To see this, we write a more exact diffusion equation :

$$\frac{\partial F}{\partial t} - \frac{\partial}{\partial z} (D \frac{\partial F}{\partial z}) + \frac{1}{p^2} \frac{\partial}{\partial p} (p^2 \frac{dp}{dt} F) = S$$

Neglecting dynamical effects, we can find a stationary solution to this equation. Since the cosmic rays effectively stream at V_A, we can write it as

$$V_A \frac{\partial F}{\partial z} - \frac{A}{p^2} \frac{\partial F}{\partial p} = S_o\ p^{-q}\ \delta(z)$$

where we have written the ionization losses of a fast particle as :

$$\frac{dp}{dt} = -\frac{A}{p^2}\ ;\ A = \frac{2\ p_1^3 V_A}{L_1}$$

The solution is :

$$F(p,z) = \frac{S_o}{2V_A\left(\frac{3\ Az + p^3}{V_A}\right)^{q/3}}$$

For an injection spectrum of the form $S \propto (\frac{E}{E_o})^{-\Gamma}$, where E is the kinetic energy and E_o = 2 MeV :

$$F(E,z) \propto \frac{\sqrt{E}}{\left(\frac{3Az}{V_A} + \sqrt{\frac{3}{2mE}}\right)^{\frac{2\Gamma-1}{3}}}$$

At a distance z from the source, the spectrum turns over at an energy $E_t \approx E_o\ (\frac{z}{L_1})^{2/3}$ (for example, if z = 100 pc, E_t ≈ 10 MeV) ; for $E \ll E_t$, the spectral index of the energy spectrum is positive and equal to 0.5.

5. Conclusion. We conclude that 2 MeV cosmic ray can fill the neutral portions of the interstellar medium only if their sources are separated from each other by a distance ≤ 200 pc. Supernovae and flare stars are not numerous enough but magnetic stars may be a good candidate.

Alternatively, if low energy cosmic rays are generated by sources that are distant from each others by more than 200 pc, the interstellar spectrum should exhibit a turn over around 10 MeV. This has interesting consequences. We recall, that, in the introduction, we stated that low energy cosmic rays have been proposed as sources of heating and ionization of the interstellar medium. The total rate of heating and ionization is proportional to the power input in low energy cosmic rays, almost independently of their mean energy or their spectrum (ST). In the recent past, this hypothesis has been put into question, because it predicted a higher population of doubly ionized states of certain ions than was observed by the Copernicus satellite (Weisheit and Tarter 1973, Meszaros 1973). It appears now possible that charge exchange reactions between doubly ionized ions and neutral hydrogen can depopulate these states, and reconcile the observations with the cosmic ray ionization theories (Steigman 1974, Collin-Souffrin 1975).

Low energy cosmic rays, with energies higher than considered here, are believed to be responsible for the nucleosynthesis of light elements Li, Be, B (Meneguzzi et al, 1973, Meneguzzi and Reeves 1975). Only one isotope of these elements, Li^7 which has a very low production threshold (9 MeV/nuc) is still a problem. Meneguzzi and Reeves (1973) find that the formation of Li^7 could also be accounted for if a low energy component is superimposed to the galactic cosmic ray spectrum. However, to obtain the desired rate of formation of Li^7 without getting too high a value of ξ , these authors must postulate that the low energy part of the spectrum has a cut off in the range 5-10 MeV. We give here a natural explanation for this cut off; thus we show that interstellar production of Li^7 is compatible with heating and ionization of the interstellar medium by low energy cosmic rays.

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