PROPAGATION OF COSMIC-RAY PRIMARY AND SECONDARY ELECTRONS IN DENSE INTERSTELLAR CLOUDS, AND IMPLICATIONS FOR GAMMA-RAY PRODUCTION

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ABSTRACT

The movement of primary and secondary electrons into and out of dense molecular clouds is inhibited by resonant Alfven waves generated by cosmic-ray nuclei and also by the cosmic-ray electrons themselves. The theory described in an earlier paper is extended to the multi-species case, including the generation of secondary electrons within the clouds. The waves cause the electron density within a cloud to diminish, and this causes a corresponding reduction in the expected flux of bremsstrahlung gamma-rays from clouds. We give the reduction for various values of cloud thickness and external cosmic-ray intensity.

Keywords: cosmic-rays, molecular clouds, Alfven waves, gamma-rays.

1. INTRODUCTION

In a previous paper (Skilling and Strong 1976, hereafter referred to as Paper 1), we showed that Alfven waves can be sustained by cosmic-ray nucleons at the boundaries of dense molecular clouds as a result of the anisotropy set up by the energy losses of the cosmic-rays across the clouds. For clouds of average column density, the effect becomes important for nucleons of energy below O(1) GeV, so that it is only of marginal importance for pion-decay gamma-ray production.

In section 2 of this paper, we extend the theory to the case where there is a mixture of cosmic-ray species, each of which generates and is scattered by the distribution of waves in a globally self-consistent fashion. This enables us, in Section 3, to investigate the propagation of cosmic-ray electrons, for which the single-species treatment of Paper 1 (good enough for the case of nucleons) is inadequate. This is particulary important for the relatively low energy (< 100 MeV) electrons which are expected to be the major source of low-energy (~ 30 MeV) gamma-rays in the Galaxy (Fichtel et al. 1976). Any inhibition of the propagation of external electrons into, and internally produced electrons out of, the clouds, will modify the expected bremsstrahlung emission. Section 4 examines this effect.

2. THEORY

Our analysis and our notation follow those of Paper 1, but now we have three distinct species of energetic particles, namely electrons (negatrons and positrons combined) and protons and Helium nuclei. Heavier particles do not have a significant effect. As before, we artificially sharpen our resonance condition between energetic particles and Alfven waves by requiring a 1:1 correspondence between wavelength $2\pi/k$ and particle rigidity

$$R = cp_s/|Z_s|e \tag{1}$$

(suffix s labels the different species; s = e for electrons, p for protons, α for Helium nuclei and s = N for general nuclei, either p or α). Thus particles of the same rigidity, albeit of different species, interact with each other via waves of the appropriate wavelength. In the presence of any density gradients, each species contributes independently to the intensity growth rate of waves propagating into the cloud, which becomes

$$-\sigma = \frac{4\pi}{3} \frac{v_A}{U_M \mathcal{J} L} \sum p_s{}^4 v_s (f_{os} - f_{cs}) \tag{2}$$

analogously to equation (3) of Paper 1. For each rigidity value, the corresponding waves quickly reach an equilibrium intensity

$$\mathcal{J} = \frac{4\pi}{3} \frac{v_A}{\Gamma U_M L} \sum p_s{}^2 v_s (I_{os} - I_{cs}) \tag{3}$$

at which damping, probably due to friction against neutral particles, at a rate Γ balances the growth rate $-\sigma$. Equation (3) describes how the waves react to given differences between the particle fluxes $I = p^2 f$ inside and outside the cloud.

A self-consistent solution demands that these differences are set up by the waves themselves, allied probably to more orthodox source and loss terms. The effect of the waves is to cause a flux

$$j_s(E)\,dE = \left[4\pi\alpha_s p_s^2 f_{os} \frac{v_A}{v_s} + \frac{4\pi p_s^2 D_s (f_{os} - f_{os})}{L v_s}\right] dE \quad (4)$$

of particles to enter each of the two sides of the cloud (cf. equation (8) of Paper 1). Here we have written $\alpha = -(p^3/f)\,\partial f/\partial p^3$ = Compton-Getting factor, and

$$D = v^2/3\nu = 4\gamma v^2/3\mathcal{I}\pi\Omega_o = 4\,pv/3\mathcal{I}\pi m\Omega_o = \quad (5)$$

spatial diffusion coefficent

for each species s. In a steady state, conservation of particles in energy range dE gives

$$2_{j_s}(E)\,dE = -\Lambda\, d\left(\frac{E\, v_s n_{cs}(E)}{\lambda_s(E)}\right) - \Lambda\, q_s(E)\,dE \quad (6)$$

for a cloud of thickness Λ atoms cm^{-2}, within which particles lose energy in a mean free path of λ_s atoms cm^{-2}. This is equation (13) of Paper 1 with an extra source term $q_s(E)dE$ particles $atom^{-1}\ s^{-1}$ to take account of secondary electron production within the cloud. Eliminating j_s and D_s between (4), (5) and (6) yields

$$\alpha_s I_{os} \frac{v_A}{v_s} + \frac{\Phi_s\, p_s (I_{os} - I_{cs})}{\sum_r p_r^2\, v_r (I_{or} - I_{cr})} + \frac{\Lambda q_s}{8\pi} = -\frac{\Lambda}{2}\frac{\partial}{\partial E_s}\left(\frac{E_s I_{cs}}{\lambda_s}\right) \quad (7)$$

where

$$\Phi_s = U_M\, \Gamma/\pi^2 m_s \Omega_{os} v_A \quad (8)$$

as in Paper 1, for the response of the particle flux density I_s to a given level of the waves. The common rigidity R (equation 1) relates the energies E_s of the different species.

Formally, (7) gives the self consistent steady-state solution for the particle spectra in the presence of waves. The singularity in (7) when $\mathcal{I} \to 0$ and correspondingly $\sum p^2 v(I_O - I_C) \to 0$ may be circumvented by noticing that the flux $j_s(E)$ in equation (4) may not exceed $\frac{1}{4} v_s (n_{os} - n_{cs})$, which is the value appropriate to completely free streaming of particles, and near which the underlying assumption of strong scattering by the waves breaks down. Thus an alternative form of (7), valid when the wave intensity predicted by (3) is inadmissibly small or even negative, is

$$\tfrac{1}{4}(I_{os} - I_{cs}) + \frac{\Lambda}{8\pi} q_s = -\frac{\Lambda}{2}\frac{\partial}{\partial E_s}\left(\frac{E_s I_{cs}}{\lambda_s}\right) \quad (9)$$

At high energies, the particle fluxes are indeed too low to produce waves at all, and (9) will hold. The losses and source are then small, and in fact the particle density inside the cloud closely matches that outside ($I_c \simeq I_o$).

However, at somewhat lower energies, losses cause I_c to fall away from f_o, the wave intensity predicted by (3) rises above the threshold for significant scattering of the particles, and equation (7) replaces (9) as a finite level of waves becomes stable.

3. APPLICATION TO GALACTIC COSMIC-RAYS

We now apply the theory to the probable mixture of cosmic-rays in interstellar space. The various terms in equations (7) - (9) were taken as follows. The standard external electron spectrum was taken to be

$$I_{oe}(E) = \begin{cases} 1.5\ 10^{-11}(E/1\ GeV)^{-1.8} & (E < 1\ GeV) \\ 1.5\ 10^{-11}(E/1\ GeV)^{-2.5} & (E > 1\ GeV) \end{cases}$$
$$cm^{-2}\ s^{-1}\ sr^{-1}\ eV^{-1} \quad (10)$$

in accordance with spectrum (a) of Goldstein et al. (1970). (This spectrum is about a factor 2 higher than the local demodulated spectrum given by Daugherty et al. (1975), but, being derived from radio measurements is probably more representative of the spectrum in the general interstellar medium). Since the electrons are always highly relativistic, we have

$$\alpha_e = \frac{\gamma_e + 2}{3} \quad (11)$$

where γ_e is the electron spectral index.

Electrons suffer energy losses from ionization and from bremsstrahlung, and these were assumed to be continuous (not strictly accurate for bremsstrahlung but good enough for the present purpose), giving a resultant mean free path

$$\lambda_e = \left(\lambda_{ie}^{-1} + \lambda_{be}^{-1}\right)^{-1} \quad (12)$$

Ginzburg (1969) (pp 55 and 73) quotes

$$\lambda_{ie} = \frac{3.4 \times 10^{18} \left(\frac{E_e}{1eV}\right)}{\left[3 \ln E_e/m_e c^2 + 20.2\right]}\ cm^{-2} \quad (13)$$

for ionization losses and

$$\lambda_{be} = 1.45 \times 10^{26}/\left[\ln E_e/m_e c^2 + 0.36\right]\ cm^{-2} \quad (14)$$

for bremsstrahlung losses. This latter formula is appropriate for electrons with $E_e < 10^3\, m_e c^2$. In this paper we assume that the clouds contain 34 Helium nucleons for every 100 hydrogen atoms (Allen, 1973). This increases the ionization loss rate per atom by a factor 1.17 (loss α no. of electrons) and the bremsstrahlung loss rate by 1.51 (loss α no. of atoms x Z(Z+1)). Electron synchrotron losses can also be included, but have a negligible effect on the results even for magnetic fields in the cloud of order 100 μG.

Secondary production spectra for positrons and negatrons in the general interstellar medium are given by Ramaty (1974). However, he used the local cosmic-ray spectrum for the producing nucleons, whereas these may well be partially excluded from the interior of dense clouds. Now for all relevant electron energies (above about 5 MeV), the dominant production mode of secondary electrons, π^o- decay, is numerically proportional to the π^o-decays which produce gamma-rays. Accordingly, we scale the Ramaty spectra down in the same ratio that gamma-ray emission (from π^o-decay) from the cloud is reduced:

$$q_e = q\ (\text{Ramaty}) \times \frac{\text{pion gamma-ray flux from cloud with waves}}{\text{pion gamma-ray flux from cloud without waves}}$$

For the standard external proton and helium spectra we use the results of Garcia Munoz et al. (1975)

$$I_{op} = 9.9\ 10^{-2}\left[10^{-6}E_T + 780\ \exp(-2.5\ 10^{-10}E_T)\right]^{-2.65}$$

$$I_{o\alpha} + 4.4\ 10^{-3}\left[2.5\ 10^{-7}E_T + 660\ \exp(-3.5\ 10^{-11}E_T)\right]^{-2.77}$$

$$\text{particles cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{eV}^{-1} \qquad (15)$$

where E_T is the total energy in eV particle. These spectra are power-laws in total energy below about 1 GeV, and therefore fall below the spectra from Webber (1968) which were used in Paper 1. For our present purpose this is satisfactory since we are mainly interested in electrons of a few tens of MeV, which have the same rigidity (and hence resonate with the same waves as) nuclei of order 0.1 MeV, for which no observational data exist. Hence by using the Garcia-Munoz spectrum in which the flux of such very low energy nuclei is negligible, we are adopting the most conservative approach to the production of waves.

Nuclei suffer energy losses from ionization according to

$$\lambda_{ip} = \lambda_{i\alpha} = \frac{3.7\ 10^{27}\ \frac{v^2}{c^2}\left[\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}-1\right]}{\left[52.26 - 2\ \ln\left[1-\frac{v^2}{c^2}\right] + 2\ \ln\left[\frac{v^2}{c^2}\right] - 2\frac{v^2}{c^2}\right]}\ \text{cm}^{-2} \qquad (16)$$

and from inelastic interactions according to

$$\lambda_{\pi p} = \lambda_{\pi\alpha} = 6.8\ 10^{25}\ \text{cm}^{-2} \qquad (17)$$

in Paper I. (Note that equation (16) is a corrected version of the corresponding equation (10) on Paper 1. The correction has the effect of reducing the nucleon specta I_{CN} within the cloud by up to a further factor of 2 below the Paper 1 values for $E_N \sim 10$ MeV; the difference is not important for that work since the pion production is not affected.)

Within the clouds we assume there are no sources of nucleons, so that

$$q_p = q_\alpha = 0 \qquad (18)$$

With all the input data now available, the three coupled, non linear first order equations (7) and (9) (protons, alphas and electrons) were solved numerically. Specifically, we used equation (9) (corresponding to waves being absent) whenever equation (7) corresponding to waves being present) predicted diffusion coefficients above the physical limits set by the speed of the resonating particles.

The solutions were parameterized by the dimensionless ratios F_1 and F_2 of Paper 1 and by a further ratio F_3. F_1 represents the magnitude of the cosmic-ray nucleon flux outside the cloud relative to the 'standard' spectrum (15), F_2 the column density of the material of the cloud itself relative to a standard cloud with column density $4.2\ 10^{22}$ cm^{-2} and F_3 represents the magnitude of the cosmic-ray electron flux outside the cloud relative to the 'standard' spectrum (10)

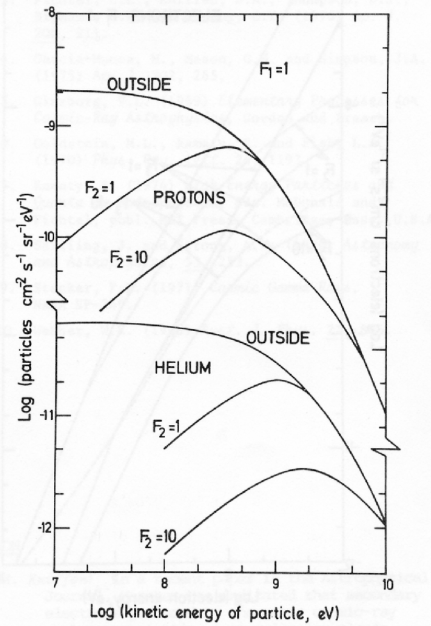

Figure 1. Proton and alpha particle spectra inside and outside cloud, for spectra outside characterized by $F_1 = 1$ and column density of cloud by $F_2 = 1$ and 10.

The graph in Figure 1 shows the p and α spectra inside the cloud both for standard parameters ($F_1 = F_2 = 1$) and for a somewhat thicker cloud exposed to the same external cosmic-ray flux ($F_1 = 1$, $F_2 = 10$). Changing the external electron spectrum parameter F_3 had no significant effect on these curves. The behavior of these nuclear spectra is as described in Paper 1, namely a progressive attenuation of the spectra inside the cloud below a certain energy of rigidity (about 400 MeV for protons with standard parameters, but as high as 10 GeV for protons in the thicker cloud with $F_2 = 10$) as the Alfven waves switch on and become progressively more important.

Electron spectra inside the cloud are shown in Figure 2 for $F_1 = 1$, $F_2 = 1$ and 10, and $F_3 = 1$ and 10. The electrons too are progressively attenuated towards lower energies due to the waves, the attenuation at 20 MeV being by factors of 5 and 20 for cloud thicknesses of $F_2 = 1$ and

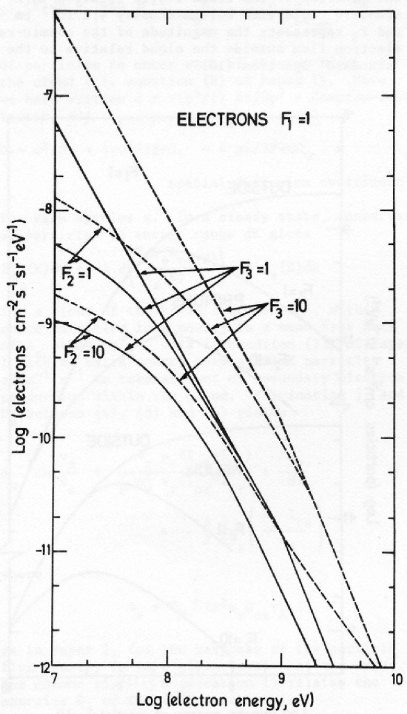

Figure 2. Electron spectra outside and inside cloud for $F_1 = 1$, $F_2 = 1$ and 10 and electron spectra with $F_3 = 1$ and 10.

10 respectively. The energy (rigidity) at which waves switch on is determined almost entirely by the protons, and hardly at all by the less powerful electrons. Nonetheless, it is interesting that with the Garcia-Munoz nuclear spectra, electrons below about 100 MeV are sufficiently numerous to dominate the production of waves. The electrons are thus themselves capable of setting up the waves required to exclude them partially from the interior (are partially trap secondaries produced inside), even in the complete absence of nuclei of the corresponding rigidities.

4. BREMSSTRAHLUNG RADIATION FROM CLOUDS

The bremsstrahlung emissivity for photons of energy E_γ from a distribution of relativistic electrons of intensity I_e is proportional to $\int_{E_\gamma}^{\infty} I_e\, dE_e$ (see e.g. Stecker (1971). The reduction in bremsstrahlung flux because of the waves is therefore given by

$$\int_{E_\gamma}^{\infty} I_{ce}\, dE_e \Big/ \int_{E_\gamma}^{\infty} I_{oe}\, dE_e$$

This is shown as a function of energy for the four cases $F_1 = 1$, $F_2 = 1$ and 10 and $F_3 = 1$ and 10, in Figure 3.

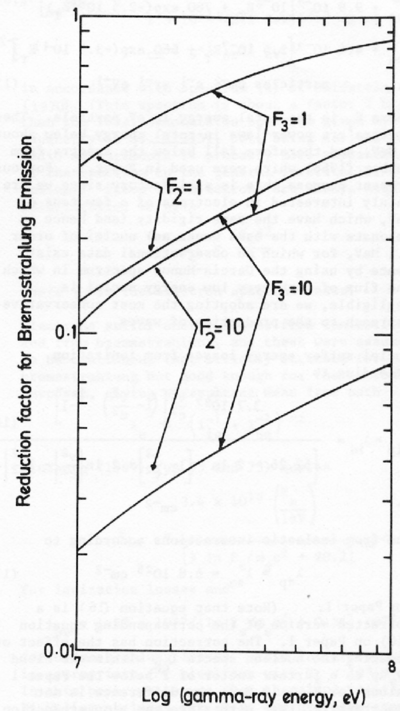

Figure 3. Reduction in Bremsstrahlung emission form clouds as a function of energy for $F_1 = 1$, $F_2 = 1$, 10 and $F_3 = 1$, 10.

For 20 MeV photons, the reduction is by a factor 0.5 for standard parameters ($F_{1,2,3} = 1$) and by the yet more significant factor 0.2 if the cloud thickness is increased to $F_2 = 10$. Increasing F_3 leads to higher wave intensities and even larger relative reductions in bremsstrahlung emission. This is the energy region for which Fichtel et al. (1976) have made predictions for the distribution of Galactic gamma-rays: the effect of the waves will clearly be considerably to modify their predictions.

A proper evaluation of the effect will require a knowledge of the distribution of column densities (i.e. of F_2) for the clouds. If as a first approximation we assume $F_2 = 1$ everywhere, then the Fichtel et al. bremsstrahlung flux should be reduced by at least a factor of 0.6 for $|l|<30^o$ (the region where molecular clouds dominate the interstellar matter distribution). This is an underestimate of the effect however because Fichtel et al. assume a higher electron intensity in denser regions so that the reduction will be further enhanced. We intend to pursue a fuller analysis of this effect with appropriate Galactic models in a later paper.

5. CONCLUSION

We have shown that cosmic-ray electrons will be partially excluded from molecular clouds, along with cosmic-ray protons and heavier nuclei, by the actionof instability generated Alfven waves. This has the effect of keeping energetic electrons away from a large fraction of the interstellar material, thus decreasing the intensity of bremsstrahlung gamma-rays of around 20 MeV which are expected to be produced within the Galaxy. The magnitude in this reduction almost certainly exceeds a factor of 1.5 for emission for $|\ell|<30^o$.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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DISCUSSION

R. Cowsik: I suspect that the resonance conditions for scattering of particles by waves is $k_{||} = \omega$. Under these conditions would ~100 MeV electrons be scattered in the same way as protons of similar rigidity (E ≈ 5 MeV)?

A.W. Strong: The resonance condition is $2\pi/k$ ~ Larmor radius of particle, so that particles of the same rigidity do indeed scatter from the same waves.

D.A. Kniffen: In a recent paper in the Astrophysical Journal, Marsher has indicated that secondary electrons produced by energetic cosmic-ray protons penetrating into molecular clouds would lead to a very large Bremsstrahlung emission from these clouds. Is this consistent with the model you have presented?

A.W. Strong: I think that Marsher assumed that secondary electrons would convect at the Alfvén speed inside the cloud, which is unlikely since the waves are rapidly damped inside. However, the effect for < 100 MeV electrons is similar for both models, namely trapping for long enough for complete energy loss inside the cloud.