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Cosmic Ray Exclusion from Dense Molecular Clouds

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Summary. Cosmic rays suffer losses due to ionization and nuclear interactions as they pass through a dense cloud of matter. Nearby, there is thus a net flux of cosmic rays towards the cloud. Such a flux can generate Alfvén waves, which restrict the cosmic ray flux which can reach the cloud. Significant depletion of cosmic rays inside the cloud can occur even when the cloud is apparently optically thin to the rays. This has implications for observed γ-ray fluxes from the clouds, and for ionization levels within the clouds.

Key words: cosmic rays — molecular clouds — gamma rays — ionization

1. Introduction

Gamma-ray observations of the Galactic plane (Fichtel et al., 1975) indicate a good correlation between the radial dependence of γ-ray emissivity and neutral and molecular hydrogen (see e.g. Strong and Worrall, 1976, Dodds et al., 1974). The zone of enhanced emission by a factor ~ 10 at galactocentric distance $R \simeq 5$ kpc can be produced with only a small increase in cosmic-ray intensity if the H_2 density is about 5 molecules cm^{-3} in this region as deduced from carbon monoxide observations (Scoville and Solomon, 1975).

Two problems remain with this interpretation however:

(a) the z-thickness of the molecular disc at $R = 5$ kpc requires the existence of a cosmic ray pressure an order of magnitude higher than locally; this would lead to more γ-rays than observed if cosmic rays could enter molecular clouds freely (Wentzel et al., 1975; Mouschovias, 1975).

(b) the lack of a large γ-ray peak in the Galactic centre corresponding to the large H_2 mass ($\sim 10^8\ M_\odot$ according to Scoville et al., 1974) and to the peak in the continuum radio emission at the Galactic centre.

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Both of these problems would be eased if there were some mechanism by which cosmic rays could be inhibited from entering the dense molecular clouds.

Such exclusion from clouds is also necessary for low energy ($\sim$ 1–10 MeV) cosmic rays if such particles are the main ionizing agent in the interstellar medium (Brown, 1973; Solomon and Werner, 1971).

The purpose of this paper is to determine whether scattering of particles by Alfvén waves has an important effect in excluding them from clouds in any of these situations.

2. The Exclusion Mechanism

The molecular hydrogen in the Galaxy occurs in clouds with typical masses 10^4–$10^6\ M_\odot$ and density 10^3–10^5 atoms cm^{-3}. Cosmic rays entering a cloud lose energy by ionization and by nuclear interactions. If the cosmic ray sources are outside the cloud, the flux emerging is less than that entering, so that an anisotropy is set up. This may cause growth of Alfvén waves in the plasma near the cloud. Such waves scatter particles in pitch angle and impede the flow of particles into the cloud. The equilibrium density of cosmic rays inside a cloud can be reduced significantly below the uniform external density in the plasma outside the cloud.

The particles must scatter through 1 radian many times as they penetrate into or out of the cloud if the overall cosmic ray distribution is to be affected to any significant degree. In this case, we can describe the effects of the waves by a collision frequency ν which is formally large (Kulsrud and Pearce, 1969, Wentzel, 1974). Now in practice an individual wave, of wavenumber k, resonates with a range of particle energies whose Larmor radii are all $O(k^{-1})$. Conversely, a single particle energy can interact with a range of wavelengths. Following Skilling, 1975a, b, c, it is formally convenient to sharpen the resonance condition by specifying that any one wave will interact with only one particle energy, and conversely [Eq. (4) of Skilling, 1975c].

This approximation will have the effect of sharpening any kinks or irregularities in the wave or particle spectra which occur within a factor 2 or so in wavelength or energy, but is not otherwise expected to alter our results.

We describe the cosmic rays, which will always be nearly isotropic, by their momentum distribution function $f(p)$, by their number density $n(E)dE = 4\pi p^2 f(p)dp$ or by their flux density per steradian $I(E) = p^2 f(p)$ ($E =$ kinetic energy). A complication arises because cosmic rays contain appreciable proportions of both protons and α-particles. For a given speed v, a nucleon suffers the same deceleration due to ionization, and nearly the same due to pion production, whether it is a bare proton or part of an α-particle. However, the species differ by a factor 2 in e/m, so that they resonate with waves of correspondingly different wavelength. Instead of greatly complicating our treatment for an effect which by no means dominates the results, we shall use p and E to denote momentum and energy per nucleon and f to describe the total nucleon density. In a given range of v, the number density of α-particles is typically 0.1 times the proton density. Thus we use

$$f = 1.4 f \text{ [protons]} . \tag{1}$$

The interactions with waves are governed by the particle charge, which appears in our formulae in the combination $m\Omega_0 \propto ZeB_0$. We average the charge over nucleons and set

$$m\Omega_0 = 0.85 (m\Omega_0) \text{ [protons]} . \tag{2}$$

We shall suppose that the distribution function is $f_0(p)$ outside the containment region and $f_c(p)$ within the cloud, with corresponding densities $n_0(E)$ and $n_c(E)$. Because of the waves, particles cannot stream freely into and out of the cloud, and the pressure differential given by $f_0 - f_c$ is held in place by the wave distribution. Accordingly the waves experience an intensity growth rate (equation App. 8 of Skilling, 1975c)

$$-\sigma = \frac{4\pi}{3} \frac{p^4 v_A}{U_M \mathscr{I}} (-v\boldsymbol{n}.\nabla f) = \frac{4\pi}{3} \frac{p^4 v_A v (f_0 - f_c)}{U_M \mathscr{I} L} \tag{3}$$

where we have defined the length-scale of the confinement region by $(-\boldsymbol{n}.\nabla f) = (f_0 - f_c)/L$. The waves also experience a damping rate Γ due to friction between the charged particles in the background medium, which partake in the wave motion, and the neutral particles which do not. In the short time $O(\Gamma^{-1}) \sim 10^9\,s$ they reach an equilibrium level

$$\mathscr{I} = \frac{4\pi}{3} \frac{p^4 v_A v (f_0 - f_c)}{\Gamma U_M L} \tag{4}$$

at which the growth balances the damping. Following McIvor, 1975, we estimate the intensity rate Γ as equal to the collision frequency of ions against neutrals, which can be obtained from the formulae of Dalgarno and Dickinson, 1968, as

$$\Gamma = v_{i-n} = 1.12 \cdot 10^{-9} \frac{n(\mathrm{HI})}{1\mathrm{cm}^{-3}} \left(\frac{\mathrm{T}}{1000\,\mathrm{K}} \right)^{-1/2} \mathrm{s}^{-1} . \tag{5}$$

These waves give the cosmic rays a collision frequency $v = \pi\Omega_0 \mathscr{I}/4\gamma$ with a corresponding spatial diffusion coefficient, [see Eq. (2) and (6) of Skilling, 1975c],

$$D_\parallel = v^2/3v = \Gamma U_M L / \pi^2 m \Omega_0 v_A p^3 (f_0 - f_c) . \tag{6}$$

Knowing $D_\parallel$, we can evaluate the net speed at which particles of a given energy move along field lines into the cloud [above Eq. (13) of Skilling, 1975a],

$$v_{\mathrm{str}} \equiv \frac{\langle v\mu f \rangle}{f} = \alpha v_A + \frac{D_\parallel (f_0 - f_c)}{Lf} \tag{7}$$

where $\alpha = -(p^3/f)\partial f/\partial p^3$. The flux of particles entering unit cross-sectional area of the cloud per unit energy interval is then

$$j(E) = \frac{4\pi p^2}{v} f(p) v_{\mathrm{str}} = \frac{4\pi\alpha p^2 f v_A}{v} + \frac{4\pi p^2 D_\parallel (f_0 - f_c)}{Lv} \tag{8}$$

from each of the two sides of the cloud. The term in v_A will dominate the diffusion term involving $D_\parallel$ if the waves grow to such a high level that diffusion becomes negligible: the particles are then forced to convect towards the cloud with the waves at speed v_A modified by the Compton-Getting factor α. The precise choice of f in this convective term will depend on exactly how the parameters of the background medium change in space, but $f = f_0$ can be predicted by assuming continuity at the outer edge of the confinement region, where the damping Γ (and thus the allowed diffusive flux) is much smaller than at the inner edge, which will be within the cloud.

In a steady state, these incoming fluxes must be balanced by the net rate of particle destruction within the cloud. Considering a fixed energy interval gives

$$2j(E) = \int_{\mathrm{cloud}} dx \frac{\partial}{\partial E} \left[n_c(E) \frac{dE}{dt} \right] \tag{9}$$

where $-dE/dt$ is the rate at which a particle loses energy by ionization and pion production. The ionization losses are effectively continuous, and a particle reduces its energy by a factor e in a depth

$$\lambda_i = 3.7 \cdot 10^{27} \frac{v^2}{c^2} (\gamma - 1) \Big/ \left(22.2 - 2 \ln \left(1 - \frac{v^2}{c^2} \right) + 2 \ln \frac{v^2}{c^2} - 2 \frac{v^2}{c^2} \right) \text{atoms cm}^{-2} \tag{10}$$

where $\gamma = (1 - v^2/c^2)^{-1/2}$ (Ginzburg and Syrovatskii, 1964). The interaction depth for pion production from thermal nuclei is $\lambda_0 = 3.4\, 10^{25}$ atoms cm^{-2} (corresponding to 57 g cm^{-2}) but a particle retains a fraction

$K=2/3$ of its energy after such a collision. The beam attenuation caused by pion production is thus governed by

$$\frac{\partial j(E)}{\partial x}=\frac{1}{\lambda_0}[-j(E)+K^{-1}j(E/K)]\simeq\frac{1-K}{K\lambda_0}\frac{\partial}{\partial E}[Ej(E)]$$

for K not too different from unity. This is of the same form as for continuous losses with attenuation length

$$\lambda_\pi=\lambda_0 K/(1-K)=6.8\ 10^{25}\ \text{atoms cm}^{-2} \tag{11}$$

above a threshold around 400 MeV. The total attenuation length is

$$\lambda=(\lambda_i^{-1}+\lambda_\pi^{-1})^{-1}. \tag{12}$$

With these losses,

$$2j(E)=-\Lambda\frac{\partial}{\partial E}\frac{Evn_c(E)}{\lambda} \tag{13}$$

where Λ is the depth of a typical cloud.

Eliminating $j(E)$ from (8) and (13) yields

$$\left.\begin{aligned}&-p\frac{\partial}{\partial p}\frac{Ep^2 f_c}{\lambda}=\frac{2}{\Lambda}(\alpha p^3 f_0 v_A+\phi)\\ &\text{or}\\ &-\frac{\partial}{\partial E}\left(\frac{EI_c(E)}{\lambda(E)}\right)=\frac{2}{\Lambda}\left(\alpha\frac{v_A}{v}I_0(E)+\frac{\phi}{\gamma mv^2}\right)\end{aligned}\right\} \tag{14}$$

in which we have defined the flux $\phi=U_M\Gamma/\pi^2 m\Omega_0 v_A$, as the equation determining $f_c(p)$.

Having treated the case in which waves are excited, we now discuss the alternative possibility that the waves may be absent. In this case, particles stream freely through the cloud, except for their ionization and scattering losses. The cosmic ray density inside the cloud closely matches that outside, but the losses induce a net flux into both sides of the cloud of

$$2j(E)=-\Lambda\frac{\partial}{\partial E}\frac{Evn_0(E)}{\lambda}. \tag{15}$$

We can use equation App. 5 of Skilling 1975c to determine the intensity growth rate of an infinitesimal seed wave [(3) is no longer applicable because v is not formally large]. Integrating by parts gives

$$\begin{aligned}-\sigma&=\frac{\pi^2 m\Omega_0 v_A}{U_M}(v_{\text{str}}-\alpha v_A)p^3 f_0\\ &=\frac{\pi^2 m\Omega_0 v_A}{U_M}\left(-\frac{\Lambda}{2}p\frac{\partial}{\partial p}\frac{Ep^2 f_0}{\lambda}-\alpha p^3 f_0 v_A\right).\end{aligned} \tag{16}$$

To prevent the wave growing until it affects the cosmic rays, we require the growth rate to be less than the damping rate. Thus

$$\begin{aligned}&-p\frac{\partial}{\partial p}\frac{Ep^2 f_0}{\lambda}<\frac{2}{\Lambda}(\alpha p^3 f_0 v_A+\phi)\\ &-\frac{\partial}{\partial E}\left(\frac{EI_0(E)}{\lambda(E)}\right)<\frac{2}{\Lambda}\left(\alpha\frac{v_A}{v}I_0(E)+\frac{\phi}{\gamma mv^2}\right)\end{aligned} \tag{17}$$

is the condition that waves can remain absent. Clearly this is fully consistent with (14) being the solution when waves are present.

At very high energies, (17) is satisfied because cosmic rays are too few to generate waves at all. Considering successively lower energies, condition (17) may, at some energy E_0, fail to be satisfied. At lower energies than E_0, waves start to be generated and the cosmic ray density within the cloud is no longer $I_c\simeq I_0$ but becomes

$$\begin{aligned}I_c(E)=\frac{\lambda(E)}{E}&\left[\frac{E_0 I_0(E_0)}{\lambda(E_0)}+\frac{2v_A}{\Lambda}\int_E^{E_0}\frac{\alpha I_0}{v}dE\right.\\ &\left.+\frac{\phi}{\Lambda}\ln\frac{\gamma_0^2-1}{\gamma^2-1}\right],\end{aligned} \tag{18}$$

the solution of (14). This spectrum falls smoothly away from the unperturbed spectrum $I_0(E)$, with I_c-I_0 and its first derivative both vanishing at E_0. The solution (18) will hold provided it predicts $I_c<I_0$, for otherwise the incoming Alfvén waves could not be excited. If, according to (18), I_c does rise again to equal I_0 as E is decreased to some value E_1, the waves must switch off at that energy. [At such a point, $I_c(E)$ is necessarily a steeper function than $I_0(E)$, so that condition (17) is satisfied, and waves can indeed be absent below E_1.] Conceivably, the waves may reappear at some yet lower energy if (17) again fails to be satisfied.

3. Reduction in γ-ray Yield

The spectrum inside the cloud predicted by (18) is conveniently parametrized by the two dimensionless ratios

$$F_1=\frac{I_0 v_A}{\phi}\bigg/\left(\frac{I_0 v_A}{\phi}\right)_{\text{standard}}\propto\frac{I_0 T^{1/2}B}{n(\text{HI})\varrho_i} \tag{19}$$

$$F_2=\frac{\Lambda}{v_A}\bigg/\left(\frac{\Lambda}{v_A}\right)_{\text{standard}}\propto\frac{\Lambda\varrho_i^{1/2}}{B}, \tag{20}$$

where the standard set of parameters is taken as

$$\begin{aligned}&B=3\ 10^{-6}\ \text{Gauss}\\ &T=10^3\ \text{K}\\ &n(\text{HI})=1\ \text{cm}^{-3}\\ &\varrho_i=4.3\ 10^{-26}\ \text{g cm}^{-3}\\ &\Lambda=4.2\ 10^{22}\ \text{cm}^{-2}\\ &I_0=\text{ local cosmic ray spectrum}\end{aligned} \tag{21}$$

giving

$$\phi=2.44\ \ 10^{-4}\ \text{cm}^{-2}\ \text{s}^{-1}$$
$$v_A=4.1\ \ 10^6\ \text{cm s}^{-1}.$$

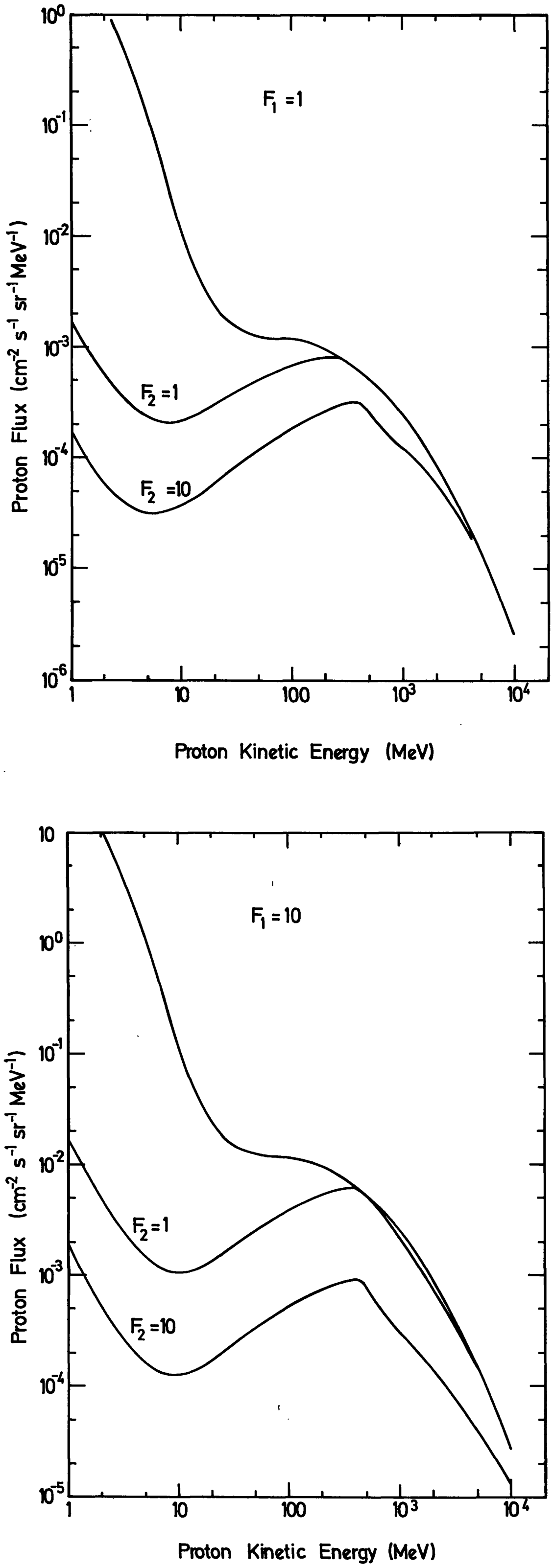

Fig. 1 a and b. Cosmic ray spectra: **a** ambient intensity = local intensity ($F_1 = 1$), **b** ambient intensity = 10 × local intensity ($F_1 = 10$). Upper curve: ambient spectrum outside cloud. Middle curve: spectrum inside "standard" cloud ($F_2 = 1$). Lower curve: spectrum inside denser cloud ($F_2 = 10$)

Table 1. The ratio (without waves/with waves) in which γ-ray emission is reduced by Alfvén waves, for various values of F_1 and F_2

F_2 \ F_1	1	2	5	10	20	50
1	1.000	1.000	1.003	1.05	1.16	1.32
2	1.000	1.02	1.20	1.47	1.67	2.14
5	1.09	1.32	1.75	2.27	2.97	4.19
10	1.35	1.71	2.51	3.42	4.70	7.08
20	1.76	2.37	3.70	5.27	7.58	10.7
50	2.70	3.86	6.42	9.65	12.7	20.4

The value for Λ is taken using the mean CO column density for the 16 clouds listed by Penzias (1974) and assuming a ratio of 3000 H_2 molecules per CO molecule as proposed by Penzias. The local cosmic ray spectrum is taken from Webber (1968) for $E < 100$ MeV and Comstock et al. (1972) for $E > 100$ MeV. Figure 1 shows the spectra inside the cloud for $F_1 = 1$ and 10 and for $F_2 = 1$ and 10. F_1 gives the effect of increasing the ambient cosmic ray density and F_2 the effect of increasing the cloud thickness.

The γ-ray photon flux produced in the cloud can be determined from the formula

$$q_{\gamma H} = 8\pi \int dE\, I(E)\sigma_{\pi^0}(E)\zeta_{\pi^0}(E)\ \mathrm{s}^{-1} \tag{22}$$

where

$$\sigma_{\pi^0}(E)\zeta_{\pi^0}(E) = \begin{cases} 0\,, & E < 400\ \mathrm{MeV} \\ 10^{-25}(E/1000)^{7.46}\ \mathrm{cm}^2\,, & 400 \leqq E < 700\ \mathrm{MeV} \\ 8.4\ 10^{-27}(E/1000)^{0.53}\ \mathrm{cm}^2\,, & E \geqq 700\ \mathrm{MeV} \end{cases}$$

(Stecker, 1973), and compared with the value it would have had in the absence of Alfvén waves. The reduction in γ-ray flux due to the Alfvén waves is shown as a function of F_1 and F_2 in Table 1.

a) Application to Molecular Clouds in the Galaxy

For the "standard cloud" with $\Lambda = 4.2 \cdot 10^{22}\ \mathrm{cm}^{-2}$ in the local cosmic ray flux, particles with $E > 400$ MeV are not affected (see Fig. 1), so that the exclusion mechanism does not affect the γ-ray yield (case $F_1 = F_2 = 1$ in Table 1). Even if I_0, and hence F_1, is increased by a factor 10, as may be the case at $R = 5$ kpc (Wentzel, 1975), the effect of exclusion is insignificant. On the other hand, if Λ (and hence F_2) is increased as well, as will be the case for the most dense clouds, the reduction in flux becomes appreciable. For example, the cloud associated with Orion A has a CO column density of $2.1\ 10^{19}\ \mathrm{cm}^{-2}$ corresponding to $\Lambda = 1.2\ 10^{23}\ \mathrm{cm}^{-2}$, again assuming 3000 H_2 molecules per CO, so that $F_2 \simeq 3$. This would give a reduction in γ-ray yield for $F_1 = 10$ by a factor 1.7. A proper assessment of the importance of exclusion in the $R = 5$ kpc region therefore requires a knowledge of the distribution of column densities among the clouds in this region. However, the mechanism does not have much effect on the γ-ray yield unless the mass is mostly in clouds with very high column densities.

b) Application to the Galactic Centre Region

The Galactic centre region ($R<300$ pc) is known to contain many large massive molecular clouds (Solomon et al., 1972), which may all be part of an expanding (or contracting) ring of radius 300 pc around the Galactic centre (Scoville, 1972). The mass of the ring is estimated as $10^8\ M_\odot$ which would give $\Lambda=7\ 10^{22}\ \mathrm{cm}^{-2}$ for a z-extent of 100 pc. Alternatively, using the figure of $A_V=200$ mag of optical extinction derived from a comparison with 100 μ fluxes (Solomon et al., 1972) and assuming $N_H/A_V=2\cdot 10^{21}\ \mathrm{cm}^{-2}\ \mathrm{mag}^{-1}$, we get $\Lambda=4\ 10^{23}\ \mathrm{cm}^{-2}$. Therefore F_2 probably lies in the range 2 to 10 for the molecular features in the Galactic centre, whether the individual clouds are treated independently, or whether the ring is treated as a whole.

Using the COS–B γ-ray longitude distribution (Bennett et al., 1976) in the Galactic centre direction, we can put a limit of $I_\gamma(>100\ \mathrm{MeV}) < 7\ 10^{-7}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ from the Galactic centre. If the cosmic ray flux at the Galactic centre were the same as locally, the $10^8\ M_\odot$ of molecular hydrogen would produce $I_\gamma(>100\ \mathrm{MeV})=1.5\ 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. While this is not a significant discrepancy in itself, the presence of the radio source Sgr A and the generally high synchrotron emission near the Galactic centre indicate the presence of high cosmic ray fluxes. This exacerbates the discrepancy, and suggests that the exclusion of cosmic rays from the clouds is an important effect.

4. Exclusion of Ionizing Particles

The maintenance of the ionization level in the intercloud medium requires an ionization rate $\sim 10^{-15}\ \mathrm{s}^{-1}$. However, studies of the ionization rate inside clouds using observations of neutral hydrogen (Solomon and Werner, 1971), molecular HD and the D/H ratio (O'Donnell and Watson, 1974) and radio recombination lines (Brown, 1973) indicate that the ionizing agent does not penetrate clouds. Possible ionizing agents are 1–10 MeV cosmic rays, soft X-rays and U-V radiation. If cosmic rays are responsible, some mechanism must be present to prevent free penetration of the cloud.

Since the clouds are optically thick to low energy cosmic rays, there is some depletion by energy losses; however, Brown (1973) finds that even when this effect is included the ionizing flux entering the cloud must be reduced by at least a further factor 5. Such a depletion, as will be shown below, is an inevitable consequence of the production of Alfvén waves.

In the absence of waves, since the clouds are opaque to 1–10 MeV particles, the ionizing flux would be $j(E)=\frac{1}{4}n_0(E)v$ per unit area of the surface. However, our analysis shows that Alfvén waves will be present around the cloud. Furthermore, the high density of cosmic rays at a few MeV excites the waves to such a high level that the diffusion term in (8) becomes negligible. Particles are convected into the cloud at the Alfvén speed, the appropriate simplification of (8) being

$$j(E)=4\pi\alpha p^2 f_0 v_A/v=\alpha n_0(E)v_A \tag{23}$$

Thus the waves *reduce the incoming particle flux by a factor $v/4\alpha v_A$*. For a subrelativistic spectrum $j(E)\propto E^{-3}$, corresponding to that of Webber (1968), we have $\alpha=10/3$, so that 1 MeV protons are reduced by a factor 25 and 10 MeV protons are reduced by a factor 80, if we take $v_A=4\ 10^6\ \mathrm{cm\ s}^{-1}$ around the cloud. This factor is almost independent of the specific parameters associated with the dense cloud, and is fully consistent with the required depletion by more than a factor 5.

Conclusions

Alfvén waves generated outside dense clouds by the net flux of cosmic rays into them are most effective at excluding cosmic rays below a few hundred MeV in energy. The MeV cosmic rays which are in principle most effective in ionizing the material in clouds are excluded very efficiently. The intensity of particles of about 1 MeV is reduced by a factor of about 25, in agreement with the requirement of Brown (1973) that the intensity be reduced by at least a factor 5.

Cosmic rays of a few GeV, which dominate the γ-ray production via π^0-decay, can be partly excluded from very dense clouds, especially if the ambient cosmic ray intensity exceeds the local value. This might be important for the interpretation of γ-ray observations of the emission from dense molecular clouds, but the effect is unlikely to be large throughout most of the Galaxy. The effect may well be significant for the Galactic centre region.

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