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A POSSIBLE MECHANISM FOR ACCELERATION OF IONS IN SOME ASTROPHYSICAL PHENOMENA

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A POSSIBLE MECHANISM FOR ACCELERATION OF IONS IN SOME ASTROPHYSICAL PHENOMENA

by

M. FRIEDMAN*

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ABSTRACT

In this paper we suggest a model for the acceleration of ions based on Petschek's theory of magnetic field annihilation. We have shown that ions can gain high energies and that energy distributions similar to those observed can be obtained. It is shown that this model prevents electrons from gaining high energy, consistent with cosmic ray observations. We have hinted that if this model is correct we can obtain from the observed ions energy distribution a relation between the (average) plasma density and the (average) magnetic field in regions where the ions are accelerated.

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CONTENTS

1. INTRODUCTION

The acceleration of charged particles is a common feature in the Universe. Tens of years of observation have provided us with a knowledge of the accelerated particles and their energy distribution. Many theories have been suggested to explain the mechanism of acceleration. In most of them the medium in which the particles are accelerated and from which they draw their energy is magnetoactive plasma. (The reader is referred to reviews by Parker[1] and by Gintzburg and Syrovatskii[2]). Gintzburg and Syrovatskii[3] have suggested that an acceleration mechanism should be Universal, namely, that any particular astrophysical phenomenon in which particles are accelerated and on which it is easy to make observations would serve as an example from which general laws may be drawn. One such example, it appears, would be the phenomenon of solar flares.

We would like to suggest here a very simple version of Fermi-type mechanism[4-5] for the acceleration of ions to very high energies such as are observed following intense solar activities. The model considered here is based on a modification of Petschek's wave theory of magnetic field annihilation. Details of the model are published elsewhere[6-7]. Inherent in Petschek's model are stationary boundary regions (Fig.1) separating much larger regions of antiparallel magnetic field B, which, with their trapped plasma, flow into the boundary with velocity $\vec{U}$. It will be shown later that in the rest frame an electric field $\vec{E} = -(1/c)(\vec{U} \times \vec{B})$ exists in the plasma from which a particular ensemble of ions can gain high energies.

We shall report here some preliminary computations (Sections 3 and 5) which show that, with parameters based on the revised model of annihilation of magnetic fields, energy distributions of the accelerated ions can be obtained. The details of each energy distribution depend on quantities characteristic of the plasma e.g. plasma density, magnetic field etc. Towards the end of this article (Section 7) we discuss the consequences of using this model for cosmic-ray acceleration.

Speiser[8] has suggested a somewhat similar model to account for the observed high energy particles coming from the tail of the magnetosphere. In his model charged particles entering the neutral sheet region (between antiparallel magnetic fields) can gain energy under the influence of an electric field. The energies of the particles depend on the spatial variations of the magnetic and electric fields as well as on the characteristic dimensions of the neutral sheet. Although his model explains satisfactorily the observed phenomenon it fails to tie together the plasma parameters into a self-consistent picture which would enable the model to be extended to other phenomena in which acceleration occurs.

2. THE FIELD GEOMETRY OF THE MODEL

Petschek's basic idea is that a situation can exist in which oppositely magnetized plasma flows into two stationary slow shock fronts. Within the fronts the inflowing magnetic energy is largely converted into kinetic energy. The outflowing plasma is both heated and ejected from the shock region from which it escapes. Four regions exist in Petschek's model (Fig.1).

I Initial flow regions

II Final flow regions

III Shock front regions

IV Diffusion region

The plasma parameters in these four regions have been discussed elsewhere[6-7]. Here we shall give only the quantities relevant to this discussion.

(1) The widths of regions IV and III are $2\delta^*$ and δ^* respectively where

$$\delta^* = \frac{c^2}{4\pi\sigma V_A M_o} \qquad \ldots (1)$$

Under the conditions of high current density in regions III and IV the plasma conductivity, σ, is[9]

$$\sigma = \frac{1}{2}\left(\frac{M}{m}\right)^{1/3}\left(\frac{4\pi n e^2}{m}\right)^{1/2} \qquad \ldots (2)$$

where m, M are the masses of electrons and ions respectively and n is the plasma number density, M_o is the Mach number in the flow region (region I)

$$M_o = \frac{U_I}{V_A} \qquad \ldots (3)$$

where V_A is the Alfvén velocity and U_I the flow velocity of plasma in region I.

According to Petschek[6] the above situation exists only for

$$M_o \lesssim 0.1 \qquad \ldots (4)$$

(2) The Y-dimension of region IV $2Y^*$ is

$$2Y^* = \frac{c^2}{4\pi\sigma V_A M_o^2} \qquad \ldots (5)$$

(3) The gometrical equations of the shock fronts (region III) can be written

$$\pm M_o Y + X = 0 \quad \ldots (6)$$

for

$$|Y| > Y^*$$

(4) An electric field $\vec{E} = (0,0,E_z)$ which is constant in the four regions is inherent in the model, and is given by

$$\vec{E} = -\frac{\vec{U}_I \times \vec{B}_I}{c} \quad \ldots (7)$$

where $\vec{B}_I$ is the magnetic field in Region I.

(5) From the Rankine-Hugoniot relations[10] we can obtain the magnetic field in these regions. In regions where discontinuities in magnetic fields occur (regions III and IV) we shall assume linear variations of the magnetic field across these discontinuities.

The relations used are:

Region I $\vec{B}_I = (-2(Y/|Y|)M_o B_{yo} f(Y),\ -(X/|X|)\ B_{yo}, 0)$

Region III $\vec{B}_{III} = (-Y/|Y|M_o B_{yo},\ 0,0)$

Region II Linear interpolation between $\vec{B}_I$ and $\vec{B}_{III}$

Region IV $B_{IV} = (-(Y/|Y|)M_o B_{yo}(1+|X|/\delta^*)f(Y), -(X/\delta^*)B_{yo}, 0)$

... (8)

where B_{yo} is the magnetic field remote from the shock regions (at infinity) and $f(Y)$ is some monotonic function fulfilling the conditions

$$\left.\begin{array}{l} f(0) = 0 \\ f(Y>Y^*) = \end{array}\right\} \quad \ldots (9)$$

3. MOTION OF AN ION IN PETSCHEK'S TYPE CONFIGURATION OF MAGNETIC AND ELECTRIC FIELDS

Given the magnetic field configuration in the different regions (Eq.8) the motion of ions can be analysed. We have found that it is very complicated to calculate analytically the trajectories of ions. However, one can get some qualitative information about the motion of the ions by looking at somewhat similar configurations to which analytical solution exists, namely:

1. The hyperbolic configuration[11],
2. Perfect antiparallel magnetic field configuration[12].

In both the above configurations the ions can have two distinct classes of orbit. In one class the ion does not cross the neutral plane (B=0). The ion gyrates and drifts in the magnetic field. The second class of orbit is one in which the ion crosses the neutral plane and moves in a 'serpentine' path.

If we now superimpose on these configurations an electric field perpendicular to $\vec{B}$, only the ions having the second kind of orbit will accelerate and gain energy as they move along the Z direction.

Reverting to the configuration defined by Eq.(8), and assume for the moment that only the Lorentz electric field exists, we can write the equation of motion of an ion in the general form

$$\frac{d}{dt}\left(\frac{M\vec{V}}{(1-(V/c)^2)}\right) = e\vec{E} + e\,\frac{\vec{V}\times\vec{B}}{c} \qquad \ldots (10)$$

where

$$\vec{E} = -\frac{\vec{U}_I \times \vec{B}_I}{c} \qquad \ldots (11)$$

and $\vec{B}_I$ is defined in Eq.(8).

Ions with velocity $\vec{V} = (V_z, V_y, V_z)$ will cross the neutral plane $X = 0$ and gain energy provided the following approximate relation holds:

$$\rho_{Li} = \frac{(V_x^2 + V_z^2)^{1/2}}{eB_a/Mc} \gtrsim \begin{cases} M_o |Y|, & |Y| > Y^* \\ \delta^* , & |Y| < Y^* \end{cases} \qquad \ldots (12)$$

where ρ_{Li} is the ion Larmor radius in an average magnetic field B_a. If the last relation does not hold the ions will gyrate around a magnetic line of force without changing their average energy.

Numerical integrations of Eq.(10) for ions were performed for several conditions. The ions were taken to move initially in the positive X direction with velocity equal to the plasma velocity U in region I and with initial positions $(X = -\delta^*, Y = Y_o < Y^*, Z = 0)$. Three sets of plasma conditions were assumed:

$$\left.\begin{array}{lll} \text{(i)} & B_{yo} = 500\text{ G},\ n = 2 \times 10^{11}\text{ cm}^{-3},\ M_o = 0.1,\ f(Y) \propto Y \\ \text{(ii)} & B_{yo} = 500\text{ G},\ n = 5 \times 10^{10}\text{ cm}^{-3},\ M_o = 0.05,\ f(Y) \propto Y \\ \text{(iii)} & B_{yo} = 500\text{ G},\ n = 2 \times 10^{11}\text{ cm}^{-3},\ M_o = 0.1,\ f(Y) \propto Y^2 \end{array}\right\} \qquad \ldots (13)$$

The maximum energies achieved are shown in Fig.2 for the cases (i) and (ii) and in Fig.3 for case (iii), for different values of Y_o.

From the detailed computations one can draw the following conclusions:

(1) Ions can gain high energies.

(2) The time during which an ion satisfies Eq.(12), and is therefore accelerated, is a sensitive function of the value of M_o and of the form of $f(Y)$, which governs the spatial dependence of B.

(3) The dependence of the final ion energy, ε, on its initial position Y_o is given by

1. $Y_o = A \exp-(\varepsilon/\varepsilon_o)$ for cases i,ii, $f(Y) \propto Y$ ... (14)

2. $Y_o = B\ \varepsilon^{-q}$ for cases iii, $f(Y) \propto Y^2$ ... (15)

where A, B, ε_o and q are functions of the magnetic field B_{yo}, the plasma density n, the Mach number M_o and the spatial variations of the magnetic field components.

4. PLASMA EFFECTS ON THE ACCELERATED IONS

In the previous Section we have demonstrated that ions can accelerate to high energies in the particular configuration of magnetic and electric fields existing in Petschek's model.

However there are two obvious objections:

(1) If all ions in a particular region accelerate the momentum of the plasma cannot be preserved without introducing an additional electric field.

(2) We have made the unjustifiable assumption that the medium, through which the particles are accelerated, does not influence the ion motions.

We must therefore examine the condition of the plasma in regions III and IV. It has been suggested[7] that in these regions the plasma is subject to current induced micro-instability, one of the main effects of which is an enormous increase in the amplitude of electric field fluctuations in the plasma with wavelengths of the order of a Debye distance $\lambda_D = (KT/4\pi ne^2)^{1/2}$, where KT is the mean thermal energy in the plasma[13,14].

By adopting the concept of 'waves' for these fluctuations one can describe these electric fields by their Fourier components

$$\vec{E}_f = \int \vec{E}_{\vec{k},\omega} \exp i\{\omega(\vec{k})t + \vec{k}\cdot\vec{r}\}\, d\vec{k}\, d\omega \qquad \ldots (16)$$

where $\omega, \vec{k}$ are the frequency and wave number and $\omega(\vec{k})$ describes the relation between them. The chief effect of such waves is to increase the electrical resistivity of the plasma[7,15] by scattering and randomizing the directed motion of the charged particles and hence to raise the temperature of the plasma.

We consider here only longitudinal waves i.e.

$$\vec{E}_{\vec{k},\omega} \,||\, \vec{k} \qquad \ldots (17)$$

whose frequency will lie to a first approximation within two regions

(1) near the electron plasma frequency

$$\omega_{pe} = \left(\frac{4\pi ne^2}{m}\right)^{\frac{1}{2}} \qquad \ldots (18)$$

(2) between zero and the ion plasma frequency

$$\omega_{pi} = \left(\frac{m}{M}\right)^{\frac{1}{2}} \omega_{pe} \qquad \ldots (19)$$

The change in the velocity of an ion, $\vec{V}$, due to its interaction with these fluctuations in a time of order one oscillation period will be

$$\delta\vec{V} = \frac{e}{M} \int \frac{\vec{E}_{\vec{k},\omega} \exp i\{\omega(\vec{k})t + \vec{k}\cdot\vec{r}\}}{i\{\omega(\vec{k}) - \vec{k}\cdot\vec{V}\}}\, d\vec{k}\, d\omega \qquad \ldots (20)$$

As we are interested in ions with high velocities we can assume that either:

(1) $$\omega(\vec{k}) - \vec{k}\cdot\vec{V} = 0 \qquad \ldots (21)$$

or

$$\omega(\vec{k}) - \vec{k}\cdot\vec{V} \ll 0 \qquad \ldots (22)$$

Simple theoretical arguments[16] show that for the type of waves considered the resonance condition (21) is not fulfilled for ions whose velocity lies in the range

$$\frac{m}{M} V_T < \frac{\vec{k}\cdot\vec{V}}{|\vec{k}|} < V_T$$

where V_T is the mean random electron velocity.

When $V > V_T$, so that we can have $\omega(\vec{k})-\vec{k}\cdot\vec{V} = 0$, the fluctuating electric field may scatter ions through a large angle in a single interaction. However, we shall show that the effect of such scattering on the ion motion is very small and can be ignored:

(1) From Eq.(19) we see that

$$\delta\vec{V} \,||\, \vec{k} \qquad \ldots (23)$$

so that after scattering the quantity $\omega-\vec{k}\cdot\vec{V}$ will change from zero to approximately $\omega-\vec{k}\cdot\vec{V} + \vec{k}\cdot\delta\vec{V}$ which in general is different from 0.

(2) The fluctuations are not coherent and their interaction time with an ion is of the order

$$\tau \sim \omega_{pe}^{-1} \qquad \ldots (24)$$

Even if we take the situation of very strong turbulence in which the electrical energy density in the fluctuations is of the same order as the thermal energy density of the particles nKT

$$E_f^2/8\pi \sim nKT$$

the change in ion velocity will be

$$\delta V \sim \frac{eE_f}{M} \omega_{pe}^{-1} = \frac{m}{M} V_T \qquad \dots (25)$$

which is 10^3 times smaller than V.

From the above arguments we can conclude that once an ion reaches a velocity

$$V > \frac{m}{M} V_T \qquad \dots (26)$$

the interaction of the type $\omega(\vec{k}) - \vec{k}\cdot\vec{V} = 0$ will not influence its motion.

When $\omega(\vec{k}) - \vec{k}\cdot\vec{V} \ll 0$ the scattering is not resonant and one has to take into account the effect of many small angle scatterings on the ion motion.

Using the random walk approximations one can calculate the mean free path, λ, for an ion to lose all its forward momentum by these fluctuations

$$\lambda = \lambda_o \frac{V^2}{\langle \delta V^2 \rangle} \qquad \dots (27)$$

where λ_o is the mean free path for a single scattering and $\langle\,\rangle$ denotes an average over many deflections. It can easily be shown that

$$\langle \delta V^2 \rangle = \left(\frac{e}{M}\right)^2 \frac{\langle E_f^2 \rangle}{(\vec{k}\cdot\vec{V})^2} \qquad \dots (28)$$

so that

$$\lambda = \lambda_o \left(\frac{M}{e}\right)^2 \frac{(\vec{k}\cdot\vec{V})^2 V^2}{\langle E_f^2 \rangle} \qquad \dots (29)$$

or

$$\lambda < \frac{4\lambda_o \varepsilon^2}{\langle (e E_f)^2 \rangle / k^2} \qquad \dots (30)$$

where ε is the kinetic energy of the ion

$$\varepsilon = \frac{1}{2} MV^2 \qquad \text{... (31)}$$

Let us define two parameters α, β such that

$$\lambda_o = \beta \lambda_D \qquad \beta \geqslant 1 \qquad \text{... (32)}$$

$$\langle (eE_f)^2 \rangle / k^2 = (KT/\alpha)^2 \quad \alpha \geqslant 1 \qquad \text{... (33)}$$

$$\lambda < \lambda_D \left(\frac{\varepsilon}{KT} \right)^2 \alpha^2 \beta \qquad \text{... (34)}$$

The parameters α and β depend on the intensity of the fluctuating electric fields in the plasma and will be equal to 1 in the condition of a strong electrostatic plasma turbulence.

We have found before that during its acceleration an ion passes through regions III and IV many times. The condition that this ion will not be affected by these fluctuations can be expressed as

$$\delta^* \ll \lambda \qquad \text{... (35)}$$

From Eq.(34) and (35) we obtain a criterion for the minimum ion energy for which we can neglect the effect of the fluctuating fields on the ion motion

$$\varepsilon > \frac{KT}{2} \left(\frac{\delta^*}{\lambda_D} \right)^{\frac{1}{2}} \frac{1}{\alpha \beta^{\frac{1}{2}}} \qquad \text{... (36)}$$

Since in general $\alpha, \beta > 1$ we relax the criterion to

$$\varepsilon \gtrsim \frac{KT}{2} \left(\frac{\delta^*}{\lambda_D} \right)^{\frac{1}{2}} \qquad \text{... (37)}$$

For the case of a solar flare where $\delta^* \approx 20$ cm and $\lambda = 2 \times 10^{-1}$ cm we require

$$\varepsilon \gtrsim 5 \ KT \qquad \text{... (38)}$$

Since ions do not lose energy in small angle scattering and since they can be accelerated whatever their initial directions (as shown in the next Section) it can be argued that the mean effect of these fluctuations on the ensemble of accelerated ions will be negligible.

In the light of the above arguments we assume that only those ions with energy

$$\varepsilon \geqslant \Upsilon KT \qquad \dots (39)$$

where

$$1 < \Upsilon < 10$$

can be freely accelerated.

Thus it is clear that only those relatively few ions which have initial energies well above the average can be freely accelerated, and so remove momentum from the system. In fact the momentum balance is maintained by the bulk of the plasma.

5. FINAL ENERGY DISTRIBUTIONS

In Section 3 we have demonstrated that ions can accelerate to high energies in the particular configuration of magnetic and electric fields existing in Petschek's model, using the simplifying assumption that all ions have the same initial (directed) velocity. To examine a more realistic situation we have integrated Eq.(10) for ions whose initial positions within the diffusion region and whose initial directions have both been randomly chosen. The initial energy of the ions has been taken as 4KT in accordance with Eq.(39).

Since we have random initial conditions for the ions, their final energies provide the required distribution.

The calculations have been performed for the following flare conditions:

$$\left.\begin{array}{ll}\text{(i)} & B_y = 500\ \text{G},\ n = 2 \times 10^{11}\ \text{cm}^{-3},\ M_o = 0.1,\ f(y) \propto y \\ \text{(ii)} & B_y = 500\ \text{G},\ n = 2 \times 10^{11}\ \text{cm}^{-3},\ M_o = 0.1,\ f(y) \propto y^2\end{array}\right\} \quad \ldots (40)$$

The initial energy of the ions has been taken as 40 keV (= 4 KT where KT is the thermal energy of electrons in solar flares found from the shock equations[10]).

Because of the very long computing time needed for such calculations only 100-150 ion orbits were computed for each of the above conditions.

Although the statistics seem very poor we can draw the following conclusions:

(1) About 70% of the ions achieve energy > 0.1 MeV

(2) 15% of all the ions have at some time a velocity component $V_y = 0$ for which we can use the calculations discussed in Section 3.

(3) The energy distributions (Figs.4 and 5) can be expressed as

$$\left.\begin{array}{ll} N(>\varepsilon) = A' \exp - (\varepsilon/\varepsilon_o') & \text{for case (i)} \\ N(>\varepsilon) = B'\ \varepsilon^{-q'} & \text{for case (ii)}\end{array}\right\} \quad \ldots (41)$$

The constants ε_o' and q' are found to be the same as ε_o and q from Eqs.(14,15) within the statistical error.

Because of the rather small number of ions used in the computation the maximum ion energy obtained by this method is not spectacular, since there is a low statistical probability of choosing an ion which would reach a high energy (Eq.41).

If we make the assumption that the result (3) is not accidental, i.e. that $\varepsilon_o' = \varepsilon_o$ and $q' = q$, the results of Section 3 can be used to get the energy distribution of the 'average' ions since $Y_o \propto N(> \varepsilon)$.

All ions with initial coordinate Y_1, and initial energy 4KT can be accelerated provided the relation (Eq.12) is fulfilled

$$Y_1 < Y_o = \frac{1}{M_o} \frac{(8KT/M)^{1/2}}{eB_a/Mc} \qquad \ldots (42)$$

where B_a is an average magnetic field.

The total number of particles N_t that satisfy the last condition is

$$N_t \sim 4L^2 Y_o n \qquad \ldots (43)$$

where L is the characteristic dimension.

If we assume that the accelerated ions originate from the tail of a Maxwellian distribution with mean energy KT, then only 3% of N_t will be influenced appreciably by the steady electric field, of which only 70% will gain energy > 0.1 MeV, then the total number of accelerated ions $N(>\varepsilon)$ will be

$$N(> 0.1 \text{ MeV}) \sim \frac{2 \times 10^{-1}}{M_o} L^2 n \frac{(KT/M)^{1/2}}{eB_a/Mc} . \qquad \ldots (44)$$

For example, if we take as a typical solar flare condition $B_a \sim 100$ G, $n \sim 2 \times 10^{11}$ cm^{-3}, $L \sim 10^{10}$ cm, $KT \sim 10^4$ eV we find $N(> 0.1 \text{ MeV}) \sim 10^{35} - 10^{36}$ particles with energy > 0.1 MeV. If we use the calculated distribution Eq.(41) with $\beta' \sim 2$ (Fig.5), we find that the number of ions with energy greater than 10 MeV will be

$$N(> 10 \text{ MeV}) \sim 10^{31} - 10^{32} \text{ particles} \qquad \ldots (45)$$

Krimigis[17] has calculated that about 10^{31} ions with energy greater than 23 MeV are produced in a solar flare event.

The parameter $f(Y)$ controls the shape of the energy distribution. It is improbable that $f(Y)$ will depend on Y in the way we have assumed; neither is it probable that $f(Y)$ will be constant in time. Computations of the kind discussed in Section 3 were therefore performed taking

$$f(Y) \propto Y^P \quad , \quad 8 > P > 2 \qquad \ldots (46)$$

The results were qualitatively similar to those for $P = 2$. If we assume that the temporal change of $f(Y)$ is slow compared with the time of acceleration (which in the case of solar flare $\sim 10^{-4}$ sec for an ion to reach energy $\sim$ 10 MeV) the results obtained will remain the same.

6. ACCELERATION OF ELECTRONS

In the previous Section we have considered only ion acceleration. This is because observations[13] show that there are far fewer high energy electrons than ions.

The mechanism that we have discussed may give an explanation of this phenomenon. We have shown that to be accelerated an ion should fulfill two conditions:

(1) It must be injected with sufficient high energy that it will not be influenced by the fluctuating electric fields in the plasma.

(2) During the acceleration the conditon Eq. 12

$$\rho_{Li} = \frac{V_i}{eB_a/Mc} \gtrsim \begin{cases} \sim \delta^* & |Y| < Y^* \\ \sim M_o\,|Y| & |Y| > Y^* \end{cases} \qquad \ldots (47)$$

where V_i is the ion velocity, should be fulfilled.

Similar conditions should be applied also to the electrons.

(1) Even if the electrons are injected with energy such that

$$\varepsilon \gg KT$$

there will be a strong interaction with the fluctuating electric fields which will randomise their velocities, in comparison to the weaker influence of the same pehnomenon for ions. Only very few electrons in the remote part of the tail of the energy distribution will not be influenced strongly by the fluctuations.

(2) During the steady acceleration the condition

$$\rho_{Le} = \frac{V_e}{eB_a/mc} \gtrsim \begin{cases} \delta^* & |Y| \leqslant Y^* \\ Mo\,|Y| & |Y| \geqslant Y^* \end{cases} \qquad \ldots (48)$$

where ρ_{Le} is the electron Larmor radius, should be fulfilled.

It can easily be seen that to suffer the same acceleration as an ion of velocity V_i, the electron must have velocity

$$V_e = \frac{M}{m} V_i$$

For these reasons we should expect very few electrons in the high energy particle spectrum resulting from this mechanism.

7. APPLICATION OF THE ACCELERATION MODEL TO COSMIC RAYS

Observations suggest that the occurrence of anti-parallel magnetic fields is not unique to the flare. For example, it has been suggested[19] that the magnetic field in the Galaxy has opposite direction to the magnetic field in the Halo.

If we speculate that a similar mechanism occurs in the boundary region between the Galaxy and the Halo we can calculate the maximum energy ions can reach.

Assuming:

$$B_{yo} \sim 3 \cdot 10^{-6} \ \mathrm{G}$$
$$n \sim 10^{-2} \ \mathrm{cm}^{-3} \qquad \ldots (49)$$

in the boundary region, the maximum electric field is

$$E \approx \frac{M_o \, B_{yo}^2}{(4\pi n M c^2)^{1/2}} \sim 3 \cdot 10^{-8} \ \mathrm{V \ cm}^{-1} \ . \qquad \ldots (50)$$

Taking the characteristic dimension L as

$$L \sim 5 \times 10^{22} \ \mathrm{cm}$$

The maximum energy an ion can achieve will be

$$\varepsilon_{max} = eEL \sim 10^{15} \ \mathrm{eV} \qquad \ldots (51)$$

The characteristic time for dissipation of the magnetic field by Petschek's mechanism is

$$\tau \sim \frac{L}{M_o V_A} = \frac{L}{M_o} \left(\frac{4\pi n M}{B_{yo}^2} \right)^{1/2} \sim 10^{10} \ \mathrm{years} \qquad \ldots (52)$$

which is the order of magnitude of the life of the Galaxy.

It can be shown, by using proper scaling laws for Eq.10, that the results obtained above for the energy distribution will be the same in this case as for the flare.

The above argument implies that there is a limit to the energy an ion can gain in the Galaxy. However, let us speculate further and say that this sort of acceleration may occur outside the Galaxy. For example, taking the approximate value for magnetic field and plasma density with the characteristic dimension in the Meta-Galaxy[2] energies $> 10^{19}$ eV can be reached.

The observed energy distribution of the ions in cosmic rays is[2]

$$N(>\varepsilon) = C\ \varepsilon^{-\ell} \qquad \ldots (53)$$

with $\ell \sim 1.7$. It is found that for certain ranges of energy, ℓ deviates from this value. We can attribute these changes to different plasma parameters in places where acceleration occurs.

8. RELATION OF THIS ACCELERATION MECHANISM TO THE FERMI TYPE

The mechanism of acceleration discussed above can be classified as Fermi type acceleration[4-5], since an ion gains energy by 'collisions' with the two moving magnetized plasmas.

Gintzburg[2] has questioned Fermi mechanism by calculating the increase in plasma density between these moving regions. He finds that in order for an ion to gain energy of 10 GeV the plasma must be compressed 10^5 times, which seems unreasonable.

Using Petschek's model it can be seen that situations of this sort are avoided by allowing the plasma to escape (Fig.1).

The main criticism of the Fermi mechanism is that in order to make it efficient ions should start with very high energies to overcome various energy loss mechanisms (e.g. a proton should have energy ~ 200 MeV and a Fe nucleus $\gtrsim 300$ GeV).

Fermi obtains an energy distribution function for ions having an energy between ε and $\varepsilon + d\varepsilon$

$$\pi(\varepsilon)d\varepsilon = \chi(Mc^2)^{\chi} \quad \varepsilon^{-(1+\chi)} \; d\varepsilon \qquad \ldots (54)$$

where $\chi = \frac{\tau}{(\Lambda/C)\beta^2}$, Λ is the mean free path for nuclear interaction, βc is the velocity of the magnetized plasmas and τ is the time of flight of an ion between the two magnetized plasmas. Fermi has suggested $\Lambda = 10^{25}$ cm for relativistic protons.

Comparing the last equation with the observed distribution function one finds that

$$1 + \tau/(\Lambda/c)\beta^2 \approx 2.7 \qquad \ldots (55)$$

which suggests $\tau \sim 1.7$ years.

The model that we have introduced suggests that τ will be of the order $\delta^*/c \sim 0.1$ sec (for $B_y \sim 3.10^{-6}$ G, $n_e \sim 10^{-2}$ electrons cc^{-1}). This is very small compared to the nuclear interaction time $\Lambda/c \sim 10^{14}$ sec, so that nuclear interactions are not important in our model. The distribution functions that we have obtained have the right form and depend only on the plasma conditions in regions where the acceleration occurs. The ejection mechanism from the region where ions are accelerated is responsible for the shape of the distribution function. In the absence of any serious energy loss (compared with the rate of acceleration) this model requires no such high injection energy. Instead, the requirement for initial energy ε_o is simply

$$\varepsilon_o > AKT \qquad \ldots (56)$$

where A is the atomic weight and KT the thermal energy of electrons in the plasma.

As τ is very small compared to Λ/c it is possible to understand the existence of medium and heavy nuclei in the cosmic rays, a phenomenon which could not be explained by the original Fermi theory.

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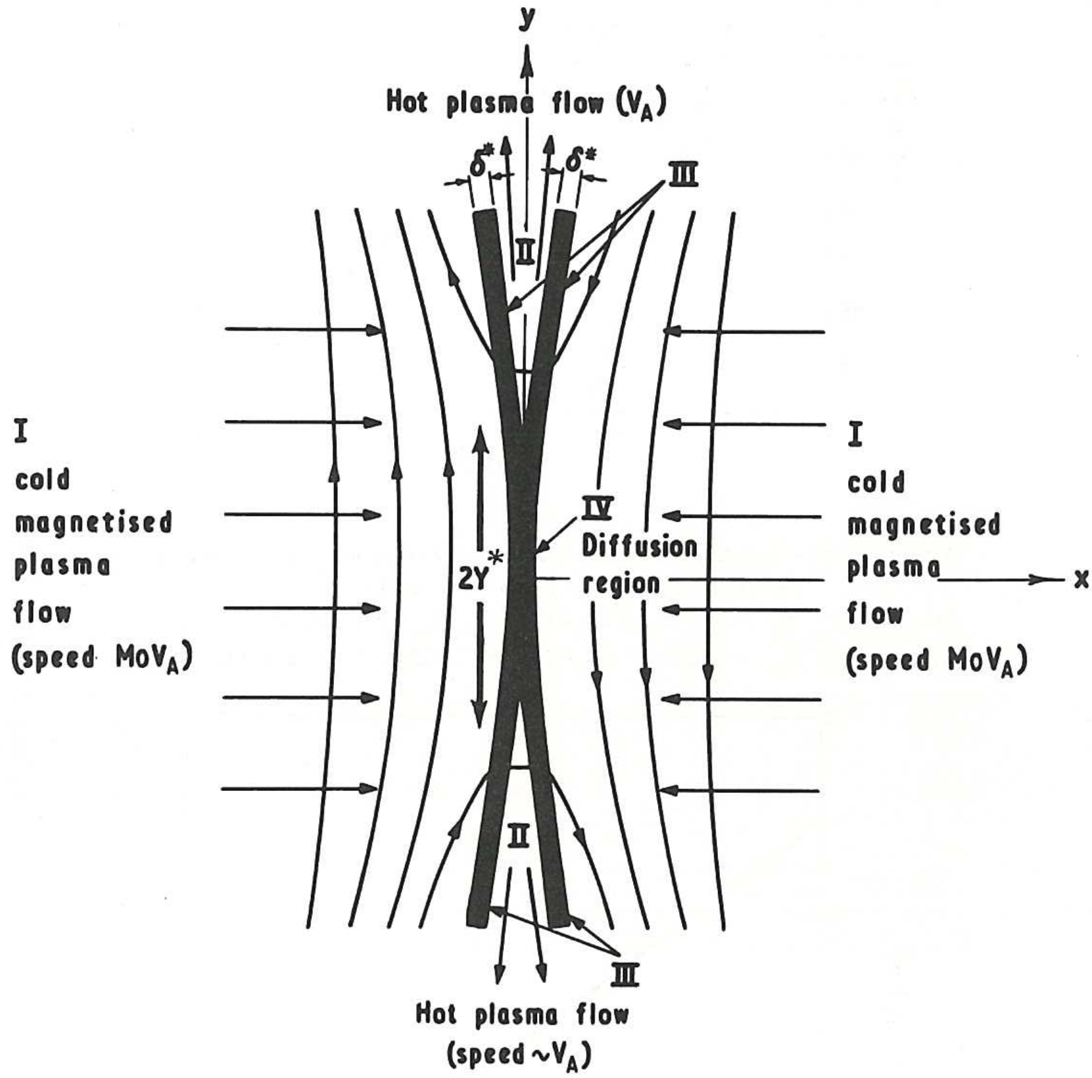

Fig. 1 (CLM-P 192)

Magnetic field and plasma flow situation in Petschek's wave model

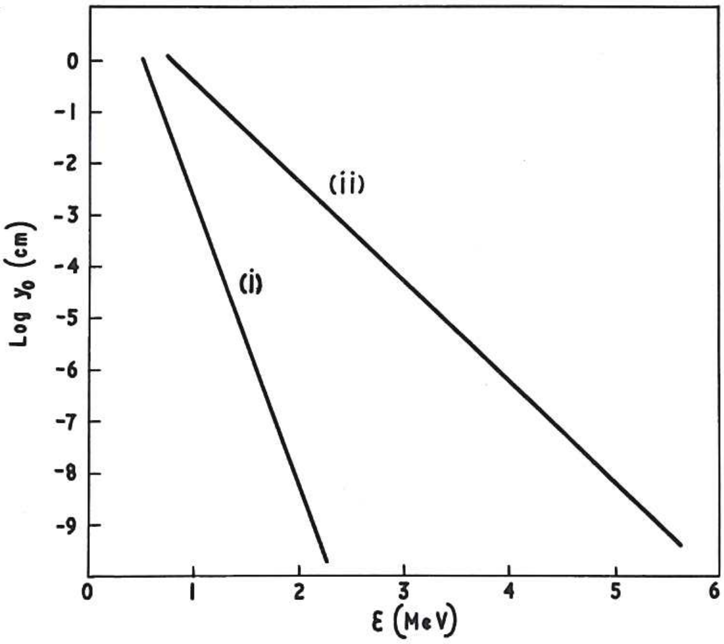

Fig. 2 (CLM-P 192)

A relation between the computed final energy of an ion and its initial Y-coordinate. The plasma parameters are:

for case (i) $B_{yo} = 500$ G, $n = 2 \times 10^{11}$ cm^{-3}, $M_o = 0.1$ and $f(y) \propto Y$

for case (ii) $B_{yo} = 500$ G, $n = 5 \times 10^{10}$ cm^{-3}, $M_o = 0.05$ and $f(y) \propto Y$

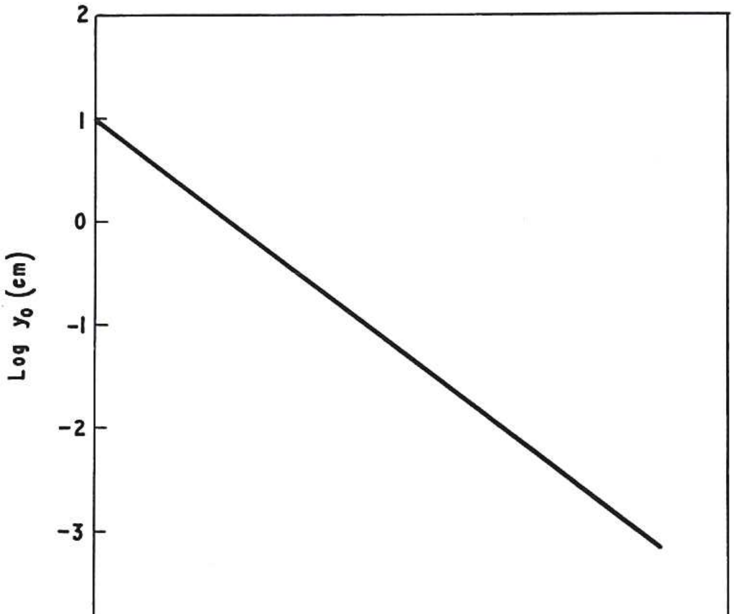

Fig. 3 (CLM-P 192)

A relation between the computed final energy of an ion and its initial Y-coordinate. The plasma parameters are:

$B_{yo} = 500$ G, $n = 2 \times 10^{11}$ cm^{-3}, $M_o = 0.1$ and $f(y) \propto Y^2$

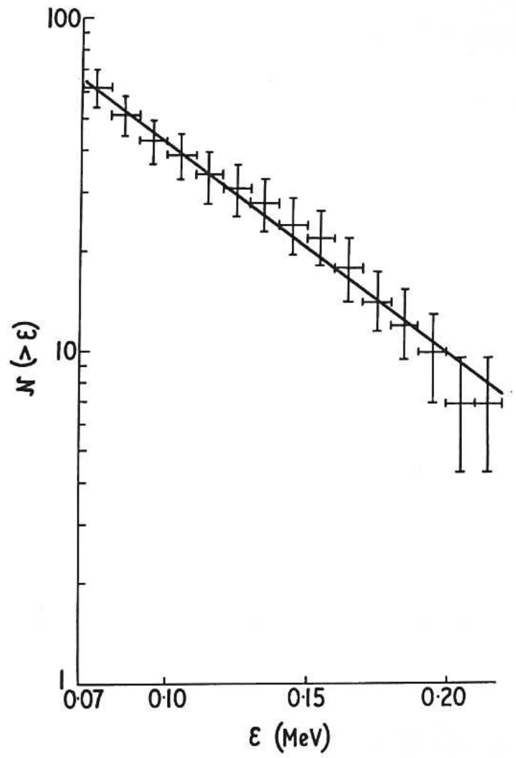

Fig. 4 (CLM-P 192)
Computed energy distribution for ions. The plasma parameters are:
B_{yo} = 500 G, n = 2 × 10^{11} cm^{-3}, M_o = 0.1 and f(y) ∝ Y

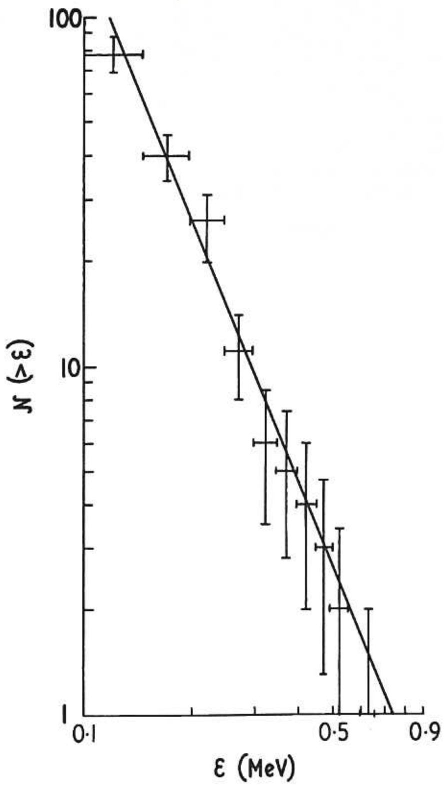

Fig. 5 (CLM-P 192)
Computed energy distribution for ions. The plasma parameters are:
B_{yo} = 500 G, n = 2 × 10^{11} cm^{-3}, M_o = 0.1 and f(y) ∝ Y^2