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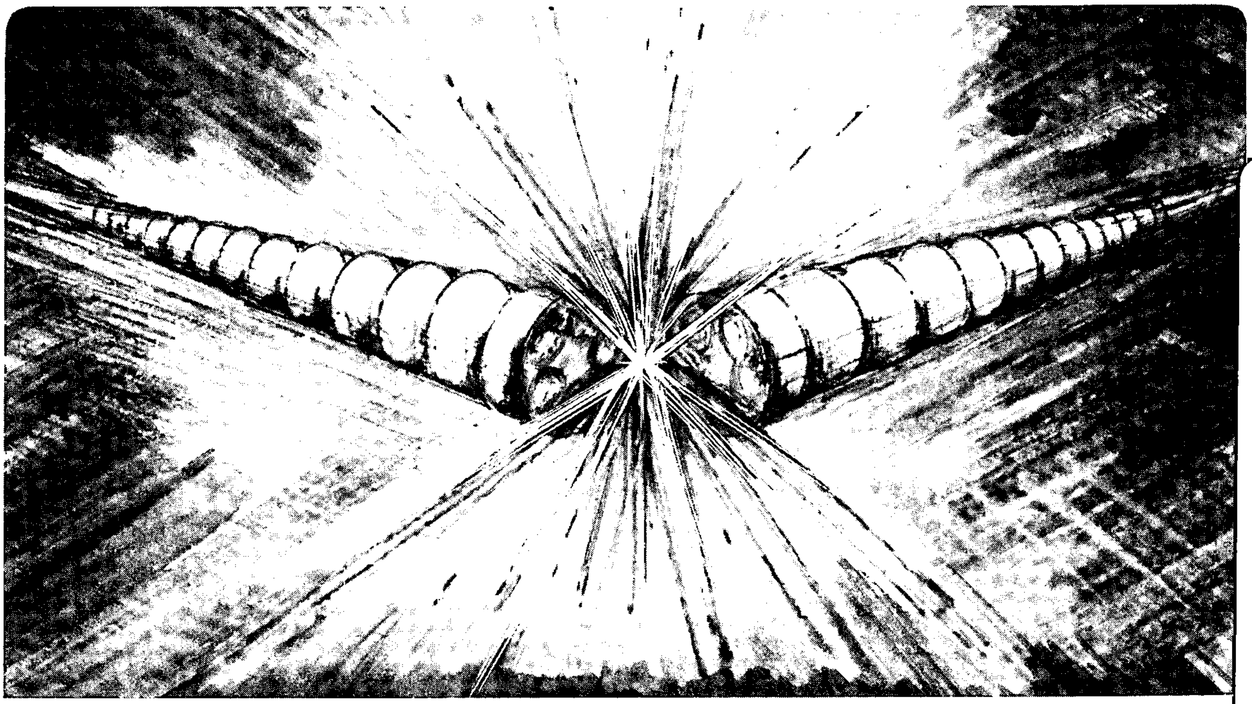

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COLLECTIVE ACCELERATION IN SOLAR FLARES*

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Abstract

Solar flare data are examined with an eye to seeing if they suggest collective acceleration of ions. That, in fact, seems to be the case. The collective acceleration mechanism of Gershtein is reviewed and the possibilities of the mechanism are discussed.

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1. Introduction

We have examined the solar flare data and note that there are a number of aspects of the data that suggest collective acceleration. In particular, timing data, energy spectrum data, and the flux data are all at least consistent with, and in a way most suggestive of, a collective mechanism of acceleration.

Following a review of the data in section 2, we discuss very briefly the mechanism proposed by Gershtein [1] in section 3. In section 4 we make some remarks concerning the possibilities of the mechanism.

2. Solar Flare Data

Timing data of solar flares have been studied by Forrest and Chupp [2], and they conclude that "the simultaneous starting times of X-rays > 40 keV and γ-ray emission show that electrons and ions were accelerated within seconds of each other".

The energy spectrum data of ions from solar flares have been studied by Reames, Richardson and Wenzel [3]. We reproduce, as Table 1, a representative sample of these data. Notice that the spectral indices are essentially the same for ^{3}He, ^{4}He, O, Fe.

Assuming the ratio of proton and electron energy is given by the present collective acceleration model, i.e. $E_{proton}/E_{electron} \cong M/m$, where M and m are the masses of proton and electron respectively, the ratio of the flux of proton to electron can be seen in Fig. 1, taken from the work in Ref. [4]. From these data one observes that the ratio of the number of accelerated protons to the number of accelerated electrons is roughly 10^{-4}. This ratio is more or less independent of the particular flare.

3. Collective Acceleration

The collective acceleration works by having ions trapped in the space charge field of a collection of moving electrons. As the electrons are accelerated to high energy the ions are dragged along at the same velocity. In this way the acceleration of both electrons and ions is simultaneous. Provided the ions aren't left behind while the electrons continue to be accelerated, the energy spectra of the ions and electrons will be similar, and so are the energy spectra of various species of ions. Finally, the ratio of ion to electron energy should be proportional to the ratio of ion to electron mass, and the ratio of ion to electron flux must be less than ratio of electron to ion mass.

All of these general features are essentially present in the data. We can not argue that the data "prove" that the collective acceleration mechanism is valid, but they certainly are consistent with the hypothesis and, we might add, most suggestive of the mechanism.

The mechanism considered by Gershtein [1] is similar to the electron ring accelerator (ERA), as originally proposed by V. I. Veksler [5]. There might be other collective acceleration mechanisms relevant to solar flares. Nevertheless, we follow, here, the discussion of Gershtein. In an ERA, we have initially a rotating ring of electrons with no longitudinal motion (a ring at rest). The ring is "loaded" with a small fraction of ions. A spatially decreasing magnetic field will convert the electron's transverse (ring/cyclotron) energy into longitudinal energy, and the ring will accelerate along the field lines. In this process (called "magnetic expansion" in the ERA literature) the ions will be dragged along.

From the adiabatic magnetic flux conservation law

$$BR^2 = B_0 R_0^2 \ ,$$

and the velocity relations

$$v_\parallel^2 = v_0^2 - v_\perp^2 \ , \quad v_\perp = \frac{eBR}{\gamma_0 mc} \ , \quad v_0 = \frac{eB_0R_0}{\gamma_0 mc} \ ,$$

one obtains for the longitudinal velocity of the electron

$$v_\parallel^2 = v_0^2 \left(1 - \frac{B}{B_0}\right) ,$$

where B_0, R_0, v_0 are the initial values for the magnetic filed, electron's gyroradius and velocity, respectively. Assuming ion moves longitudinally at the same velocity, $v_\parallel$, as the electrons, the relativistic energy of ion is given by

$$E = Mc^2 \frac{\gamma_0 m}{\left[m^2 + \beta_0^2 \gamma_0^2 m^2 \frac{B}{B_0}\right]^{1/2}} \ .$$

In the ERA literature this formula is usually evaluated in the relativistic limits, so

$$E = Mc^2 \sqrt{\frac{B_0}{B}} \ ,$$

but for solar flares a non-relativistic approximation is (almost always) valid, and we obtain

$$T = \frac{M}{m}\left(1 - \frac{B}{B_0}\right)T_e \ ,$$

where T is the kinetic energy of the ion and T_e is the initial transverse kinetic energy of the electron.

The magnitude of the electric field produced by a ring containing N electrons may be estimated by it's maximum value at the edge of the ring tube

$$E = \frac{eN}{\pi Ra} \ ,$$

where a and R are the minor and major radius of the electron ring, respectively. The energy gain of an ion of charge q moving in a distance Δz in the space charge field of the electron ring is given by

$$q\left(\frac{eN}{\pi Ra}\right)\Delta z \ .$$

This must be equal or larger than the kinetic energy gain of the ion

$$T_e\frac{M}{m}\left|\frac{1}{B_0}\frac{dB}{dz}\right|\Delta z \ ,$$

if the ion is to remain trapped in the field of the electron ring, i.e.

$$\frac{Nqe}{\pi Ra} \geq \frac{M}{m}T_e\left|\frac{1}{B_0}\frac{dB}{dz}\right| \ ,$$

which gives in terms of the electron density, n, in the electron ring

$$n[\mathrm{cm}^{-3}] \geq 10^{15}\frac{T_e[\mathrm{MeV}]}{a[\mathrm{cm}]L_B[\mathrm{cm}]} \ ,$$

where we have assumed the ion to be a proton, and

$$L_B \equiv \frac{1}{\left|\frac{1}{B_0}\frac{dB}{dz}\right|} \ .$$

Taking typical values of the magnetic field and its gradient inside solar flares, $B_0 \sim 100$ Gauss,

$dB/dz \sim 10^{-6}$ Gauss/cm, and assuming $T_e \sim 100$ keV and $a \sim 1$ cm, we have $n > 10^6\ \mathrm{cm}^{-3}$. This condition is easily satisfied in solar flares. The major radius of the electron ring, taken to be the electron gyroradius given by $R[\mathrm{cm}] = 1.7 \times 10^3\ (\gamma^2 - 1)^{1/2}/B_0\ [\mathrm{Gauss}]$, is about 11 cm.

4 Remarks on Electron Ring Formation

In the previous section we have considered the acceleration of ions by well-formed electron rings. The model, however, is silent on the subject of electron ring formation. To trap and accelerate ions effectively a few conditions are required in the ring formation. First, there must be a rotating clouds of energetic electrons accelerated along the magnetic field lines, second, the electrons must be bunched to proper scale longitudinally, and third, the bunching structure must be preserved long enough along the passage of beam propagating through ambient solar plasma.

We could say the following on the first condition: when solar flares erupt, magnetic flux is created by circulating currents in the solar surface. The associated flux lines fan out into space (often as far as the planetary regions) and then return to the sun. During the initial period where the magnetic flux is increasing with time electrons in the solar plasma are accelerated by the inductive electric field in orbits perpendicular to the flux lines (Faraday's law). After this initial acceleration phase is over (i.e. the magnetic flux reached it's peak in time) these electron clouds are moving in the direction of the diverging flux away from the sun. Their orbital kinetic energy perpendicular to the flux lines is thereby converted into axial kinetic energy (parallel to the flux lines). The energetic bursts of electrons and synchrotron radiation due to electron gyration are indeed observed during solar flares.

We may also contemplate the following bunching mechanism for the second condition. In the solar atmosphere, the accelerating electron clouds have to travel in an ambient plasma of density $n_0 \sim 10^{12}\ \mathrm{cm}^{-3}$, thus Langmuir waves could be excited, for example, by beam-plasma instability. As a result, the traveling electron clouds become longitudinally bunched, providing an acceleration field for the ions following each bunch.

To estimate the acceleration field, let's consider the field amplitude given by the wave breaking limit,

$$eE\,[\tfrac{\mathrm{eV}}{\mathrm{cm}}] \approx \sqrt{n\,[\mathrm{cm}^{-3}]}\ .$$

Assuming $n \approx 10^8\ \mathrm{cm}^{-3}$ for the electron beam and the Langmuir wave has an amplitude of, say, 10 % of the value at the wave breaking limit, to accelerate protons to 100 MeV requires that the Langmuir waves be coherent for 1000 m. Of course, since dB/dz is so small, the Langmuir wave amplitude can be even less, but then the coherence length must be longer.

The bunching scale in this model must be of the order of λ, the Langmuir wavelength. For effectively excited Langmuir waves it is required that $\lambda >> \lambda_D$, where λ_D is the electron Debye length. At a typical temperature of 100 eV in solar flare the Debye length is about 10^{-2} cm. The minor radius of 1 cm we took for the electron ring seems to be a reasonable number in this regards.

What we have seen is that a fairly strong acceleration field for ions may indeed be generated by the excitation of Langmuir waves in solar plasma. The next question is whether the acceleration could be maintained long enough by this process. According to the linear theory of the beam-plasma instability [6], the growth rate of the Langmuir waves given by $0.7\omega(n/n_0)^{1/3}$ is around 10^9 sec^{-1}, where ω is the background electron plasma frequency. At this rate the beam would lose its energy and become thermalized in 10^{-9} sec, which is extremely fast comparing to 10^{-5} sec, the time it takes to accelerate protons to 100 MeV. Of course, this estimate is only an extrapolation based on the linear theory, in fact a whole host of nonlinear phenomena may take place well before the Langmuir waves reach the wave breaking limit. Therefore to really answer the question on the stability of electron ring one has to pursue a nonlinear analysis, which is beyond the scope of the present paper.

However we may point out that similar issues have been raised for electron beams traveling far in the corona. There, as supported by the observations of type III solar radio bursts, the plasma oscillations excited by traversing electron beams have been known to last much longer than that predicted by the quasi-linear theory. We may also resort to an explanation proposed for this process, the beam recycling mechanism [7], which shows that beams highly inhomogeneous in their density and velocity structure could maintain themselves against quasi-linear diffusion and therefore sustain the excitation of the Langmuir waves.

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Table 1 Spectral Indices for Various Particle Species.

^{3}He	3.4 ± 0.2
^{4}He	3.3 ± 0.7
O	3.4 ± 0.5
Fe	3.4 ± 0.4

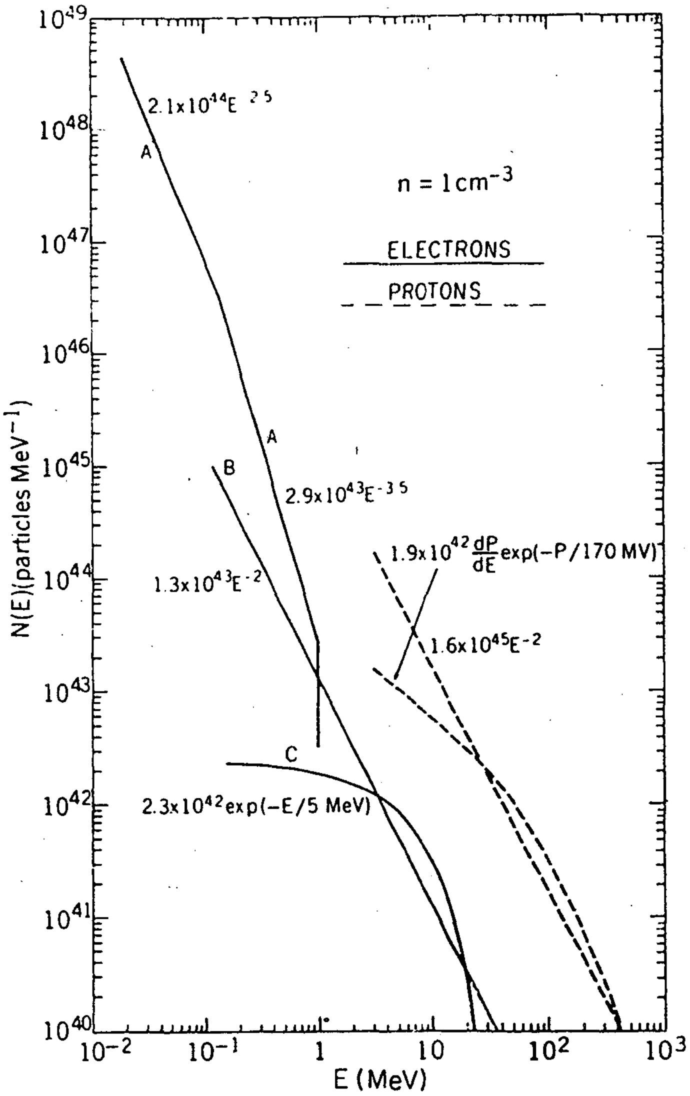

Figure 1 Flux of Electrons and Protons as a Function of Their Kinetic Energy.

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