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Acceleration of Electrons in Solar Flares

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Abstract

Acceleration of electrons by Langmuir plasma turbulence and by the Fermi mechanism are suggested to explain the two-stage acceleration processes observed in hard X-rays from solar flares. A model for particle acceleration in flares is presented.

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Acceleration of Electrons in Solar Flares

I. Introduction

Recent observations of solar hard X-rays of energies greater than 10 keV by Frost and Dennis (1971) with an OSO-5 instrument have shed new light on the particle acceleration processes in solar flares. The hard X-ray emission that they observed consists of an impulsive burst with photon energies up to 100 keV in the initial phase of the flare, and a second burst with much harder photon spectrum, extending up to 250 keV. Both types of burst showed nonthermal characteristics. The harder burst type maintained its power law spectrum for as long as 40 minutes. Frost and Dennis (1971) argue that these observations indicate the occurence of a two-stage acceleration process. In the first stage, which coincides with the flash phase of the Hα flare, electrons are accelerated up to 100 keV on a time scale of only a few seconds. The second stage acceleration occurs almost immediately thereafter, and raises electrons to much higher energies. The rise time for the second stage burst is much longer than for the first, typically lasting a few minutes. Kane and Anderson (1970) in their observations of impulsive solar flare X-rays $\geqslant$ 10 keV with instruments aboard OGO-5 also find that the spectrum of the emitting electrons becomes much steeper beyond 100 keV. However, they did not observe the second hard X-ray burst, probably due to instrumental limitations.

The idea of two stage acceleration has been inferred previously by De Jager (1969) from solar radio burst observations. However, the mechanisms involved have not been definitely established. If the first stage is due to induced electric field (De Jager, 1969; Frost and Dennis, 1971) then it is difficult to explain why the induced electric field has a maximum value around 100 keV. A long standing problem is the establishment of an induced field in a highly ionized plasma as exists in the flare. Here we present an alternative explanation: acceleration by Langmuir plasma turbulence that is generated by plasma instabilities. We show below that this mechanism is plausible in the initial phase of a solar flare. We believe that the electrons are continuously accelerated in the second stage and we show that the Fermi mechanism could be reponsible for the second stage acceleration.

II. First Stage Acceleration

In laboratory experiments, plasma turbulence is frequently observed when an instability sets in. Associated with such instabilities are the appearance of high energy particles, microwave emissions, and X-ray emissions (Smullin and Getty, 1962; Alexeff, Neidigh, Reed, Shipley, and Harris, 1963; Hamberger, Malein, Adlam, and Friedman, 1967; Babykin, Gavrin, Zavoisky, Nedoseyev, Rudakov, and Skoryupin, 1967). The situation is solar flares is rather similar. It seems resonable to investigate whether the high energy flare phenomena are due to plasma turbulence created by an instability. For a concrete example we consider the flare model in which annihilation of magnetic fields occurs at the neutral points or lines (Petschek, 1963). In the vincinity of the neutral lines the large gradient in magnetic field $\underline{B}$ sets up a current density $\underline{j}$ as given the Maxwell equation

$$\nabla \times \underline{B} = \frac{4\pi}{c} \underline{j} \tag{1}$$

where c is the speed of light. Taking a plausible thickness $\delta \simeq 10^2$ cm for the diffuse region (Friedman and Hamberger, 1969), we find for an electron density $n \sim 10^{10} \mathrm{cm}^{-3}$, $\Delta B \sim 500$ gauss, that the drift velocity of electrons, V_d, is

$$V_d \sim \frac{j}{n\,e} \sim \frac{c}{4\pi n\,e} \frac{\Delta B}{\delta} \sim 3 \times 10^9 \text{ cm/sec} \tag{2}$$

where e is the electronic charge. This velocity is much greater than the thermal velocity of the electrons

$$V_{th} \sim \left(\frac{k\,T_e}{m_e}\right)^{\frac{1}{2}} \sim 4 \times 10^8 \text{ cm/sec} \tag{3}$$

where k is Boltzman's constant, m_e the electron mass, and $T_e \simeq 10^6$ K the electron temperature in the lower corona. As the phase velocity of the electron plasma oscillation, V_{ph}, lies in the range $V_{th} < V_{ph} < \infty$, the condition of generating plasma waves via the Cerenkov emission process, $V_d > V_{th}$, is well satisfied by the current-driven electrons moving with velocity V_d. Note that electron plasma oscillations (also called Langmuir oscillation) with phase velocity $V_{ph} < V_{th}$ are heavily Landau damped (Boyd and Sanderson, 1969). As a result of this current-driven instability small scale Langmuir plasma turbulence is generated (Kadomtsev, 1965). Owing to the many degrees of freedom of a plasma, Langmuir plasma turbulence is also readily generated by shock waves, by high frequency radiations, and by many other plasma instabilities.

From the above calculation we see that the Langmuir plasma turbulence can be generated by the flare instabiltiy. Once the plasma turbulence is generated, it is possible for the electrons to be accelerated statistically due to particle-wave interactions. The average increase of particle energy E with time t is given by the diffusion equation (Melrose, 1968):

$$\frac{dE}{dt} = \frac{1}{E^2} \frac{\partial}{\partial E} (E^2 D) \tag{4}$$

The diffusion coefficient D is related to the energy distribution in phase space, $W(V_{ph})$, of the Langmuir plasma turbulence by

$$D = \frac{e^2 \omega_{pe}^2}{V^3} \int_{V_{th}}^{V} \frac{dV_{ph}}{V_{ph}} W(V_{ph}) = \frac{e^2 \omega_{pe}^2}{V^3} \int_{\frac{\omega_{pe}}{V_{th}}}^{\frac{\omega_{pe}}{V}} \frac{dk}{k} W(k) \qquad (5)$$

where $\omega_{pe} = (4\pi ne^2/m_e)^{\frac{1}{2}}$ is the electron plasma frequency, V is the electron velocity, and $k = \omega_{pe}/V_{ph}$ is the wave number of the plasma wave. Notice that we have approximated the dispersion relation for electron plasma waves at finite temperature by $\omega \simeq \omega_{pe}$, where ω is the oscillation frequency of plasma waves. The lower limit in the integral is set at V_{th}, because plasma waves with phase velocities less than V_{th} are heavily Landau damped, and hence do not contribute to the interactions with particles. Now substituting (5) into (4), we find for non-relativistic particles that

$$\frac{dE}{dt} = \frac{e^2 \omega_{pe}^2}{m\ V^3} W(V_{ph} = V) \qquad (6)$$

where m is the mass of the accelerated particle. The acceleration rate for non-relativistic particles depends therefore strongly on the turbulence wave spectrum. Since no waves with $V_{ph} < V_{th}$ exist, we see from (6) that only particles with velocities $V \gtrsim V_{th}$ are accelerated by Langmuir plasma turbulence. The energy of the plasma waves, $W(V_{ph})$, is related to the energy of the plasma turbulence, $w(V_{ph})$, by the relation

$$W(V_{ph}) \simeq w(V_{ph})\left(\frac{V_{ph}}{\omega_{pe}}\right)^3 \tag{7}$$

The spectrum of plasma energy density, $w(V_{ph})$, is not well known, and only a rough estimate is possible. Pikel'ner and Tsytovich (1968) have calculated the stationary spectrum of Langmuir plasma turbulence for the case $T_e \simeq T_i$, where T_i is the ion temperature, for excitation by many kinds of plasma instabilities. They show that owing to various non-linear processes, a stationay spectrum of Langmuir plăsma turbulence can be produced. For example, in the current-driven instability discussed above, plasma waves with $V_{ph} \sim V_{th}$ are emitted initially. Then non-linear processes such as waves scattering on electrons, and on ions, and wave-wave interactions, transform the initially low phase velocity plasma waves to higher phase velocities. The shape of the resulting spectrum of the Langmuir turbulence depends strongly on the energy input, Q ergs/cm^3-sec, into the plasma oscillations. The bulk of the energy of the plasma turbulence will reside in a Maxwellian peak centered at the wave number k_o, if the energy input to the plasma oscillation Q is large. Now,

$$k_o = k_* \left(\frac{8\, n\, T_e\, \nu_e^2}{\omega_{pe}\, Q}\right)^{\frac{1}{2\nu - 2}} \tag{8}$$

where $k_* = \frac{1}{\lambda_{De}}\left(\frac{m_e}{m_i}\right)^{\frac{1}{2}}$, $\lambda_{De} = (kT_e/4\pi n e^2)^{\frac{1}{2}}$ is the Debye length,

$\nu_e \simeq 50nT_e^{-5/2}$ is the electron collion frequency, and ν is a numerical constant between 2.8 and 4. The condition for the formation of the Maxwellian bump is $k_o \ll k_*$. Otherwise the spectrum of plasma turbulence will be more or less flat within the range $k_{min} \simeq k_* \lesssim \omega_{pe}/V_{th}$. Taking $T_e \sim 10^5$ K, $n \sim 10^{10}$ cm^{-3}, and $\nu \simeq 3$, we find the condition that the bump forms, $k_o \ll k_*$, requires that $Q \gg 4 \times 10^{13}$ erg/cm^3-sec. Even if we assume that the total flare energy of $\sim 10^{32}$ ergs is dumped in the plasma turbulence if a volume $\sim 10^{25}$ cm^3 in one second, we will not obtain a large enough excitation Q to generate a bump in the Langmuir turbulence spectrum. In view of the great uncertainty of the spectrum of this turbulence, we shall assume that for the case of solar flares the resulting turbulence spectrum is constant, i.e., w = constant within the range $k_* \lesssim k \lesssim \omega_{pe}/V_{th}$, and is zero outside. The acceleration rate (Equations (6) and (7)) is then

$$\frac{dE}{dt} = \frac{e^2}{m\,\omega_{pe}} w = \frac{e^2}{m\,\omega_{pe}} \eta \frac{B^2}{8\pi} \tag{9}$$

where $w = \eta B^2/8\pi$ and η is the fraction of the annihilated magnetic field energy that goes into plasma turbulence energy. Setting $n \sim 10^{10}$ cm^{-3}, $B \sim 250$ gauss, we find, for electrons, $m = m_e$,

$$\frac{dE}{dt} \doteq 10^2 \eta \quad \text{erg/sec.} \tag{10}$$

In order that thermal electrons with $E \simeq 10$ eV ($T_e \simeq 10^5$ K) be accelerated, the acceleration rate must exceed the ionization loss rate given by

$$\left(\frac{dE}{dt}\right)_{Ion} \simeq \frac{e^2 \omega_{pe}}{E^{\frac{1}{2}}} \left(\frac{m_e}{2}\right)^{\frac{1}{2}} \ln \frac{E}{\hbar \omega_{pe}} \simeq 6 \times 10^{-7} \text{ erg/sec} \qquad (11)$$

where $\hbar = h/2\pi$ and h is Planck's constant. This requires that the transformation efficiency $\eta \gtrsim 6 \times 10^{-9}$. Note that the thermal level of the Langmuir plasma turbulence $w_{th}/nkT_e \sim 1/(6\pi^2 n \lambda_{De}) \simeq 3 \times 10^{-8}$, giving $\eta_{th} = w_{th}/(B^2/8\pi) \simeq 2 \times 10^{-12}$ (for $T_e \sim 10^5$ K, $n \sim 10^{10}$ cm^{-3}, B $\sim$ 250 gauss). The condition for weak plasma turbulence, $w_{th} \ll w \ll nkT_e$, is therefore well satisfied for $10^{-4} \gtrsim \eta \gtrsim 6 \times 10^{-9}$. Now the time for a thermal electron of energy ~ 10 eV to be accelerated to a final energy ~ 100 keV is given by

$$t \simeq \frac{E}{(dE/dt)} \simeq \frac{1.6 \times 10^{-9}}{\eta} \quad \text{sec.} \qquad (12)$$

For $10^{-4} \gtrsim \eta \gtrsim 6 \times 10^{-9}$, the time needed for acceleration is $10^{-5} \lesssim t \lesssim 0.3$ second, which is consistent with the impulsive hard X-ray observations. The value of η in terms of the physical parameters of a specific instability is not known. However, Zaitsev (as quoted by Bhatia and Tandon ,1970) has estimated that in a collisionless shock with $n \sim 10^8 - 5 \times 10^9$ cm^{-3}, $B \sim 300 - 10^4$ gauss, the maximum value of η is around $10^{-3} - 10^{-4}$. Our estimate of η is therefore not unresonable.

We have shown that the Langmuir plasma turbulence is capable of accelerating electrons in a time scale compatible with the observations. The cut-off in the electron spectrum is due to the cut-off in the spectrum of the plasma turbulence which has a minimum wave number $k_* \simeq 0.6$ (for $T_e \sim 10^5$ K). This corresponds to $V_{ph} \simeq 10^{10}$ cm/sec, or a particle energy of the order of 100 keV. Since $w(V_{ph} \gtrsim 10^{10}$ cm/sec$) \simeq 0$, no particles can be accelerated beyond about 100 keV. Note that the acceleration rate by Langmuir plasma turbulence is, in this case, inversely proportional to the particle mass. Hence protons are not as efficiently accelerated as electrons in the impulsive phase of solar flares. This agrees with Lin (1969), who observed that in many cases only 10 - 100 keV electrons are observed in interplanetary space following solar flares, while no protons are associated with them.

III. Second Stage Acceleration

Frost and Dennis (1971) suggest that in the second stage the acceleration is associated with a shock front that also generates the type II radio burst. The type II burst at frequency of 80 MHz for the March 30, 1969 event occurs at a plasma level $\sim 4.5 \times 10^5$ km with a local electron density $\sim 8 \times 10^5$ cm^{-3} (if we assume that the density over the active region is 10 times greater than that of the normal corona). Frost and Dennis (1971) suggest that the electrons that emitted hard X-rays were accelerated at about 18 seconds earlier than the type II burst. If this is so, then, the level of the hard X-ray electron acceleration occurred at the height $\sim 4.3 \times 10^5$ km, assuming that the shock front propagated at a speed of about 10^3 km/sec (Kundu, 1965). This height of the hard X-ray burst corresponds to a density of 10^6 cm^{-3}, which is much smaller than those usually deduced from solar X-ray observations (Takakura, 1969; Holt and Cline, 1968). Thus, it remains to be shown that the shock front indeed accelerates the electrons that emit the hard X-rays.

An important question is how the electrons could maintain their nonthermal power law for as long as 40 minutes, at least in the observed energy range from 40 keV to 250 keV while losing energy by both radiation and ionization. Let us consider an arbitrary anisotropic electron distribution that is initially accelerated. Owing to electron-electron collisions with the ambient plasma, the high energy electrons are scattered in momentum as well as in energy space, and as a result the distribution tends toward isotropy and becomes Maxwellian at about the same time scale as given by (Rossi and Olbert, 1970), namely:

$$t_{ee} \simeq \frac{3\, m_e^{\frac{1}{2}}\, T_e^{3/2}}{4\, (2\pi)^{\frac{1}{2}}\, e^3\, n\, \ln\Lambda} \text{ sec} \qquad (13)$$

where T_e is the final electron temperature, n is the electron density, and $\ln\Lambda$ is the usual Coulomb logarithm. Taking $\ln\Lambda \simeq 18$ in the ranges of density and temperature of interest to solar flares ($n \sim 10^8 - 10^{12}$ cm^{-3}, $T_e \sim 10^4 - 6 \times 10^7$ K), we find that $t_{ee} \lesssim 7$ seconds. That is the electron distribution will become thermalized in a time scale much short than that indicated by the second hard X-ray burst. The long duration of the second hard X-ray burst with nonthermal characteristics indicates then that electrons are continuously accelerated, and thereby replace the electrons which have been thermalized. It can also be argued that the electrons are initially accelerated by some mechanism, then trapped and stored in the corona. In that case, the hard X-rays would be produced through the gradual leaking of electrons from the storage region to lower levels of the atmosphere. However, it is not clear how a large number of high energy electrons could be confined by the relatively small magnetic fields in the corona. Here we suggest that in the second stage, particles are continuously accelerated by the statistical Fermi mechanism in collisions with the magnetic irregularities. These irregularities are continuously generated by the magnetic disturbances which are associated with the continuous energy input to the flare.

The rate of energy increase for the statistical Fermi mechanism is given by

$$\frac{dE}{dt} = \frac{4\,u^2}{\tau\, c^2}\, E \tag{14}$$

where u is the velocity of the propagation of the magnetic inhomogeneity, an τ is the mean collision time of the particles with the magnetic irregularities. In order for the acceleration to be effective the energy increase due to the Fermi mechanism must be greater than the ionization loss, which is the most important loss for electrons with energies less than 100 keV. From (11) and (14), we find that the injection energy is

$$E_{in} = \left(\frac{e\,c\,\omega_{pe}}{2\,u}\right)^{4/3} \left(\frac{m_e}{2}\right)^{1/3} \left(\tau \ln \frac{E}{\hbar\,\omega_{pe}}\right)^{2/3} \tag{15}$$

The velocity of the propagation of the magnetic inhomogeneity is of the order of the Alfven velocity, i.e., $u \simeq B/(4\pi m_p n)^{\frac{1}{2}} \simeq 10^8$ cm/sec for $B \sim 200$ gauss, and $n \sim 10^{10}$ cm^{-3} (m_p is the proton mass). Taking the injection energy to be 10 keV which is provided by the initial heating and the first stage acceleration, we find from (15) that the mean collision time of particles with the magnetic irregularities is $\tau \simeq 2 \times 10^{-5}$ second. This gives a characteristic scale of field inhomogeneity of 1.5×10^5 cm. This length scale is of the same order of magnitude as that of the fine structure of inhomogeneity observed in Hα flares (Suemeto and Hiei, 1959). Now, the time needed for acceleration from an initial energy E_i to a final energy E_f is, from (14),

$$t_{acc} \simeq \frac{\tau c^2}{4 u^2} \ln \frac{E_f}{E_i} \qquad (16)$$

With $E_i \sim 10$ keV, $E_f \sim 250$ keV, $u \sim 10^8$ cm/sec, the acceleration time is $t_{acc} \simeq 2$ seconds. Therefore, the Fermi mechanism is capable of accelerating electrons to high energies in a very short time interval. The final electron energy is limited by the bremsstrahlung and the synchrotron radiation losses (Švestka, 1970).

IV. Discussion

In view of the above calculations, we propose the following model for acceleration of electrons in solar flares, with particular reference to the March 30, 1969 event (Frost and Dennis, 1971).

The instability that triggers the release of the flare energy generates a Langnuir plasma turbulence. The plasma turbulence then accelerated electrons stochastically (cf.: Hall and Sturrock, 1968; Tsytovich, 1966). The cut-off of the spectrum of plasma turbulence determines the cut-off of the acclerated electrons. The acceleration time is short enough to be consistent with the observations, as we have seen. The electrons that escape outward then give rise to the type III radio burst while the electrons that move downward to the denser atmosphere emit the impulsive hard X-rays. After the initial instabilities and the collapse of the gases, hydromagnetic turbulence is generated. And we believe that in this stage, stored flare energy is gradually released in a less violent manner than in initial instability of the flare. This release of the flare energy could occur through magnetic field annihilation (cf.: Petschek, 1963). In the present model the period of bulk energy release is identified with the long time scale observed for second stage hard X-ray burst. In this stage, because of the continuous input of energy, magnetic disturbances are continuously generated. Hence the Fermi statistical mechanism continuously accelerates electrons and protons to high energies, giving rise to the proton events, the type II radio burst, and the gradual hard X-ray burst. At the same time, the ambient plasma is heated and gives rise to soft X-rays; thus a thermal plasma co-exists with a population of nonthermal high energy electrons.

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