IMPULSIVE ACCELERATION AND BULK HEATING OF FLARE PLASMA BY PLASMA TURBULENCE

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Abstract

A new paradigm of the non-thermal thick target model for the impulsive phase of solar flares is described, where plasma waves or turbulence play a major role in the acceleration of particles and a prominent role in the impulsive heating of footpoints of flare loops, as is seen in the January 26, 1992 flare by YOHKOH. This modification makes the required energy and physical conditions more reasonable and has an important bearing on the heating of the corona and the Neupert effect.

1. Introduction

The non-thermal thick-target model has been very successful in explaining most of the observed characteristics of flares during the impulsive phase. In this model, particles are accelerated somewhere in the corona and produce hard x-rays, gamma-rays and microwaves as they travel down the magnetic fields, shaped as loops, lighting up and delineating the flaring loops. There exist, however, many unanswered questions and some observations that do not fit this simple picture. On the theoretical side, even though it is generally accepted that the source of flare energy is the magnetic field and that annihilation of this field provides the flare energy, there is no general agreement as to how and what fraction of this energy goes into accelerating particles or heating the plasma. On the observational side, evidence is mounting that more energy is required to explain all the observed radiation than the amount available from > 20 keV electrons. The YOHKOH observation (e.g., Jan. 26, 1992 flare) demonstrated this clearly.

I would like to discuss a modification of the thick target model which can overcome these difficulties. I propose that plasma waves and turbulence which can be generated during reconnection can play a more prominent role, than hitherto acknowledged, in the acceleration of particles, in the transport of energy and in the bulk heating of the plasmas.

2. Acceleration Mechanism

Direct acceleration by *electric fields* parallel to the magnetic field lines is one possible mechanism, but there are arguments against this being the whole story. One reason is that the Dreicer field is low and to accelerate particles up to GeV energies required by recent gamma-ray observations would imply acceleration regions $> 10^{14}$cm for normal resistivity. Furthermore, the particle spectra obtained by this mechanism are unlike that required for flares and tend to be unstable so that the process is quenched by conversion of their energy into plasma turbulence.

A second mechanism, *Acceleration by shocks*, which has been successfully applied to the galactic cosmic rays, is also a possibility. However, there is no evidence for shocks in the majority of flares (except perhaps in long lasting ones). Furthermore, efficient acceleration by shocks requires repeated scattering of particles. The most logical agent for such scatterings is plasma turbulence.

The third possibility is *acceleration by turbulence* which can be produced during the reconnection process. In lieu of support for this model, I would like to dispel several myths generally associated with acceleration by turbulence.

a. *Acceleration by turbulence is slow.* This may be true for acceleration of cosmic rays in the interstellar medium, but it is decidedly not true for solar flares. Very generally, the acceleration or scattering time scale for electrons can be written as $\tau_a = C\Omega_e^{-1}(B^2/\delta\pi W_w)^2$, where $\Omega_e = 1.6 \times 10^7 B\mathrm{s}^{-1}$ is the electron gyrofrequency and $W_w \simeq 8\pi < \delta B^2 >$ is the turbulence energy density. The coefficient C depends on the nature and spectrum of the turbulence, and on the energy and pitch angle of the electrons. For typical conditions, $B \sim$ 500G, $\delta B \simeq 10^{-3}B$ and $C \simeq 10$ this time $\tau_a = 10^{-3}$s which is sufficiently fast.

b. *Turbulence cannot accelerate low energy electrons.* This is true for Alfvén waves and low frequency Whistlers, but this is not the case for high frequency Whistlers (Hamilton and Petrosian 1991) and for the waves in the electromagnetic branch with low wave vectors when the ratio of plasma frequency ω_p to gyrofrequency is ≤ 0.3 (Dung and Petrosian 1994). Figure 1 shows the variation with momentum of τ_a for the combined effect of all waves, which is sufficiently short for solar flares at all energies.

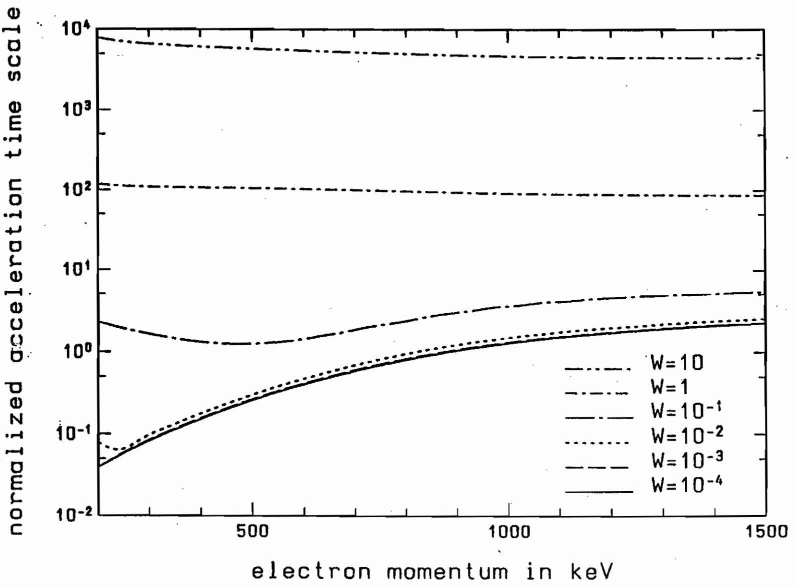

Fig. 1. Acceleration time scale in units of $\Omega_e^{-1}(B^2/\delta\pi W_w) \simeq 10^{-3}$s as a function of electron momentum for several values of the ratio $W = \omega_p/\Omega_e$ (from Dung and Petrosian 1994).

c. *Acceleration by turbulence gives rise to a power law or Bessel function type spectra.* This is true only in the simplest and most unrealistic treatment of the problem, which involves many assumptions (see e.g., Petrosian 1993), such as: quasilinear approximation, pitch angle isotropy, neglect of losses, spatial homogeneity and treatment of the advection by a simple escape time which is generally assumed to be a constant. Not all of these assumptions are valid in all situations. For example, for a slightly more realistic model where the escape time is a function of energy, one obtains a variety of spectra depending on the relative energy dependence of acceleration and escape times (Park and Petrosian 1994). Inclusion of energy losses will also cause spectral deviations from simple power laws. As shown by Hamilton and Petrosian (1991), inclusion of Coulomb collisions leads to steepening of the spectra at low energies so that they resemble a thermal tail. Deviation from a simple power law can occur at high energies when synchrotron losses are important (see Bech et al 1992 and Petrosian 1993). It is clear that similar deviation can come about when the pitch angle distribution is explicitly considered and spatial inhomogeneities are taken into account.

I conclude that acceleration by plasma waves is a logical possibility and can accelerate electrons quickly to high energies and explain the variety of electron spectra seen in flares.

3. Thick Target Model?

There are various inconsistencies between observations and the thick target model. I would like to concentrate on aspects which have bearing on the presence of turbulence.

Thermal versus Non-Thermal Emissions. As mentioned above, Hamilton and Petrosian (1991) show that collisional losses plus acceleration give rise to spectra which mimic the high energy tail of a "thermal" spectrum often seen in flares. However, there is still a distinction between bremsstrahlung emission by such particles interacting with a background (cold) plasma and a thermal bremsstrahlung emission from a hot plasma. In the first case, the yield of hard x-rays by the accelerated particles is small: $Y_{non-th} \simeq 10^{-6}$ (see e.g., Petrosian 1973), while in the second case, in the absence of other cooling processes, all the energy can be emitted as x-rays $Y_{th} \leq 1$. Because of this, it is generally believed that the soft ($<$ 10keV) x-ray emission is thermal, otherwise the required number or energy of accelerated non-thermal electrons will be too large when extended to the keV range. This is a reasonable explanation for the gradual soft x-rays emitted after the impulsive phase and arising primarily from large volumes at the top of a loop. The soft x-rays arise from the hot plasma being heated and evaporated by the hard x-ray emitting particles. This, however, cannot be the case for the soft x-ray impulsive emission observed by YOHKOH for the January 26, 1992 flare (see Hudson et al 1993 and in these proceedings).

Impulsive Soft X-Ray Emissions. This flare, in addition to the slowly varying soft x-ray emission which rises gradually over a period of 10 minutes, emits soft x-rays (1 to 2 keV) from a footpoint with an impulsive (~60 seconds) time profile similar to that of the hard x-rays (>15 keV). If we assume that the soft and hard x-rays are emitted by the accelerated electrons whose spectrum extends to 1 keV, we are faced with the dilemma of too much energy mentioned above. The above authors, therefore, attribute this 1 to 2 keV emission to thermal bremsstrahlung by compact plasma which is heated by the hard x-ray emitting electrons.

Based on very general arguments, I now show that this does not alleviate the problem with the energy requirement if the plasma is heated collisionally. This is because the conduction heat loss becomes large. If the plasma is heated by electrons of energy E (in units of mc^2), we expect that the size of the heated region, and therefore its temperature scale height, $h_T = T/|\nabla T|$, to be the order of the mean free path $\lambda_{coll} \simeq E^2/(4\pi n r_0^2 \ln \Lambda)$, where n is the density $r_0\, 2.8 \times 10^{-13}$ and $\ln\Lambda \simeq 20$ is the Coulomb logarithm. It is easy to show then that the conductive cooling time

$$\tau_{cond} \simeq (3/2) nkT h_T / \kappa |\nabla T| \simeq 0.15 h_T^2 n r_0^2 \ln \Lambda / c T_*^{5/2}, \tag{1}$$

where κ is the heat conduction coefficient and $T_* = kT/mc^2$. Now for $h_T \simeq \lambda_{coll}$ we obtain

$$\tau_{cond} = 0.02(E/T_*)^{5/2}\tau_{coll} \simeq 2 \times 10^{-6}(E^4/T_*^3)\tau_{brem}, \tag{2}$$

where $\tau_{coll} \simeq \lambda_{coll}/c\sqrt{2E}$ is the collision time and τ_{brem} is the thermal bremsstrahlung emission time scale ($\sim nkT/\dot{E}_{brem}$). For $E \simeq 10$keV and $kT = 1$ keV, $\tau_{cond} \simeq 5\tau_{coll} = 4 \times 10^{-5}\tau_{brem}$, so that the yield of thermal bremsstrahlung $Y_{th} = \tau_{cond}/\tau_{brem} < 10^{-4}$ which is far from unity.

If the observed 1 to 2 keV emission ($\sim 4\times10^{26}$ erg s^{-1}) is due to thermal bremsstrahlung from a $T \simeq 10^7$K hydrogen plasma, we need an emission measure of 10^{50}cm^{-3}, so that for a loop cross sectional area of 10^{18}cm^2 we obtain $n^2h_T \simeq 10^{32}$cm^{-5}. Combining this with the relation $nh_T = n\lambda_{coll} = 4 \times 10^{19}$cm^{-2}(for $E = 10$keV), we find a very high density, $n \simeq 5 \times 10^{12}$ cm^{-3}, and an unreasonably thin layer, $h_T = 4 \times 10^6$ cm, so that $\tau_{cond} \simeq 0.004$s and $\tau_{brem} \simeq 10^2$s. We estimate the peak hard x-ray emission (> 15keV) to be about 10^{24} erg s^{-1} for this flare, which for $Y_{non-th} = 10^{-6}$ amounts to $\mathcal{E}_e = 10^{30}$ erg s^{-1} for the energy of accelerated electrons. If all this energy goes into heating the footpoint to a temperature of 10^7K, then the rate of soft x-ray emission would be $\tau_{cond}\mathcal{E}_e/\tau_{brem} = 4 \times 10^{25}$erg s^{-1} which is less than the observed 10^{27}erg s^{-1} of soft x-rays from the footpoint.

Heating by Plasma Turbulence. These problems with short conduction time and the energy balance can be alleviated if the temperature scale height is increased. This can come about if the rapid heating of the footpoint is produced by an agent which deposits its energy over a region $\gg \lambda_{coll}$. One possibility is heating the footpoints by plasma waves or turbulence, which have a longer damping scale than λ_{coll}. As expected, some of the turbulence resulting from reconnection can travel down the loop and damp in the higher density regions. If $\lambda_{wave} = \zeta\lambda_{coll}$ then $n \propto \zeta^{-1}$, $h_T \propto \zeta$ and $Y_{th} \propto \zeta$, so that for $10 < \zeta < 100$ all the above difficulties will be eliminated.

4. Summary

Plasma waves or turbulence can play a very important role during the impulsive phase of flares not only in accelerating particles which produce hard x-rays and gamma-rays, but also in the direct impulsive heating of the plasma which could produce the impulsive soft x-ray emission seen in several flares by YOHKOH. Therefore, energy budget calculations based on the energy of hard x-ray emitting electrons is only a lower limit. More energy may be transported down the loop by waves. This alters our view of how the thermal thick-target models work and how the Neupert effect comes about. This has important implications on the heating of the corona.

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References

1. Bech, F.-W., Steinacker, J. and Schlickeiser, R., 1990, *Solar Physics* **129**, 195.
2. Dung, R. and Petrosian, V., 1994, *Ap. J.*, **421**.
3. Petrosian, V., 1993, *Acceleration, Transport and Radiation by Electrons in Solar Flares.* High Energy Physics of Solar Flares Conference, Waterville Valley, NH, March, 1993.
4. Petrosian, V., 1973, *Ap. J.*, **186**, 291.
5. Hamilton, R.J. and Petrosian, V., 1992, *Ap. J.*, **398**, 350.
6. Hudson, H. S., Strong, K. T., Dennis, B. R. and Zarro, D., Inda-Koide, M., Kosugi, T. and Sakao, T., 1994, *Ap. J.*,, (in press).
7. Park, B. T. and Petrosian, V., 1994, *Ap. J.*, To be published.