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Turbulent particle acceleration in large solar flares

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Abstract. Gamma ray observations in some solar events of large extension or long duration are still in need of adequate theoretical interpretation. In particular, to account for the gamma-ray emission at late stage of large solar events, one of the suggestions is that particles are accelerated at the source for rather long times. On the other hand, there are some evidence of that metric radio wave emission after large (complex) solar events is due to particles accelerated in the low corona. In this paper, we obtain the power density spectra (PDS) of the metric radio emission for the events of 29 September 1989 and 15 June 1991. Those spectra are assumed to represent the spectrum of the MHD turbulence in the low corona. We then introduce them in the equations for the stochastic acceleration of ambient coronal particles, mainly wave growth rate and momentum diffusion. We give preliminary evidence of particles with sufficiently large energies to produce the gamma-ray emission in large solar events.

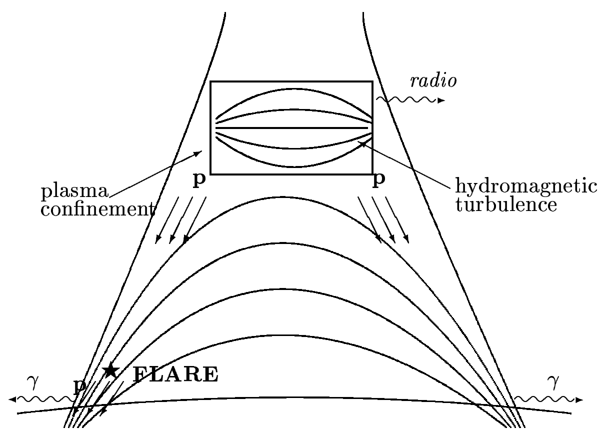

Fig. 1. Schematic picture of plasma confinement in a coronal loop, formed well after the flare. The γ rays are assumed to be produced both at the time of the impulsive phase and during the gradual phase when accelerated particles are dumped into the solar atmosphere. The radio emission is supposed to be produced by the confined plasma.

1 Introduction

Solar gamma rays from flares are one of the most conspicuous manifestations of the presence of energetic particles in the solar atmosphere. The gamma ray emission is produced by accelerated electrons and ions interacting with the ambient solar atmosphere, and they provide important information on many aspects of the physics of the Sun, including the fundamental problem of particle acceleration in flares. Recently, Pérez Enríquez et al. (2000) have proposed a schematic model to explain observations of gamma rays, as well as SEPs and metric radio emission from the large solar events of 29 September, 1989 and 15 June, 1991 (Figure 1).

In this paper we put this model to the test by assuming that the distribution of turbulence in the hot loop that arises during the gradual phase of large flares is well represented by the power spectra of the metric radio emission (Section 2). The calculations of the acceleration rate of and initial Maxwellian distribution of particles is done theoretically in section 3. We discuss, in section 4, the plausibility that this model is consistent with one of episodic acceleration and subsequent trapping. This would allow particles to be dumped into the chromospheric plasma to produce gamma ray emission for several hours, as it has been observed in some large flares.

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2 Power spectra of coronal radio emission from large flares

It is well-known that radio emission associated with different solar perturbations is an important paremater as a source of diagnostic information about the processes of particle accel-

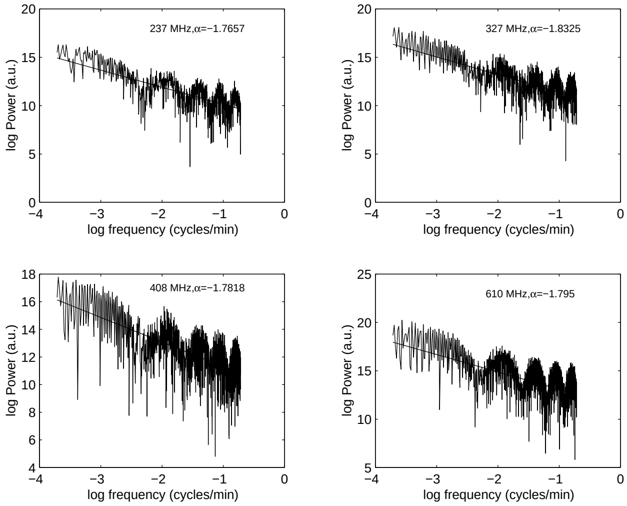

Fig. 2. Power spectra of the temporal evolution of the radio emission at 237, 327, 408 and 610 MHz as observed at the Trieste Observatory for the delayed phase of the event of 29 September, 1989

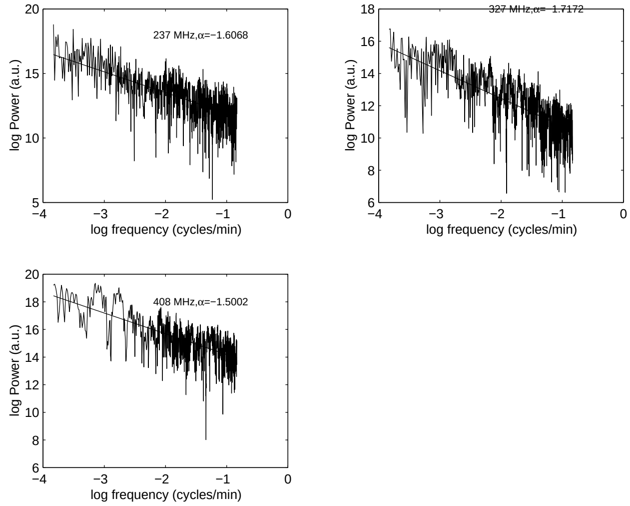

Fig. 3. Power spectra of the temporal evolution of the radio emission at 237, 327 and 408 MHz as observed at the Trieste Observatory for the delayed phase of the event of 15 June, 1991

eration at/near the Sun. In particular, the temporal behaviour (time profiles) of radio emission intensities at different wavelengths may reflect some peculiarities in the location and nature of particular sources of accelerated ions and electrons producing gamma rays (GR) and radio waves, respectively (see Akimov et al., 1996).

With this in mind, recently Pérez Enríquez*et al.* (1998, 2000) have examined the radio emission data for two large (powerful) solar events of 29 September 1989 and 15 June 1991, the latter with long duration GR emission. Notably, in these events some similarities in the radio emission profiles have been observed, namely, both present two clear (distinct) phases (prompt and delayed ones), and in both the delayed phase seems to be oscillatory in the MHz range. Even though the radio emission is produced by electrons moving in magnetic fields, they remain a part of the plasma that allows for the radio emission to be used as an evidence of plasma confinement in the solar corona. The power spectra corresponding to time series of 29 September, 1989 and 15 June, 1991 events are shown in Figures 2 and 3, respectively.

The fluctuation of the radio flux have been reported and studied by many authors (see e.g. Aschwanden, 1987, and references therein). This so called 'pulsations' include a wide range of phenomena from strictly sinusoidal oscillations up to rather quasi-periodic patterns or fine structure observed in the metric, decimetric, microwave range and also in the X-ray flux (Svestka et al., 1982; Svestka, 1994). The study of pulsations is concentrated on well defined fluctuations in the flux, i.e. in events in which the fluctuations are obvious from the register and the period can be found directly, as well as the duration and, in general, the shape of such pulsations. According to Lara (1998) and Lara and Pérez-Enríquez (1998), in events of high polarization, the fluctuations usually observed in the microwave emission are partly due to the corresponding fluctuations in the magnetic field of the region. The power spectrum of a time series gives information about the spectral composition of the fluctuations in the process that generate the time series. In particular, performing a spectral analysis of the solar flux in radio wavelenghts is possible to obtain the fluctuations in the source region magnetic field-plasma structures. The power spectrum of the solar flux observed at a fixed frequency (ν) gives the importance of the fluctuations for each frequency ($f = 1/t \neq \nu$) inside the Nyquist interval.

It is important to note that the time duration of the fluctuations (t) is directly related to the size of the source, in the sense that biger sources can change slowly and hence produce long time flux fluctuations and viceversa. Hence, in principle, it is possible to determine the physical scale of the fluctuation. Then, we can use the flux time spectrum to approximate the scale spectrum and hence measure the degree of turbulence of the process as the slope of the spectrum tends to 5/3.

For each specific case, the emision mechanisms states the relation between the plasma and the magnetic field in the radiated flux. Although, in general, independently of the emission mechanisms involved, we assume that the flux spectrum can be used to determine the hidromagnetic turbulence at the source. Only when the radio flux is highly polarized, we are able to determine the magnetic field turbulence.

In what follows, we shall use these results to the metric radio emission. On the one hand, this emission is representative of the behaviour of the plasma electrons in the region. On the other, we propose that the power spectrum of the metric radio emission is proportional to the power spectrum of the hydromagnetic turbulence in these large loops. That is, we assume that we can use the power scpectra en Figs. 2 and 3, to model the stochastic acceleration of protons in the corona during these type of events.

3 The stochastic particle acceleration process in the low corona

Contrary to what happens to particles of coronal plasma, protons trapped in high intensity magnetic fields that form after some large flares cannot escape freely into interplanetary space. Rather, they move with the magnetic field and remain trapped for long periods of time. Meanwhile, the electrons scatter around more readily than the protons but escape more easily off the magnetic field. Therefore the plasma electrons are heated rather than accelerated, and as they stream in the magnetic field lines give up radio emission at frequencies corresponding to the region where they are produced.

While trapped in the magnetic field the proton population can interact with other particles or with magnetic irregularities (hydromagnetic turbulence, for example) and be accelerated to energies as high as those allowed by the size and intensity of the magnetic field trap. as more particles become part of the process of acceleration, the particle energy density increases so that the actual process of particle energization is limited by the energy density of the magnetic field.

The Fokker-Planck can be written as a diffusion equation in momentum space as

$$\frac{\partial f(p)}{\partial \tau} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D(p)\frac{\partial f(p)}{\partial p}\right), \quad (1)$$

where $f(p)$ is the particle distribution function and $D(p)$ is the diffusion coefficient,

$$D(p) = p^2 \int \frac{d^3k\, d\omega}{(2\pi)^4}\gamma(k,\omega)\frac{< \delta B(k,\omega)\delta B^*(k,\omega) >}{B_0^2}, \quad (2)$$

where ω and k are the turbulence frequency and wave number, respectirvely,

$$\gamma(k,\omega) = \frac{\omega^2}{\mid k \mid V}\left(1 - \frac{\omega^2}{k^2V^2}\right)^2 \quad (3)$$

is the wave growth rate, V is the velocity of the particle, B_0 is the magnitude of the magnetic field and $\delta B(k,\omega)$ is the Fourier transform of the magnetic fluctuations associated with the turbulence. At the early stages of the build-up the collision frequency of Coulomb collisions and magnetic scattering by irregularities affects the rate of acceleration. When the particle flux is sufficiently anisotropic to produce its own turbulence the collision frequency adjusts itself to provide an efficient acceleration (Melrose, 1974). In figure 4, we present the growth rate of waves as a function of wave number and wave frequency, and in figure 5, we give preliminary results concerning the diffusion coefficient in momentum space for high frequencies.

The proposition is then that the turbulence causes the particles to become anisotropic through acceleration and these generate resonant waves that scatter them. So, provided the scattering rate, ν, is in the range

$$\omega\frac{v_A}{v}\left(\frac{\delta B}{B}\right)^2 \ll \nu \ll \omega\frac{v}{v_A}, \quad (4)$$

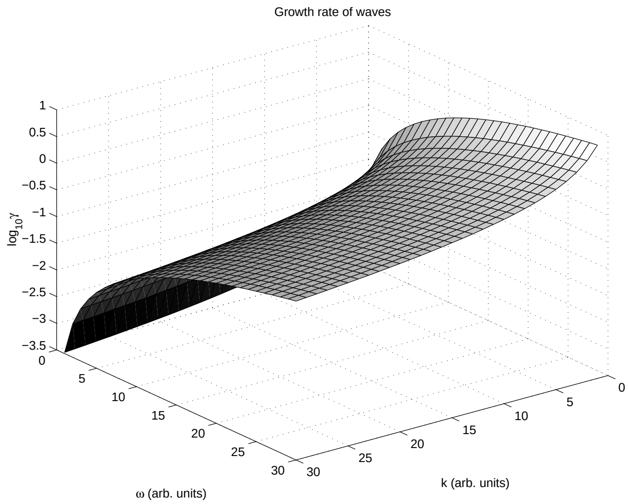

Fig. 4. Numerical calculation of the growth rate of waves, expression (3), as a function of wave number k and frequency ω

where v_A is the Alfvén velocity, the particles are efficiently accelerated. As calculated by Melrose (1980) anisotropization and isotropization balance each other in the steady state situation and

$$\nu \sim \omega\frac{v_A}{v}\frac{\delta B}{B}, \quad (5)$$

so that the acceleration time grows slowly with the particle energy E as $\tau_A \sim E^{1/2}$ for a given turbulence frequency ω. Now, for a typical value of the coronal magnetic field of 100 G, the Alfvén velocity is of the order of 4×10^8 cm s^{-1}. For values of $\delta B/B \simeq 0.01$ (weak turbulence) and $\omega \simeq 2 \times 10^3$ s^{-1} we obtain

$$\nu = \frac{8 \times 10^9}{V}, \quad (6)$$

where $v > \frac{3}{2}v_A$.

4 Discussion and Conclusions

We have proposed that well after the impulsive phase of a large flare, as the magnetic field reconstructs the active region, plasma may get confined in a kind of magnetic bottle (figure 1), where hydromagnetic turbulence may be at work. In such a turbulent environment the particles may undergo stochastic acceleration to build up a loss cone distribution (Pérez Enríquez, 1985). With this acceleration mechanism, the highest energy particles become anisotropic and come finally into the loss cone to produce the gamma rays. In the process, the impinging of the particles into the solar atmosphere gives rise to heating and consequent ”evaporation” of chromospheric material that contribute to the enrichment of plasma in the confinement, and the process repeats itself. So, only during the particle precipitation into the atmosphere are gamma rays produced. Such process stops only when the

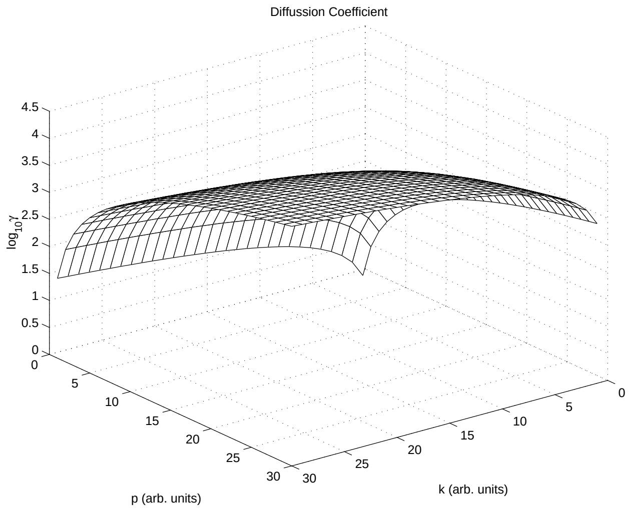

Fig. 5. Numerical calculation of the diffusion coefficient in momentum space, expression (2), for high frequencies. Both k and p are in arbitrary units.

plasma pressure becomes larger than the magnetic pressure or the magnetic field itself is disrupted. Either way, the pressure balance is broken.

Overall, we are inclined to treat our results within the framework of the more general concept of multiple acceleration that seem to characterize large (complex) solar events (e.g. Miroshnichenko et al., 2001).

Our conclusions are the following:

1. High energy particles impinging into the solar atmosphere during the delay phase of large flares can produce gamma rays for some time.

2. The character of the acceleration and build-up indicate that the gamma ray flux involved should be intermittent rather than continuous.

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