Acceleration, Dynamics and Emission of Energetic Particles in Flare Loops

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Abstract. Charged particle acceleration by DC electric field in solar flare loop is considered. It is shown that acceleration is quite effective even for electric field value much less than Dreicer field. Two problems of particle acceleration are discussed: (i) Huge quantity of accelerated particles which needs preliminary particle injection into acceleration regime; (ii) Colgate paradox: huge current value (> 10^{15} A) and magnetic field (> 10^6 G) are produced due to high acceleration rate ≈ 10^{37} el/s. The ways out are discussed. Peculiarities of propagation and emission of accelerated particle in coronal magnetic loop are analyzed. It is shown that due to wave-particle interaction the relativistic electron propagated along loop axis with the velocity 30 times less compared to light velocity. The reason for low polarization degree of Hα emission generated by ~1 MeV protons is the scattering of protons on small-scale Alfven wave turbulence.

Keywords: solar flare loops; particle acceleration; wave-particle interaction

Introduction

Charged particle acceleration under solar flare condition is the question up to now. There are several reviews devoted to this problem (see e.g. [2,15]). Quite a lot physical mechanisms are considered usually in the context of electron and ion acceleration on the Sun. First and second orders Fermi mechanisms, betatron acceleration, magnetic pumping, acceleration in shock waves, and in DC electric field are among them.

Collapsing trap model of acceleration proposed by Somov and Kosugi [17] combines first order Fermi mechanism, betatron, and shock wave acceleration, and can supply acceleration rate of about 10^{28} – 10^{29} el/s. However there are some disadvantages of the collapsing trap model. In particular, no wave-particle interaction was taken into account; productivity of the mechanism is much less than revealed from hard X-ray data, ≈ 10^{35} – 10^{36} el/s [15]. Moreover based on TRACE and RHESSI observations Sui et al [20] concluded that the most of impulsive hard X-ray events occur before the cusp structure in flare loop was seen. It means that electron acceleration predominantly occurs before a cusp formation.

Stochastic acceleration in millions micro-current sheets [22] suggests very complex magnetic structure of the flare site. Moreover high acceleration rate requires also the coherence for millions current sheets. The problem of this mechanism is how to organize such coherent situation. Magnetic pumping looks quite perspective mechanism for the particle acceleration in solar flares. Nevertheless it is necessary to understand the reasons of particle randomization between pulses of the magnetic field.

But the most direct way to gain particle energy is the acceleration in DC-electric field. We will consider here this acceleration mechanism in more details. Two problems are arising due to high productivity of particle acceleration on the Sun. The first one is the sources of additional particle injection into the acceleration process. The second one is the very high electric current driven by accelerated electrons (Colgate paradox). We consider also the consequences of plasma turbulence on propagation and emission of the energetic particles. These problems are discussed in the frame of coronal loops – the fundamental magnetic structure of solar active regions.

Acceleration in DC-electric field

Alfven and Carlqvist [1] proposed an electric circuit analog of a flare based on the measurements of vertical electric currents $I \sim 10^{11}$ A in the neighborhood of a sunspot [16]. This phenomenological approach helps us to understand the principal characteristics of flares and was advanced by many authors [11,14,18,23,24]. Indeed, the main problem of the flare energy release rate $RI^2 \sim 10^{19}$ – 10^{21} W is how to explain the high resistance ($R \sim 10^{-3}$ – 10^{-2} Ohms) needed for the electric current of about $I \approx 3\times(10^{10}$ - $10^{11})$ A. Classical Spitzer resistance is too low, about $R \le 10^{-11}$ Ohms in the solar photosphere and corona. Zaitsev and Stepanov [23] have shown that the reason for such high resistance is the Cowling conductivity in partially ionized plasma under non-steady-state conditions which is 8-10 orders less compared to the Spitzer one.

Coronal magnetic loops can be formed not only in the neighborhood of a sunspot, but also in the nodes of super-granulation cells (Fig.1). Generation of the electric currents occurs in region 1 where ion gyrofrequency is much less compared to the collision frequency of ions and neutrals ($\omega_{ci} << \nu_{in}$), but electron gyrofrequency exceeds collision frequency of electrons and neutrals ($\omega_{ce} >> \nu_{en}$). Thus the ions are dragged by a neutral plasma component during the convective flows but the electrons are closely bound to

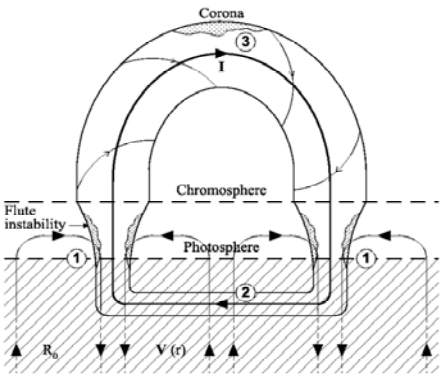

Fig.1. Cartoon model of current-carrying magnetic loop with footpoints located at the nodes of super-granulation cells. Converging plasma flows generate the electric current in region 1. Current flows through coronal part of a loop and closes just under photosphere, near the level τ_{5000} = 1. Ballooning mode of the flute instability can be a trigger for the penetration of dense plasma from chromosphere or prominence into a loop [24].

the magnetic field lines. This results charge separation and the electric field E_r arises. Both E_r and B_z generate a Hall current j_φ, and as a result B_z in a loop grows. The amplification of magnetic field continues until the field enhancement due to the convection is compensated by the magnetic field diffusion. Maximal value of the magnetic field is determined by energy×time of the convective motion. Hence the convective plasma flows (≈ 0.3-1 km/s) generate the electric current in region 1. This current flows through the coronal part of a loop from one foot point to another and closes in region 2 (where the optical thickness of radiation at the wavelength = 5000 Å, τ_{5000} = 1). Ballooning mode of the flute instability provokes high Cowling resistance in a loop due to the penetration of neutral particles from the chromosphere or from the prominence (region 3) into the current channel (Fig.1).

In the frame of the electric circuit model from generalized Ohm's law one can find the electric field component parallel to the magnetic field [24]:

$$E_{//} = \frac{\vec{E}\vec{B}}{B} = \frac{1-\alpha}{2-\alpha}\frac{\sigma V_r B^2}{enc^2(1+\xi B^2)}\frac{B_r}{B},$$

$$\xi = \frac{\sigma\alpha^2}{(2-\alpha)c^2 nM\nu_{in}}.$$

Here σ is the Spitzer conductivity, α is the relative number of neutrals, V_r and B_r are components of plasma velocity and magnetic field across the loop axis, M is ion mass. The number of runaway electrons per second is [12]:

$$dN/dt = 0.35 n\nu_{ei}V_{acc}x^{3/8}\exp(-\sqrt{2x} - x/4),$$

where $x = E_D/E_{||} >> 1$, $E_D = m\nu_{ei}V_{Te}/e$ is the Dreicer field, n is plasma density, V_{acc} is the volume of acceleration region, ν_{ei} is the electron-ion collision frequency, V_{Te} is the velocity of the thermal electrons. If for example the flute instability develops near the loop footpoint (Fig.2) with the plasma parameters n = 10^{11}cm^{-3}, T = 10^5 K, V_{acc}= 3×10^{24} cm^3, the observed values of $dN/dt \approx 10^{35}$ el/s for 100 keV electrons reach at quite small electric field $x = E_D/E_{||} = 25$ [24]. It should be noted an important peculiarity of this mechanism: electrons and ions are accelerated in the opposite directions.

There are some indications in favor of the acceleration in DC-electric field. Gamma- and hard X-ray emission of the flare on July 23, 2002 observed by RHESSI was quite surprising: the centroid of 2.2 MeV source was displaced from the centroid of HXR sources [7]. This picture can be explained if MeV ions responsible for 2,223 MeV neutron-capture line precipitate into one footpoint of the flare loop, but >100 keV electrons precipitate into another footpoint. In the flare of October 28, 2002 the 2.2 MeV sources were separated by ~ 15 arcsec from HXR footpoint sources [10].

Paradoxes of acceleration models

Miller et al [15] paid into attention on two problems in particle acceleration on the Sun. (i) Hard X-ray data suggest that acceleration rate can be as high as $dN_e/dt \approx 10^{37}$ el/s which gives quite large quantity of superthermal electron N_e(>20 keV) ≈ 10^{37}-10^{39}. For the typical plasma density in a loop $n \approx 10^{10}$ cm^{-3} and the loop volume of 10^{27} cm^3 the entire loop contains about 10^{37} electrons. It means that bulk loop plasma must be in the acceleration regime. Certainly it is difficult to find any physical mechanism for such kind of acceleration. A hybrid thermal/nonthermal model [8] suggesting maximum acceleration rate of 10^{34} el/s does not help in this situation.

Zaitsev and Stepanov [25] concluded that an additional source of particles injected in the current-carrying loop is needed. Two candidates can be considered in this context. The first one is the dense plasma of the chromosphere, $n \approx 10^{16}$cm^{-3}, and the second source is the plasma of the prominence, $n \approx 10^{14}$ -10^{15} cm^{-3}. The tongues of these plasmas can penetrate into a flaring loop due to the ballooning instability. The instability threshold depends on the ratio of the gas pressure to the magnetic field pressure $\beta = 8\pi nk_BT/B^2 \geq 0.1$-0.3. For chromospheric plasma and prominence matter this condition is well satisfied. (ii) Even for the moderate productivity of the accelerator, $dN_e/dt \approx 10^{35}$ el/s, we obtain the electric current I ≥ 10^{15} A. It gives the magnetic field value $B \geq 10^6$ G which is impossible for the Sun. The way out was proposed by Holman [9] who suggested that a loop consists of 10^4-10^6 current filaments having oppositely directed electric fields. There is more natural explanation by Lee and Sudan [13]: in the front of the beam of accelerating electrons B_Φ is changed. As the result E_z appears and produces the current directed opposite to the electron beam.

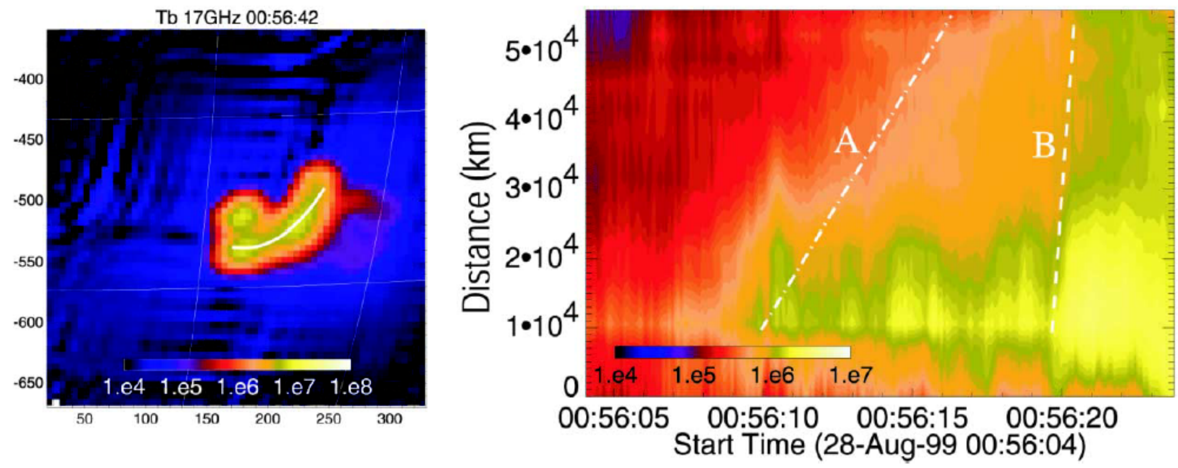

Fig.2. Time variation of the 17 GHz intensity distribution along the microwave loop observed by Nobeyama Radioheliograph. Solid white line in the left panel indicates the propagation trajectory of the emission front. Dash-dotted line 'A' corresponds to the speed of ≈ 10^4 km/s and dashed line 'B' corresponds to the light speed.

Consequences of wave-particle interaction

Coronal loops with magnetic field ≥ 100 G is, in fact, the magnetic mirror trap for accelerated particles. Indeed, the gyroradius of ~100 keV electrons $r_c = V/\omega_c \approx 10$ cm and the mean free path of ~100 keV electrons in the corona ≈ 10^{10}-10^{11} cm exceeds the loop typical scale ≈ $10^8 - 10^{10}$ cm. Thus, a loss cone for the energetic particles is formed because only particles with $(V_\perp/V_\|)^2 > \eta - 1$ are trapped in a loop. Here $V_\perp$ and $V_\|$ are transverse and parallel velocity components in respect of magnetic field, $\eta = B_{max}/B_{min}$ is the magnetic mirror ratio. Thermal plasma and high-energy particles with a loss-cone anisotropy are unstable against generation of various small-scale waves under cyclotron resonance condition $\omega - k_\| V_\| - s\omega_c = 0$. Whistler wave instability is most important for energetic electrons. As for anisotropic superthermal ions they generate preliminary the Alfven waves $\omega = k_\| V_A$. Wave instabilities in coronal loops can determine the dynamics energetic particles. For quite powerful source of energetic particles $J > J_* = cB\eta/4\pi eL$ the strong diffusion regime of particles on waves is realized [3]. Strong diffusion means that the mean time of pitch-angle scattering by about $\pi/2$ is less than the free travel time of particles in a loop, $t_d < t_0 = L/V$. Here L is the loop length, V is the particle velocity. Two effects of strong diffusion should be mentioned in this context. (i) Because the rate of pitch-angle diffusion is much large than the velocity diffusion rate the distribution function of energetic particle is almost isotropic. Only small anisotropy exists to support the wave generation. (ii) A particle interacting with small-scale waves stochastically changes its velocity direction, i.e. the particle motion along the loop axis can be described as diffusion. An anomalous viscosity appears resulting from the wave turbulence and slowing down the particle motion. Therewith the particle propagation velocity is about the wave phase velocity. Below we describe some consequences of strong diffusion.

Turbulent propagation of electrons in a flaring loop

Solar flare on 28 August 1999 observed by Nobeyama Radioheliograph at 17 and 34 GHz revealed an unusual behavior of the microwave source (a coronal loop) after injection of ≥ 1 MeV electrons (Fig.2). The observations indicated on two injections of energetic electrons into a loop. After first injection (A) the propagation velocity of the emission front along the loop was of about 10^4 km/s, which is 30 times less than the velocity of relativistic electrons generating gyrosynchrotron emission at 17 and 34~GHz. Stepanov et al [19] interpreted this anomalous propagation in terms of the strong diffusion of relativistic electrons interacting with plasma turbulence. A cloud of highly energetic electrons responsible for microwave emission generates low-frequency whistler waves, and a turbulent "wall" in the loop is formed. The electrons undergo strong resonant scattering due to the wave-particle interaction, and the emission front propagates with the wave phase velocity, which is much lower than the particle velocity. For the first injection (A) in the flare of 28 August 1999 (B = 200 G, loop length $L = 7\times10^9$ cm, mirror ratio η = 2) the flux power of injection source $J \approx 3\times10^{12}$ el/cm^{2}s ≈ $10J_*$ [19]. The second injection (B) was weaker, $J < J_*$, and electrons propagated nearly with light velocity.

Time delay of gamma-ray vs HXR emission

There are evidences that in some flares the peaks of gamma-ray line emission generated by energetic ions delayed with respect to 300 keV peaks by 2-40 s [6]. This time delays were explained usually in terms of two-step acceleration: in the first step, primary electrons are accelerated, and in the second step, ion acceleration occurs. Strong diffusion regime can explain such time delays in the case of simultaneous acceleration of ions and electrons in a flare loop [4]. Indeed "turbulent" propagation time from the loop top to the footpoint of the energetic electrons which generate the whistlers is about $t_e \approx \eta t_0(mV^2/MV_A^2)$, and the propagation time for ions which excite Alfven waves is $t_i \approx t_0(V/2V_A) = L/2V_A \geq 10t_e$ ~ 1-10 s. Here $t_0 = L/V$, V is the typical particle velocity.

Absence of linear polarization in H_α emission

Linear polarization up to 20% in H_α emission of solar flares has been reported in numerous papers. Linear impact polarization can be driven by precipitating ≤ 1 MeV ions in the flares. Bianda et al [5] using high sensitivity observations of H_α polarization of 30 flares with ZIMPOL system didn't find any indications on the polarization more than 0.07%. Absence of linear polarization in H_α emission means that the distribution of precipitating particles should be isotropic. Bianda et al [5] suggested the following reasons for the absence of linear polarization: (1) instability of Alfven waves excited by energetic protons and proton isotropization on waves; (2) isotropization due to proton-neutral collisions; (3) defocusing by the converging magnetic field. Therewith they considered that factors (2) and (3) are most important. Tsap and Stepanov [21] proposed that the main reason for proton isotropization is the wave-particle interaction. Accelerated protons propagate toward loop footpoints and penetrate into the level of Hα emission. High degree of particle isotropy is due to the excitation of small-scale Alfven waves by energetic protons and effective pitch-angle scattering of particles. Estimations have shown that threshold for Alfven wave instability requires relative density of ≤ 1 MeV protons $n_1/n \geq 4\times10^{-6}$. Alfven waves scatter the protons and make them almost isotropic for the diffusion time $t_d \approx 5\times10^{-3}$ s << $t_0 = L/V \approx 1$s. This is necessary condition for strong diffusion. Sufficient condition requires $J > J_* \approx 5\times10^{12}$ pr/cm²s [3]. Acceleration rate of ~ 1 MeV protons in solar flares ranges from 10^{33} to 10^{34} pr/s [15]. For the loop cross section $S \approx 10^{17}$ cm² it gives $J \approx (10^{16} - 10^{17})$ pr/cm²s >> J^*. In the case of weak particle source and low level of Alfven wave turbulence ($B_A^2/B^2 < 10^{-5}$) strong diffusion is not realized and Hα emission is linearly polarized.

Conclusions

We have shown that coronal magnetic loops, the fundamental structures of the solar atmosphere, are the regions of effective particle acceleration. Alfven—Carlqvist's view of a coronal loop as an equivalent electric circuit allows a good understanding of physical processes in a loop. Various mechanisms of charged particle acceleration work in the flaring loops, but acceleration in DC-electric field is the most direct way to gain particle energy. To supply the sufficient number of accelerated particles (10^{37}-10^{39}) an additional particle injection in acceleration regime are needed. The sources of additional injection can be the dense chromosphere plasma and/or prominence matter penetrating into a loop due to, for example, the ballooning instability. Wave-particle interaction plays the important role in dynamics and emissions of high-energy particles in a loop and can explain the peculiarities in high-energy particle propagation, as well as in time delays of HXR vs gamma emission, and polarization in H_α emission.

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