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Electron Acceleration in Collapsing Magnetic Traps during the Solar Flare on July 19, 2012: Observations and Models

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Abstract. Using the appropriate kinetic equation, we considered the problem of propagation of accelerated electrons into the solar corona and chromosphere. Its analytical solution was used for modelling the M7.7 class limb flare occurred on July 19, 2012. Coronal above-the-loop-top hard X-Ray source was interpreted in the thin-target approximation, the foot-point source - in the thick-target approximation with account of the reverse-current electric field. For the foot-point source we found a good accordance with the RHESSI observations. For the coronal source we also got very accurate estimate of the power-law spectral index, but significant differences between the modelled and observed hard X-ray intensities were noticed. The last discrepancy was solved by adding the coronal magnetic trap model to the thin target model. The former one implies that the trap collapses in two dimensions, locks and accelerates particles inside itself. In our report, we confirm an existence and high efficiency of the electron acceleration in collapsing magnetic traps during solar flares. Our new results represent (e.g. for RHESSI observations) the theoretical prediction of the double step particle acceleration in solar flares, when the first step is the acceleration in reconnection area and the second one – the acceleration in coronal trap.

Keywords. acceleration of particles, Sun: corona, flares, magnetic fields, X-rays

1. Introduction

The acceleration of charged particles to high energies remains a topical problem of modern astrophysics as applied to phenomena different in their scales and nature, for example, solar flares. The latter are of particular interest for two reasons. The first one is the studying and forecasting magnetic storms and other manifestations of space weather, which are directly related with accelerated particles. The second one is the studying the physical particle acceleration mechanisms, because they can be investigated most comprehensively with high spatial, temporal, and spectral resolutions. At present, the achieved accuracy of electromagnetic radiation detectors onboard spacecraft is so high that the observational data allow us to reconstruct a complete picture of particle acceleration and propagation in the solar atmosphere and, thus, to check whether the existing model assumptions are correct. The overall picture and scenario of a solar flare may be considered without exaggeration to have been well studied (Somov 2012; Somov 2013; Krucker *et al.* 2008) – magnetic reconnection plays a decisive role in this manifestation of solar activity.

Let's consider the particles acceleration process during solar flares (Somov & Kosugi 1997). The electrons and ions are pre-accelerated by the electric field in the reconnecting current layer (RCL in Figure 1). After this first step in the acceleration process, they end up in the coronal magnetic trap (trap in Figure 1), whose length and cross-sectional size (thickness) decrease rapidly. In such a collapsing trap the captured particles are

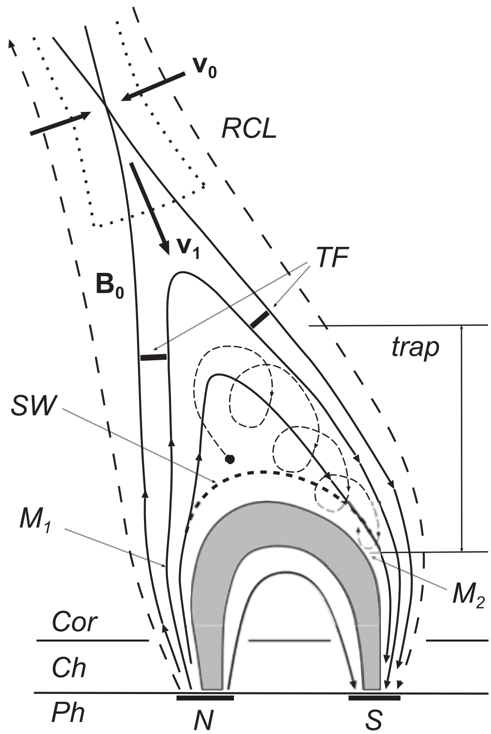

Figure 1. The coronal magnetic trap (trap) between the turbulent front (TF) and the magnetic mirrors (M1, M2). The dashed spiral indicates the trajectory of a trapped electron. SW is the shock wave separating the hot and cold plasmas. RCL is the high-temperature reconnecting current layer, the source of primarily accelerated electrons.

reflected from the shock wave or from the magnetic mirrors M1 and M2 in Figure 1. Inside the collapsing trap the charged particles acquire an additional acceleration through the first-order Fermi mechanism and betatron heating. Such a picture was called double step acceleration in Somov & Kosugi 1997 and has not yet been confirmed by convincing observations of flares, remaining predominantly a theoretical prediction. In this short report we present the new observations, which possible confirm the double step acceleration model.

2. Multi-wavelength observations of the flare and models

The July 19, 2012 flare was observed at the solar limb by the RHESSI, GOES, and SDO spacecraft (Liu 2013) with a high accuracy, making it suitable for investigating the magnitude and efficiency of the possible additional electron acceleration in the corona. The data on the spectrum, locations, and spatial scales of the coronal and chromospheric hard X-ray sources are described in detail in Krucker & Battaglia 2014 and Krucker *et al.* 2015. We calculated the energy flux density of the electrons accelerated in the reconnecting current layer (to fit the intensity of the hard X-ray spectrum observed in the chromosphere footpoint) or, more precisely, the fast electrons escaping from the current layer through the turbulent front (TF) in schematic Figure 1 within the framework of a self-consistent thick-target model with a reverse current (Gritsyk & Somov 2014). The need to consider the reverse current, which compensates for the electric current carried by a bundle of fast moving electrons, is obvious. If it did not exist, bundles of accelerated

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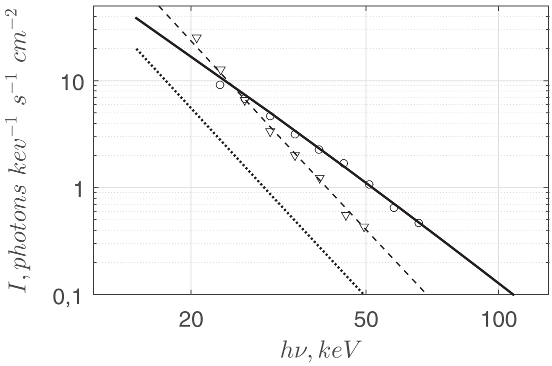

Figure 2. Observed and calculated hard X-ray spectra for the July 19, 2012 solar flare. The results of modelling the chromospheric source are represented by the straight solid line; the observations are indicated by the circles. The results of modelling the coronal source without and with allowance for the electron acceleration in the collapsing magnetic trap are represented by the dotted and dashed straight lines, respectively; the observations are indicated by the triangles.

electrons would generate enormous currents ($\sim 10^{17}$ A) and, consequently, huge magnetic fields, which are not observed in the actual flares. We applied the formalism of the thin-target model (Somov & Syrovatskii 1976) to calculate the intensity of the coronal hard X-ray source. To explain the observed emission simultaneously in the chromosphere and the corona, we supplemented the models mentioned above (Gritsyk & Somov 2017) by the model of a collapsing magnetic trap (Somov & Kosugi 1997).

The solid line in Figure 2 represents the hard X-ray spectrum for the chromospheric source of the July 19, 2012 flare that was calculated in the thick target model with a reverse current. It is clearly seen that the calculated X-ray spectrum in the chromosphere closely coincides with the observed one in both intensity and slope. The spectrum of the coronal source calculated in the thin-target approximation is also presented in Figure 2. Let's discuss the important conclusion of this report: it is fundamentally impossible to model the observed spectra of the coronal and chromospheric hard X-ray sources in terms of the classical flare model. Indeed, the difference of slope indexes of these spectra $\varphi_{Cor} - \varphi_{Ch} = 2$ always in the classical model, while according to the observations of the July 19, 2012 flare, $\varphi_{Cor} - \varphi_{Ch} \approx 1.6$. In the model with a reverse current the observed ratio of the slopes is naturally obtained for the observed flare parameters. In other words, the thick-target approximation with a reverse current not only accurately describes the X-ray spectrum of the chromospheric source, but also allows the slope of the spectrum in the corona to be properly estimated. The intensity of the coronal source (the dotted line in Figure 2), which is lower in the model than the observed one by a factor of ≈ 4.5, constitutes an exception. In our opinion, such a marked difference between the calculated and observed intensities, while the spectral slopes closely coincide, is a weighty argument for the idea of the existence of particle acceleration and its high efficiency in the collapsing magnetic trap formed by convergent magnetic field lines in the upper part of the flare loop (Figure 1). Such an observational picture was predicted theoretically by Bogachev & Somov (2007), but in the absence of accurate space experiments it has had no convincing confirmation until now.

3. Conclusions

Today, the study of solar flares in the context of space weather is of great practical importance. The key point in this issue is the process of primary energy release and related with it acceleration of charged particles to high energies. For studying the role of different acceleration mechanisms, we considered a model for the limb flare of July 19, 2012, for which highly accurate satellite observations (primarily from the RHESSI spacecraft) are available. This flare was chosen for our modelling due to the presence of a bright coronal hard X-ray source, which was observed synchronously with the sources located in the chromosphere near the flare loop footpoints. The flare model is based on the analytical methods proposed in earlier papers (Syrovatskii & Shmeleva 1972; Somov & Kosugi 1997; Somov & Bogachev 2003; Gritsyk & Somov 2014). The classical flare model based on the thick-target approximation was shown to be inapplicable for the description of solar flares with a coronal X-ray source, because it incorrectly predicts the slope of its spectrum.

Our attention was focused on investigating the coronal hard X-ray source that, in our opinion, is attributable to the existence of collapsing magnetic traps produced by magnetic reconnection. Convincing arguments for the existence of coronal traps and their decisive role in the particle acceleration in solar flares constitute the main result of this report. This result was obtained from general assumptions about the pattern of particle acceleration during solar flares, with the main one being the assumption about the existence of double step electron acceleration (Somov & Kosugi 1997). Owing to the existing and prospective space experiments, one might expect new confirmations of our conclusions.

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