Evidence for Field-parallel Electron Acceleration in Solar Flares

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Abstract

It is proposed that the coincidence of higher brightness and upward electric current observed by Janvier et al. during a flare indicates electron acceleration by field-parallel potential drops sustained by extremely strong field-aligned currents of the order of $10^8$ A m$^{-2}$. A consequence of this is the concentration of the currents in sheets with widths of the order of 1 m. The high current density suggests that the field-parallel potential drops are maintained by current-driven anomalous resistivity. The origin of these currents remains a strong challenge for theorists.

Key words: Sun: corona – Sun: flares – Sun: magnetic fields – Sun: X-rays, gamma rays

1. Introduction

It is generally accepted that the energy released in a solar flare originates from the reconnection of coronal magnetic fields. Much less agreement exists about the detailed processes accelerating the electrons to the energies appearing in the hard X-ray emissions. There are three groups of theoretical models (e.g., Aschwanden 2006): Stochastic or second-order Fermi acceleration, shock acceleration, and acceleration by the dc electric field components along the magnetic field lines. The latter process has gained much theoretical attention since the paper by Alfvén & Carlqvist (1967). Subsequent investigations, e.g., by Colgate (1978), Holman (1985, 2012), Haerendel (1994, 2012), Volwerk & Kuijpers (1994), Emslie & Hénoux (1995), and Tsuneta (1995), were demonstrations of the principal possibility and its implications, but electron acceleration by reconnection or turbulence processes remained in the forefront of flare theories. The reasons are twofold. First, energy conversion in the dense coronal plasma demands the existence of extremely narrow current sheets, i.e., they scale way out of the ranges of observability. Second, no convincing process was offered for the generation of such narrow structures. The data discussed in this paper present the first observational evidence for the existence of field-parallel acceleration. We owe this to the advances in solar observations, in particular to the high spatial resolution of 3D photospheric magnetic fields by the Helioseismic Magnetic Imager (HMI) magnetograph on the Solar Dynamics Observatory, which allows for the determination of the vertical electric currents outside of the photosphere.

2. The Evidence

It is not uncommon that in a scientific paper far-reaching conclusions are being drawn from rather uncertain observational or experimental results. The opposite is much rarer, namely that the authors do not point out important information contained in a rather accurate data set. I refer to Figure 6 in the paper by Janvier et al. (2014). It contains on the left two images of the 2011 February 15 flare obtained by AIA 335 Å, one before, and the other after the peak of the flare. In the middle one sees the distribution of vertical currents, $J_z$, for the same times superposed over the saturated AIA 335 Å images. The figures on the right are of no concern here. My point is the following: when comparing the left and middle images, it clearly transpires that an asymmetric brightness distribution exists between upward and downward currents. The upward current contours clearly coincide with the higher intensity. This is confirmed by the more energetic emissions at 94 Å shown in Figure 5 of Musset et al. (2015). Indeed, there is no overlap between the brightness contours in this figure with that of the downward current region shown in Figure 1 (bottom of the same paper) but rather a striking coincidence with those of the upward current. Also the hard X-ray contours from RHESSI, analyzed by the latter authors, exhibit a preferred coincidence of the maxima with the upward current ribbons (compare with the remark in Section 4.2 of Musset et al. 2015). It must be noted, however, that there is no one-to-one correspondence between the upward current and high intensity. A current intensity correlation with the original data is needed to put this conclusion derived from visual inspection of printed papers on firmer grounds.

Even in the absence of a thorough data analysis, one can derive the following conclusion: if the direction of the current matters for the precipitation of high-energy electrons, in particular in the most intense flare ribbons, this can only mean that somewhere in the upward current loop there must exist a field-parallel potential drop accelerating or at least post-accelerating the electrons carrying the downward energy flux. The latter is the more surprising, as the configuration of the 2011 February 15 flare, with upward- and downward-directed magnetic fields only separated by a narrow channel, was such that reconnection at high altitude should have been the main source of the energy flux, with no preference for one of the two polarities.

3. Consequences

Presentation of the evidence is not enough. There are severe consequences resulting from the energy deposition rate by the field-aligned electron beam and the accelerating potential. On the first, we have to make an assumption because of its limited spatial resolution. I use the combined high-resolution optical and hard X-ray observation of a X6.5 flare by Krucker et al. (2011) as a reference. The authors determined an energy deposition rate above 18 keV of $>5 \times 10^{12}$ erg s$^{-1}$ cm$^{-2}$. The...
electron acceleration by a parallel electric field might have provided only part of the total energy flux. Taking this into account and in order to be concrete, I choose an energy flux of \( F_E = 10^{11} \text{erg cm}^{-2} \text{s}^{-1} \) above 5 keV. The underlying assumption is that the accelerating potential drop was at least 10 kV and on average one-half of that was picked up by the runaway electrons. Further, assuming that the runaway electrons carried away only half the locally converted energy, and dividing the latter by a potential difference of 10 kV, yields \( j_\parallel = 2 F_E / \Phi_0 = 10^4 \text{A m}^{-2} \). This is a disturbing result in view of photospheric currents up to only about 80 mA m\(^{-2}\) found by Janvier et al. (2014; see their Figures 2 and 3). On the other hand, the high currents are not in conflict with some of the above cited theoretical models. And if I had chosen a substantially lower energy flux, it would not have changed the conclusion that a significant contribution to the energy deposition by field-parallel electron acceleration implies the presence of extremely high current densities.

The discrepancy between the observed and implied current densities by many orders of magnitude raises questions, perhaps disbelief, but also challenges the theorist. High current densities imply very narrow widths. By contrast, the determination of the 3D photospheric field and current density suffers from the limited spatial resolution of about 1".5. I therefore assume that the magnetic perturbation field due to the upward current amounted to about 10% of the vertical field of up to about 2000 G (Janvier et al. 2014; Musset et al. 2015). This corresponds to a considerable shear field. A current of \( 10^8 \text{A m}^{-2} \) would have to have a width of only 1.6 m for generating a 200 G perturbation field. Shear field and electron (and ion) acceleration are intimately connected because it is the conversion of magnetic energy by the release of magnetic shear stresses, enabled by the decoupling action of the parallel electric potential drop, that supplies the energy for the acceleration process (Haerendel 2007). In other words, a field-aligned current capable of converting free magnetic energy corresponding to a shear field of 200 G into an energy flux of \( 10^{11} \text{erg cm}^{-2} \text{s}^{-1} \) carried by 5 keV electrons would have to be concentrated in a sheet of the order of 1.6 m. Such currents would not be detectable with present days’ resolution of 3D magnetic field measurements.

On the theoretical side, such extremely dense currents have the merit of falling into the range required for the generation of anomalous resistivity by current-driven micro-turbulence. Haerendel (2012) derived for the critical current density

\[
j_{\text{crit}} = 8.3 \times 10^3 \text{A m}^{-2} \cdot \left( \frac{n}{10^{10} \text{cm}^{-3}} \right) \cdot \left( \frac{T_e}{10 \text{MK}} \right)^{1/2}.
\]

Depending on the altitude of the accelerating potential drop and the actual coronal density, \( n \), and electron temperature, \( T_e \), one can obtain critical current densities close to the above derived values. If this limit is actually reached by current filamentation, micro-turbulence would be driven, the resistivity greatly increased, and strong parallel potential drops could be sustained.

4. Discussion

The main issue arising from the first conclusions derived above is how and where extreme current densities can be created. The mere lack of today’s observability is not a valid argument against their existence. The same situation exists with respect to the transverse current densities postulated for the reconnection process. The fact that they must be of similar magnitude as that of the here derived parallel currents has not prevented the general acceptance of the reconnection process. On the other hand, it is unlikely that such thin field-aligned current filaments or sheets emerge out of the photosphere. The high resistivity around the temperature minimum would lead to fast dissipation, irrespective of its direction. This leads to the question: can such currents be generated in the corona due to the dynamics of the flare plasma? And how would they continue into the photosphere? These are extremely challenging questions.

Origin in the corona would require generation of steep gradients in the perturbation field. What comes to mind is filamentation by magnetic braiding (Wilmot-Smith et al. 2009) or the creation of an enormous amount of small-scale current sheets by the plasmoid instability (Huang & Bhattacharjee 2016). Another way would be that strong shear forces, by distorting a loop of, say 1000 km width, create a drop of the perturbation field of a few meters width, thereby producing an extended, but very thin, current sheet. Such a solution was proposed by the author (Haerendel 2012). Most tempting is the association with reconnection in a Quasi-Separatrix Layer (QSL), as suggested for the discussed event by Janvier et al. (2014). As it has been shown by Aulanier et al. (2006), parallel electric fields are not only important in this situation, but are mainly responsible for particle acceleration. Thus, a QSL reconnection does imply a dependence on the direction of the field-aligned current. However, the numerical models are not yet developed to the stage that one could expect current densities and electric fields to be anywhere close to reality. In fact, the model of Aulanier et al. (2006) employs resistivities by six orders of magnitude above anomalous resistivity and currents by about six orders of magnitude below those postulated above.

Whether braiding, current sheet formation, or extreme magnetic diffusivity, this short paper is not meant to present answers to these questions. The main intention is to direct attention to an observation that seems to support significant contributions to a flare by high-energy electrons accelerated in highly concentrated field-aligned currents. A few consequences have been pursued with respect to current density and width. An immediate goal would be to stimulate further searches for other cases of strong imbalances of the energy fluxes between upward and downward vertical currents. If more cases become known, acceleration in the corona by parallel electric fields would move out of the shades of speculation into the light of a viability.

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