Global aspects of solar flares

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Abstract. Existing global models for flares do not include an essential ingredient in the electrodynamics: the inductive electric field due to the time-varying magnetic field. How the large ($\approx 10^{10}$ V) electromotive force and the current it drives can be included in a model is discussed. Alfvén waves play an important role in transporting energy and potential, and in redistributing current on a global scale.

1. Introduction

Global aspects of solar flares were emphasized in flare models from the 1940s to the 1980s, as is evident from Hudson's solar flare cartoon archive.[1] Most of the flare models that emerged are variants of either the CSHKP model [1, 2, 3, 4] or of a circuit model [5, 6, 7]. In a CSHKP model, the magnetic energy release occurs through magnetic reconnection in a current sheet along the axis of a coronal streamer. In a circuit model, the energy release is attributed to current dissipation due to the turning on of an effective resistance in a current-carrying coronal loop. It is widely accepted that a flare involves release of magnetic energy stored in the corona prior to a flare. Some flares involve the eruption of a magnetic arcade, due to internal or external reconnection following post-emergence shearing or twisting, resulting in the 'two-ribbon' photospheric emission pattern observed from either side of a magnetic polarity-inversion line. In other (non-eruptive or compact) flares, the energy release is driven by newly emerging magnetic flux impinging on and reconnecting with existing magnetic flux, and the energy goes primarily into energetic electrons, rather than into the kinetic energy of a coronal mass ejection. The magnetic free energy is associated with coronal currents of order 10^{11} A that are observed in vector magnetogram data. The currents are assumed to flow along coronal loops and close deep inside the Sun. CSHKP and circuit models incorporate neither the effect of newly emerging magnetic flux nor the boundary condition that the current at each footpoint does not change significantly on the timescale of a flare. These deficiencies partly motivated the development of quadrupolar models [8, 9, 10, 11] in which magnetic reconnection allows transfer of flux and current between two pairs of bipolar footpoints. Figure 1 illustrates such a model. An essential feature of the physics that is not included in any existing model is an inductive electric field. From Faraday's equation, the 'potential' (the line integral of the electric field around any closed path) is equal to minus the rate of change of the enclosed magnetic flux, and this is very large in a flare, $\Phi = 10^9$–10^{10} V. In this paper I discuss how Φ can be included in a global model [12, 13], and I indicate how including it might help resolve two long-standing related problems.

[1] see http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

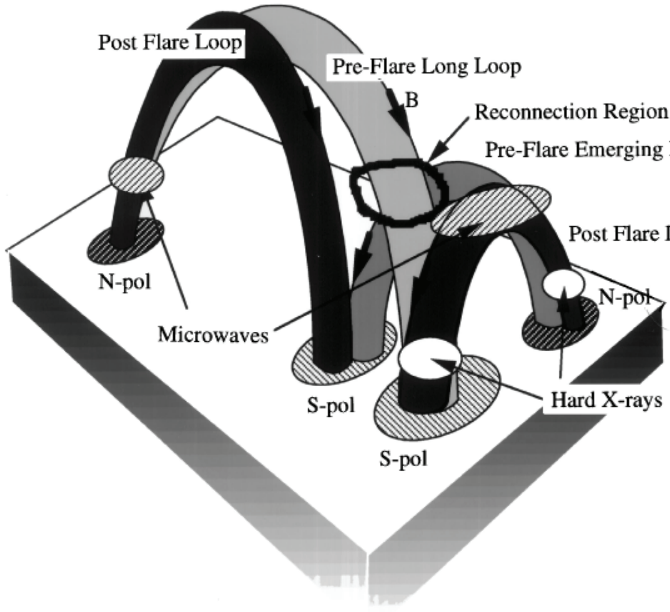

Figure 1. A cartoon of a quadrupolar model [10]. The pre-flare loops reconnect to form the post-flare loops, and the generator region corresponds to the indicated Reconnection Region.

The two problems are 'bulk energization' of electrons and the 'number problem'. Most of the nonthermal energy in a non-eruptive flare goes into bulk energization of the $\varepsilon = 10$–$20\,\mathrm{keV}$ electrons that produce hard X-ray bursts and type III radio bursts. The acceleration requires a parallel electric field [14], but how this develops is not understood; moreover, there is no obvious explanation as to why electrons are not accelerated to a much higher energy, of order $e\Phi$. Two aspects of the number problem are that the rate accelerated electrons precipitate, $\dot{N} > 10^{36}\,\mathrm{s}^{-1}$, implies a current, $e\dot{N}$, that greatly exceeds the maximum possible current that can exist in the corona [15], and that the total number of electrons that are accelerated during a flare greatly exceeds the number in the flux loop prior to the flare [16, 17]. These problems are related in that the power released, $I\Phi$, may be written as $\dot{N}\varepsilon$, with $e\dot{N} = MI$ and $e\Phi = M\varepsilon$, where the multiplicity factor is of order $M = 10^6$. A successful model needs to explain this multiplicity.

2. Parameters for a flare

A global model involves bulk parameters, and characteristic values for these parameters are needed. The power and energy released in flares cover several orders of magnitude. Here I assume a large flare with a power of $I\Phi = 10^{21}$ W and a flare time $\tau = 10^3$ s, resulting in the release of 10^{24} J of magnetic energy. The magnetic energy stored in a single magnetic loop is $\frac{1}{2}LI^2$, and assuming two loops one has $LI^2 = 10^{24}$ J. The current is assumed to be $I = 10^{11}$ A, from vector magnetogram data. The inductance depends primarily on the length of the loop, and a change in the stored energy requires a reduction in the length of the loop [9]. The resulting change in the inductance is assumed to be $\Delta L = 10^2$ H. The rate of change in the magnetic flux, LI, then implies $\Phi = \Delta L\, I/\tau = 10^{10}$ V.

The fact that such a large value of Φ must be present during a flare was already in the literature in the 1930s [18], but it is not included explicitly in CSHKP or quadrupolar models, and it is attributed incorrectly to a photospheric dynamo in most circuit models. This 'potential' is more appropriately interpreted as an electromotive force (EMF), which drives a current around a circuit. The current that this EMF drives must be 'new' in the sense that it did not exist prior to the onset of the flare. The currents flowing through the footpoints do not have time to change during a flare, so this 'new' current must involve redirection of the pre-flare currents. The path of this 'new' current must form a closed loop that encloses the changing magnetic flux, and includes a cross-field portion in the region where the reconnection occurs [13]. The flare is driven by a 'generator', where both I and Φ are across field lines in the corona. There is no obvious generator in a CSHKP model, and the generator is incorrectly identified with a photospheric dynamo in a circuit model. The generator in a quadrupolar model is indicated in Figure 1.

3. Analogy with substorms

The concept of a generator region is familiar in the context of geomagnetic substorms. Our understanding of substorms and flares has complementary aspects, such that the analogy between them is useful in identifying generic properties of magnetic explosions [12]. A specific property that is obvious for substorms is that the generator region is widely separated from the acceleration (of auroral electrons) region. This requires that the magnetic energy released in the generator propagate over a long distance before it dissipates through acceleration of electrons. Fletcher and Hudson [19] applied this to a model for flares, illustrated in Figure 2, in which they emphasized energy transport by Alfvén waves. Haerendel [20, 21] pursued the analogy between flares and substorms in further detail.

A specific model for energy transport between the generator and the acceleration region in substorms [22, 23] involves large-amplitude Alfvén waves. The electric field in the wave may be described in terms of a wave potential. The waves also transport potential along field lines, mapping the cross-field Φ at the generator onto the top of the acceleration region. There is also a parallel current, $J_\parallel$, associated with the wave. Alfvén waves have no net parallel current associated with them, that is, the integral of (the wave-associated) $J_\parallel$ over area perpendicular to the field lines must vanish. In the simplest case there is one area with current flowing up and a neighboring area with an equal current flowing down. These up and down currents close across field lines at the generator and across field lines in the ionosphere or photosphere. The Alfvén wave effectively sets up a loop current, with up and down field-aligned currents closing across field lines at boundaries. This closed loop pattern is well recognized in the context of substorms [24], where it is called a current wedge. Essentially the same effect had been recognized much earlier in a laboratory context [25]: a current driven across field lines in the body of the plasma tends to close through field-aligned currents to a boundary where Ohm's law allows closure. In the solar context, this conducting boundary can be identified as the photosphere. The cross-field (Pedersen) conductivity of the photosphere [26, 27] is large enough to allow such closure. The concept of a current wedge has already been invoked in at least one solar model [28, 29].

A further relevant idea, attributed to Gurnett [30], is that the equi-potential surfaces (above the acceleration region) must close across field lines somewhere above the highly conducting boundary. Closure of the equi-potential surfaces implies a parallel electric field, and this field is assumed to accelerate electrons, drawing energy from the Alfvén waves and causing them to damp. In other words, a postulated loss of wave energy to accelerated electrons implies that the waves damp, so that the wave potential decreases with decreasing height, with the resulting gradient of this potential implying the $E_\parallel$ that transfers the wave energy to electrons. Although a full understanding of the dissipation/acceleration process requires a specific mechanism for setting up $E_\parallel$ [31], this idea allows one to infer that the global physics requires such an $E_\parallel$ must be develop.

4. Discussion and Conclusions

Existing solar flare models omit an essential part of the basic electrodynamics: the inductive electric field and associated EMF. Release of magnetic energy implies that the magnetic flux in

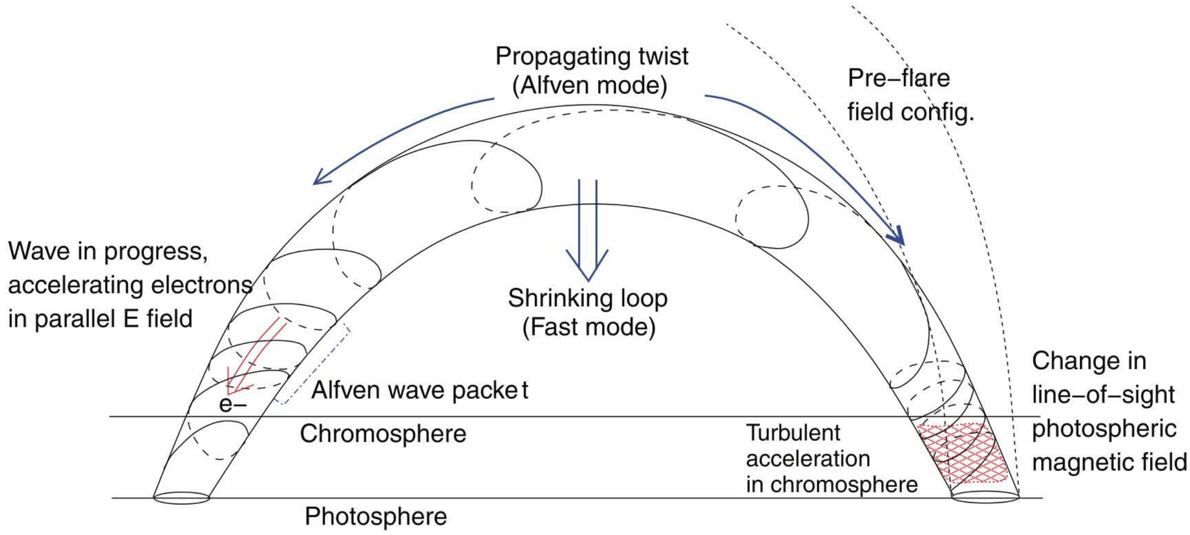

Figure 2. A cartoon showing a model due to Fletcher and Hudson [19] for energy release in a flare in which energy is transported from an energy release site (effectively at the top of the loop), via Alfvén waves to an acceleration region in the chromosphere.

the corona is decreasing, and Faraday's law implies an EMF (of order 10^{10} V) around any path that encloses this changing flux. This EMF drives a flare-related current that allows the coronal current distribution to change as the magnetic structure changes. The EMF plays a central role in any magnetic explosion, and an acceptable global model for flares must take it into account explicitly.

Alfvén waves transport energy and potential along field lines, and redistribute current across field lines. They link the widely separated generator and acceleration regions. Their damping in the acceleration region is due to the development of $E_\parallel \neq 0$ that accelerates the electrons.

A multiplicity M is needed to relate Φ to the potential Φ/M that observations imply is available to accelerate the electrons. The only plausible explanation for M was proposed by Holman [14]: the current flows back and forth M times between the generator and the acceleration region, with the effective EMF driving each pair of up and down flows being Φ/M.

4.1. Acknowledgments
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