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IMPLOSIONS IN CORONAL TRANSIENTS

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ABSTRACT

Coronal events such as flares or coronal mass ejections derive their energy from the energy stored locally in the magnetic field. This leads to the conjecture that a magnetic implosion must occur simultaneously with the energy release. The site of the implosion would show the location of preflare energy storage, and its detection should have a high priority. The *Transition Region and Coronal Explorer* EUV observations, for example, have sufficient resolution to show the geometry of a flare implosion by following the motions of tracers in the images.

Subject headings: Sun: corona — Sun: flares — Sun: magnetic fields

1. INTRODUCTION

The coronal magnetic field, according to generally accepted views, serves two roles during a transient event such as a flare or a coronal mass ejection. The field physically contains the energy, and it also imposes geometrical structure (before and after an event) because of the frozen-field condition. This Letter explores the basic physical consequences of this situation, summarizing them in a conjecture. The conjecture points out that these events should involve *implosions*, which, if successfully observed, would help to clarify the basic physics of the transient.

What makes this important? We frequently see apparent eruptions of the solar magnetic field, most spectacularly in the "coronal mass ejections" (CMEs; e.g., Hundhausen 1998; Hudson & Webb 1997). Solar flares and other low-coronal phenomena (surges, sprays, jets) also frequently involve ejections. In almost no case do we see inward motions focused toward the site of energy release, as predicted by the conjecture described below. Successful observations of such motions would show us directly where the energy stored prior to the transient had resided, which would help in identifying the nature of the instability leading to the transient (flare and/or CME).

2. BASIC PRINCIPLES AND ASSUMPTIONS

The discussion below assumes that a coronal transient event—a major disturbance, such as a flare or a CME—evolves rapidly with respect to the Alfvén transit time of the photosphere. In other words, the energy required for the event must come from the corona directly (assumption A) because of the low Alfvén speed in the photosphere. Second, we assume that gravitational potential energy plays no significant role (assumption B). Finally, we assume low plasma β (assumption C). This last assumption represents an idealization because high-β regions probably do occur in solar flares (e.g., McKenzie & Hudson 1999). The three assumptions do not conflict in general with current theoretical ideas regarding coronal activity on large scales.

With these assumptions, the conservation of energy implies that the quantity $\int_V (B^2/8\pi)dV$, where the integration covers the entire corona, must decrease between the static states before and after the energy release. This statement would hold, no matter what mechanism actually releases the energy, since the approach here depends just on the geometry of the coronal magnetic field. In essence, the addition of stress to a model coronal field originally describable as a potential or a force-free field causes it to inflate, as shown by numerical experiments (e.g., Sturrock et al. 1994). This corresponds intuitively to the idea that increasing the strength of coronal currents generates an additional magnetic field from sources above the photosphere, thereby increasing the coronal magnetic pressure and inflating the structure. A transient involving only an expansion of the field, which thus implies an increase of the stored energy, could not occur as the result of an instability.

One should note that on the short timescale assumed here, the currents linking the corona and the photosphere cannot change appreciably, so that a coronal event must involve a restructuring of the existing coronal current system in such a way as to diminish the energy contained in the field (Melrose 1997). This restates assumption A.

3. CONJECTURE AND COMMENTS

The need for a reduction in $\int_V (B^2/8\pi)dV$ suggests that individual magnetic field lines must somehow contract over a substantial volume of the corona in order to generate energy for radiation or other observable phenomena. If these effects include expansion of other parts of the coronal field, a further compensating implosion in other regions must simultaneously take place. The idea of contraction may not always have a well-defined meaning, though, because during the event itself, a magnetostatic description of the field would not apply. The field lines may reconnect and lose their identities. However, even though the field lines may become scrambled, the photospheric footpoints must remain anchored in place because of "line-tying," and their connections could decrease in length and so reduce the stored energy. Bearing this in mind, I propose the following conjecture: *During a transient, the coronal field lines must contract in such a way as to reduce* $\int_V (B^2/8\pi)dV$. This conjecture, although precisely stated (assumptions A, B, and C), may not have a general proof that applies to the real corona for CMEs because of the presence of the solar wind reaction force at work on large scales. But it should apply to any transient involving energy release on a timescale consistent with the energy available in a volume determined by the coronal Alfvén speed, which sets the limit on the volume capable of

TABLE 1
ENERGETICS

Phenomenon	Energy (ergs)	Δt (s)	B (G)	n_e (cm^{-3})	R^* (cm)	E^* (ergs)
Impulsive spike	10^{29}	1	300	10^9	2.1×10^9	3.6×10^{31}
Flare impulsive phase	10^{30}	10	300	10^9	2.1×10^{10}	3.6×10^{34}
Arcade flare loops	10^{31}	10^3	10	10^9	5.9×10^{10}	5.5×10^{33}
CME from streamer	10^{32}	10^4	1	10^8	2.2×10^{11}	1.7×10^{33}

supplying energy that can focus into the energy-release site, as discussed below.

4. OBSERVATIONAL IMPLICATIONS

The conjecture stated in § 3 sounds inconsistent with most of the observational material. Normally, the large-scale motions seen in eruptive flares (and, of course, in CMEs) seem *explosive* rather than *implosive* (e.g., Moore et al. 1999). The "shrinkage" of magnetic field lines in the posteruptive phase (Švestka et al. 1987; Forbes & Acton 1996; Hiei & Hundhausen 1996; cf. McKenzie & Hudson 1999 and Wang et al. 1999), however, fits the expectation from the conjecture. The shrinkage of the reconnected coronal field lines (possibly including the effects of the slow shocks, in this picture) would supply the energy for the heating of the postflare loops. The impulsive phase of a flare or the time of rapid acceleration of a CME presents the greatest observational dilemmas. At these times, the energy release rate reaches a maximum, thus requiring the strongest implosion.

For a specified time interval of energy release, the reduction in magnetic pressure must take place within a volume accessible to the energy flow during that time. We estimate this by taking the Alfvén speed v_A as a limit. The energy available E^* within the accessible volume V^* for a given timescale Δt thus becomes

$$E^*(\Delta t) < \int_{V^*} \left(\frac{B^2}{8\pi}\right) dV \sim \frac{B^2}{8\pi}\frac{4\pi}{3}(\Delta t v_A)^3,$$

where V^* represents the volume with a surface defined by the energy flux (speed v_E) integrated along its streamline up to the timescale Δt, so that a point on this surface would be defined schematically by $\int (1/v_E)dt = \Delta t$. Because we do not have a good understanding of the coronal magnetic field or of the nonlinear dynamics of the flow, we cannot be quantitative and can only carry out schematic dimensional estimates. Table 1 gives such estimates, for which E^* scales as $B^5 n_e^{-3/2}$ for a given Δt. Table 1 shows the spatial scales (lower limits) implied by representative timescales and physical conditions for the impulsive and gradual phases of a major flare and for a CME originating in the streamer belt away from an active region.

Table 1 confirms the well-known result that sufficient energy can exist within an accessible region (e.g., Klimchuk 1996). By the conjecture, to get the full available energy (E^*) would of course require the total collapse of the magnetic field within a region of the estimated size scale (R^*). Current instrumentation can resolve these spatial scales. The E^* value for the last row in Table 1 (the streamer) exceeds the energy requirement by only an order of magnitude. In sum, appropriate observations with existing telescopes should allow us to locate the implosions. Success at this would allow us not only to identify the source of the flare energy but also to sharpen our knowledge of the physical parameters.

Relaxing assumption C (low-plasma β) would allow new timescales to enter, and in fact the energy release of the impulsive phase often has a "bursty" behavior, which might reflect the temporary storage of energy in the gas. However, the temporary storage of magnetic energy in the form of the internal energy of the plasma would tend to worsen the mismatch in the first row of Table 1.

5. CONCLUSION

To understand solar flares and CMEs theoretically, we need a fuller knowledge of their geometry. In this Letter, we state the conjecture that an energy-releasing coronal transient event, such as a flare or a CME, must originate in a magnetic implosion. We have not yet detected such implosions, implying that they occur via invisible large-scale flows or else perhaps on unobservably small spatial scales. I do not think that the observations suggest the first explanation since eruptive flares (e.g., Nitta & Akiyama 1999) and coronal dimmings thought to produce CMEs (e.g., Hudson & Webb 1997) normally show outward motions, rather than inward, on large scales. These imply increases of magnetic energy according to the conjecture stated here. But as noted above, E^* scales as $n_e^{-3/2}$, so that potentially invisible low-density regions might preferentially supply the implosive energy transport. The densities listed in Table 1—taken from observations of the phenomena resulting from the implosions—might have little to do with the prior state of the corona leading to the events.

The importance of this conjecture lies in the fact that current coronal observations have reached a spatial resolution that is adequate for detecting small-scale implosive motions, such as those that might occur in the impulsive phase of a solar flare. Even for a single impulsive spike, as estimated in Table 1, we would expect an implosion on an observable spatial scale, even for total "magnetic annihilation." The current *Transition Region and Coronal Explorer* (*TRACE*) observations in particular provide an excellent means for exploring the consequences of this conjecture; Aschwanden et al. (1999) have shown that movies of *TRACE* data can easily resolve transverse motions of coronal magnetic field lines with velocity amplitudes on the order of tens of kilometers per second. The implosion conjecture should encourage the acquisition and analysis of high-resolution *TRACE* data during the impulsive phase of a flare. The use of a single filter at the most rapid cadence would give the best chance of seeing rapid small-scale implosive motions that might reflect changes in the coronal current distribution (see Melrose 1997).

In addition to *TRACE* observations, we repeat a suggestion made by Hudson & Khan (1996; see also Kurokawa et al. 1994) regarding conjugate footpoint brightenings: millimeter-wave, hard X-ray, or in general any photospheric/chromospheric/transition region observations with adequate temporal and spatial resolution could map out the field-line connectivity by pairwise temporal correlation. This would apply especially to very short (subsecond) timescales because of energy transport by fast electrons. In a sense, the detection of conjugate brightness variations would provide the most direct measure of coronal loop length as a flare develops. For this purpose, high-resolution observations from observatories on the ground, with sufficient time resolution, might succeed in detecting any remapping resulting from reconnection.

The conjecture stated here has a clear statement within its three assumptions, one of which (low β) probably does not matter theoretically. The conjecture makes no assumption about the particular mode of energy release from its pre-event magnetic source. Magnetic reconnection and the restructuring of the field that results from it, of course, represent the likeliest kind of theory, but we must know the geometry in order to understand how the reconnection works. Different scenarios for magnetic reconnection imply different sites for the energy sources and therefore different implosion signatures.

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