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MAGNETIC TOPOLOGY OF IMPULSIVE AND GRADUAL SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

We examine the magnetic topology at the Sun that leads to the two classes of impulsive and gradual solar energetic particle (SEP) events so as to address new observations that seem to blur this classification, for example, that coronal mass ejections (CMEs) can accompany events of both classes. In our model, the unusual element abundances in impulsive SEP events result from resonant stochastic acceleration in magnetic reconnection regions that incorporate open magnetic field lines, allowing both accelerated ions and ejected plasma to escape. In the large gradual events that produce classic CMEs, reconnection occurs on closed field lines beneath the CME where the accelerated particles are trapped so they plunge into the solar atmosphere to produce a flare; they cannot escape. The SEPs seen at 1 AU in these large gradual events are accelerated by the shock wave driven outward by the CME. The shock-accelerated particles are derived from the local plasma and from reaccelerated suprathermal ions from previous impulsive or gradual SEP events.

Subject headings: acceleration of particles — shock waves — Sun: abundances — Sun: corona — Sun: particle emission

1. INTRODUCTION

Recent evidence has defined two distinct classes of solar energetic particle (SEP) events (Reames 1990, 1995, 1999a; Kahler 1992, 1994; Gosling 1993; Tylka 2001) described as follows:

1. Ions in "impulsive" SEP events are characterized by unusual abundance enhancements, relative to coronal abundances, by factors of ~1000 in ^{3}He/^{4}He, ~10 in Fe/O (Reames 1999a), and ~1000 in ($Z > 50$)/O (Reames 2000). High ionization states of elements C through Fe reflect a hot plasma source. These events have durations of several hours, are small and numerous (~1000 yr^{-1} on the visible disk at solar maximum), and have long been associated with small solar flares and type III radio bursts (Reames, von Rosenvinge, & Lin 1985; Reames & Stone 1986; Reames et al. 1988). Particles from an impulsive event are confined to a narrow (~20°) longitude range. The unusual abundances presumably arise from resonant wave-particle interactions in the reconnection region (Fisk 1978; Temerin & Roth 1992; Miller & Reames 1996; Roth & Temerin 1997; Litvinenko 2001).
2. Ions in "gradual" SEP events have, on average, element abundances and ionization states similar to those of the corona and solar wind. The events are relatively rare (~20 yr^{-1} at solar maximum), they last several days, sometimes span more than 180° in solar longitude, and are strongly associated with shock waves driven out from the Sun by fast coronal mass ejections (CMEs) and *not* with solar flares (Kahler et al. 1984; Gosling 1993; Reames 1995, 1999a; Tylka 2001). The theory of proton-excited Alfvén waves has been employed to understand both the acceleration of the particles by shock waves (Lee 1983, 1997) and the transport of particles outward from a shock (Ng & Reames 1994; Ng, Reames, & Tylka 1999) that can induce substantial time variations in the abundances (Tylka, Reames, & Ng 1999).

Modest enhancements of ^{3}He or Fe that are sometimes seen in large gradual events, and even at intensity peaks at the time of shock passage, are believed to arise from residual suprathermal ions from previous impulsive SEP events that are swept up and accelerated by the CME-driven shock (Mason, Mazur, & Dwyer 1999; Desai et al. 2001; Tylka et al. 2001).

However, there are certain puzzling observations that seem to blur this simple picture of SEP event classification. Gamma-ray line measurements in large flares that accompany CMEs suggest that the ions accelerated in these events are also ^{3}He rich (Mandzhavidze, Ramaty, & Kozlovsky 1999) and Fe rich (Murphy et al. 1991), but Cliver et al. (1989) found a poor correlation between intensities of gamma-ray lines and peak proton intensities at 1 AU. If ions with unusual abundances are associated with all flares, why are they not also present in all SEP events? If impulsive SEP particles cannot escape from large flares, how can they escape so easily from small ones?

Even more damning for our event classification, it would seem, are the recent observations of fast CMEs accompanying some *impulsive* SEP events (Kahler, Reames, & Sheeley 2001). Is the presence of these narrow CMEs coincidental or do they form a distinct class of their own? How can we reconcile these disparate observations with the two-class model of SEP events?

In this Letter we propose a simple paradigm, based on the magnetic topology that controls the SEP events. The paradigm retains the idea of two distinct underlying physical mechanisms of acceleration of the energetic particles. For our purpose, we define "closed" magnetic field lines as those for which the entire length of the line above the photosphere lies within our region of interest. The full length of these closed field lines can generally be traversed by MeV protons on timescales of seconds to hours. "Open" magnetic field lines may extend well beyond 1 AU and cannot be traversed by energetic ions during the typical timescale of an SEP event.

2. IMPULSIVE SOLAR ENERGETIC PARTICLE EVENTS

The diagram in Figure 1 illustrates a typical setting we propose for acceleration leading to impulsive SEP events. This diagram is similar to the ones considered by Kahler et al. (2001) for impulsive SEP events with CMEs and was proposed by Shimojo & Shibata (2000) to describe X-ray jets and the source of the 10–100 keV electrons that produce interplanetary type III radio bursts (Robinson & Benz 1998). In the figure, a reconnection region is produced when magnetic flux of one polarity emerges from the photosphere beneath open field lines of the opposite polarity. This reconnection region is rich in

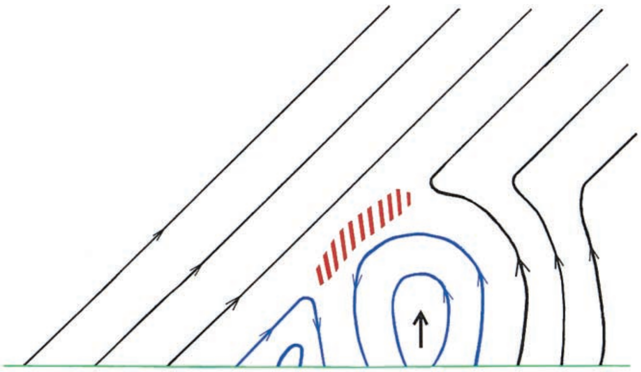

FIG. 1.—Example of the magnetic topology that produces X-ray jets, type III radio bursts, and impulsive SEP events. Closed (*blue*) field lines emerging from the photosphere reconnect (*red hatched region*) with overlying open (*black*) field lines of opposite polarity. Energetic particles are accelerated by resonant wave-particle interactions in this turbulent region, producing SEPs with unusual abundances that can easily escape. Plasma can also escape to form a narrow CME.

wave turbulence that can result in resonant stochastic acceleration of both electrons (Miller, LaRosa, & Moore 1996) and ions (Temerin & Roth 1992; Miller & Reames 1996; Roth & Temerin 1997; Litvinenko 2001) with the unusual abundances that are observed.

The field topology shown in Figure 1 lends itself to the easy escape of accelerated particles; in many cases they are able to escape all the way to 1 AU to be seen as an impulsive SEP event. It is also possible for hot plasma from the reconnection region to be ejected along magnetic field lines upward and to the right of the figure. In sufficiently large events, this ejection may be observed in white-light coronagraphs. Such CMEs are relatively narrow since the plasma is confined to limited bundle of magnetic field lines emanating from the source. Perhaps the acceleration, especially of low-energy electrons, even continues in the turbulent ejecta as it rises through the corona.

Type III radio bursts, produced by streaming 10–100 keV electrons, provide a measure of the scope of the phenomenon depicted in Figure 1; they occur at a rate of ∼10,000 yr^{-1} during solar maximum. Type III bursts and the streaming electrons that produce them always accompany ^{3}He-rich events (Reames et al. 1985, 1988; Reames & Stone 1986). However, for some type III bursts, the electrons do not reach 1 AU, and even when type III electrons do reach 1 AU, they are not always accompanied by measurable intensities of ions.

3. GRADUAL SOLAR ENERGETIC PARTICLE EVENTS

Figure 2 illustrates the typical magnetic topology that leads to an eruptive CME and a gradual SEP event. While details of the eruptive process may vary in different models (see Forbes 2000), the process is likely to involve reconnection among closed magnetic loops that are themselves buried beneath an overburden of other closed loops. Particles accelerated in this region are trapped; eventually they scatter into the loss cone and plunge into the solar atmosphere at the footpoints of the magnetic field lines in a timescale of hours. Gamma-ray line measurements suggest that the physical process of acceleration in the reconnection region may be identical to the process we have described for impulsive events. Narrow gamma-ray lines from the atoms in the ambient plasma show coronal abundances, while Doppler-shifted broad gamma-ray lines from the accelerated beam show ^{3}He-rich, Fe-rich energetic particles (Murphy et al. 1991; Ramaty, Mandzhavidze, & Kozlovsky 1996; Mandzhavidze et al. 1999). The abundance enhancements result from the physics of acceleration and are not present in the source plasma.

Most CMEs from this process erupt at speeds that differ minimally from that of the solar wind; hence, they produce no significant shock wave and no SEP event. They occur at a rate of ∼900 yr^{-1} (Webb & Howard 1994) at solar maximum. Only a small percentage of CMEs drive shock waves fast enough to accelerate ions to MeV energies (Reames, Kahler, & Ng 1997). Gradual SEP events occur at a rate of ∼20 yr^{-1}, at solar maximum, and their peak intensities increase rapidly with CME speed (Reames 1999b; Kahler 2001). Fast CME-driven shocks accelerate ions from the ambient plasma of the corona and solar wind, or from any suprathermal ions remaining from earlier impulsive or gradual SEP events.

By including a strong reconnection region in Figure 2, we do not mean to suggest a strong coupling between flares and CMEs (see Kahler 1992). Some gradual SEP events are associated with CMEs that are launched from "disappearing filament" events with no associated impulsive flares (Kahler et al. 1986). Even in events with associated flares, asymmetries can produce flares at one end or the other of the filament region and the flare size is poorly correlated with the properties of

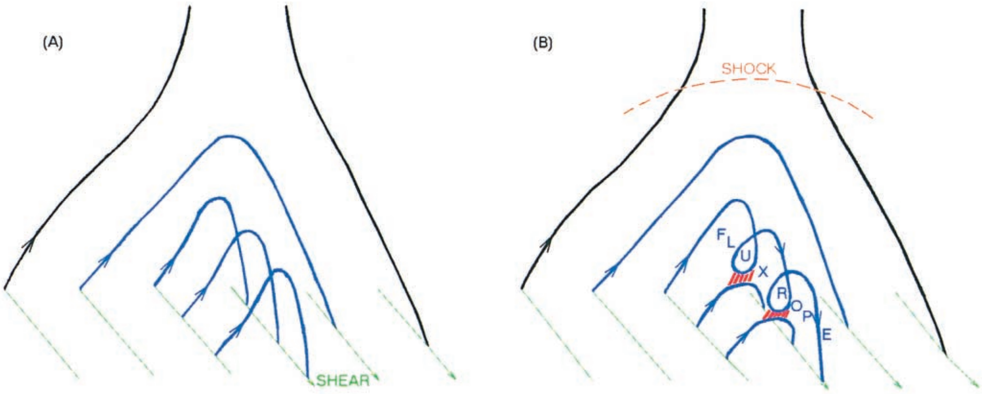

FIG. 2.—Evolution of the magnetic topology that produces large CMEs and gradual SEP events. Magnetic reconnection occurs entirely on closed (*blue*) field lines (*red hatched region*), and all accelerated particles are trapped until they eventually plunge into the solar atmosphere. Gamma-ray lines produced by these particles in the flare show the same abundances of energetic ions as in impulsive events, but here no particles escape. If the CME is sufficiently fast, it drives a shock wave that expands over a wide span of solar longitude, accelerating particles as it goes. These shock-accelerated particles form the gradual SEP event.

the CME. However, the point of Figure 2 is to suggest that any particles that *are* accelerated in the reconnection region are deeply imbedded in closed field lines and are much more likely to plunge into the photosphere than to escape to 1 AU.

As the CME lifts off, electrons accelerated near the footpoints of the loops produce quasi-periodic type III–like radio emission that forms inverted U structures, which rise to considerable heights in the corona before descending along the closed loops (Aschwanden et al. 1993). Electrons are also accelerated at the shock wave ahead of the CME to produce the type II radio bursts and the outward-streaming shock-accelerated type III events (Dulk et al. 2000). Electrons inside the CME and those ahead of the shock are *not* the same electrons. However, we should also note that particles producing "normal" type III bursts (Fig. 1) that are spawned near the onset of a CME-related event (Fig. 2), perhaps at its periphery, might be a significant source of the remnant impulsive suprathermals that are later accelerated by the shock in some events (Desai et al. 2001). Some CME models (Antiochos, DeVore, & Klimchuk 1999) show a weak reconnection region above the CME; such regions, which are not observed, would nevertheless be unlikely to contribute significant acceleration.

When gradual SEP events are observed from sources near central meridian, protons intensities of ∼1–100 MeV rise to a plateau of intensity, occasionally peaking at the time of shock passage. Behind the shock, the intensities fall precipitously by as much as 2 orders of magnitude when the spacecraft enters the magnetic cloud or ejecta from the CME (e.g., Cane, Reames, & von Rosenvinge 1988). Thus, by the time the CME reaches Earth, perhaps 2 days after leaving the Sun, particles from the original reconnection event have completely dissipated. Abundances of those few energetic particles that *are* inside the CME suggest that they have leaked in from the outside. However, onsets from new injections of SEPs near the Sun, either impulsive or gradual, are sometimes seen when an observer is inside a CME at 1 AU (Kahler & Reames 1991). In addition, fast CMEs often overtake slower ones (Gopalswamy et al. 2001), a process that undoubtedly affects the injection, acceleration, and transport of the particles.

4. DISCUSSION AND CONCLUSIONS

We have described a model for the magnetic field topology that explains why impulsive SEP events are associated with only type III radio bursts and small solar flares and why they are occasionally accompanied by narrow CMEs. The model also explains why energetic particle abundances derived from gamma-ray line measurements in large flares differ so greatly from those in gradual SEP events and why the impulsive SEPs escape the Sun so easily in small events but not in large ones.

While impulsive and gradual SEP events are defined, in practice, by source topology, the underlying fundamental difference is in the acceleration mechanisms. For impulsive SEP events, that mechanism is resonant stochastic acceleration; for gradual SEP events, it is shock acceleration. The two classes of acceleration are much more clearly defined than the two classes of events, and the terms impulsive and gradual, originally derived from the timescale of soft X-rays, are rather obsolete since the events are only statistically distinguished by timescales alone.

In this Letter we see no need to consider "mixed," "compound," or "hybrid" events (e.g., Cliver 1999). These phenomenological terms are of little use in defining the underlying physics. However, we do recognize the reacceleration by shock waves of remnant ions from previous impulsive and gradual SEP events that are overtaken by a shock. This process tends to blur the abundance discrimination between events, as do the abundance variations that can occur during transport from large events. Solar events themselves are rich and complex, and a wide variety of conditions can occur. Beneath the complexity, however, the field lines are either open or closed, and ion acceleration occurs by either the resonant-stochastic or shock mechanisms, as far as we know.

One prediction of this model may be tested by comparing SEP abundances derived from broad gamma-ray lines observed by the recently launched *Ramaty High Energy Solar Spectroscopic Imager* with those measured in the associated SEP events on the *Wind* spacecraft. The abundances should correspond only for the small impulsive events of the type described by Figure 1.

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REFERENCES

Antiochos, S. K., DeVore, C. R., & Klimchuk, J. A. 1999, ApJ, 510, 485
Aschwanden, M. J., Benz, A. O., Dennis, B. R., & Gaizauskas, V. 1993, ApJ, 416, 857
Cane, H. V., Reames, D. V., & von Rosenvinge, T. T. 1988, J. Geophys. Res., 93, 9555
Cliver, E. W. 1999, in AIP Conf. Proc. 516, 26th Int. Cosmic-Ray Conf. (Salt Lake City), ed. B. L. Dingus, D. B. Kieda, & M. H. Salamon (Woodbury: AIP), 103
Cliver, E. W., Forrest, D. J., Cane, H. V., Reames, D. V., McGuire, R. E., von Rosenvinge, T. T., & McDowall, R. J. 1989, ApJ, 343, 953
Desai, M. I., Mason, G. M., Dwyer, J. R., Mazur, J. E., Smith, C. W., & Skoug, R. M. 2001, ApJ, 553, L89
Dulk, G. A., Leblanc, Y., Bastion, T. S., & Bougeret, J.-L. 2000, J. Geophys. Res., 105, 27,343
Fisk, L. A. 1978, ApJ, 224, 1048
Forbes, T. G. 2000, J. Geophys. Res., 105, 23,153
Gopalswamy, N., Yashiro, S., Kaiser, M. L., Howard, R. A., & Bougeret, J.-L. 2001, ApJ, 548, L91
Gosling, J. T. 1993, J. Geophys. Res., 98, 18,949
Kahler, S. W. 1992, ARA&A, 30, 113
———. 1994, ApJ, 428, 837
———. 2001, J. Geophys. Res., 106, 20,947
Kahler, S. W., Cliver, E. W., Cane, H. V., McGuire, R. E., Stone, R. G., & Sheeley, Jr., N. R. 1986, ApJ, 302, 504
Kahler, S. W., & Reames, D. V. 1991, J. Geophys. Res., 96, 9419
Kahler, S. W., Reames, D. V., & Sheeley, Jr., N. R. 2001, ApJ, 562, 558
Kahler, S. W., Sheeley, Jr., N. R., Howard, R. A., Koomen, M. J., Michels, D. J., McGuire, R. E., von Rosenvinge, T. T., & Reames, D. V. 1984, J. Geophys. Res., 89, 9683
Lee, M. A. 1983, J. Geophys. Res., 88, 6109
———. 1997, in Coronal Mass Ejections, ed. N. Crooker, J. A. Jocelyn, & J. Feynman (Geophys. Monogr. 99; Washington, DC: AGU), 227
Litvinenko, Y. E. 2001, in AIP Conf. Proc. 598, Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber (Woodbury: AIP), 311
Mandzhavidze, N., Ramaty, R., & Kozlovsky, B. 1999, ApJ, 518, 918
Mason, G. M., Mazur, J. E., & Dwyer, J. R. 1999, ApJ, 525, L133
Miller, J. A., LaRosa, T. N., & Moore, R. L. 1996, ApJ, 461, 445
Miller, J. A., & Reames, D. V. 1996, in AIP Conf. Proc. 374, High Energy Solar Physics, ed. R. Ramaty, N. Mandzhavidze, & X.-M. Hua (Woodbury: AIP), 450
Murphy, R. J., Ramaty, R., Kozlovsky, B., & Reames, D. V. 1991, ApJ, 371, 793
Ng, C. K., & Reames, D. V. 1994, ApJ, 424, 1032
Ng, C. K., Reames, D. V., & Tylka, A. J. 1999, Geophys. Res. Lett., 26, 2145

Ramaty, R., Mandzhavidze, N., & Kozlovsky, B. 1996, in AIP Conf. Proc. 374, High Energy Solar Physics, ed. R. Ramaty, N. Mandzhavidze, & X.-M. Hua (Woodbury: AIP), 172

Reames, D. V. 1990, ApJS, 73, 235

———. 1995, Rev. Geophys. Suppl., 33, 585

———. 1999a, Space Sci. Rev., 90, 413

———. 1999b, in AIP Conf. Proc. 516, 26th Int. Cosmic-Ray Conf. (Salt Lake City), ed. B. L. Dingus, D. B. Kieda, & M. H. Salamon (Woodbury: AIP), 289

———. 2000, ApJ, 540, L111

Reames, D. V., Dennis, R. B., Stone, R. G., & Lin, R. P. 1988, ApJ, 327, 998

Reames, D. V., Kahler, S. W., & Ng, C. K. 1997, ApJ, 491, 414

Reames, D. V., & Stone, R. G. 1986, ApJ, 308, 902

Reames, D. V., von Rosenvinge, T. T., & Lin, R. P. 1985, ApJ, 292, 716

Robinson, P. A., & Benz, A. O. 1998, Sol. Phys., 194, 345

Roth, I., & Temerin, M. 1997, ApJ, 477, 940

Shimojo, M., & Shibata, K. 2000, ApJ, 542, 1100

Temerin, M., & Roth, I. 1992, ApJ, 391, L105

Tylka, A. J. 2001, J. Geophys. Res., 106, 25,333

Tylka, A. J., Cohen, C. M. S., Deitrich, W. F., Maclennan, C. G., McGuire, R. E., Ng, C. K., & Reames, D. V. 2001, ApJ, 558, L59

Tylka, A. J., Reames, D. V., & Ng, C. K. 1999a, Geophys. Res. Lett., 26, 2141

Webb, D. F., & Howard, R. A. 1994, J. Geophys. Res., 99, 4201