The search for a causal link between CMEs and large flares

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Abstract. It would be remarkable if the two most dramatic and energetic solar transients, the large CME (coronal mass ejection) and large flare, were truly independent. The search for a causal connection is on-going, but so far has not been established. A separate, but longstanding problem is the source of the energy released in a large flare, as in many, if not all, cases this does not appear to come from the active region magnetic field. We discuss here a model whereby non-thermal energetic particles provide both the link between CMEs and flares, and a significant part of the flare energy. From an energetics viewpoint ions dominate, and to avoid gamma ray production which would be observable by current instrumentation, the ions should be below around 1 MeV/nucleon. Plausible ways of generating an adequate ion population within the CME structure, which for large events is over 90 degrees in projection, are indicated. Evidence for the release into space of some of this population is presented. The non-thermal electrons responsible for the hard X-ray and microwave signatures are generated near the chromospheric flare site, together with the highly relativistic ions which often accompany large flares.

Index Terms. Coronal mass ejections, solar flares, energetic particles, global energetics.

1. Introduction

The purpose of this paper is to consider the energetics of large solar flares, their associated coronal mass ejections (CME) and the energetic particles accompanying them. Together these phenomena form the most energetic of solar transients and it would be remarkable if they were independent, or if even one was independent of the others. We use timing and energy arguments to find a way to relate them and to produce a coherent and self-consistent explanation.

Some four decades ago Elliot (1964, 1969) suggested that energetic particles, gradually accelerated in the corona over a period of the order of a day before a major flare, could suddenly be dumped into the lower solar atmosphere to provide the energy for the optical flare. Part of the motivation for this suggestion was to provide a relatively slow coronal acceleration process for producing the > 1 GeV protons emitted at the time of some large flares. The highest energy protons very occasionally reach energies up to 25 GeV. Such a gradual acceleration to these high energies should be visible via gamma ray production. The lack of such gamma ray emission prior to large flares was unsupportive of this model and it was largely abandoned. The problems that Elliot was trying to address were the energy supply for flares and the acceleration mechanism for highly relativistic protons. These have not yet been solved.

It has been generally accepted that the energy for transient solar activity comes from magnetic fields in the region above the photosphere. How high into the corona is relevant for flare energetics is unclear, but the thrust of much of the work to date has only considered magnetic fields associated with the active region, and therefore the relevant coronal height is just of the order of the scale of the active regions, namely around 50000 km. The consensus has been that the energetic particles present in the flare's impulsive phase, especially the electrons, have been accelerated in this same general region, although some models have attributed acceleration of the solar energetic particles seen later in the interplanetary medium in association with fast CMEs to the CME-driven shock. Thus strictly speaking they are independent of the flare. However, when the energy source is addressed, it is clear that the active region magnetic fields do not supply all the energy needed for the flare. For large flares 10^{32} erg is needed over a timescale ~ 10^3 s. This is the first problem.

The second problem concerns the supply of the non-thermal electrons deduced from the impulsive flare X-ray emissions. For large flares the electron beam strength (under the conventional beam models) above ~15 keV is ~ 10^{36} - 10^{37} electrons/s. For large flares this corresponds to a total of 2 10^{40} electrons (Emslie and Brown, 1985) which at a density of ~10^9 cm^{-3} is equal to all the electrons in a volume of the order of (3 10^{10} cm)^3 or almost (0.5 solar radii)^3. Clearly the corona cannot supply these electrons, which leaves the chromosphere as the most probable source.

Simnett (2003) addressed these problems with a flare concept based on gradually populating a large coronal structure, of typical length scale around 2 solar radii, with energetic ions (referred to hereinafter as protons) up to

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energies around 1 MeV. The coronal structure would accumulate the protons up to the equipartition energy, when the structure would erupt as a CME and the trapped particles would provide most of the energy to power the optical flare. The electrons for the X-ray burst were accelerated in or near the chromosphere by a secondary process associated with the dumping of the protons. Note that not all erupting magnetic structures would be expected to be triggered by an excess of trapped particles, but such particles would certainly contribute to the onset of instability. Low (2001) has pointed out that the coronal magnetic field is naturally sheared by footpoint motion, and that an eruption is simply the way the corona releases the shear. The mass in a CME is not essential to the eruption, so that in addition to the process which releases the shear, energy must be deposited at the base of the corona to drive the excess mass observed in a CME into the corona.

The key unknowns in this model are the mechanisms for accelerating the particles that populate the large coronal structure, the mechanism for dumping the trapped particles, and the acceleration of the GeV protons. In our view none of these is as critical as either of the two problems identified above.

2. Energetics considerations

Estimates of the total magnetic energy in the active region surrounding a major flare typically do not show an adequate diminution following the flare, which proves that the active region magnetic field is not the main energy source. We now estimate the potential for the high corona to supply the energy. Following Simnett (2003), consider a large coronal loop system of radius 1.5 solar radii, cross section of 10^{21} cm^2 with a field strength of 2G. The total magnetic energy is ~5 10^{31} ergs. Thus in principle such a structure could contain an energetic particle population of this energy without disruption; and if the energy could be transferred to the active region it could power the major part of the flare. The limit to the stability of the large structure may well occur when the total energy of the trapped particles approaches the total energy of the magnetic field. Therefore, the trigger for the eruption of the CME seen at the time of a major flare could be the final input of energy from, say, a small-scale reconnection within the overall configuration. As the active region producing the flare is an integral of the system, then motions within the region, such as emerging flux, could suffice. Note we do not advocate this process namely the high pressure of trapped particles, to account for the eruption of all CMEs.

3. Characteristic timescales

How rapidly can a large coronal structure empty of particles following ejection? Suppose that the ejection of the magnetic field structure causes the mirror points above the flare site to move into the chromosphere. This would be a natural consequence of a reducing magnetic field strength at the footpoint. The length of the coronal loops is around (1.5 π solar radii) = 3.5 10^{11} cm. The protons we are advocating travel at c/50 (~200 keV) - c/25 (~1 MeV). Thus the timescale to dump the population is around 100s. (Some particles have to go to the other mirror point and back.) The trigger is supposedly caused by flux cancellation of the active region fields with the fields in the coronal structure. The rising phase of flares can last longer than this. This is not a problem, as the CME, if above the local Alfven speed, drives a shock, which accelerates particles as it moves out into the interplanetary medium. Some fraction of the accelerated particles, possibly of the order of 50% (Simnett, 1985) may stream back to the active region, thus providing a continued supply of seed particles and energy. This is a natural explanation of long duration soft X-ray events.

4. Coronal energetic particle acceleration

Evidence for high coronal particle acceleration has been available since ~1970 (see Lin, 1985 for a review of the early observations). Typically electrons are accelerated impulsively up to around 10 keV, released into the interplanetary medium, where they are adiabatically focused and arrive at 1 AU as a collimated beam. From analysis of the electron spectrum, Potter et al. (1980) established that the events originated in the corona above ~1.5 solar radii (sun centred). It was suggested by Cliver and Kahler (1991) that the particle acceleration occurred as a result of reconnection in the neutral current sheets of coronal streamers.

Such reconnection events are difficult to observe, but recent measurements (Simnett, 2004) of bi-directional flows detected by the LASCO C2 coronagraph (Brueckner et al., 1995) have indicated that the typical projected altitude of such events is between 3 and 4 solar radii. Simnett noted that the marked absence of events originating below 3 solar radii was real and not a limitation of the observations. This suggests that the 1.5 solar radii loops suggested above are not an overestimate, and may in fact be too small. The original theory for such reconnection advanced by Petschek (1964), involving the formation of oppositely-directed shocks, is a plausible explanation.

Particle acceleration in such events is difficult to estimate. The impulsive electron events reviewed by Lin (1985) were typically low energy, below 20 keV. However, observations by Robinson and Simnett (2002) and Simnett (2005) have shown that the electron spectrum may extend occasionally up to 200 keV. It is inconceivable that the process does not also accelerate protons. The Sun is a quasi-continuous source of non-thermal protons (Simnett, 2001) which extend up to MeV energies, even at times of quiet solar activity. MeV proton counterparts of impulsive electron events are difficult to observe at 1 AU, as the velocity of such protons is ~c/25 and they therefore take several hours to cover 1 AU. Thus the continuous low energy solar proton emission could be a manifestation of the ionic part of the coronal accelerator. Fig. 1 shows the 337 - 594 keV ion intensity from the EPAM instrument (Gold et al., 1998) on the ACE spacecraft for 60 days towards the end of 2005, when the Sun was quiet. It is clear that there are many distinct events during this period.

Also shown in Fig. 1 is the 38-53 keV electron intensity, which is virtually uncorrelated with the protons. The data are plotted as hourly averages. We believe the data shown in Fig. 1 are supportive of our contention that protons up to ~ 1 MeV are accelerated in the corona in the absence of chromospheric flares. The Sun was extremely quiet during most of this period, with only three GOES C1 class X-ray flares from day 267 - day 315. It may be no accident that the most active period in terms of chromospheric activity was from day 316 - day 322, which was the minimum in the ion intensity seen at ACE. One hypothesis is that coronal energy release is a continuous process, and when the output goes primarily to the chromosphere, it therefore does not go into the interplanetary medium.

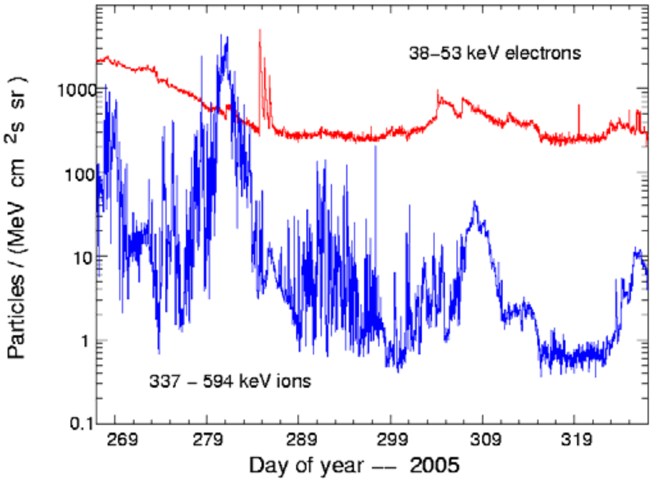

Fig. 1. The intensity-time history of 38-53 keV electrons (upper trace) and 337 - 594 keV ions (lower trace) measured by the ACE/EPAM detector from day 267 - day 327 2005. The data are plotted as 30 minute averages.

Lin (1985) has estimated the electron energy/event as 10^{25} – 10^{26} erg. However, because of the uncertainty in the geometry of the release into the interplanetary medium, energy losses and energy in the low energy part of the spectrum, this may be underestimated by a factor of 10-100 (Lin 1985).

We adopt as a working hypothesis that the energy in the ions may be $\sim 10^3$ times the energy in the electrons (cf m_p/m_e). Then the energy /event may plausibly be in the region 10^{30} - 10^{31} erg. Lin has emphasized that such events are the most common of all solar electron events, and occur many times/day over the whole Sun.

Therefore based on the above discussion there is not an energy problem in providing the additional energy input for flares via energetic particles accelerated in the high corona.

5. Discussion

In the search for a causal link between large flares, CMEs and particle acceleration we have so far not addressed proton acceleration to the highest energy. This is not a consequence of CME-driven shock acceleration, as many extremely fast, large CMEs do not accelerate protons to >> GeV energies. Also, the timing of the acceleration, when it is sufficiently closely defined as in the 20 January 2005 event (Simnett, 2006) shows that the relativistic protons are accelerated impulsively and early in the event, inconsistent with CME acceleration. We have suggested (Simnett 2003) that the trapped coronal protons form a seed population to the active region, which then further accelerates them, by the mechanism of choice, to the highest energy. The active region magnetic fields provide the means of achieving this, although the precise details are not known.

Fig. 2 shows how the spectrum might appear. The spectrum from the seed population is shown going out to ~1 MeV. Acceleration at the flare site adds the hatched region. It should be noted that the flare accelerator does not have to accelerate ions from the ambient thermal plasma to GeV energies, but from the non-thermal seed population.

Note that there are not large numbers of energetic electrons, say >10 keV, in the seed population. We know this primarily because of the lack of coronal microwave radio emission prior to flares. Therefore the place where the electrons responsible for the non-thermal hard X-ray and microwave bursts are accelerated has to be very close to where they are seen, which initially is the chromosphere. Strong, very localized shocks formed when the ions impact the chromosphere might be a candidate; or strong, very transient and localised E-fields, as suggested by Simnett and Haines (1990). In any case, the electrons must be accelerated by a secondary process, and therefore they do not contribute to the primary energy budget.

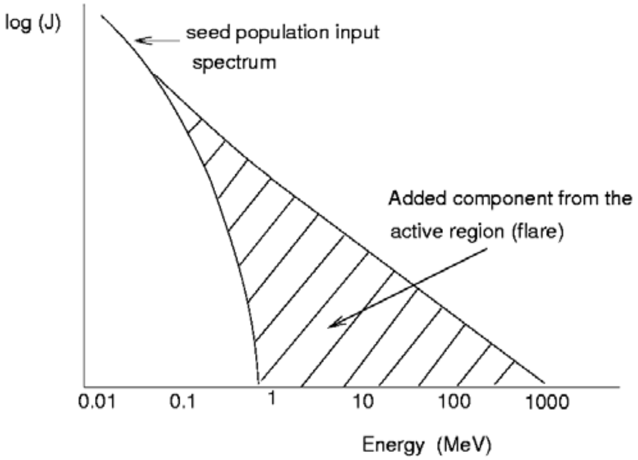

Fig. 2. The energy spectrum of the seed population, shown as the left part extending to around 1 MeV, and the additional flare population, shown hatched. The ordinate scale is deliberately left blank to allow for variations in spectral index from actual events.

In summary, we make the following points:

(1) Magnetic reconnection in the high corona, up to 4 solar radii, accelerates the ambient coronal plasma to modest non-thermal energies, typically up to ~10 keV for

electrons and ~ 1 MeV for protons. Closed coronal magnetic fields provide a leaky trap for these particles. For large flares energy from this reconnection contributes the dominant part of the flare energy, with the charged particles as the intermediate energy transfer mechanism.

(2) The trapped population builds up until the coronal magnetic field can no longer contain it and the structure erupts. The trigger may very well come from "re-arrangement" of one footpoint of the CME structure due to motion within the active region where the flare occurs. If energy deposition from the leaky trap has carried to the chromosphere, then "evaporated" plasma provides the excess mass for the eruption to be visible as a CME. Some of the population will escape into the interplanetary medium, but it will normally not be identified as such at 1AU due to particles from the flare itself, and those accelerated by the CME-driven shock.

(3) The flare region may accelerate the seed (trapped) population to much higher energy, thereby producing on occasion highly relativistic protons.

(4) The CME-driven shock may provide additional acceleration, but not to GeV energies.

(5) This model provides a causal link between large CMEs and large flares, with significant energy transfer via non-thermal protons up to ~ 1 MeV.

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