THE RADIO-SILENT START OF AN INTENSE SOLAR GAMMA-RAY FLARE

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Abstract. Radio-silent γ-ray flares are solar flares that lack any significant emission in the (non-thermal) radio wave band during their impulsive hard X-ray and γ-ray emission phases. Flares with extremely suppressed long-wavelength spectra have previously been reported by White *et al.* (1992) and have been discussed in different context by Hudson and Ryan (1995). A striking example of a radio-silent flare was observed by SMM during the onset of the 6 March 1989 energetic γ-ray flare. We argue that the absence of radio emission at wavelengths longer than microwave wavelengths is an indication of the compactness of the flare rather than that the flare did not exhibit non-thermal properties. Probably the flare site was restricted to altitudes above the photosphere in a newly emerging loop configuration lower than the equivalent altitude corresponding to an emission frequency of 1.4 GHz. This implies the presence of a dense and highly magnetized closed field configuration confining the electron component which causes the impulsive γ-ray continuum. Reconnection in such a configuration did not lead to open magnetic fields and streamer formation. Acceleration of particles in the γ and hard X-ray bursts was restricted to closed field lines. Thermal expansion of the loop system may subsequently lead to the generation of radially propagating blast waves in the solar corona which are accompanied by type II solar radio bursts and decimetre emissions. The emission during the onset of the flare was dominated by a continuum originating from electron bremsstrahlung at X-ray and γ-ray energies with only little evidence for the presence of energetic ions. It is, therefore, concluded that energetic electrons have been primary and not secondary products of the particle acceleration process.

1. Introduction

The acceleration of charged particles during solar flares can be studied in a wide energy range from the metre radio band up to X-ray energies and, in rarer cases, even up to high-energy γ-rays. The combination of metre and decimetre radio emissions on the one hand and X-ray measurements on the other can provide important information about the topology and evolution of flares. It enables one, in particular, to determine the acceleration site of the charged particles (especially energetic electrons) as well as the relation between the onset and progress of chromospheric evaporation and the evolution of the flare. Recently, Aschwanden and Benz (1995, 1997) have developed a powerful technique of analysis, which relies on the availability of radio and X-ray observations. Electron time-of-flight measurements have

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been carried out by Aschwanden *et al.* (1996) who inferred that the acceleration site of the particles in the flares investigated lies above a semicircular loop in a cusp-like (helmet streamer) magnetic field configuration. Such a configuration is in most cases manifested by the occurrence of solar type III radio bursts.

Flares without a signature in the meter and decimeter radio wave bands are rare. A multi-wavelength analysis of an electron-dominated γ-ray flare with radio emission has recently been presented by Trottet *et al.* (1998). A similar event has been analysed by Vilmer *et al.* (1999) without reference to radio emission. The flare analysed by Trottet *et al.* (1998) showed little sign of γ-ray line emission and was thus identified as electron dominated. However, in addition to microwave emission it also exhibited impulsive metric and decimetric radiation making it a radio-loud γ-ray flare different from the class of flares discussed in the present paper. GAMMA-1 observation of a very energetic (up to 300 MeV) electron dominated disk flare has been reported also by Kurt, Akimov, and Leikov (1996). In those cases when the non-thermal radio emission is absent, the analysis of Aschwanden *et al.* (1996) is not applicable. Simnett and Benz (1986) first investigated hard X-ray flares observed by the SMM Hard X-Ray Burst Spectrometer (HXRBS) and found that a fraction of $\sim$ 15% of the detected events did not show any emission at radio frequencies below $<$ 1 GHz. These flares were in the majority weak GOES class events. In addition to the hard X-ray flares, Simnett and Benz (1986) also examined a subset of γ-ray flares (at $>$ 300 keV photon energy) observed by the Gamma-Ray Spectrometer (GRS) on SMM. They obtained a fraction of $\sim$ 11% of flares without emission at frequencies $<$ 1 GHz. From this result they concluded that the non-appearance of type III bursts proved that type III radio bursts had not been excited in these cases. They also concluded that the type III bursts observed in most of the other flares were a mere secondary phenomenon appearing in the course of solar flare particle acceleration (cf., also, the review by Simnett, 1995).

In the present communication we add to these observations and present measurements of a particular intense solar γ-ray flare in the radio regime and at X- and γ-ray energies whose energetic start was practically devoid of any emission in the metre and decimetre wave bands. From this remarkable behaviour we will comment on the location of particle acceleration and on the role that electrons play in solar flares.

2. Observations

One day after crossing the east limb of the Sun, the large and complex active region NOAA/SESC No. 5395 produced an intense and long lasting flare on 6 March 1989, starting at 13:50 UT. This flare saturated the GOES X-ray detectors. It was estimated as an X15-flare. Optically, the flare was classified as a 3B-event (see NOAA, *Preliminary Report and Forecast of Solar Geophysical Data* and NOAA *Technical Memorandum* ERL SEL-82,1994). SMM came into full sunlight around

13:55:40 UT. At that time the flare had already evolved at low energy X-rays. According to measurements of one of our small X-ray spectrometers attached to the Gamma-Ray Spectrometer (GRS) (Forrest *et al.*, 1980), the flare began to rise at energies above 100 keV around 13:56:10 UT. In order to decide whether the flare was already energetic before SMM came into full sunlight, it is of importance to inspect the temporal history of the 2.2 MeV neutron capture line which is a proxy for nucleonic interactions. The second panel of Figure 5 shows the evolution of this line. There is no indication of an emission right after the night/day transition at 13:55:40 UT. A measurable positive excess can be observed after 13:57:46 UT only. It is, therefore, safe to conclude that no energetic phase was missed by SMM during the time when SMM was in Earth occultation.

In the upper part of Figure 1 the temporal history of the first few minutes of this flare is shown in different energy bands from high energy X-rays to high energy γ-rays. It is apparent that the flare was very impulsive during this time interval. The first maximum around 13:58 UT and the short burst at 13:59:24 UT were at the highest emissions above 10 MeV photon energies ever recorded by GRS. These bursts and to a lesser degree the following burst from 14:01:30 to 14:03:30 UT (shown in Figure 5) were electron-dominated (see Rieger and Marschhäuser, 1990; Marschhäuser, Rieger, and Kanbach, 1994; Rieger, Gan, and Marschäuser, 1998). Events of this type, if compared to 'normal' γ-ray line flares, exhibit an unusually flat continuum at MeV energies. As a consequence the γ-ray lines begin to disappear (cf., Vilmer *et al.*, 1999; see also Section 3.4).

In the lower part of Figure 1 the dynamic radio spectrum for this same time interval as recorded by the Ondřejov radio spectrometer in the frequency range 200–1200 MHz is shown. The spectrum contains artificial noise over the whole frequency range visible as vertical streaks and horizontal dark lines. This noise and lines are caused by disturbances in the recording TV system of the Ondřejov radio spectrometer and by man-made interferences, respectively.

It is very instructive that the enormously intense and hard γ-ray burst with its maximum around 13:58:10 UT does not exhibit any radio signature over the entire accessible radio band. Any meter or decimeter type III bursts are totally absent. Only at the very end of this burst, From 13:58:40 UT to 13:59:05 UT, a weak solar radio emission arises between 700–1000 MHz. Similarly, the second short hard γ-ray burst at 13:59:24 UT exhibits no counterpart in the radio waves. This remarkable 'radio-silence' is confirmed by recordings of the Nançay radio spectrometer that showed only narrow band bursts (150–250 MHz) during the time interval 13:55:20–56:20 UT (M. Poquérusse, private communication).

The intermediate radio emission at 13:58:40 UT is composed of a group of narrow high frequency U-bursts recognizable from their steep reversing frequency drifts. Their lower frequency cut-off decreases in time, indicating the rise of the radio source in the lower corona. Clearly, these U-bursts are the signature of fast electron beams injected into a closed field configuration at the later stage of the first γ-ray burst.

Later in the flare, at 14:00:40 UT (not shown in the figure), some high-frequency spikes appear and, an intense low-frequency type II burst develops. However, the most remarkable feature of the whole sequence of radio emissions is the above mentioned almost total radio silence around the energetic gamma burst and start of the flare at 13:57 UT. Prior to the flare, from 10:45 UT approximately up to the onset of the flare, a weak type I noise storm had been recorded in the 100–300 MHz frequency range. Single frequency records at 260 MHz confirmed this observation. But it is not clear if this noise storm had anything in common with the γ-ray burst or even with the flare under consideration. Furthermore, an unidentified, narrow band long-lasting radio emission has also been present at around 1080 MHz. This emission is at an approximately stable frequency but intensifies during the declining phase of the 13:58 UT γ-ray burst. Probably it does not directly belong to the γ-ray source region but is a secondary effect that may have originated in the source environment or even elsewhere.

It is also of interest to note that the Potsdam radio spectrometer around the time in question does not show any peak at the frequency of 1470 MHz (H. Aurass, personal communication). Contrary to this lack of meter and decimeter radio emissions, the burst was exceptionally intense at microwave frequencies. The Bern microwave telescope (lowest frequency 3.1 GHz in single frequency mode, otherwise 4 GHz) was saturated up to frequencies of 5.2 GHz and showed emissions up to 13 000 s.f.u., 20 000 s.f.u., and 30 000 s.f.u. at 19.4 GHz, 35 GHz, and 50 GHz, respectively (A. Magun, personal communication). Emissions of such an enormous power at these high frequencies are very rarely reached during a sunspot cycle.

3. Discussion

3.1. Flare Site and Topology

The enormously splashy character of the hard X- and γ-ray emission implies that electrons must have been accelerated in a very short time to the high energies >10 MeV capable of emitting γ-rays in thick-target emission. This again involves the presence of highly energetic electron beams which, in any conventional model, should be capable of exciting plasma waves and as a consequence of these waves should generate type III solar radio bursts.

The absence of any meter and decimeter radio emission during the main flare burst at 13:58 UT calls for an acceleration site in a dense low-lying and/or dense coronal loop system. The observations thus suggest the presence of a highly confined magnetic field configuration that does not allow for leakage of electron beams in order to explain the absence of the otherwise expected related type III radio emission. Within a thick-target flare model, the simplest way to interpret the absence of any observable radio emission in these wavelengths is to assume that the flare took place within a dense closed strong magnetic field loop system. A sufficiently densely populated loop containing a strong magnetic field and reaching high up into the corona would serve this requirement as well as the low-lying loop system we suggest.

The fact that the very intense microwave source at 13:58 UT was optically thick apparently up to frequencies of 50 GHz, implying also a rather high magnetic field strength, can be taken as support for this view, though the dense and well extended loop model cannot and should not be excluded as a realistic possibility. Recent potential field re-constructions of solar magnetic fields based on SOHO observations (Schrijver *et al.*, 1997) suggest an exceptionally complicated chromospheric magnetic field configuration even under undisturbed solar conditions, consisting of many very small magnetic loops (see also, Day,1998). Most of these little loops do not extend far into the corona but form a complicated low-lying magnetic system or ‘carpet’ as it is called (Day, 1998). Twisted magnetic fields are also believed to be involved. The reasonable and common assumption is that continuous weak reconnection in this magnetic loop configuration releases enough energy to heat the solar corona and to cause its expansion. Whether this heating is produced directly in the reconnection process or proceeds via secondary dissipation of reconnection generated Alfvén waves is an interesting but, in our context, less important question.

During flare conditions, one may suggest that newly emerging magnetic flux will explosively enhance the reconnection rate locally when breaking through the magnetic configuration. A similar model has been proposed earlier by Heyvaerts, Priest, and Rust (1977) for a small flare (see also Priest, 1987) when the emerging flux interacts with the overlying solar magnetic field. Numerical simulations by Yokoyama and Shibata (1995) have recently given new support to this model (see also Shibata, 1998; Aschwanden, 1998).

Figure 2 shows a schematic of the time sequence and evolution of a loop reconnection process as a variation of the Heyvaerts *et al.* model. Similar ‘four-legged’ flare models have been proposed earlier by Hanaoka (1996, 1997) and Nishio *et al.* (1997). It is assumed that a concentrated magnetic loop emerges into a pre-existing magnetic loop configuration. When this new loop contacts the pre-existing loop, reconnection sets in and reconfigures the magnetic field without opening the magnetic field lines. This is in contrast to the cases when reconnection sets in on the top of a loop. Such a loop-top acceleration case was inferred, e.g., by Masuda *et al.* (1994) and has formed the basis for the flare models of Aschwanden (1998) and Shibata (1998). Masuda *et al.* (1994) used *Yohkoh* X-ray observations of a compact hard X-ray western limb flare on 13 January 1992. In the latter case an extended current sheet and a streamer will be generated. The particles that are accelerated in the reconnection process (or in its debris) can freely escape along the open streamer magnetic field. Type III bursts will necessarily be generated in this case during the very first phase of the flare by escaping electron beams passing through the low-density corona. It is probably important to note that Masuda *et al.* (1994) did not observe intense type III activity in relation to their flare. This fact is difficult

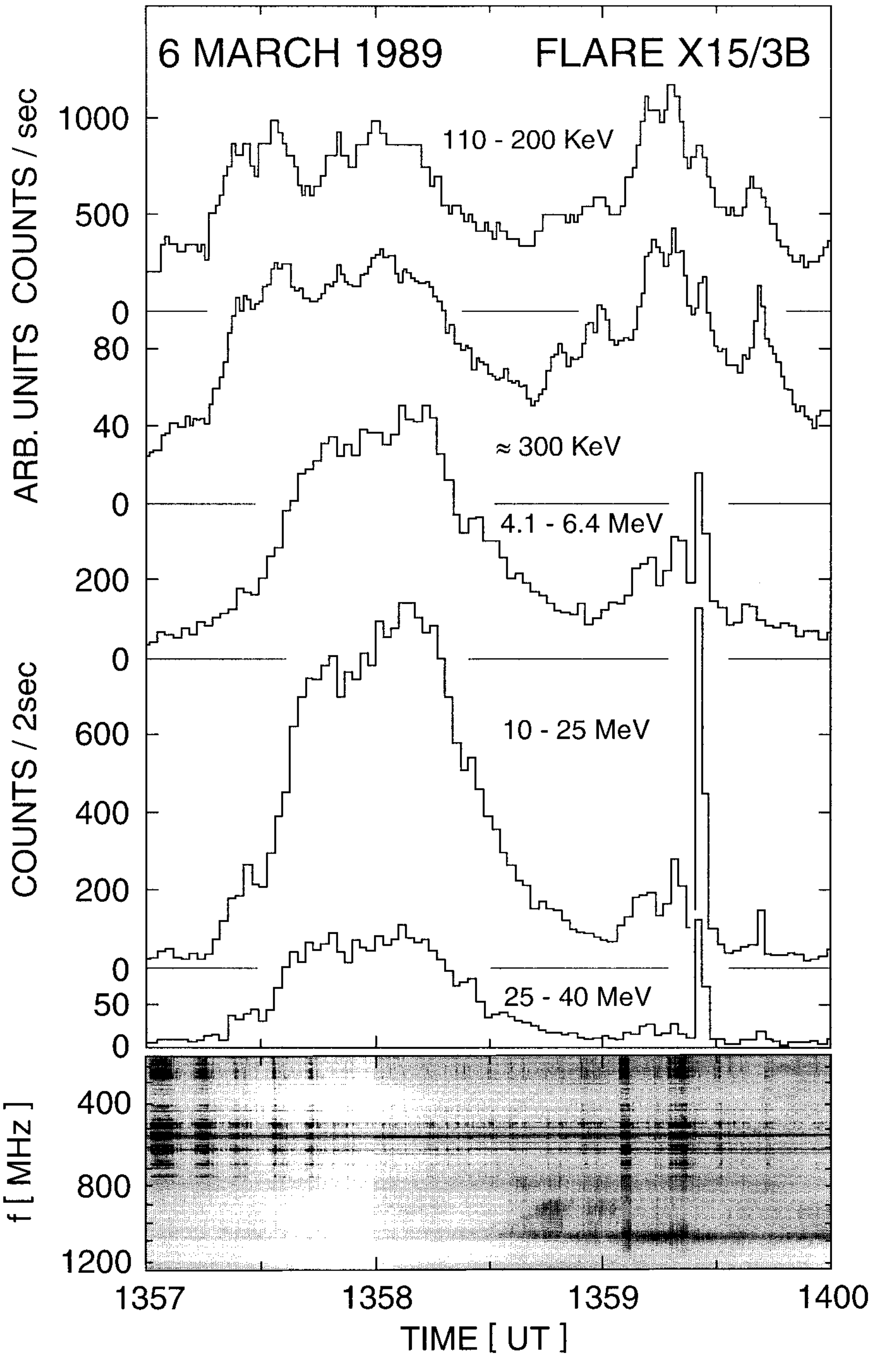

Figure 1. The 6 March 1989 solar γ-ray flare. Time history (upper part) and dynamic radio wave spectrum (Ondřejov) between 200–1200 MHz. No radio emissions are observed during the burst phase of the flare. The vertical streaks and horizontal dark lines in the dynamic radio spectrum are of artificial origin.

to understand in an open top-loop flare model and remains to be explained. Our model deviates from this commonly accepted model in that no open field lines are produced. Therefore, no type III bursts are ejected, and the flare stays radio-silent.

3.2. ELECTRON ACCELERATION

In contrast to the streamer and original Heyvaerts, Priest, and Rust (1977) newly emerging flux models, the loop emerging flux model makes it impossible for the initially accelerated particle beams to escape into the upper corona. In the simplest case, all energetic particle beams are confined to the common four-legged interior of the reconnected magnetic loop configuration. As Figure 2 suggests, the beams are ultimately directed downward everywhere into the chromosphere and photosphere towards the footpoints of the two interacting loops. As a consequence, no typical type III burst signature can be caused at radio frequencies if only the interacting loops are located low enough in the chromosphere or corona. Alternatively, as mentioned earlier, any radio signature would also not be visible if the loop plasma is dense enough. In this case, the loop might even reach far out into the corona without causing a radio signature (Aschwanden *et al.*, 1992). The accelerated beams may bounce back and forth between the foot points of the two loops until they relax and are depleted by wave-particle interactions. The deposition of the beam energy into the plasma may, in addition to the direct heating in reconnection (e.g., Parker, 1990), cause further collisionless heating of the loop plasma, but its amount is too small to generate the required expansion needed to cause the type II shock wave. The main mechanism relies on reconnection-associated collisionless current dissipation which lets the loops expand, driving the blast wave out into the corona, the signature of which is the type II shock wave that develops in the later phase of the flare. The radio continuum at higher decimeter frequencies, which coincides with the appearance of the type II shock wave at later time in the flare, signifies this hot trapped particle component.

The significance of such a scenario lies in its ability to explain the absence of type III radio bursts during the initial burst phase of the flare. In Figures 3 and 4 we combined the model with the radio observations for the two phases of the 13:58 UT γ-ray burst. During the main phase of the γ-ray burst the contacting loop system lies far below the radio range of the Ondřejov spectrograph. Any beams accelerated from the energy release region either ran down to the loop foot points where they emitted gamma and hard X-rays, or were confined to the level below the 2 GHz level, while the heated and accelerated trapped particle component inside the loop system emitted optically thick microwaves.

At the end of the 13:58 UT γ-ray burst the loop expanded and rose into the radio wave domain of the spectrograph. At this time the high energy γ-ray burst had ceased, and the emission was about to become almost purely X-ray. The group of U-bursts maps the rising loop field and visualises the injected trapped electron beams probably bouncing between the loop mirror points until the new accelera-

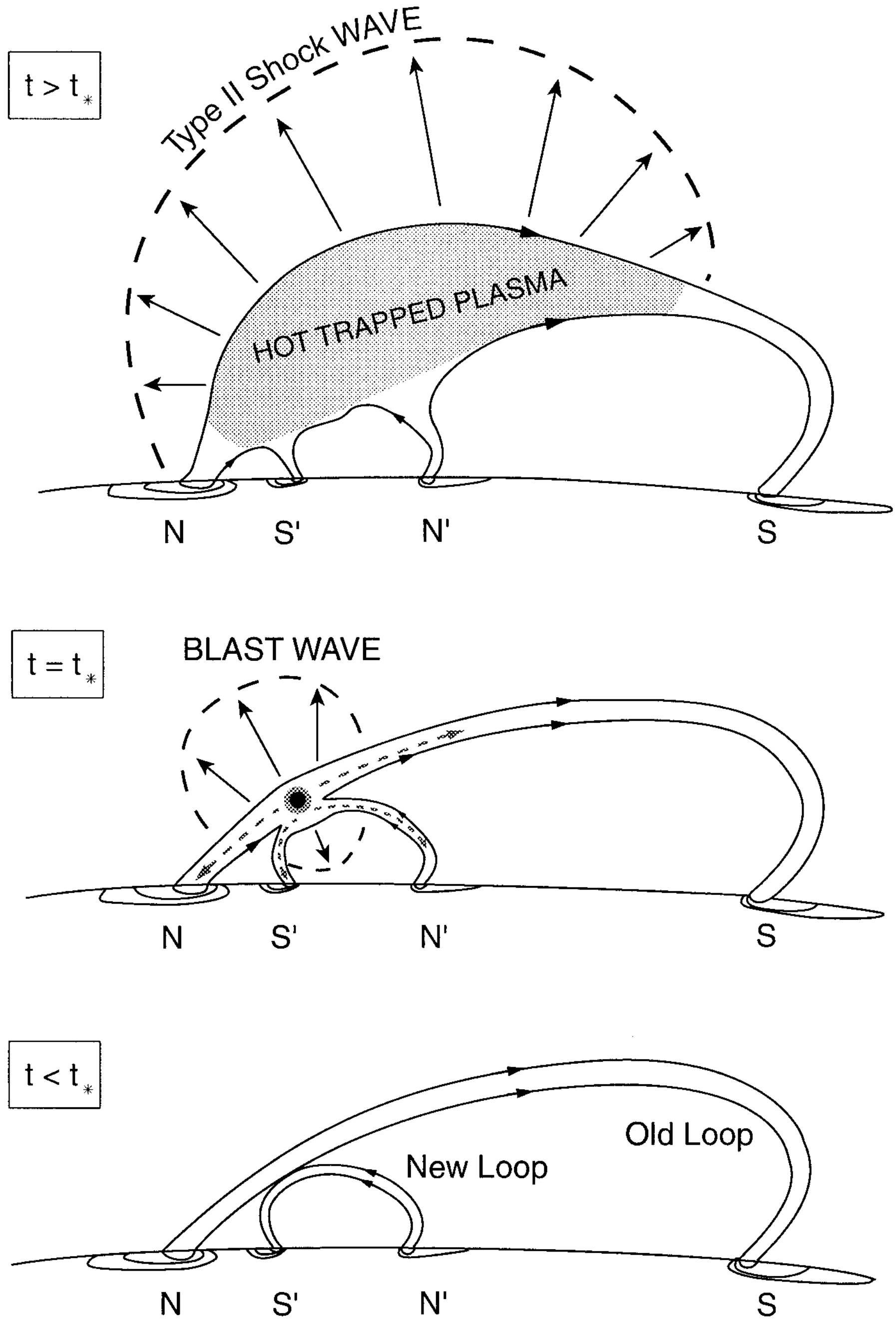

Figure 2. Schematic of a newly emerging loop interacting with a low-lying magnetic structure as a slight modification of the Heyvaerts, Priest, and Rust (1977) newly emerging flux model. Low-lying magnetic loops of opposing polarity contact each other and reconnect while no open magnetic flux is generated. The result is a four-legged loop. Particles are accelerated into beams down to the footpoints of the loops and cause gamma- and X-ray radiation. Heating makes the loop expanding and driving a blast shock wave into the corona with no companion type III bursts.

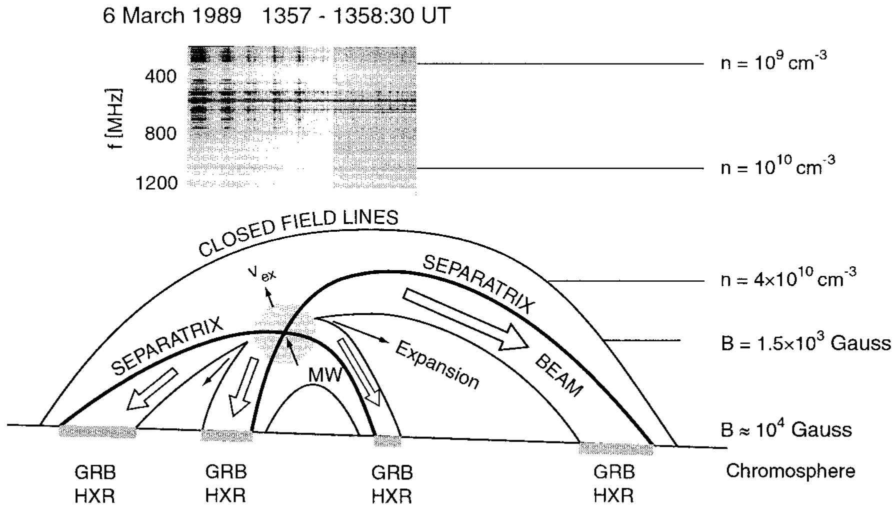

Figure 3. Combination of the dense loop model and the radio spectrum (*top*) for the first phase of the 6 March 1989 γ-ray burst. The loop system during the energy release phase lies so low that its top does not reach into the radio domain of the Ondřejov radio spectrometer. The spectrum does not exhibit any solar radio emission. Note that the vertical and horizontal dark lines are of artificial origin. All accelerated beams are on closed field lines and excite the γ-ray (GRB) and hard X-ray (HXB) bursts when hitting the dense chromospheric target. Microwave emission (MW) takes place in correlation with beam injection in the strong magnetic field region $B > 1.3 \times 10^3$ G. The separatrix does not divide the magnetic field configuration into open and closed field lines. Rather it distinguishes the regions between field lines interconnected between the loops (*inner part*) and those belonging to only one of the two loops involved. The shaded spot marks the reconnection-acceleration-diffusion region. In the solar co-ordinate system the net displacement of this spot is outward.

tion event sets in at 13:59:24 UT. Again, the absence of any type III radio bursts suggests that in none of the phases of this whole event until this time and still later open field lines had been produced or had become involved into the gamma and hard X-ray process.

The model may throw some light on the generation mechanism of the very high particle energies needed in order to produce γ-ray and hard X-ray flares which are dominated by the presence of energetic electrons. These high electron energies probably arise almost immediately as a consequence of reconnection of the strong loop fields though they may not be an attribute of the reconnection process itself. Reconnection remains a relatively slow process that is at most about 10% efficient. The magnetic disturbance caused by reconnection propagates as a (possibly kinetic) Alfvén wave along the magnetic field down into the chromosphere. For very strong magnetic fields participating in the reconnection, its velocity can be high. Since the propagation distance is comparably short, the passage from the reconnection site to the loop foot points requires little time.

It is sometimes assumed that the Alfvén pulse produces a strong field-aligned electric potential drop and, in addition, a broad spectrum of waves near the lower-

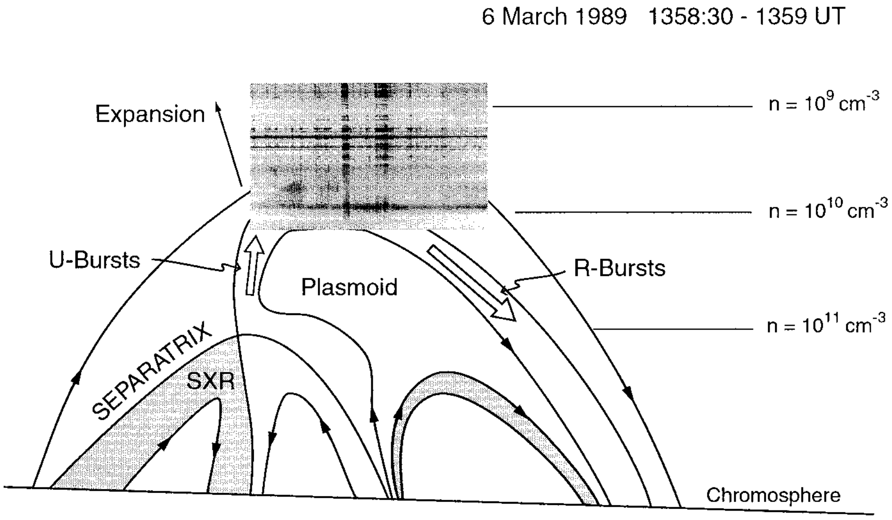

Figure 4. During the second declining phase of the γ-ray burst the loop system rises into the lower corona to the $n \approx 10^{10}$ cm^{-3} density level. U bursts signals the bouncing electron beams in this late phase inside the closed loop configuration. Note again that all the vertical and horizontal dark lines are of artificial origin.

hybrid frequency. Electrons picking up the electric potential field will reach high energies (Haerendel, 1994) in very short times comparable to the propagation time of the Alfvén pulse. Alternatively, electrons can be stochastically accelerated in broadband wave spectra (Zweibel and de La Beaujardiře, 1990) in particular when the waves are localized (Treumann, Dubouloz, and Pottelette, 1995; Dubouloz *et al.*, 1995) or their self-consistent quasilinear spectral evolution is taken into account (Miller, LaRosa, and Moore, 1996). Similar stochastic mechanisms have also been proposed for ion acceleration, based on measurements of fluctuating electric fields in the aurora (Hultqvist, 1996), and as a tool for generating γ-ray lines (Miller and Dermer, 1995; Miller and Roberts, 1995). In addition, electron acceleration can be amplified in the slow shocks developing far away from the reconnection point. These shocks are caused by the ion component but will also heat electrons.

The two former processes act on a very short time-scale. Direct acceleration in an electric field proceeds almost immediately within one electron transition time once the magnetic field-aligned potential drop has been built up. It should, however, accelerate ions as well. In a dense closed loop configuration these ions would generate γ-ray lines. This is seen in the temporal history of the 2.2 MeV neutron capture line photons (Figure 5) and in the appearance of prompt γ-ray lines which break through the continuum radiation, as has been shown by Marschhäuser, Rieger, and Kanbach (1994).

Earth's auroral observations *in situ* (Haerendel *et al.*, 1976; Wescott *et al.*, 1976; Mozer and Kletzing, 1998) occasionally indicate that such potential drops may exist along the magnetic field lines. Kinetic theory predicts that a given large potential drop will almost immediately decay into many microscopic double layers of a few Debye lengths extension and of moderate potential drops. This has been confirmed by more recent observations (cf., Boström *et al.*, 1988; Mälkki *et al.*, 1993; Ergun *et al.*, 1998). Such a set of double layers acts like a stochastic distribution of localised wave trains when interacting with trespassing electrons. In addition, because of the narrowness of the single layers, the interaction with ions will be considerably reduced, which would be in qualitative agreement with our observations (see also Bech, Steinacker, and Schlickeiser, 1990). Recently, Miller (1999) has argued in similar spirit that, also for short enough loop lengths, the ions escape before reaching $\approx$ 1 MeV, where they would begin to resonate with the fast mode waves and suffer very high acceleration. Hence, low lying loops of short loop lengths imply plenty of low energy ions ($<$1 MeV) and plenty of electrons at relativistic energies.

3.3. ESTIMATES

Since it is known that type III solar radio bursts are non-thermally excited by fast electron beams, either at the electron plasma frequency $f \approx f_{pe}$ or its second harmonic $f \approx 2f_{pe}$, respectively, the lack of such plasma emissions up to 1.47 GHz in the γ-ray burst implies that the local plasma density in the acceleration site was higher than 3×10^{10} cm^{-3}, assuming that the fundamental should have been visible. Such loop densities are not unreasonable even for extended coronal loops where densities up to 10^{10}–10^{12} cm^{-3} have been reported. For instance, Aschwanden *et al.* (1992) found the turnover frequency of a coronal U-burst at 1.4 GHz at a height of 130 000 km. Hence, dense loops may reach higher altitudes above the photosphere. The acceleration must have taken place entirely on closed field lines.

The absence of a radio continuum at 1.47 GHz implies that any trapped component is confined as well. If the continuum is caused by the maser mechanism, the loop magnetic field must have been stronger than $B \approx 530$ G. This is in reasonable agreement with the microwave observations. These suggest that the field was weaker than $B \approx$ (1.1–1.4) G. The value of the loop magnetic field thereby is comparable to photospheric magnetic fields.

Acceleration of electrons up to relativistic energies of tens of MeV and emission of the γ-ray continuum during the burst phase presumably take place within $t < 2$ s (see the spiky burst at 13:59:24 UT in Figure 1). The electrons have speed $v \approx c$. Hence, for a semicircular loop of radius 2000 km, the electrons form a spiralling (conical) beam of pitch angle $\theta \approx 89°$. Thus they are close to their mirror point. For some flares of the lower hard X-ray energies ($>$ 20 keV) even shorter acceleration times of the order of $t \approx 0.2$ s have been reported (Kiplinger *et al.*, 1983). Such short time scales have been confirmed by relating the X-ray events to radio ‘spikes’ at decimetre wavelengths (Benz, 1985; Güdel, Aschwanden, and Benz, 1991). Weak low-energy electron beams along the magnetic field in recon-

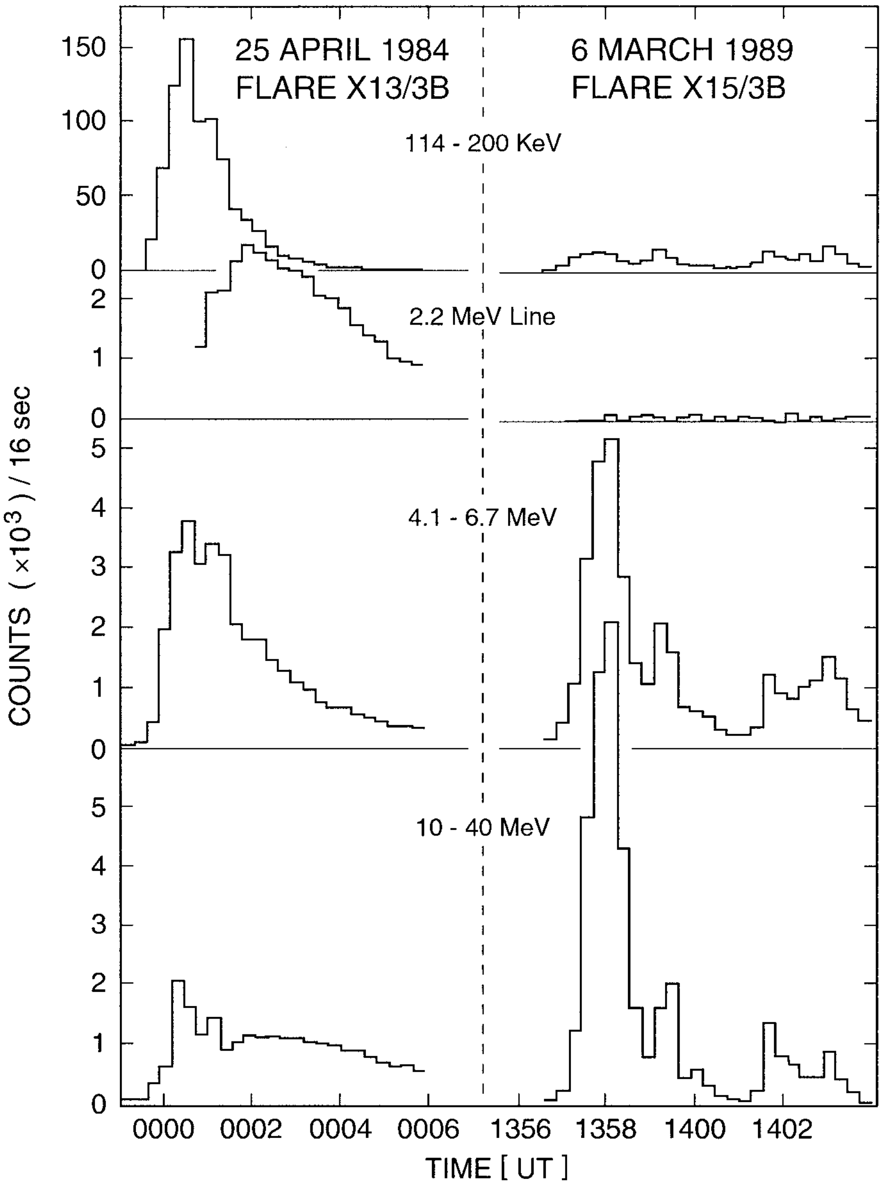

Figure 5. Temporal histories of the γ-ray flare of 24–25 April 1984 (*left*) and of the onset of the 6 March 1989 flare in selected energy channels as observed with SMM. Note the low flux and non-typical time evolution of the 2.2 MeV neutron capture line of the flare on the right.

nection have been inferred from observations in the geomagnetic tail (Schriver *et al.*, 1990). These beams are confined to the magnetic separatrix that passes through the reconnection point. Since they are of low energy, they are not the beams that are responsible for the γ-ray continuum in the γ-ray burst. Instead, they signal the very early onset of the flare, possibly in its pre-heating phase. The relevant electron beams are accelerated a short time later either in electric potential fields or in a stochastic acceleration process. Their energy is provided by the reconnection of the magnetic field. For a $B \approx 1000$ G magnetic field to be annihilated, the available power per particle at the $n_e \approx 10^{10}$ cm^{-3} height level is about P/electron $\approx 25\alpha(n_e/n_b)$ eV s^{-1}. Here α is the efficiency of the reconnection process, and n_b/n_e is the fraction of particles in the high-energy electron beam. Usually, the efficiency will be $\alpha < 0.1$. In order to obtain the maximum energy of ≈ 50 MeV within 1 s, not more than a fraction of n_b (50 MeV) $< 5 \times 10^{-8} n_e$ electrons can have been accelerated out of the electron background. This number implies that the acceleration site had to be located at a height below, say, the $n_e \approx 10^{11}$ cm^{-3} level.

The presence of the U-bursts in the later phase of the γ-ray burst (in case it is actually related to the flare under question) gives an indication of the loop size. For electron velocities of the order of 5×10^4 km s^{-1} in the U-bursts the ≈ 1 s duration of the U-burst suggests that the loop length was of the order of 50 000 km. Such loop lengths are not unreasonable and agree with either horizontally stretched loops or dense coronal loops extending to large heights, as has been discussed above.

3.4. Electron versus Ion Flare Model

The energetic event discussed in the preceding section will now be considered from the view point of a flare model proposed by Simnett. In order to alleviate the requirements for the high number of electrons calculated from the emission of bremsstrahlung during intense solar flares, Simnett developed a flare scenario where electrons are secondary products of flare accelerated protons or ions (Simnett, 1986; Simnett and Haines, 1990; Simnett, 1991, 1995). In this model, a quasi-neutral beam composed of ions and electrons accelerated in the corona, impinges on the transition zone where the beam electrons are scattered, while the ions continue their field-aligned spiral motion. Charge separation sets up an electric potential which, for intense beams, must be neutralised by electrons accelerated subsequently in the potential drop. These secondary accelerated electrons are responsible for the non-thermal X-ray burst via excitation of bremsstrahlung in the chromosphere.

This model has experienced support recently when it was recognized that during some energetic flares more energy is transferred to accelerated ($>$1 MeV) protons than to accelerated ($>$20 keV) electrons (Ramaty *et al.*, 1995; Murphy *et al.*, 1997). However, whereas Simnett's (1986) model, apart from these energy considerations, solves some problems of the flare, it cannot easily be applied to the type of flare discussed in the present paper for the following reasons.

In Figure 5 the temporal history of the hard-X and γ-ray burst of the 6 March 1989 flare is shown for a number of different energy bands (right) together with the energetic flare of 24 April 1984 (left). This latter flare was also recorded by the GRS. Panel 1 contains the emission at high-energy X-rays originating from electron bremsstrahlung. The neutron-capture line at 2.2 MeV which is a proxy for nucleonic interactions, is shown versus time in panel 2. The energy interval 4.1–6.7 MeV is sometimes called the nuclear energy range, because it contains the strong nuclear de-excitation lines of carbon and oxygen. For a 'normal' flare like the event of 24 April 1984, most of the emission in this interval comes from a superposition of these lines (Share and Murphy, 1995), electron bremsstrahlung being a minor contribution there. However, for the bursts occurring at the start of the 6 March 1989 flare, line radiation in the nuclear range and at 2.2 MeV is insignificant. The bursts are characterised by a prevailing continuum of bremsstrahlung from high-energy electrons (Rieger and Marschhäuser, 1990).

At photon energies > 10 MeV, the emission can be composed of bremsstrahlung from highly relativistic electrons as well as from pion decay radiation (Forrest *et al.*, 1985). If pion decay radiation contributes substantially during a flare, the photon spectrum tends to flatten above ~ 40 MeV (Murphy, Dermer, and Ramaty, 1987). This is the case for the 24 April 1984 event during the gradual peak of the 10–40 MeV energy range shown on the left-hand side of Figure 5.

The spectrum of the burst at 13:58 UT of the 6 March 1989 flare, however, exhibits a dramatic drop at energies above ~ 60 MeV (cf., e.g., Petrosian, McTiernan, and Marschhäuser, 1994). Therefore, it must be concluded that pion decay radiation is missing in this event and that the radiation observed (panel 4) originates solely from bremsstrahlung of very high-energy electrons. According to Simnett's (1986) flare scenario, these high-energy electrons should be secondaries. If this would be the case, we should observe copious amounts of protons and ions with comparable energies to be present in the beam. These heavy particles have energies high enough to excite the nuclei of the solar atmosphere and to produce free neutrons, which subsequently can be captured by protons. In such a case one should necessarily observe strong emission of the neutron capture line.

The observations, however, are vastly different from what would be expected. (1) The time history of the 2.2 MeV line is non-typical for such an impulsive event. Its fluence is smaller by a large factor than that of the 24 April 1984 flare even if we take into account that the 2.2 MeV-line photons are attenuated by about a factor of 2 due to near-limb location (heliocentric angle $\approx 78°$) of the flare site (Hua and Lingenfelter, 1987). (2) The continuum dominates the energy range where nuclear de-excitation lines are prominent in normal flares (Rieger and Marschhäuser, 1990). These lines are not attenuated in flares, which are close to the limb because they originate above the photosphere (Hua, Ramaty, and Lingenfelter, 1989). We are, therefore, driven to conclude that the non-thermal electrons which were responsible for the X-ray and γ-ray emission burst at the start of the flare were not secondary but have been accelerated in the primary flare acceleration process (Emslie, 1996). This conclusion is substantiated by the fact that the energy contained in the > 20 keV electrons exceeds the energy of the > 1 MeV protons by a factor of about 20.

4. Conclusions

Investigation of radio-silent γ-ray bursts in the solar atmosphere suggests that sometimes the flare acceleration site must be located in very dense loop systems confining the initially-generated electron beams which are responsible for the γ-ray continuum emission to a closed magnetic field configuration below an equivalent altitude corresponding to the upper limit of the observed dynamic radio wave spectrum. Energy release and particle acceleration occur on closed field line configurations with no electrons escaping into the corona. A hint about the configuration of the flux tubes in which these events may occur can be obtained by observations with high spatial resolution of the order of a few arc sec. Although such an accuracy is currently not reachable at MeV energies and will not be possible during the next sunspot maximum, it is within the reach of the Hard X-ray Telescope (HXT) on *Yohkoh* and the approved NASA project HESSI that is to be launched around the year 2000. Measurements at high photon energies (> 300 keV) could be complemented by microwave and submillimeter/IR telescopes with high spatial resolution (Costa *et al.*, 1995; Kaufmann, 1996).

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