High Energy Solar Physics: Anticipating HESSI
ASP Conference Series, Vol. 206, 2000
R. Ramaty and N. Mandzhavidze, eds.

Spectral Evolution of an Intense Solar Gamma-Ray Flare During its Radio-Silent Start

Erich Rieger and Holger Marschhäuser

Max-Planck-Institut für extraterrestrische Physik, D-85740 Garching, Germany

Abstract. The start of the 6 March 1989 energetic γ-ray flare observed by the Gamma-Ray Spectrometer (GRS) on SMM was a prominent example of a radio-silent event. Such events offer the possibility to deduce the minimum density of the medium in which the acceleration of charged particles, electrons and ions, took place. Because the flare start was intense, spectral evolution could be studied at high temporal resolution. It is found:

- A γ-ray line spectrum appears at the very onset of the flare, when the ambient density, deduced from micro-wave data, was $\gtrsim 10^{11}$ cm^{-3}. At successively lower ambient densities, electron-dominated bursts follow the γ-ray line event. It is, therefore, concluded that the electron-dominated outcome of these bursts did not arise from a high ambient density.
- The constant ion production rate represented by the 4–8 MeV excess flux during the first few minutes, makes us hypothesize that the gamma-ray line emission and the electron-dominated bursts originated from different areas.

1. Introduction

Radio-silent flares are solar events that lack any significant emission in the meter and decimeter radio band during their impulsive hard X-ray and γ-ray phases. As shown by Simnett & Benz (1986), events of this type are rare. Radio-silent events or flares, however, offer the possibility to calculate the minimum ambient density in which the acceleration of charged particles, took place. These minimum densities could be a constraint for acceleration mechanisms in addition to analyses of the timing of flares at X-rays and γ-rays (Forrest and Chupp, 1983; Rieger, 1989).

The onset of the 6 March 1989 energetic γ-ray flare observed by SMM was a prominent example of a radio-silent event, studied extensively by Rieger, Treumann & Karlický (1999). It was concluded that reconnection, which led to the acceleration of charged particles, proceeded in closed magnetic field configurations with no electrons escaping into the Corona. The radio silent start of the flare, moreover, was electron-dominated, a situation, where intense electron bremsstrahlung continuum at MeV energies obscures nuclear γ-ray lines (see Rieger & Marschhäuser, 1990; Hudson & Ryan, 1995; Trottet et al., 1998, and Rieger, Gan & Marschhäuser, 1998). By studying the spectral evolution of

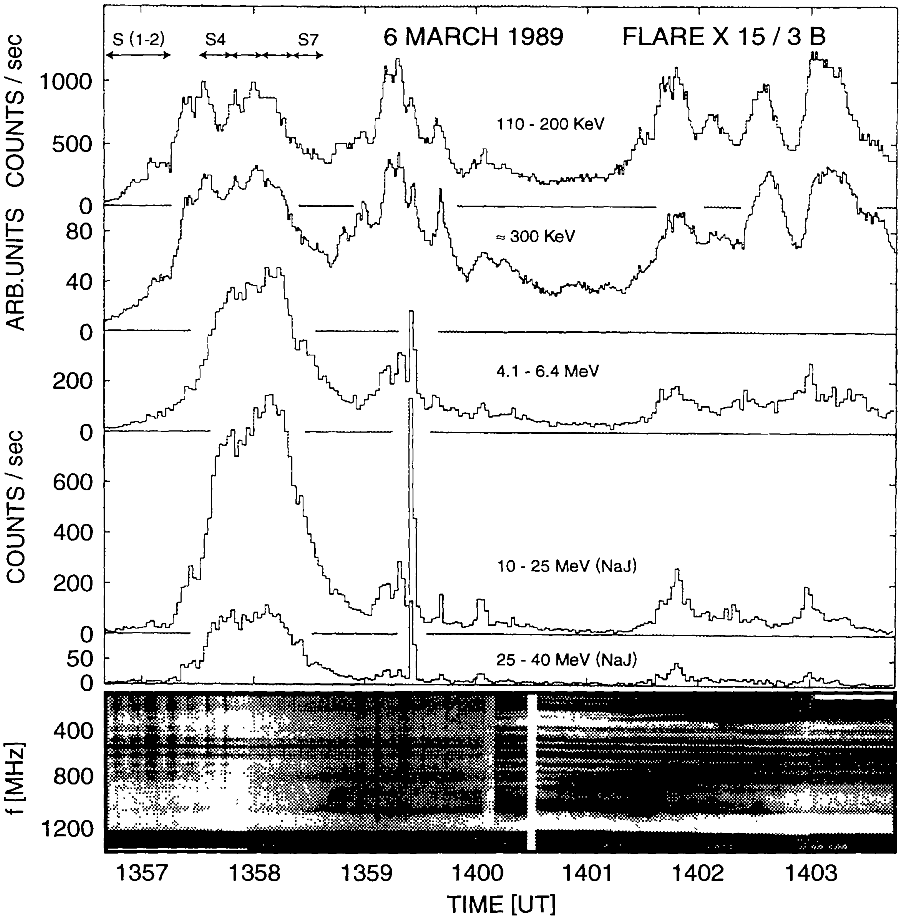

Figure 1. Time history in different energy channels and dynamic radio-wave spectrum (Ondřejov) between 200-1200 MHz (lower part) of the start of the 6 March 1989 solar γ-ray flare. The time intervals of the flare spectra shown in Fig. 2 (left) are indicated by horizontal arrows in the upper left corner. Vertical streaks and horizontal dark lines in the dynamic radio spectrum are of artificial origin.

the flare start we investigate in this paper the question, if the high density in which acceleration occurred may have suppressed the acceleration of the heavy particles to a certain degree, thus leading to an electron-dominated event.

2. Observations

The flare occurred in NOAA active region 5395, one day after the crossing of the east limb of the Sun. It was classified an X15/3B flare (see NOAA, Solar-Geophysical Data comprehensive reports, Number 541, Part II, September 1989 and NOAA, Technical Memorandum ERL SEL-82, 1994). In Fig. 1 the first 7 minutes of this long lasting event are shown at high-energy X-rays and in the γ-ray regime. In the lowest panel, the dynamic radio spectrum for the same time interval recorded by the Ondřejov radio spectrometer in the frequency range 200-

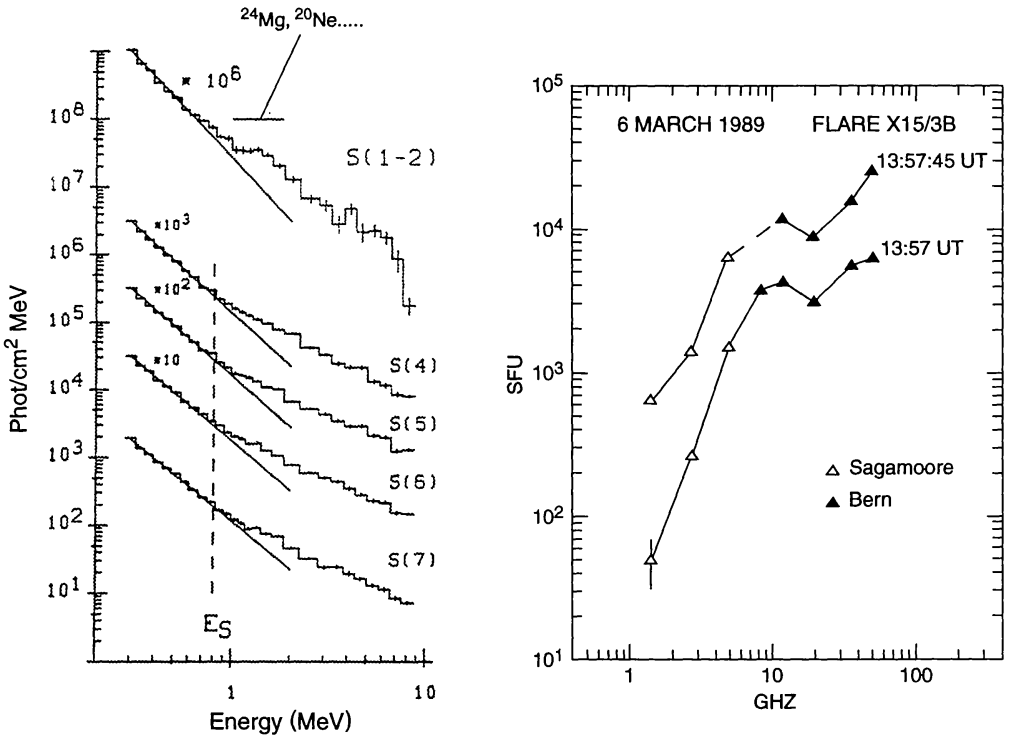

Figure 2. Left: Background subtracted and deconvolved photon spectra during the onset of the flare (taken from Fig. 6.14 of Marschhäuser, 1993, dissertation). E_S denotes the energy where the signal departs significanly from the low-energy continuum.
Right: Micro-wave spectra during 2 different times of the flare onset.

1200 MHz ist presented (M. Karlický, private communication). The spectrum contains artificial noise over the whole frequency range, visible as vertical streaks and horizontal dark lines. It is most remarkable that this intense and impulsive start of the flare is radio-silent for several minutes up to about 14:00 UT. Only from 13:58:40 to 13:59:05 UT a weak solar radio emssion consisting of an array of U-bursts is apparent between 700 and 1000 MHz. This '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 – 13:56:20 UT (M. Poquérusse, privat communication). After 14:00 UT high-frequency continuum pulsations are visible. At frequencies below 400 MHz a type II develops after 14:01 UT in temporal coincidence with burst-like emissions at X-ray and γ-ray energies.

In Fig. 2 (left) the background reduced and deconvolved photon spectra of the very beginning of the flare, including the first impulsive burst at high-temporal resolution are presented (taken from Marschhäuser, 1993, Fig. 6.14). The time intervals of the respective spectra are indicated in Fig. 1 by horizontal arrows. It is of interest to note that the spectrum denoted S(1-2) from 13:56:40 UT – 13:57:13 UT shows all the aspects of a γ-ray line spectrum, namely the separation from the best fit low-energy (0.3-0.8 MeV) power law above 1 MeV, where lines begin to dominate the emission, an indication of the Carbon line at 4.43 MeV and an intensity drop above $\sim$ 7.2 MeV caused by the absence of strong nuclear lines above this limit (see Share & Murphy, 1995 and Vestrand et al., 1999). Because of the delayed nature of the neutron capture line there is not yet an indication in the spectrum at 2.2 MeV during the first 33 sec of the flare. The line spectrum disappears as soon as the electron-dominated event with its intense MeV continuum sets in (S4-S7). A similar spectral evolution was seen during the start of the energetic 3 June 1982 flare, where an interval with a γ-ray line spectrum was followed by a short duration electron-dominated event (Trottet et al., 1994; Rieger, 1994).

In Fig. 2 (right) the micro-wave spectrum is shown at 13:57 and 13:57:45 UT representing the onset and the first intense burst, respectively. The lower frequencies are taken from the Sagamore hill micro-wave spectrometer, because the Berne instrument (A. Magun, private communication) had an overflow there.

Shown in Fig. 3 is the electron production rate, represented by the 0.3-0.8 MeV electron bremsstrahlung continuum flux and the ion production rate, represented by 4-8 MeV nuclear excess flux for 5 different time intervals from 13:56:40 to 14:03:45 UT. These are: (1) the onset of the flare from 13:56:40 – 13.57:13 UT; (2) energetic burst from 13:57:13 – 13:58:50 UT; (2) the short impulsive event from 13:59:23 – 59:27 UT; (3) an intermediate interval from 14:00 – 14:01:34 UT, and (4) the second energetic burst from 14:01:34 – 14:03:45 UT.

The flux values for intervals 1 and 4 are from Marschhäuser (1993), for intervals 2, 3 and 5 from Rieger, Gan & Marschhäuser (1998).

3. Discussion

According to Fig. 1, there is a lack of plasma emission up to 1.2 GHz during the first energetic electron-dominated γ-ray burst. As it is known that type III solar radio bursts are excited non-thermally by fast electron beams at the electron plasma frequency, this radio-silence implies that the local plasma density in the acceleration site was higher than $2 \cdot 10^{10}$ cm^{-3} (Park, Petrosian & Schwartz, 1997). Did the high-density inhibit the acceleration of ions? Without going into detail about ion and electron acceleration in a high-density medium, it can be demonstrated that in the case considered here, high density did not influence the electron rich outcome. In Fig. 2 (left) it is shown that the flare at the very start had already all the aspects of a γ-ray line flare. For the first 33 seconds the total nuclear excess fluence between 4 and 8 MeV is 6.6 ± 2.3 γ/cm^2 and the best-fit power law continuum fluence between 0.3 and 0.8 MeV is 107 ± 5 γ/cm^2 (Marschhäuser, 1993). Inserted into Fig. 7 in Vestrand (1988), which is a compilation of all the GRS flares of cycle 21, we see that the event is like a normal γ-ray line flare, although the plasma density was even higher than during the following electron-dominated burst, namely $\geq 10^{11}$ cm^{-3} (see Fig. 2 (right)).

An interesting aspect is also evident if we consider the ion and electron production rate represented in Fig. 3. The ion production rate contrary to the electron production rate is constant within the error bars during the first 4 minutes, including the electron-dominated burst around 13:58 UT and the 4 sec flash at 13:59:24 UT. These events, apparently, did not contribute significantly to the nucleonic flux of the flare onset in contrast to the 0.3-0.8 MeV

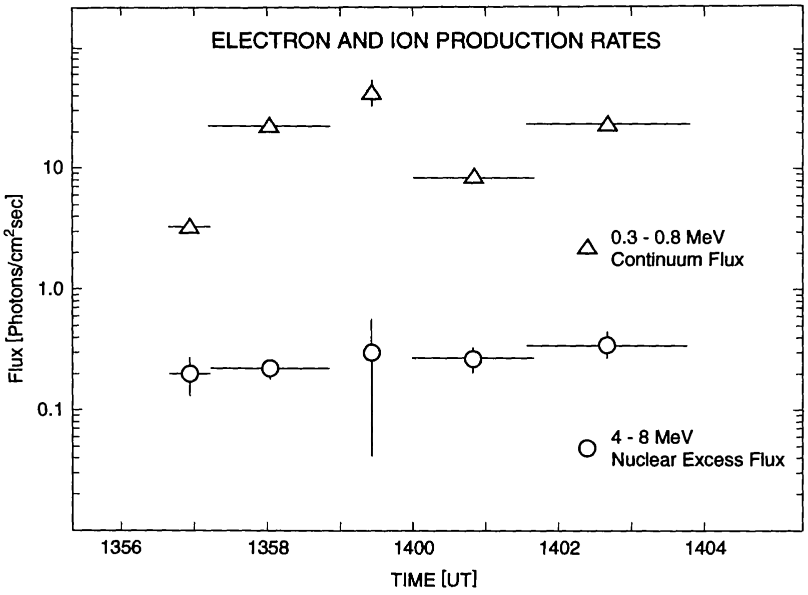

Figure 3. 0.3-0.8 MeV continuum flux and 4-8 MeV nuclear excess flux representing the electron and ion production rates, respectively, during 5 different time intervals of the flare (see the text).

continuum flux, which increased dramatically. This constancy suggests that the nucleonic emission may have orignated from an area spatially separated from the electron-dominated bursts, implying particle acceleration on different magnetic flux tubes (see also Chupp et al. (1993) for a spatially complex flare). If this assumption is correct, then the ion production, causally connected with the electron-dominated bursts, is much smaller than originally estimated by Rieger, Gan and Marschhäuser (1998).

4. Conclusions

Spectral analysis of the start of an intense solar γ-ray flare shows that electron and ion acceleration can proceed in a high-density medium ($\gtrsim 10^{11}$ cm^{-3}). A similar result was obtained by Trottet et al. (1998) for electron acceleration alone. The flare evolves spectrally from a γ-ray line event over intermediate electron-dominated bursts back to a γ-ray line flare. These phases occur at successively lower densities evidenced by micro-wave and radio observations. A causal connection between the high density of the ambient medium where particles were accelerated and the electron rich outcome of the bursts is, therefore, not possible. Electron-dominated events, on the other hand, could be the result of DC electric field acceleration by flux tube fracture (Haerendel, 1994), by reconnection of current sheets (Litvinenko, 2000; Kliem, 2000) or by stochastic acceleration operating in small volumina (Miller, 2000). Preliminary results obtained with the newly built Solar Submillimeter-wave Telescope (SST) at El Leoncito (Argentine) demonstrate that high-frequency radiation can indeed come from very small volumina (Kaufmann, 1996 and 2000).

From the spectral evolution we conjecture that the different flare phases are spatially separate. It is the hope that HESSI with its imaging capability up to a few 100 keV and its high spectral resolution at MeV energies (Lin, 2000) and observations in the sub-mm/far-infrared domain will shed more light on these special events.

Acknowledgments. The authors thank Marian Karlický (Ondřejov Observatory), A. Magun (Inst. Angew. Physik, Univ. Bern), M. Poquérusse (Obs. de Paris Section de Meudon, DASOP and CNRS), and the Sagamore Hill station for providing radio and micro-wave data. This work was supported by the Bundesministerium für Forschung und Technologie under contract number 010K017-ZA/WS/WRK 0275:4.

References

Chupp, E.L., Trottet, G., Marschhäuser, H., Pick, M., Soru-Escaut, I., Rieger, E., & Dunphy, P.P. 1993, A&A, 275, 602

Forrest, D.J., & Chupp, E.L. 1983, Nature, 305, 291

Haerendel, G. 1994, ApJS, 90, 765

Hudson, H., & Ryan, J. 1995, ARA&A, 33, 239

Kaufmann, P. 1996, in High-Energy Solar Physics, eds. R. Ramaty, N. Mandzhavidze, X.-M. Hua, AIP Conf. Proc. 374, (NY:AIP), 379

Kaufmann, P. 2000, these proceedings

Kliem, B. 2000, these proceedings

Lin, R.P. 2000, these proceedings

Litvinenko, Yu.E. 2000, these proceedings

Marschhäuser, H. 1993, Dissertation, Universität München

Miller, J.A. 2000, these proceedings

Park, B.T., Petrosian, V., & Schwartz, R.A. 1997, ApJ, 489, 358

Rieger, E. 1989, Solar Phys., 121, 323

Rieger, E., & Marschhäuser, H. 1990, in Max '91 Workshop No. 3, eds. R. Winglee & A. Kiplinger (Estes Park, CO), 68

Rieger, E. 1994, ApJS, 90, 465

Rieger, E., Gan, W.Q., & Marschhäuser, H. 1998, Solar Phys., 183, 123

Rieger, E., Treumann, R.A., & Karlický, M. 1999, Solar Phys., 187, 59

Share, G.H., & Murphy, R.J. 1995, ApJ, 452, 933

Simnett, G.M., & Benz, A.O. 1986, A&A, 165, 227

Trottet, G., Chupp, E.L., Marschhäuser, H., Pick, M., Soru-Escaut, I., Rieger, E., & Dunphy, P.P. 1994, A&A, 288, 647

Trottet, G., Vilmer, N., Barat, C., Benz, A., Magun, A., Kuznetsov, A., Sunyaev, R., & Terekhov, O. 1998, A&A, 334, 1099

Vestrand, W.T. 1988, Solar Phys., 118, 95

Vestrand, W.T., Share, G.H., Murphy, R.J., Forrest, D.J., Rieger, E., Chupp, E.L., & Kanbach, G. 1999, ApJS, 120, 409