Properties of Coronal Mass Ejection and Type II Solar Radio Burst Associated with a Sustained >100 MeV Gamma-ray Emission Event Observed by Fermi/LAT

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Abstract: Sustained gamma-ray emission (SGRE) events observed by Fermi/LAT at >100 MeV energies are associated with fast and wide coronal mass ejections (CMEs) from the Sun. These CMEs are similar to those that cause ground level enhancement in solar energetic particle (SEP) events. CME-driven shocks have been suggested to be the acceleration site of the >300 MeV protons producing the >100 MeV gamma-ray emissions. Correlation between the durations of SGRE events and type II solar radio bursts that are produced by shock-accelerated electrons support the idea. We discuss the CME and type II radio burst properties associated with the SGRE event observed on 7 June 2011. The near-Sun speed of the CME was 1680 km/s and it accelerated relatively fast. It produced an SEP event with a fluence spectral index of 2.22 ± 0.22 and it was associated with a GOES M2.5 X-ray flare. At the end time of type II radio burst, the shock had traveled to a radial distance of 75.5 R_{sun} and had a speed of about 1000 km/s. The estimated durations of the SGRE and type II radio burst were 3.08 ± 1.67 hr and 10.93 ± 0.32 hr, respectively. We discuss briefly also the limitations of the gamma-ray, CME, and radio observations.

Introduction

Long-duration gamma-ray flares (LDGRFs) at the Sun have been detected since the1980s (e.g.,[1]). Recently, observations by the Fermi Large Area Telescope (LAT; [2]) have shown that solar eruptions where the >100 MeV gamma–ray emission outlasts the GOES X-ray flare by several hours occur occasionally (e.g., [3]–[4]). We call these events sustained gamma-ray emission (SGRE) events. The >100 MeV SGRE is dominated by gamma-rays resulting from the decay of neutral pions created in interactions of >300 MeV protons precipitating into the solar chromosphere from the solar corona (e.g., [5]). The origin of the high-energy protons is still debated. Flare-accelerated protons that are trapped and/or reaccelerated in the coronal loops sufficiently long after the X-ray flare itself has disappeared has been suggested as a particle source candidate (e.g., [1]). However, the long duration trapping of high-energy protons in coronal loops is difficult to obtain, because high levels of turbulence effectively scatter particles into the loss cone. Another suggested source for the >300 MeV protons is the shock front driven by a fast coronal mass ejection (CME) launched during the solar eruption. The facts that SGRE events are detected during behind-the-solar-limb eruptions indicating an extended source of gamma-rays (e.g., [6]–[7]) and that the durations of type II solar radio burst, which are produced by CME-shock accelerated electrons, correlate with SGRE durations ([8]–[9]) provide support for the CME-driven shock as the high-energy particle source (see Fig. 1).

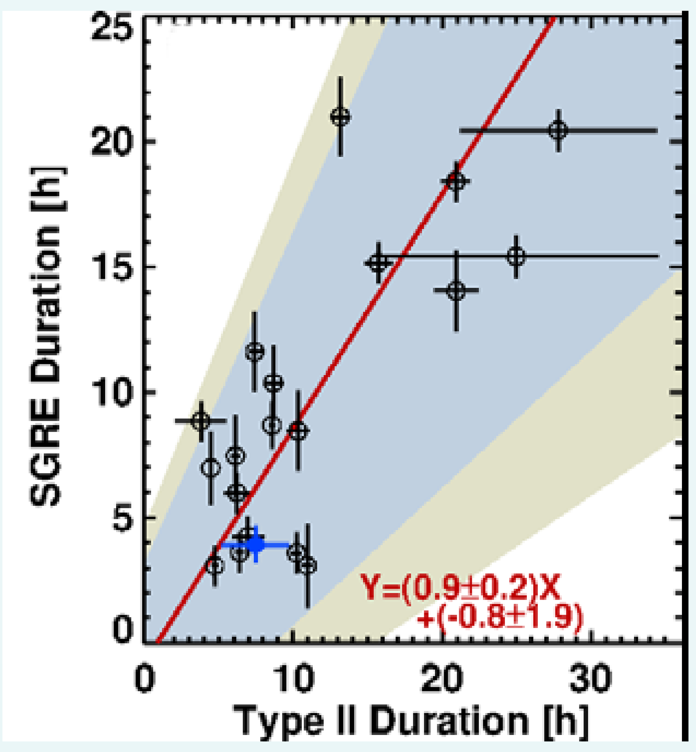


Figure 1 Type II duration v SGRE duration for SGRE events >3 hr (courtesy of [9]).

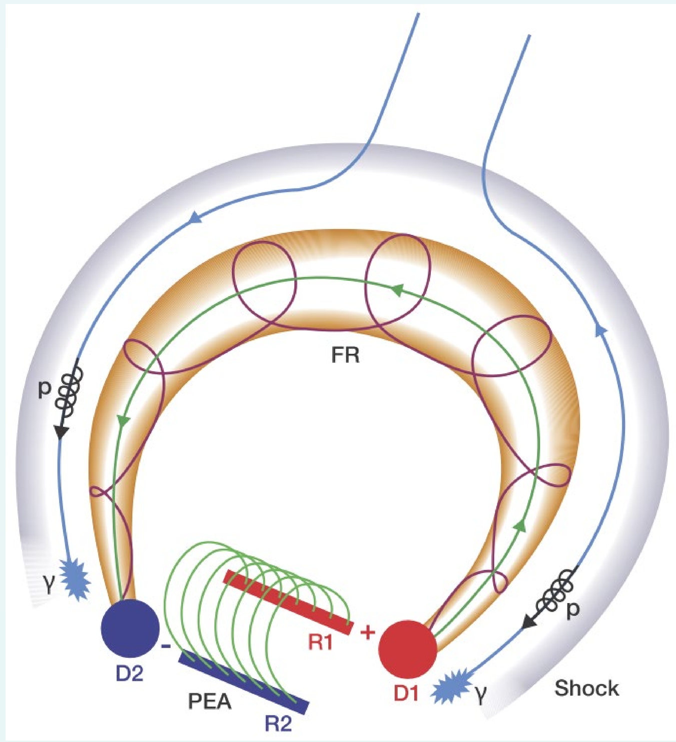


Figure 2 Schematic CME-shock model (courtesy of [5]).

CME-shock model

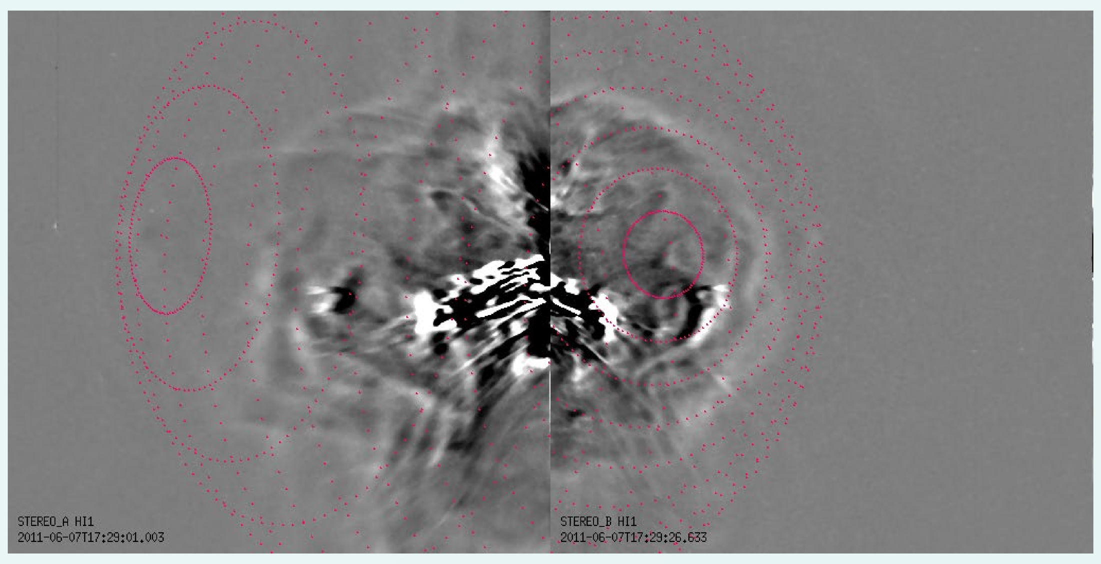
All CMEs associated with SGRE events are halo CMEs that are known to be fast and wide. The average space speed of the SGRE-associated CMEs is ~2000 km/s [9]. The speed is similar to the average speed of CMEs producing the so-called ground level enhancement (GLE) events observed by neutron monitors on Earth. The GLE events are produced by high-energy protons with energies several hundreds of MeVs. Therefore, the CME-driven shock could be the origin of the >300 MeV protons resulting in SGRE events.

The key aspects of the CME-shock model shown in Fig. 2 are:

1. Magnetic field lines within the sheath region connect back to the Sun in areas outside the foot points of the CME flux rope, therefore providing a natural explanation for the spatially extended source of gamma-ray emission.
2. The magnetic field lines are pushed ahead of the CME body as it propagates outwards and therefore, they maintain a continuous connection between the shock and the solar atmosphere required for long-duration SGRE events.
3. The foot points of the field lines could be in the regions with a lower magnetic field strength, which will increase the number of precipitating protons, because magnetic mirroring will be less effective.

The 7 June 2011 CME

Figure 3 Shock model fitted to the CME nose in the white-light images of the STEREO-A&B Heliospheric Imagers. Source of the type II radio emission at lower frequencies is known to be close the shock nose, which is the fastest part of the shock [11].



The near-Sun space speed of the CME launched on 7 June 2011 at 06:49 UT was estimated to be 1680 km/s and initial acceleration was relatively high towards the heliographic direction S15W54. The CME was associated with a solar energetic particle event with a fluence spectral index of 2.22 ± 0.22, which is in the range typical for GLE events [10].
The distance of the shock at the end of the type II radio burst was estimated by fitting a spherical shock to the three pairs of near-simultaneous white-light images of the CME taken at three different times by STEREO-A&B Heliospheric Imagers (see Fig. 3). The radial distance was estimated to be about of 75.5 R_{sun} and the CME space speed about 1000 km/s, suggesting a strong interplanetary shock ahead of the CME.

SGRE and type II radio burst

Fermi/LAT measures solar gamma-ray emission only during a fraction of the orbit, an average duration is about 30 minutes [4]. Duration of the >100 MeV gamma-ray emission estimated from the X-ray peak time to the midpoint of the last data point above the background level and the following data point. Type II radio burst duration estimated by eye from the Wind/WAVES dynamic spectrum.

GOES M2.5 X-ray flare at the heliographic location S21W54

SGRE event
X-ray peak (M2.5) time: 06:41 UT
SGRE end time: 09:46 UT
Duration: 3.08 ± 1.67 hr

Type II radio burst
Type II start time: 06:45 UT
Type II end time: 17:41 UT
Duration: 10.93 ± 0.32 hr

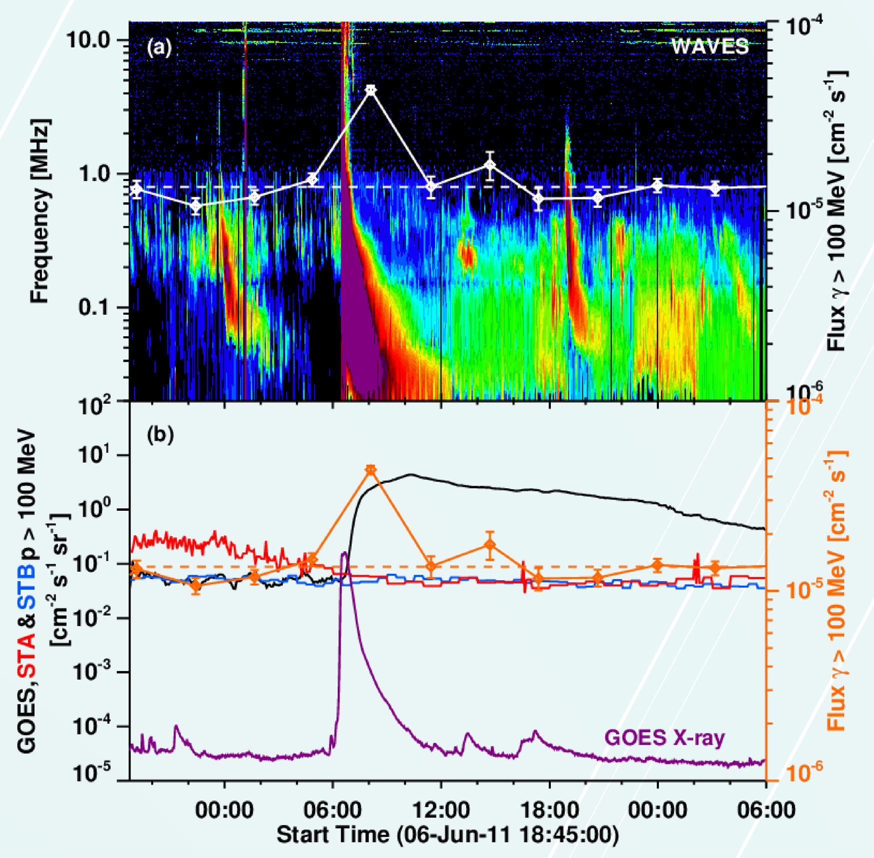


Figure 4 (a) Wind/WAVES radio dynamic spectrum and Fermi/LAT >100 MeV gamma-ray flux (white diamonds) plotted on it. (b) STEREO-A&B (red, blue) and GOES (black) >100 MeV proton flux, Fermi/LAT >100 MeV gamma-ray flux (orange diamonds) and GOES X-ray flux (magenta; in arbitrary units).

Discussion and conclusions

The definite answer to the question of the origin of SGRE events at the Sun still eludes us because the Fermi/LAT gamma-ray observations do not provide the time and spatial resolution required for the identification of the gamma-ray source location on the solar disk. Likewise, the source of the high-energy protons is also uncertain because we must rely on remote radio observations of type II solar radio bursts produced by the electrons accelerated at the CME-driven shock to infer the existence of a strong shock ahead of the associated CME. The existence and location of a sufficiently strong interplanetary shock front is difficult to confirm from the white-light images, because the shock front is a thin structure. Parker Solar Probe and Solar Orbiter observations made closer to the Sun could provide some answers on the role of CME-driven shocks in producing SGRE events in the near future.
In conclusion, we believe that the 7 June 2011 SGRE event discussed here could be explained as a result of >300 MeV proton flux originating from the CME-driven shock, while it propagated up to the radial distance of 75.5 R_{sun}. The basic mechanism of shock acceleration and particle propagation are relatively well understood. The CME-shock model can provide an explanation to all the particle and radio observations associated with the SGRE event.

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