What Do the SEP events and the Associated High- Energy Flares of 2012 March 7 Tell Us About Long Duration Gamma-Ray Flares?

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Long Duration Gamma-Ray Flares (LDGRF)

- Extremely long duration (hours), smooth exponential decay, often with minute(s) delay after impulsive phase.
- High energy $\pi$-decay produced ($>1$ GeV) photons.
- No primary electron component detected.
Where do they originate and how?

- Delayed onset, relativistic ion energies, long duration—similar to GLEs. Maybe the coronal shock that produces a GLE can feed particles back to the Sun to radiate. If not shocks, then where?
- Let’s examine this? Are there counterexamples?
  1. Find a shock/SEP event with no LDGRF—but maybe poor connection back to Sun, or
  2. find a LDGRF with no corresponding shock/SEP event to provide particles.
2012 March 7 may be such an event

- Two X-class flares one hour apart from AR 11429 N16°E29°, X 5.4, 00:02 UT (peak 00:24 UT) and X1.4, 01:05 UT (peak 01:14 UT).

Summarizing results of Kouloumvakos et al. (2016)

- First X5 flare/CME responsible for SEP event at Earth and STA 2800 km-s⁻¹. Supported by Ding et al. (2016) and Richardson et al. (2014).
- Inferred shock (slower) from second X1 flare, just low corona phenomenon, but no IP particle production. Supported by above researchers.
- X5 active region had oor connection to Earth, producing diffusive-like SEP event. Only STB has good connection to WL or EUV signatures.
- Clear low-corona particle activity from both events (X/γ and μ waves)
Dubbed “impulsive phase” by Ajello et al.
Alternative Continuous Acceleration Process in Static Structure

- Leakage from ends of rarified large loop \((10^9 \text{ cm}^{-3}, >10^5 \text{ km})\)
- Long lasting MHD turbulence resonant with \(~100 \text{ MeV}\) protons.
- Inject monoenergetic protons \((20 \text{ MeV})\)
- Diffusion in \(x\) and \(p\). \(\tau = L^2 / \pi^2 \kappa\)
- Delay comes from transport and pion threshold.

\[
\frac{\partial f}{\partial t} = p^{-2} \frac{\partial}{\partial p} \left\{ p^2 \left[ D(p) \frac{\partial f}{\partial p} - f \dot{p}(p) \right] \right\} + \frac{\partial}{\partial x} \left( \kappa \frac{\partial f}{\partial x} \right) - \frac{f}{T} + Q(x,p,t)
\]

 condos action Hi-E emission
Possible Complications

• Energy loss from collisions with electrons. OK if density is low—large loop.

• Curvature and gradient drifts. Could be an issue for the 20-h 2012 March 7 event. *Could be path for getting particles into IP space.*

• Maintenance of turbulence to both trap and accelerate the ions. *Easy to initiate, and may have been detected* (*De Moortel et al.*, 2014). Turbulence itself could be trapped.

• We also take the spatial diffusion coefficient $\kappa$ to be independent of energy and position, making the momentum diffusion $\propto p^2$. 
Continuous Acceleration model for 1st Flare (X5)

Requires loop length > 1 R\textsubscript{\odot}
Both Events

The bright solar flare of March 2012

At time of centroid displacement

CME at 0.5 AU

TABLE 4

<table>
<thead>
<tr>
<th>Event Class</th>
<th>Conversion</th>
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<th>Arrival Time</th>
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PSF 68% corresponds to the 68% containment radius calculated from the PSF of the instrument for an energy and direction equal to the energy and direction of the event.

The sensitivity of the Fermi-LAT enables the investigation of several aspects of solar flares that were not previously accessible, in particular the spectral evolution during the impulsive phase and throughout the temporarily extended phase, as well as the localization of the >100 MeV emission. The data for the exceptionally bright solar flares of 2012 March 7 represent an excellent opportunity to study the details of these characteristics. Here we focus on the possibility of constraining the emission and acceleration processes.

For the initial four time intervals the projected location of the gamma-ray emission is consistent with the position of the active region #11429. While in the last two time intervals the localizations are slightly displaced with respect to this region, but still consistent with the solar disk.

GOES fluxes began to rise at about 00:05:00 UT, and continued to increase for over an hour, while Fermi-sunrise started roughly six minutes after the peak of the first flare at 00:30:00 UT. This coincided with the gradual decay phase during which the hard X-ray (HXR) emission is relatively soft. The GBM detected only weak emission above 100 keV during the first flare. On the other hand, the second flare had a large flux in the 100-300 keV range and a significant flux above 1 MeV, which indicates acceleration of electrons up to several MeVs.

The derivative of the GOES flux has a pulse shape with a similar structure to that of the lowest energy GBM channel. These pulses show the usual soft-hard-soft spectral evolution in the HXR regime. However, the LAT >100 MeV emission has a monotonically decreasing flux that is approximately exponential with a \( \sim 30 \) m decay period. There is no significant evidence for an upturn in flux during the X1.3 flare, while the derived proton index does show some variation. The pion-decay model, which fits well, requires a relatively hard proton spectrum with the power-law index, \( s \), ranging between \( \sim 3.0 \) and \( \sim 3.5 \).

The spectrum is initially soft, but then exhibits evidence of spectral hardening during the second flare, as also appears to be the case in the HXR regime (Figure 1). The hardening seems to start \( \sim 20 \) minutes before the start of the X1.3 flare. However, the significance of this early hardening is less than \( 3 \). If this is real, explanations for spectral hardening during the decay phase can be an intensification of the acceleration rate or, alternatively, to trapping of accelerated particles in a coronal loop with a converging magnetic field configuration (see below).

The temporally extended emission is characterized by a slight increase of the gamma ray flux starting at approximately 2:15:00 UT; the flux reaches its maximum at 9:00 UT on 2012 March 7.
Summary

• Two LDGRFs occurred on 2012 March 7, separated by about one hour.
• Both produced similar HXR/$\gamma$ and $\mu$ wave intensities but differing by $5\times$ in SXR.
• Earlier flare produced LDGRF with a ~1 $R_\odot$ loop.
• Having the second IP shock produce 20-h emission at the Sun is unattractive from other observations.
• Second flare produced the 20-h LDGRF with no contribution from IP space.
• Compatible with trapping and acceleration in a magnetic structure between AR11429 and AR11423, but needs further study.
• No particle in space registered $>1$ GeV (PAMELA collab., priv. comm.)
• Particles in space $>500$ MeV roughly comparable to or less than those deduced from $\gamma$ data (de Nolfo et al., 20 minutes ago)
Future Work for Loop

- Investigate possibilities of losing coronal loop particles into space, e.g., curvature and gradients drifts and how that affects fits.

- Must investigate other parts of parameter space, e.g., length scales, and other acceptable parameters for good fits.

- Interpret fit parameters in the context of other data.

- Study other LDGRFs to search for patterns and similarities.
ARGOMoon
Italy’s Eye on the Moon

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwiPpeHE8tHaAhXCMd8KHZTtBJYQ3ywIKTAA&url=https%3A%2F%2Fwww.youtube.com%2Fwatch%3Fv%3DJsHuSqLIEw&usg=AOvVaw1cPRNsqAfWty5Po2uNhKlO