Origin of Long-Duration Gamma-ray Flares and Their Connection with SEPs

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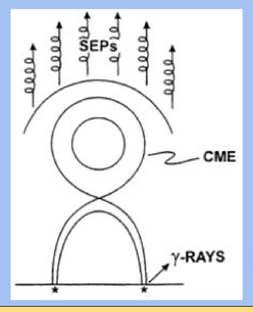
Introduction

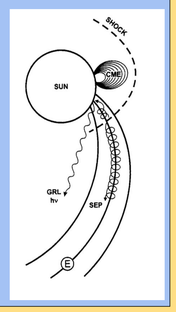
Gamma-ray solar flares provide the opportunity to examine particle acceleration mechanisms associated with solar activity. We expect gamma-rays to be emitted during the flare's impulsive phase, but long-duration gamma-ray flares with delayed emission lasting several hours suggest an extended acceleration phase inconsistent with shorter-duration gamma-ray flares. The origin of long-duration gamma-ray flares remains a puzzle.

To investigate the origin of these long-duration events, we examine associated solar phenomena related to impulsive (X-ray flares) and shock (coronal mass ejections (CMEs) and DH Type II radio bursts) acceleration, and solar energetic protons (SEPs). Associated SEPs are particularly significant in this study since gamma-rays are produced in pion-decay processes resulting from acceleration of ~300 MeV protons. In the flare acceleration scenario, gamma-rays are produced in flare loops while SEPs are produced in CME shocks (diagram A at right). In the shock scenario, some of the accelerated high-energy protons will escape on open-field lines into space potentially detected as SEPs at Earth while others will loop back to the Sun producing gamma-rays (diagram B at right).

A

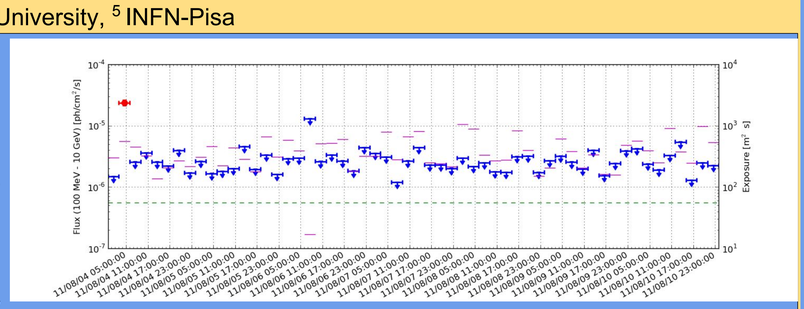


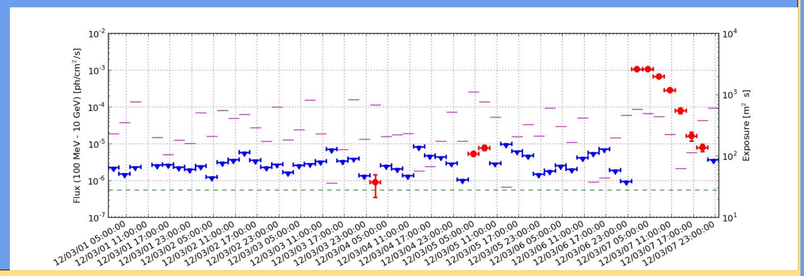
B



Fermi LAT

The Fermi Gamma-ray Space Telescope scans the entire sky every 3 hours, allowing for continuous solar observations of 20-40 minutes multiple times per day. Solar gamma-ray flares were identified at > 100 MeV with the Large Area Telescope (LAT). Example LAT light curves are shown at right, with the background in blue and flare detections in red. The bottom panel shows a long-duration gamma-ray flare.

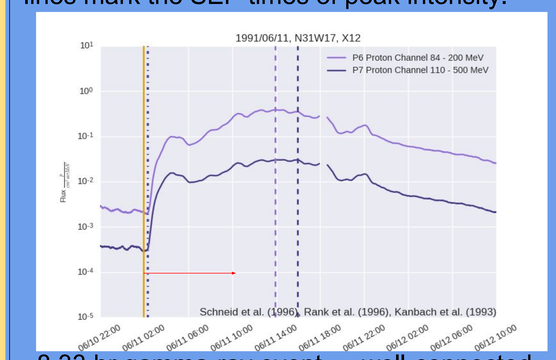




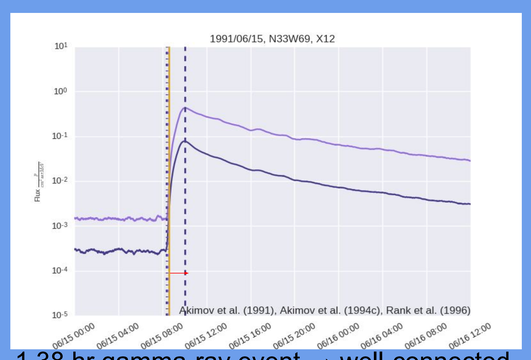
Research Question: *What is the origin of long-duration gamma-ray flares? We investigate the association of long-duration gamma-ray events with SEPs and other solar events to study their origin and connection to high-energy proton acceleration from CME-driven shocks or flares.*

SEP Analysis

We show GOES proton flux data for several SEP events associated with long-duration gamma-ray flares. The red arrow extends the length of the gamma-ray event duration, the yellow line marks the gamma-ray event on-set, the maroon line marks the X-ray flare on-set, the dotted navy line marks the CME on-set, the orange dashed line marks the DH Type II burst on-set, the dash-dotted lines mark the SEP on-sets, and the dashed lines mark the SEP times of peak intensity.

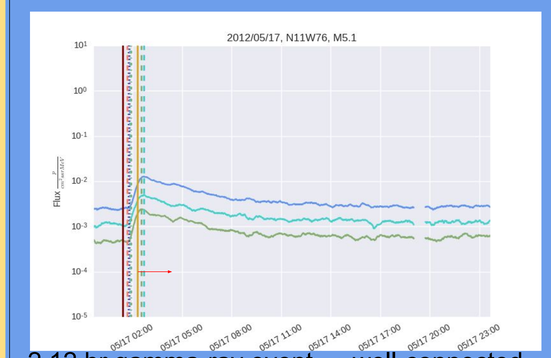


8.33 hr gamma-ray event → well-connected SEP

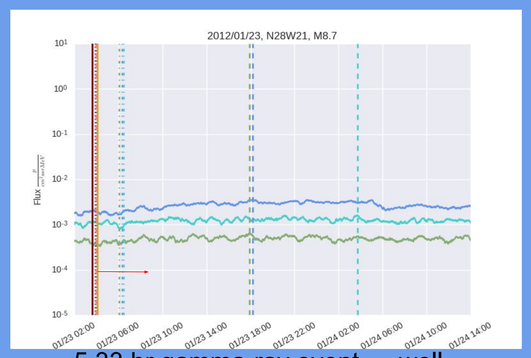


1.38 hr gamma-ray event → well-connected SEP

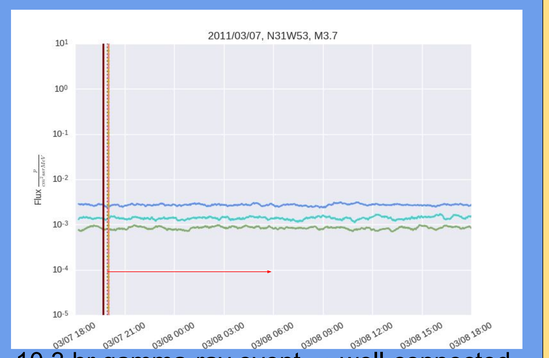
14.33 hr gamma-ray event → poorly-connected, delayed SEP



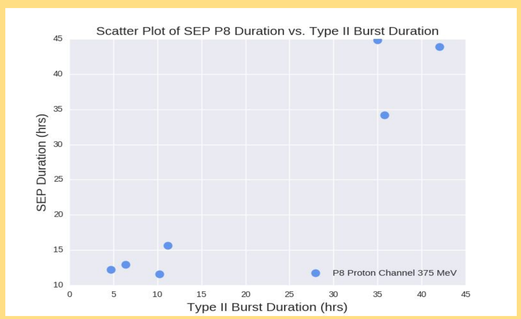
2.12 hr gamma-ray event → well-connected SEP



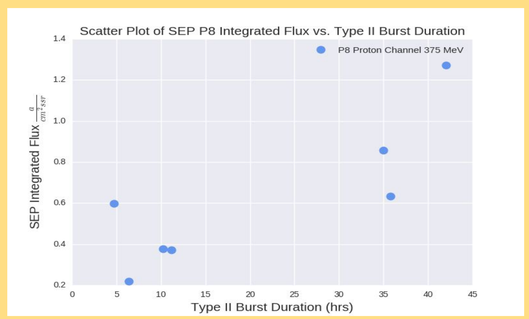
5.33 hr gamma-ray event → well-connected, but weak SEP



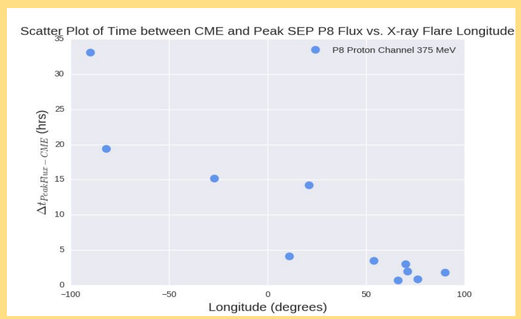
10.3 hr gamma-ray event → well-connected, but no SEP



All of the gamma-ray events were associated with DH Type II radio bursts in Wind/WAVES. Longer duration bursts are associated with longer-duration SEP events.



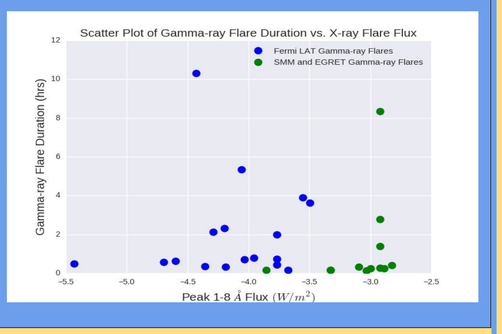
DH Type II bursts (shock indicators) with longer durations are associated with higher intensity high-energy SEP events.



SEPs are detected more frequently and promptly when originating in the west than those in the east.

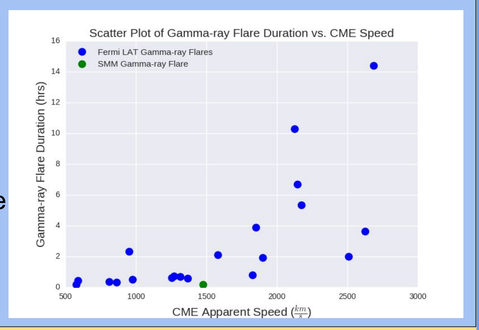
X-ray Flares and Gamma-ray Flares

Peak GOES X-ray flare flux for flares associated with gamma-ray events does not correlate with gamma-ray flare duration (right) or flux. The longest duration gamma-ray events are not always associated with the brightest X-ray flares.



CMEs and Gamma-ray Flares

Using the SOHO LASCO CDAW CME catalog we found CMEs associated with gamma-ray events. At right, we show the correlation between CME speed and gamma-ray flare duration. Long-duration events are generally associated with fast CMEs.



Discussion

We did not find strong correlations between X-ray flares and gamma-ray flares, but we did see correlations between shocks (CMEs and DH Type II radio bursts) and gamma-ray properties, suggesting that shocks are more likely to accelerate protons that lead to long-duration gamma-ray flares.

In general, we find that Western flares have a better magnetic connection to Earth than Eastern flares, as expected. However, the 3/7/2011 event is well-connected and one of the longest-duration events observed and is not associated with high-energy SEPs. This event challenges our understanding of long-duration gamma-ray events and will be a focus of future research.

Acknowledgments

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