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Fermi Large Area Telescope observations of high-energy gamma-ray emission from the X-class solar flares of 2012 March 7

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On 2012 March 7 two bright X-class flares originating from the active region NOAA AR 11429 erupted within an hour of each other, marking one of the most active days of Solar Cycle 24. The *Fermi* Large Area Telescope (LAT) observed both the impulsive and the long duration phases of these two bright flares detecting gamma-rays up to 4 GeV and $>$ 100 MeV emission for $\sim$ 20 hours. Thanks to the increased sensitivity of the LAT we were able to accurately localize the high-energy gamma-ray emission to the same active region from which the X-ray emissions associated with these flares originated. Here we present the Fermi LAT detections of these bright solar flares and the implications for the emission processes tied to these explosive phenomena.

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1. Introduction

On 2012 March 7 two bright X-class flares originating from the active region NOAA AR#:11429 erupted within an hour of each other, marking one of the most active days of Solar Cycle 24. Orbital sunrise for *Fermi* occurred less than six minutes after the peak of the first flare, triggering the *Fermi* Gamma-Ray Burst Monitor (GBM) at 00:30:32.129 UT. The >100 MeV emission from these flares was detected by the *Fermi* LAT for ∼20 hours setting a new record for the duration of detected gamma-ray emission from a solar flare. During these flares, the LAT >100 MeV all sky count rate[1] was dominated by the gamma-ray emission from the Sun[2], which was nearly 100 times brighter than the Vela Pulsar in the same energy range.

2. *Fermi* LAT observations

During the impulsive phase (the first eighty minutes) the X5.4 flare was so intense that the LAT anti-coincidence detector suffered from pulse pileup (see [1] for a full description of this effect) and consequently was analyzed with the LAT Low Energy technique (LLE) (appendix A of [2]) whereas the extended phase was analyzed with the standard instrument response functions. To investigate whether the emission mechanisms at work are due to bremsstrahlung from accelerated electrons or decay of pions from interactions of accelerated hadrons, we fit the data with three models: for the former we use a power law and a power law with an exponential cut-off and for the later we used templates based on a detailed study of the gamma rays produced from pion decay (R. Murphy private communication). We find that the spectra can be adequately described by a power law with a high energy exponential cutoff, or as resulting from the decay of neutral pions produced by accelerated protons and ions with an isotropic power-law energy distribution. The resulting light curves are shown in Figure 1.

The LAT > 100 MeV emission during the impulsive phase is relatively hard and decreases monotonically with no significant evidence for an upturn during the second flare. Whereas the derived proton spectral index obtained from the pion-decay model does show some variation ranging between ∼3.0 and ∼3.5. The spectrum is initially soft, but then exhibits evidence of spectral hardening during the second flare, which is also the case in the HXR regime (see the left panel of Figure 1). The hardening of the LAT spectrum seems to start ∼20 minutes before the start of the X1.3 flare. However, the significance of this early hardening is less than 3σ. 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 approximately 4:00:00 UT. The peak of the light curve is broad and the flux after t_0=12:00 UT decays exponentially as $F(t) \propto \exp[-(\mathrm{t}-\mathrm{t_0})/\tau]$, with $\tau \approx 2.7$ hours. The gamma ray spectrum and thus the required particle spectrum softens monotonically with no sign of an early rise or a plateau as seen in the flux.

During the ∼ 20 hours of detected flaring gamma-ray emission, the LAT measured 5 photons with E > 2.5 GeV and reconstructed direction less than 1° from the center of the solar disk. Two of these were detected during the impulsive phase with energies ∼2.8 GeV and ∼4 GeV and the remaining three during the extended emission, including one with energy ∼4.5 GeV at 07:30UT.

[1] for `P7SOURCE_V6` class

[2] Illustrated by the astronomy picture of the day,http://apod.nasa.gov/apod/ap120315.html

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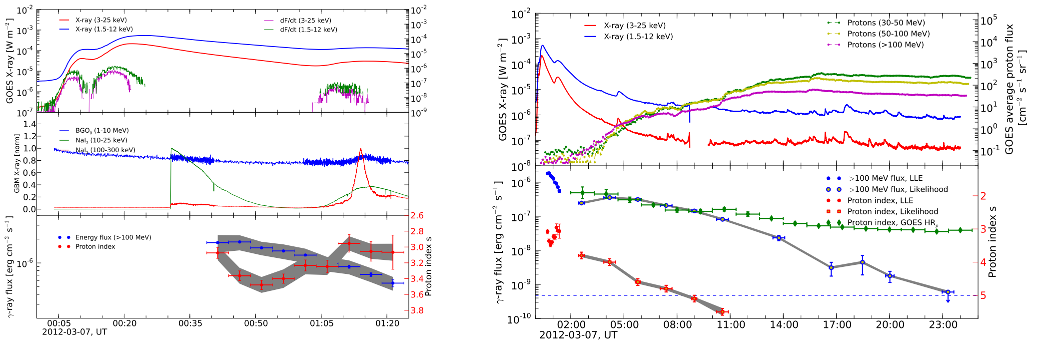

Figure 1: Left figure:Composite light curves for 2012 March 7 flare, covering the first ∼80 minutes. Top left panel: soft X-rays from the GOES 15 satellite and the first derivatives of the fluxes are on the right axis. Middle left panel: hard X-rays count rates from the GBM and bottom left panel shows the LAT >100 MeV gamma-ray flux and derived proton spectral index. **Right figure**: The long lasting emission. Top right panel: soft X-rays from the GOES 15 satellite, the 5-minute averaged proton flux is on the right axis. Bottom right panel: >100 MeV gamma ray flux measured by the LAT. The Blue/red circles represent the flux and the derived proton spectral index for the first ∼80 minutes of the flare with the LLE analysis. The gray bands correspond to the systematic uncertainty associated to flux and to the estimated proton index and the horizontal dashed line corresponds to the value of the gamma-ray flux from the steady Sun, from [3].

3. Interpretation

The *Fermi* LAT observations of the flares of 2012 March 7 provide an excellent opportunity to study the spectral evolution during the impulsive phase and throughout the temporally extended phase. Thanks to the high sensitivity of the LAT we find that during most of the long duration emission the gamma-rays appear to come from the same active regions responsible for the flare emission. The fluxes and spectra of the high-energy gamma-rays evolve differently during the impulsive phase and the sustained emission but in both phases we find that the emission is well described by the pion templates. From these data we suggest that the most likely scenario for production of high energy gamma-rays is that they are produced by energetic protons (rather than electrons) that are accelerated in the corona (rather than in the associated fast CME shock) continuously during the whole duration of the emission.

References

[1] M. Ackermann, et al., *Fermi Detection of γ-Ray Emission from the M2 Soft X-Ray Flare on 2010 June 12*, *ApJ* **745**

[2] M. Ackermann, et al., *Impulsive and Long Duration High-Energy Gamma-ray Emission From the Very Bright 2012 March 7 Solar Flares*, *ArXiv e-prints* [1304.5559]

[3] A. A. Abdo, et al., *Fermi Large Area Telescope Observations of Two Gamma-Ray Emission Components from the Quiescent Sun*, *ApJ* **734**

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