Shedding new light on the Sun with the Fermi LAT

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for the Fermi/LAT collaboration

Fifth international Fermi Symposium - Nagoya University
Gamma-ray emission from the Sun

- The sun is a steady, faint source of gamma-rays (produced by the interactions of CR with the solar atmosphere and with the solar radiation field);
- High-energy emission (up to GeV) has been observed in solar flares:
  - In the past decades, only two long-lived (hours long) gamma-ray emissions were observed by EGRET (e.g. Kanbach+93, Ryan00)
  - It was unclear where, when, how the high-energy (HE) particles responsible for gamma-ray emission are accelerated

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<th>Month</th>
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</tr>
</tbody>
</table>

Kanbach et al. 1993

Ryan 2000

Light curve (E>50 MeV) of 1991 June 11 flare
Gamma-ray emission from the Sun

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• High-energy emission (up to GeV) has been observed in solar flares:
  • In the past decades, only two long-lived (hours long) gamma-ray emissions were observed by EGRET (e.g. Kanbach+93, Ryan00)
  • It was unclear where, when, how the high-energy (HE) particles responsible for gamma-ray emission are accelerated

• Complex flare build up (magnetic filed structures, loops and Active Region);
• Magnetic fields reconnect releasing energy which accelerate particles;
• Particles are trapped by magnetic field lines and interact with the solar atmosphere, producing gamma-rays;
• Some of the particles have access to the open filed line and escape into interplanetary space;
• They can also be accelerated by the CME shock;
Nicola Omodei – Stanford/KIPAC

Impulsive & Sustained flares with Fermi LAT

- Ackermann et al. 2012, ApJ...745..144A
- Sustained emission observed up 20 hours

See the poster 11.03 on the SunMonitor for more details on the continuous monitor of the sun with Fermi LAT!
Solar flares detected by the LAT >100 MeV

- Xtreme and Moderate flares detected
- I: impulsive emission
- I/S: we cannot distinguish between impulsive and Sustained.
- S: We don’t see the impulsive emission because the Sun was not in the FoV, but we detect sustained emission
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<table>
<thead>
<tr>
<th>Date</th>
<th>GOES X-Ray Class, Start–End*</th>
<th>Type</th>
<th>Duration (hr)</th>
<th>CME Speed (km s⁻¹)</th>
<th>Fermi Time Window</th>
<th>TS²</th>
<th>Flux¹</th>
<th>Energy Flux¹</th>
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Solar flares detected by the LAT >100 MeV

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- All associated with fast CME

### Table 1: Solar Flares Detected by the Fermi LAT from 2008 August to 2012 August

<table>
<thead>
<tr>
<th>Date</th>
<th>GOES X-Ray Class, Start–End</th>
<th>Type</th>
<th>Duration (hr)</th>
<th>CME Speed (km s⁻¹)</th>
<th>Fermi Time Window</th>
<th>TS</th>
<th>Flux (10⁻³ ph cm⁻² s⁻¹)</th>
<th>Energy Flux (10⁻³ erg cm⁻² s⁻¹)</th>
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<td>2.5 ± 0.3</td>
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<tr>
<td>2011 Mar 8</td>
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<td>S</td>
<td>2.3</td>
<td>796</td>
<td>09:43, 45</td>
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<td>11.0 ± 0.9</td>
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<tr>
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<td>2.2</td>
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<td>3.6 ± 0.3</td>
<td>11.0 ± 0.9</td>
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<td>19:45, 11</td>
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<td>9.6 ± 2.2</td>
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<td>2012 Mar 7</td>
<td>X5.4, 00:02-00:40</td>
<td>I/S</td>
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<td>2684</td>
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<td>21:05, 30</td>
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<td>2.8 ± 0.6</td>
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<td>23:19, 52</td>
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<td>3.5 ± 0.2</td>
<td>10.4 ± 0.7</td>
</tr>
</tbody>
</table>

Let’s focus on impulsive events: SOL2010-06-12T00:57

- Data analysis of the joint GBM and LAT data provides useful information about the underlying accelerated particle distributions:
  - Electron Bremsstrahlung dominates at < 1 MeV energies
    Not a simple powerlaw: hardening followed by a roll-off (at 2.4 MeV); not compatible with transport effects alone;
  - Protons/ions: gamma-ray spectral features as a proxy of the accelerated ion spectrum

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy of gamma-ray</th>
<th>Energy of the ions</th>
<th>Derived accelerated ion spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Capture</td>
<td>2.2 MeV</td>
<td>10-50 MeV</td>
<td>3.2 (10-50 MeV)</td>
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<tr>
<td>Nuclear lines</td>
<td>5-20 MeV</td>
<td>50-20 MeV</td>
<td>4.3 (50 -300 MeV)</td>
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<tr>
<td>Pions</td>
<td>&gt;300 MeV</td>
<td>&gt;280 MeV</td>
<td>4.5 (&gt;300 MeV)</td>
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</table>

Acknowledgments


See the R. Desiante talk on Impulsive flare at Parallel 13A on Thursday (GRB & SF)
A very bright Solar Flare was detected on March 7, exceeding:

- 1000 times the flux of the steady Sun;
- 100 times the flux of Vela;
- 50 times the Crab flare;
- High energy emission (>100 MeV, up to 4 GeV) lasts for ~20 hours
- Softening of the spectrum with time

LAT 1 day all sky data >100 MeV
The longest lasting gamma-ray emission: March 7, 2012

- Impulsive emission correlated with X-ray flux;
- Sustained Gamma-ray flux better correlated with SEP rather than X-ray
• Events corrected for the “fish-eye-effect”
• 95% CL error circle with systematic error added in quadrature
• Location of the gamma-ray emission consistent with the location of the Active Region 11429
• Time resolved localization shows consistency with the AR at earlier times, becoming less constrain at later times
Behind-the-Limb flares

- **SOL131011**: M1.5 GOES class flare erupted at 7:01:00 UT
- EUV and HXR data reveal that the active region is \(\sim 11°\) behind the visible Solar limb at the time of the flare;
- *Other behind the limb flares have been detected, stay tuned!*

![Images of solar flares viewed from B and Earth, and a diagram showing the relative positions of B, A, SUN, Mercury, Venus, and EARTH.](image-url)
Behind-the-Limb flares

- HXR footpoints were occulted during RHESSI coverage and part of LAT detection
Where does the gamma-ray emission come from?

Footpoints not visible at the time of the gamma-ray detection
High density region required for gamma-ray production
Where does the gamma-ray emission come from?

Footpoints not visible at the time of the gamma-ray detection
High density region required for gamma-ray production
Solar Spaghetti

Composite AIA SDO image with magnetic field model overlaid

Magnetic field lines connect different regions across the solar surface
Understanding particle acceleration and gamma-ray emission at the Sun

- Particles accelerated during the impulsive phase interact with the solar surface (right below the photosphere) producing gamma-rays (pion production most likely)
- Part of the accelerated particles can escape and eventually can be re-accelerated by the CME shock (This also explains the correlation with SEP)
- Continuously accelerated particles can travel along magnetic field lines, and interact with the dense solar surface in front of the solar limb.
- Alternatively, CME re-accelerated particles can travel back to the Sun along magnetic field lines and interact with dense region, explaining the long lasting emission.