Solar Protons above 500 MeV in the Sun’s Atmosphere and in Interplanetary Space

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Overview

There are at least two sites for particle acceleration at or near the Sun:

• at the coronal reconnection site that launches the CME
• at the CME-driven shock
• perhaps others?

The relationship and relative contributions of these different sites to the energetic particle population is still a matter of debate, particular at the highest energies, i.e., protons at >500 MeV.

“Routine”, precise Fermi observations of >100 MeV solar gamma-rays offer a new avenue of investigation, including the distinction between the impulsive and sustained (or “extended”) phases of the flare.

Long-duration solar gamma-ray flares have been observed before (i.e., Kanbach et al. 1992), but never in the numbers and with the precision of Fermi. These observations permit more detailed analysis than ever before.

In this work, we compare estimates of the number of >500 MeV protons:

• in interplanetary space (in-situ measurements by satellites & by neutron monitors)
• in the solar atmosphere (remotely-sensed, derived from gamma-rays)
Outline

1. **>500 MeV protons at the Sun**: Review of the Fermi observations of sustained emission of >100 MeV gamma-rays in solar events.

2. **>500 MeV Solar Protons in Interplanetary Space:**
   - GOES/HEPAD data
   - Transport Corrections
   - Spatial Distributions
   - How obtained?
   - Systematic Uncertainties?

3. **Quantitative Comparisons**: Number of >500 MeV protons at the Sun and in IP Space

4. **Implications**:
   - Origin of the Fermi sustained–emissions
   - Acceleration processes for high-energy solar protons
A Brief Review of Fermi/LAT Observations

GOES SXR: 1-8 A
RHESSI or Fermi/GBM: HXR 100-300 keV
Fermi/LAT: >100 MeV gamma-rays

2011 Mar 07

These are short time intervals: first ~30-40 minutes of the event.
But there's more...
In these 20 events:

Delays between peak of HXRs and onset of >100 MeV γ-ray range from <1 minute to several 10s of minutes.

All of the sustained-emission events are accompanied by a broad, fast (>800 km/s) CME and HXRs (>100 keV).

But not all events with a broad, fast CME and/or >100 keV HXRs show sustained >100 MeV γ-ray emission.
>100 MeV γ-rays are produced by nuclear interactions of >300 MeV protons that generate pions in the solar atmosphere.

By modeling the observed gamma-ray emission, we can obtain information on:

- The number of high-energy protons hitting the Sun’s atmosphere (i.e., >500 MeV)
- Their spectral shape

This report

Future work
On the spatial localization of the source-region of the Fermi sustained emissions....

There is no evidence – *for or against* – the sustained emission coming from a compact source region:

- At 100 MeV, Fermi point-spread function is ~0.5 degree, which is also the size of the Sun.

- Even in the strongest events with the best gamma-ray statistics, the *centroid* of the >100 MeV emission is probably localized to within only a quadrant (octant?) of the Sun.

- More information on this issue will come from the Fermi team.
On the spatial localization of the source-region of the Fermi sustained emissions....

However, in at least some events, the source of the sustained emission cannot be only at the associated Active Region (AR):

- Fermi saw sustained emission in the event of 2013 October 11, where STEREO-B EUV observations put the associated AR at E106.

- Other sustained-emission events were seen from ARs very near to the limb, where the gamma-rays headed toward Earth would have been absorbed in the solar-atmosphere (i.e, “limb darkening”): 27 Jan 2012 at W85, 2012 May 17 at W77, 13 May 2013 at E80, 14 May 2013 at E77, 25 Feb 2014 at E82

These events indicate that the source of the sustained emission can be as much as 20-30 degrees away from the AR.
>500 MeV Solar Protons in Interplanetary Space

Very high energy solar proton measurements are available only at Earth:

- Neutron monitors in Ground-Level Events (GLEs)
- GOES/HEPAD
- PAMELA
- AMS-02

Note: STEREO reports protons only up to 100 MeV
>500 MeV Protons from GOES/HEPAD: 2011-2014

We await:

- More Events!
- Better data from PAMELA and AMS-02
Neutron Monitors and GOES/HEPAD

HEPAD data from NGDC
Reprocessed per Sauer Memo (unpublished, 2007)
*Independent of the NM analysis*

HEPAD and NM estimates of >500 MeV fluence typically agree to within ~30%.
>500 MeV Protons from GOES/HEPAD: 2011-2014

We will come back to these two events:
We now have estimates for the fluence of >500 MeV protons in IP space at Earth.

The gamma-ray analysis estimates the TOTAL NUMBER of protons IN THE SOLAR ATMOSPHERE.

We need an analogous estimate of the TOTAL NUMBER of protons IN INTERPLANETARY SPACE.

Mewaldt et al. (2005) outlined a heuristic approach to this problem:

\[
N_{IP} = 2\pi R_0^2 J_{Earth} \frac{C_{spatial}}{C_{transport}} \quad \text{(where } R_0 = 1 \text{ AU)}
\]
Interplanetary Protons: “Crossing Correction” at >500 MeV

\[
C_x = \frac{J_{\text{omni}}}{|J_{\text{forward}}| - |J_{\text{reverse}}|} = \frac{0.5^* (|J_{\text{forward}}| + |J_{\text{reverse}}|)}{|J_{\text{forward}}| - |J_{\text{reverse}}|}
\]

\[C_x = 1.9 \pm 0.3\]

\[C_x = 2.3 \pm 0.3\]

Analysis of the world-wide Neutron Monitor Network by D. F. Smart & M.A. Shea.
Analytic crossing-correction calculations by Chee K. Ng, assuming:

- Delta-function injection of particles at the Sun, i.e. short duration
- IP transport according to:
  \[ \lambda = \lambda_0 \left( \frac{P}{GV} \right)^\alpha \left( \frac{R}{AU} \right)^\beta \]
  
  with various parameter values.

Bieber et al. (2004) modeled intensities and anisotropies observed by the Spaceship Earth NM network on 2001 April 15 with \( \lambda_0 = 0.34 \text{ AU} \), \( \alpha = 0.3 \), and \( \beta = 0 \).

- Observations over 1 day
Interplanetary Protons: “Crossing” Correction” at >500 MeV
Analytic & Monte Carlo Calculations

Analytic crossing-correction calculations by Chee K. Ng, assuming:

- Delta-function injection of particles at the Sun, i.e. short duration
- IP transport according to:
  - \( \lambda = \lambda_0 \frac{P}{GV} \alpha \frac{R}{AU} \beta \)
  
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- Observations over 1 day

Monte-Carlo crossing-correction calculations by Eileen Chollet (Chollet et al. *JGR*, 2010), using the same scattering law & parameters.

Analysis of NM data and two different theoretical techniques all confirm \( C_x \sim 2 \), with a factor of 2 systematic uncertainty.

We henceforth assume that \( C_x \sim 2 \) is also applicable to other events for protons at >500 MeV.
Interplanetary Protons: Spatial Distribution

2012 January 23 Solar Energetic Protons from STEREOs and GOES
Interplanetary Spatial Distribution: Two Methods

**Gaussian fits to GOES & STEREOs**

- Available only for energies well below 500 MeV
- Not available for all events

**Distribution centered at** $\Phi_0 = 58^\circ$

**Symmetric fall-off** $\Lambda_\Phi = 23^\circ$

$$J(\Phi) = J_0 \exp\left(-\left|\frac{\Phi - \Phi_0}{\Lambda_\Phi}\right|\right) \Rightarrow C_{\text{spatial}}$$
Spatial Correction Factor

For sources at \( \sim W20-W90 \), models agree to within a factor of two.

For eastern sources, larger systematic uncertainty in this correction:
- 07 March 2012, at E27
- 11 April 2013, at E13

Extremely large systematic uncertainty causes some events to be omitted:
- 25 Feb 2014, at E82

Models for Source Location Correction:
- Exponential, peak at W58, based on historical GLEs
- Gaussian, peak at W58, use average width from STEREO-era Events
- Gaussians from STEREO-era Events, peak and width different in each event
Results

Fluence at Earth

Number of Interplanetary Protons

We can now compare $N_{\text{protons}} (>500 \text{ MeV})$ at the Sun (from Fermi) and in Interplanetary space (from this analysis).
The Fermi $\gamma$-ray analysis (Share et al., in preparation) provides separate estimates for $>$500 MeV protons at the Sun in the impulsive and sustained phases of the flare.

**Impulsive Phase** (hard x-ray emission, $\sim$10 minutes)

**Sustained Phase** ($>$100 MeV gamma-rays, $\sim$4 hours in this event)
Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

Impulsive Phase of the Flare

\[\gamma\text{-rays from RHESSI and CORONAS}\]
Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

Impulsive Phase of the Flare

![Graph showing the number of >500 MeV protons at the Sun vs. in interplanetary space during the impulsive phase of a solar flare. The graph includes data points for specific dates, with purple representing upper limits and blue representing measurements.](image)

**Purple:** upper limits
**Blue:** measurements
Implications: for the impulsive flare

Impulsive Phase of the Flare

>500 MeV protons in the impulsive flare are typically \(\sim 1\% \) or less of the interplanetary protons. This makes it EXTREMELY UNLIKELY that the impulsive flare is the primary source of the interplanetary protons at >500 MeV.

Energetic particles primarily on closed loops
Number of $>500$ MeV Protons: at the Sun vs. in Interplanetary Space

**Sustained Phase of the Flare**

![Graph showing the number of >500 MeV protons at the Sun vs. in interplanetary space. The graph includes data points for specific dates and shows a correlation with a correlation coefficient $cc = +0.94$.]

17 May 2012: Large uncertainty in gamma-ray analysis due to location and possibly extended source.
Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

Sustained Phase of the Flare

Purple: upper limits
Blue: measurements
Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

Sustained Phase of the Flare

07 March 2011: Upper-limit on IP protons but a typical number of sustained phase protons.
Sustained Phase of the Flare

>500 MeV protons in the sustained emission are typically 5-10% of the interplanetary protons.

The sustained emission arises from the interplanetary proton population:

- a highly plausible idea.

But how?
GOES/HEPAD >330 MeV Protons

Time-Scale Comparisons:

- 18 hours
- 3 hours
- 46 hours
- 8 hours

Fermi >100 MeV gamma-rays
The SEP Reservoir

The CME-driven shock produces SEPs in the upstream region ahead of the shock.

But the CME-driven shock also releases SEPs into the downstream region, where they effectively become trapped in the expanding “bottle” between the Sun and the shock.

The formation of the downstream SEP reservoir was first discovered through multi-spacecraft observations at 1 AU and beyond (McKibben 1972; Roelof et al. 1992, Reames et al. 1996, 1997, 2010, 2013; Lario 2010).

But the formation of the reservoir presumably begins much closer to the Sun.
The SEP Reservoir: *interesting things happen there!*

Cross-field transport occurs in the turbulence in the downstream region, leading to the formation of large-scale intensity and spectral invariance.

These same processes occur for high energy particles early in the event. Some of the particles in the nascent reservoir arrive on field lines that lead them back to the Sun, where they generate the Fermi sustained emission.
The Devil is in the Details...

2013 May 22
SXR: M5.0, N14W87. CME: 1466 km/s
Seen in HEPAD; but not in Fermi

2011 March 07
SXR: M3.5, N30W47. CME: 2125 km/s
Seen in Fermi; but not in HEPAD
Summary

Temporal structure of Fermi observations of $>100$ MeV solar gamma-rays provide unambiguous evidence for two distinct particle acceleration processes operating at/near the Sun:

- The impulsive flare, coincident with the HXR emission, typically lasting $\sim 10$ minutes
- The sustained emission, lasting for $\sim 1$-20 hours after the HXR emission

We estimated the total number of $>500$ MeV protons:

- in the solar atmosphere (from the $>100$ MeV gamma-rays) of $\sim 10^{28}$ to $10^{31}$
- In interplanetary space (from observations at Earth) of $\sim 10^{29}$ to $10^{32}$

with large event-to-event variation.

Typically, the relative number of $>500$ MeV protons is

\[ \text{Interplanetary Space : Sustained Emission : Impulsive Flare} = 100 : 5 - 10 : 0.1 - 1 \]

The comparatively small number of $>500$ MeV protons in the Impulsive Flare make it highly-unlikely that the impulsive flare is a significant contributor to the interplanetary population.

The number of $>500$ MeV protons in the Sustained Emission make it highly plausible that they come from the interplanetary population, most likely via the nascent SEP reservoir that forms downstream of the CME-driven shock,

The CME-driven shock is the primary source of solar energetic protons, both at the Sun and in interplanetary space, even at $>500$ MeV.
Back-ups
Number of $>500$ MeV Protons:
at the Sun vs. in Interplanetary Space

Impulsive Phase of the Flare

Sustained Phase of the Flare

![Graph showing the number of $>500$ MeV protons at the Sun vs. in Interplanetary Space for different events.]
Cycle 24 has been a disappointment...
Gaussian Fits to Observed Longitude Distributions
Onset Timing in the 2012 May 17 Ground-Level Event

SEP Velocity Dispersion Analysis

Solar Particle Release:
01:45.3 UT ± 1.1 minutes
Compare: 2012 March 7 (non-GLE) and 2012 May 17 (GLE)
• We have combined satellite/riometer and neutron-monitor data to derive absolutely normalized, event-integrated proton spectra for GLEs.
• Spectra have been derived for 59 (out of 67) GLEs since 1956.
• See Herbst et al. (SH31C-07) for another application of our GLE catalogue.
Interplanetary Protons: Spatial Distribution

2012 May 17 Solar Energetic Protons from STEREOs and GOES