

Fermi Large Area Telescope observations of high-energy gamma-ray emission from behind-the-limb solar flares

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Fermi-LAT >30 MeV observations have increased the number of detected solar flares by almost a factor of 10 with respect to previous space observations. These sample both the impulsive and long duration phases of *GOES* M and X class flares. Of particular interest is the recent detections of three solar flares whose position behind the limb was confirmed by the *STEREO*-B spacecraft. While gamma-ray emission up to tens of MeV resulting from proton interactions has been detected before from occulted solar flares, the significance of these particular events lies in the fact that these are the first detections of >100 MeV gamma-ray emission from footpoint-occulted flares. We will present the *Fermi*-LAT, *RHESSI* and *STEREO* observations of these flares and discuss the various emission scenarios for these sources and implications for the particle acceleration mechanisms.

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1. Introduction

During its first seven years in orbit, the *Fermi* Large Area Telescope (Atwood et al., 2009) has detected >30 MeV gamma-ray emission from more than 40 solar flares, nearly 10 times more than EGRET (Thompson et al., 1993) onboard the *Compton Gamma-Ray Observatory*, GRS (Forrest et al., 1985) onboard the *Solar Maximum Mission (SMM)* and CORONAS-F (Kuznetsov et al., 2011). The *Fermi* detections sample both the impulsive (Ackermann et al., 2012a) and the long-duration phases (Ackermann et al., 2014) including the longest extended emission ever detected (~ 20 hours) from the SOL2012-03-07 *GOES* X-class flares (Ajello et al., 2014). *Fermi*-LAT has also provided the first detections of >100 MeV emission from three occulted solar flares. These observations sample flares from active regions originating from behind both the eastern and western limbs and include an event associated with the second ground level enhancement event (GLE) of the 24th Solar Cycle. These detections present a unique opportunity to diagnose the mechanisms of high-energy emission and particle acceleration in solar flares.

2. Behind-the-limb flares detected by the *Fermi*-LAT

In this section we briefly present the observational overview for these events. Table 1 lists the start times, estimated *GOES* classes, Active Region (AR) locations, CME speeds and total energy released in >100 MeV gamma-rays for the three behind-the-limb flares detected by *Fermi*-LAT.

Date (UTC)	Estimated <i>GOES</i> class	AR position	CME speed (km s ⁻¹)	Total energy (ergs)
2013 Oct 11 07:01	M4.9	N21E106 (10° b.t.l)	1200	3×10^{23}
2014 Jan 06 07:40	X3.5	S8W110 (20° b.t.l)	1400	5×10^{21}
2014 Sep 01 11:00	X2.1	N14E126 (36° b.t.l)	2000	2×10^{25}

Table 1: Behind-the-limb flare properties. The start time of the flare is estimated from *STEREO* imaging. The *GOES* class is evaluated using *STEREO*-observed extreme ultraviolet intensity, as described by (Nitta et al., 2013). The CME speed listed here is the 2nd-order speed at $20 R_{\odot}$ taken from the LASCO online catalog and the total energy released is for the >100 MeV LAT emission assuming a smooth time profile.

2.1 SOL2013-10-11

On 2013 October 11 at 07:01 UT a *GOES* M1.5 class flare occurred with soft X-ray emission lasting 44 min and peaking at 07:25:00 UT. The left panel of Figure 1 shows the *GOES*, *STEREO*-B, *RHESSI*, *Fermi* Gamma-ray Burst Monitor (GBM; Meegan et al., 2009) and LAT lightcurves of this flare. The LAT detected >100 MeV emission for ~ 30 min with the maximum of the flux occurring between 07:20:00–07:25:00 UT. *RHESSI* coverage was from 07:08:00–07:16:40 UT, overlapping with *Fermi* for 9 min. Based on the *STEREO*-B 195 \AA we estimate the *GOES* class of this flare if the active region had not been occulted to be an M4.9.

Images in the right panel of Figure 1 from the *STEREO*-B Extreme UltraViolet Imager (EUVI; Wuelser et al., 2004) and the *SDO* Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) of

the photosphere indicate that the active region (AR) was $\sim 10^\circ$ behind the limb at the time of the flare. From these images we find that the off-limb *RHESSI* source lies within the 68% error circle of the LAT emission. This, however, does not exclude that the emission originates from the visible side of the solar disk.

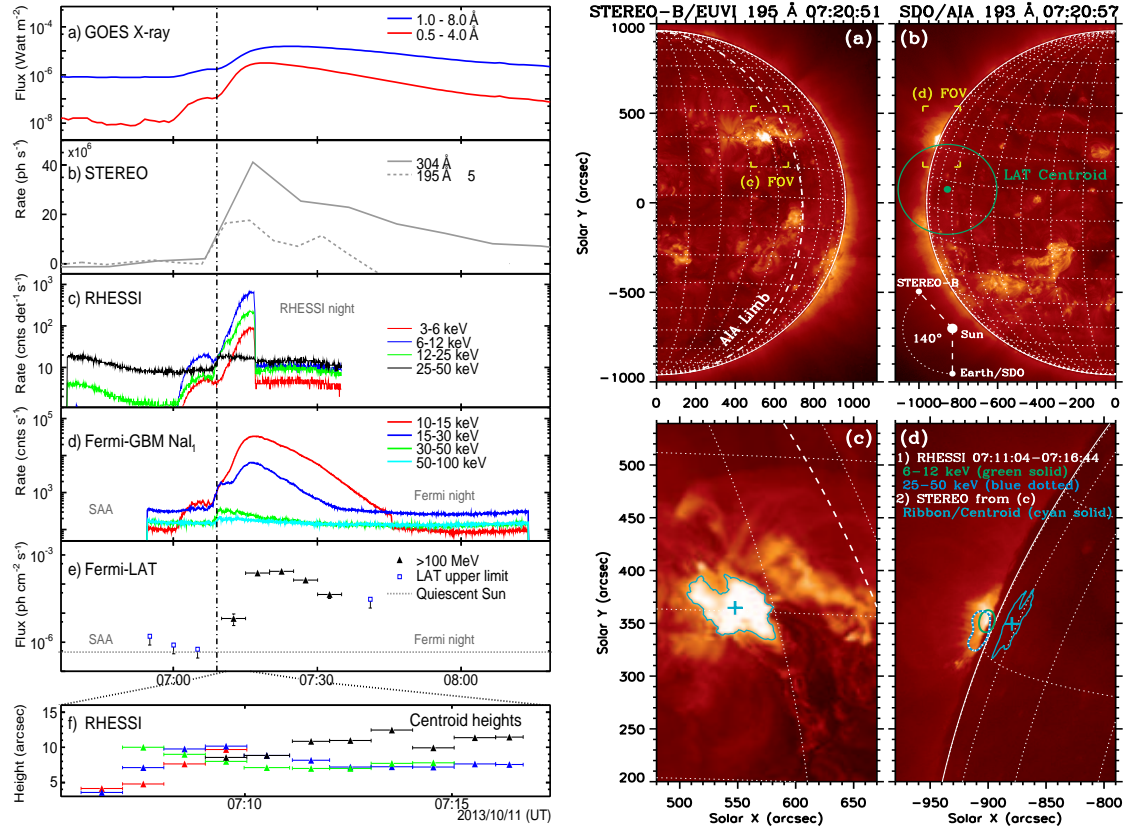


Figure 1: Left panel: Light curves of the 2013 October 11 flare (Pesce-Rollins et al., 2015) as detected by a) *GOES*, b) *STEREO*, c) *RHESSI*, d) *GBM*, e) *LAT*, and heights of the *RHESSI* emission centroid (f) with the same color coding as in c). *Fermi* exited the South Atlantic Anomaly (SAA) at 06:57:00 UT. The vertical dashed line represents flare start time (7:01 UT). Right panel: *STEREO-B* (left) and *SDO/AIA* (right) images near the flare peak. The white-dashed line in (a) and (c) represents the solar limb as seen by *SDO*. The green line in (b) shows the 68% error circle for the *LAT* emission centroid. The cyan contour and plus sign in (c) mark the *STEREO* flare ribbon and its centroid, respectively. Their projected view as seen from the *AIA* perspective is shown in (d), in which the centroid is located at 10° behind the limb. The green and blue-dotted contours in (d) show *RHESSI* sources. The rectangular brackets in (a) and (b) mark the field of view (FOV) for (c) and (d), respectively.

2.2 SOL2014-01-06

On 2014 January 6 a solar flare occurred at approximately 07:42:00 UT from the AR located S8W110 ($\sim 20^\circ$ behind-the-limb). Both *STEREO* spacecraft had a full view of the AR and detected a large filament erupting from the AR starting from 07:44:00 UT. Figure 2 shows the evolution of this filament as seen from the visible solar disk by *SDO/AIA* 171. *LASCO* detected a halo CME

with first C2 appearance at 08:00:00 UT with a 2nd-order Speed at $20 R_{\odot}$ of 1385 km/s. A ground

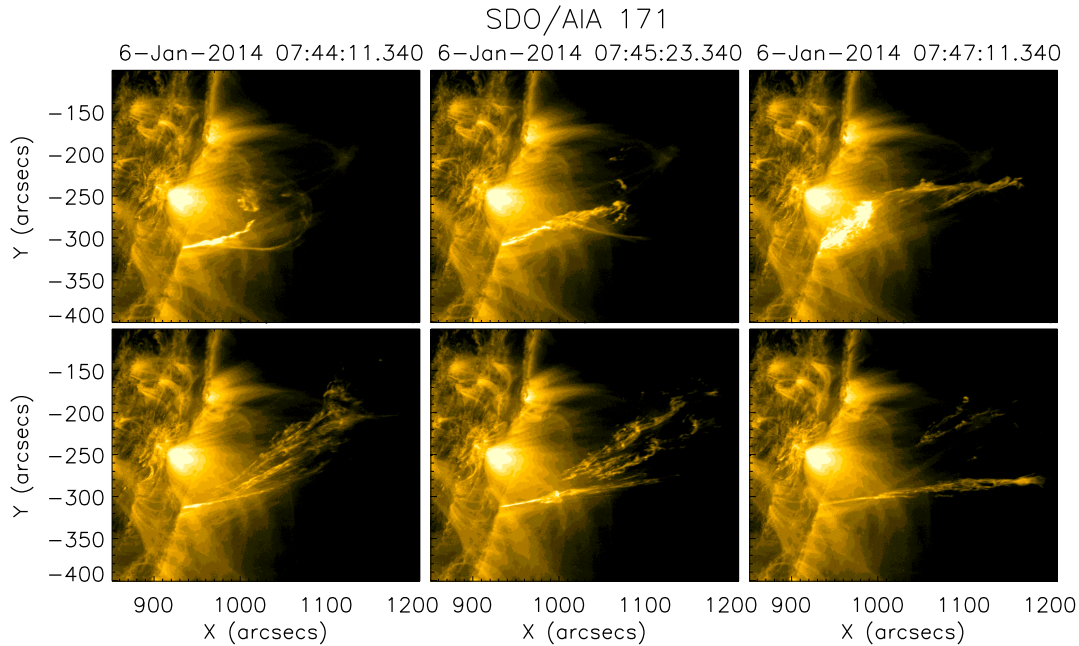


Figure 2: Evolution of the filament eruption associated to SOL2014-01-06 as seen from *SDO/AIA* 171.

level enhancement (GLE) was also reported in association with this flare making it the second GLE of Solar Cycle 24. Thakur et al. (2014) report that this event (GLE72) was primarily observed by the South Pole neutron monitors with an increase of $\sim 2.5\%$ over the background level. The increase in the *GOES* proton flux was evident up to energies >700 MeV. Based on the onset times of the SEPs detected at Earth combined with the onset time of the GLE it is possible to estimate the particle acceleration time at the Sun. We find that a straight line fit to the onset times as a function $1/\beta$ gives the acceleration time to be on 2014 January 6 at $07:49 \pm 3$ minutes UT. This is in agreement with the solar particle release time of 07:47 UT reported by Thakur et al. (2014).

STEREO-B HET data show no significant increase in the proton fluxes during this event indicating that the magnetic connection between the CME and Earth was privileged with respect to that of the *STEREO* spacecraft. The peak rate detected by *STEREO* was 2.5×10^5 photons s^{-1} in its 195 Å channel, corresponding to a *GOES* X3.5 if it had not been occulted.

Upon exiting the the SAA at 07:55:00 UT both detectors onboard *Fermi* detected emission from this flare. The LAT detected >100 MeV emission for approximately 20 minutes and the GBM detected emission in the 10's of keV range. No evidence of extended >100 MeV emission was detected by the LAT. *RHESSI* detected off-limb emission starting around 8:20 UT (upon exiting the SAA) also in the 10's of keV for over 40 minutes from this flare.

2.3 SOL2014-09-01

On 2014 September 1 a bright solar flare occurred from AR 12158 which was located at N14E126 ($\sim 36^\circ$ behind the limb). LASC0 detected a halo CME with first C2 appearance at

11:12:00 UT with a 2nd-order Speed at $20 R_{\odot}$ of 1216 km/s. A Type II radio burst with an estimated velocity of 2079 km/s was also measured in association with this flare. *STEREO-B* had an unblocked view of the entire flare and detected a maximum rate of 1.7×10^7 photons s^{-1} in its 195 Å channel, corresponding to a *GOES* X2.1 class if it had not been occulted (Nitta et al., 2013). The composite lightcurve of *STEREO-B*, *GOES* X-ray, *RHESSI*, *Fermi*-GBM and *Fermi*-LAT data

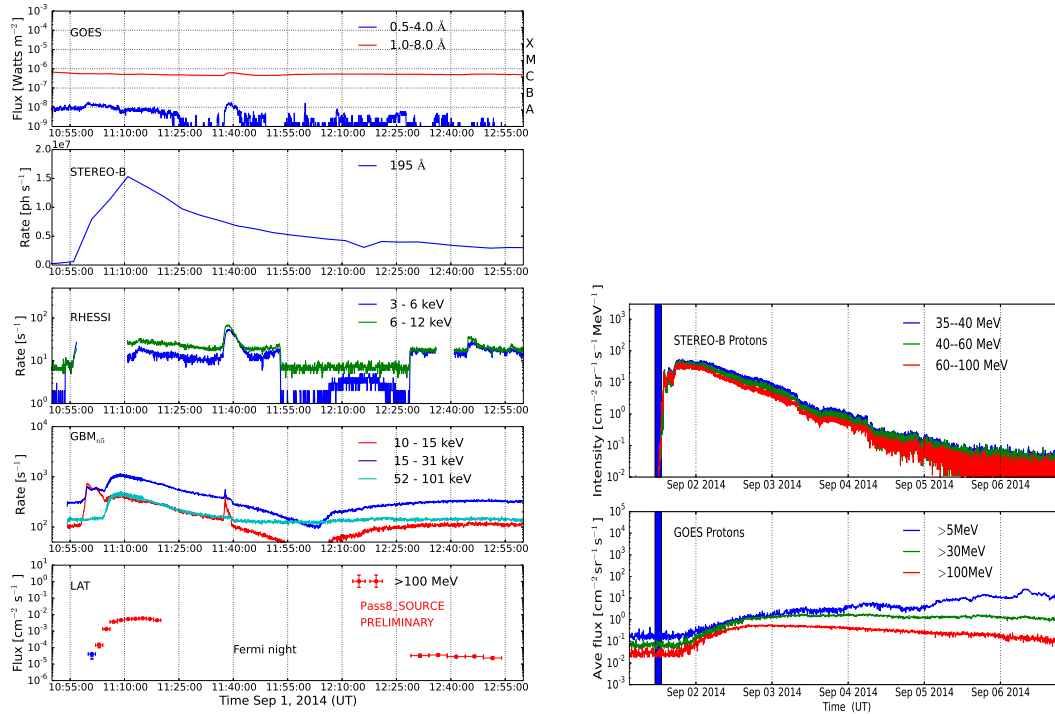


Figure 3: Left panel: Composite lightcurve of *STEREO-B* EUV, *GOES* X-ray, *RHESSI*, *Fermi*-GBM and *Fermi*-LAT data for SOL2014-09-01. Right panel: *STEREO-B* HET proton and *GOES* SEP proton flux. The blue band in the right hand panel represents the time interval in which the *Fermi*-LAT detected gamma-ray emission.

for this flare is shown in Figure 3. The high-energy flare emission lasts for ~ 2 hours but the LAT detected >100 MeV emission for ~ 1 hour due to the *Fermi* night between 11:30 and 12:25 UT. The peak LAT flux occurred between 11:10:00–11:15:00 UT. Thanks to improvements provided by the new LAT event selection (*Pass8*¹) we gained 10 minutes of detected coverage with respect to *Pass7*_REP of this flare during the impulsive phase. As shown in the left panel of Figure 3 the *STEREO-B* 60–100 MeV proton flux starts to increase roughly 3 hours after the start of the flare whereas the *GOES* >100 MeV proton flux shows an increase roughly 9 hours later.

The GBM detected emission in temporal coincidence with the LAT emission in both the BGO and NaI instruments. *RHESSI* was in the SAA from 10:55:00 to 11:11:00, upon exiting the SAA it detected emission up to 12 keV. Imaging in this time interval with *RHESSI* shows a source located

¹A summary of the *Fermi*-LAT *Pass8* performance can be found here http://www.slac.stanford.edu/exp/glast/groups/canda/lata_Performance.htm.

at approximately heliocentric coordinates $[-900'', 400'']$ which is in the vicinity of the LAT time integrated >100 MeV emission centroid. If the *RHESSI* source is the looptop of the behind-the-limb flare then the minimum height needed for this source to be visible from $\sim 40^\circ$ behind-the-limb would be $\sim 10^{10}$ cm. In fact, X-ray emission from a flare located $\sim 40^\circ$ behind-the-limb has been detected before by *RHESSI* (Krucker et al., 2007).

The LAT measured 18 `P8R2_SOURCE` photons with energies >1 GeV and reconstructed direction less than 1° from the center of the solar disk. 15 of these, including a 3.5 GeV photon, arrived between 11:08 and 11:20 UT.

3. Discussion

We present the *Fermi*-LAT observations of high-energy gamma-ray emission from three behind-the-limb solar flares (SOL2013-10-11, SOL2014-01-06 and SOL2014-09-01) together with multiwavelength data from *STEREO*, *GOES* and *RHESSI*. Based on our work in Pesce-Rollins et al. (2015) we can exclude the scenario in which the gamma-ray emission occurred at the AR position due to the large optical depths involved. Although the scenario in which the emission originates from the Corona is not entirely excluded, we suggest that the gamma-ray emission detected by the LAT was caused by protons accelerated at the CME-driven shock. In this scenario, also proposed by Cliver et al. (1993), the particles are accelerated on open field lines and can either precipitate to the visible disk and produce gamma-ray emission or escape to be observed as SEPs. Further studies on the precipitation rate of the protons producing the observed gamma-ray emission from these behind-the-limb flares is currently underway together with detailed comparison of the flare characteristics with other on-disk *Fermi*-LAT detections (paper in preparation).

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