GLAST Solar System Science

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Abstract. We briefly discuss *GLAST's* capabilities for observing high-energy radiation from various energetic phenomena in our solar system. These emissions include: bremsstrahlung, nuclear-line and pion-decay gamma-radiation, and neutrons from solar flares; bremsstrahlung and pion-decay gamma radiation from cosmic-ray interactions with the Sun, the Moon, and the Earth's atmosphere; and inverse Compton radiation from cosmic-ray electron interactions with sunlight.

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SOLAR-FLARE OBSERVATIONS

GLAST can study solar-flare electromagnetic radiation from 10 keV to 25 MeV using the GBM and from ~30 MeV to energies in excess of tens of GeV using the LAT. No other instrument will be available to observe the Sun in the LAT's energy band during the upcoming solar maximum. *GLAST* observations will be correlated with high-resolution imaging/spectroscopy by *RHESSI* from ~1 keV to 16 MeV, with other space-borne observatories such as *ACE*, *TRACE*, *SOHO*, *HINODE*, and *STEREO*, and with ground-based observatories. The LAT will have >20% solar exposure during normal observations and up to about 60% exposure during targets of opportunity. Such targeted observations will enable solar active regions producing several X-class flares to be observed for up to ~12 days, such as those observed by *RHESSI* in January 2005 and December 2006, during solar minimum.

Solar activity is expected to rise in 2008 and peak about 3 to 4 years later. Based on observations by the *Solar Maximum Mission (SMM)* gamma-ray spectrometer, the GBM will detect in excess of 100 solar flares emitting at energies >300 keV during Solar Cycle 24; of these as many as 30-50 may be observed by the LAT >30 MeV. Even though the *GLAST* launch occurs near solar minimum high-energy flares may occur during the first year of the Mission. This was clearly shown by the extreme solar activity over 8 days at solar minimum beginning 2006 Dec. 5 when the Sun erupted producing three X-class flares and three M-class flares and associated intense solar energetic particle (SEP) activity. These events were also unexpected because the active region producing the emission emerged from behind the limb of the Sun.

What We Learn From Solar-Flare Gamma Rays and Neutrons

There is growing evidence that flare ions and electrons are accelerated by the release of energy during magnetic reconnection [1]. The location of this energy release is believed to be in the upper corona. Plotted in Figure 1 is a cartoon that depicts a scenario for particle acceleration during a flare. Ions and electrons from the acceleration site can propagate into the chromosphere where they interact to produce bremsstrahlung, nuclear-line, and pion-decay radiations. In Figure 2 we plot the summed gamma-ray spectrum from 19 flares observed by the gamma-ray spectrometer on *SMM* along with the fitted components that include electron bremsstrahlung; narrow, broad, and unresolved nuclear de-excitation lines; and the positron annihilation and neutron-capture lines. Ratios of these lines provide both information on the accelerated-particle spectrum and composition and the ambient abundance where the interactions take place [2]. Studies indicate that the energy contained in accelerated ions is often comparable to that in flare-accelerated electrons [3]. Some of the flare-accelerated particles can escape into interplanetary space on open field lines and contribute to SEP events [4]; however a bulk of the SEPs are believed to be accelerated by strong shocks accompanying high-speed coronal mass ejections related to the flare [5]. It is also possible that some of these shock-accelerated particles will interact in the solar atmosphere. The GBM on *GLAST* will observe nuclear lines and bremsstrahlung with comparable sensitivity to the *SMM* spectrometer but with reduced spectral resolution.

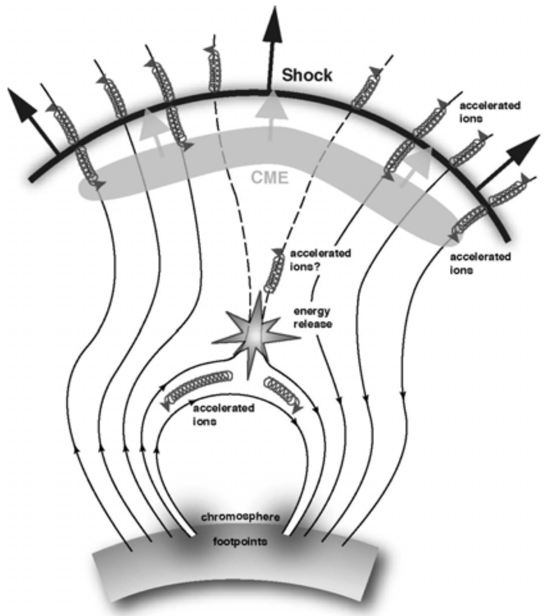

Fig 1. Cartoon illustrating particle acceleration during a flare.

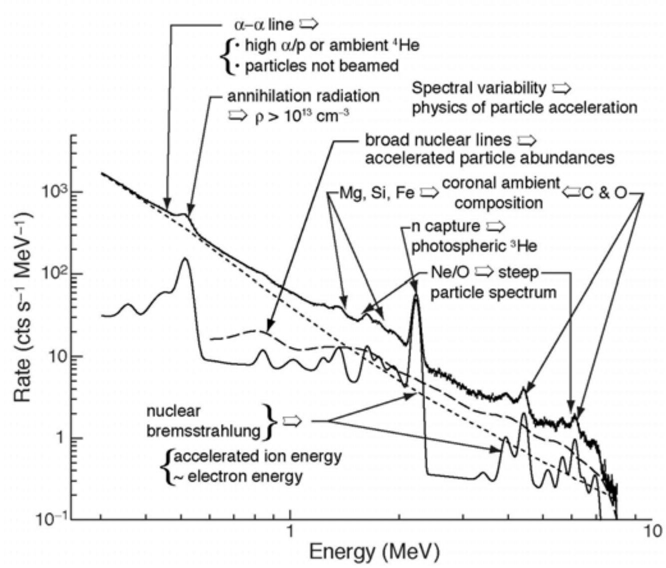

Fig 2. Components of a solar-flare gamma-ray spectrum.

Flare-accelerated protons with energies >300 MeV interact deep within the chromosphere and in the photosphere producing neutral and charged pions [6, 7]. Decay of the neutral pions produces a gamma-ray spectrum with a broad maximum at ~70 MeV while positrons and electrons from decay of the charged pions produce a bremsstrahlung spectrum. In Figure 3 we plot the calculated pion-decay gamma-ray spectra for accelerated ions having power-law spectra with indices of 2 and 4 along with the nuclear-line spectra produced by those particles. Very hard particle spectra produce pion-decay emission that dominates over the nuclear-lines. Comparison of the intensities of pion-decay and nuclear-line spectra provides a sensitive measure of the spectral index of high-energy ions. The gamma-ray spectrum above 10 MeV can also contain significant bremsstrahlung from flare-accelerated electrons. The relative contributions of primary bremsstrahlung and pion-decay gamma-radiation can be fit by models such as those used in the analysis of the 1991 June 11 flare spectrum observed by the EGRET experiment on the *Compton Gamma Ray Observatory* (*CGRO*) that is plotted in Figure 4 [8].

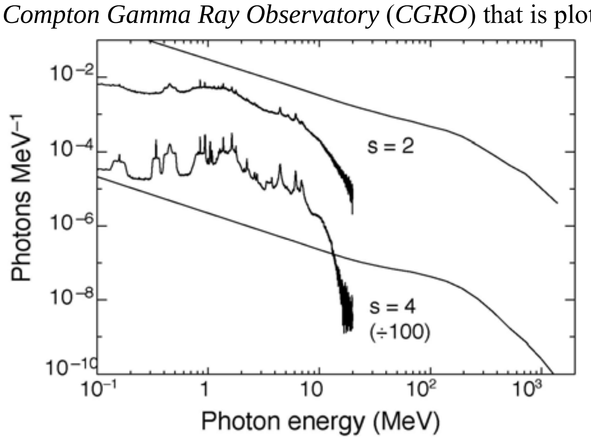

FIG 3. Comparison of nuclear-line and pion-decay contributions.

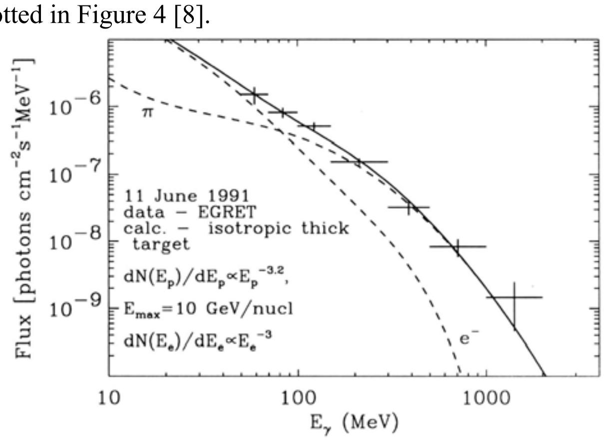

FIG 4. EGRET observation of the 1991 June 11 solar flare.

High-energy radiation from the 1991 June 11 flare was observed for several hours suggesting continued acceleration and/or long-term trapping. *RHESSI* observations of emission >17 MeV plotted in Figure 5 indicates that high-energy interactions also occurred in the solar atmosphere for at least two hours following the impulsive phase of the 2005 January 20 flare. The *RHESSI* image of this flare plotted in Figure 6 reveals two hard X-ray footpoints (contours) lying in two ribbons revealed by UV images made by *TRACE* [9]. The centroid of radiation from the 2.223 MeV neutron capture line is identified by the thick white circle about ten arcsec to the E/SE of the peak in hard X-rays in the northern footpoint. For comparison we also show the ~30 arcsec position uncertainty of the LAT for >500 MeV pion-decay photons. Thus the LAT will be able to determine whether high-energy protons also were contained within the closed magnetic loops ending in the footpoints. Neutrons produced by particle interactions can escape into space and also be detected by the LAT [7, 10]. Measurement of neutrons provides additional information on the spectrum and directionality of the interacting ions at the Sun. A study is currently underway to determine the LAT's sensitivity to solar neutrons [10].

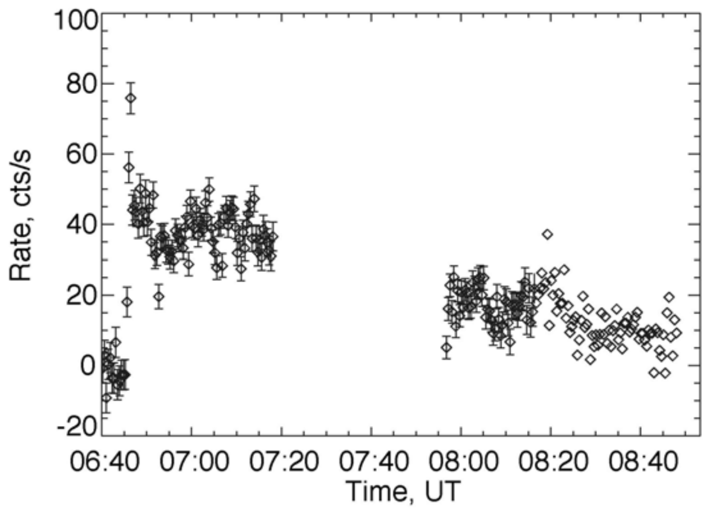

FIG 5. Extended >20-MeV emission in the 2005 January 20 flare.

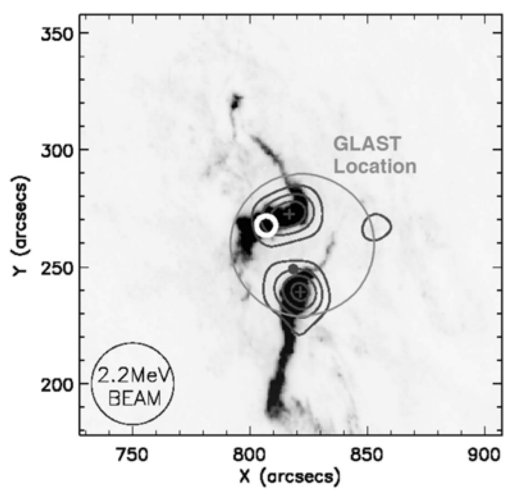

FIG 6. 500-MeV source location accuracy from LAT.

OTHER SOLAR SYSTEM OBSERVATIONS

Cosmic-Ray Proton/Electron Interactions In The Inner Heliosphere

The Sun and inner heliosphere will also be non-flaring sources of high-energy gamma-radiation. The flux of pion-decay photons from cosmic-ray interactions in the photosphere is estimated to be of order $10^{-7}\ \gamma\ cm^{-2}\ s^{-1}$ and is sensitive to the magnetic field in the vicinity of the Sun [11]. These fluxes appeared to be below the sensitivity of EGRET experiment [12]; however, a recent study using an extended database [13] detected both the solar pion-decay radiation and a halo of inverse-Compton scattered sunlight by cosmic-ray electrons [14]. These techniques can readily be applied to the LAT database to provide information on solar modulation of cosmic-ray ions and electrons near the Sun.

Observations Of The Earth And Moon

Terrestrial Gamma-Ray Flashes

The BATSE experiment on *CGRO* discovered very hard gamma-ray flashes that have durations of ~1 ms, occur at a global rate of tens per day, and appear to be due to electrical discharges associated with thunder storms [15]. Comparison of the BATSE and *RHESSI* spectra with calculations indicates that there may also be a source at a higher altitude than the tops of thunder storm clouds [16]. A sum of the *RHESSI* observations indicates that the spectrum of the flashes extends up to at least ~20 MeV [17]. These terrestrial flashes will therefore be detectable by the GBM and perhaps even by the LAT.

Earth Albedo

Although *GLAST* will primarily be pointed away from the Earth during normal operations it may have the opportunity to detect the high-energy gamma-ray albedo from cosmic rays interacting in the Earth's atmosphere. Such measurements were first made from space using *SAS*-2 [18] and more recent observations were made using EGRET [19]. These observations reveal a halo emanating from the Earth's limb with the west/east asymmetry expected from differences in magnetic rigidity. An SEP event containing particles with energies exceeding a few GeV may also produce atmospheric gamma-rays detectable by the LAT.

Lunar Observations

Cosmic rays also interact with the lunar surface to produce a high-energy albedo that has been detected by EGRET at a flux level of $\sim 5 \times 10^{-7}\ \gamma\ \mathrm{cm^{-2}\ s^{-1}}$ [12]. Plotted in Figure 7 is the image of the moon recorded by EGRET. *GLAST's* $\sim 1^{\circ}$ angular resolution will still not be able to resolve the lunar source but its 30-arc sec centroid accuracy may reveal some asymmetries in the lunar emission. The spectrum of lunar albedo gamma rays contains both bremsstrahung and pion-decay components. The spectra measured by EGRET at two times in the solar cycle are plotted in Figure 8 along with calculations. The effects of solar modulation of the cosmic-ray flux are reflected in these spectra.

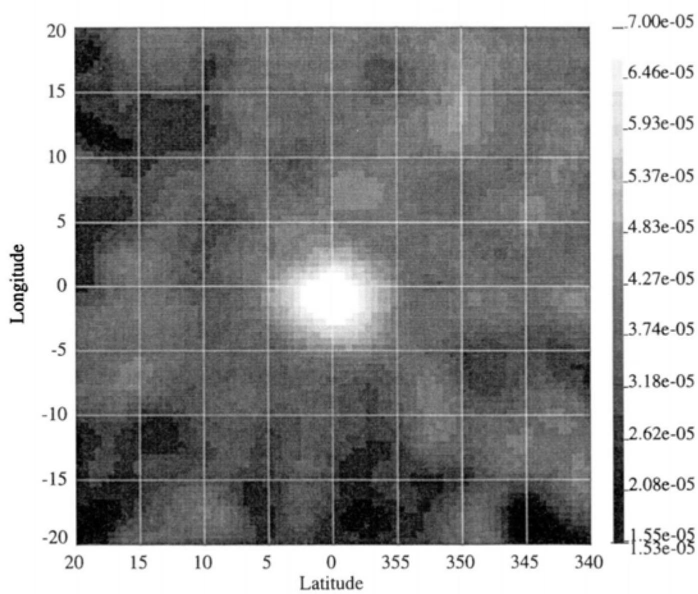

Fig. 7. Image of the moon observed in gamma-ray by EGRET

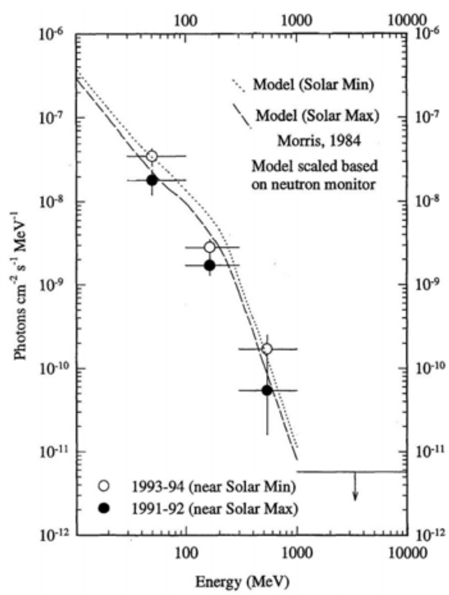

Fig 8. Lunar gamma-ray spectra observed by EGRET

INSTRUMENTAL ISSUES

The *GLAST* LAT is not expected to suffer the same saturation effects suffered by EGRET during the intense impulsive phase of large solar flares. The LAT's anticoincidence system is comprised of individual tiles that have very efficient light collection and an effective threshold of a few hundred keV, high enough to avoid the extreme rates suffered by EGRET. In addition the response time of the LAT's silicon tracker is orders of magnitude faster than the spark chambers on EGRET. The only concern was how the tracker would respond to the intense flux of hard X-rays during the peak of the largest flares. For a flare with peak hard X-ray intensity ~10% of the largest expected $\sim 2.2 \times 10^{5}$ photons $\mathrm{s^{-1}}$ will reach the top Si layer in each tower after attenuation by the ~ 0.1 mm of W converter. Requiring that >30 keV be deposited in the top layer of silicon reduces the rate to $\sim 5 \times 10^{3}$ counts $\mathrm{s^{-1}}$, which yields a dead time of only ~1% [20].

Unlike EGRET the LAT cannot just use its calorimeter to measure the spectra of solar flares. Under normal operating conditions the LAT tracker determines which events will be spectroscopically analyzed by the CsI calorimeter. As a result a solar flare that occurs outside the field of the tracker cannot be studied. In order to access the entire sky the spacecraft with perform ± 35^{o} offsets each orbit and will also rotate to optimize sunlight on the solar panels. This will likely compromise the ability to obtain accurate background determinations for gamma-ray spectroscopic studies using the GBM. For flares with durations exceeding about 100 sec, backgrounds are normally obtained by using data obtained ± 15 orbits from the flare when the average geographic location is the same. This will not be as significant a problem for extended (7 – 10 days) solar Targets of Opportunity during periods of heightened solar activity.

ACKNOWLEDGMENTS

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