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Fermi Observation of Solar System Gamma-Ray Sources

Monica Brigida on behalf of the Fermi Collaboration
Dipartimento Interateneo di Fisica "M. Merlin"
Via Amendola 167, 70126 Bari - Italy
E-mail: monica.brigida@ba.infn.it

The Large Area Telescope (LAT) onboard the Fermi Gamma-ray Space Telescope (Fermi) is a pair-conversion detector operating at energies from 20 MeV to >300 GeV. Its main operating mode is the all-sky survey. Since the beginning of the mission the Fermi-LAT has observed the high-energy gamma-ray emission from the sources in the solar system: the Sun, the Moon, and the Earth. This emission is induced by Galactic cosmic ray (CR) interactions with their surface. Additionally, an extended emission around the sun is produced by CR electrons via inverse Compton scattering of solar photons. In this paper we report the current status of observations of the solar system sources.

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1. Introduction

CR interactions with the surface of the solar system bodies give raise to their gamma-ray emission. The brightness of this emission is changing over the solar cycle due to the change of the Galactic CR flux opposite to the variations of the solar activity. Such CR-induced emission has been observed from the Sun, the Moon, and the Earth.

The gamma-ray emission from the Moon is due to the interactions of Galactic CR nuclei (mainly protons) with the surface layers. The main processes involved are the production and decay of neutral pions and kaons by ions, bremsstrahlung by electrons and Compton scattering of the secondary photons. The first calculation of the lunar gamma-ray emission was done by [1]; more recent detailed calculations [2] were done using the Geant4 framework [3], giving an integral flux F(E $>$ 100 MeV) = 5 $\times$ 10^{-7} cm^{-2} s^{-1} for a period of lower solar activity. It was shown that the spectrum of gamma-rays from the Moon is steep with an effective cutoff around 3-4 GeV (600 MeV for the inner part of the lunar disk) and exhibits a narrow pion-decay line at 67.5 MeV. The spectrum of the lunar gamma-rays emission is soft. Due to the kinematics of the collision, the secondary particle cascade from cosmic ray particles hitting the lunar surface at small zenith angles develops deep into the rock making it difficult for gamma-rays to get out. Therefore the lunar gamma-ray emission is produced by a small fraction of splash albedo particles in the surface layer of the moon rock. High energy gamma-rays can be produced by cosmic ray particles hitting the Moon surface with a more tangential trajectory; thus only a very thin limb should contribute to the high energy emission.

The quiet gamma-ray emission from the Sun has been first proposed by H. S. Hudson [4] and is expected to have two different components. The first one (disk emission) is generated from hadronic CR interactions with the gaseous solar atmosphere [5]. The integral flux above 100 MeV was predicted to be $F(> 100\ \mathrm{MeV}) \sim (0.22-0.65)\times 10^{-7}$ photons cm^{-2} s^{-1} for their “nominal" model, depending on the solar activity. The second component of the solar emission is due to the IC scattering of CR electrons with solar photons in the heliosphere and is predicted to be extended in a large region around the Sun [6, 7]. For a moderately high – moderately low level of the solar modulation, as decribed by [6] the integral IC flux at a distance from the Sun position $\leq 6^\circ$ is predicted to be $F(> 100\ \mathrm{MeV}) \sim (2.0-4.3)\times 10^{-7}$ photons cm^{-2} s^{-1}, correspondingly. Orlando and Strong [8] calculated a flux $F(\geq 100\ \mathrm{MeV}) = 2.18\times 10^{-7}$ cm^{-2} s^{-1} at distance from the Sun $\leq 10^\circ$, at the maximum of solar activity.

The gamma-ray telescope EGRET on the Compton Gamma-Ray Observatory (CGRO), operated from 1991 to 2000 and detected the gamma-ray emission from the Earth [11], the Moon [10, 8] and the Sun [8].

Early analysis of EGRET observations of the Moon yielded the integral flux of F(E$>$ 100 MeV) = $(4.7\pm 0.7)\times 10^{-7}$ cm^{-2} s^{-1} [10]. A later reanalysis confirmed the detection and yielded a flux F(E $>$ 100 MeV) = $(5.55\pm 0.65)\times 10^{-7}$ cm^{-2} s^{-1} averaged over the entire mission duration [8].

Although a similar interaction of CR occurs on the Sun, EGRET has not observed the quiet Sun emission and reported only an upper limit of 2.0×10^{-7} photons cm^{-2} s^{-1} above 100 MeV at 95% confidence level [10]. More recent reanalysis of the EGRET [8] taking into account both components of the solar gamma-ray emission, disk and IC, yielded a flux $F(> 100\ \mathrm{MeV}) = (1.8\pm$

$1.1) \times 10^{-7}$ cm^{-2} s^{-1} for the disk and $F(> 100$ MeV$) = (3.8 \pm 2.1) \times 10^{-7}$ cm^{-2} s^{-1} for the IC component for elongation angles $\leq 10^{\circ}$.

The Fermi/LAT has observed also the Earth during the commissioning phase and with a dedicated Earth limb observation in September 2008 [11]. A similar emission mechanism should be detected from any other solid object in the solar system. Therefore asteroids and small planets without atmosphere should emit gamma-rays produced from pion-decays coming from the hadronic interactions by cosmic-rays hitting the surface of these bodies [12].

We report report here the updated observations of the solar and lunar gamma-ray emission, previously presented [13] [14] [15], and a summary of the Sun detection by Fermi [16].

2. Data Selection

The data sample used includes the scientific data collected since August 4, 2008 to February 2010. We use for this analysis the "Diffuse" class [17], corresponding to the events with the highest probability candidates as photons.

As the Moon and the Sun are moving source, we developed a code in order to perform the analysis of the data in a source-centred system: the events were mapped onto a celestial coordinate system centred on source instantaneous position. Coordinates were computed using JPL ephemeris libraries [1] taking into account parallax corrections. In order to have a better sensitivity to the solar and lunar emission, other sources of background has been reduced with the following selections:

- Zenith angle $< 105^{\circ}$ in order to exclude photons from the Earth's limb;
- the Sun ar the Moon should be at least 30° under or above the galactic plane in order to reduce the diffuse components and avoid the brightest sources on the Galactic plane;
- the angular separation between the Moon and Sun should be more than 20°, in order to remove the Moon emission component from the Sun sample and viceversa;
- we remove also time intervals corresponding to the Moon or Sun passing within 20° from a brigth source;

During the whole period the Sun was at minimum of its activity.

3. Analysis method and results

In our analysis, the main sources of background are the galactic and extragalactic emission in the source centered frame. Moreover to evaluate the background in this relative coordinate frame, we consider a trailing source (fake source) following the same path of the real source in the sky but displaced at least of 30°. We evaluate in this way the background in the relative coordinates and comparing the two data sets.

In figure 3 we report the event density vs. the angular distance from the position of the Sun and the Moon. Event density from the fake source is superimposed as a dashed line and show the background in our analysis.

[1] link:http://iau-comm4.jpl.nasa.gov/access2ephs.html

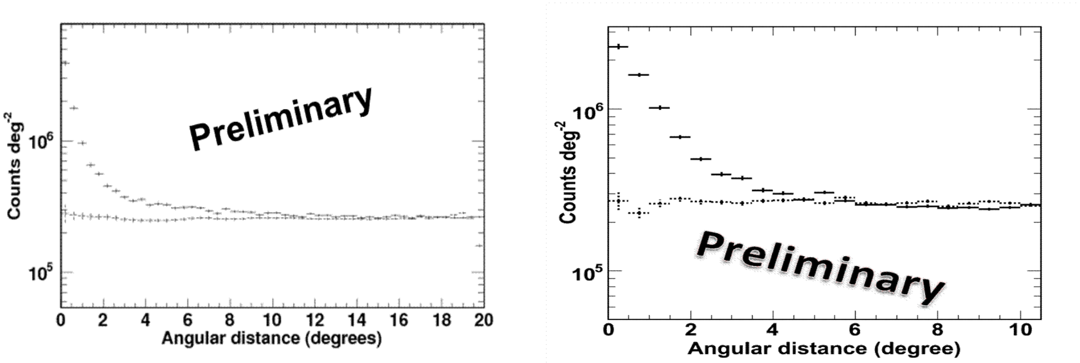

Figure 1: The event density vs. the angular distance from the center of the Solar (left) and Lunar (right) position for photons of energy above 100 MeV. The solid line is referred to the emission from the source and the dotted line from the fake source.

Different methods can be used to compute the flux from a source, mainly based on a the maximum likelihood analysis. The Fermi standard method for the spectral evaluation and computation of the source flux is the *Gtlike* [2] tool, consisting in a binned or un-binned likelihood analysis of LAT data [17]. A preliminary analysis is performed by fitting the fake source data in order to obtain a model for the background events. Then we fit the source sample by adding the proper functional form for the source spectrum to the fitted background model. The analysis for the lunar data yields the a best fit with a logParabola:

$$dN/dE = N_0(E/E_b)^{\alpha+\beta \log(E/E_b)}, \tag{3.1}$$

where $N_0 = (79.9 \pm 10.3) \times 10^{-9}$, $\alpha = 1.72 \pm 0.09$, $\beta = 0.49 \pm 0.03$, $E_b = 52.9 \pm 3.1$ MeV.

As the result of the fit we obtain a flux as F(E $>$ 100 MeV) = $(1.21 \pm 0.02 \pm 0.20) \times 10^{-6}$ ph cm^{-2} s^{-1}. Figure 3 shows the Moon spectra obtained with *Gtlike* tool.

The Sun centered LAT data has been analyzed using the background model as described above with fixed papameters, a point-like disk component modeled with a power law spectrum and an extended diffuse component calculated into nested rings. In this way, the separation of the two different emission components from the Sun is obtained with a model independent metod. Figure 3 show the Sun spectra: the disk and IC diffuse components are reported separately. The spectral energy distribution (SED) from the disk emission is well fitted by a single power law with a spectral index of 2.11 ± 0.73, reported as a dashed line in left plot in figure3.

The fit for the Sun gives as a result value of the flux above 100 MeV of $(4.63 \pm 0.21 \pm 0.90) \times 10^{-7}$ ph cm^{-2} s^{-1} for the disk component, and of $(6.77 \pm 0.67 \pm 0.55) \times 10^{-7}$ ph cm^{-2} s^{-1} for the diffuse IC component (in a region of 20° radius).

4. Conclusions

In this paper we demostrate the observing capabilities of Fermi-LAT by presenting detection of the Sun and Moon over the first 18-months of the Mission. We also report the integral fluxes

[2]Available from *Fermi* Science Support Center (FSSC), http://fermi.gsfc.nasa.gov/ssc

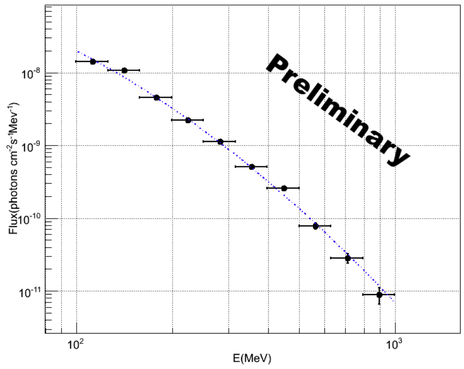

Figure 2: Moon Spectrum reconstructed from the first 18 months of observations by Fermi (points). The dashed line is best fit.

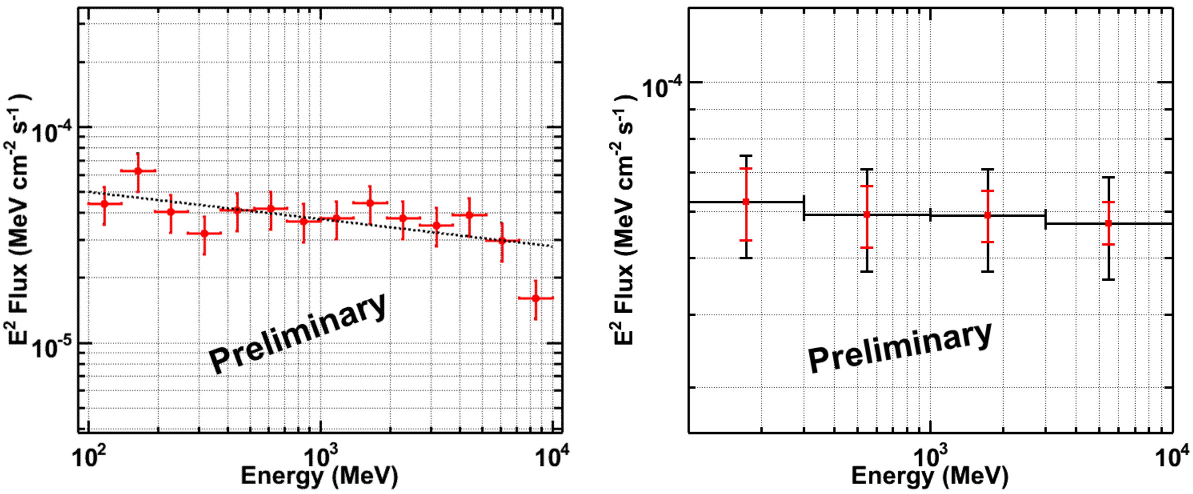

Figure 3: The Sun Spectral Energy Distribution (SED) reconstructed from the first 18 months of observations by Fermi (points): the disk component (left) and the IC diffuse component (right) are separately reported.

and spectra, in comparison with the previous observations and the theoretical evaluation. Fermi observations of the Sun and Moon emission can be used to obtain information about CR interactions with the bodies in the Solar System and about the variation of CR flux over the current solar cycle.

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References

[1] D. J. Morris, J. Geophys. Res. A 89,1068, (1984)

[2] I. V. Moskalenko and T. A. Porter, Astrophys. J. 670, 1467 (2007)

[3] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instrum. Meth. A 506, 250 (2003)

[4] H. S. Hudson, Proc. Gamma-Ray Obs. Workshop (1989)

[5] D. Seckel et al., ApJ 382, 652-666 (1991)

[6] I. V. Moskalenko et al., ApJ 652, L65-L68 (2006)

[7] E. Orlando and A. W. Strong, 2007, Ap&SS, 309, 359 (2007)

[8] E. Orlando and A. W. Strong , A&A., 480, 847-857 (2008)

[9] D. Petry, 2005, in American Institute of Physics Conference Series, Vol. 745, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian, H. J. Volk, and D. Horns, 709-714 (2005)

[10] D. J. Thompson at al., J. Geophys. Res. A 102, 740 (1997)

[11] A. A. Abdo et al., Phisycal Review D 80, 122004 (2009)

[12] I. V. Moskalenko and T. A. Porter, International Cosmic Ray Conference, 2, 759 (2008)

[13] M. Brigida for Fermi Collaboration, proceedings of The XLIVth recontre de Moriond “Very High Energy Phenomena in the Universe, 115 (2009)

[14] N. Giglietto for Fermi Collaboration, PROCEEDINGS OF THE 31st ICRC Lodz (2009)

[15] E. Orlando for Fermi Collaboration, AirXvi: 0907.0557

[16] Abdo A. A. (Fermi Coll.) "Fermi-LAT Observations of Two Gamma-Ray Emission Components from the Quiescent Sun", accepted by APJ

[17] W. B. Atwood et al., ApJ 697, 1071-1102 (2009)