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Moon and quiet Sun gamma-ray emission seen by Fermi

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Abstract The Fermi Gamma-ray Space Telescope is an international mission supporting two science instruments, the Gamma-Ray Burst Monitor (GBM), covering the energy range from few keV to 40 MeV, and the Large Area Telescope (LAT), a pair-conversion detector operating at energies from 30 MeV to >300 GeV. The Fermi Telescope was successfully launched on June 11, 2008 and has been surveying the sky in gamma rays since August 2008. During the first months of the mission, Fermi has detected high-energy gamma rays from the Moon and quiet Sun since the first weeks of data taking. This emission is produced by interactions of cosmic rays; by nucleons with the solar and lunar surface (albedo), and electrons with solar photons in the heliosphere. The heliospheric emission is produced by inverse-Compton scattering and is predicted to be extended. Both Moon and the quiet Sun was detected by EGRET on CGRO with low statistics, but Fermi is the only gamma-ray mission capable of detecting the Moon and the quiet Sun and monitoring it over the full 24th solar cycle. Here we present the analysis relative to the first months including the observation of the Moon and the Sun, the spectral analysis, the fluxes measurements and finally a comparison with models and previous detections.

Key words. Gamma Rays: solar emission – Moon: gamma ray emission – Sun: gamma ray emission –

1. Introduction

Fermi was successfully launched on June 11, 2008 onto a low Earth circular orbit at an altitude of 565 Km, an inclination of 28°.5 and an orbital period of 96 min long. The observatory consists of the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The LAT (Atwood et al. 2009) is a pair-production telescope with a large effective area and field of view (2.4 sr), sensitive to gamma rays between 30 MeV and > 300 GeV. After a commissioning phase devoted to the instrument fine tuning and calibrations, the LAT began its normal science operations on 11 August 2008. Since than, several scientific results have been obtained with these early data. The mission was designed with a five-year lifetime and a goal of at least ten years of operations. In this paper we report the detection and preliminary analysis of gamma-ray emission from the Sun and Moon, as observed by *Fermi*-LAT. The possibility of a solar quiet gamma-ray emission has been first proposed by Hudson et al., pointing out the detection capabilities of the EGRET mission (Hudson 1989).

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The quiet Sun emission is expected to have two different components: the first one is the γ-ray albedo generated by the hadronic Cosmic Ray (CR) interactions with the gasseous solar atmosphere (Seckel et al. 1991). The second one is due to the Inverse-Compton (IC) scattering of CR electrons with solar photons in the heliosphere. This last component is predicted to be extended in a large region around the Sun (Moskalenko et al. 2006) (Orlando and Strong 2007). The Moon emission results from the interaction of CR nucleons with its surface (albedo) (Morris 1984) (Thompson et al. 1997). However, the Moon surface is solid and this make the lunar albedo spectrum very different with respect the solar one. EGRET observed high-energy gamma radiation from the Moon with an energy spectrum consistent with an albedo model (Moskalenko et al. 2007). The EGRET computed flux is F(> 100 MeV) = $(4.7 \pm 0.7) \times 10^{-7}$ photons cm^{-2} s^{-1} (Thompson et al. 1997), about 24% below the expected value (Morris 1984). The observed spectrum is very steep and shows a cut-off at about $3 - 4$ GeV. Althought a similar interaction of CR occurs on the Sun, EGRET has not observed the quiet solar emission and reported a 95% confidence upper limit on the Sun gamma flux of about 2.0×10^{-7} photons cm^{-2} s^{-1} at E > 100 MeV (Thompson et al. 1997). More recent reanalysis (Orlando and Strong 2008) of EGRET solar data using both disk and halo contributions yielded a total flux of $(4.44 \pm 2.03) \times 10^{-7}$ photons cm^{-2} s^{-1} for E > 100 MeV from the Sun, with the disk component exstimated about 1/4 of the total flux.

2. Data selection

The selected data sample includes the data collected since 4 august, 2008 to the end of february 2009. We have applied a zenith cut of 105° to eliminate photons from the Earth's limb. The Sun or the Moon should be at least 30° below or above the galactic plane in order to reduce the diffuse components and avoid the brightest sources on the galactic plane. Finally, the angular separation between Moon and Sun should be more than 20°, in order to remove the Moon emission component from the Sun and viceversa. We use for this analysis the "Diffuse" class (Atwood et al. 2009), corrisponding to the events with the highest probability candidates as photons. We use Science Tools version v9r11 and IRFs (Instrumental Response Functions) version P6_V3. During the months covered by this analysis, the Sun is at the beginning of the 24^{th} solar cycle and hence in a period of minimum activity. Then, the quiescent solar gamma-ray flux during this period is expected to be at its maximum.

3. Analysis and results

As the Sun and the Moon are moving sources, 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 Sun and Moon instantaneous position. Coordinates were computed using JPL libraries[1] taking into account parallax corrections. Moreover to evaluate the background in this relative coordinate frame, we use a fake source method: we consider the Moon and the Sun path in the sky and we use as fake position the first position in the source path, at least 30° displaced from the true source. In this way the fake source is moving across the sky exactly like the real source. In our analysis we select a region of interest (ROI) of 10° around the source position.

Figure 1 shows the smoothed count maps centered on the Sun and Moon position obtained in 7-months accumulation of photons from August 2008 to the end of February 2009, at photon energies above 100 MeV. These plots are an update of the count maps already published in (Giglietto 2009) and in (Brigida 2009) with a reduced data collection.

Emission from the Sun and Moon is cleary visible and centered on the expected positions in the relative coordinate frames. Figure 2 and 3 show the count map of photons with E > 100 MeV and within 10° from the Sun and Moon position projected onto Rigth Ascension and Declination. The coordinates shown are offsets of celestial coordinates in degrees rela-

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

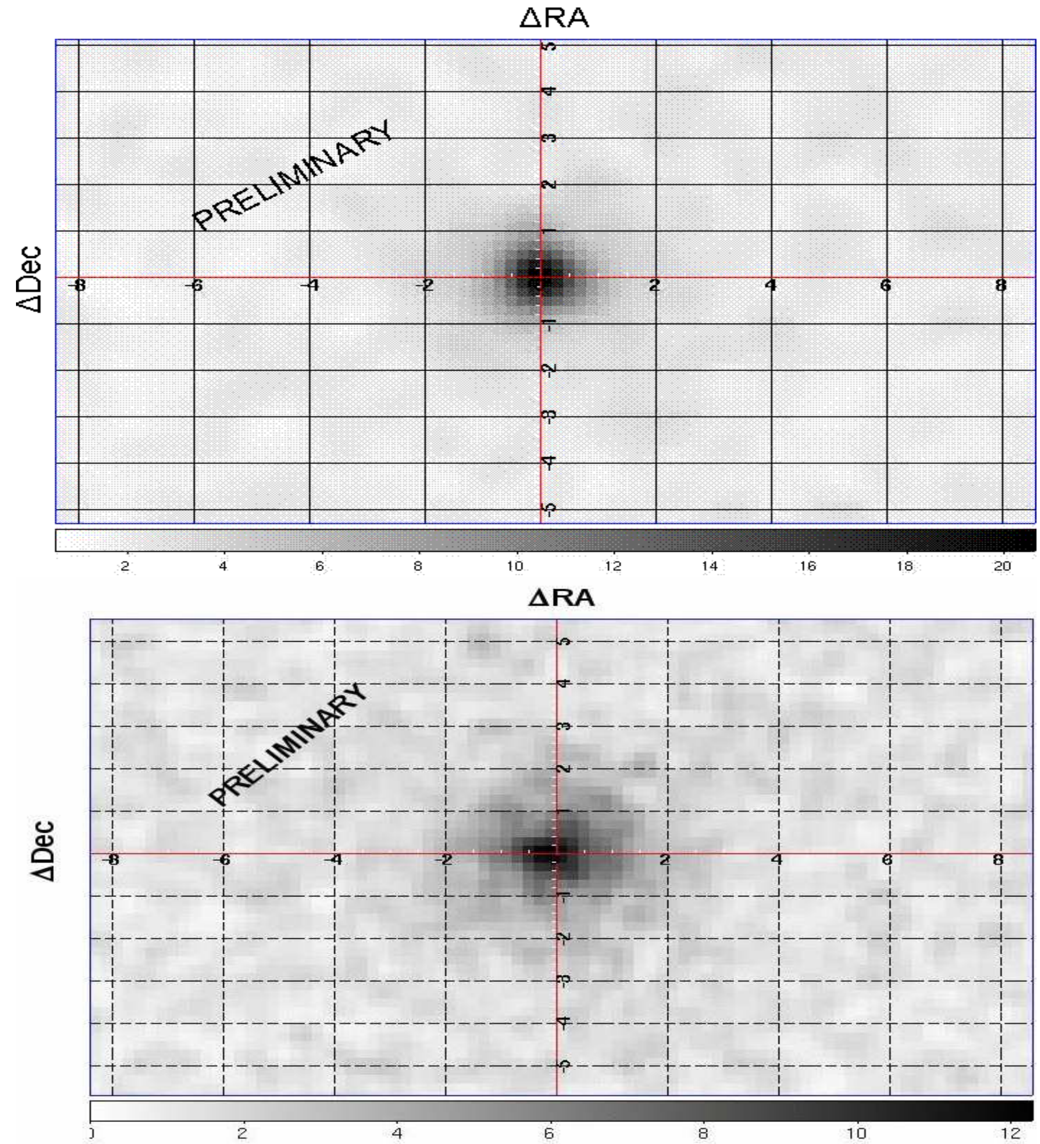

Figure 1. Sun and Moon gamma ray emission observed between August 2008 and end of February 2009. The images show the count map for E > 100MeV photons in a coordinate frame centred on the source position, the bin width used is 0.2 degrees. The image is then slightly smoothed; the gray scale used is proportional to the counts.

tive to the Sun and Moon position. Counts from the fake sources are superimposed as a dashed line and show the behaviour of the background in the Sun and Moon analysis data.

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 spectra evaluation and source flux computation is the *gtlike* tool, consisting in a binned or unbinned likelihood analysis of LAT data (Mattox et al. 1996). Maximum likelihood method was applied in the analysis of EGRET data as parameter estimation, and it is applied in the analysis of Fermi data as well. The likelihood statistic L is the probability of obtaining observational data given an input model. In our case, the input model is the distribution of gamma-ray sources on the sky, and includes their intensity and spectra. We use this likelihood to find the best fit model parameters. These parameters include the description of a source's spectrum, its position, and intensity. The preliminary analysis is performed by fitting the the fake source data in order to obtain a model for the background events. Than, we fit the source data sample with the proper function summed to the fixed background model. The fit for the Sun data shows good results for a power law of index of -2.08 ± 0.03 in the energy range between 100 MeV and 10 GeV. A preliminary value of the total flux for the Sun (albedo and IC component) gives F(> 100 MeV) = $4.6 \pm 0.3 \times 10^{-7}$ photons cm^{-2} s^{-1} using the *gtlike* method. The fit for the Moon data indicates a fit with a power law of index -3.13 ± 0.03 between 100 MeV and 1 GeV; the flux resulting from the fit gives a value of F(> 100 MeV) = $1.1 \pm 0.20 \times 10^{-7}$ photons cm^{-2} s^{-1}. The computed errors include the stastical incertaines and the estimation of the overall systematical error of about 20%.

4. Conclusions

The gamma-ray emission from the Moon and quiet Sun has been confirmed by *Fermi* in the first seven months of the Mission. In this paper we also report the first exstimation of flux from the Sun and the Moon, showing the good agreement with the previous observations

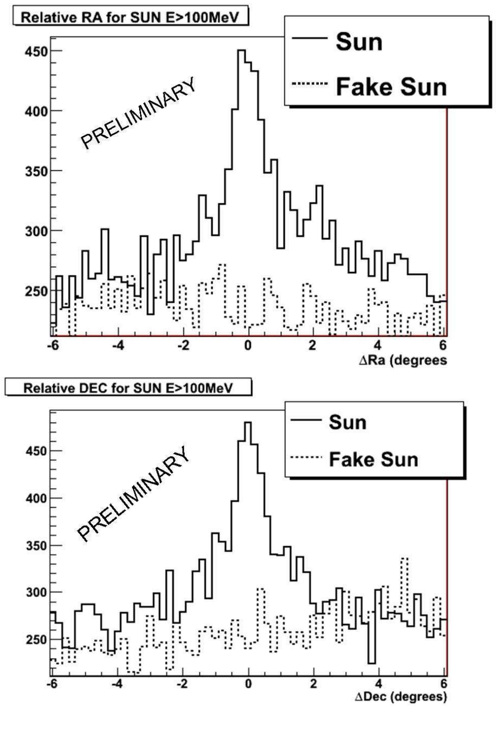

Figure 2. Count maps of events with angular separation from the Sun and $E > 100$ MeV, as a function of the Rigth Ascension and Declination. Offset in degrees with respect to the Sun position. The dashed lines show the fake Sun count map distributions.

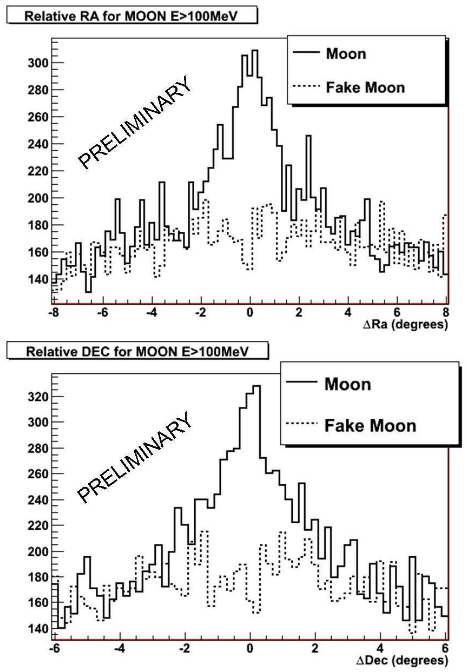

Figure 3. Count maps of events with angular separation from the Moon and $E > 100$ MeV, as a function of the Rigth Ascension and Declination. Offset in degrees with respect to the Moon position. The dashed lines show the fake Moon count map distributions.

and the theoretical evaluation. Our preliminary flux estimation for the lunar γ emission is F(> 100 MeV) = $1.1 \pm 0.2 \times 10^{-7}$ photons cm^{-2} s^{-1}. The Sun flux computation give a preliminary value of F(> 100 MeV) = $4.6 \pm 0.3 \times 10^{-6}$ photons cm^{-2} s^{-1} These results indicate that *Fermi* data analysis will provide fundamental information about the Sun and Moon emission and the modulation of cosmic ray fluxes during the 24^{th} solar cycle.

5. DISCUSSION

WOLFANG KUNDT: Please tell us the hardness of your observed solar and lunar γ-ray spectra.

NICOLA GIGLIETTO: The differences observed in the two spectra arise mainly from the mechanisms involved in γ-ray production: for the Moon case, the spectrum is coming from the secondary particles originated by cosmic ray interactions with the lunar surface, that produce hadrons and in particular π_0s that finally decays in γ-rays. For the Sun case the γ-ray emission has a similar mechanism too but the surface material and denstity is different from the Moon case, moreover the Sun has the Inverse Compton emission component due to the Galactic Cosmic Ray electrons interacting in the heliosphere. Therefore the lunar spectrum is similar to that expected and these observations confirmed to be softer than the solar spectrum.

GUSTAVO E. ROMERO: Why the gamma-rays from the Sun are not absorbed by pair creation in the solar photon field?

NICOLA GIGLIETTO: The gamma emitted in the solar heliosphere should exhibit some level of attenuation due mainly do the UV photons, however this effect, that for example might be evident in far AGNs due the abudance of UV photons in the star formation era, should be reasonable negligible for the Sun emission. The papers citedMoskalenko et al. (2006, 2007) didn't explicitely take into account for that effect, however the solar spectrum here reported doesn't show an evident attenuation; in that case we should have observed a break at higher photon energies in the gamma-ray solar spectrum.

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