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Gamma-ray emission from the Moon as observed by Fermi

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Summary. — The Large Area Telescope (LAT) on board the Fermi satellite is exploring the gamma-ray sky in the energy range from 20 MeV to > 300 GeV. Since the start of the science phase of the mission the LAT has detected high-energy gamma rays from the Moon. This emission is produced by interactions of cosmic-rays nuclei with the lunar surface and depends on the level of solar activity. Moon was detected by EGRET on CGRO with low statistics, but Fermi is the only gamma-ray mission capable of detecting the Moon over the full 24th solar cycle. Here we report the detection of gamma-ray emission from the Moon during the first 18 months of observation showing the status of the analysis and interpretation.

PACS `07.85.-m` – X- and γ-ray instruments.
PACS `96.20.-n` – Moon.
PACS `96.60.Tf` – Solar electromagnetic emission.

1. – Introduction

Fermi was successfully launched on 2008 June 11 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 [1] is a pair-production telescope with a large effective area and field of view (2.4 sr), sensitive to gamma rays between 20 MeV and 300 GeV. After a commissioning phase devoted to the instrument fine tuning and calibrations, the LAT began its normal science operations on 2008 August 11. Since then, several scientific results have been obtained with these early data.

In this paper we report the detection and mesurements of gamma-ray emission from the Moon, as observed by *Fermi*-LAT. The Moon emission results from the interaction of cosmic ray nucleons with its surface [2, 3]: the main processes involved are the production and decay of neutral pions and kaons by ions. Cosmic ray interaction with the lunar surface is well established and gamma-ray spectrum computed in [2]. More recent calculations have been performed taking into account the Lunar Prospector observations, using a detailed description of the regolite lunar surface [4] and GEANT4 [5] taking into account alla the interactions with the specific composition of the lunar rock [6].

Early analysis of EGRET observations of the Moon yielded the integral flux of $F(E > 100\,\text{MeV}) = (4.7 \pm 0.7) \times 10^{-7}\,\text{ph}\,\text{cm}^{-2}\,\text{s}^{-1}$ [3]. A later reanalysis confirmed the detection and yielded a flux $F(E > 100\,\text{MeV}) = (5.55 \pm 0.65) \times 10^{-7}\,\text{ph}\,\text{cm}^{-2}\,\text{s}^{-1}$ averaged over the entire mission duration [7], about 24% below the expected value [2]. Moreover the same work indicates that the lunar gamma-ray spectrum should exhibit a narrow 67.5 MeV line due to neutral pions decaying at rest and a steep spectrum with a cut-off at about 3–4 GeV.

These calculations indicate that the kinematics of the collisions of cosmic rays hitting the lunar surface produce a secondary particle cascade that develops deep in the rock. A small fraction of the secondary low energy pions are directed toward to lunar surface and decay to produce a soft-ray spectrum. Finally since the high energy rays can be produced by cosmic rays hitting the lunar surface with almost tangential traiectories, the limb of the disk surface should give the larger contribution to the emission.

Although similar physical processes are involved, the γ-ray spectra of the Earth, the Moon, and the Sun are very different. The Moon is so far the only observed γ-ray–emitting body with the solid surface. For the Sun the γ-ray emission from the disk, due to the interactions of cosmic ray nuclei with the solar atmosphere [8], is accompanied by extended and brighter γ-ray emission due to the inverse Compton scattering of Galactic cosmic ray electrons off solar photons [4, 9, 10].

Calculations of interactions of cosmic rays with the lunar surface are fairly straightforward and involve a well-measured spectrum and composition of cosmic rays near the Earth and composition of the Moon rock. A similar emission mechanism should be detected from any other solid object in the Solar System. Therefore planets should emit rays produced from pion decays coming from the hadronic interactions by cosmic rays hitting the surface of these bodies. We report report here the updated observations of the lunar-ray emission, previously presented, and the status of the search.

2. – Data selection

The data sample used was includes the scientific data collected since 2008 August 4 to 2010 February 4. We use for this analysis the "Diffuse" class [1], corrisponding to the events with the highest probability candidates as photons.

As the Moon is a 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 Moon instantaneous position. Coordinates were computed using JPL libraries [11] taking into account parallax corrections. In order to have a better sensitivity to the Moon emission, other sources of background have been reduced with the following selections:

- Zenith angle $< 105°$ in order to exclude photons from the Earth's limb;
- the Sun or 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 Moon and Sun should be more than 20°, in order to remove the Sun emission component;
- we remove also any time interval occurring when any bright object is within 5° from the Moon;

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

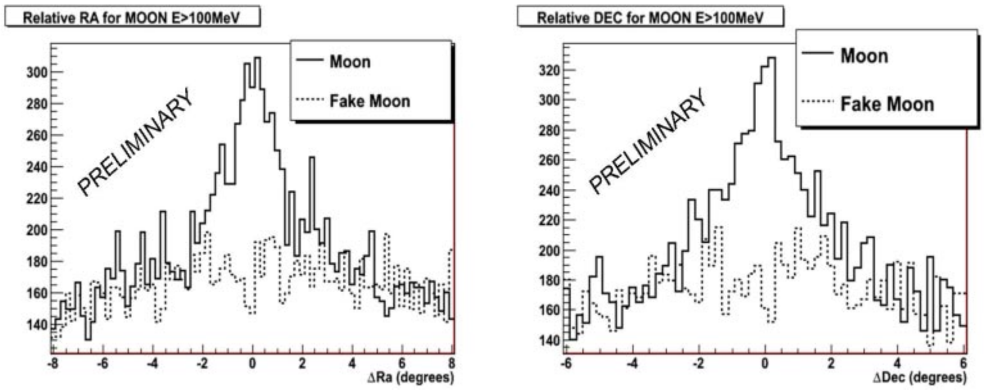

Fig. 1. – Count maps of events with angular separation from the Moon and $E > 100\,\mathrm{MeV}$, as a function of the right ascension and declination. Offset in degrees with respect to the Moon position. The dashed lines show the fake Moon count map distributions.

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 fake source following the same Moon path in the sky but at least 30° displaced from the real source. We evaluate in this way the background in the relative coordinates and comparing the two data sets.

Figure 1 shows count maps of photons above 100 MeV and within 20° from the Moon position projected onto right ascension and declination. The coordinates shown are offset of celestial coordinates in degrees relative to the Moon position. Counts from the fake sources are superimposed as a dashed line and show the background in our analysis. The plot are an update of previous observation reported with a reduced statistics [12].

Different methods can be used to compute the flux from a source, mainly based on the maximum-likelihood analysis. The Fermi standard method for spectra evaluation and source flux computation is the GtLike tool, consisting in a binned or un-binned likelihood analysis of LAT data [1]. A preliminary analysis is performed by fitting the fake source

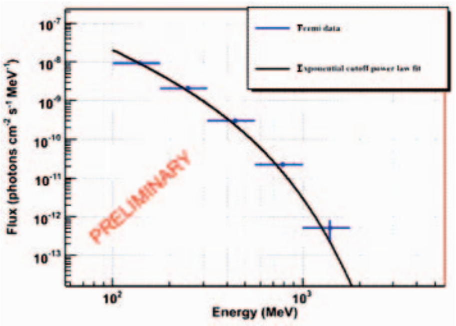

Fig. 2. – Moon spectrum for $E > 100\,\mathrm{MeV}$. Superimposed the best fit.

data in order to obtain a model for the background events. Then, we fit the source data sample with the proper free function summed to the fixed background model. The analysis for the Moon data indicates a best fit with a power law with exponential cut-off.

As a result of the fit we obtain a flux as $F(> 100\,\mathrm{MeV}) = (1.21 \pm 0.02 \pm 0.20) \times 10^{-7}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$. Figure 2 shows the Moon spectra obtained with GtLike tool.

The computed errors include the statistical uncertainties and the estimation of the overall systematical error of about 20%.

4. – Conclusions

In this paper we demonstrate the observing capabilities of Fermi-LAT by presenting detection of the Moon over the first 18 months of the Mission. We also report the exstimation of flux from the Moon, in comparison with the previous observations and the theoretical evaluation. These results indicate that Fermi data analysis will provide fundamental information about the Moon emission and the modulation of cosmic ray fluxes during the solar cycle.

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