Search for gamma rays from asteroids in the Solar System with the Fermi LAT

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All known small Solar System bodies have a diameter between 1 m and a few hundreds of kilometers. Like all Solar System bodies, asteroids can be passive sources of high-energy gamma rays, which are produced when energetic charged cosmic rays impinge on their surfaces. Since the majority of known asteroids lie in an orbit between the orbits of Mars and Jupiter (known as the Main Belt), we expect them to produce a diffuse emission close to the ecliptic plane. In this work, we propose a model of the gamma-ray emission from the asteroids, written in terms of their size distribution. We show that the data collected by the Large Area Telescope (LAT) onboard the Fermi satellite can provide a way to constrain the asteroids gamma-ray emission model and, in turn, their size distribution.

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1. Introduction

All Solar System Small Bodies (SSSBs) can be divided into three main families: the Main-Belt asteroids, lying between the orbits of Mars and Jupiter; the Trojans, which share an orbit with a larger planet or Moon; and the Trans-Neptunian objects, belonging to the Kuiper Belt. All these bodies are mainly composed of carbon, silica or metal. All known asteroids have a size > 1 m and the majority of them lies in the Main Belt. Like all bodies in the Solar System, they can be passive sources of gamma rays produced by the interaction of Cosmic Rays (CRs) with the material they are composed of [1]. Therefore, a diffuse gamma-ray emission is expected to be observed along the ecliptic plane. This observation could provide a way to further investigate the properties of known asteroids and, in particular, the distribution of their sizes to diameters < 1 m. In this work, we propose a modelization of the gamma-ray diffuse emission from the ecliptic plane in terms of the asteroids size distribution. We show how to constrain this distribution by reconstructing the gamma-ray flux from the sky with the Fermi-LAT data.

2. Asteroids gamma-ray emission

Assuming the asteroids to be spherical, the gamma-ray differential flux (in units of $\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$) produced by N asteroids of radius r at different distances d_i from the Earth, observed in the sky pixel centered at spatial coordinates (λ, β), can be written as:

$$\phi_\gamma(E_\gamma, r, \lambda, \beta) = \pi r^2 \, I_\gamma(E_\gamma, r) \, N(r) \sum_{i \in \mathrm{l.o.s.}} \frac{\omega(\lambda, \beta, d_i)}{\Delta\Omega \, d_i^2} \tag{1}$$

where $\omega(\lambda, \beta, d_i)$ is the fraction of bodies at distance d_i from the Earth located in the sky pixel centered at (λ, β), $\Delta\Omega$ is the solid angle subtended by the pixel, and the sum extends to all bodies along the line of sight (l.o.s.) pointing from the Earth towards the direction defined by the coordinates (λ,β). In the previous formula, $I_\gamma(E_\gamma, r)$ is the gamma-ray intensity at the production site, and can be written as:

$$I_\gamma(E_\gamma, r) = \sum_i \int Y_i(E_\gamma|E_k, r) I_i(E_k) dE_k \tag{2}$$

where $I_i(E_k)$ is the energy spectrum of the i-th CR species impinging on the asteroid (mainly i = protons, He nuclei and electrons) and $Y_i(E_\gamma|E_k, r)$ is the yield of gamma rays with energy E_γ produced by a cosmic ray of i-th species with energy E_k interacting with an asteroid of radius r. We have evaluated the yields $Y_i(E_\gamma|E_k, r)$ with a dedicated simulation based on the FLUKA code [2]. We define a SSSB as a density-homogeneous spherical body, whose radius can assume values from 10 cm to 100 km. Figure 1 shows the intensities obtained by folding the yield calculated with silica asteroids with two limiting cosmic-ray spectra, namely the Local Interstellar Spectrum (LIS) [3] and the spectra measured at the Earth's surface by the AMS-02 experiment [4]. For $r > 10\,\mathrm{m}$, one can see that the shape of the curves starts to be independent of the radius and approaches the one of the Moon. This is due to the fact that cosmic-ray nuclei have an interaction length of a few tens of $\mathrm{g/cm^2}$, and the gamma-ray absorption length is even shorter. When the asteroid size is larger than both these characteristic lengths, the gamma-ray emission becomes independent of the size.

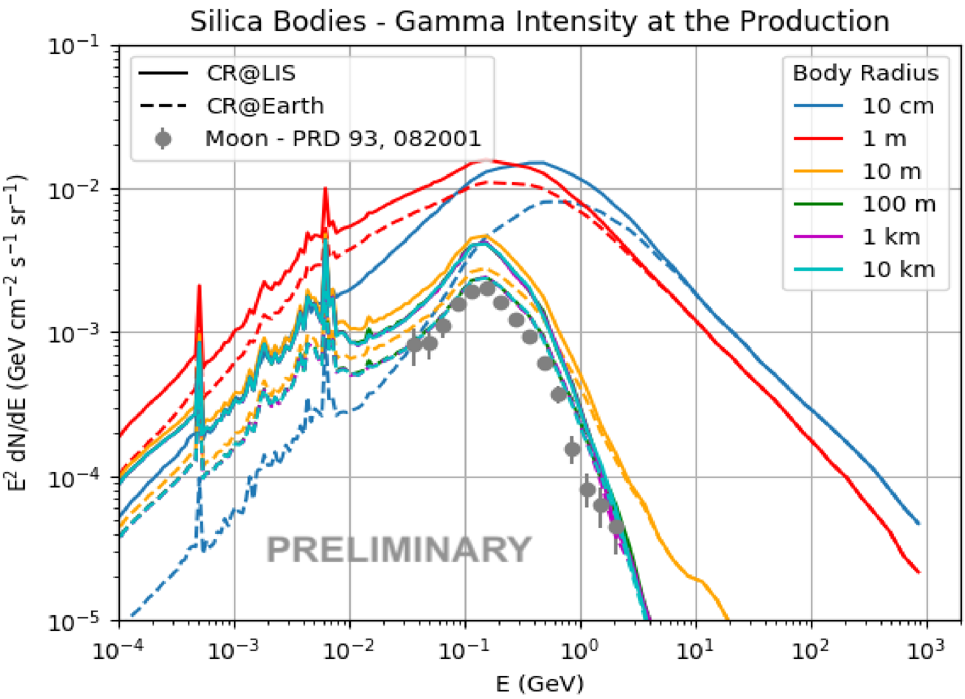

Figure 1: Gamma-ray intensities at the production from silica bodies with different radii. All spectra have been calculated by using the LIS spectra from ref. [3] (solid lines) and the spectra measured by AMS-02 [4] (dashed lines). The grey points represent the Moon intensity as reconstructed in ref. [1].

The factor $\sum_i \omega(\lambda, \beta, d_i)/d_i^2$ has been calculated by sampling 10^7 times the asteroids orbital parameters from their distributions as reported in the Solar System Small Bodies JPL catalog [5] and assuming all asteroids to have circular orbits. The result is the spatial map shown in Figure 2.

3. Constraining the asteroids population

Starting from $I_\gamma(E_\gamma, r)$ and $\sum_i \omega(\lambda, \beta, d_i)/d_i^2$, one can use the measured gamma-ray flux to constrain the number $N(r)$. We have used the Fermi-LAT [7] data to reconstruct the flux from the ecliptic plane in the time interval from August 2008 to December 2020. In order to avoid the contamination from the Galactic Plane (see Figure 2), we selected six Regions of Interest (RoIs) of width 40° in both ecliptic longitude and latitude, each one having a minimum distance of about 17° from the center of the Galactic Plane. The RoIs are centered at the ecliptic longitudes 0°, 40°, 140°, 180°, 220° and 320° and at the ecliptic latitude 0°.

The data sample used for the analysis was extracted from the Pass 8 P305 ULTRACLEANVETO dataset (which is the most recommended for studies of diffuse emission that require the lowest level of CR contamination), with energies from 56 MeV to 1.78 TeV. The analysis was performed using the `fermitools` (version 2.0.8) [8] and `fermipy` (version 1.0.1) [9], implementing a fitting procedure based on a Poisson-maximum-likelihood approach. In our results, which will be shown in a future work, we found no detection of a new source. In each RoI and energy bin, we used `fermipy` to

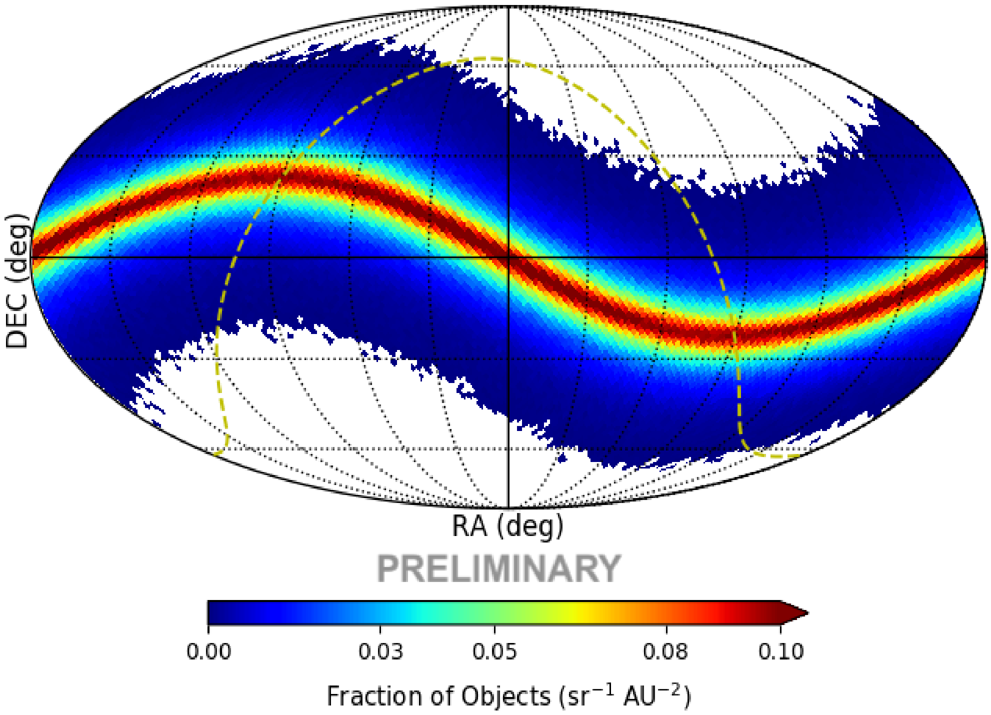

Figure 2: Asteroids spatial map built by sampling 10^7 times the asteroids orbital parameters from their distributions in the JPL catalog. Each sky pixel contains the fraction of asteroids in that sky portion, divided by their squared distance from the Earth. The yellow dotted line represents the center of the Galactic Plane. The map was built using HEALPix with Nside = 32 [6].

derive a likelihood scan for the asteroids source, described according to the model presented in Section 2. Having a log-likelihood scan $\ln \mathcal{L}_i^r$ in the i-th energy bin and in the r-th RoI, one can calculate the corresponding log-likelihood $\ln \mathcal{L}_i^r(f(E))$ for a given spectral model $f(E)$. Assuming the log-likelihood functions in each bin to be mutually independent, the total log-likelihood for the model is given by

$$\ln \mathcal{L}(f) = \sum_i \sum_r \ln \mathcal{L}_i^r(f(E)). \tag{3}$$

This procedure is repeated multiplying the model by a normalization factor k to obtain a vector of $\ln \mathcal{L}(kf)$ as a function of k. The value of k for which $\ln \mathcal{L}(kf) = \ln \mathcal{L}(kf)_{max} - 2.71/2$ provides an upper limit at 95% confidence level on k. Since the spectral model of the asteroids source depends on $N(r)$, one can then set constraints on the asteroids size distribution.

4. Conclusions

We have proposed a model describing the diffuse emission of Small Solar System Bodies. The model depends on three factors. The first one is the intensity at production site, which depends on the species and on the intensities of the cosmic rays impinging on the asteroids surface and on the relative gamma-ray yield. We evaluated the yield with the FLUKA code and we used two limiting cosmic-ray spectra, namely the LIS and the spectra measured at the Earth's surface. The second factor is the spatial distribution of asteroids. For each pixel into which the sky was divided, this factor is the fraction of bodies at a given distance from the Earth, divided by the square distance and summed along the line of sight. We estimated this factor by sampling 10^7 times the asteroids orbital parameters from the JPL database. The third factor is the number of asteroids of a given radius. This number is known from optical measurements for radii above few km. The measurement of the gamma-ray flux could provide an estimate of this number for smaller radii, given that the other two factors were computed. In the results from the data analysis, which will be shown in a future work, we found no detection of a new source. A combined-likelihood analysis approach will be adopted to constrain the asteroids size distribution.

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