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Local gamma-ray sources

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Summary. — The quiet Sun, the Moon, the Earth and other Solar System objects are sources of high-energy gamma rays. The emission is produced by interactions of Galactic cosmic rays: by nucleons in the surface and atmosphere of the sources via hadronic interactions, and by electrons on solar photons in the heliosphere via inverse Compton scattering. Both emissions depend on the solar activity and hence on the modulation of cosmic rays in the heliosphere. At the minimum of the solar activity, Galactic cosmic rays have their maximum flux, and hence the brightest gamma-ray emission is expected. For this reason, solar and lunar emission provides a unique probe of cosmic-ray propagation in the inner heliosphere. Here I give a review of the gamma-ray emission mechanisms from the local sources, and present the status of the observations.

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1. – Introduction

Local bodies in the Solar System are expected to shine in gamma rays. The emission is produced by interactions of Galactic cosmic rays with the surface or atmosphere of the bodies and in the heliosphere. Known objects bright in gamma rays are: the Earth, the Moon, the Sun and small Solar System bodies such as asteroids. In the following sections I discuss the gamma-ray production mechanisms and the status of the observations.

2. – The Earth

The Earth produces gamma-ray emission by cosmic-ray interactions with the atmosphere, as a result of cosmic-ray cascades. It is produced mainly by protons and heavier

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nuclei, through the decay of neutral pions and kaons, and by electrons and positrons, through bremsstrahlung. The spectrum of the emitted gamma rays is not uniform across the Earth's disk. The spectrum of the inner part of the disk is soft because secondaries scattered in the forward direction tend to have higher energy than the ones scattered in the backward direction. Due to the kinematics of the collisions, the cross-sections of these processes at high energies are peaked in the forward direction. Cosmic rays that enter the atmosphere near grazing incidence produce showers and gamma rays. They move in the forward direction and can penetrate the thin atmospheric layer, making the limb bright when viewed from orbit. Calculations of the geometric effect of shower production and absorption in the atmosphere and the production of a bright gamma-ray horizon have been made [1]. Then a Monte Carlo code was developed [2] for gamma-ray production by cosmic-ray interactions, which was in agreement with the spatial and spectral measurements by various balloon-borne and spacecraft instruments. A more detailed study of the gamma-ray emission was made by [3], using the data from the second Small Astronomy Satellite, SAS-2. These measurements showed a peak of gamma-ray emission towards the Earth horizon, with a factor of 10 larger intensity than seen towards the nadir direction. Moreover these measurements show a modulation of the intensity for the east-west effect as expected from the deflection of cosmic rays in the Earth's magnetic field. These effects were confirmed also by EGRET [4]. Observation of the gamma-ray emission from the Earth is important for better understanding the interaction and production of secondary gamma-rays in the Earth's atmosphere. In turn, it can provide information on the spectrum of primary cosmic rays, interaction cross-sections, atmospheric properties, and the deflection of primary cosmic rays by the geomagnetic field.

Fermi-LAT has now enabled much improved studies of the atmospheric emission. These data provide a picture of the gamma-ray emission from the Earth's atmosphere with good angular and spectral resolution. During the survey mode (the routine science operation), Fermi-LAT points away from the Earth because of the gamma-ray brightness of the Earth at GeV energies [5]. However, during the commissioning phase of the LAT, the Earth's limb was often close to the LAT field of view. Moreover, a dedicated observation of the Earth's limb was made in September 2008. Both these datasets were used for the analysis of the atmospheric emission in [5]. Two-dimensional intensity maps, azimuthal, zenithal profiles and energy spectra of the Earth's emission have been derived. They show a bright limb at the Earth's horizon, mostly generated by grazing-incidence cosmic-ray showers coming directly towards the LAT. The spectrum of the emission has a power-law shape up to 500 GeV with spectral index of 2.8, which reflects the CR spectral index. Moreover, Fermi-LAT observations revealed a soft-spectrum in the nadir region, which is dominated by gamma-rays back-scattered at large angles. The emission shows a softer spectrum with increasing energies, due to the increasing collimation of secondaries. The east-west modulation for energies below 10 GeV is also evident, caused by the deflection of primary cosmic rays in Earth's magnetic field. This effect is reduced at higher energies, as expected.

3. – The Moon

Gamma-ray emission from the Moon is caused by interactions of Galactic CR nuclei, mainly protons, with the lunar surface. The main processes involved in the lunar emission are production and decay of secondary neutral pions and kaons produced by cosmic rays hitting the lunar surface, bremsstrahlung, and Comptonization of primary and secondary electrons and positrons. Calculations of interactions of CRs with the lunar surface involve the knowledge of the spectrum and composition of CR near the Earth and the composition of the Moon rock, which is studied using the samples returned by the lunar missions and by remote sensing.The first model of the lunar gamma-ray emission was done using a Monte Carlo simulation for cascade development [2]. The SAS 2 experiment operated from November 1972 through June 1973, near solar minimum obtained only an upper limit to the lunar gamma-ray flux. The 95% confidence upper limit of $2.2 \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ on the flux above 100 MeV was just below the calculated value for solar minimum: $1.54 \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [2]. Subsequently, the gamma-ray telescope EGRET on CGRO (operated from 1991 to 2000) detected the emission from the Moon with high statistical significance [6]. Averaged over the solar cycle, the integral gamma-ray flux of the Moon above 100 MeV as observed by EGRET was $(4.7 \pm 0.7) \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Subdivision of the EGRET data in two samples, data taken during the solar maximum 1991-1992 and data taken during period of moderate activity 1993-1994, yields $3.5 \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and $6 \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ respectively, indicating that the lunar flux is higher near the solar minimum [6]. A reanalysis of the same data by [7] for the entire solar cycle gave a flux $(5.5 \pm 0.7) \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 100 MeV, with a spectral index of 3 in agreement with previous analysis. Recently a simulation using the GEANT4 Monte Carlo framework to calculate the gamma-ray emission from the Moon was made by [8], using recent measurements by BESS and AMS for the CR. They show that the spectrum is steep with an effective cut-off 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. They found a soft spectrum produced by a small fraction of low-energy splash particles in the surface layer of the lunar rock. The high-energy gamma rays can be produced by CR particles hitting the lunar surface with a more tangential trajectory. However, since it is a solid target, only the very thin limb contributes to the high energy emission. The gamma-ray flux depends on the solar modulation and hence it can be used to infer the incident CR spectrum. Simultaneous measurements of CR proton and helium spectra by PAMELA [9], and observations of the lunar gamma rays by LAT, can be used to test the model predictions and to monitor the CR spectrum near the Earth.

The detection by Fermi-LAT of the gamma-ray emission from the Moon has been widely reported (*e.g.* [10-12]). The Fermi-LAT observations were taken entirely during the period of the prolonged anomalous solar minimum and yielded an integral flux $(1.21 \pm 0.02[\mathrm{stat}]\ ^{+0.2}_{-0.2}[\mathrm{syst}]) \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 100 MeV and a spectral index around 3 [12]. The higher flux with respect to previous measurements by EGRET may reflect the anomalous period of solar minimum in which Fermi was operating (Abdo *et al.*, in preparation).

4. – The Sun

The Sun is an extremely bright source of high-energy gamma rays during solar flares when accelerated electrons and nuclei interact with the solar atmosphere [13,14]. The first report on the EGRET detection of high-energy solar flare was in 1993 by [15] on the June 11, 1991 solar flare. Preliminary upper limits with Fermi-LAT above 100 MeV have been derived for all solar flares detected so far by other missions and experiments (RHESSI, Fermi, GBM, GOES) [16]. Apart from such emission in its active state, the Sun exhibits also an induced gamma-ray emission in its quiet state. Solar quiet gamma-ray astronomy started playing a significant role in the early 1990's thanks to the EGRET mission. The importance of gamma-ray emission from the quiet Sun as an interesting possibility for highly sensitive instruments such as EGRET was pointed out by [17]. Estimates [18] indicated that the flux of gamma rays produced by cosmic-ray interactions on the solar surface would be detectable by EGRET. This emission is due hadronic interaction of Galactic CR with the solar atmosphere and is restricted to the solar disk. This work [18] provided the first and so far only detailed theoretical study of gamma-ray emission from interactions of CR protons in the solar atmosphere. The integral flux above 100 MeV was predicted to be $F(> 100\,\mathrm{MeV}) = (2.2–6.5) \times 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the "nominal" model, which takes into account CR propagation in the interplanetary magnetic field. They lower limit corresponds to the cascade development in the forward direction, while the upper limit corresponds to mirrored showers, *i.e.* reflected by the photospheric magnetic field back to the surface. Attempts to observe solar emission with EGRET by [6] did not show any excess of gamma rays consistent with the position of the Sun, and yielded only an upper limit of $2.0 \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 100 MeV at 95% confidence level.

The existence of an additional, spatially extended component of the solar emission due to the inverse Compton (IC) scattering of CR electrons on solar optical photons was realised only recently [19, 20, 7]. The intensity of the emission has a maximum in the direction of the Sun and varies approximately as the inverse of the angle from the Sun. Formulations for calculating the intensity and distribution of the IC emission are given in [19, 20] and [7]. The IC flux depends on the CR electron spectrum at different heliocentre distances, which varies with the solar activity and is in fact the only unknown in the calculations (the solar photon field and the physics of the IC process are accurately known). In fact, IC gamma-ray flux changes over the solar cycle anti-correlated with the solar activity. It is estimated to vary of a factor of 2 in a region within 5° around the Sun.

The first detection of the gamma rays from the quiet Sun was obtained only recently in a reanalysis of the EGRET data [7]. They took into account both components of the solar gamma-ray emission, disk and IC, and allowed for the influence of Galactic emission and background sources. They reported a full analysis including the spectrum of disk and extended components. They found a flux ($> 100\,\mathrm{MeV}$) of $(3.8 \pm 2.1) \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the IC component within 10° of the Sun, consistent with their model estimate of $2.18 \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for solar maximum conditions and the same region. Their reanalysis yielded a flux ($> 100\,\mathrm{MeV}$) of $(1.8 \pm 1.1) \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the disk component, which is in agreement with the predictions by [18] within big errors, due to the limited sensitivity of the instrument. This result was very promising for the Fermi mission which is able to observe the quiet Sun with high statistical significance and on a daily basis. Observations of the IC emission can yield information about CR electron spectra at different heliospheric distances simultaneously and thus contribute to studies of solar modulation of Galactic CRs. Moreover, the extended emission from the Sun has to be taken into account in other analyses, since it can be strong enough to be a confusing background for Galactic and extragalactic diffuse emission studies.

Recent analysis of the solar emission with Fermi-LAT has been reported in many conferences (*i.e.* [21-24]) since the beginning of the mission. Fermi-LAT has detected gamma-ray from the quiet Sun and has clearly discriminated between the two emission components. The reported period of observations corresponds to the extended period of low solar activity when the gamma-ray flux is maximum. The reported flux of $(3.4 \pm 0.6) \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the disk component and $(1.1 \pm 0.3) \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the IC component within 20° radius is in agreement with an IC model, using the electron spectrum measured by Fermi above 7 GeV [25]. These results are preliminary; a complete analysis with higher accuracy is in preparation by the Fermi-LAT team.

5. – Small Solar System bodies

Small Solar System objects are also expected to be bright in gamma rays. Calculations have been performed ([26] and [27]) of the gamma-ray flux produced by cosmic-ray interactions with the solid rock and ice in Main Belt asteroids (MBAs), Jovian and Neptunian Trojan asteroids, and Kuiper Belt objects (KBOs) and in the Oort Cloud, using the Moon as a template. A majority of the MBAs and KBOs have their orbits distributed near the ecliptic. The dynamical estimate of the total mass of the asteroid belt is close to 5% of the mass of the Moon [28]. The total mass of asteroids is dominated by large bodies, while the gamma-ray emission is dominated by small bodies, since the latest are more numerous. The sizes of asteroids generally cannot be directly observed (except for a small number of asteroids studied by spacecraft flybys or stellar occultation, or those well observed by radar) and are instead estimated using apparent magnitude, optical and infrared albedos, and distances. Smaller sizes are very difficult to detect, and one must bear in mind the observational bias of the incompleteness of the small asteroid sample. Most MBAs have a semimajor axis between 2.1 and 3.3 AU with a low-eccentricity orbit. In the estimates [26] an average circular orbit with radius 2:7 AU was assumed. The Jovian Trojan populations of asteroids are collections of bodies in the same orbit as Jupiter located at the L4 and L5 Lagrange points of the Jupiter-Sun system. The Trojans are thus concentrated in two regions rather than distributed over the entire ecliptic as for the MBAs. Kuiper Belt objects are distributed between 30 and 100 AU [29]. Analysing the EGRET data [26] infer the diffuse emission from the MBAs, Trojans, and KBOs to have an integrated flux of less than $6 \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (100–500 MeV), depending on the number of small bodies in each system. Detection by Fermi can provide direct information about the number of small bodies and the KBO flux can be used to probe the spectrum of CR nuclei close to the interstellar conditions. Up to now no detection of these objects with Fermi-LAT has been reported.

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