Map of the low energy gamma ray fluxes at altitude 500 km

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Abstract. Results of the statistical study of gamma ray fluxes in the energy channels 0.12 - 0.32, 3.0 - 8.3 MeV, measured by the instrument SONG on board the low altitude high inclination satellite CORONAS-I, are presented. The geographic maps based on sets of data in March - June 1994 are constructed and the latitudinal distribution (i.e. the variation of average fluxes with vertical cut - off rigidity) for higher energies is given. The irregular spatial structures of gamma ray flux increases in the subauroral zone and at lower latitudes are discussed.

Key words: Gamma rays – cosmic rays – Earth's atmosphere

1. Introduction

The study of the spatial distribution of gamma rays at low altitudes is important to test the models for the production of gamma rays in Earth's environment and to understand the dynamics of the Earth's radiation belts. Such measurements contribute to the construction of radiation models in the Earth's magnetosphere. In addition, observed gamma ray fluxes are a background that must be subtracted in near-Earth satellite observations to obtain the gamma ray fluxes from solar energetic emission or other celestial objects in this and similar experiments. Since cosmic rays and also the population of trapped energetic particles in the geomagnetic field have a dependence on the level of solar activity the systematic measurements of gamma rays is important. The projects CORONAS-I and planned CORONAS-F can be useful for such types of studies.

Gamma rays observed in the near-Earth space experiments are a superposition of atmospheric gamma rays and of diffuse cosmic gamma rays. An appreciable amount of detected gamma rays belong to gamma-ray background

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that include: (i) prompt background due to gamma rays and neutrons produced by local cosmic rays, and (ii) decays of radionuclides activated by cosmic-ray bombardment. Complex information about gamma rays production in space in the region 100 keV to 100 MeV can be found in Chupp (1976). Atmospheric gamma rays are produced by interactions of cosmic ray protons, alpha particles, and electrons with oxygen and nitrogen nuclei in the atmosphere. At higher energies, gamma rays are created mainly by the decay of π^o mesons from high energy nuclear interactions, while at lower energies the gamma rays are produced primarily by bremsstrahlung of primary, secondary and reentrant electrons (Beuermann, 1971; Daniel and Stephens, 1974; Martin *et al.*, 1975).

Previous satellite results on gamma rays at low altitude have been reported by Golenetskiy *et al.* (1971, 1975); Kraushaar *et al.* (1972); Imhof *et al.* (1976); Gur'yan *et al.* (1979); Thomson *et al.* (1981); Efimov *et al.* (1985); Forest (1989); Ryumin *et al.* (1996) and Bogomolov *et al.* (1997). Mainly atmospheric gamma rays have been explored in most of the above experiments. The observations of Kraushaar *et al.* (1972), Gur'yan *et al.* (1979), Thomson *et al.* (1981), and Forest (1989) were for gamma rays with energy above approximately 30 MeV. Golenetskiy *et al.* (1971), Imhof *et al.* (1976) and Efimov *et al.* (1985) reported results below about 6 MeV from satellites with high-inclination orbits. The satellite investigations of Ryumin *et al.* (1996) and Bogomolov *et al.* (1997) were for energies from about 100 keV to 100 MeV. Apart from a few properties the latitude dependence of gamma-radiation intensity has been carried out in the above experiments. Gamma ray lines features from the Earth's atmosphere has been studied from satellites by Mahoney *et al.* (1981); Letaw *et al.* (1989) and Willett and Mahoney (1992).

Although several earlier measurements of gamma ray flux at low altitudes exist, there are not numerous extensive statistical studies revealing the features of the gamma ray flux distribution at the altitude 500-km. In this paper we present geographic maps of average fluxes of gamma rays within the period of three months. The latitudinal dependence in the energy range 3.0 - 8.3 MeV is given and compared with previous results.

2. Experiment

Low altitude satellite CORONAS-I has been devoted to the study of various aspects of solar activity. The SONG device is a part of the complex measuring high energy electromagnetic and corpuscular emissions from the Sun. Energetic particles are detected by a CsI(Tl) crystal scintillator with diameter 20 cm and thickness 10 cm viewed by three photomultipliers, surrounded by magnetic shielding. The whole scintillator counter is placed under a 4π-anticoincidence shielding against charged particles. The shielding is made of a plastic scintillator 2 cm thick and consists of two parts. The lower one protects the CsI from below and from the sides and is viewed by one photomultiplier. The upper part is thick,

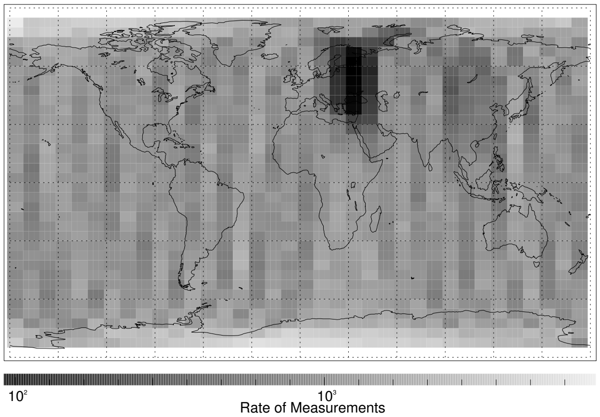

Figure 1. The map of measurements covered by the SONG apparatus in individual pixels

situated in front of CsI and is viewed by two photomultipliers through the light conductors. More details are in Baláž *et al.* (1994). The CORONAS-I satellite was launched on March 2, 1994 into a nearly circular orbit with an altitude of 500 km and inclination $I = 83°$. The SONG device was placed on the platform for scientific instruments about 1 m from the upper end of the satellite body. The nominal orientation during its first working period (up to July 5, 1994) was with its longitudinal axis directed toward the Sun. This was true for both day as well as night passes (SONG was oriented towards the Earth on night side of orbit).

Here we analyze the monitoring mode of measurement with a 2.5-sec resolution in two (the lowest and highest energies) out of the four energy channels measuring the gamma rays used by the SONG instrument.

3. Data set

The data set analyzed in this paper was collected over the period from March 1994 to June 1994. The extent of the set is 1.4×10^6 data points with the time resolution 2.5 s. For the following analysis two energy intervals of gamma rays have been selected, namely $E_A = 0.12 - 0.32$ MeV, and $E_B = 3.0 - 8.3$ MeV. The data have been divided into pixels according to the geographic coordinates with the step of 5° in latitude and of 10° in longitude. The average number of points of measurements covering one individual pixel is 1200. The total data coverage is displayed in Figure 1. In most of the regions the number of points is above 700 with some exceptions, where many errors in the data were identified. The conspicuously light area (about 100 measurements) in the north hemisphere is related to regions of data reception.

For each of these pixels the estimate of the mean and dispersion have been evaluated assuming a normal distribution of the measurement points. It should be noted this is the zero-th approach suitable for a rough description of flux distribution. The chi-square test of the normality of distribution did not unambiguously confirm the normality of the distribution for each pixel. There are at least two effects influencing the inhomogeneity of the distribution, namely (a) - the temporal variability, especially at high latitudes due to the variations in flux of high energy electrons precipitating into the atmosphere, and (b) - the changes in the orientation of the detector (the orientation with respect to magnetic field is not identical for all passes at any given pixel).

A correction of the flux of gamma rays was done on a daily basis, adjusting its absolute value to the ratio of average primary cosmic rays measured by a high cut-off rigidity neutron monitor station at Haleakala, and of high energy measurements by the SONG instrument (channel measuring protons $E_p > 70$ MeV, and electrons $E_e > 55$ MeV) at low latitudes, $L = 1.05$, L - McIlwain's parameter (for dipole approximation $\cos^2 \Lambda = L^{-1}$ at the earth's surface, Λ - invariant latitude (Roederer, 1970))(Kuznetsov *et al.*, 1997). To recalculate the flux of gamma rays from the count rate (in units of photons per cm^2.s.ster) the effective area was taken from the figure displaying its dependence on energy of gamma rays (Baláž *et al.*, 1994). For the energy range 0.12 - 0.32 MeV its value is 258 cm^2 and for the energy range 3.0 - 8.3 MeV it is 213 cm^2. As for the characteristic value of the solid angle within which gamma rays are detected by the SONG device, $2.6 \pm 1.0\pi$ ster was used according to Ryumin *et al.* (1996).

The values obtained from the measurement in the energy range 0.12 - 0.32 MeV have been corrected for the induced background. The procedure is described in Ryumin *et al.* (1996). The reason is that in the raw data there are observed the different latitudinal profiles for low and high gamma ray energies at SONG device. This is most probably caused by the fact that a significant contribution for gamma rays below 2.1 MeV is caused by the decay of the long living radioisotopes induced due to the interactions of cosmic rays with the detector material. The effect is described in Johnson *et al.* (1993). Since the latitudinal dependence of the induced gamma rays is practically absent (Dean *et al.*, 1991), the induced contribution was simply subtracted as a constant from the detected gamma ray flux. The estimate of the induced gamma ray flux was done by comparison of the latitudinal dependencies in the channels 0.12 - 0.32 MeV and 8.3 - 16 MeV, respectively (the induced gamma ray flux caused by the radiation belt protons should be higher than such an estimated value).

4. Review of gamma ray fluxes

According to section 3 the correction for induced background was done in the low energy channel. The result is seen in Figure 2 (upper panel). The lower panel of Figure 2 shows the distribution of high-energy gamma ray fluxes. It

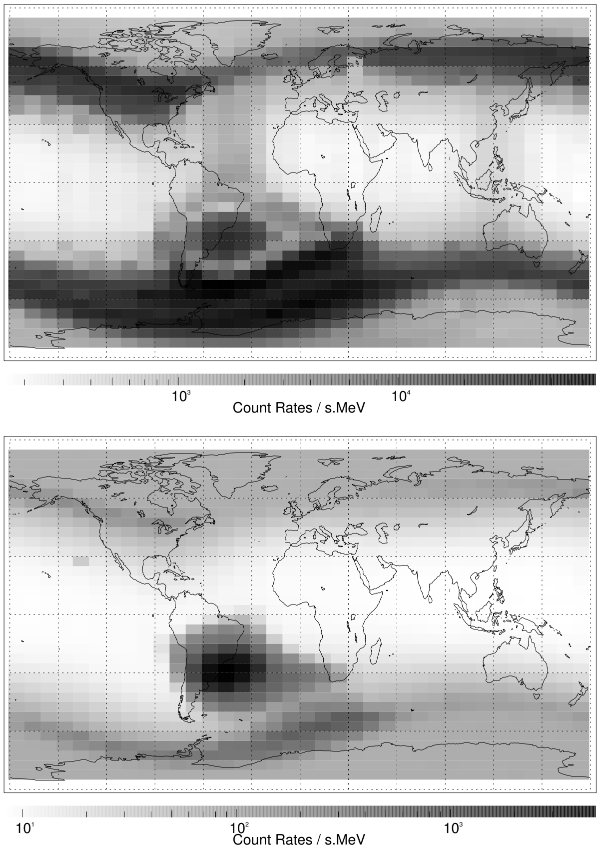

Figure 2. The maps of average fluxes of gamma ray in the energy ranges 0.12 - 0.32 MeV (upper panel) and 3.0 - 8.3 MeV (lower panel).

uses a black and white colour map with 256 colour tones. If **F** is the matrix of the average fluxes of gamma rays, then the colour vector **C** is calculated using the interpolation formula $c_k =$ integer part $(255(\log(f_{ij}/I)/\log(S/I)))$, where $c_k, k = 0, 1, \ldots, 255$ is the element of vector **C**, $f_{ij}, i = 1, 2, \ldots, 34$; $j = 1, 2, \ldots, 36$ is the matrix element, and $S(I)$ is the maximum (minimum) element of the matrix **F**.

The picture obtained should be assumed to be the combined effect of albedo gamma rays from the Earth's atmosphere, locally produced gamma rays and of diffuse cosmic gamma ray having no latitudinal dependence.

The irregular distribution of the gamma radiation in the various geographical regions is associated with the structure of the real magnetic field (there are anomalies in the distribution of the field strength at low altitudes) (Vernov *et al.*, 1967). On both of the panels of Figure 2, the high fluxes of gamma rays mainly

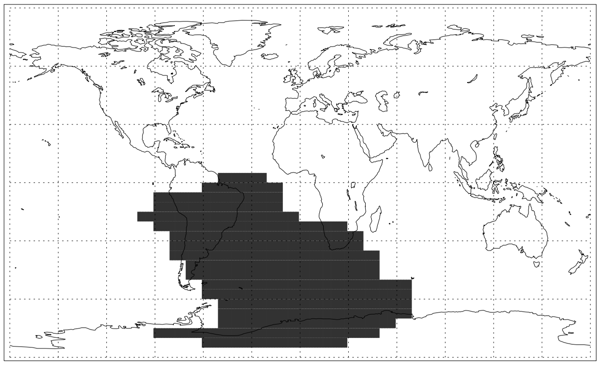

Figure 3. Geographical position of regions where $Hmin > 200$ km.

observed in the Brazilian magnetic anomaly (BMA) region ($L \sim 1.15 \div 1.8$) and in the bellow one ($L \sim 2.5 \div 5$) are most probably associated with trapped regions ($Hmin > 200$ km, $Hmin$ - minimum altitude of mirror points of azimuthally drifting particles), the so-called inner and outer belt, respectively. The stable trapped regions are displayed in Figure 3.

We can see the difference in the energy spectra (assuming the ratio of the count rate in two channels) in (a) the BMA region and in (b) the gap between belts ($L \sim 1.7 \div 2.2$). In (a) a rather harder spectra is seen than that in (b). It should be noted that higher energies (Galper *et al.*, 1997) have found in the gap region between inner and outer belt significantly softer energy spectra of gamma rays than that in the inner zone. The unstable belt of energetic electrons may be formed after electron injection and their consequent radial diffusion during and after the strong magnetic disturbances (Blake *et al.*, 1992; Xinlin *et al.*, 1993). Such electron population can have a relatively large lifetime.

The high fluxes of energetic gamma rays observed in the 3.0 - 8.3 MeV channel in the BMA region are probably related to the high-energy electrons and their bremsstrahlung. By comparison of the extent of regions of high energy proton and electron population, Bogomolov *et al.* (1997) have recently suggested at 400 km the gamma rays at energy above 5 MeV are most probably produced by high energy electrons and not via the proton interactions with residual atmosphere and their secondaries.

Excluding the effects of trapped and quasitrapped high energy particles, the latitudinal distribution of gamma ray intensity in the form of general dependence on geomagnetic cut-off rigidity of primary cosmic rays have been obtained. Figure 4 displays it for the channel 3.0 - 8.3 MeV. For each pixel the L and $Hmin$ for the position of its centre have been calculated. In Figure 4 the data is selected for those pixels, where $Hmin < 200$ km. The vertical cut-off rigidity is computed as $R(GV) = 14.9/L^2$, using the approximation of the formula (5) in

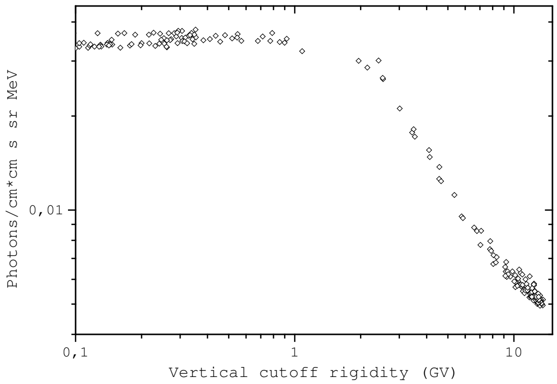

Figure 4. Latitudinal distribution of gamma rays in the energy channel 3.0 - 8.3 MeV.

the paper Shea, Smart and Gentile (1987). For $R > 2$ GV the power spectrum fit of the latitudinal dependence $R^{-\alpha}, \alpha = 0.942 \pm 0.013$. This is consistent with other experiments (Ryumin *et al.*, 1996; Efimov *et al.*, 1985; Forest *et al.*, 1989). The preliminary estimate of the differential flux of gamma rays from 3.0 - 8.3 MeV is 5×10^{-3} and 3.5×10^{-2} photons/cm^2 s sr MeV at the equator and the pole, respectively. The values obtained are comparable to the ones from Imhof *et al.* (1976) and Ryan *et al.* (1977).

5. Summary

The relatively high number of measurements of the SONG instrument on the low altitude, polar orbiting satellite CORONAS-I resulted in the obtaining of the geographic distribution of gamma ray flux at 500 km in two energy intervals, namely 0.12 - 0.32 and 3.0 - 8.3 MeV. At low energies the induced background has been corrected. Two features of the distribution are apparent: a - latitudinal albedo flux caused by cosmic ray primaries and having an approximately 7 to 1 ratio of polar to equatorial flux comparable with other earlier experiments at different altitudes and energies, b - different energy spectra in the regions where energetic electrons being their most probable cause can be trapped, namely the inner zone with hard spectra and a much softer one in the region between the inner and outer zone.

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