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Editors

Massimo Bianchi
Robert T. Jantzen
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The GAMMA-400 space mission for measuring high-energy gamma rays and cosmic rays

on behalf of GAMMA-400 collaboration

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The scientific goals of the GAMMA-400 space mission and the design of the new space-based gamma-ray telescope GAMMA-400 are presented. GAMMA-400 is a dual experiment dedicated to the study of gamma rays and electrons, protons and nuclei. It has aimed to a broad range of scientific topics, such as search for signatures of dark matter, studies of Galactic and extragalactic gamma-ray sources, especially Galactic Center, Galactic and extragalactic diffuse emission, as well as high-precision measurements of cosmic rays spectra. GAMMA-400 will have the best parameters when measuring gamma rays: the angular resolution $\sim$0.01 deg. (at 100 GeV), the energy resolution $\sim$1% (at 100 GeV), and the proton rejection factor $\sim 10^6$ and will be able to measure gamma-ray and cosmic-ray electron + positron fluxes in the energy range from 100 MeV to 20 TeV, as well as protons and nuclei up to the knee (10^{15}-10^{16} eV).

Keywords: Gamma rays; cosmic rays; dark matter.

1. Introduction

The GAMMA-400 gamma-ray telescope is intended to measure the fluxes of gamma-rays and cosmic-ray electrons and positrons in the energy range from 100 MeV to several TeV [1]. Such measurements concern with the following scientific tasks: investigation of point sources of gamma-rays, studies of the energy spectra of Galactic and extragalactic diffuse emission, studies of gamma-ray bursts and gamma-ray emission from the Sun, as well as high precision measurements of spectra of high-energy electrons and positrons, protons and nuclei up to the knee. But the main goal for the GAMMA-400 mission is to perform a sensitive search for signatures of dark matter particles in high-energy gamma-ray emission. To fulfill these measurements the GAMMA-400 gamma-ray telescope possesses unique physical characteristics in comparison with previous and present experiments. The main strength of the GAMMA-400 instrument is its expected excellent angular and energy resolution for gamma rays above 10 GeV. The GAMMA-400 experiment will be installed onboard of the Navigator space platform, manufactured by the NPO Lavochkin Association, able to accommodate high mass - large volume scientific payload. The expected orbit of the payload will mean that observations will not suffer disruption from Earth occultation hence allowing for deep observations of the sources of interest.

Due to the duality of the GAMMA-400 experiment there are two different performances. First one is for high energy gamma-rays and electron/positron measurements and another one for proton and nuclei study. These GAMMA-400 instrument characteristics are addressed in the paper. The comparison with the performance of currently operating space mission Fermi-LAT [2, 3] is also presented.

2. The GAMMA-400 gamma-ray telescope

The GAMMA-400 physical scheme is shown in Figure 1. Starting from the top, the telescope is composed by the following layers:

- an anticoincidence system (AC) is composed by plastic scintillators, located both on top and on the lateral side of the apparatus. The system is essentially used to veto charged particles.
- a converter-tracker system (C) consists of 13 layers of double (x, y) silicon strip coordinate detectors (pitch 0.08 mm). The first three and final two layers have no tungsten while the middle eight layers are interleaved with tungsten conversion foils. The thickness of tungsten absorber is 0.1 X_0. The total converter-tracker thickness is about 1 X_0. Using the first three layers without tungsten allows us to measure gamma rays down to approximately 20 MeV. The system is used to pair convert the photons and to precisely reconstruct the photon direction by the detection in the silicon layers of the e+/e- pair.
- a Time of Flight system (TOF) is formed by plastic scintillators S1 and S2, separated by approximately 500 mm. This system is used both to generate the trigger for the apparatus and to reject albedo particles by measuring their velocity.
- a finely segmented imaging calorimeter CC1. CC1 is composed by 2 layers of CsI(Tl) crystals, each 1 X_0 deep, interleaved with 2 silicon microstrip layers of the same type used for the converter-tracker. The thickness of CC1 is $2X_0$. The imaging calorimeter is used to significantly improve the photon angular resolution by precisely measuring the converted e+/e- pair after a large 50 cm lever arm below the converter-tracker.

- the scintillation detectors S3 and S4 improve hadrons and electromagnetic showers separation.
- a deep, isotropic and homogeneous calorimeter CC2, made by 28×28×12 small cubic CsI(Tl) crystals (with 3.6 cm side), developed on the basis of the CaloCube project R&D [4]. The overall dimensions of the calorimeter are the following: 1m×1m×0.48 m, corresponding to $54.6X_0 \times 54.6X_0 \times 23.4X_0$ or $2.5\lambda_I \times 2.5\ \lambda_I \times 1.1\lambda_I$. Using a deep calorimeter allows us to extend the energy range up to several TeV for gamma rays and to reach an energy resolution of approximately 1% above 100 GeV. The overall mass (∼2000 kg), coupled to the large dimensions, will allow optimal detection of high energy hadrons, up to 10^{15}eV, with an effective geometric factor of the order of 4 m^2×sr, giving the possibility to directly probe on orbit the knee region. This is accomplished by detecting particles not only on the top surface, but also on the lateral side, hence significantly increasing the overall geometrical factor.
- a neutron detector (ND), located below the CC2, is used to improve the proton/electron ratio [5].

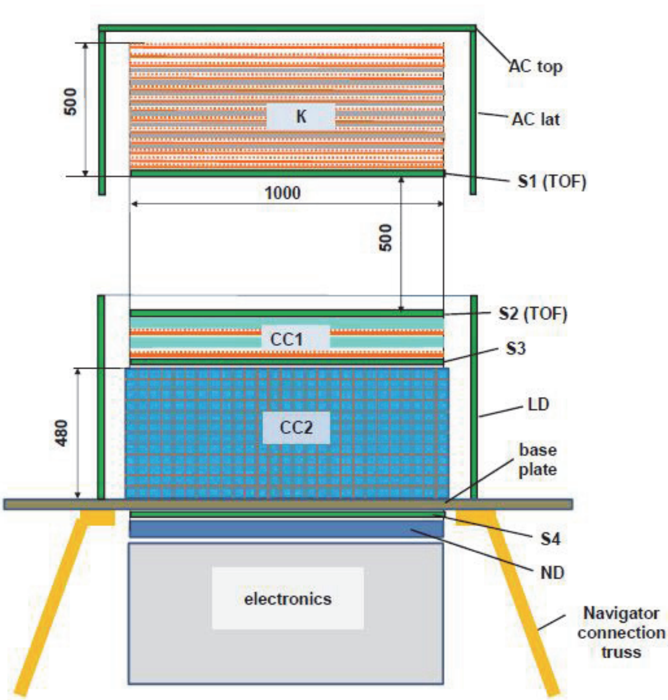

Fig. 1. Schematic drawing of the GAMMA-400 telescope.

3. The GAMMA-400 gamma-ray telescope performance.

To calculate GAMMA-400 instrument performance the following main trigger for gamma registration was used: the signal from energy release in S1 has to be early time than the signal in S2 and the signal in AC system has to be less than the value of threshold selected in such way to suppress the back splash influence. For what concern the instruments performances in the gamma detection, Figures 2 and 3 show respectively the effective area, the angular and the energy resolution of the GAMMA-400 instrument. In Figure 2a the dependence of effective area from initial energy of gamma with vertical incidence and in Figure 2b the dependence of effective area from the incidence angle of the initial 100 GeV gamma are presented. These curves were obtained taking into account the main trigger signal of GAMMA-400: S1 & S2 & (no AC). Time and segmentation methods are used to reduce the influence of backscattering particles created when incident γ-rays interact with the calorimeters matter and move in the opposite direction [6]. The effective area of GAMMA-400 is approximately twice lower than total effective area of Fermi LAT [7]. However, for a full comparison of the performances it is necessary to take into account the optimized choice of the pointing strategy for important sources or for the whole sky survey, considering that the full sky is available to GAMMA-400, due to the peculiar orbit, very far away from any possible earth occultation. Moreover, the high energy part of the photon spectrum can be investigated with the calorimeter CC2 only, with an angular resolution better than two degrees. This way the acceptance can be significantly increased, reaching a level of $\sim$4 m^2.

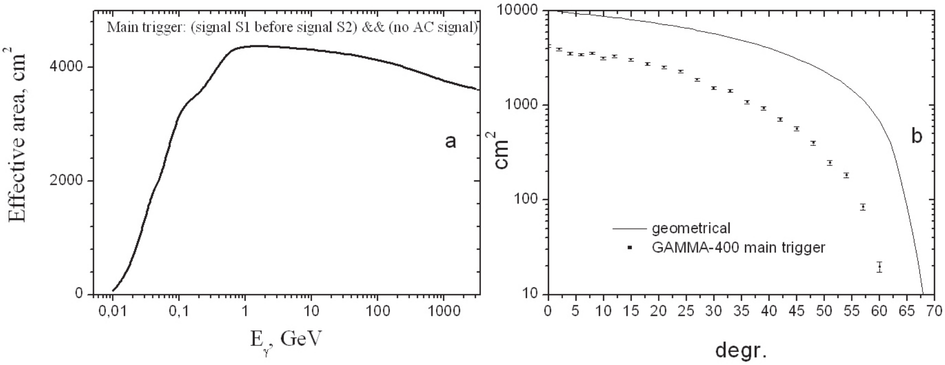

Fig. 2. Effective area of GAMMA-400 in the photon detection. The dependence of effective area from initial energy of gamma with vertical incidence (a). The dependence of effective area from the incidence angle of the initial 100 GeV gamma (b).

The energy dependence of GAMMA-400 angular resolution (68% containment) is presented in fig. 3a. The GAMMA-400 angular resolution is comparable to the

Fermi LAT in the 100 MeV - few GeV range, while is significantly better above few GeV. This is accomplished by a proper combination of the excellent spatial resolution and the long lever arm available in between the converter-tracker and the CC1 calorimeter. The low energy part (less than 500 MeV) of GAMMA-400 angular resolution curve was obtained for gamma events converted in the upper thin layers of converter-tracker system. Taking into account the power-law behavior of gamma spectrum, the reducing of effective area is not so important for such energies.

The performance of the instrument for what concern the energy resolution is demonstrated in Figure 3b. It clearly overpasses the Fermi one above few hundreds MeV, reaching a resolution better than 2% for the multi GeV range. This is possible thanks to the excellent performances of the homogeneous and very deep calorimeter, able to fully contain electromagnetic shower generated by multi-TeV photons.

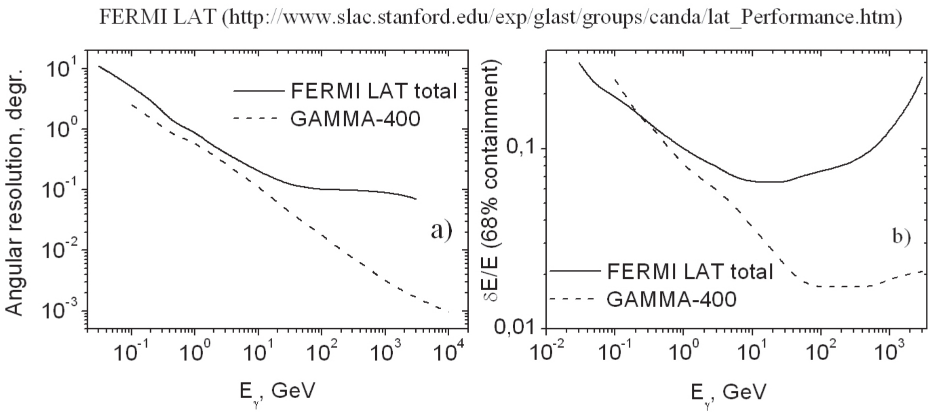

Fig. 3. The angular and energy resolutions of GAMMA-400 in the photon detection. The dependence of angular resolution from initial energy of gamma (a). The dependence of energy resolution from initial energy of gamma (b). The characteristics of FERMI LAT are also presented.

To demonstrate the advantage of of GAMMA-400 instrument against FERMI LAT while exploring high energy gamma, the experimental data obtained during FERMI LAT mission (http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi) in the vicinity of Galactic center for energy range 10-100 GeV and selected for maximum zenith angle less, than 90^0, were used. These data are shown in Fig. 4a for region around Galactic center with Galactic coordinates:-1<l<0.76; 0.285<b<0.3. Totally there are 1228 events. Also Fig.4 contains the map of radio (red color), infra-red (green color) and X-ray (blue color) radiation. In this region there are four point sources identified in third source FERMI LAT catalog (http://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/). For cleanness, around the position of each source the circle line, having radius equal average value of $\mathrm{psf}_{68}=0.13^0$ for FERMI LAT, is drawn. If the position of each source is known then applying maximum likelihood method it is possible to perform the data simulation for average psf_{68} value of GAMMA-400. The results of simulation are presented in Fig.4b. Four sources (yellow, magenta, red and green points) are also identified from the diffuse background (orange points), but in significantly more compact region comparing Fig.4a. Around each source in Fig.4b the circle line, having radius equal average value of psf_{68}=0.06^0 for GAMMA-400, is drawn. This simulation demonstrates the possibility of the GAMMA-400 to look for the small scale structure, which is unreachable by FERMI LAT.

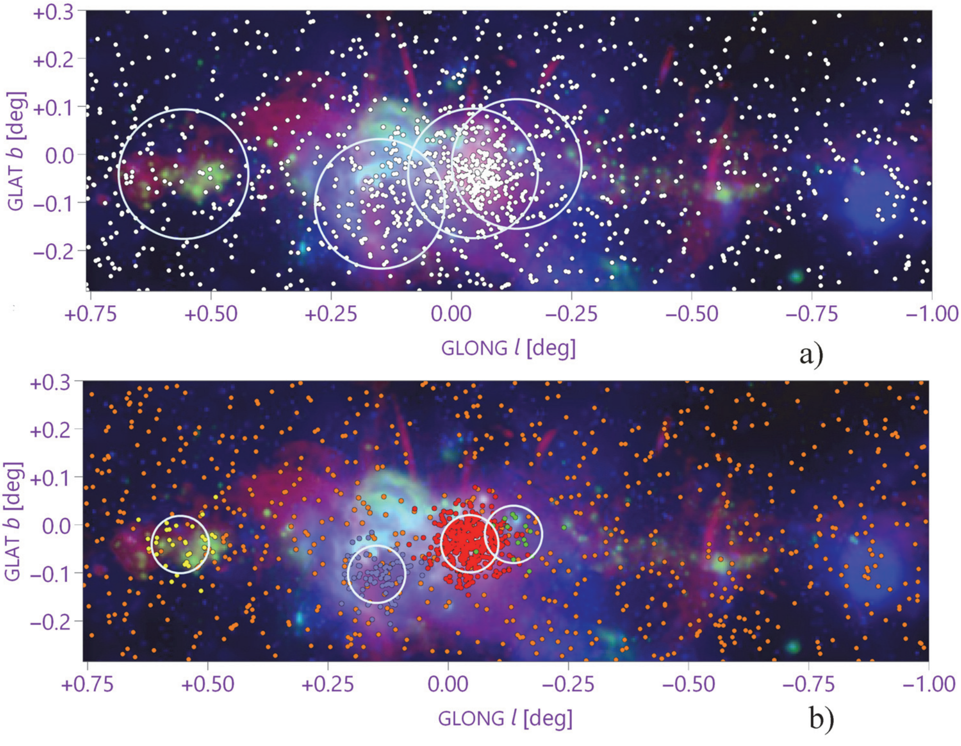

Fig. 4. The experimental data obtained during FERMI LAT mission in the vicinity of Galactic center for energy range 10-100 GeV and selected for maximum zenith angle less, than 90^0(a). The results of simulation obtained by applying maximum likelihood method for average psf68 value of GAMMA-400 (b). Four sources (yellow, magenta, red and green points) are identified from the diffuse background (orange points) in (b), but in significantly more compact region comparing (a).

The GAMMA-400 observatory is also an optimal tool for the very high energy hadron detection. For this item two critical parameters exist in the detection system: the acceptance that should be as large as possible, to have the possibility to measure a significant amount of the 10^{15} eV particles, and the hadronic energy resolution.

The large area homogeneous and isotropic calorimeter, accepting particles from all sides, gives us for the first time the possibility to directly observe in space such high energy hadrons. Table 1 shows the expected number of high energy protons and heliums nuclei for a 10 years exposure of the GAMMA-400 experiment, assuming the Polygonato model [8], with an expected p/e rejection factor better than 10^5 [3], and with a realistic reconstruction efficiency of the order of 40%. We can observe that we expect to collect a statistic larger than 100 events both for protons and helium, allowing a detailed probe of the interesting knee region, that has never been directly investigated with an in orbit detector up to now.

Protons and Helium (Polygonato model)											
Effective GF (m^2 sr)	σ(E)/E	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E>4 PeV	
		p	He	p	He	p	He	p	He	p	He
~4	35%	7.8×10^3	7.4×10^3	4.6×10^2	5.1×10^2	1.2×10^2	1.5×10^2	28	43	5	10

Table 1. Expected number of proton and helium events in 10 years data taking, according to the Polygonato model.

4. Conclusion

The GAMMA-400 instrument has been designed for the optimal detection of gamma rays in a broad energy range (from 100 MeV up to several TeV), with excellent angular and energy resolutions. The observatory will also allow precise and high statistic studies of the electron component in the cosmic rays up to the multi TeV region, as well as protons and nuclei spectra up to the knee region.

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