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To cite this article: N P Topchiev *et al* 2019 *J. Phys.: Conf. Ser.* **1181** 012041

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Space-based GAMMA-400 mission for direct gamma- and cosmic-ray observations

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Abstract. The future space-based GAMMA-400 mission is intended for direct gamma- and cosmic-ray observations in the highly elliptic orbit during 7-10 years. GAMMA-400, currently developing gamma-ray telescope, will observe in the energy range from ~20 MeV to several TeV some regions of the Universe (such as Galactic Center, Fermi Bubbles, Crab, Cygnus, etc.) with the unprecedented angular ($\sim 0.01^\circ$ at $E_\gamma = 100$ GeV) and energy ($\sim 1\%$ at $E_\gamma = 100$ GeV) resolutions better than the Fermi-LAT, as well as ground gamma-ray telescopes, by a factor of 5-10. GAMMA-400 will also study cosmic rays in the energy range of up to ~20 TeV due to deep calorimeter (22 r.l. and 53 r.l. for vertical and lateral events, respectively). GAMMA-400 will permit to resolve gamma rays from dark matter particles, identify many discrete sources (many of which are variable), to clarify the structure of extended sources, to specify the data on the diffuse emission. GAMMA-400 will also specify the sources and the spectra of cosmic-ray electrons + positrons.

1. Introduction

At present, AGILE, Fermi-LAT, CALET, and DAMPE perform observations of discrete gamma-ray sources in space. The third Fermi-LAT catalog (3FGL) contains 3033 sources for the energy range from 100 MeV to 300 GeV, but 33% of gamma-ray sources are unidentified [1]. The ground-based facilities VERITAS, MAGIC, H.E.S.S., HAWC and others observe only 215 gamma-ray sources in the energy range more than 100 GeV (<http://tevcat.uchicago.edu/>). It is important to note that the observational data were mainly obtained for the energy ranges < 100 GeV for Fermi-LAT and > 100 GeV for ground-based facilities and these data overlap poorly for many gamma-ray sources. The frontier range around 100 GeV is still very interesting for investigations.

Another very interesting and important goal when studying gamma-ray sky is indirect searches of dark matter (DM). WIMPs with mass between several GeV and several TeV are still considered as the most probable candidate. WIMPs can annihilate or decay with the production of gamma rays. This emission can have both continuous energy spectrum or monoenergetic narrow lines. Up to now, there are no data on DM gamma-ray lines from space- and ground-based instruments.



Fermi-LAT, PAMELA, AMS-2, CALET, and DAMPE obtained energy spectra for primary cosmic-ray (CR) electrons + positrons, but their fluxes practically do not match in the energy range more than 50 GeV [2].

Therefore new direct observations of gamma-ray emission in the energy range from ~ 20 MeV up to several TeV and electron + positron fluxes and up to 20 TeV are required using the space-based telescope with much better separation from background, angular and energy resolutions in order to identify many gamma-ray sources, resolve DM gamma-ray lines, clarify energy spectra of CR electrons + positrons.

2. The GAMMA-400 gamma-ray telescope

The GAMMA-400 gamma-ray telescope will be installed onboard the Russian space astrophysical observatory [3-5]. The GAMMA-400 main scientific goals are: precise uninterrupted up to hundred days measurements of Galactic Center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga, Sun, and other regions, extended and point gamma-ray sources, diffuse gamma rays, dark matter searching, measuring CR electron + positron fluxes with unprecedented angular ($\sim 0.01^\circ$ at $E_\gamma = 100$ GeV) and energy ($\sim 1\%$ at $E_\gamma = 100$ GeV) resolutions.

2.1. The GAMMA-400 physical scheme

The physical scheme of the GAMMA-400 gamma-ray telescope is shown in figure 1. GAMMA-400 includes:

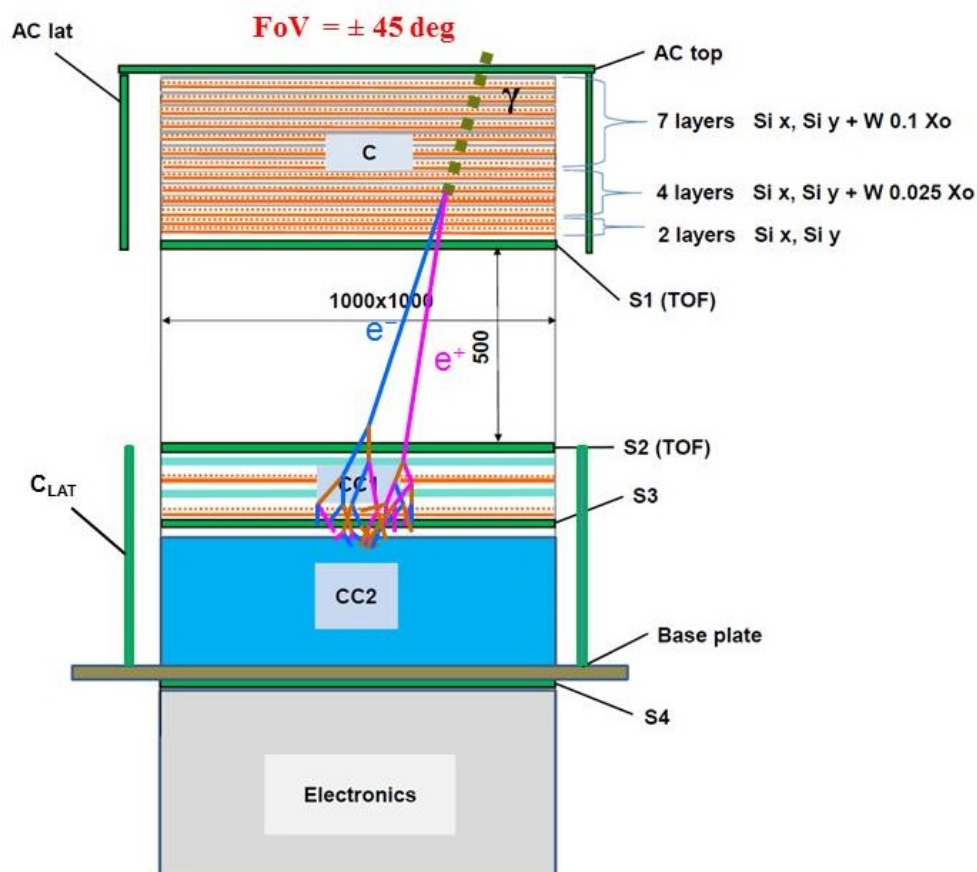


Figure 1. The GAMMA-400 physical scheme.

- plastic scintillation anticoincidence top ACtop (1280×1280 mm) and four lateral ACLat (1280×600 mm) detectors with efficiency of 0.99995 and time resolution of 300 ps;

- converter-tracker (C), consisting of 13 pairs of planes of silicon strip detectors (X and Y coordinates, 1000×1000 mm) with pitch of 0.08 mm and analog readout. First 7 and 4 pairs have W converter foils of $0.1 X_0$ and $0.025 X_0$ thick each, respectively. Last 2 pairs do not have W;

- time of flight system (ToF) from plastic scintillation detectors (S1 and S2, 1000×1000 mm) spaced by 500 mm with coefficient of separation for top/down moving particles of 1000 and time resolution of 300 ps;

- calorimeter (CC1 and CC2). CC1 (1000×1000 mm) consists of two layers of CsI(Tl) scintillation crystals and silicon strip detectors (X and Y coordinates) with pitch of 0.08 mm. CC2 (1000×1000 mm) consists of 28×28 CsI(Tl) crystals. Total thickness of calorimeter is $\sim 22 X_0$ ($\sim 1.0 \lambda_0$) and $\sim 54 X_0$ ($\sim 2.5 \lambda_0$) for vertical and lateral particle detection, respectively;

- plastic scintillation detectors (S3 and S4, 1000×1000 mm) for improving hadron and electromagnetic shower separation;

- four lateral scintillation detectors of calorimeter (Clat) for detecting lateral electrons + positrons.

After interaction of incident gammas with GAMMA-400 matter the backscattering omnidirectional particles (mainly, 1-MeV photons and electrons) are arisen. In order to exclude backscattering particles, all scintillation detectors consist from two independent 10-mm layers of 100-mm strips and fast timing methods are used. Timing methods use the difference in time in AC and S1 ToF to separate incoming and backscattering particles.

The GAMMA-400 energy range for gamma-ray studies is from ~ 20 MeV to several TeV and up to ~ 20 TeV for electrons + positrons. The field of view (FoV) for detecting particles from top is $\pm 45^\circ$. The geometrical factor for detecting electrons + positrons from vertical directions is $\sim 1.3 \text{ m}^2\text{sr}$ and from four lateral directions using Clat is $\sim 2 \text{ m}^2\text{sr}$.

2.2. The GAMMA-400 performance

2.2.1. Calculation results

Model calculations of the GAMMA-400 gamma-ray telescope performance were carried out using the “GEANT4.10.01.p02” software package. Examples of interaction of gammas with the GAMMA-400 matter for $E_\gamma = 0.1, 1, 10$ TeV are shown in figures 2a-2c.

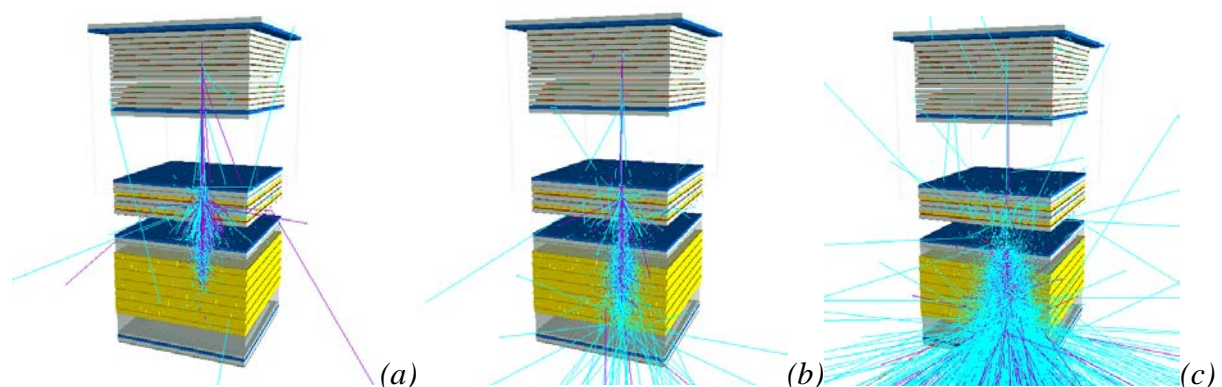


Figure 2. The development of electromagnetic shower in the GAMMA-400 gamma-ray telescope for: (a) $E_\gamma = 0.1$ TeV, (b) $E_\gamma = 1$ TeV, (c) $E_\gamma = 10$ TeV. Electrons and positrons are marked by blue and violet colors, respectively, secondary gammas are not shown for better visualization.

As a result of calculations, we obtained the following dependences:

- the effective area vs the energy (figure 3a). The effective area is $\sim 5000 \text{ cm}^2$ for the energy more than 10 GeV;
- the effective area vs the angle of incidence of particles for $E_\gamma = 1, 10, 100$ GeV (figure 3b);
- the energy resolution vs the energy (figure 3c). The energy resolution for $E_\gamma = 100$ GeV is $\sim 1\%$;

- the angular resolution vs the energy (figure 3d). The angular resolution for $E_\gamma = 100$ GeV is $\sim 0.01^\circ$.

Using the combined information from all GAMMA-400 detector systems, it is possible to reach an effective rejection of protons from electrons. The methods to separate electron from protons presented in [6] are based on the difference of the development of hadronic and electromagnetic showers inside the instrument. For the current physical scheme the rejection factor for vertical protons is about 3×10^5 .

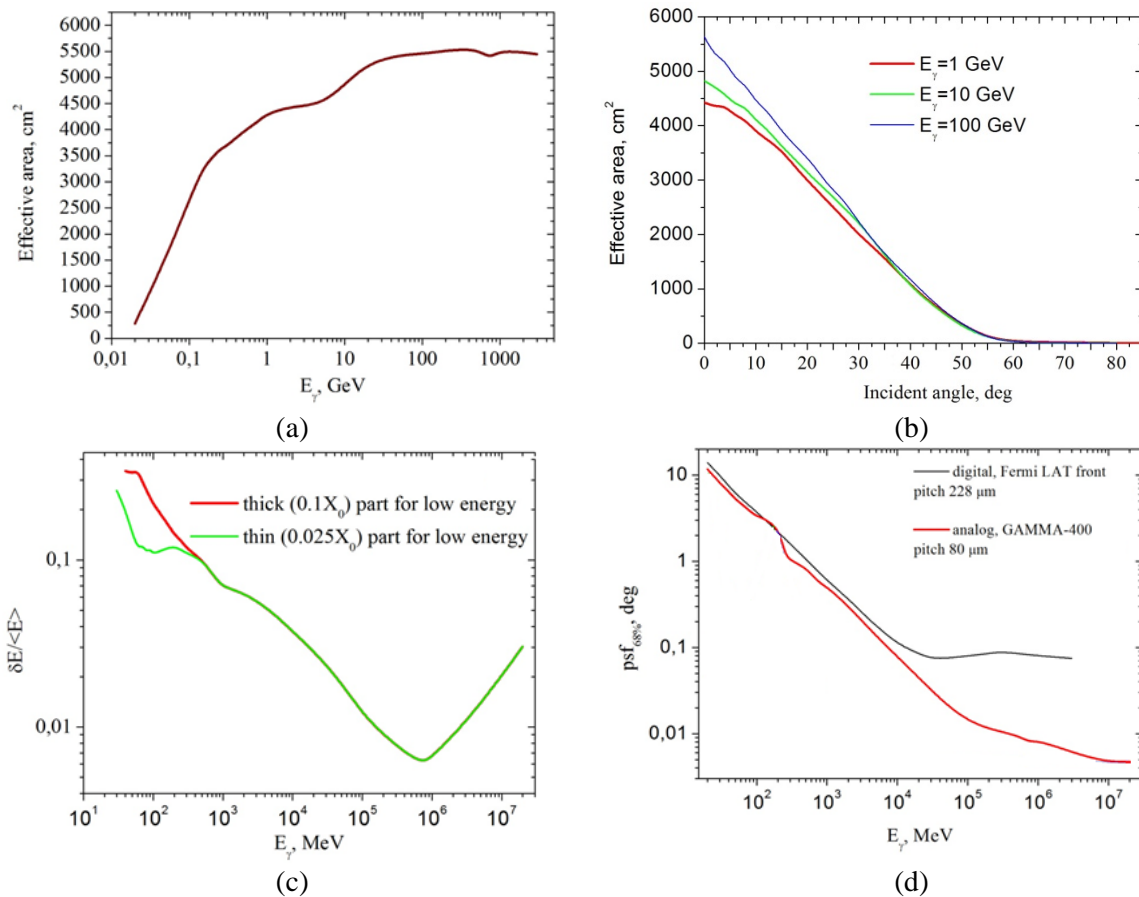


Figure 3. The GAMMA-400 dependences: (a) the effective area vs the energy for vertically incident particles; (b) the effective area vs the angle of incidence of particles for $E_\gamma = 1, 10, 100$ GeV; (c) the energy resolution vs the energy for two parts of converter: 4 panels with W of $0.025 X_0$ and 7 panels with W of $0.1 X_0$; (d) the angular resolution vs the energy for: GAMMA-400 (80- μ m pitch, analog readout) and Fermi-LAT (228- μ m pitch, digital readout).

2.2.2. Calibration results

Some laboratory prototypes of the GAMMA-400 detector systems were calibrated at the synchrotron of Lebedev Physical Institute on positron beam up to the energy of 300 MeV.

The CC2 prototype consisted of 4 scintillator crystals CsI(Tl) with dimensions of $36 \times 36 \times 372$ mm and silicon photomultipliers SensL MicroFC-60035 mounted on the end of each crystal. Positron beam with a diameter of 10 mm was directed to the center of crystal along its axis. The prototype energy resolution of 10% for the positron energy of 300 MeV was obtained. This result coincides with calculations.

Studies of time resolution of the AC prototype were performed. The prototype consists of two strips of scintillator BC-408 with dimensions of $1280 \times 100 \times 10$ mm each viewed by four silicon photomultipliers SensL MicroFC-60035-SMT and front-end electronics. The time resolution for scintillator strips was about 300 ps.

3. The preliminary GAMMA-400 scientific program

3.1. The GAMMA-400 astrophysical observatory

The GAMMA-400 astrophysical observatory will be installed onboard of the Navigator space platform, which is designed and manufactured by the Lavochkin Association.

The GAMMA-400 experiment will be initially launched into a highly elliptical orbit (with an apogee of 300 000 km and a perigee of 500 km, with an inclination of 51.4°), with 7 days orbital period. Under the influence of gravitational disturbances of the Sun, Moon, and the Earth after ~ 6 months the orbit will transform to about an approximately circular one with a radius of ~ 200 000 km and will not suffer from the Earth's occultation and be outside the radiation belts. A great advantage of such an orbit is the fact that the full sky coverage will always be available for gamma-ray astronomy, since the Earth will not cover a significant fraction of the sky, as is usually the case for low-Earth orbit. Therefore, the GAMMA-400 source pointing strategy will hence be properly defined to maximize the physics outcome of the experiment. The launch of the GAMMA-400 space observatory is planned for the middle of the 2020s.

3.2. Observation of the Galactic plane

GAMMA-400 will study continuously over a long period of time different regions of Galactic plane, for example, Galactic center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga with FoV of $\pm 45^\circ$ (figure 4). Using the gamma-ray fluxes from 3FGL, we can expect the number of sources (N_s) with gammas more than 10 and gammas (N_γ) for different energy ranges, when GAMMA-400 will observe several regions during 100 days (table 1).

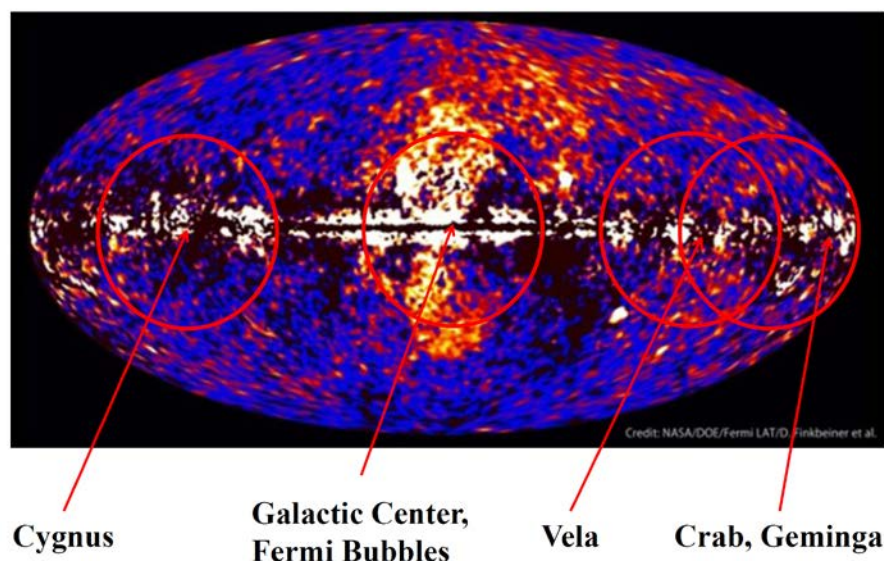


Figure 4. The Fermi-LAT all-sky gamma-ray data (in galactic coordinates), where Galactic center, Fermi Bubbles, Cygnus, Vela, Crab, and Geminga are marked by red circles, corresponding to the GAMMA-400 FoV of $\pm 45^\circ$. These regions will be observed with GAMMA-400.

3.3. Dark matter searching

Main targets to search for gamma rays from dark matter are:

Milky Way. The center of Milky Way is, apparently, the best potential source of dark matter emission possessing the largest J-factor. Moreover, recently, the anomaly excess of gamma-ray emission in the GeV energy range was revealed near the Galactic center (the region of about one degree) [7], which can be well described by dark matter with mass of several tens of GeV and

annihilation cross section of about standard thermal 10^{-26} cm³/s. However, this observed excess can have another interpretation - the presence of population of millisecond pulsars [8]. Therefore, the new GAMMA-400 observational data can help to solve this problem, using the best angular and time resolutions.

Milky Way satellites are considered for a long time as the strongest sources of constraints for dark matter, because they have sufficiently large J-factors and at the same time have considerably less gamma-ray background in comparison with the Galactic center. GAMMA-400 will be able to specify the constrain area.

Other objects. Another potentially interesting objects are other galaxies and their clusters, where dark matter presents and can emit gamma rays. GAMMA-400 with the highest energy resolution of ~1% will have unique sensitivity for detecting dark matter.

Table 1. Expected number of sources (N_s) with gammas more than 10 and gammas (N_γ) for different energy ranges, when GAMMA-400 will observe several regions during 100 days.

Energy range	100 MeV- 100 GeV		1 GeV- 100 GeV		10 GeV- 100 GeV	
	N_s	N_γ	N_s	N_γ	N_s	N_γ
Galactic center b=0°, l=0°	723	5.2x10 ⁵	422	4.8x10 ⁴	21	1365
Crab + Geminga b=0°, l=190°	495	3.1x10 ⁵	175	3.9x10 ⁴	11	1020
Vela b=0°, l=265°	649	5.2x10 ⁵	280	6.3x10 ⁴	9	1165
Cygnus b=0°, l=75°	604	3.2x10 ⁵	269	3.1x10 ⁴	12	1010

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