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High-energy gamma- and cosmic-ray observations with future space-based GAMMA-400 gamma-ray telescope

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Abstract. The future space-based GAMMA-400 gamma-ray telescope will be installed on the Navigator platform of the Russian Astrophysical Observatory. A highly elliptical orbit will provide observations for 7-10 years of many regions of the celestial sphere continuously for a long time (~ 100 days). GAMMA-400 will measure gamma-ray fluxes in the energy range from ~ 20 MeV to several TeV and electron + positron fluxes up to ~ 20 TeV. GAMMA-400 will have an excellent separation of gamma rays from the background of cosmic rays and electrons + positrons from protons and an unprecedented angular (~ 0.01° at E_γ = 100 GeV) and energy (~ 1% at E_γ = 100 GeV) resolutions better than for Fermi-LAT, as well as ground-based facilities, by a factor of 5-10. Observations of GAMMA-400 will provide new fundamental data on discrete sources and spectra of gamma-ray emission and electrons + positrons, as well as the nature of dark matter.

1 Introduction

At present AGILE, Fermi-LAT, CALET, 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 above 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 investigation.

Another very interesting and important goal in the studies of 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 mono-energetic 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, DAMPE obtained energy spectra for primarily cosmic-ray (CR) electrons + positrons, but their fluxes practically do not match in the energy range more than 50 GeV [2].

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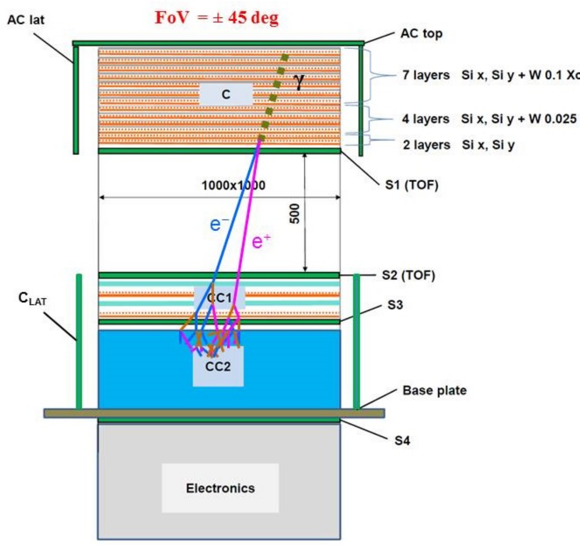

Figure 1. The GAMMA-400 physical scheme

Therefore new direct observations of gamma-ray emission in the energy range from ~ 20 MeV up to several TeV and electron + positron fluxes 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 and 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 electron + positron fluxes with unprecedented angular (~ 0.01° at E_γ = 100 GeV) and energy (~ 1% at E_γ = 100 GeV) resolutions.

2.1 The GAMMA-400 physical scheme

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

GAMMA-400 includes:

- 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 have no W;
- time of flight system (ToF) consisting of 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 ~ 22 X_0 (~ 1.0 λ_0) and ~ 54 X_0 (~ 2.5 λ_0) for vertical and lateral particle detection, respectively;
- plastic scintillation detectors (S3 and S4, 1000×1000 mm) for improving hadronic and electromagnetic shower separation;
- four lateral scintillation detectors of calorimeter (Clat) for detecting lateral particles.

After interaction of incident gamma rays with the GAMMA-400 matter the backscattering omnidirectional particles (mainly 1-MeV photons and electrons) are arisen. Figure 2 shows the simulation result for primary 100-GeV gamma ray. In order to exclude backscattering particles, all scintillation detectors consist of two independent 10-mm layers and fast timing methods are used.

The GAMMA-400 energy range for gamma-ray studies is from ~ 20 MeV to several 1 TeV and up to ~ 20 TeV for electrons + positrons. The field of view (FoV) for detecting particles from top is ±45°. The geometrical factor for detecting electrons + positrons from vertical and four lateral directions is ~3 m^2sr.

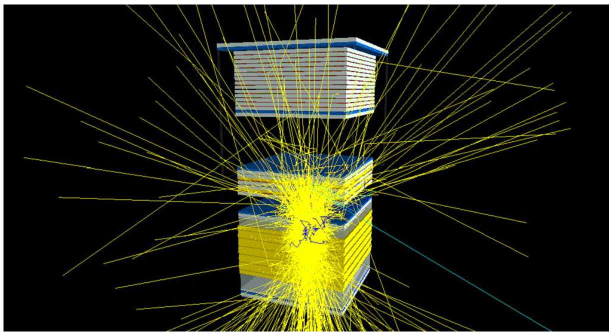

Figure 2. The interaction of the 100-GeV gamma ray with the GAMMA-400 matter with the formation of backscattering particles. Secondary gammas, positrons and electrons are marked by yellow, violet and blue colors respectively

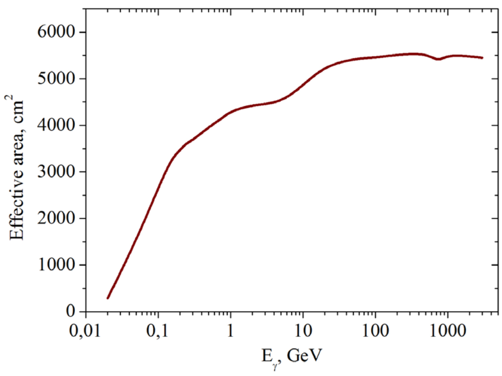

Figure 3. The dependence of the effective area vs the energy for vertically incident particles

2.2 The GAMMA-400 performance

Model calculations of the GAMMA-400 gamma-ray telescope performance were carried out using the "GEANT4.10.01.p02" software package. As a result of calculations, we obtained the following dependences:

- the effective area vs the energy (Fig. 3), which is ~ 5000 cm^2 for energies greater than 10 GeV;
- the effective area vs the angle of incidence of particles for E_γ = 1, 10, 100 GeV (Fig. 4);
- the energy resolution vs the energy (Fig. 5). The energy resolution for E_γ = 100 GeV is ~ 1%;
- the angular resolution vs the energy (Fig. 6). The angular resolution for E_γ = 100 GeV is ~ 0.01°.

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.

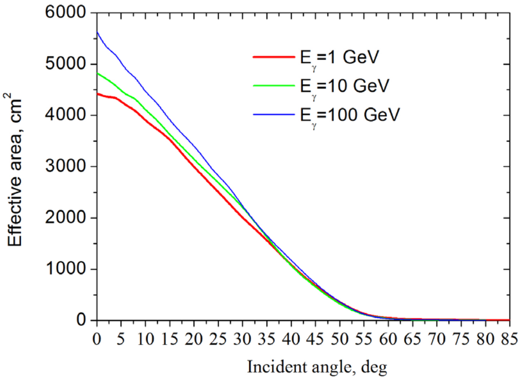

Figure 4. The dependence of the effective area vs the angle of incidence of particles for E_γ = 1 GeV; E_γ = 10 GeV; E_γ = 100 GeV

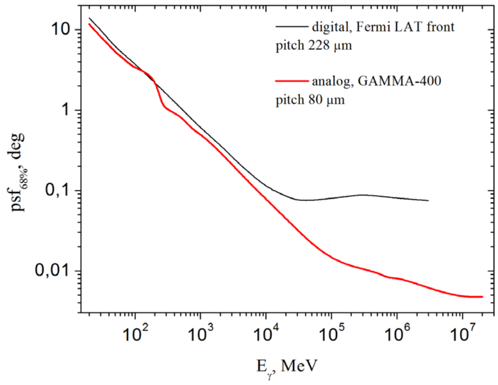

Figure 6. The dependence of the angular resolution vs the energy for: GAMMA-400 (80 μm pitch, analog readout) and Fermi-LAT (228 μm pitch, digital readout)

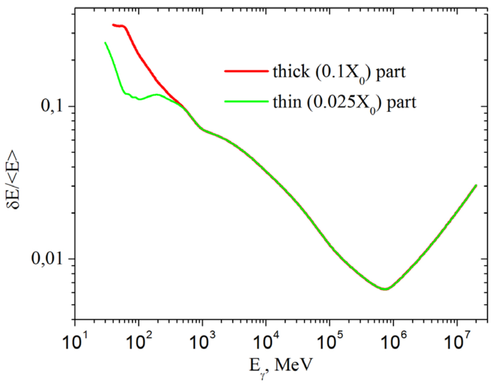

Figure 5. The dependence of the energy resolution vs the energy for two parts of the converter: 4 panels with W=0.025X_0 and 7 panels with W=0.1X_0

2.3 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 and includes a gamma-ray telescope, an X-ray telescope and plasma detectors.

Using the Navigator space platform gives the GAMMA-400 experiment a highly unique opportunity for the near future gamma- and cosmic-ray science, since it allows us to install a scientific payload (mass of ~ 4100 kg, power consumption of 2000 W, and telemetry downlink of 100 GB/day, with lifetime more than 7 years), which will provide GAMMA-400 by the means to significantly contribute as the next generation instrument for gamma-ray astronomy and cosmic-ray physics.

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.

2.4 Comparison of GAMMA-400 with Fermi-LAT and ground-based facilities

The GAMMA-400 gamma-ray telescope has numerous advantages in comparison with the Fermi-LAT:

- highly elliptical orbit (without the Earth's occultation and away from the radiation belts) allows us to continuously observe with an aperture of ±45° different gamma-ray sources over a long period of time with the exposition greater by a factor of 8 than for Fermi-LAT operating in the sky-survey mode;
- thanks to a smaller pitch (by a factor of 3) and analog readout in the coordinate silicon strip detectors, GAMMA-400 has an excellent angular resolution;
- due to the deep (~ 22 X_0) calorimeter, GAMMA-400 has an excellent energy resolution and can provide more reliably the detection of gamma rays up to several TeV for vertically incident events;
- owing to the better gamma-ray separation from cosmic rays (in contrast to Fermi-LAT, the presence of a special trigger with event timing, time-of-flight system, two-layer scintillation detectors), GAMMA-400 is significantly well equipped to separate gamma rays from the background of cosmic rays and backscattering events.

GAMMA-400 will also have better angular and energy resolutions in the energy region 10-1000 GeV in comparison with current and future space- and ground-based

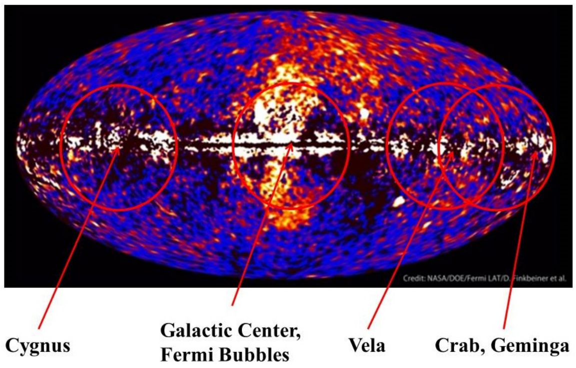

Figure 7. Galactic center, Fermi Bubbles, Crab, Cygnus, Vela, geminga and other regions will be observed with the GAMMA-400 FoV of $\pm 45^0$

Table 1. Expected number of sources, N_s, 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	
Direction	N_s	N_γ	N_s	N_γ	N_s	N_γ
Galactic center $b=0^0$, $l=0^0$	723	5.2×10^5	422	4.8×10^4	21	1365
Crab + Geminga $b=0^0$, $l=190^0$	495	3.1×10^5	175	3.9×10^4	11	1020
Vela $b=0^0$, $l=265^0$	649	5.2×10^5	280	6.3×10^4	9	1165
Cygnus $b=0^0$, $l=75^0$	604	3.2×10^5	269	3.1×10^4	12	1010

instruments: VERITAS, MAGIC, H.E.S.S., CTA, and HAWC and it allows us to fill the data gap at an energy of ~ 100 GeV between the space- and ground-based instruments.

3 The preliminary GAMMA-400 scientific program

3.1 Galactic plane

GAMMA-400 will study continuously over a long period of time different regions of Galatic plane (Fig. 7), for example, Galactic center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga with FoV of ±45°. Using the gamma-ray fluxes from 3FGL, we can expect the number of sources (N_s) and gammas (N_γ) for different energy ranges, when GAMMA-400 will observe several regions during 100 days (Table1).

3.2 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 [7]. 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) [8], 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 cm^3/s. However, this observed excess can have another interpretation - the presence of a population of millisecond pulsars [9]. Therefore, the new GAMMA-400 observational data can help to solve this problem.

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

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