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ELEMENTARY PARTICLES AND FIELDS
Experiment

GAMMA-400 Gamma-Ray Observations in the GeV and TeV Energy Range

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Abstract—The future space-based GAMMA-400 γ-ray telescope will operate onboard the Russian astrophysical observatory in a highly elliptic orbit during 7 years. Observing γ-ray sources from Galactic plane, γ-ray bursts, γ-ray diffuse emission, γ rays from the Sun, and γ rays from dark matter particles will be performed uninterruptedly for a long time ($\sim$100 days) in point-source mode in contrast to scanning mode for Fermi-LAT and other space- and ground-based instruments. GAMMA-400 will measure γ rays in the energy range from $\sim$20 MeV to several TeV units, have the unprecedented angular ($\sim$0.01° at $E_\gamma = 100$ GeV) and energy ($\sim$2% at $E_\gamma = 100$ GeV) resolutions better than for Fermi-LAT, as well as ground-based γ-ray facilities, by a factor of 5–10, and perfectly separate γ rays from cosmic-ray background.

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1. INTRODUCTION

At present Fermi-LAT performs observations of γ-ray emission in space. The fourth Fermi-LAT catalog (4FGL) contains 5065 sources for the energy range from 50 MeV to 1000 GeV, but $\sim$30% of γ-ray sources are unidentified [1]. The ground-based facilities VERITAS, MAGIC, H.E.S.S., HAWC and others observe only 243 γ-ray sources in the energy range above 100 GeV (http://tevcat.uchicago.edu/).

A very interesting and important goal in the studies of γ-ray sky is to search for dark matter (DM). WIMPs with mass between several GeV units and several TeV units are still considered as the most probable candidate. WIMPs can annihilate or decay with the production of γ rays. This emission can have both a continuous energy spectrum or monoenergetic narrow lines. Up to now, there are no data on DM γ-ray lines from space- and ground-based instruments. Other DM candidates are ALPs from nearby supernova explosion.

Another urgent problem is to search for and study γ-ray bursts (GRBs). Despite the discovery of 186 GRBs with Fermi-LAT and GBM [2] it represents an initial step in understanding the processes behind high-energy emission from γ-ray bursts.

2. THE GAMMA-400 GAMMA-RAY TELESCOPE

The GAMMA-400 γ-ray telescope [3–6] and additional instruments (ART-XC X-ray telescope and magnetic plasma detectors) will be installed onboard the Russian space astrophysical observatory (Fig. 1). Gamma- and X-ray telescopes are installed coaxially without overlapping fields of view.

GAMMA-400 includes high data transmission radio complex with high gain antenna. As a ground receiving station, it is proposed to use the radio-astronomy complex based on the RT-22 radio-telescope in Pushchino (Lebedev Physical Institute), the same station as for Radioastron mission (Spectr-R) (Fig. 2).

The GAMMA-400 main scientific goals are: precise uninterrupted up to $\sim$100 days measurements of Galactic Center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga, Sun, and other regions, extended and point γ-ray sources, GRBs, diffuse γ rays, dark matter searching with unprecedented angular ($\sim$0.01° at

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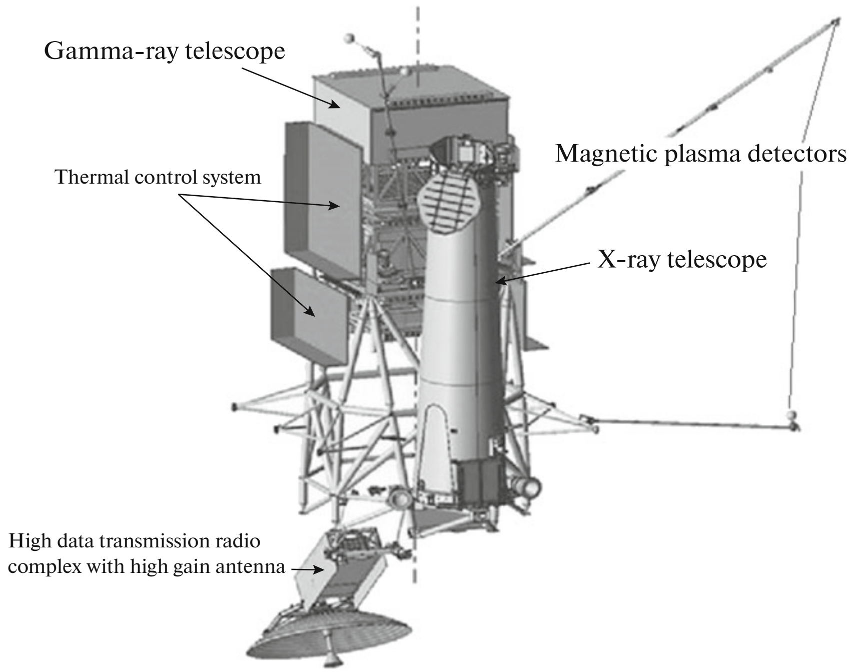

Fig. 1. GAMMA-400 scientific complex including GAMMA-400 γ-ray telescope and additional instruments: ART-XC X-ray telescope, magnetic plasma detectors, high data transmission radio complex with high gain antenna, thermal control system.

$E_\gamma = 100$ GeV) and energy ($\sim$2% at $E_\gamma = 100$ GeV) resolutions.

2.1. The GAMMA-400 Physical Scheme

The physical scheme of the GAMMA-400 γ-ray telescope is shown in Fig. 3.

GAMMA-400 includes:

—plastic scintillation anticoincidence top AC top (1280 $\times$ 1280 mm) and four lateral AC lat (1280 $\times$ 600 mm) detectors with efficiency of 0.99995 and time resolution of 200 ps;

—converter-tracker (C), consisting of 13 pairs of planes of scintillating fiber detectors (X and Y coordinates, 1000 $\times$ 1000 mm) and analog readout. The first 7 and 4 pairs have W converter foils of 0.1 X_0 and 0.025 X_0 thick each, respectively. The last 2 pairs have no W;

—time-of-flight system (ToF) consisting of plastic scintillation detectors (S1 and S2, 1000 $\times$ 1000 mm) spaced by 500 mm with coefficient of separation for top/down moving particles of 1000 and time resolution of 200 ps;

—the calorimeter (CC1 and CC2). CC1 (800 $\times$ 800 mm) consists of CsI(Tl) scintillation crystals and scintillating fiber detectors (X and Y coordinates) without W. CC2 (800 $\times$ 800 mm) consists of 22 $\times$ 22 CsI(Tl) crystals. Total thickness of calorimeter is $\sim$18 X_0 ($\sim$0.9 λ_0) and $\sim$42 X_0 ($\sim$2.0 λ_0) for vertical and lateral particle detection, respectively;

—four lateral scintillation detectors (LD) for detecting lateral particles;

—plastic scintillation detectors (S3 and S4, 800 $\times$ 800 mm) for improving hadronic and electromagnetic shower separation.

After interaction of incident γ rays with the GAMMA-400 detector matter the backscattering omnidirectional particles (mainly, 1-MeV photons) are arisen. 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 γ-ray studies is from $\sim$20 MeV to several TeV. The field of view (FoV) for detecting particles from top-down directions is $\pm 45°$. In GAMMA-400, the common trigger $(\overline{\mathrm{AC}} \times \mathrm{ToF})|(\mathrm{S3} \times \mathrm{ToF})$ is used for detecting low- and high-energy particles.

Moreover, GAMMA-400 can detect γ rays from lateral directions using trigger $\overline{\mathrm{LD}} \times \overline{\mathrm{S_3}} \times \overline{\mathrm{S_4}} \times \mathrm{CC_2}$.

2.2. The GAMMA-400 Performance

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

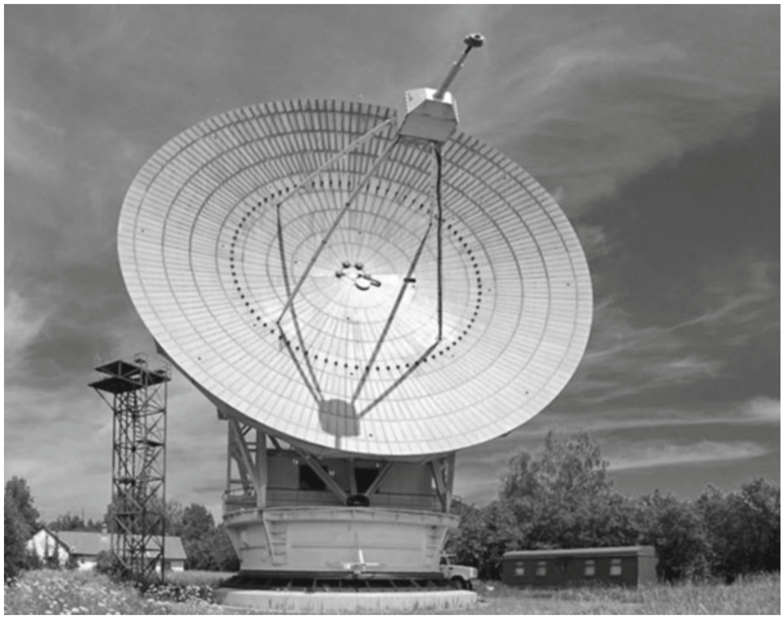

Fig. 2. RT-22 radio-telescope in Pushchino as a ground receiving station.

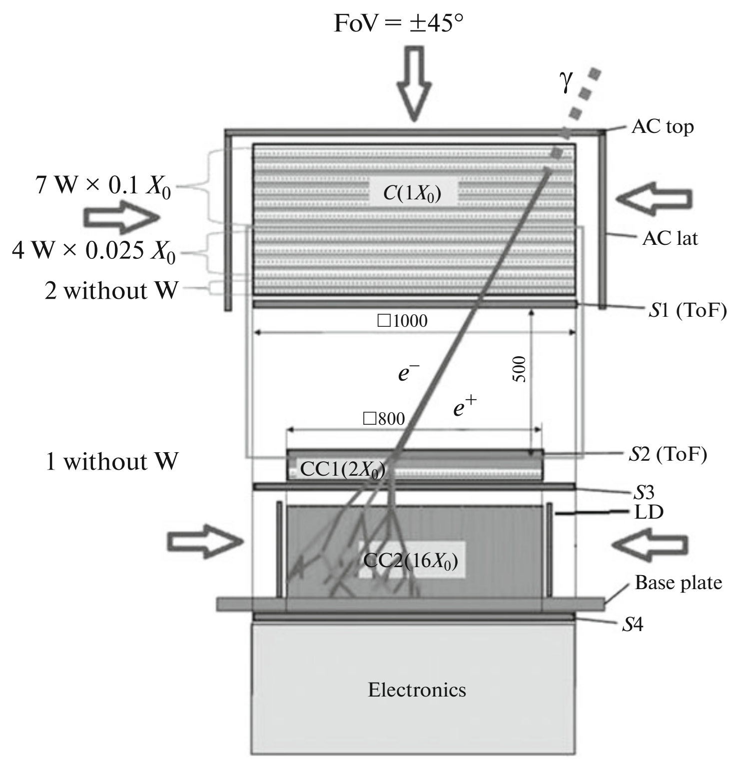

Fig. 3. GAMMA-400 γ-ray telescope physical scheme. GAMMA-400 consists of anticoincidence system AC (top and lateral detectors), converter-tracker C, time-of-flight system ToF from scintillation detectors $S1$ and $S2$, two parts of calorimeter CC1 and CC2, lateral detectors LD, scintillation detectors of the calorimeter $S3$ and $S4$.

—the angular resolution vs the energy (Fig. 4). The angular resolution for $E_\gamma = 100$ GeV is $\sim 0.01°$;

—the energy resolution vs the energy (Fig. 5). The energy resolution for $E_\gamma = 100$ GeV is $\sim 2\%$.

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 electrons from protons presented in [7] are based on the difference of the

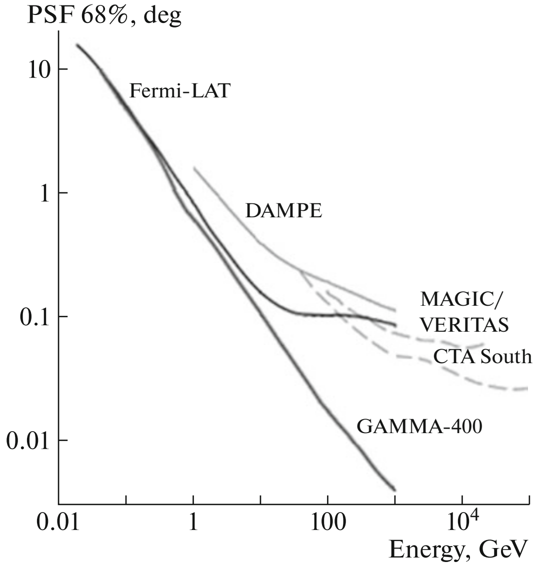

Fig. 4. The angular resolution vs the energy for GAMMA-400, Fermi-LAT, DAMPE, MAGIC, VERITAS, CTA.

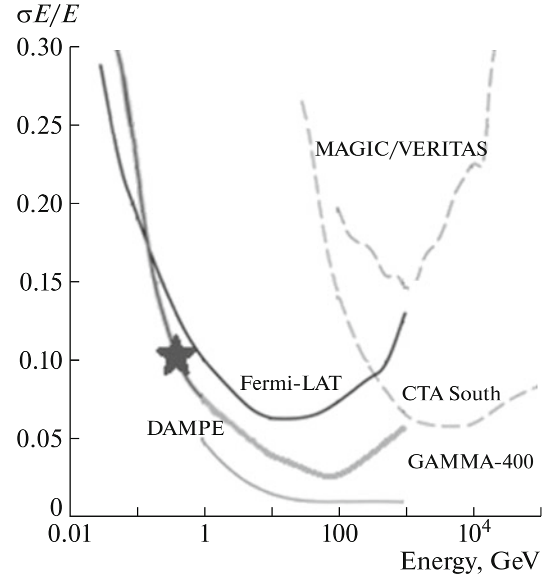

Fig. 5. The energy resolution vs the energy for GAMMA-400, Fermi-LAT, DAMPE, MAGIC, VERITAS, CTA. GAMMA-400 experimental energy resolution of 10% for the energy of 300 MeV obtained at LPI electron synchrotron in Troitsk is marked with an asterisk.

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.

For testing and calibrating, prototypes from some detector systems were manufactured and calibrated on positron beams at the S-25R electron synchrotron (Lebedev Physical Institute, Troitsk) in the energy range of 100–300 MeV.

2.3. The GAMMA-400 Astrophysical Observatory

The GAMMA-400 scientific payload will be installed onboard of the Navigator space platform, which is designed and manufactured by the Lavochkin Association and includes the γ-ray telescope, an X-ray telescope, and magnetic plasma detectors.

Using the Navigator space platform gives the GAMMA-400 experiment a highly unique opportunity for the near future γ- and cosmic-ray science, since it allows us to install the scientific payload (mass of ∼3000 kg, power consumption of 2000 W, and telemetry downlink of 100 GB/day, with lifetime more than 7 years), which will provide the significant contribution of GAMMA-400 as the next generation instrument for γ-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 γ-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 be properly defined to maximize the physics outcome of the experiment. The launch of the GAMMA-400 space observatory is planned for 2030.

2.4. Comparison of GAMMA-400 with Fermi-LAT and Ground-Based Facilities

The GAMMA-400 γ-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 observe with the aperture of ±45° different γ-ray sources continuously 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 using scintillating fibers and analog readout in the coordinate detectors, as well as time-of-flight system, GAMMA-400 has an excellent angular resolution;

- due to the deep ($\sim$18 X) calorimeter, GAMMA-400 has an excellent energy resolution and can provide more reliably the detection of γ rays up to several TeV for vertically incident events;
- owing to the better γ-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 γ rays from the background of cosmic rays and backscattering events.

GAMMA-400 will have also the better angular and energy resolutions in the energy region 10–1000 GeV in comparison with current and future space- and ground-based instruments: VERITAS, MAGIC, H.E.S.S., CTA, and HAWC and it allows us to fill the data gap at the energy of $\sim$100 GeV between the space- and ground-based instruments.

It is necessary to note that at present various γ-ray telescopes are developed to study γ-ray emission in the medium energy (e-ASTROGAM [8] and AMEGO [9]) and high energy (HERD [10] and AMS-100 [11]) range. Performance of these telescopes in comparison with GAMMA-400 and Fermi-LAT is presented in Table 1.

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, Galactic center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga with FoV of $\pm 45°$.

3.2. Dark Matter Searching

Generally there are two wide classes of DM candidates, which are potentially accessible by GAMMA-400—WIMPs and ALPs. Below we briefly describe the main targets for searches of both candidates.

Galactic Center region historically represents the most favorable target for WIMP annihilation (decay) searches due to the biggest $J(D)$-factor. In this context a mysterious γ-ray excess identified a while ago (e.g. [12]) around the GC attracts a great interest. It peaks at few GeV, extends up to $\approx 10°$ around the GC and can be well-fitted by annihilating WIMPs with the mass of several tens of GeV and cross section around the thermal value $\sim 10^{-26}$ cm^3/s. However alternative explanations of the excess origin indeed exist. They include the emission from millisecond pulsars (both prompt and secondary), molecular clouds and others. The future high-resolution data from GAMMA-400 will be very important for the ultimate determination of the excess origin.

Another interesting aspect is the searches for hypothetical narrow spectral lines due to DM annihilation or decay directly into photons. This represents very pristine DM signature, since no other astrophysical processes are expected to produce such lines at the energies above $\sim$0.1 GeV. We provided some estimates of GAMMA-400 sensitivity to the diphoton annihilation cross section in [6]. However our most recent simulations showed that the sensitivity presented in [6] tends towards slightly optimistic side—realistically we would expect our sensitivity to be comparable with that of Fermi-LAT after 12–15 years of its operation. At the same time DAMPE has comparable sensitivity too [13]. Hence, it can be possible in the future to stack together the data from all three telescopes and significantly extend the sensitivity to narrow lines by such joint data analysis.

ALP discovery potential by catching a nearby supernova explosion. Fermi-LAT has not been able to observe any supernova explosion in the Local Group due to rarity of such events. However such observation would be extremely valuable for constraining ALP properties. Thus in case of such luck GAMMA-400 will be able to probe ALP-photon coupling constant values down to $g_{a\gamma} \sim 10^{-13}$ GeV^{-1} for ALP masses below $\sim$1 neV! The chance to catch such event over the mission lifetime is about 10%. But the very high sensitivity of this probe still makes it one of the main GAMMA-400 objectives in the area of DM searches. The detailed calculations on this subject can be seen in [6].

ALP signature searches in the pulsar spectra. Recently the tentative ALP signature in the spectra of pulsars was identified in Fermi-LAT data [14]. However this detection is not reliable yet, and the future additional GAMMA-400 observational data on those pulsars will be able potentially to confirm or deny robustly this preliminary signal.

Other targets include globular clusters, nearby galaxies, dwarf satellites, hypothesized axion clouds around neutron stars, etc.

3.3. Searching for GRBs

Using detection of GRBs from top-down and lateral directions GAMMA-400 will discover many new GRBs ($\sim$10 GRBs per year).

Table 1

	Space-based γ-ray telescopes						Ground-based facility
	medium energy			high-energy			
	e-ASTROGAM	AMEGO	Fermi-LAT	GAMMA-400	HERD	AMS-100	CTA
Country	Europe	USA	USA	Russia	China	Europe + USA	
Energy range	0.3 MeV–3 GeV	0.2 MeV–10 GeV	50 MeV–1 TeV	20 MeV–1 TeV	0.5 GeV–10 TeV	1 GeV–10 TeV	>50 GeV
Observation mode	Scanning	Scanning	Scanning	Point-source	Scanning	Scanning	Scanning
Orbit	Circular, ∼550 km	Circular, ∼550 km	Circular, ∼550 km	Highly elliptical, 500–300 000 km	Circular, ∼400 km	*L2*	
Angular resolution	0.1°	1°	0.1°	∼0.01°	0.1°	∼0.01°	0.1°
Energy resolution	20%	10%	10%	∼2%	1–2%	1–2%	15%

4. CONCLUSIONS

After Fermi-LAT the GAMMA-400 mission will greatly improve the direct data of low-energy and high-energy γ rays due to unprecedented angular and energy resolutions, large area, and continuous long-term simultaneous coaxial gamma-ray and X-ray telescope observations. GAMMA-400 space observatory is scheduled to launch for ∼2030.

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