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The Future Space-Based GAMMA-400 Gamma-Ray Telescope for Studying Gamma and Cosmic Rays

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Abstract—The future space-based γ-ray telescope GAMMA-400 will be installed on the Navigator platform of the Russian astrophysical observatory. A highly elliptical orbit will allow prolonged (~100 days) continuous observations of many regions of the celestial sphere for 7–10 years. GAMMA-400 will measure fluxes of γ-ray emission in the energy range of ~20 MeV to several TeV and electrons + positrons to ~20 TeV. The γ-ray telescope will have excellent separation of γ-ray emissions against the background of cosmic rays and electrons + positrons from protons, along with unprecedented angular (~0.01° at E_γ = 100 GeV) and energy (~1% at E_γ = 100 GeV) resolutions 5–10 times better than for the Fermi-LAT and ground-based γ-ray telescopes. GAMMA-400 observations will provide fundamentally new data on discrete sources and spectra of γ-ray emissions and electrons + positrons.

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INTRODUCTION

Work on the GAMMA-400 γ-ray telescope continues in accordance with Russian Federal Space Program for 2009–2015 and 2016–2025 [1–3]. The GAMMA-400 γ-ray telescope is designed to study high-energy cosmic γ-ray emissions and the electron–positron (below, electron) component of cosmic rays (CRs) in the high-energy range. The resulting data will contribute to determining the nature of the dark matter in the Universe and developing the theory of the origin of high-energy CRs.

Studies of high-energy cosmic γ-ray emissions are now under way both in space (AGILE, Fermi-LAT, CALET, DAMPE), and on the Earth's surface (H.E.S.S., MAGIC, VERITAS, HAWC). The Fermi-LAT telescope has recorded γ-ray emissions with energies of 0.1–100 GeV from ~3000 discrete sources, around one-third of which were not associated with astrophysical objects [4]. Ground-based γ-ray telescopes have recorded γ-ray emissions with energies of more than 100 GeV from only ~200 sources (http://tevcat.uchicago.edu/). Note that the energy spectra of γ-ray emissions in the energy region of around 100 GeV from many sources, recorded both by the Fermi-LAT telescope and ground-based facilities, practically do not overlap. The energy spectra of the fluxes of primary CR electrons obtained with Fermi-LAT, PAMELA, AMS-2, CALET, and DAMPE in the energy range of more than 50 GeV do not coincide [5]. We must therefore develop a new generation space-based telescopes with much better angular and energy resolution for directly recording γ-ray emissions of high and ultrahigh energies and the CR electron component, in order to search for and identify sources, and determine the spectra of γ-ray emissions and the electron component of CRs. The GAMMA-400 telescope, which will be installed at the Russian astrophysical observatory, will be such a unique instrument. GAMMA-400 is a successor to the Fermi-LAT generation of space-based γ-ray telescopes.

THE GAMMA-400 GAMMA-RAY TELESCOPE

Figure 1 shows the physical layout of the GAMMA-400 telescope, which includes

—an upper (AC_{top}) (1280 × 1280 × 20 mm) and four lateral (AC_{lat}) (1280 × 600 × 20 mm) double-layer anticoincidence scintillation detectors that ensure efficient (0.99995) detection of charged particles and a time resolution of 300 ps;

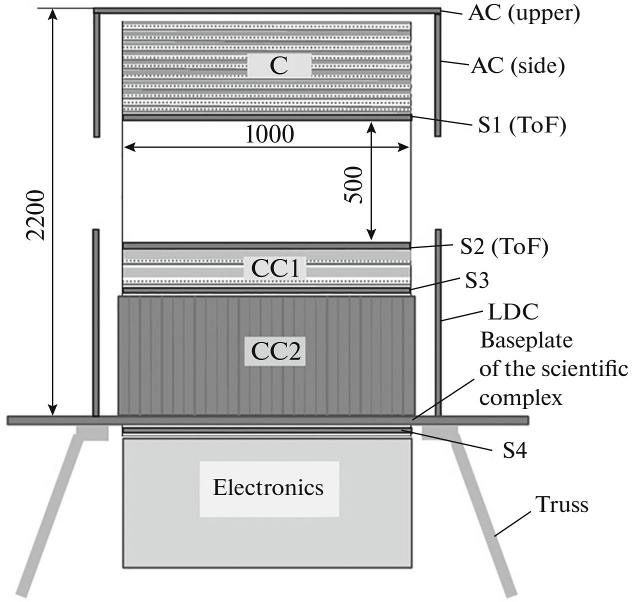

Fig. 1. Physical layout of the GAMMA-400 γ-ray telescope: AC_{top}, upper anticoincidence detector; AC_{lat}, lateral anticoincidence detector; C, converter/tracker; S1 (ToF) and S2 (ToF), scintillation detectors of the time-of-flight system; CC1 and CC2, coordinate-sensitive calorimeter; S3 and S4, scintillation detectors; LDC, lateral detectors of the calorimeter.

—a converter/tracker (C) consisting of 13 pairs of planes of silicon strip detectors (*X*- and *Y*-coordinates) with a strip pitch of 0.08 mm (it is 0.24 mm for Fermi-LAT) and an analog readout that doubles the accuracy of determining the location of a particle's passage, compared to the binary readout used in Fermi-LAT. Tungsten converters are located on the 11 upper panels: 7 panels 0.1 r.l. thick and 4 panels 0.025 r.l. thick (where r.l. is the unit of radiation length). The total thickness of the converter/tracker for the vertical incidence of particles is ~1 r.l.;

—a time-of-flight system (ToF) of two-layer plastic scintillation detectors S1 (1000 × 1000 × 20 mm) and S2 (1000 × 1000 × 20 mm). Detectors S1 and S2 are separated by a distance of ~500 mm; the ToF provides a separation of at least 1000 for events from above and below and has a time resolution of more than 300 ps;

—a coordinate-sensitive calorimeter (CC) with the area of 1000 × 1000 mm^2. The CC consists of two parts: CC1 and CC2. (a) CC1 consists of 2 layers. Each layer is a set of scintillation crystals CsI(Tl) and two-layer (with mutually perpendicular strips) silicon strip detectors with a pitch of 0.08 mm. CC1 is 2 r.l. thick; (b) CC2 consists of 28 × 28 CsI(Tl) crystals. Each crystal with dimensions of 36 × 36 × 370 mm is inside a carbon fiber grating 0.4 mm thick. CC2 is ~20 r.l. thick. (c) The total thickness of the calorimeter for normal incidence of particles is ~22 r.l. (8.6 r.l. for Fermi-LAT) or 1.0 i.l. (where i.l. is the length of nuclear interaction). The total thickness of the calorimeter for detecting particles from lateral directions is 54 r.l. or 2.5 i.l.

—two-layer plastic scintillation detectors C3 and C4 of the calorimeter with dimensions of 1000 × 1000 × 20 mm;

—two-layer plastic lateral detectors of the calorimeter (LDC).

Segmentation and time approaches are used to eliminate backscattering particles (mainly photons with ~1 MeV) generated by interaction with the calorimeter matter and directed in all directions (including upward, which blocks the AC detector).

GAMMA-400 is able to investigate γ-ray fluxes in the energy range of ~20 MeV to several TeV and fluxes of the CR electron component in the range of several GeV to ~20 TeV from both top–down (the GAMMA-400 field of view is ±45°), and four lateral directions with a total geometrical factor of more than 3 m^2 sr. The γ-ray telescope uses a single trigger, $\overline{AC} \times S1 \times S2$, to record γ-ray emissions of both high and low energies. Figure 2 shows the dependences of the effective area; the GAMMA-400 angular and energy resolutions, depending on the γ-ray energy; and the dependence of the effective area on the angle of incidence of particles. GAMMA-400 will have unprecedented angular (~0.01° at E_γ = 100 GeV) and energy (~1% at E_γ = 100 GeV) resolutions 5–10 times better than those of Fermi-LAT and ground-based telescopes. The proton rejection factor is ~5 × 10^5. When calibrating the calorimeter prototype at the S-25R synchrotron of the Lebedev Physical Institute on a positron beam with an energy of 300 MeV, an energy resolution of 10% was obtained, which corresponds to the results from calculations.

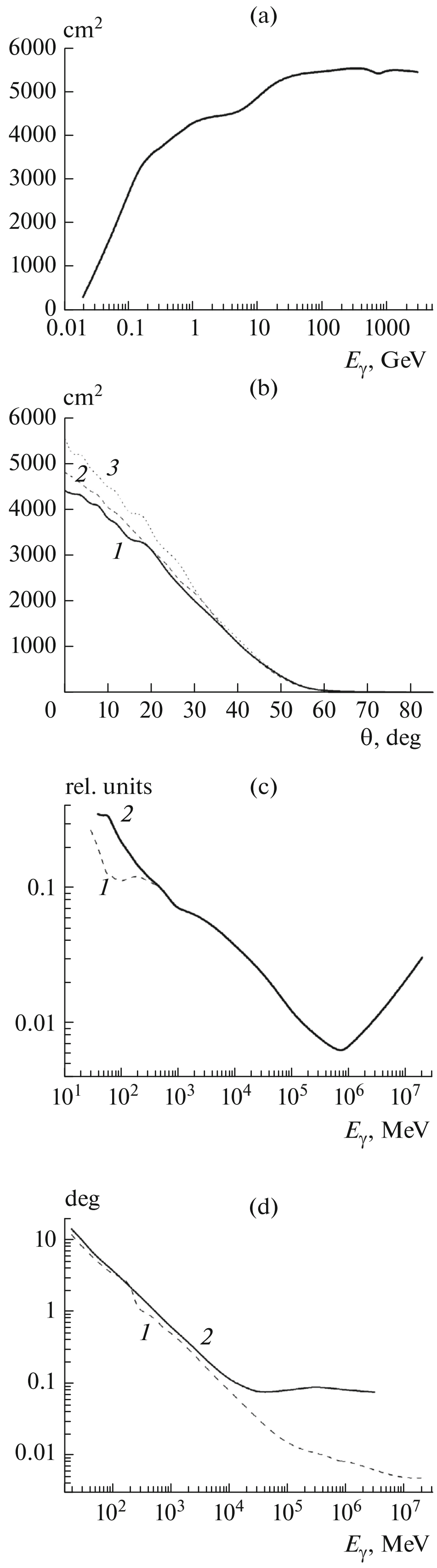

Fig. 2. GAMMA-400 γ-ray telescope performance: (a) Dependence of the effective area on the energy for vertically incident particles; (b) dependence of effective area on the angle of incidence of particles for (*1*) $E_\gamma = 1$ GeV; (*2*) $E_\gamma = 10$ GeV; and (*3*) $E_\gamma = 100$ GeV. (*c*) Dependence of energy resolution on energy for parts of the converter: (*1*) from 4 tungsten panels 0.025 r.l. thick; (*2*) from 7 tungsten panels 0.1 r.l. thick; (*d*) dependence of angular resolution on energy for (*1*) GAMMA-400 (pitch, 80 μm; analog readout); (*2*) Fermi-LAT (pitch, 228 μm; digital readout).

The main mode of GAMMA-400 operation is precision measurements of individual regions of the celestial sphere (e.g., the Galactic center) with continuous observations of up to 100 days in a highly elliptical orbit outside the radiation belts and without shading the γ-ray telescope's field of view of the Earth.

CONCLUSIONS

Compared to the Fermi-LAT telescope, the GAMMA-400 γ-ray telescope will provide several times better angular and energy resolution in the energy range of ~20 MeV to ~1000 GeV and at energies above 10 GeV. The angular resolution for $E_\gamma = 100$ GeV is ~0.01°, and the energy resolution is ~1%. The possibility of continuous long-term observation of individual regions of the celestial sphere (e.g., the Galactic center) will allow us to make considerable progress in performing precision studies of discrete γ-ray sources, measuring the energy spectra of Galactic and extragalactic diffuse γ-ray emission, resolving fluxes of γ-ray emissions, and determining the CR electron–positron component, which could be associated with the annihilation or decay of dark matter particles.

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