ISSN 1063-7729, Astronomy Reports, 2018, Vol. 62, No. 12, pp. 882–889. © Pleiades Publishing, Ltd., 2018.

GAMMA-400 Project*♯

A. M. Galper[1,2**], **N. P. Topchiev**[1***], and **Yu. T. Yurkin**[2]

[1] *Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia*

[2] *National Research Nuclear University "MEPhI," Moscow, Russia*

Received August 1, 2018; in final form, August 25, 2018

Abstract—Extraterrestrial gamma-ray astronomy is now a source of a new knowledge in the fields of astrophysics, cosmic-ray physics, and the nature of dark matter. The next absolutely necessary step in the development of extraterrestrial high-energy gamma-ray astronomy is the improvement of the physical and technical characteristics of gamma-ray telescopes, especially their angular and energy resolutions. Such a new generation telescope will be GAMMA-400, currently under development. Together with an X-ray telescope, it will perform precise and detailed observations in the energy range of ~20 MeV to ~10 000 GeV and 3–30 keV the Galactic plane, especially, toward the Galactic Center, Fermi Bubbles, Crab, Cygnus, etc. The GAMMA-400 will operate in the highly elliptic orbit continuously for a long time with the unprecedented angular (~0.01° at $E_\gamma = 100$ GeV) and energy (~1% at $E_\gamma = 100$ GeV) resolutions, exceeding the Fermi-LAT as well as ground-based gamma-ray telescopes by a factor of 5–10. GAMMA-400 will permit resolving gamma rays from annihilation or decay of dark matter particles, identifying many discrete sources (many of which are variable), clarifying the structure of extended sources, specifying the data on the diffuse emission, as well as measuring electron + positron fluxes and specifying electron + positron spectrum in the energy range from 1 GeV to 10 000 GeV.

DOI: `10.1134/S1063772918120223`

1. CURRENT GAMMA-RAY STUDY CHALLENGES

1.1. Analysis of Gamma-Ray Results According to the Fermi-LAT and Ground-Based Facility Data

Gamma-ray astronomy studies the range of the electromagnetic spectrum from ~0.1 MeV. The main processes of the high-energy gamma-ray emission generation are interaction of cosmic-ray protons with interstellar matter, inverse Compton scattering, bremsstrahlung, synchrotron radiation, etc.

Since 1967, space-bourne gamma-ray telescopes began investigating gamma-ray emission: OSO-3 (1967, [1]), Cosmos-208 (1968, [2]), ANNA-3 (Cosmos-251, 1968 [3]), SAS-2 (1972–1973, [4]), COS-B (1975–1982, [5]), GAMMA-1 (1990–1992, [6]), EGRET (1991–1998, [7]), AGILE (2007 to present, [8]), Fermi-LAT (2008 to present, [9]), CALET (2015 to present, [10]), DAMPE (2015 to present, [11]). The largest volume of data was obtained with the Fermi-LAT instrument.

Since 2008 Fermi-LAT operates in the circular near-Earth orbit in the scanning mode and surveying full sky every three hours. Up to now, three catalogs of gamma-ray sources have been published based on the Fermi-LAT observational results: 1FGL [12] and 2FGL [13] for the energy range from 100 MeV to 100 GeV, 3FGL [14] for the energy range from 100 MeV to 300 GeV. Moreover, three catalogs of high-energy gamma-ray sources were published: 1FHL for the energy above 10 GeV [15], 2FHL for the energy range of 50 GeV–2 TeV [16], and 3FHL for the energy range of 10 GeV–2 TeV [17].

Figure 1 [18] shows the percentage of the different types of 3030 gamma-ray sources according to the 3FGL. However, 33% of gamma-ray sources are unidentified and there are no data in the energy range of 20–100 MeV. From [14], it is seen that during four years of the Fermi-LAT operation the real exposure time of the source observations is only ~12% or $\frac{1}{8}$ of the total operation time.

Based on results of gamma-ray observations at energies above 100 GeV by ground-based facilities VERITAS [19], MAGIC [20], H.E.S.S. [21], and others, the TeVCat catalog (http://tevcat.uchicago.edu/)

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[*] The article is published in the original.

[**] E-mail: `AMGalper@mephi.ru`

[***] E-mail: `tnp51@yandex.ru`

[♯] Paper presented at the Third Zeldovich meeting, an international conference in honor of Ya.B. Zeldovich held in Minsk, Belarus on April 23–27, 2018. Published by the recommendation of the special editors: S.Ya. Kilin, R. Ruffini, and G.V. Vereshchagin.

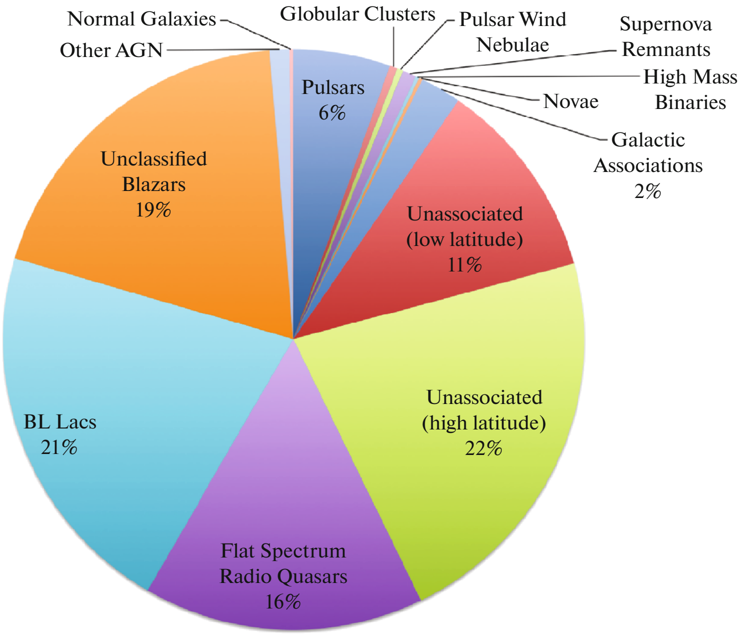

Fig. 1. The percentage of the different types of gamma-ray sources [7] according to the 3FGL.

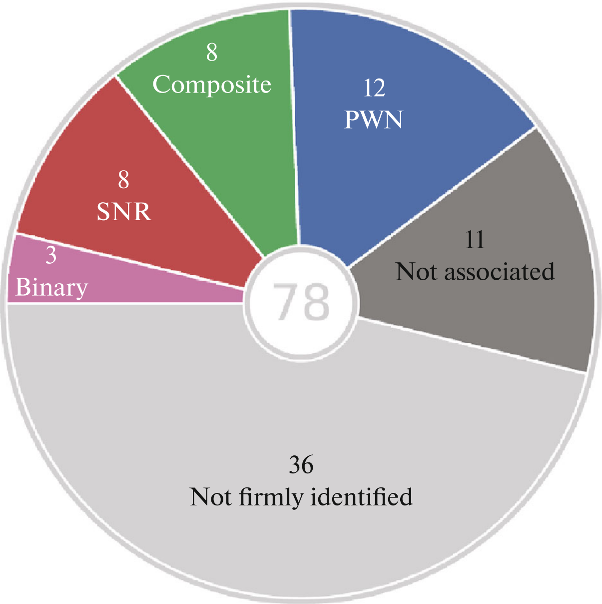

Fig. 2. Composition of Galactic discrete gamma-ray sources recorded by H.E.S.S. [22].

of discrete gamma-ray sources was created, which contains only ~210 sources. Figure 2 shows the composition of Galactic discrete gamma-ray sources recorded by H.E.S.S. [22]. It is seen that 47 from 78 sources are not associated and firmly identified.

It is important to note that the observational data from Fermi-LAT and ground-based facilities were obtained for the energy ranges, which overlap poorly for many gamma-ray sources and sometimes do not overlap at all. Hence, the frontier range around 100 GeV is still very interesting for investigations. In addition, the angular resolution of Fermi-LAT, existing ground-based telescopes, and even planned CTA [23] in the region of around 10–300 GeV is only ~0.1°. A much better angular resolution is required in order to identify many gamma-ray sources.

1.2. Indirect Searches of Dark Matter

Dark matter (DM) is 23% of the Universe mass composition (Fig. 3). Another very interesting and

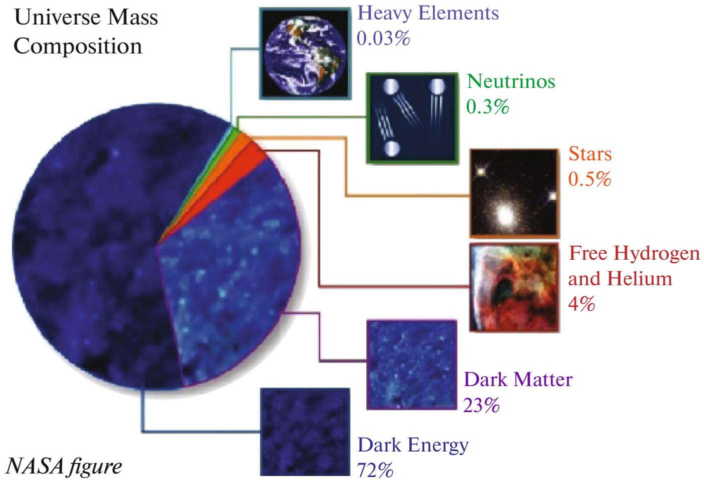

Fig. 3. Universe mass composition.

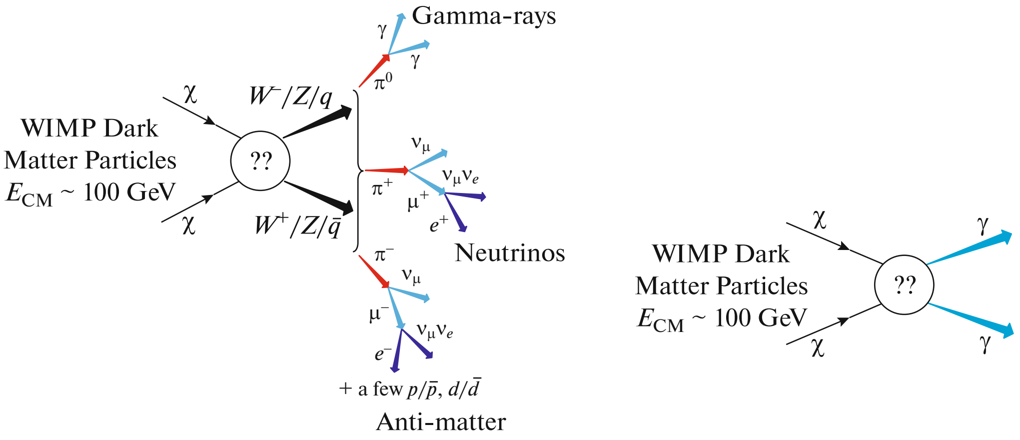

Fig. 4. Possible channels of WIMP annihilation $\chi\chi \to b\bar{b}, \tau^+\tau^-, W^+W^-, \mu^+\mu^-, q\bar{q}, ZZ$ with the gamma-ray production [25].

important goal for the studies of gamma-ray sky is indirect searches of dark matter. In general, an exact physical nature of DM is a top puzzle in the modern astrophysics.

Many candidates on the DM role are proposed. However, WIMPs with mass between several GeV and several TeV are still considered as the most probable candidate [24]. WIMPs can annihilate or decay with the production of gamma rays. This emission can have both continuous energy spectrum or monoenergetic lines. This depends on which annihilation channel realizes in the nature. The continuous spectrum would come in the case of annihilation into particle pairs like

$$\chi\chi \to b\bar{b},\ \tau^+\tau^-,\ W^+W^-,\ \mu^+\mu^-,\ q\bar{q},\ ZZ \qquad (1)$$

(Fig. 4, left [25]) or others and gamma-ray lines would be produced in the case of direct annihilation into photons $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$ (Fig. 4, right [25]).

To resolve gamma-ray lines from the background it is necessary to have a high-energy resolution. Figure 5 shows expected energy spectrum for the annihilation of 300-GeV WIMP producing gamma rays ($\gamma\gamma$, γZ, and γH lines), which can be resolved from the background by various telescopes with the energy resolutions of 10%, 5%, and 0.5% [26]. Note that the energy resolution of Fermi-LAT and ground-based facilities is only 10–15% at the energy of 10–300 GeV. Thus, as seen from Fig. 5, the future telescopes need to have 1–2% energy resolution.

2. THE GAMMA-400 GAMMA-RAY TELESCOPE

Thus, to resolve unidentified gamma-ray sources and search for the potential gamma-ray lines from DM we need a gamma-ray telescope with the angular resolution of several hundredth degrees and the energy resolution of few percent for the energy of

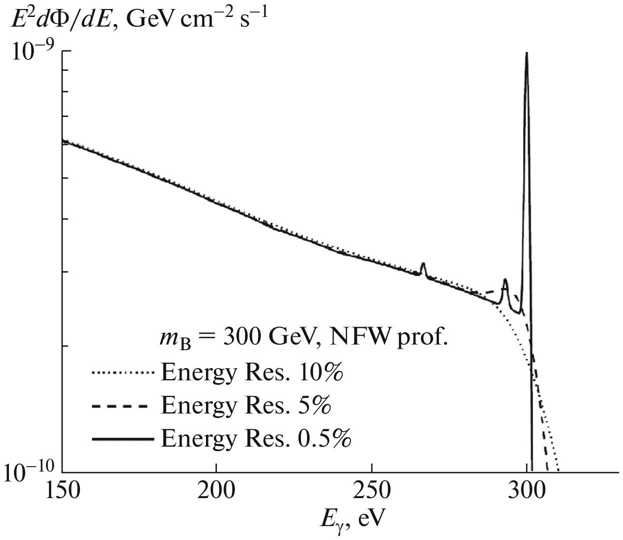

Fig. 5. Expected energy spectrum for the annihilation of 300-GeV WIMP producing gamma rays ($\gamma\gamma$, γZ, and γH lines), which can be resolved from background by various gamma-ray telescopes with the energy resolutions of 10%, 5%, and 0.5% [26].

~100 GeV. Such a new generation telescope will be GAMMA-400, which will be installed onboard the Russian space observatory [27–32]. The GAMMA-400 project was proposed by Prof. L. Kurnosova and Academician V. Ginzburg.

The GAMMA-400 main scientific goals are dark matter search by means of gamma-ray astronomy; precise and detailed observations of the Galactic plane, especially, Galactic Center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga, Sun, and other regions, extended and point gamma-ray sources, diffuse gamma rays with unprecedented angular (~0.01° at $E_\gamma > 100$ GeV) and energy (~1% at $E_\gamma > 100$ GeV) resolutions, as well as measurement electron + positron fluxes.

2.1. The GAMMA-400 Physical Scheme and Performance

The physical scheme of the GAMMA-400 gamma-ray telescope is shown in Fig. 6. The GAMMA-400 can investigate gamma rays from ~20 MeV to ~10 000 GeV with the field of view (FoV) of ±45°.

GAMMA-400 consists of plastic scintillation anticoincidence top and lateral detectors (ACtop and AClat), converter-tracker (C), plastic scintillation detectors (S1 and S2) for the time-of-flight system (ToF), two-part calorimeter (CC), plastic scintillation detector (S3).

The anticoincidence detectors surrounding the converter-tracker are used to distinguish gamma rays from significantly larger number of charged particles (e.g., in the region of 10–100 GeV), the flux ratios for gamma rays to electrons and protons are $\sim 1:10^2:10^5$.

All scintillation detectors consist from two independent 1-cm layers. The time-of-flight system, where detectors S1 and S2 are separated by approximately 500 mm, determines the top-down direction of arriving particles. The additional scintillation detector S3 improve hadron and electromagnetic shower separation.

The converter-tracker consists of 13 layers of double (x, y) silicon strip coordinate detectors (pitch of 0.08 mm). The first seven layers are interleaved with tungsten conversion foils with $0.1X_0$, next four layers with tungsten conversion foils with $0.025X_0$ (where X_0 is the radiation length), and final two layers have no tungsten. Using the four $0.025X_0$ layers allows us to measure gamma rays down to approximately 20 MeV. In this case, the gamma-ray trigger for the energy range of 20–100 MeV and 100 MeV–10 000 GeV is the same: AC × S1 × S2. The total converter-tracker thickness is about $1X_0$. The converter-tracker information is used to precisely determine the direction of each incident particle.

The two-part calorimeter measures particle energy. The imaging calorimeter CC1 consists of 2 layers of double $(x,\ y)$ silicon strip coordinate detectors (pitch of 0.08 mm) interleaved with planes from CsI(Tl) crystals, and the electromagnetic calorimeter CC2 consists of CsI(Tl) crystals. The thickness of CC1 and CC2 is $2X_0$ and $20X_0$, respectively. The total calorimeter thickness is $22X_0$ or $1.0\lambda_0$ (where λ_0 is nuclear interaction length). Using a deep calorimeter

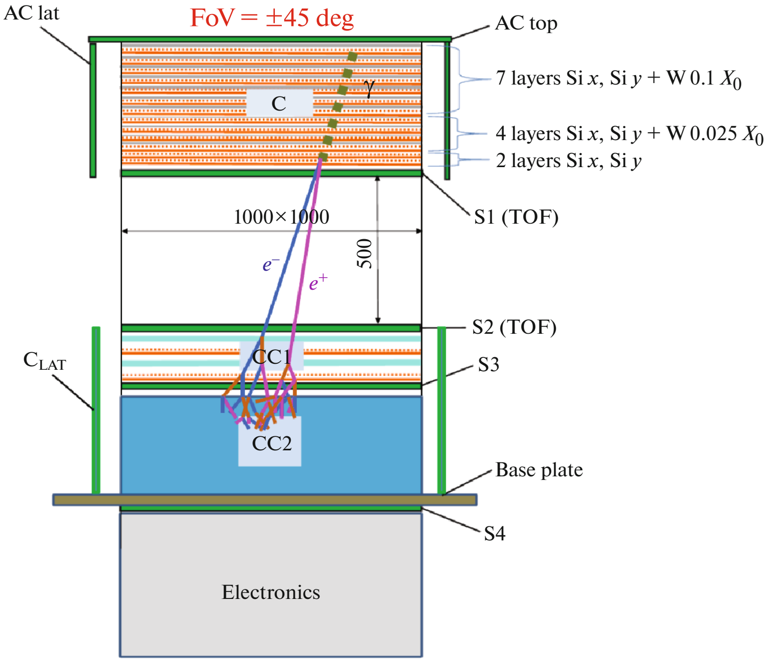

Fig. 6. The GAMMA-400 physical scheme.

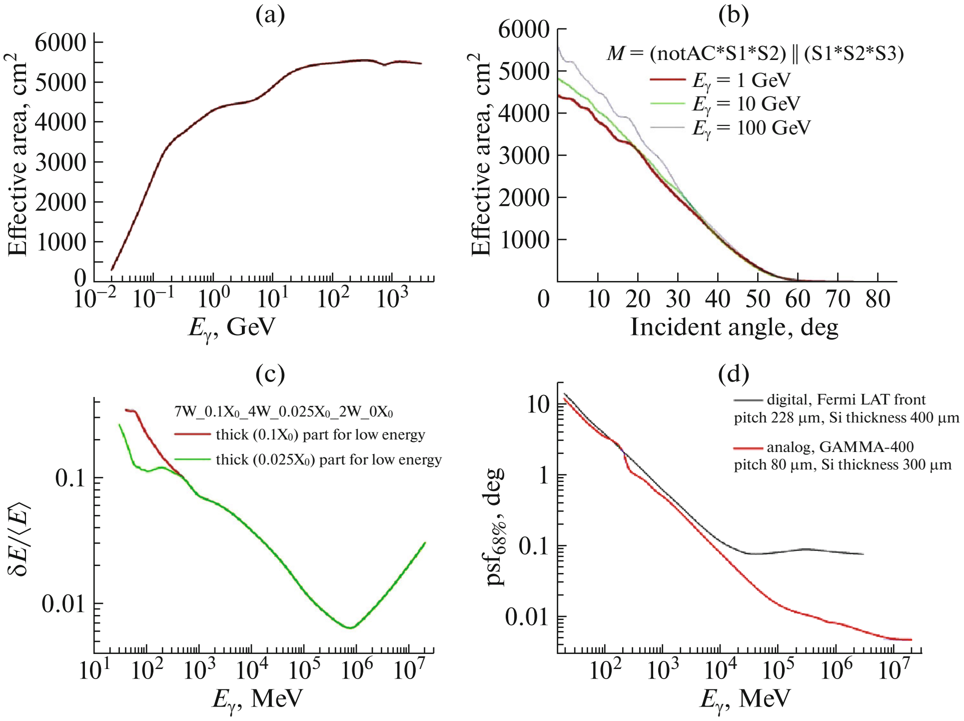

Fig. 7. GAMMA-400 performance: (a) effective area vs. energy; (b) effective area vs. incident angle; (c) energy resolution vs. energy; (d) angular resolution vs. energy.

allows us to extend the energy range up to ∼10 TeV for gamma rays and to reach an energy resolution about 1% above 100 GeV. GAMMA-400 can measure electron + positron fluxes from on-axis telescope direction and from lateral directions with CC2 (the thickness of CC2 for lateral directions is $53X_0$ or $2.5\lambda_0$).

Figures 7 show the GAMMA-400 performance: the dependences of effective area (a), energy (c), and

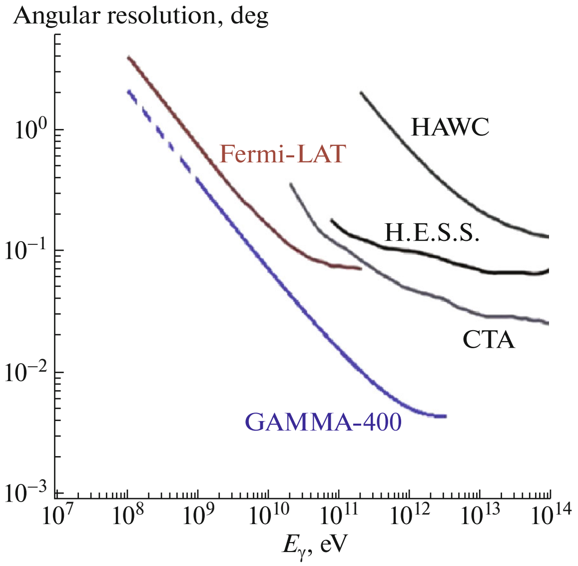

Fig. 8. Comparison of angular resolutions for GAMMA-400, Fermi-LAT, H.E.S.S., HAWC, and CTA.

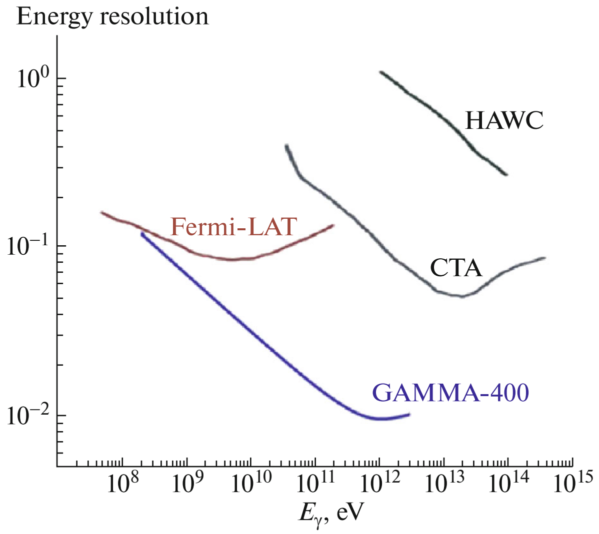

Fig. 9. Comparison of energy resolutions for GAMMA-400, Fermi-LAT, HAWC, and CTA.

angular (d) resolutions versus energy and effective area versus incident angle (b).

Figures 8 and 9 show the comparison of angular and energy resolutions for GAMMA-400, Fermi-LAT, H.E.S.S., HAWC, and CTA.

GAMMA-400 has numerous advantages in comparison with the Fermi-LAT (Table 1):

- highly elliptical orbit (without the Earth's occultation and away from the radiation belts) allows us to observe with the full aperture of ±45° different gamma-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 a smaller pitch (by a factor of 3) and analog readout in the coordinate silicon strip detectors, GAMMA-400 has an excellent angular resolution above ~20 MeV;

- due to the deep ($\sim 22X_0$) calorimeter, GAMMA-400 has an excellent energy resolution and can more reliably to detect gamma rays up to ~10 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 have also the better angular and energy resolutions in the energy region 10—10 000 GeV in comparison with current and future space- and ground-based instruments: VERITAS [19], MAGIC [20], H.E.S.S. [21], CTA [23], and HAWC [33] (Figs. 8 and 9) and it allows us to fill the gap at the energy of ~100 GeV between the space- and ground-based instruments.

GAMMA-400 will study continuously over a long period of time different regions of the Galactic plane, for example, the Galactic center, Fermi Bubbles, Crab, etc. with FoV of ±45°. In particular, using the gamma-ray fluxes obtained by Fermi-LAT, we can expect that GAMMA-400, when observing the Galactic center with an aperture of ±45° during 1 year will detect: 57 400 photons for $E_\gamma > 10$ GeV; 5240 photons for $E_\gamma > 50$ GeV; 1280 photons for $E_\gamma > 100$ GeV; 535 photons for $E_\gamma > 200$ GeV.

The main targets to search for gamma rays from dark matter are:

- **The Milky Way.** The center of Milky Way is, apparently, the best potential source of dark matter emission possessing the largest J-factor [24]. Moreover, recently, an anomalous excess of gamma-ray emission in the GeV energy range was revealed near the Galactic center (the region of about one degree) [34], which can be well described by dark matter with a mass of several tens of GeV and annihilation cross section of about standard thermal 10^{26} cm^3 s^{-1}. However, this observed excess can have another interpretation—the presence of a population of millisecond pulsars [35]. Therefore, the new GAMMA-400 observational data can help solve this problem.

Table 1. Comparison of GAMMA-400 with the Fermi-LAT

	Fermi-LAT	GAMMA-400
Orbit	Circular, 565 km	Highly elliptical, 500–300 000 km (without the EarthTs occultation)
Operation mode	Sky survey (3 hours)	Point observation (up to 100 days)
Source exposition	1/8	1
Energy range	$\sim$100 MeV–$\sim$300 GeV	$\sim$20 MeV–$\sim$10 000 GeV
Effective area ($E_\gamma > 1$ GeV)	$\sim$5000 cm^2	$\sim$4000 cm^2
Coordinate detectors—readout	Si strips (pitch 0.23 mm) digital	Si strips (pitch 0.08 mm) analog
Angular resolution	$\sim3°$ ($E_\gamma = 100$ MeV) $\sim0.2°$ ($E_\gamma = 10$ GeV) $\sim0.1°$ ($E_\gamma = 100$ GeV)	$\sim2°$ ($E_\gamma = 100$ MeV) $\sim0.1°$ ($E_\gamma = 10$ GeV) $\sim0.01°$ ($E_\gamma = 100$ GeV)
Calorimeter thickness	CsI(Tl), $\sim8.5X_0$	CsI(Tl) + Si, $\sim22X_0$
Energy resolution	$\sim$18% ($E_\gamma = 100$ MeV) $\sim$10% ($E_\gamma = 10$ GeV) $\sim$10% ($E_\gamma = 100$ GeV)	$\sim$10% ($E_\gamma = 100$ MeV) $\sim$3% ($E_\gamma = 10$ GeV) $\sim$1% ($E_\gamma = 100$ GeV)
Proton rejection factor	10^3	5×10^5
Mass, kg	2800	$\sim$4000
Telemetry downlink volume, GB/day	15	100

- **Milky Way satellites** have been 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.

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

2.2. The GAMMA-400 Space Observatory

Aboard the space observatory, along with the GAMMA-400 gamma-ray telescope, an X-ray telescope will be installed. Simultaneous observations in the X-ray and gamma-ray ranges of the Galactic plane, especially, Galactic center, Fermi bubbles, Crab, etc. will greatly improve our understanding of the processes taking place in the astrophysical objects.

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

Using the Navigator space platform gives the GAMMA-400 experiment a highly unique opportunity for the near future gamma-ray, X-ray, and cosmic-ray science, since it allows us to install a scientific payload (mass of 4500 kg, power consumption of 2000 W, and telemetry downlink of 100 GB/day, with lifetime more than 7 years), which will provide GAMMA-400 with the means to significantly contribute as the next generation instrument for gamma-ray, X-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 action of gravitational disturbances of the Sun, Moon, and the Earth after $\sim$6 months the orbit will transform to about an approximately circular one with a radius of $\sim$200 000 km and will not suffer from the Earth's occultation and shielding by 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 scheduled for the middle of 2020s.

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