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From the PAMELA mission to the GAMMA-400 project – the indirect search for signatures of dark matter

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Abstract. In 2008, the PAMELA magnetic spectrometer has discovered unpredicted abundance of the ratio of the galactic positron flux to the total positron and electron flux at high energies. It does not agree with the cosmic-ray fluxes calculated using the GALPROP code. This abundance was called the “PAMELA anomalous effect” and one of the explanations of this effect was the appearance of the additional electron and positron flux due to annihilation or decay of the dark matter particles. Later the precision PAMELA results were confirmed by the Fermi-LAT gamma-ray telescope and the AMS-02 magnetic spectrometer. Currently, the new GAMMA-400 project is being developed. The one of its main goals is to search for signatures of dark matter particles, which produce gamma rays. The GAMMA-400 gamma-ray telescope will have unprecedented angular and energy resolutions. PAMELA and GAMMA-400 are the instruments with the best characteristics for their time, which will improve our understanding of the nature of dark matter. At present, the problem of the nature of dark matter still remains the main challenge in high-energy astrophysics.

1. Searching for dark matter particles

The nature of dark matter is still unknown. Dark matter (DM) is ~23% of the Universe mass composition (figure 1). The presence of DM in the Universe is observed solely from its gravitational influence on the behavior of astrophysical objects. Among the huge number of possible candidates for the role of DM particles, supersymmetric particles, sterile neutrinos, axions, etc. are considered. The most commonly considered and studied are weakly interacting massive particles (WIMPs), whose mass can lie in the range from ~ GeV to ~ TeV.

Attempts to study the properties of DM particles are carried out by direct and indirect detection methods. The indirect detection method consists in recording not DM particles themselves, but the products of their annihilation or decay: charged particles of cosmic rays (the experiments PAMELA, AMS-02, ATIC, IACTs, Fermi-LAT, Auger, CTA, GAPS), cosmic gamma rays (the experiments Fermi-LAT, GAMMA-400, HESS-II, MAGIC, VERITAS, HAWC, CTA), neutrinos (the experiments IceCube/DeepCore/PINGU, ANTARES/KM3NET, BAIKAL-GVD, Super-Kamiokande/Hyper-Kamiokande) [1].

Possible channels for WIMP annihilation $W^+W^-, Z^0Z^0, b\bar{b}, t\bar{t},\ \tau^+\tau^-$ with producing secondary electrons and positrons, protons and antiprotons, gamma rays and direct annihilation channels $\chi + \chi \to \gamma + \gamma$, which result in producing monoenergetic gamma rays are shown in figure 2 [2].

The PAMELA instrument had the best for its time characteristics allowing one to obtain the precision results, which can for the first time associate with dark matter. The upcoming GAMMA-400 space experiment also has the best characteristics at present, which can allow us to improve our knowledge on the DM nature.

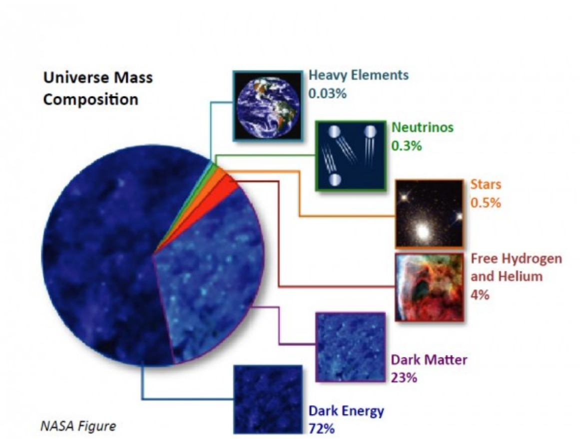

Figure 1. Universe mass composition.

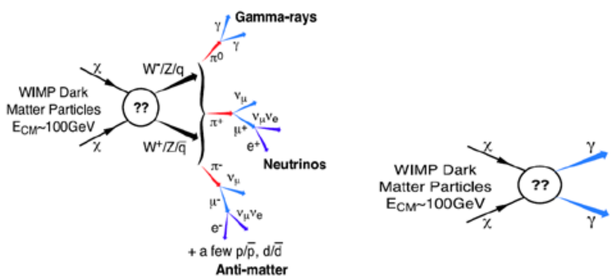

Figure 2. Possible channels of WIMP annihilation to produce electrons and positrons, protons and antiprotons, gamma rays, etc. [2].

2. The PAMELA magnetic spectrometer

The PAMELA (Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics) satellite experiment was designed to study the charged component of the cosmic radiation (especially antiparticles) and to search for structures in cosmic-ray spectra from new astrophysical sources or dark matter. PAMELA was launched onboard the Russian Resurs-DK1 satellite on June 15, 2006 from the Baikonur cosmodrome (Kazakhstan). The satellite was placed in a quasi-polar 70° inclination orbit at an altitude varying between 350 km and 600 km. The mission, which was planned to last 3 years, lasted almost 10 years.

Figure 3 shows the PAMELA instrument scheme [3]. PAMELA is a powerful particle identifier using a permanent magnetic spectrometer with a variety of specialized detectors for cosmic-ray direct measurements in space with unprecedented precision. A fully comprehensive description can be found in [4].

In 2008, PAMELA has discovered unpredicted abundance of the ratio of the galactic positron flux to the total positrons and electrons flux at high energies (figure 4, [5]). It does not agree with the cosmic-ray fluxes calculated using the GALPROP code [6]. This abundance was called the “PAMELA anomalous effect” and one of the explanations of this effect was the appearance of the additional electrons and positrons flux due to annihilation or decay of the DM particles.

Later the precision PAMELA results were confirmed by the Fermi-LAT gamma-ray telescope [7] and the AMS-02 [8] magnetic spectrometer (figure 5, [8]).

The antiproton intensity multiplied by $E3$ is shown in figure 6 [9] in comparison with the theoretical calculations [10] involving an additional source in the form of the annihilation of DM particles at high energies. Solid lines in figure 6 demonstrate uncertainty in the predicted flux of only the secondary component.

The PAMELA experimental results make it possible to study the nature of hypothetical massive DM particles, in particular, to set certain limits to the parameters of corresponding models. According to the PAMELA data the antiproton to proton ratio in the energy range > 10 GeV has some excess in comparison with theoretical calculations. This can be explained by the contribution of DM particles.

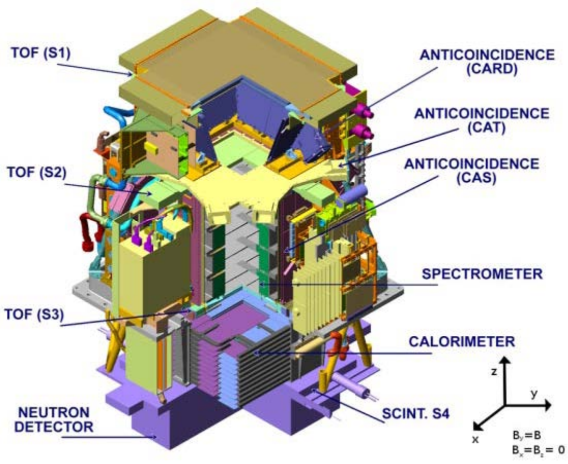

Figure 3. The PAMELA instrument scheme [3].

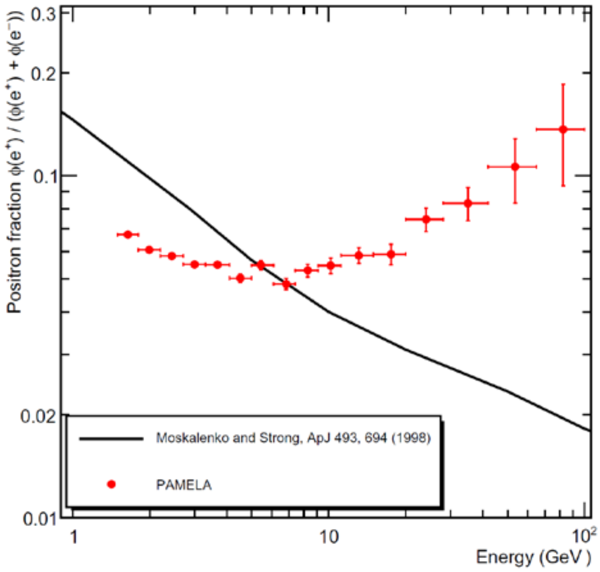

Figure 4. PAMELA positron fraction compared with a theoretical model [5]. The solid line shows a theoretical calculation [6] for pure secondary positron production during the propagation of cosmic rays in the Galaxy.

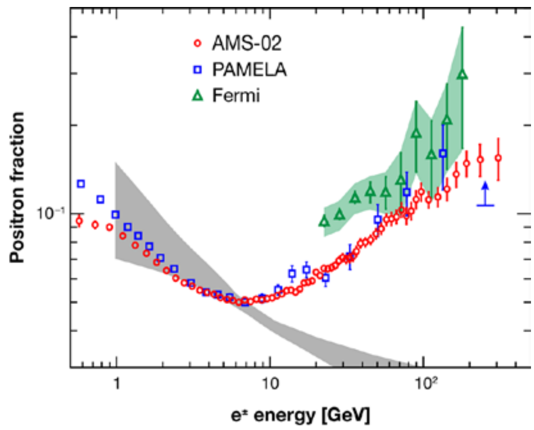

Figure 5. The positron fraction compared with the measurements from PAMELA, Fermi-LAT [7], and AMS-02 [8].

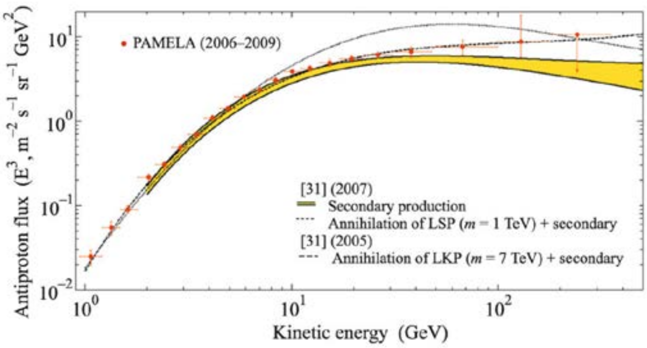

Figure 6. Antiproton intensity (multiplied by *E*3) vs the energy [9]. The yellow band shows uncertainty in the secondary antiproton flux for different diffusion models in the interstellar medium. Dashed and dotted lines correspond to the signal caused by the annihilation of different hypothetical DM particles [10].

3. The GAMMA-400 gamma-ray telescope

The GAMMA-400 gamma-ray telescope [11-15] is a bridge between the space-based and ground-based gamma-ray experiments, which will study gamma rays from low energy of ~20 MeV and up to high energy of several tens of TeV. The GAMMA-400 main scientific goals are: dark matter searching by means of gamma-ray astronomy; precise measurements of 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_γ = 100 GeV) and energy (~1% at E_γ = 100 GeV) resolutions. GAMMA-400 will be installed onboard the Russian space observatory.

3.1 The GAMMA-400 physical scheme

The physical scheme of the GAMMA-400 gamma-ray telescope is shown in figure 7. The GAMMA-400 energy range for gamma-ray studies is from ~20 MeV to ~10000 GeV. The GAMMA-400 field of view (FoV) is ±45°.

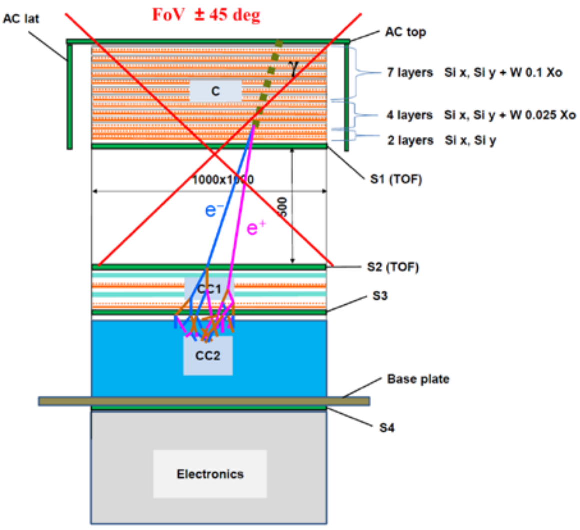

Figure 7. The GAMMA-400 physical scheme.

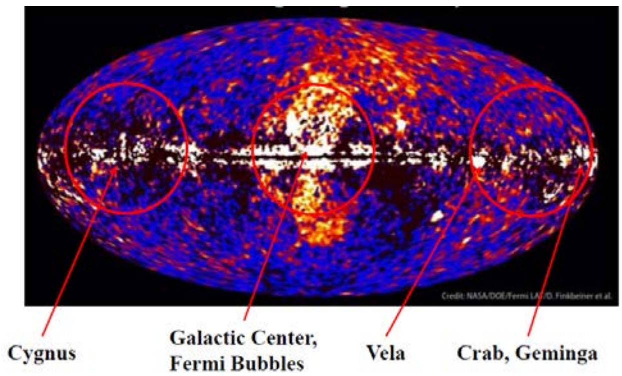

Figure 8. Galactic center, Fermi Bubbles, Crab, Cygnus, Vela, Geminga, and other regions will be observed with the GAMMA-400 FoV of ±45°.

GAMMA-400 consists of plastic scintillation anticoincidence top and lateral detectors (AC top and AC lat), converter-tracker (C), plastic scintillation detectors (S1 and S2) for the time-of-flight system (ToF), calorimeter (CC), and plastic scintillation detectors (S3 and S4).

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 ~ $1:10^2:10^5$.

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 detectors S3 and S4 improve hadron and electromagnetic shower separation.

The converter-tracker consists of 26 layers of single *x* and *y* silicon strip coordinate detectors with a pitch of 0.08 mm. Fourteen layers are interleaved with 0.1 X_0 tungsten conversion foils, next 8 layers with 0.025 X_0 tungsten conversion foils, and final four layers have no tungsten. This configuration allows us to measure gamma rays down to ~20 MeV and up to ~10000 with one trigger. The total converter-tracker thickness is ~1 X_0. The converter-tracker information is used to precisely determine the conversion point and the direction of each incident particle. Using the last four layers without tungsten will make it possible to measure the polarization of gamma rays in the energy range from ~20 to ~60 MeV.

The two-part calorimeter CC measures particle energy and consists of CsI(Tl) crystals. The total calorimeter thickness is ~23 X_0 or ~1.0 λ_0 when detecting vertical incident particles and ~43 X_0 or ~2.0 λ_0 when detecting laterally incident particles. Using the deep calorimeter allows us to extend the energy range up to several tens TeV for gamma rays, and to reach the energy resolution of ~1% at E_γ = 100 GeV.

3.2 The GAMMA-400 gamma-ray observatory

The GAMMA-400 gamma-ray 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 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 also include X-ray telescope with the energy range of 5-30 keV together with the gamma-ray telescope. GAMMA-400 will provide with the means to significantly contribute as the next generation instrument for gamma-ray astronomy, X-ray, 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 ~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 shielding by the radiation belts. The launch of the GAMMA-400 space observatory is planned for the middle of the 2020s.

4. The anticipated GAMMA-400 scientific output

4.1. Galactic plane

GAMMA-400 will study continuously over a long-term period different regions of Galactic plane (figure 8), for example, Galactic center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga 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 aperture of ±45°during 1 year will detect: 57400 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.

4.2 Dark matter searching

When detecting gamma rays from DM, the intensity from gamma rays is calculated by

$$\frac{d\Phi}{d\Omega dE} = \frac{1}{2}\frac{\langle\sigma v\rangle}{m_\chi^2}\frac{dN_\gamma}{dE} \times \frac{J}{4\pi} \, [\mathrm{erg\ s^{-1}\,cm^{-2}\,GeV^{-1}\,sr^{-1}}], \quad J = \int_{l.o.s.} \rho^2(\vec{r})dl.$$

Here, $\langle\sigma v\rangle$ is particle annihilation cross section, m_χ is particle mass, dN_γ/dE is the spectrum of gamma rays from annihilation, $\rho(\vec{r})$ is the DM density of investigated object [16].

The Galactic center is, apparently, the best potential source of DM emission possessing the largest *J*-factor [17]. 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) [18], which can be well described by DM with mass of several tens of GeV and annihilation cross section of about standard thermal 10^{-26} $\mathrm{cm^3/s}$. However, this observed excess can have another interpretation - the presence a population of millisecond pulsars [19]. Therefore, the new GAMMA-400 observational data can help to solve this problem. Dwarf galaxies are considered for a long time as the strongest sources of constraints for DM, 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 able to specify the constrain area. Potentially interesting objects are other galaxies and their clusters, where DM presents and can emit gamma rays. GAMMA-400 with the highest energy resolution of ~1% will have unique sensitivity for detecting DM.

5. Conclusions

PAMELA mission has made a significant contribution to search for dark matter particles. GAMMA-400 mission represents a unique opportunity to continue the search for dark matter particles in the gamma-ray low- and high-energy range and X-ray range with unprecedented angular and energy resolutions. The best GAMMA-400 characteristics will lead to new best results. According the new

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approved Russian Federal Space Program 2016-2025 the GAMMA-400 space observatory is scheduled to launch in 2025-2026.

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