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The GAMMA-400 Space Experiment: Gammas, Electrons and Nuclei Measurements

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Abstract

The present design of the new space gamma-ray telescope GAMMA-400 for the energy range 50 MeV – 3 TeV is presented. The proposed instrument has an angular resolution of 1-2 degrees at E(γ) ~100 MeV and ~0.01 degrees at E(γ) > 100 GeV and an energy resolution ~1% at E(γ) > 100 GeV. By means of a deep segmented calorimeter high energy electron flux can be studied, with a proton rejection factor of about 10^6. The GAMMA-400 experiment is optimized to address a broad range of science topics, such as search for signatures of dark matter, studies of galactic and extragalactic gamma-ray sources, galactic and extragalactic diffuse emission, gamma-ray bursts, as well as high-precision measurements of spectra of high energy electrons, protons and nuclei up to the knee.

Keywords: space experiments, gamma-ray telescope, cosmic rays, dark matter, cosmic rays acceleration

1. Introduction

The GAMMA-400 space mission is included in the long term Russian Federal program for space, devoted to the observation of high energy gamma rays and the high energy electrons and positrons [1]. The experiment is intended to improve the angular and energy resolutions obtained by other space missions for gamma and electron detections in the 50 MeV – 3 TeV energy range.

In its original design approved by the Russian Federal

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Agengy for Space (Roscosmos), the angular resolution (0.01° @ 100 GeV) is obtained by a stratified converter, interleaved with high resolution position measurements of the produced electron-positron pair by microstrip silicon planes. The optimal energy resolution (∼1% at >100 GeV), as well as a good identification of the electromagnetic component on the huge number of hadrons, is obtained by a deep – ≥25 radiation lengths (X_0) – and highly granular BGO calorimeter which top part is segmented and read also by several microstrip Si(x,y) planes.

Italian teams participating in the PAMELA experiment were asked by the Russian colleagues and by Roscosmos to consider the participation in the project of the GAMMA-400 and to its mission. The Italian teams accepted the invitation in consideration that the characteristics of the spacecraft (supplying 2 kW of power to an instrument of 2600 kg), the planned long duration of the mission (∼10 years) and the very elongated orbit (perigee 500 km, apogee 300.000 km) provide excellent opportunities for an advanced detector able to study not only gamma-rays and electrons but also the nuclei component of cosmic rays.

2. Spacecraft and orbit

The GAMMA-400 instrument will be installed on the spacecraft "Navigator", already used in other astrophysical missions. It is three axes stabilized and its mass is 900 kg. The instrument will be installed on the upper part of the spacecraft, Fig. 1. The solar panels and the heat radiators are at a lower level and do not interfere with the field of view of the instrument. The attitude can be maneuvered for pointing gamma sources when required. Given the isotropy of the electron and nuclei fluxes, their registration will also go on in all these phases of the mission.

The spacecraft will be placed in a very elongated orbit with an inclination angle of 51.8°. The initial orbit, after some months, evolves to a very high circular orbit (100.000 – 200.000 km) with an orbital period of about 7 days. This is not only a very favorable condition for the electric supply but also for a long duration pointing of a given source without the dead time due to the Earth occultation.

The integrated flux of galactic cosmic rays will be of about one order of magnitude more intense than that in low Earth orbit (LEO), due to the absence of the protection of the terrestrial magnetic field, but, on the other side, there will be no crossing of Earth radiation belts. The expected integrated radiation intensity is of about few tens krad in the 10 years of mission duration.

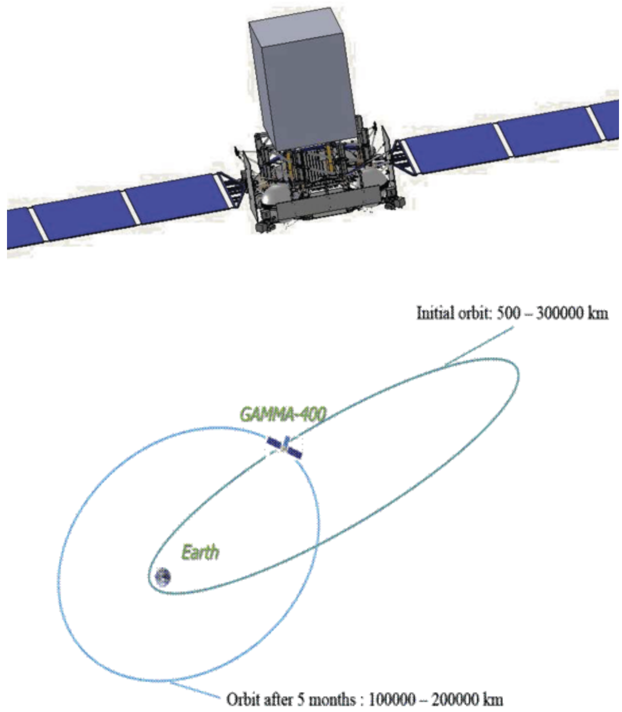

Figure 1: Top: the "Navigator" spacecraft; the gray box represent the GAMMA-400 apparatus. Bottom: the GAMMA-400 planned orbits.

3. The Russian "baseline" proposal

The scheme of the instrument proposed by the Russian groups for the high energy gamma and electrons spectrum measurements is assumed as a baseline configuration. Improvements and modifications are foreseen to possibly extend the physics goals. Performance, mass and cost have to be determined in the final configuration.

The GAMMA-400 gamma-ray telescope in its baseline version, Fig. 2, includes the following detectors [2]:

- anticoincidence system (AC);
- silicon-tungsten converter (C);
- Time-of-Flight system (TOF);
- position sensitive system (C+CD);
- silicon-CsI calorimeter (CC1);
- homogeneous BGO calorimeter (CC2);
- neutron detector (ND);
- a system of determining the orientation (star sensor) and all the needed front-end and read-out electronics (not shown in figure).

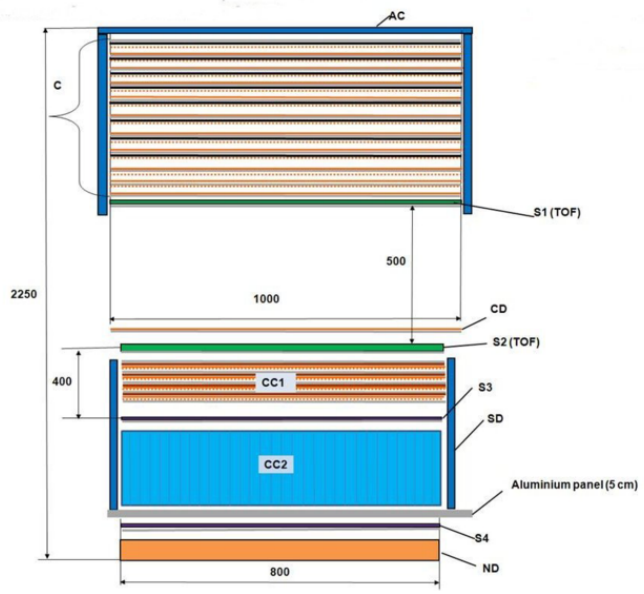

Figure 2: The GAMMA-400 instrument, schematic view of the "baseline" proposal. Where not otherwise stated, lenghts are expressed in mm.

The silicon-tungsten converter consists in ten planes of 0.1 X_0 each (for a total depth of $\sim$1 X_0) with a strip pitch of 500 μm. The silicon-CsI calorimeter is made of five layers of 0.75 X_0 CsI planes interleaved by silicon detectors and it is used to achieve a good pointing resolution, in the case of electromagnetic showers, and to improve the overall instrument angular resolution also thanks to the large lever arm obtained by separating the upper part of the instrument from the calorimeter by about 50 cm. The homogeneous calorimeter is made of 1024 vertical BGO bars for a total 22 X_0 (vertical particle direction) and about 70 X_0 for particles entering from the sides.

4. The "italian" proposal: towards a multipurpose instrument

Thanks to the high mass and power budget of the spacecraft and thanks to its foreseen orbit it is possible to configure the mission for accomplishing, besides the gamma astronomy and the precise electron plus positron spectrum measurement, very important tasks in the domain of astroparticle physics and astrophysics, such as:

- the extension of the gamma observation capability down to the poorly investigated low energy range, 50–300 MeV;
- The study of the proton and helium spectra up to the knee region (10^{14}-10^{15} eV) and the measurement of the individual flux of all the nuclei in cosmic ray up to the actinide group, and the energy spectra of the most abundant of them.

GAMMA-400 can be designed for a breakthrough in gamma-ray astrophysics in the range 50 MeV – 3 TeV obtained by an optimal effective area and a Point Spread Function (PSF) substantially better than the current generation. Diffuse emission across the Galaxy can be completely resolved and correlated with radio and optical surveys. Diffuse gamma-ray sources (SNRs, PWNe, star forming regions, gamma-ray bubbles, the galactic center region) can be studied with unprecedented accuracy. Extragalactic sources can be detected with great accuracy and sensitivity comparable or larger than Fermi-LAT at 1 GeV. Dark matter studies of the galactic center region can be addressed by resolving individual features in gamma-rays with unprecedented accuracy, improving the current angular resolution by a factor larger than about four in the GeV range. Besides the many astrophysical studies that are possible with GAMMA-400, in the 50-300 MeV range, the observation of the transition from hadronic dominated to leptonic dominated emissions is also expected. Thanks to the good energy resolution, GAMMA-400 will be able to study this transition, opening new possibilities of investigation not yet possible. It will be possible, in fact, to have a model-independent measurement of the electron to proton ratio at the sites of acceleration of cosmic rays. Also, a clear detection of the emission of bremsstrahlung from SNRs and therefore the measurement of the density of electrons, in conjunction with the observation of the radio synchrotron emission, would lead to an independent estimate of the magnetic field in these objects.

GAMMA-400 is also a unique opportunity to investigate fundamental questions in cosmic-ray physics concerning the origin, acceleration and propagation of charged particles. From an energetic point of view it was realized already in the fifties that Super Nova explosions released sufficient energy to power the cosmic rays in the Galaxy. A viable mechanism was proposed in the seventies and recent measurements of synchrotron X-rays and TeV gamma-rays point unambiguously to supernovae remnants (SNR) [3, 4] as the acceleration site of at least electrons. However, the vast majority of the cosmic rays are protons and heavier nuclei with electrons representing only one percent of the total flux. While convincing, the evidences of SNR as acceleration sites of all cosmic rays are not conclusive and this is especially true for the acceleration mechanisms proposed to explain the cosmic-ray spectrum. Moreover, the paucity of high energy (TeV) data concerning secondary nuclei (i.e. nuclei produced by cosmic rays during their propagation in the Galaxy) seriously limits our understanding of the interplay between propagation and acceleration. Recent precise measurements of the positron component in the cosmic-rays by PAMELA [5, 6] and Fermi [7] of the electron energy spectra, Fig. 3, by

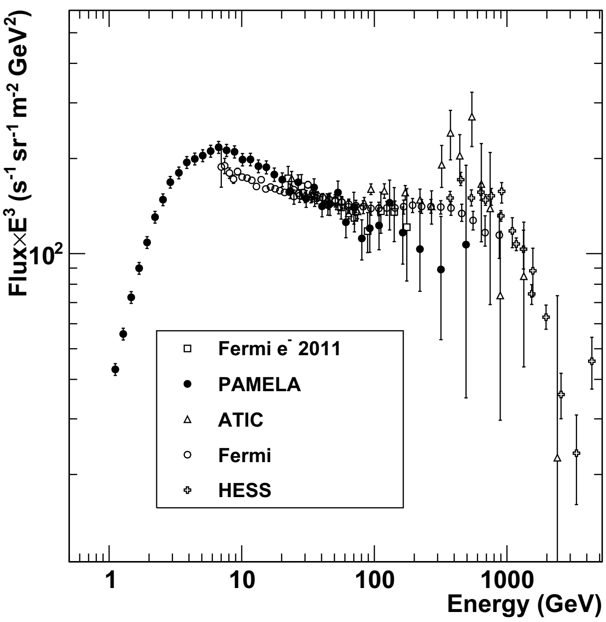

Figure 3: Electron spectrum as measured by PAMELA, Fermi, ATIC and HESS.

PAMELA [8] ATIC [9], FERMI [7, 10] and HESS [11] have provided clear indications that the electron and positron spectra are more complicated than previously expected and require a new understanding of cosmic-ray acceleration and propagation plus, possibly, additional new sources. These sources can be either of astrophysical (e.g. pulsars [12]) or of particle physics nature (e.g. annihilation of dark matter [13]). While these results are quite compelling, they are not sufficiently precise and complete to allow clear conclusions to be drawn. Indeed, it is only the combination of these measurements with information from gamma-ray and cosmic-ray nuclei spectra that will disentangle various issues of cosmic-ray propagation from acceleration models and new sources. Moreover, about 50 years ago a clear change (the so called "knee") in the energy spectrum of cosmic rays was observed around 10^{15} eV. Since then, more data have been acquired confirming the first evidence, but no theoretical explanation have yet been accepted as fully satisfactory by the cosmic-ray community. While yet unclear, the origin of the knee is probably related to the acceleration mechanism. In fact in diffusive shock acceleration model cosmic rays are accelerated in blast waves of SNR and a rigidity-dependent limit, above which the diffusive shock acceleration becomes inefficient, is predicted. The maximum energy attainable by a nucleus of charge Z may range from $Z\times10^{14}$ eV to $Z\times10^{15}$ eV depending on the model and types of supernovae [14]. Hence, the cosmic-ray spectrum would be the convolution of single spectra weighted by their relative abundances. Then, the knee would result from the convolution of the various cutoffs while the spectral composition would become heavier. An alternative explanation of the knee is adopted by models that relate it to leakage of cosmic rays from the Galaxy. In this case the knee is expected to occur at lower energies for light nuclei as compared to heavy ones, due to the rigidity-dependence of the Larmor radius of cosmic rays propagating in the galactic magnetic field [15]. More recent acceleration models account for the dynamical interaction between the shock front and accelerated particles. The resulting energy injection spectrum is not anymore a single power law identical for all cosmic rays, but deviations would be present with hardening of the spectra at higher energies. Hence, additional structures would appear in the energy spectra of cosmic rays probably in the TeV region with possible spectral differences between the various species [15]. The majority of the data in the knee (10^{14}-10^{16} eV) region have been collected by ground detector arrays that, measuring the secondary particles produced by cosmic rays interacting with the Earth's atmosphere, indirectly determine the energy and composition of the cosmic radiation. At lower energies, up to about 10^{14} eV the cosmic ray spectra have been directly measured mostly by balloon-borne experiments. Both the statistical and systematic uncertainties of these measurements significantly hinder the interpretation of the data. It is of fundamental importance to significantly increase the existing statistics of direct measurements and bridge the existing energy gap between direct and indirect measurements. Measuring with great precision the energy spectra of cosmic-ray components from proton up to iron for energies up to 10^{15} eV will significantly help in discriminating between various acceleration models and it will provide a powerful cross-check to ground based measurements.

Hence, it is very exciting the possibility of building an instrument capable of observing simultaneously the various components of cosmic and gamma rays in order to test with unprecedent precision the cosmic ray sources, acceleration and propagation models.

5. GAMMA-400: a new generation dual instrument

The design of a multipurpose instrument for the GAMMA-400 mission must start from the scheme of the instrument proposed by the Russian groups for the high energy gamma and electron+positron spectrum measurements, section 3. An important requirement from the Russian collaboration is that the main goal of the experiment should not be compromised by the revision. This means that the GAMMA-400 upgraded version must be able to measure high energy gamma rays and electrons plus positrons with the same or better angular and energy resolutions as for the baseline version.

The tentative configuration presently under consideration is schematically drawn in Fig. 4. It consists of two main parts, a converter and tracker system and a finely segmented calorimeter.

The converter and tracker section must be optimized for a good angular resolution of the high energy gammas. It should consist, as proposed by Russians, of about 1 X_0 of tungsten stratified in layers interleaved by microstrip Si(x,y) planes with a small pitch (order of 100–500 μm). Tungsten layers are very thin (~0.03 X_0) for minimizing the multiple scattering of the e-pair of the converting gamma. Such a homogeneous small radiation length converter will take care of the conversion of gammas in the 50–300 MeV energy range and of the measurement of the position of the produced e-pair. Simulations are under way for determining the number of planes, the gap among them, the thickness of the silicon sensors and the possible introduction of very thin tungsten layers in the package. A further microstrip Si(x,y) plane with 100 μm pitch, placed middle way between the converter and the calorimeter, supplies a lever arm for an optimal measurement of the angles of the e-pair in the case of higher energy gammas.

The converter and tracker section could cover an area $\sim 1.1\times 1.1$ m^2 and should be very compact in the vertical coordinate in order to maintain a good geometry factor (GF$\geq$0.5 m^{2}sr) for the nuclei reaching the calorimeter from the top.

A set of scintillation counters, suitably segmented, will be inserted in this section or around it for trigger and anticoincidence purpose.

The calorimeter must be deep for ensuring a good energy resolution, and have a sufficient granularity for identifying the electromagnetic component in the hadronic shower. Furthermore the need of maximizing the geometrical factor for electrons and nuclei requires that it would be also as much as possible homogeneous and isotropic in order to accept, identify and measure energy of the charged particles impinging on it

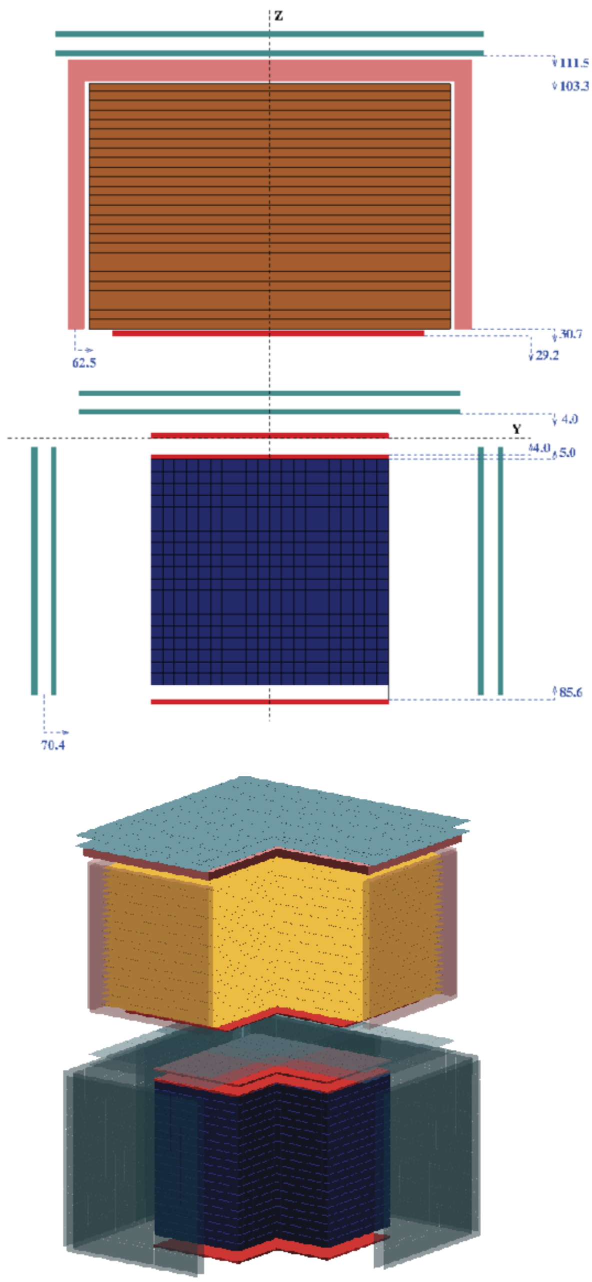

Figure 4: Top: schematic view of a preliminary GAMMA-400 upgraded version. Bottom: 3D view of the same geometrical version, to be noticed the cubic calorimeter made of CsI small cubes.

without crossing the upper section of the instrument, i.e. from the sides. By equipping with suitable detectors for tracking and measuring the charge along the four sides of the calorimeter it is possible to obtain an effective global geometrical factor GF$\geq$3.5 m^{2}sr, where this estimate includes the efficiency for nuclei interaction in first half interaction length after entering the calorimeter.

A long duration observation with such a large GF gives, for the first time in cosmic ray research, the possibility of directly studying the chemical composition of cosmic rays in the knee region, a major achievement long pursued in last decades. This approach requires the designing and testing of an innovative configuration for the calorimeter. The material should be changed from the proposed BGO to CsI which permit to keep a large acceptance and a depth of about 1.8 interaction lengths (λ_0), despite its lower density. The structure must maintain the imaging capability, for example composing the calorimeter by many small crystals. Assuming for the calorimeter a cubic shape, with 0.8×0.8×0.8 m^3 volume the CsI mass would be of about 1600 kg, still compatible with the total mass allocated to the GAMMA-400 instrument.

In the most straightforward solution the sensible volume could be constituted by small cubic CsI crystals, whose granularity determines the imaging capability of the calorimeter. The total number of small crystals depends from their side: about 8000 for 1.5 X_0 (3.2 cm) side, reaching about 33000 for 1 X_0 (2.2 cm) side. A more isotropic configuration would require spherical CsI crystals, which could be approximated by a trunked octahedron shape. The advantage is that of assuring uniformity for all direction. A preliminary simulation study, however, shows that the cubic approximation gives similar results.

Such a homogeneous and isotropic imaging calorimeter fulfills the original Russian requirements for the gammas, and is also capable to perform several other tasks, such as the measurement of the proton flux with a good efficiency and an effective electron to proton separation.

The charge of incoming particle must be measured before its interaction with other part of the instrument: on top of the converter and tracker block for particles coming from the top and at some distance from the sides of the calorimeter for particles coming from the side. Two layers of silicon pixels are sufficient, whose granularity must deal with the backscattering from the calorimeter. Shape and area of the pixels will be determined by simulation on the final configuration of the whole instrument. Tentatively it can be assumed 1×1 cm^2 square pixels. Moreover, the charge detectors must be equipped with a very large dynamic range electronics, enabling to measure Z up to the actinides without introducing ancillary counters, which (given the large dimensions) would significantly contribute to the total mass.

6. Conclusions

The GAMMA-400 mission thanks to its mass, power budget and to its orbit is a unique opportunity to build a new generation dual instrument.

GAMMA-400 can become a gamma-ray/cosmic-ray mission with substantial differences with respect to the current generation of gamma-ray astrophysics missions (AGILE and Fermi-LAT), cosmic-ray satellite (PAMELA, AMS in the ISS, and in the near future CALET) and balloon-borne instruments.

GAMMA-400 will substantially improve the current generation of gamma-ray instruments in space (AGILE and Fermi) and will provide unique data for astroparticle and astrophysics in the energy range 30 MeV – 3 TeV during the foreseen mission period 2018-2028. GAMMA-400 data will have a crucial impact on a large variety of scientific topics ranging from Dark Matter studies, compact objects and black holes, cosmic-ray origin and propagation, exotic transients and Gamma-Ray Bursts.

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