National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

3. The results of scientific research on completed space missions obtained by Russian scientists in 2014-2015

The angular distribution of cosmic ray positrons by data of PAMELA experiment on board satellite Resurs-DK 1

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The angular distribution of positron fluxes was studied on the all celestial sphere with the goal of searching of anisotropy of cosmic ray positron fluxes in energy range from 10 till 200 GeV on the base of PAMELA experiment data. It was shown that measured positron arrival direction distribution corresponds to isotropic flux. High level of dipole anisotropy is about δ=0.076 with 95% confidence probability. The obtained results give the opportunity to exclude the local sources up to tens of parsec and favor the explanation of high energy positron excess explanation by decay or annihilation of hypothetical dark matter particles.

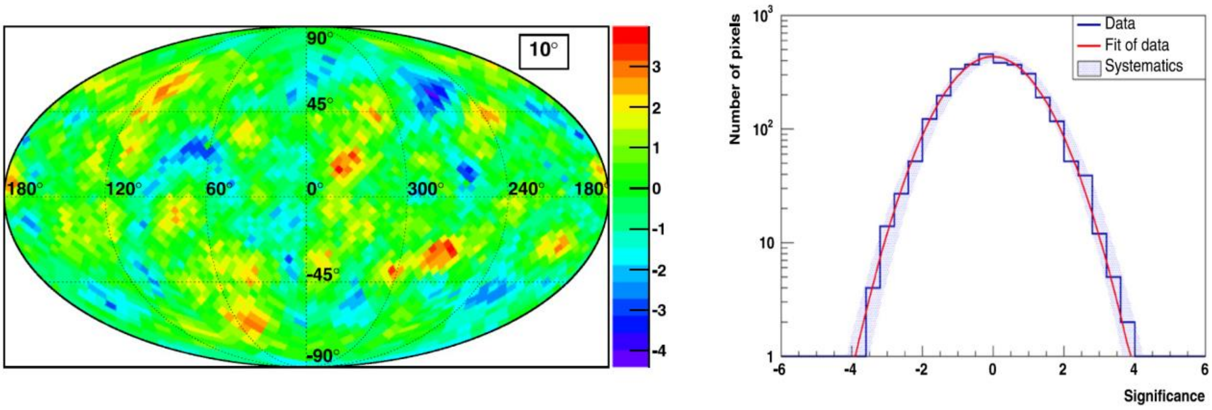

Fig.1 (left): the map of deviations (in σ) of isotropic distribution for positrons with energy 10-200 GeV in galactic coordinate system; (right): the distribution histogram (blue line) and expected distribution in the case of isotropic flux (red line), grey band displays the systematic errors of measurements.

The modulation of galactic cosmic ray electron fluxes inside heliosphere on the experimental data of PAMELA experiment on board Resurs-DK1 satellite.

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The precision measurements of variations of galactic electron fluxes with energies from 70 MeV till 50 GeV were carried out in frame of PAMELA experiment during the period of abnormally low solar activity at the end of 23 cycle (from July 2006 till December 2009) for semiannual intervals. The effects of Solar modulation of cosmic rays in heliosphere significantly change the particle spectra lower than 30 GeV. The comparison of new experimental data with models gives the unique possibility for explanation of cosmic ray modulation mechanisms inside heliosphere.

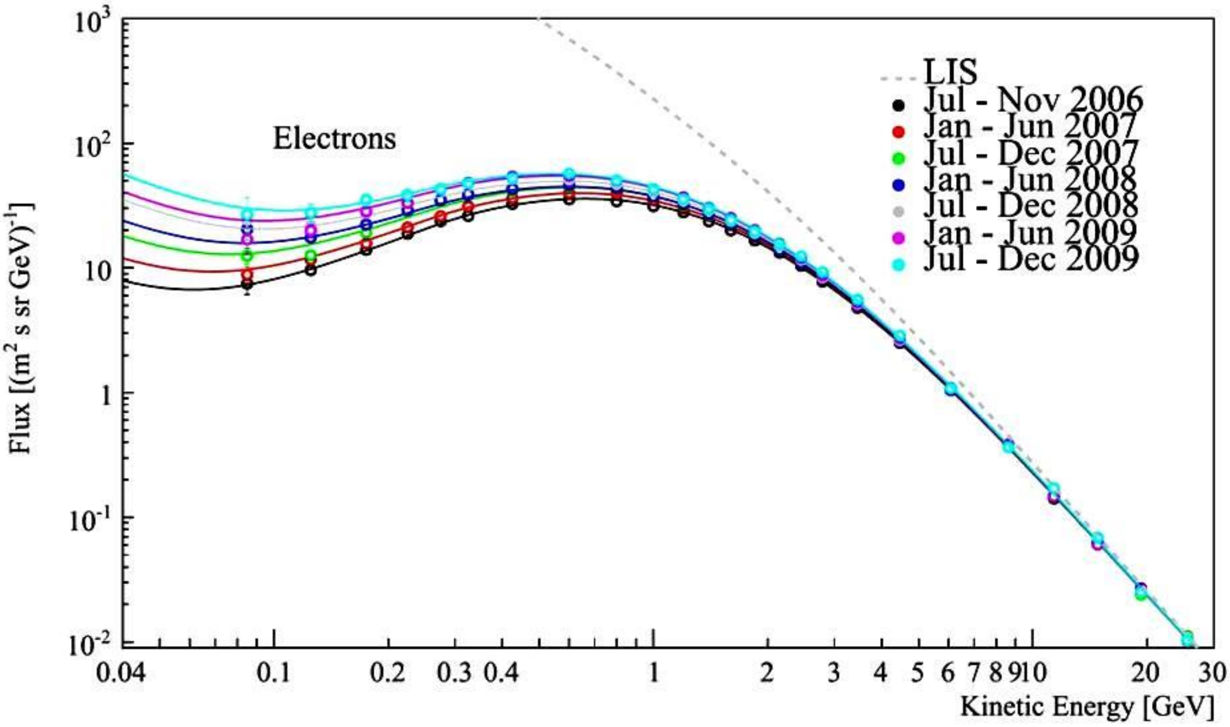

Fig.2. The cosmic ray electron energy spectra near the Earth during the period from July 2006 till December 2009 in comparison with the results of model calculations. LIS - the local interstellar spectrum on the boundary of heliosphere.

ARINA and VSPLESK satellite experiments for study of variations of high-energy proton and electron fluxes in the near-Earth space. Report for 2014 - 2015 (main results)

1. Description of ARINA and VSPLESK satellite experiments.

The stationary radiation environment in the near-Earth space is formed by the superposition of galactic cosmic rays, atmospheric albedo particle fluxes, and charged particles trapped by the geomagnetic field (radiation belt). Today it is important to study the changes of radiation conditions in the near-Earth space including the radiation belt, which appear as variations of charged particle fluxes in a wide energy range.

Satellite experiment ARINA was carried out since 2006 till 2016 (Russian spacecraft Resurs-DK1), and VSPLESK experiment on board the International Space Station was fulfilled since 2008 till 2013 [1, 2]. Scintillation spectrometers ARINA and VSPLESK, developed by MEPhI, are identical in physics scheme and have the same performances like acceptance, energy range, energy and angle resolution, field of view, etc. Multilayer scintillation detector (MSD) is main part of the spectrometers. Charged particles (electrons, protons) moving forward and arriving in the instrument aperture sequentially pass through scintillation layers C1, C2, C3, etc. up to C10, lose energy, and are absorbed in the MSD. Backward particles and particles passed through the entire instrument are cut by detector C10 operating in the anticoincidence mode. Thus, particles stopped in the MSD are electrons with energies of 3 - 30 MeV and protons with energies of 30 - 100 MeV. They are identified by the energy release in each layer under when passing through the instrument (MSD) and by the range in it. The electron and proton energy is measured by their range in MSD layers. The physics scheme and performances of the instrument are described in detail in [3]. Spectrometers allow to study the energy spectra and temporal profiles of particle fluxes.

High statistics of particles, accumulated during 2006-2015 years in ARINA and VSPLESK experiments, allowed to make the detail map of particle fluxes in the near-Earth space. For that a 4-th dimensional space (L and B coordinates, longitude and pitch-angle) was used. Additionally time (date) of observation was used as a fifth coordinate for taking into account the dependence of particle fluxes on phase of 11-year solar cycle and changing the global geomagnetic field. Such a detail approach allows to study various species of particle flux variations. Among them there are bursts of particles with duration about several seconds, caused by local disturbances of the radiation belt (lightning, earthquakes etc.), resulting in particle precipitation from it, several-hour (day) variations, interrelated with solar flares and geomagnetic storms, year scale changes, induced by 11-year solar cycle and global drift of geomagnetic field.

Main experimental results, obtained in 2014 – 2015, are presented here.

2. Dynamics of high-energy electron flux in the outer radiation belt.

Obtained results are presented in [4].

The ARINA and VSPLESK instruments carried out continuous measurements of high-energy electron flux and its energy spectrum in low-Earth orbits in the range 3-30 MeV with 10 – 15 % energy resolution. A time profile of electron flux in different L - shells has been studied since 2006. Detail analysis of experimental data on ultra relativistic (greater than 3 MeV) electrons in the outer radiation belt zone (L~3 – 8) is fulfilled. It was shown a large variability of flux of such electrons there. The sharp effects in electron flux (as rise and as drop) in magnetosphere interrelated with solar flares and coronal mass ejections have been observed.

Typical behavior of ultra relativistic electrons in outer radiation belt is shown in Figure 1. This figure presents the variation of 4 6 MeV electron flux at L=3 - 3.5 during 2012. The periods of significant (greater than some hundreds times) changing the flux of electrons were analyzed. Series of powerful solar flares and CME in the March 2012 gave rise to strong disturbance of the magnetosphere of the Earth (Dst about - 100 nT).

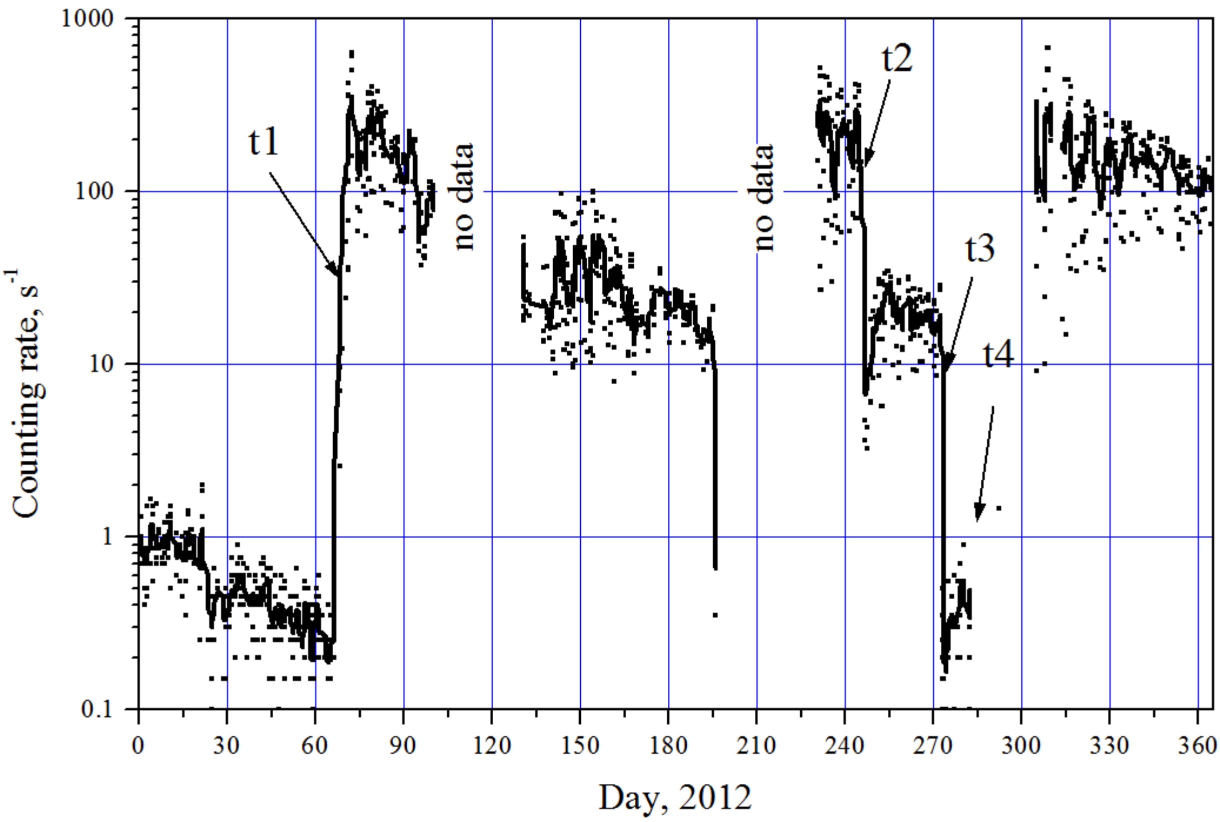

Figure 1. Variation of flux of 4 – 6 MeV electrons at L=3 - 3.5 observed by ARINA in 2012. Points is counting rates of electrons in 20 s intervals. Curve is approximation of experimental data. Arrows (t1, t2, t3, t4) mark sharp changing electron flux.

Arrows (t1, t2, t3, t4) in the figure mark the sharp changing (grows or drop) in 4-6 MeV electron flux. Each of these changing coincides with time of strong magnetospheric disturbances with Dst value about - 100 nT, caused by solar events (flares, CME, etc.). Also it is necessary to mark that ARINA and VSPLESK observations revealed that the strong geomagnetic storm is able to cause as sharp increase as sharp decrease of ultra relativistic electron flux in outer radiation belt.

2. Long-term variation of high-energy proton flux in the inner radiation belt.

Obtained results are presented in [5, 6].

2.1. Drift of South Atlantic Anomaly region in proton flux [5].

A geographical distribution of particle fluxes has been studied on the ARINA and VSPLESK experimental data. It is known that there is a movement of global geomagnetic field, leading to drift of South Atlantic Anomaly (SAA) region. This effect was observed in high-energy proton flux with ARINA and VSPLESK measurements. The analysis of temporal changing the position of proton (about 50 MeV) maximum for each separate L-shell was carried out. The drift of position of particle flux maximum was measured. The speed of the drift is about 0.45º±0.07º longitude/year in west direction (Figure 2). Analysis showed that speeds of this drift for different L-shells are practically the same. The value of the measured speed is in accordance with drift of global magnetic field of the Earth.

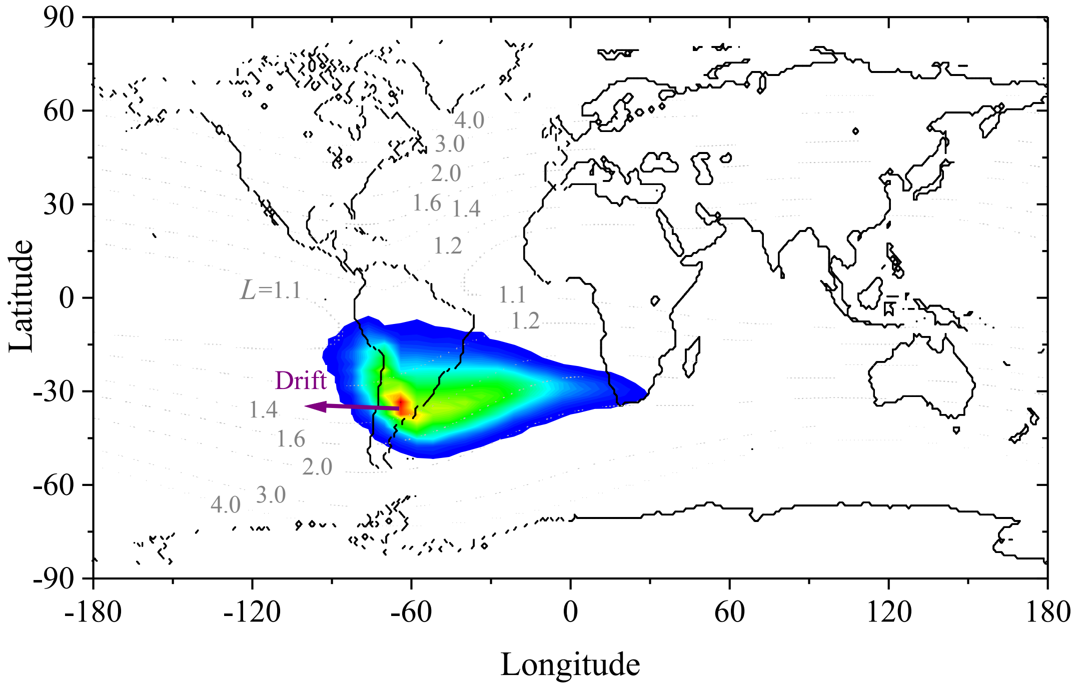

Figure 2. Drift of SAA region on the data of radiation belt proton flux (ARINA experiment, 2014 - 2015).

2.2. Variation of proton flux during the solar cycle [6].

Continuous measurements with ARINA include falling/minimum and rising/maximum phases of 23/24 solar cycles. Variation of proton flux in the inner radiation belt during 2006 - 2014 is presented in Figure 3. Anticorrelation of proton flux with solar activity is clearly visible. The ratio between proton fluxes in solar minimum and solar maximum reaches the value ~ 7.

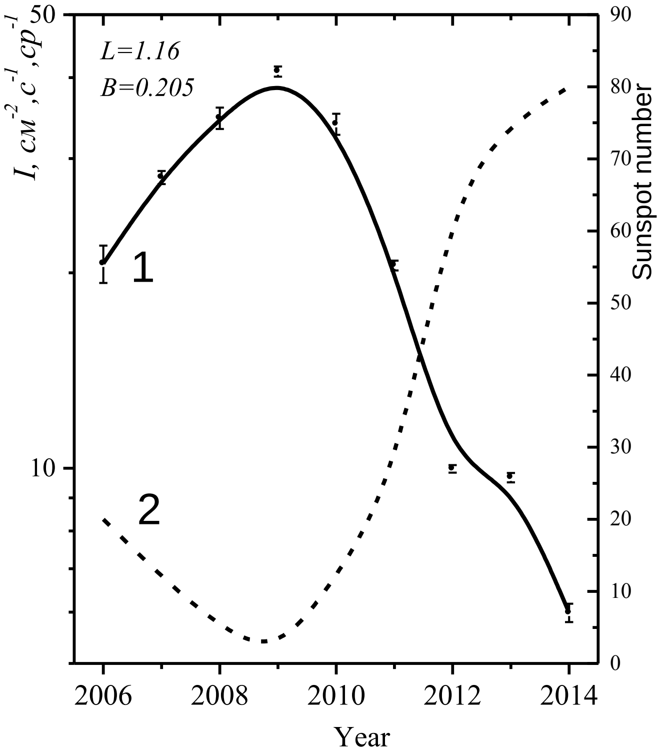

Figure 3. Variation of high-energy proton flux *I* (curve 1) in the inner radiation belt during the solar cycle (curve 2 – mean value of sunspot number).

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Solar x-ray and gamma-ray spectrometer GRIS

GRIS (Gamma and Roentgen radiation of the Sun) is a prospective hard X-ray and gamma-ray spectrometer of solar flares with the energy range from 50 keV to 200 MeV (*Kotov et al., 2015*). It is also designed for registration of high energy neutron fluxes (>30 MeV). The experiment is included in the Russian ISS scientific program and it is under development now.

The instrument will provide opportunities to investigate:

- Electron and ion acceleration and propagation mechanisms during the different phases of solar flares;
- Elemental composition and other parameters of accelerated particles and solar plasma at the gamma-ray generation region.

By means of:

- Bremsstrahlung and gamma-ray lines measurements in the energy range 50 keV to 15 MeV with a relatively high energy (3.5-4.5% @ 662 keV) and temporal (10 ms) resolution;
- Pion decay radiation measurements in the energy range up to 200 MeV;
- Direct solar neutron flux measurements in the energy range above 30 MeV.

The supplementary tasks of the GRIS instrument are:

- Measurements of spectral and temporal characteristics of the cosmic and local background radiation near to the Russian Orbital Segment of the ISS;
- Energy spectra and time curves of terrestrial and cosmic gamma ray bursts measurements with the temporal resolution up to 20 us.

The instrument includes two detector heads: a low energy spectrometer (LES) based on a fast scintillator with relatively high energy resolution 3.5–4.5% at 662 keV ($LaBr_3(Ce)$ or $CeBr_3$) and size of ø7.62×7.62 cm, and a high energy spectrometer (HES) based on ø12×15 cm CsI(Tl) scintillator. Thanks to n/γ discrimination capability of CsI(Tl) crystals, the HES spectrometer is also intended for neutron registration. To reduce a charge particle background count rate the HES detector is surrounded by two anticoincidence shield detectors (ACDs) based on a polystyrene scintillator. The first one represents a dome and covers CsI(Tl) crystal from above. The second ACD shields a backward direction. Together with CsI(Tl) they form a phoswich detector and are viewed by the same PMT. The schematic view of the GRIS detector unit is represented in Fig. 1, and the spectrometers characteristics in Table 1.

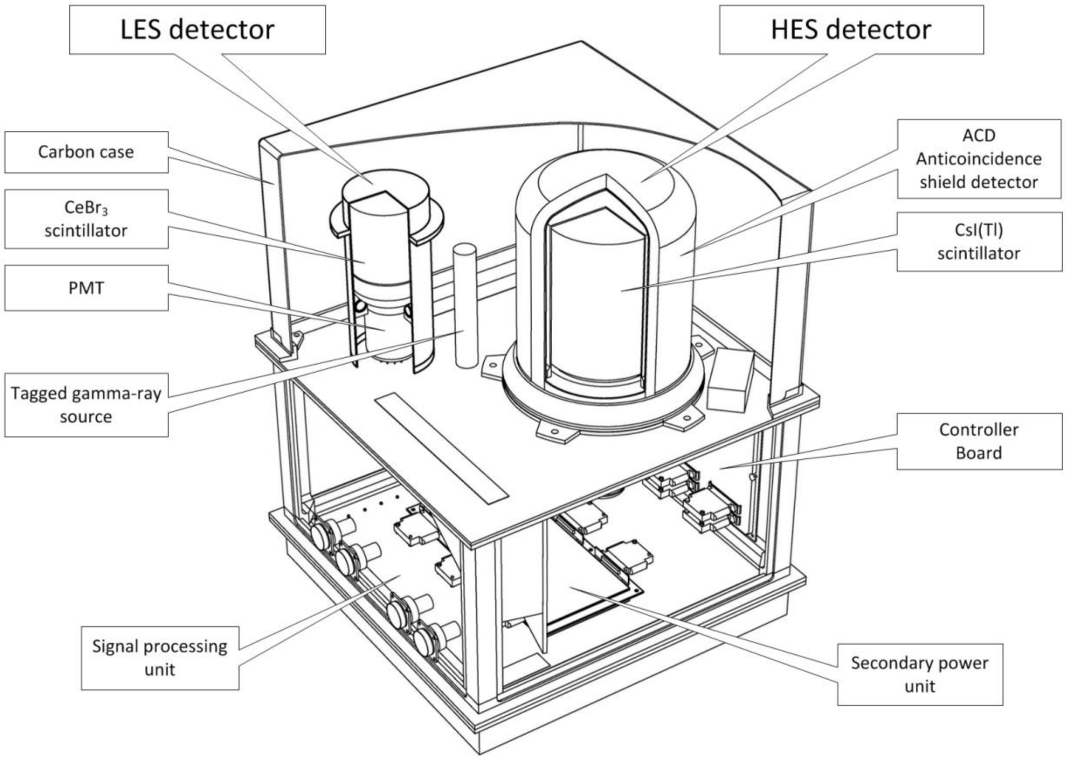

Fig. 1. The GRIS detector unit

The two detectors approach of GRIS makes it possible to measure different spectral components of solar flares in the broad energy range: intensive fluxes of bremsstrahlung and narrow gamma-ray lines due to the fast LES detector with relatively high energy resolution, high energy pion decay radiation and direct solar neutrons by means of the HES detector.

The apparatus will be mounted on a biaxial oriented platform outside the Zvezda service module of the ISS. The platform allows us to increase the Sun observation time inside the detectors field of view (30°) from 6-7% (in case of the stationary mounting of the detector unit) to 52%.

GRIS measured data in the broad energy rage of solar gamma-ray and neutrons obtained simultaneously with observations in the other energy ranges of the electromagnetic spectrum (radio, ultraviolet and X-ray imagers) and particle flux measurements (neutron monitors and charged particle space based detectors) would provide data for detailed investigation of solar flare development in the particle acceleration and propagation phases, which can improve the Solar flare theoretical models.

Table 1 The GRIS spectrometers characteristics

Mass of the detector unit	30 kg
Power consumption	30 W
High Energy Spectrometer (HES)	
Prime detector	CsI(Tl) scintillator ø12×15 cm
Gamma-ray energy range	0.2 to 200 MeV
Gamma-ray energy resolution	8 % FWHM @662 keV
Neutron energy range	>30 MeV
n/γ discrimination quality	1/1000 (expected)
Low Energy Spectrometer (LES)	
Prime detector	$LaBr_3$(Ce) or CeB_{r3} ø7.62×7.62 cm
Gamma-ray energy range	0.05 to 15 MeV
Gamma-ray energy resolution	3.5-4.5% FWHM @ 662 keV

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