Detector of Extreme Energy Cosmic Rays on Board Lomonosov Satellite

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Detector EECR on Lomonosov Satellite.

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Abstract.

In works of Greisen, Zatsepin and Kuzmin an abrupt change (GZK cutoff) of cosmic ray energy spectrum at energy 5×10^{19} eV, was predicted if cosmic ray sources uniformly distributed in Universe, i.e. most of them are at cosmological distances from the Earth.

Models of early Universe could be validated by experimental results on shape of cosmic rays energy spectrum and their mass composition at energies beyond the GZK limit. Experimental study of cosmic ray particles with such high energies encounters difficulty of their very low intensity. To some extent this difficulty has been overcome by measuring atmospheric fluorescence radiation accompanying ultrahigh energy cosmic ray (UHECR) event in the atmosphere. Fluorescence signal could be detected by ground-based detectors at distances 10-40 km from the UHECR track at large area of the atmosphere ~1000 km^2. Greater area in the atmosphere could be observed by the space-based fluorescence detectors looking down to the atmosphere from orbit heights 400-500 km. In SINP MSU in cooperation with other institutions a pioneering space detector for UHECR study has been developed. It is prepared for launch in 2012 on board Lomonosov satellite. Advantages and assets of space UHECR detectors are discussed.

KEYWORDS: ultrahigh energy cosmic rays, atmosphere fluorescence.

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1. Introduction

Solution of one of the most interesting problems in cosmic ray (CR) physics, origin of cosmic rays of the highest energies, near GZK limit (5×10^{19} eV), is directly related to the legacy that was left by D.V. Skobeltsyn, G.T. Zatsepin, S.N. Vernov, A.E. Chudakov and G.B. Khristiansen. S.N. Vernov was the first to pay attention to the crucial role of electromagnetic showers in the cascade process of interactions produced by a primary CR proton. In analysis of data from detectors onboard high altitude balloons he showed the existence of an efficient mechanism for energy transfer from a primary proton to an electron-photon cascade (Vernov & Charakhch'yan, 1948; Baradzej et al, 1948). This conclusion was reached on the eve of discovery of the neutral pion, which production in proton-nuclei interactions gave a real mechanism for such energy transfer. After neutral pion discovery, it became clear that the primary proton energy is converted mainly to the cascade of electrons and photons and, in a long run, is expended in process of ionization of atmospheric atoms and molecules. Thus the total number of particles in an electron-photon cascade in the atmosphere, the main component of the extensive air shower (EAS), became a measure of the energy of high energy primary CR particles.

In 1952 D.V. Skobeltsyn, G.T. Zatsepin and S.N. Vernov suggested to build a large EAS array within the new Moscow State University territory. The EAS array was constructed under the leadership of G.B. Khristiansen, and became one of the world's largest arrays for EAS study in 1960-s. A change of the primary CR energy spectrum at 3×10^{15} eV was ultimately established on this array. A knee in the integral spectrum index from 1.7 for $E < 3 \times 10^{15}$ to 2.1 for energies above 3×10^{15} eV was recorded as a discovery (Vernov et al. 1971) with priority to the 1958 work by Khristiansen and Kulikov (Khristiansen & Kulikov, 1958). Study of the primary CR energy spectrum at energies 10^{15}–10^{17} eV continues at present. The most plausible explanation for the knee in the spectrum observed at 3×10^{15} eV is an influence of two factors: (1) maximum energies of the particles accelerated in Galactic sources (supernova envelopes) are roughly corresponded to these energies and (2) particle diffusion mean free path in the Galaxy increases at these energies so that particles leave the Galaxy faster.

2. Fluorescence of the atmosphere and its use for remote observation of EAS

In searching for the most appropriate method for measuring primary CR particle energy based on the EAS electron-photon component data, A.E. Chudakov suggested to use the EAS

Cherenkov and fluorescence radiation in the atmosphere as a measure of the number of EAS electrons. In his pioneering experiment (Zatsepin & Chudakov, 1962) the Cherenkov light detector was used for search of gamma-ray sources. Later the fluorescence of the atmosphere (the radiation of excited atmospheric molecules and atoms during their ionization) was suggested for measuring the EAS cascade curve and EAS primary energy (Belyaev & Chudakov, 1966). Both those types of radiation turned out to be in the region of high atmospheric transparency, making it possible to develop ground-based Cherenkov and air fluorescence detectors for observation of electron-photon showers high in the atmosphere. This type of observation has an important advantage over direct electron flux measurement: it makes possible to measure the number of electrons at shower development maximum, which is proportional to the primary energy. In addition, measurement of the atmospheric depth at which the shower reaches its maximum allows the primary CR particle mass to be estimated.

Cherenkov EAS detectors are widely used, both in studying the energy spectrum and mass composition of high energy CRs ($E > 10^{15}$ eV) and in searching for point sources with comparatively low energies ($10^{10} – 10^{12}$ eV).

Fluorescence detectors play a special role in studying the highest energy EASs. The fluorescence yield per one electron is very low and this method can be used only for huge electron fluxes in showers with energies above 10^{18} eV. Since the fluorescence radiation is isotropic, this method allows us to search for and to measure showers at large area in the atmosphere (up to ~1000 km^2) using a small number of detector stations. This distinguishes the method of fluorescence observation from the method of observation of Cherenkov radiation concentrated in a narrow angle cone (~5°) in direction of the primary CR particle. Advantages of the new method for accurate measurement of the primary energy and for measuring EASs at distances up to 20 km were demonstrated by operation of the first fluorescence detector, Fly's Eye detector (Baltrusaitis et al. 1985). Fluorescence method for measuring primary energy and EAS cascade curve became a reliable method for studying EASs of ultrahigh energies after creation of the HiRes detectors (Boyer et al. 2002) and a system of fluorescence detectors at the Pierre Auger Observatory operating in conjunction with network of ground-based EAS particle detectors (Abraham et al. 2004).

3. The Greisen-Zatsepin-Kuzmin effect

In 1966, immediately after discovery of cosmic microwave background radiation (CMBR) with a temperature of 2.7 K, that was left after the Big Bang, Greisen, Zatsepin, and Kuzmin (Greisen, 1966), (Zatsepin & Kuzmin, 1966) showed that a cutoff could exist in the CR energy spectrum near 5 $\times 10^{19}$ eV due to interaction of CR protons and nuclei with CMBR photons. Detection of such a cutoff in the spectrum would suggest that sources of CRs with such high energies are located at cosmological distances >100 Mpc. This prediction aroused great interest in studying CRs of the highest (extreme) energies. On Vernov's initiative, a collaboration was created between two leading USSR institutes in the field of EAS research (Skobeltsyn Institute of Nuclear Physics of MSU and Lebedev Physical Institute of Academy of Sciences) and construction of then largest Yakutsk array with an operation area of 20 km^2 was started in the late 1960s near Yakutsk. Yakutsk array was put into operation by staff of the newly founded Institute of Space Physics and Aeronomy of the Siberian Department of the Academy of Sciences in 1975. The Volcano Ranch (USA), Haverah Park (Great Britain), and Narrabri (Australia) arrays were also constructed approximately at the same time. Measurements at energies far beyond the first knee in the spectrum (above 10^{17} eV) were performed at these arrays with exposure of 100 km^2 sr yr. Later arrays with larger working area (AGASA in Japan with area of ~100 km^2, Fly's Eye and HiRes arrays in USA with array ~1000 km^2 at energies >10^{19} eV) showed that the CR spectrum at energies ~3 × 10^{18} eV (still far from the GZK limit) returns to the shape that is observed before the knee. Figure 1 presents the currently available data on the CR energy spectrum in a wide range of energies from 10^{12} to 10^{20} eV. The data from the unique SINP calorimeter that operated onboard the PROTON satellite (Grigorov et al. 1970) are presented here in the range of "low" energies; the data from the MSU EAS (Sulakov, 1999), Tunka (Chernov et al. 2005), and Kascade Grande (Haungs et al. 2009) arrays are presented in the knee region of the spectrum. The data from the Yakutsk array (Pravdin et al. 2009) and from the last generation EAS arrays, HiRes (Abbasi et al. 2005), the Pierre Auger Observatory (Kampert, 2011) are presented at the highest energies. As we see from the Fig. 1, at energies above the first knee, some data disagree in absolute intensity. This is a result of difficulty in measuring the absolute energy for each of the experimental arrays. If we give preference to the data obtained by the calorimetric method (in this method primary energy is in proportion to total number of particles in a cascade), then three regions where the spectrum changes its shape are clearly distinguished: (1) the first knee in the spectrum toward its softening at E ~ 3 × 10^{15} eV, (2) the return to a "hard" spectrum at 3 × 10^{18}–10^{19} eV, and (3) the new knee in the spectrum toward its softening at the GZK limit ~5 × 10^{19} eV. Nature of the first knee was discussed above. Return to a hard spectrum at 3 × 10^{18} eV suggests that bulk of the particle flux at such ultrahigh energies is produced by extragalactic accelerators with a maximum energy much higher than the Galactic ones. Note that the contribution from extragalactic CRs at 10^{15} – 10^{16} eV (designated by the dashed line in the figure) is an order of magnitude smaller than that from Galactic CRs.

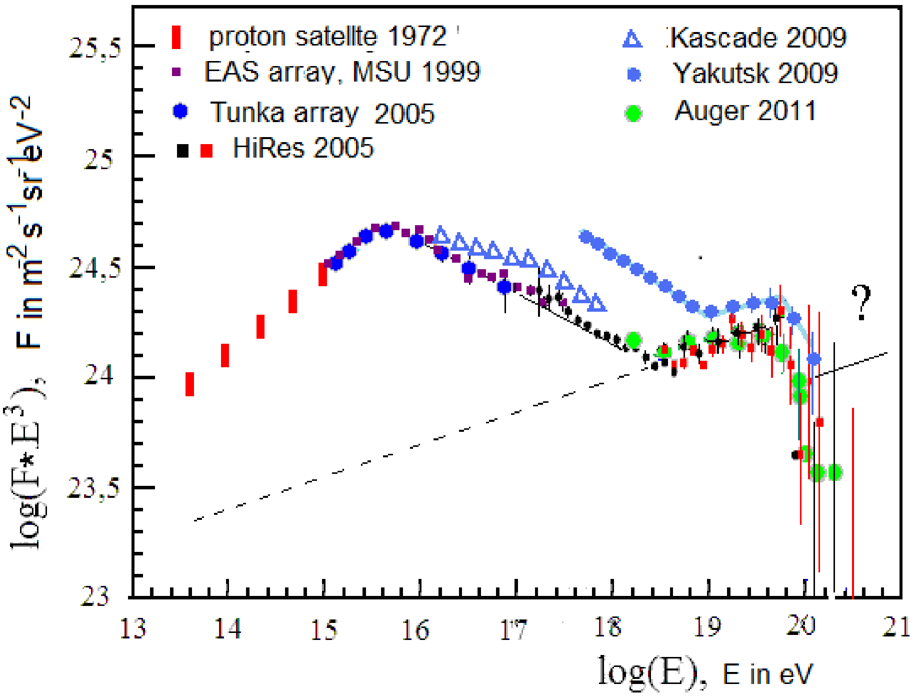

Fig. 1 Cosmic ray energy spectrum in wide range of energies.

The energy spectrum at extremely high energies ($E > 5 \times 10^{19}$ eV) is very difficult to measure due to small number of such particles. A traditional array of many EAS particle detectors with the operation area of several thousand kilometers is one of the ways to resolve this task but it suffers from inaccurate measure of the primary energy. Better way is a combination of particle detector array and fluorescence detectors observing at the same area. At night time fluorescence detectors allow us to calibrate the primary energy measure but the main event statistics is collected in all day exposure of the particle detector array. Two such “hybrid” arrays have already been constructed with areas of ~3000 km^2 (the Pierre Auger Observatory in Argentina) and ~700 km^2 (the Telescope Array in Utah, USA). So far the exposure of these arrays is insufficient to reach final conclusions about the energy spectrum at $E > 10^{20}$ eV, but the experimental data from the Pierre Auger Observatory confirm the HiRes array data on existence of a change in the energy spectrum near GZK limit. At the same time, one can see that currently available statistics of events do not provide convincing evidence for the sharp cut-off of the energy spectrum at $E > 10^{20}$ eV. So far searches for particles and their sources with $E > 2 \times 10^{20}$ eV are possible.

Numerous astronomical data on the extragalactic objects capable of accelerating charged particles to energies much higher than 10^{19} eV have been accumulated in the recent decades. An obvious indicator that an object of size D can accelerate particles to energy E (eV) is the existence of a magnetic field B (G) along the whole length of this object such that the particle gyroradius $R = E / (3 \times 10^4 B)$ cm is smaller than D. These sources include: radio galaxies

(galaxies with intense radio emissions); active galactic nuclei containing black holes; colliding galaxies.

All these sources contain gas (plasma) jets moving with speeds approaching the velocity of light. Such jets play the role of the shock waves that are needed for operation of an accelerator. Active galactic nuclei (AGN) with gas jets turned out to be the most promising among the astrophysical objects that are candidates for extremely high energy CR sources. The recent data from the Pierre Auger Observatory array (Kampert, 2011), in which a correlation was found between the arrival direction of particles with an energy above 6×10^{19} eV and AGN sources, may be considered as hope for obtaining data on sources of particles with energies of the order of the GZK limit in coming years.

4. Pioneering Space based detector for study of cosmic rays beyond GZK limit

As can be seen from the previous section, the data from the existing ground-based detectors of extremely high energy cosmic rays (EECR) have not yet given the final answer to the question of the existence and physical nature of particles near and above the GZK limit. To solve this problem, a technique for observing EECR particles with an exposure two orders of magnitudes larger than the existing detectors should be found. The method of EAS fluorescence observation from satellites proposed by Linsley (Linsley & Benson, 1981) may become such a technique. SINP MSU was ready to create a space-based EECR detector owing to its great experience in operation both ground-based EAS arrays and cosmic ray orbital detectors. In collaboration with JINR (Dubna) and Universities of Korea and Mexico space-based detector TUS (Tracking Ultraviolet Setup) has been suggested (Khrenov et al. 2001), (Khrenov et al. 2004).

The space-based detector has the following advantages:

1) EECR particle track can be observed on a huge area of the atmosphere owing to great distance from the detector to the atmosphere. At orbit height of Lomonosov satellite (500 km), TUS detector surveys a 6400 km^2 area of the atmosphere.

2) In 1 year of in-orbit operation, one and the same detector observes the entire celestial sphere. This will allow to study distribution of EECR sources, despite a possible inaccuracy of determining the primary particle energy. An unavoidable difference in absolute value of the energy measured by different ground-based arrays causes difference in EECR intensity in different sky regions covered by different arrays.

At the same time, transferring a fluorescence detector to a satellite orbit encounters a number of difficulties:

(a) Observation of EAS from a distance that is approximately a factor of 10 greater than in ground-based arrays requires higher sensitivity and resolution of the optical system and the photo detector. The desirable resolution of one detector pixel should be equal to the diameter of the lateral electron distribution in a shower. For a satellite orbit height of 500 km, the angular resolution of the orbital detector should be 0.4–2 mrad, which is an order of magnitude higher than that of the existing ground-based detectors, 20 mrad.

(b) The light noise level of nighttime atmosphere in observations from a satellite varies on-route. The data from Universitetsky–Tatiana satellite (Sadovnichii et al. 2011) give estimates for the intensity of background UV radiation variation: from 5×10^7 – $2\ 10^8$ photon cm^{-2} sr^{-1} s^{-1} (lower value – at moonless nights above oceans, high value – above aurora zones and city lights) to 2×10^9 photon cm^{-2} sr^{-1} s^{-1} (at full moon nights). At specially chosen locations of ground-based arrays, this noise does not exceed 5×10^7 photon cm^{-2} sr^{-1} s^{-1} at moonless nights.

(c) During flight above low latitudes, where electric activity of the atmosphere is high, impulsive noise from lightning and accompanying high altitude discharges is added to average noise level.

(d) Technology of an orbital fluorescence detector should satisfy the complex conditions in which any space technology works.

Bearing these difficulties in mind a program for gradual conversion of the technology of fluorescence detectors from ground-based version to a space version was formulated. TUS detector is the first comparatively “simple” instrument that will approve reliability and stability of optical system and photo detector designed for operation in space.

This detector consists of two main parts: the mirror-concentrator with an area of 1.8 m^2 (Fig. 2) and the photo detector composed of 256 pixels located at the mirror focus (Fig. 3).

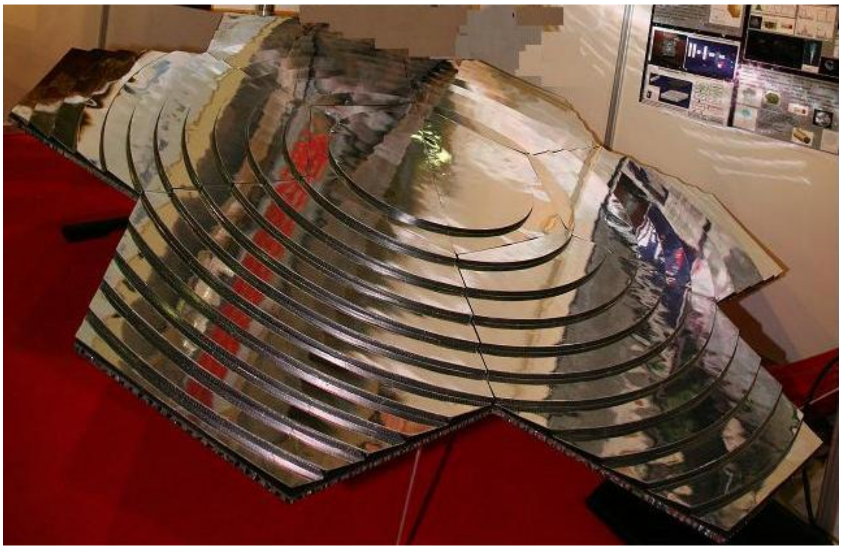

Fig. 2 TUS detector mirror-concentrator.

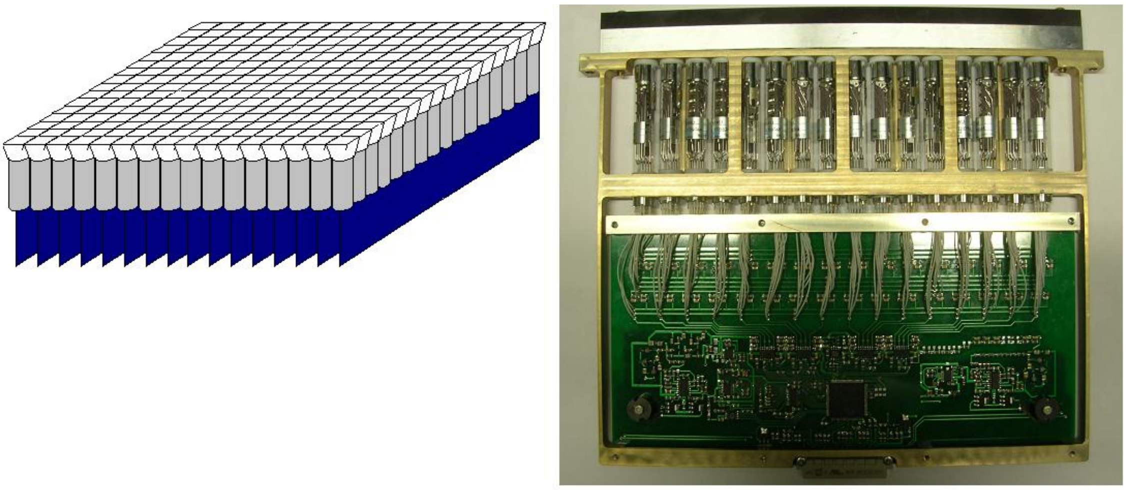

Fig. 3 TUS detector photo receiver. Pixels are grouped in 16 clusters with 16 pixels in every cluster (left panel). One cluster (right panel).

The mirror is designed as sum of the central parabolic mirror and 11 parabolic rings focusing a parallel beam to one focal point. In this design a thickness of the mirror construction is small (3 cm) which is important for mirror implementation into satellite construction. Focal distance from the mirror surface is 1.5 m. The mirror is cut to hexagonal segments with diagonal 63 cm. Mirror segments are made of carbon plastic strengthened by honey comb aluminum plate so that the mirror construction is temperature stable in wide range of temperatures (from -80° to +80°C). Mirror surface is obtained as plastic replicas of aluminum press forms (one for central mirror part and one for lateral parts). Plastic rings then covered by aluminum film and protected by MgF_2 coat in vacuum evaporation process. Reflectivity of the mirror surface at wavelength 350 nm (average for the atmosphere fluorescence) is 85%. Expected life time of the mirror is not less than 3 years.

Photo detector pixels are photomultiplier tubes PMT R1463 of Hamamatsu with multi-alcali cathode of 13 mm diameter. Quantum efficiency of the PMT cathode is 20% for wavelength 350 nm. PMT’s multi-alcali cathode (instead of usually used bi-alcali cathode in ground-based fluorescence detectors) was chosen for operation in wider range of temperature in which cathode operates in linear regime. To make the detector field of view (FOV) uniformly filled with pixels the light guides with square 15×15 mm entrance and circle output adjusted to PMT cathode were used. Optical point spread function of the mirror has diameter less than 15 mm, Fig. 4, so TUS resolution of EAS track coordinates is of about 15 mm at focal distance 1.5 m, i.e. angular resolution is 10 mrad. Photo detector consists of 16 PMT clusters each of 16 tubes. Every cluster has its own electronics board which is connected to central “mother” board. The whole TUS detector FOV is 0.16 rad.

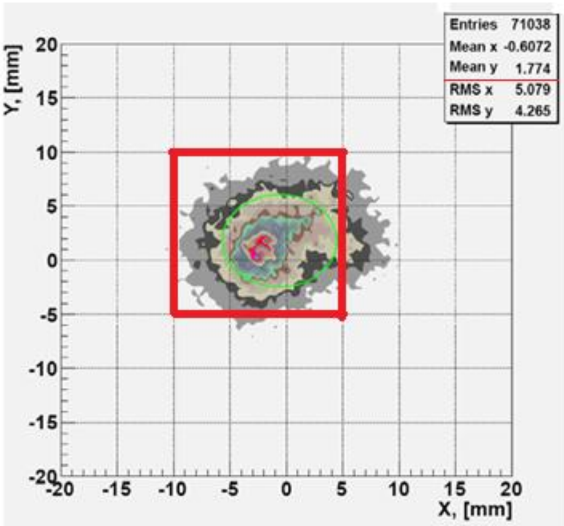

Fig.4 Optical point-spread function (curves) against pixel size (15 mm).

Today TUS detector is the main part of scientific payload of Lomonosov satellite (Fig.5) to be launched in 2012 in honor of the 300-year anniversary of M.V. Lomonosov – founder of the Moscow State University.

TUS triggering by EECR events is organized taking into account main feature of the EECR signal in the detector: its amplitude represents number of fluorescent (or scattered Cherenkov) photons arriving at the detector mirror in subsequent time intervals. For events with direction close to vertical in the atmosphere signal develops in one pixel, for events with “horizontal” directions signal moves from pixel to pixel. Optimum integration time for selection of useful event is determined by the shortest signal duration in one pixel. For TUS detector it is t_i=12.8 μs in case of horizontal event direction. At the first stage of trigger a signal in integration time t_i with threshold q_1 is selected. Selection is done in every PMT cluster, coordinates of “hit” pixels are sent to the electronics mother board. At the second stage the map of “hit” pixels is analyzed. “Horizontal” events are selected as events with subsequent in time signals in “m” neighboring pixels, “vertical” events are selected as “n” subsequent in time signals in one pixel. Triggering parameters “q_1”,“m” and “n” are controlled from the mission center. Compromise between a low energy threshold for UHECR events and low rate of “false” triggering will be achieved in control of the triggering parameters. Preliminary estimates of TUS energy threshold is 70 EeV at regions with low intensity of atmosphere glow, at moonless nights. By trigger command all pixel data kept for 256 μs in operative memory are sent to main detector memory. The satellite will transmit data to mission center at frequency 2.4 GHz. For TUS detector there is a limit in data flux: 200 Mbytes per day.

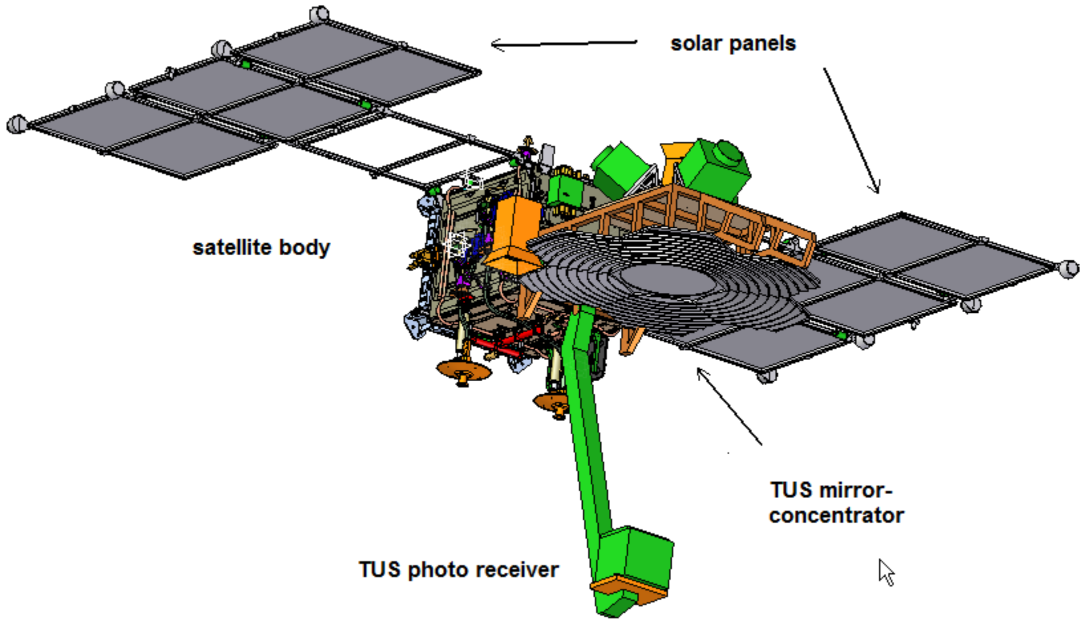

Fig. 5 TUS detector onboard Lomonosov satellite.

TUS detector elements (PMTs, their power supply, electronics for selecting and recording useful events) were tested in operation onboard Universitetsky–Tatiana microsatellites (Sadovnichii et al. 2011). The duty cycle of TUS detector was estimated from these data for various CR particle threshold energies. It was shown that the TUS detector will have an exposure of 12000 km^2 sr yr in 3 years of its in-orbit operation for EECR particles with energies above 300 EeV, which is approximately equal to exposure of Pierre Auger Observatory, which is the largest currently active ground-based array. It should be emphasized that both types of detectors, space based and ground based, are not mutually exclusive but rather complement each other (Khrenov, 2002).

The next space detector planned to be KLYPVE detector at Russian segment of International Space Station. Area of the mirror-concentrator in this detector has to be increased to 10 m^2 and number of photo detector pixels – to be increased to 2500.

Detector at geostationary orbit with mirror area of ~1000 m^2 and up to millions pixels in mirror focal plane was proposed (Khrenov et al, 2001) as the largest scale version of the “telescope” space detector that could survey the atmosphere on the entire Earth’s disk. Great efforts will be required to implement such a program.

Apart from the above-mentioned detectors being designed in Russia, an International collaboration of universities and institutes (with participation of Russian scientists) is preparing a space detector based on using wide FOV optics of Fresnel lenses and use of large number of photo detector channels (up to 100000): the JEM-EUSO detector (Takahashi, 2008). Expected exposure of JEM-EUSO for EECR particles with energies above 10^{20} eV in 3 years of operation will be 10^6 km^2 sr yr.

5. Conclusion

Further progress in studying EECR is related to creation of space-based detectors. Time for new interesting results in the field of EECR physics is approaching.

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