PROPOSAL

for the High-energy Physics in the Atmosphere (HEPA) project competition at the Cosmic Ray Division of A. I. Alikhanyan National Laboratory

Measurements of near-UV emission of TGF, EAS and intra-cloud discharges

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1. Scientific goals of the project:

Measurements of extensive air showers and thunderstorm phenomena ***emission in the near-UV range*** with a wide-angle field of view, high-sensitivity photometer with high temporal resolution

2.Scientific tasks

a. Study of the near-UV emission related to thunderstorm ground enhancements (TGEs) and terrestrial gamma-ray flashes (TGF) in a wide temporal scale.
b. Testing of lens photometer capabilities for registering fluorescence radiation from extensive air showers (EASs).
c. Measurements of near-UV background conditions on the Aragats mountain
d. Probing of the possible EAS and lightning relations
e. Measurements of fluorescent TGF emission
f. Study the EAS fluorescent signal in a thunderstorm region characteristics and peculiarities
g. Search for a possible EAS from relativistic dust grains (TUS-like events)

3. State of the art and scientific relevance

Radiation from the Earth's atmosphere, including in the near UV range (300–400 nm), is an important manifestation of various processes occurring in the atmosphere. These are processes of both an internal nature, associated with electrical currents (thunderstorm phenomena) or with anthropogenic influence, and the result of an external impact on the Earth’s atmosphere: penetration of energetic ionizing radiation, cosmic rays in a wide range of energies, the passage of meteors, etc. Measurements of the spatiotemporal structure of the emission make it possible to study not only the mechanisms of processes in the Earth's atmosphere, but also the sources of their origin, including astrophysical ones. In this case, the atmosphere acts as a source of luminescence, a natural optical filter, as well as a huge detector that converts the energy of highly ionizing radiation into optical range recorded from a spacecraft or ground-based means.

As early as 1925, highly atmospheric effects over thunderstorm areas were predicted, associated with increased ionization, fluxes of energetic particles and optical phenomena [1]. Later, these phenomena were recorded by optical cameras [2–4], and the presence of energetic gamma-ray fluxes correlated with thunderstorm areas [5], as well as beams of electrons and positrons, was established [6]. Studies of these phenomena from satellites is being conducted at M.V. Lomonosov Moscow State University, starting with the first scientific and educational satellite "University-Tatyana", launched in 2005 [7]. A classification of such transient atmospheric events (TAE) has been developed, the main mechanisms of occurrence have been proposed and worked out [8], and global characteristics have been studied: frequency of occurrence and distribution around the globe, total energy release [9], influence on the chemical composition of the atmosphere [10]. However, a number of important questions remain unresolved: what is the relationship between gamma and optical transients, what is the main mechanism for the formation of energetic gamma rays in the atmosphere, is there a relationship between extensive air showers and the appearance of TAE, etc. Observations carried out in the near-UV band are of particular interest, since this spectral range is associated with intra-cloud and above-cloud processes, which can be important for the mechanism of initiation and formation of a lightning discharge. Some of the first observations and descriptions of such events were made using data from the Moscow State University satellites [11, 12].

Terrestrial gamma-ray flashes are bursts of hard X- and gamma-rays produced via bremsstrahlung from runaway electrons accelerated in the electric fields of thunderstorms. The TGFs are reported to typically last from a few tens up to a few hundred microseconds, and have individual photon energies up to ~40 MeV. Analysis of the energy spectra of TGFs and lightning radio atmospherics indicate that they are produced below 21 km altitude, most likely between 10 and 15 km.

Recent observations of TGFs which were made in the ASIM project on board the ISS demonstrate that TGF onsets are always before or at the same time as the optical pulse onsets [13]. Such temporal relation between optical and gamma rays fluxes can be in favor of the relativistic runaway electron avalanche (RREA) mechanism of TGF formation, suggested in [14]. On the other hand, in [15] optical measurements at 180–230, 337, and 777.4 nm related to 69 TGFs measured by the ASIM detector were analyzed. It was shown that the pulses have rise times comparable to lightning but longer durations, pulse amplitudes at 337 nm are ~3 times larger than at 777.4 nm and these results support the leader-streamer mechanism for TGF generation.

So the underlying mechanism for creating the observed TGF photon fluxes is still unclear and should be investigated. One possibility is to measure spatial structure and spectral peculiarities of the optical signal in the near-UV wavelength band. For example, in [16] it was shown that optical emissions, appearing as the low-energy signature of the underlying electron acceleration mechanism, are a good probe to point to key ingredients in TGF production. The spatial area and $2PN_2/1NN_2^+$ are significantly different for RREA and streamer zone optical emission.

During propagation through the atmosphere, a TGF can produce a kind of EAS-like fluorescent emission. The mechanism of fluorescence production described in [17] naturally occurs in the atmosphere with the presence of large quantities of energetic X-rays and gamma rays. This can be considered as a new type of TAE. Observation of this TAE could lead to a significant improvement of the understanding of TGFs. This processes can develop between cloud and ground as well as in the upper part of the thundercloud since the TGF may be a manifestation of the so-called thunderstorm ground enhancements (TGEs) on a small time scale [18], discovered at Aragats station.

Another possible application of the available telescope lies in the field of cosmic ray physics. The point is that one of the important methods for studying ultra-high energy cosmic rays (energies starting from approximately 1 EeV) is the registration of fluorescent radiation (scintillation) in the ultraviolet (UV) band in the Earth's night atmosphere, which occurs during the development of an extensive air shower (EAS). An important advantage of fluorescent telescopes compared to surface detectors of various types is that they allow one to estimate the energy of primary particles and the depth of maximum of an EAS. Both main modern experiments aimed at studying ultra-high energy cosmic rays - the Pierre Auger Observatory in Argentina and the Telescope Array in the USA - have a number of different fluorescence telescopes (FTs). The main telescopes with mirrors larger than 10 square meters are directed at an elevation of up to 30 degrees and are designed to register signals from EAS generated by cosmic rays with an energy above 1 EeV. Similar telescopes as part of the Auger installation (HEAT) and telescopes with mirrors with an area of 3.7 square meters as part of the Telescope Array (TALE), are directed at angles from 30 to 60 degrees to the horizon, making it possible to lower the threshold for detecting EASs approximately by an order of magnitude, down to ~0.1 EeV. An alternative approach based on the use of small telescopes with an aperture size of the order of 1 m^2 has been developed since the early 2010s (FAST project, Privitera, 2012). Results from testing prototypes of this experiment provide encouraging results.

All FTs mentioned above are reflecting telescopes. However, another scheme is also possible, namely a refractor telescope. A telescope of this type was developed by the JEM-EUSO collaboration to study ultra-high energy CRs from a low-Earth orbit. A prototype of such a telescope, equipped with two Fresnel lenses with an area of 1 m^2 (EUSO-TA), operates on the territory of the Telescope Array experiment. Since 2019, another prototype of a full-scale telescope has been operating on board the International Space Station as part of the Russian-Italian experiment, Mini-EUSO. It is a small fluorescent telescope built according to the same optical design with two Fresnel lenses. The purpose of the experiment on board the ISS is to study the night glow of the Earth in the UV, to study transient atmospheric phenomena, meteors and other phenomena that continue to radiate in the UV. The presented project proposes to move a similar telescope to Mount Aragats for the summer of 2024 and install it at a large angle to the horizon. This will make it possible to test for the first time the applicability of telescopes of this type for recording the fluorescent glow of EASs at high altitudes above sea level (i.e., significantly closer to the maxima of extensive air showers than in the Pierre Auger Observatory and Telescope Array experiments). If successful, this will allow developing a setup consisting of multiple similar telescopes for cosmic ray studies.

4. The Instrument

The detector represents a wide-field of view highly sensitive telescope with a high temporal resolution (from 1 us). It is based on the experience and solutions used in the Mini-EUSO project [19]. The optical system is presented by two Fresnel lenses, produced from a UV-transparent PMMA. It provides a focusing inside one pixel of the photodetector, which has a size of 3×3 mm. Area of the entrance window is 490 cm^2.

The detector focal surface (FS), consists of a matrix of 12 multi-anode photomultiplier tubes (MAPMTs, Hamamatsu Photonics R11265-M64), arranged in an array of 2×6 elements. Each MAPMT consists of 8×8 pixels, resulting in a total of 768 channels. The MAPMTs are grouped in so-called Elementary Cells (ECs) of 2×2 MAPMTs. Each EC has an independent high voltage power supply and board connecting the dynodes and anodes of the four photomultipliers. Each EC (including filters, MAPMTs and the High Voltage Power Supply - HVPS) is potted with Arathane to avoid electrostatic discharges and short circuits from microscopic floating debris. Each MAPMT in the EC is read by an ASIC that performs single photon counting and sends the data to the FPGA (Zynq) board.

The effective focal length of the system is 205 mm (focal length 300 mm), with a point spread function of 1.2 MAPMT pixels. UV bandpass filters (2 mm of UFS1 material) are placed in front of the MAPMTs to predominantly select wavelengths between 300 nm and 400 nm to perform observations where most of the fluorescence emission from extensive air showers initiated by cosmic rays interacting in the atmosphere is emitted (300–430 nm range).

The detector was developed and produced for the pulsating aurora measurements. It is being operated in Kola peninsula within the PAIPS project [20, 21].

The angular resolution is near 10 mrad, minimal temporal resolution is 1 us in trigger mode and 1 ms in continuous monitoring mode of operation. Thus, it can measure emission in different time scales.

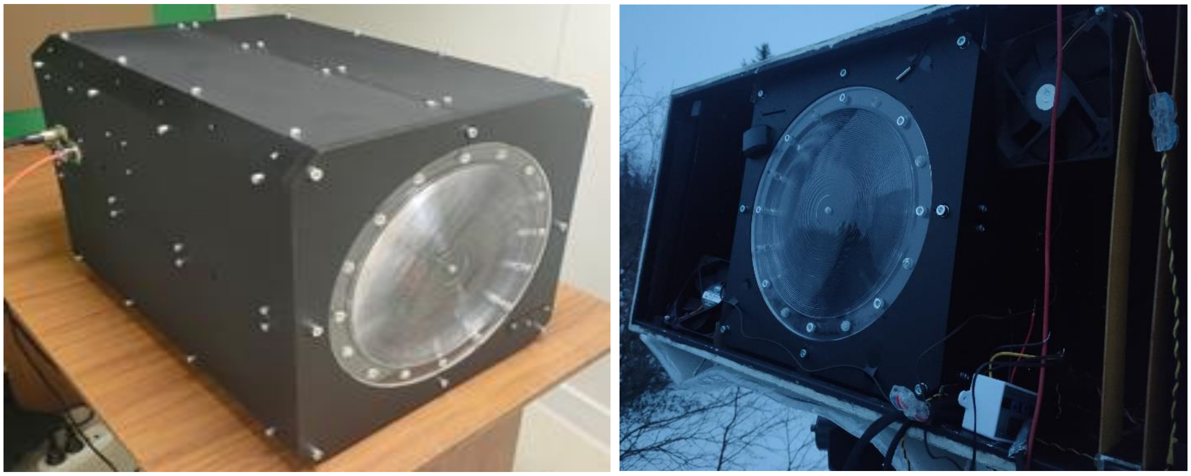

Figure 1. Left: the Mini-EUSO-like fluorescence telescope suggested for installation at the Aragats station. Right: the telescope installed at the Lovozero observatory, Kola Peninsula, Russia.

5. Proposed measurements and data analysis

The detector is planned to operate continuously during night time in trigger and monitoring modes thus a type of measurements and field of research depends on meteorological conditions and atmospheric illumination (anthropogenic and natural)

5.1 Clear sky measurements

This type of measurements is aimed to measure background conditions for EAS measurements at high altitudes, search for possible EAS events and study a variety of events which may cause EAS trigger (transient background). Due to the high altitude location, the detector is placed close to the maxima of EASs. This provides a lower energy threshold and increases the EAS registration statistics.

High altitude location of the set-up allows us to test the possibility of some EAS-like signals to be produced by relativistic dust grains. An EAS produced by this kind of primary particles should have its depth of maximum close to those of EAS in the PeV range, but its luminosity as high as of an EeV EAS or even brighter. An event of this kind was registered during the TUS orbital experiment, but measurements of a single event can’t rule out its other possible origins, anthropogenic or atmospheric.

For this kind of measurements, data of the Aragats charged particle (CP) detector will be used to find correlations of UV pulses with CPs of EASs. Weather station and the all-sky camera will be used to monitor observational conditions and to calculate the exposure of the telescope.

5.2 Thunderstorm measurements

This type of measurement is aimed to investigate a fine temporal structure of a thunderstorm near-UV emission related to intra-cloud discharges, TGFs and lightning discharges during all its stages. Observations in the inclined direction will allow us to observe processes above clouds, i.e., conventional transient luminous events (sprites, jets, ELVES, etc.).

It is important to understand location and sequence of processes responsible for charged particle acceleration in the thunderstorm cloud, producing high energy gamma-rays coming with optical emission. High temporal resolution and spatial resolution of the detector will allow studying the structure of optical emission during TGEs, search for possible TGF formation by electron-photon avalanche fluorescent emission.

For this kind of measurements, data of all Aragats station facilities are of great importance. It is important to locate a lightning discharge by EMP measurements since a single telescope measurements provide only angular resolution, CP detectors will allow one to measure the stage of the TGE development and to study UV emission production relative to the TGE termination. All-sky cameras are important to know the position of clouds in the telescope field of view.

To install the telescope at the Aragats Observatory, a waterproof box with a UV transparent entrance window is required. It is desirable that the box can be rotated in the azimuthal and zenith directions. A dimensional drawing of the telescope is attached to the proposal.

6. Experience of the team

The team of the proposal has a huge experience in the development of fluorescence detectors and telescopes aimed at studying different kinds of radiation in the nocturnal atmosphere of Earth, running the respective experiments and the consequent data analysis. They were at the core of the development of "University-Tatyana", "University-Tatyana-2", "Vernov" orbital experiments, as well as of the world's first orbital prototype telescope TUS onboard the "Lomonosov" satellite aimed at testing the possibility of registering UHECRs from a low-Earth orbit. The team takes active participation in the activities of the international JEM-EUSO collaboration. As such, it took part in the development of the Mini-EUSO telescope, which is in operation on board the International Space Station since 2019, and of the EUSO-SPB2 stratospheric experiment. Besides this, the team is delivering a ground experiment at Kola Peninsula, Russia, see above.

7. Team members

P.A. Klimov (Principal Investigator, project manager)

A.A. Belov (Principal Engineer)

M.Yu. Zotov (UHECR PI)

A.S. Murashov (Engineer, pcb designer)

D.A. Trofimov (PhD student)

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8. Some publications of the team in the last 5 years

2023 *Variations in Pulsating Aurora Emission in 337 nm and 391 nm Nitrogen Spectral Lines during Geomagnetic Substorms*. Klimov P., Nikolaeva V., Belov A., Kozelov B., Murashov A., Roldugin A., Sharakin S. в журнале Universe, том 9, № 10, с. 441

2023 *Neural Network Based Approach to Recognition of Meteor Tracks in the Mini-EUSO Telescope Data*. Zotov Mikhail, Anzhiganov Dmitry, Kryazhenkov Aleksandr,... Belov Alexander A.,... Klimov Pavel et al. в журнале Algorithms, издательство MDPI (Basel, Switzerland), том 16, № 9

2023 *An Orbital Detector of Ultra-High-Energy Cosmic Rays: Status and Prospects of the KLYPVE Project*. Belov A.A., Klimova P.A., Sharakin S.A., Zotov M.Yu. в журнале Bulletin of the Russian Academy of Sciences: Physics, издательство Allerton Press Inc. (United States), том 87, № 7, с. 867-869

2023 *Near-UV Pulsations in the Aurora Region Measured by Orbital Telescope TUS during High-Intensity and Long-Duration Continuous AE Activity*. Klimov Pavel, Kalegaev Vladimir, Sigaeva Ksenia, Ivanova Alexandra, Antonyuk Grigory, Benghin Viktor, Zolotarev Ivan. в журнале Remote Sensing, издательство MDPI (Basel, Switzerland), том 15, № 1

2023 *Observation of night-time emissions of the Earth in the near UV range from the International Space Station with the Mini-EUSO detector*. Casolino M.,... Belov A.A.,... Klimov P. et al. в журнале Remote Sensing of Environment, издательство Elsevier BV (Netherlands), том 284, с. 113336

2022 *System of Imaging Photometers for Upper Atmospheric Phenomena Study in the Arctic Region*. Klimov Pavel, Sharakin Sergei, Belov Alexander, Kozelov Boris, Murashov Alexei, Saraev Roman, Trofimov Daniil, Roldugin Alexei, Lubchich Vladimir. в журнале Atmosphere, издательство MDPI (Basel, Switzerland), том 13, № 10

2022 *UV telescope TUS on board Lomonosov satellite: Selected results of the mission*. Barghini Dario, Bertaina Mario, Cellino Alberto, Fenu Francesco, Ferrarese Silvia, Golzio Alessio, Ruiz-Hernandez Oliver, Klimov Pavel, Montanaro Antonio, Salsi Anthony, Sharakin Sergei, Sigaeva Ksenia, Zotov Mikhail. в журнале Advances in Space Research, издательство Pergamon Press Ltd. (United Kingdom), том 70, № 9, с. 2734-2749

2022 *Onboard Performance of the Level 1 Trigger of the Mini-EUSO Telescope.* Battisti M., Barghini D., Belov A.A.,... Klimov P. et al. в журнале Advances in Space Research, издательство Pergamon Press Ltd. (United Kingdom), том 70, № 9, с. 2750-2766

2022 *Optical complex for the study of pulsating aurora with sub-millisecond time resolution on the basis of the Verkhnetulomsky observatory*. Belov A.A., Klimov P.A., Kozelov B.V., Barrillon P., Blin-Bondil S., Marszał W., Murashov A.S., Parizot E., Prévôt G., Roldugin A.V., Sharakin S.A., Szabelski J., Takizawa Y., Trofimov D.A. в журнале Journal of Atmospheric and Solar-Terrestrial Physics, издательство Pergamon Press Ltd. (United Kingdom), том 235

2022 *Совместная регистрация пульсирующих сияний на спутнике Ломоносов и камерой всего неба на Кольском полуострове*. Климов П.А., Козелов Б.В., Ролдугин А.В., Сигаева К.Ф. в журнале Известия Российской академии наук. Серия физическая, том 86, № 3, с. 375-379

2022 *Status of the K-EUSO Orbital Detector of Ultra-High Energy Cosmic Rays*. Klimov Pavel, Battisti Matteo, Belov Alexander A., Bertaina Mario, Bianciotto Marta, Blin-Bondil Sylvie, Casolino Marco, Ebisuzaki Toshikazu, Fenu Francesco, Fuglesang Christer, Marszal Wlodzimierz, Neronov Andrii, Parizot Etienne, Picozza Piergiorgio, Plebaniak Zbigniew, Prevot Guillaume, Przybylak Marika, Sakaki Naoto, Sharakin Sergey, Shinozaki Kenji, Szabelski Jacek, Takizawa Yoshiyuki, Trofimov Daniil, Yashin Ivan, Zotov Mikhail. в журнале Universe, том 8, № 2

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2018 *The integration and testing of the Mini-EUSO multi-level trigger system*. Belov Alexander, Bertaina Mario, Capel Francesca, Fausti Federico, Fenu Francesco, Klimov Pavel, Mignone Marco, Miyamoto Hiroko. в журнале Advances in Space Research, издательство Pergamon Press Ltd. (United Kingdom), том 62, № 10, с. 2966-2976

2018 *Mini-EUSO: A high resolution detector for the study of terrestrial and cosmic UV emission from the International Space Station*. Francesca Capel, Alexander Belov, Marco Casolino, Pavel Klimov. в журнале Advances in Space Research, издательство Pergamon Press Ltd. (United Kingdom), том 62, № 10, с. 2954-2965

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