Prospects of Observing Gamma-Ray Bursts with Orbital Detectors of Ultra-High-Energy Cosmic Rays

M. S. Pshirkov and M. Yu. Zotov

Abstract—TUS (Tracking Ultraviolet Set-up), the first orbital telescope of ultra-high energy cosmic rays (UHECRs), has demonstrated that instruments of this kind have much broader capabilities and can also detect various transient luminous events, meteors, anthropogenic glow and other processes taking place in Earth atmosphere in the UV frequency range. In this short paper, we address the question whether an orbital detector of UHECRs can also register gamma-ray bursts (GRBs) via the fluorescent glow of irradiated nocturnal atmosphere. We analyse the latest Fermi GBM catalog of GRBs and properties of several active and perspective instruments. The study reveals that even an advanced detector with parameters of an optical system similar to that of the KLYPVE-EUSO (K-EUSO) or POEMMA telescopes and an appropriate trigger tuned to register events that evolve much slower than an extensive air shower, has very modest capabilities in this respect and will be able to observe only a few GRBs per year of operation.

DOI: 10.1134/S1063772921040041

1. INTRODUCTION

Gamma-ray bursts (GRBs) are one of the most violent astrophysical phenomena: with apparent luminosities that can exceed $10^{52} \text{erg s}^{-1}$, they are observed up to high redshifts $z = 8–9$. GRBs comprise two distinct classes of different origin: “long” and “short” ones depending on whether their durations are greater or less than two seconds [1–3]. Long GRBs are thought to be produced during a core collapse of massive stars, so-called SN Ib/c-type supernovae, and have a typical duration larger than several seconds, while short bursts appear to be associated with the merger of two neutron stars into a new black hole or a neutron star with a black hole to form a larger black hole [4, 5].

The majority of GRBs except for the brightest ones are registered from space because their $\gamma$-ray spectrum peaks at several hundred kiloelectronvolts, and Earth atmosphere is absolutely opaque for these photons. The attenuation length corresponds to a grammage $X_0 \sim 10 \text{ g cm}^{-2}$, which means most of the energy will be absorbed at altitudes larger than 30 km. Ionization caused by $\gamma$-rays will produce a considerable fluorescent emission of nitrogen atoms, which can be registered by a dedicated instrument [6]. On the other hand, this emission is similar to fluorescence observed in extended air showers (EAS) initiated by ultra-high energy cosmic rays (UHECRs) with energies above $\sim 50$ eV. Thus, orbital detectors of UHECRs theoretically can register GRB-induced effects as well. This option attracted considerable interest after TUS, the world’s first orbital telescope of UHECRs demonstrated that a scientific device of this kind can operate as a multi-purpose instrument capable of registering ultraviolet (UV) illumination of very different nature. In particular, it registered hundreds of flashes caused by lightning strikes, multiple transient luminous events (TLEs), among them more than two dozen of so called ELVEs (short-lived optical events that manifest at the lower edge of the ionosphere as bright rings expanding at the speed of light up to a maximum radius of $\sim 300$ km [7]) as well as miscellaneous other flashes seemingly related to thunderstorm activities [8–12]. It also detected multiple meteors, UV pulsations in the sub-auroral regions, various anthropogenic lights and flashes of a yet unknown origin, including a number of unexpected flashes that demonstrated waveforms and kinematics of the signal very similar to those expected from EAS but with a much higher luminosity [13, 14]. Besides this, it was demonstrated that even a comparatively simple device...
like TUS can register so called nuclearites, nuggets of a hypothetical strange quark matter [15].

The surprising variety of different phenomena registered by TUS motivated us to address the possibility of registering GRBs with this instrument and a number of other orbital UHECR detectors that are being actively developed these days. It was interesting to estimate if an UHECR telescope can contribute to the GRB science by complementing results of dedicated experiments. The point is that none of the existing GRB detectors observes the whole celestial sphere at any given moment of time. Thus, there is a chance that a GRB escapes from being registered just because it took place in a “blind zone” of a dedicated instrument. Registering a GRB with a supplemental tool could be helpful in such a situation. It is important to note here that an orbital UHECR detector could provide information on the time of the trigger, an approximate light curve of the flash and even an approximate direction to the GRB by an analysis of non-uniformity of illumination of the field of view of the detector. However, one should take into account that an observed pattern of GRBs will strongly differ from that of an EAS (or a TLE): instead of a confined and quasi-linear image of a shower (or a compact image of a TLE), the effect will manifest itself in a coherent increase of the ultraviolet background illumination over the whole field of view of an instrument since the whole atmosphere will glow brighter for some time. The respective timescale will also be much larger: from a fraction of a second to possibly a few dozen (and even more) seconds for GRBs instead of a few dozen microseconds in case of an EAS.

Motivated by the truly multi-purpose nature of TUS, we employ the Fermi GBM catalog of GRBs [16] to study if an orbital detector of UHECRs can register a GRB thus complementing observations of dedicated instruments. We consider technical parameters of the TUS detector, the KLYPVE-EUSO (K-EUSO) [17] and POEMMA [18] telescopes, which are being actively developed, and the Mini-EUSO instrument, which is currently working on board the Russian segment of the International Space Station (ISS) and is mostly aimed at studying the UV background of the night atmosphere of Earth [19]. The results are generic and can be easily extended for other detectors.

1 The latter opportunity was kindly pointed out by Toshikazu Ebisuzaki (RIKEN).
2 The TUS telescope did not have side shields, so that a trigger could be caused by an illumination of the mirror by a flash located far from the field of view, resulting in a signal over the whole focal surface. This situation is excluded in the future detectors, see below.

2. ORBITAL DETECTORS OF UHECRS

The TUS detector was launched into orbit on April 28, 2016, as a part of the scientific payload of the Lomonosov satellite and operated till late 2017. The satellite had a sun-synchronous orbit with an inclination of 97.3°, a period of approximately 94 min, and a height of about 500 km. The telescope consisted of two main components: a parabolic mirror-concentrator of the Fresnel type and a square-shaped 256-channel photodetector aligned to the focal plane of the mirror [8, 20]. The mirror had an area of about 2 m² and a 1.5 m focal distance. The detector had a rectangular field of view of 9°×9°, which covered an area of approximately 80 × 80 km at sea level. The angular resolution of a single channel was equal to 10 mrad, which results in a 5 × 5 km area at sea level.

The TUS electronics could operate in four modes intended for detecting various fast optical phenomena in the atmosphere on different timescales. The main mode was aimed at registering UHECRs and had a time sampling rate of 0.8 μs. Time sampling windows of 25.6 μs and 0.4 ms were utilized to study TLEs of different kinds, and a 6.6 ms time bin was available to detect micro-meteors and possibly space debris. Each complete data record written in any mode of operation consisted of 256 time bins of the respective duration.

The K-EUSO telescope, which is aimed to be installed on board the International Space Station (ISS) after 2022 for a 2-year mission, is a much more advanced instrument [17, 21–23]. In its latest version, it is expected to have a Schmidt-type optical system with the main mirror-reflector of a 4 m diameter, an entrance pupil of a 2.5 m diameter and a 1.75 m focal length. The telescope will have a circular field of view with a diameter equal to 40°, resulting in an instantaneous geometrical area of nearly 6.7×10⁴ km² at sea level for the ISS altitude of around 400 km.

The focal surface of K-EUSO will have a design similar to that of the JEM-EUSO telescope [24, 25]. It will consist of nearly 120 thousand multi-anode photomultiplier tubes (MAPMTs) grouped into 52 photodetector modules (PDMs). A strong point of the data acquisition system of K-EUSO is its flexibility. Similar to JEM-EUSO, the instrument will operate with a sampling time of 2.5 μs in the main mode of operation, aimed at registering UHECRs. In case of a trigger, the data will be acquired for at least 320 μs, i.e., 128 time bins. Longer sampling rates can be employed to register slower phenomena such as TLEs, meteors or nuclearites (strange quark matter). For example, a sampling time of 2.56 ms (=1024×2.5 μs) with the total record duration of 2.6 s can be used for registering meteors [26].

One of the most ambitious orbital projects in the field of UHECRs is the POEMMA experiment [18]. POEMMA will consist of two identical satellites flying in concordance at low Earth orbits with the ability to
observe overlapping regions of the nocturnal atmosphere at angles ranging from nadir to just above the limb of Earth. The altitudes of the satellites will vary from 525 km up to 1000 km with different separations and pointing strategies. Similar to K-EUSO, the optical system of each detector will consist of a Schmidt-type telescope with a 45° field of view and an optical aperture of 2.3 m in diameter with a single correction plate. It was estimated that the total area of observation by two satellites at an altitude of 525 km and separation of 925 km operating in the stereo mode for registering UHECRs will be of the order of $3.24 \times 10^5$ km$^2$ [18].

Finally, let us briefly consider Mini-EUSO, a small UV telescope that is operating on board the ISS since October, 2019, looking down on Earth through a nadir-facing, UV-transparent window from inside the Russian Zvezda module [19]. Its main scientific goal is to produce a high-resolution map of UV emissions from Earth. It can also register TLEs, meteors, space debris, nuclearites, bioluminescence, thus obtaining detailed information about the UV background level, necessary for the successful development of K-EUSO and other experiments of the EUSO program [27]. Strictly speaking, Mini-EUSO is not an UHECR detector but it is interesting to look closer at its technical capabilities since it is one of the pathfinders of the future UHECR missions.

Mini-EUSO is based on a single PDM, which consists of 36 MAPMTs, each with 64 pixels. An optical system of two double-sided Fresnel lenses with a diameter of 25 cm is employed to focus light on the PDM in order to achieve a circular field of view of $44\degree$, which results in $\approx 8.2 \times 10^4$ km$^2$ at sea level. The aperture of the detector equals 490 cm$^2$. The PDM detects UV photons and is read out by the data acquisition system with a sampling rate of 2.5 $\mu$s and a spatial resolution of 6.11 km. The instrument utilizes a multi-level trigger system [19, 28].

The first-level trigger of Mini-EUSO is configured to detect UHECR-like events with a time resolution $\tau = 2.5 \mu$s. An event is triggered if a signal collected in 20 $\mu$s exceeds the background level by 8$\sigma$. A whole record consists of 128 time steps thus occupying 320 $\mu$s. At the second level, the time resolution equals 320 $\mu$s. Once again, a record consists of 128 samples, giving 40.96 ms of data. The level of excess of the signal over the background and the number of time samples used to estimated the signal can be altered during the flight. This mode works independently from the first one and is intended for registering transient luminous events and other phenomena with a similar duration. The “slow” second-level trigger is implemented in Mini-EUSO for the very first time in the whole JEM-EUSO family of detectors [28]. Besides these, a continuous readout with a resolution of 40.96 ms is implemented. This mode does not have a trigger. It is intended for mapping the Earth UV background and to search for meteors, space debris and strange quark matter during an offline analysis. Duration of one record in this mode equals 5.24 s.

### 3. SENSITIVITY OF AN UHECR TELESCOPE TO GRBS

As was already mentioned above, photons coming from a GRB are mostly absorbed at altitudes higher than 30 km. Only a minor fraction of their energy is radiated in the fluorescence process, while the rest is lost in collisions and internal quenching. The key question is the fluorescence yield of photons in air.

The pioneering studies of fluorescence emission in gases induced by rapid particles date back to mid-1950’s [29], see [30] for a review of this and other early works. The first investigation of nitrogen fluorescence emission with respect to cosmic-ray detection (i.e., for electron-air collisions) was performed some ten years later, when comprehensive measurements were accomplished by Bunner [31]. The 1970’s gave rise to an interest in the possibility of detecting astrophysical X-ray [32] and gamma-ray transients [33] via atmospheric fluorescence. It was shown in particular that when X-rays interact with air, their energy is quickly converted to electron energy via the photoelectric effect or Compton scattering, so that one can use results for electron measurements to infer the fluorescence efficiency of air when excited by X-rays. The absolute fluorescence efficiency at low pressure was found to be $=0.0035$ for both photon-air and electron-air collisions at energies from a few kiloelectronvolts to 100 keV, with the efficiency for lower energy photon-air collisions being only slightly lower than that for electron-air, see [32, Figs. 2–4]. Later on, Catalano et al. [6] studied if gamma-ray bursts can be registered with a dedicated orbital detector by the fluorescence emission of the atmosphere. They adopted the fluorescence efficiency in the range $0.002–0.004$ basing on the results by Bunner [31].

Since the fluorescence efficiency of photon-air collisions equals that of electron-air collisions at low density and pressure ($\rho = 2 \times 10^{-4}$ g cm$^{-3}$, $p \sim 1$ kPa) in the energy range of interest, one can employ newer experimental results. In what follows, we adopt the fluorescence efficiency $\eta = 3.5 \times 10^{-3}$ following [34, 35]. The estimate was obtained using the total efficiency in all bands in the 300–400 nm range and taking into account a low pressure of the environment, see Table 3 and Eq. (8) in [34]. The number of signal photons from a GRB can be written as

$$N_s = \frac{\eta}{4\pi} A \Omega F_{GRB},$$
where $\varepsilon \sim 3–4$ eV is the typical energy of a UV photon in the range of interest (300–400 nm), $A$ is the area of the optical aperture of an instrument, $\Omega$ is the size of its field of view, and $F_{\text{GRB}}$ is the fluence of a GRB.

The rate of background illumination for a particular orbital instrument can be written as $R = \frac{A \alpha}{\Omega}$, where the background level $R$ is the UV glow of the nocturnal atmosphere. Observations performed with Tatiana and Tatiana-2 satellites demonstrated that it varies in a broad range $R = (3 \times 10^9 – 10^8)$ photons cm$^{-2}$ sr$^{-1}$ even during moonless nights, depending on the type of the surface with the lowest levels at medium latitudes above deserts, forests and oceans but also depending on the cloud coverage, and it can be an order of magnitude higher during full-moon periods [36].

It is now straightforward to estimate the signal-to-noise ratio SNR for a particular GRB and an orbital instrument:

$$\text{SNR} = \frac{N_t}{\sqrt{R_s F_{\text{GRB}}}} = \frac{\eta}{4\pi \sqrt{\Omega}} \frac{A \sqrt{F_{\text{GRB}}}}{\sqrt{t_{\text{GRB}}}},$$

where $t_{\text{GRB}}$ is the duration of a GRB. Assuming the lowest possible background illumination $B$ according to the Tatiana data, we arrive at

$$\max(\text{SNR}) = 9.1 \times 10^3 \frac{A \sqrt{F_{\text{GRB}}}}{\sqrt{t_{\text{GRB}}}},$$

where $A$ is expressed in units of cm$^2$, $\Omega$ is in steradians, $F_{\text{GRB}}$ is in erg cm$^{-2}$, and $t_{\text{GRB}}$ is in s.

We are now ready to estimate capabilities of the detectors discussed above to register a GRB. We employed the latest Fermi GBM gamma-ray burst catalog [16] exploiting the high level of sensitivity of the GBM and its large field of view (8 sr). We considered the sample available on May 10, 2020. The sample contained 2799 events registered in almost 12 yr of operation. We assumed $t_{\text{GRB}} = T_90$ in Eq. (1) and extracted $T_90$ and the fluence $F_{\text{GRB}}$ for all events in the catalog and performed calculations for each of them separately. We also considered two subsets of the data set: one with short GRBs with the prompt duration $T_90 < 2$ s (461 events), and a complementary set of long GRBs with $T_90 > 2$ s (2338 events).

Finally, one has to estimate corrections coming from the limited acceptance of an UHECR telescope working as a “GRB detector”. First, the acceptance is constrained by geometric considerations: the zenith angle $\theta$ of a potentially detectable GRB must be small enough, otherwise there will be a considerable suppression: $F_{\text{GRB}} \rightarrow F_{\text{GRB}} \cos \theta$. Assuming conservatively $\theta \sim 60^\circ$, we get 1/4 of the celestial sphere. Next, the fraction of time with the lowest background level used above is of the order of 15% of all time in orbit [37]. As a result, only $\approx 4\%$ of all GRBs can be registered (with an appropriate trigger) by an orbital telescope of UHECRs.

Let us look at the results presented in Table 1. Fermi GBM has detected 2799 bursts in $\approx 11.8$ yr of operation with effective coverage of 2/3 of the celestial sphere. That means one can expect K-EUSO to register 2.1 bursts in average every year (with SNR > 3) of operation in space providing it has an appropriate “slow” trigger. Approximately the same number of registered GRBs can be expected from any single telescope of the POEMMA mission. The stereo mode of observing UHECRs extends the capabilities of POEMMA to register GRBs by approximately 1.5 times. The numbers will increase up to 3.1 and 4.8, respectively if one takes SNR > 2. Chances of Mini-EUSO and TUS to detect a GRB are slim.

### 4. CONCLUSIONS

It was demonstrated by the TUS experiment that orbital detectors of ultra-high-energy cosmic rays can be useful is studying a variety of other phenomena. In this paper, we addressed the question if such instruments are able to detect gamma-ray bursts via the fluorescent glow of irradiated nocturnal atmosphere to complement observations of dedicated experiments.
Our estimates made for several active and next-generation projects show that their capabilities are quite modest in this respect. Even an advanced detector with parameters of an optical system similar to that of the K-EUSO or POEMMA telescopes and an appropriate trigger tuned to register events that evolve much slower than an extensive air shower, will be able to observe only 2–3 GRBs per year of operation.

ACKNOWLEDGMENTS

We thank the anonymous referee for numerous insightful comments that allowed us to clarify some important issues in the text. We also thank Mario Bertainia for a valuable comment, and Alexander Belov and Pavel Klimov for helpful discussions of the design of K-EUSO and Mini-EUSO. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors acknowledge support of the Interdisciplinary Scientific and Educational School of Moscow University “Fundamental and Applied Space Research”.

REFERENCES

1. R. W. Klebesadel, in Gamma-ray Bursts—Observations, Analyses and Theories, Ed. by Cheng Ho, R. I. Epstein, and E. E. Fenimore (Cambridge Univ. Press, Cambridge, 1992), p. 161.
2. J. P. Dezalay, C. Barat, R. Talon, R. Syunyaev, O. Ter- ekhov, and A. Kuznetsov, AIP Conf. Ser. 265, 304 (1992).
3. C. Kouveliotou, C. A. Meegan, G. J. Fishman, N. P. Bhat, M. S. Briggs, T. M. Koshyt, W. S. Paciesas, and G. N. Pendleton, Astrophys. J. 413, L101 (1993).
4. P. Kumar and B. Zhang, Phys. Rep. 561, 1 (2015).
5. B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, et al., Astrophys. J. Lett. 848, L12 (2017).
6. O. Catalano, J. Linsley, G. Pizzichini, B. Sacco, and L. Scarsi, in Proceedings of the 25th International Cosmic Ray Conference, Durban, South Africa, July 30—Aug. 6, 1997, Ed. by M. S. Potgieter, C. Raubenheimer, and D. J. van der Walt (Potchefstroom Univ., Transvaal, South Africa, 1997), Vol. 7, p. 365.
7. H. Fukunishi, Y. Takahashi, M. Kubota, K. Sakanoi, U. S. Inan, and W. A. Lyons, Geophys. Res. Lett. 23, 2157 (1996).
8. B. A. Khrenov, P. A. Klimov, M. I. Panasyuk, S. A. Sharakan, et al., J. Cosmol. Astropart. Phys., No. 9, 006 (2017).
9. M. Zotov and the Lomonosov UHECR/TLE Collab., in Proceedings of the 2016 International Conference on Ultra-High Energy Cosmic Rays (UHECR2016), Kyoto, Japan, October 11—14, 2016, JPS Conf. Proc. 19, 011029 (2018).
10. P. Klimov, B. Khrenov, S. Sharakan, M. Zotov, et al., in Proceedings of the 6th International TEPA Symposium on Thunderstorms and Elementary Particle Acceleration (TEPA-2016), Byurakan, Armenia, October 3—7, 2016, Ed. by A. Chilingarian (Yerevan Physics Inst., 2017), p. 122.
11. M. Yu. Zotov and the Lomonosov UHECR/TLE Collab., Phys. Part. Nucl. 49, 612 (2018).
12. P. Klimov, B. Khrenov, M. Kaznacheeva, G. Garipov, et al., Remote Sens. 11, 2449 (2019).
13. M. Zotov and the Lomonosov UHECR/TLE Collab., in Proceedings of the 26th Extended European Cosmic Ray Symposium E 2018, in conjunction with 35th Russian Cosmic Ray Conference (RCRC 2018), Barnaul, Russia, July 6—10, 2018 (Altai Gos. Univ., Barnaul, 2018), p. 135.
14. B. A. Khrenov, G. K. Garipov, M. A. Kaznacheeva, P. A. Klimov, et al., J. Cosmol. Astropart. Phys., No. 03, 033 (2020).
15. K. Shinozaki, A. Montanaro, M. Bertainia, F. Fenu, and S. Ferrarese, in Proceedings of the 36th International Cosmic Ray Conference (ICRC2019), Madison, WI, July 24—Aug. 1, 2019, Proc. of Sci. 36, 545 (2019).
16. A. von Kienlin, C. A. Meegan, W. S. Paciesas, P. N. Bhat, et al., Astrophys. J. 893, 46 (2020).
17. P. Klimov, M. Casolino, and the JEM-EUSO Collab., in Proceedings of the 35th International Cosmic Ray Conference (ICRC 2017), July 10—20, 2017, Bexco, Busan, Korea, Proc. of Sci. 301, 412 (2017).
18. A. V. Olinto, J. H. Adams, R. Aloisio, L. A. Anchordoqui, et al., in Proceedings of the 35th International Cosmic Ray Conference (ICRC 2017), Bexco, Busan, Korea, July 10—20, 2017, Proc. of Sci. 301, 542 (2017).
19. F. Capel, A. Belov, M. Casolino, and P. Klimov, Adv. Space Res. 62, 2954 (2018).
20. P. A. Klimov, M. I. Panasyuk, B. A. Khrenov, G. K. Garipov, et al., Space Sci. Rev. 212, 1687 (2017).
21. G. K. Garipov, M. Yu. Zotov, P. A. Klimov, M. I. Panasyuk, et al., Bull. Russ. Acad. Sci.: Phys. 79, 326 (2015).
22. M. Panasyuk, P. Klimov, B. Khrenov, S. Sharakan, et al., in Proceedings of the 34th International Cosmic Ray Conference (ICRC2015), The Hague, The Netherlands, July 30—Aug. 6, 2015, Proc. of Sci. 34, 669 (2015).
23. M. Casolino, A. Belov, M. Bertainia, T. Ebisuzaki, and the JEM-EUSO Collab., in Proceedings of the 35th International Cosmic Ray Conference (ICRC 2017), Bexco, Busan, Korea, July 10—20, 2017, Proc. of Sci. 301, 368 (2017).
24. J. H. Adams Jr. and the JEM-EUSO Collab., Exp. Astron. 40, 3 (2015).
25. J. H. Adams Jr. and the JEM-EUSO Collab., Exp. Astron. 40, 19 (2015).
26. J. H. Adams Jr. and the JEM-EUSO Collab., Exp. Astron. 40, 253 (2015).
27. M. Casolino and the JEM-EUSO Collab., in Proceedings of the 35th International Cosmic Ray Conference (ICRC 2017), Bexco, Busan, Korea, July 10–20, 2017, Proc. of Sci. 301, 370 (2017).
28. A. Belov, M. Bertaina, F. Capel, F. Fausti, F. Fenu, P. Klimov, M. Mignone, and H. Miyamoto, Adv. Space Res. 62, 2966 (2018).
29. A. E. Grün and E. Schopper, Zeitschr. Naturf., A 9, 134 (1954).
30. F. Arqueros, J. R. Hörandel and B. Keilhauer, Nucl. Instrum. Methods Phys. Res., Sect. A 597, 23 (2008).
31. A. N. Bunner, PhD Thesis (1967).
32. J. L. Elliot, SAO Spec. Rep. 341 (1972).
33. T. C. Weekes, J. Atmos. Terr. Phys. 38, 1021 (1976).
34. M. Nagano, K. Kobayakawa, N. Sakaki, and K. Ando, Astropart. Phys. 20, 293 (2003).
35. M. Nagano, K. Kobayakawa, N. Sakaki, and K. Ando, Astropart. Phys. 22, 235 (2004).
36. G. K. Garipov, B. A. Khrenov, M. I. Panasyuk, V. I. Tulupov, A. V. Shirokov, I. V. Yashin, and H. Salazar, Astropart. Phys. 24, 400 (2005).
37. J. H. Adams Jr., S. Ahmad, J.-N. Albert, D. Allard, et al., Astropart. Phys. 44, 76 (2013).