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研究課題名（和文）Next generation detectors for study from balloon and space of terrestrial and cosmic UV signals

研究課題名（英文）Next generation detectors for study from balloon and space of terrestrial and cosmic UV signals

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研究成果の概要（和文）：非常にエネルギーの高い宇宙線がどこで作られているか判明していない。そのような宇宙線観測に必要な技術を確立するために2017年に気球実験EUSO-SPB1、2019年より国際宇宙ステーション実験Mini-EUSOを実施した。どちらも宇宙線が空気中を通った時に発する紫外線の軌跡を検出するため、軽量フレネルレンズを使った高感度高速カメラを用いている。紫外線背景光マップの取得、エルブスなどの高高度大気発光や流星など様々な瞬間発光現象を観測した。

研究成果の学術的意義や社会的意義
Mini-EUSO is currently the only detector in space devoted to the search of UHECR with E>1e20eV and nuclearites. This represents a huge step forward in the development of future large area detectors in space. SPB1 flight was successful, a new flight EUSO-SPB2 is being prepared for flight in 2022

研究成果の概要（英文）：The origin of ultra high energy cosmic rays is still in mystery. We conducted a balloon-borne experiment, EUSO-SPB1, in 2017 and a space mission, Mini-EUSO, onboard the international space station since 2019 to pave for future missions to observe such high energy cosmic rays on orbit. In the both projects, light-weight Fresnel lens optics and high-speed cameras with high sensitivity were used so that cosmic ray tracks can be detected in ultraviolet. UV background map of the Earth is being acquired at various places. Many transient phenomena such as Elves (transient light at high atmosphere), lightning and meteors have been observed in UV band.

研究分野：ultra high energy cosmic ray from space

キーワード：cosmic rays　strange quark matter　Space station　UV emission　ELVES

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

The origin and nature of ultra high energy cosmic rays (UHECR), particles with energy above E ~ $6x10^{19}$ eV is still unknown and constitutes one of the great unsolved mysteries in physics. UHECR are thought to be coming from extragalactic distances (~ 100 Mpc). At this energy they are less bent by the galactic and intergalactic magnetic fields, thus raising hopes for opening "charged particle astronomy" via direct identification through angular association with known astrophysical sources.

Data from ground-based observatories, Telescope Array in the Northern hemisphere and Auger in the Southern hemisphere have confirmed the presence of a cutoff (GZK) at energies greater than E ~ $6x10^{19}$ eV, due to the interactions of UHECR particles with Cosmic Microwave Background photons, limiting to 100 Mpc the astronomical horizon beyond which UHE cosmic ray sources cannot contribute significantly to the flux measured on Earth. Auger has reported an anisotropy and possible correlation between events with E ≥ $5.7x10^{19}$eV and the distribution of nearby galaxies [CIT1], although the correlation is weaker in recent analysis. In the Northern Galactic hemisphere, Telescope Array has shown the presence of intermediate scale anisotropy with an excess of particles above E ≥ $5.7x10^{19}$eV [CIT2]. The uncertainties and difficulties in pinpointing at one or more astronomical sources are due to the low cosmic ray flux (above E ~ $6x10^{19}$ eV is of the order of 1 particle/km^2/sr/century), requiring a joint approach between the existing ground based telescopes and the development of a new generation of space-borne detectors, the latter being complementary to those on ground, since they offer complete and uniform coverage of the celestial sphere and have potential for exposures larger by several orders of magnitude.

２．研究の目的

Aim of this proposal is to detect UHECR from above ground for the first time, through the measurement of UV light emitted by the cosmic ray atmospheric showers. This observation has not yet been performed due to the technical challenges of limited mass, power and size posed by balloon and space borne detectors. This goal can be achieved with this project thanks to the use of Japan-developed Fresnel lenses and Multi-Anode Photomultiplier technology, with a read-out by next-generation, low power electronics.

For this purpose we propose - in the framework with the international EUSO collaboration - to develop and realize new optical systems and electronics to construct two novel instruments (see Figure 1): 1) a balloon payload for shower observations at 40 km altitude (EUSO-SPB - Super Pressure Balloon) and 2) a space-borne detector for observations from the International Space Station (ISS), Mini-EUSO detector. In this proposal we ask funding to follow the EUSO-SPB, the final integration and launch campaign of MINI-EUSO and the subsequent mission planning and data analysis of the two experiments.

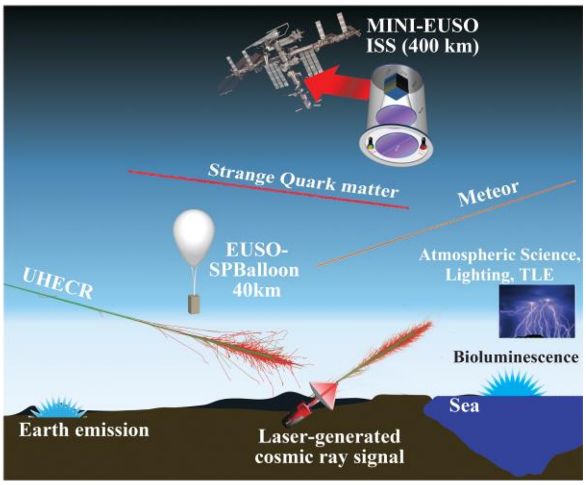

Figure 1: Scheme of the main science objectives and detectors of this proposal. A) EUSO-SPB, a NASA stratospheric balloon payload which will observe UHECR from above with a 1 sq. meter Fresnel Lens system. B) MINI-EUSO which will observe Ultraviolet emissions inside the International Space Station (25 cm diameter optics).

Scientific goals (summarized in Figure 1):

a) Study and observations from above the ground of UHECR showers at $E>10^{18}$ eV. EUSO-SPB will detect and measure for the first time UV showers from the stratosphere (40 km). Depending on the duration of the flight (with the new sealed balloon technology the flight can last several months) and weather conditions, we expect from 50 to 150 cosmic ray events.

b) Search for events at $E>10^{21}$ eV and anomalous signals from the ISS (MINI-EUSO, 400km). Observation of artificial, ground-based laser-generated $E>10^{21}$ eV UHECR events.

c) Measurement of UV emissions of different regions of night-time Earth with high

spatial (6.5km) and temporal resolution (2.5μs and above) from 400 km altitude.
d) First night-time map of the Earth in UV range (data will be made publicly available).
e) Search for strange quark matter(nuclearites burning in the atmosphere) and study of meteors
Additional interdisciplinary science goals:
f) Study of atmospheric phenomena such as Sprites, Elves, lighting, in the UV range and in the μs-ms range, in cooperation with other devoted instruments such as ASIM and GLIMS.
g) Study of UV-bioluminescence of flora and fauna produced by algae, plankton and other organisms.

３．研究の方法

(1) EUSO-SPB: The flight will use the NASA Super Pressure Balloon (SPB) technology. The novel (only two flights have been done so far) sealed balloon technology allows observation periods of 30 to 90 days (several circum-Antarctic turns). This telescope employs a 1m^2 optics (±6 deg field of view) with a two-lens Fresnel optic developed by the proponents, Fresnel lenses and a focal surface of 2304 channels (36 Multianode Photomultipliers, MAPMTs, Figure 5) realized by RIKEN. The duration of the flight, improved optics design and manufacturing, electronics and trigger system allows to detect from 50 to 150 cosmic ray events with E>10^{18} eV.
(2) Mini-EUSO telescope on board the International Space Station. This project has been approved by ASI (Italian Space Agency) and the Roscosmos (Russian Space Agency) with launch scheduled for late 2017 in the framework of the next Italian astronaut (Paolo Nespoli) flight on the ISS, with observations continued by Russian cosmonauts and lasting for three years. The telescope consists of two double sided, 25 cm diameter Fresnel lens optical system (to be realized by RIKEN), and a 2304-pixel focal surface detector similar to that of EUSO-SPB. Field of view is +-19°. Observation will take place from the UV-transparent window of the Zvezda module of the Russian section of the ISS. All systems are standalone, only power is provided by the ISS. Quick-look data are partially downlinked from station computers and periodically sent to Earth with Hard Disks by Soyuz capsules.
A number of asynchronous and triggered acquisitions evaluate the background on different temporal (from μs, to ms and s) and spatial scales as well as moon phase conditions and period of the year. We will also realize and make public the first UV night map of the Earth, of crucial relevance not only for the UHECR community but also for biological and environmental sciences.
We will perform measurement of artificial showers generated by shooting lasers from the ground in the field of view of the detector when the ISS passes above the lasers. Furthermore, the trigger will look for E>10^{21} eV UHECR events and search for anomalous signals, placing an upper limit after one year of observations.

４．研究成果

In 2019 the engineering and the flight models of Mini-EUSO have been completed. All the phases of integration, calibration and pre-flight qualification tests were completed first in Japan, subsequently in Italy and Russia and finally at the cosmodrome of Baikonur. The detector has been launched toward the international space station on August 22, 2019 with an uncrewed Soyuz MS-14 capsule. It was turned on October 7th 2019 and is currently undergoing periodic data acquisition in the Russian section of the ISS. The commissioning was successfully completed, with analysis of a selection of data directly downlinked to ground via telemetry. Analysis of the data obtained from the station so far show the correct functioning of the telescope. UV maps have been created. Among the phenomena observed we have the observation of observation of the UV emissions from the Earth in different conditions of moonlight, lighting and artificial lights from towns, observations of meteors of varying size and velocity, Transient
Luminous events such as ELVES, superluminal ring like structures that expand in the ionosphere after being triggered by and underlying Intra-cloud lightnings. Pouches containing the full data set are returned with a Soyuz capsule to the ground. The pouches are rotated every six months. Work on the analysis of EUSO-SPB balloon flight has continued in parallel to the preparation of the next balloon flight (EUSO-SPB2)

currently scheduled from New Zealand in 2022. This involved mostly the electronics and detectors of the focal surface and the study of the various lens systems.

(1) EUSO-SPB flight

EUSO-SPB is a 40M$ (40億円) NASA mission, which funds and is responsible for the mission. The payload and instrumentation is built by the EUSO collaboration, led and coordinated by RIKEN. In RIKEN the Fresnel lenses which comprise the optics and tested and calibrated the Hamamatsu photomultiplier focal surface (2304 Pixels). Furthermore we developed the data acquisition system, the real time quick look for data and engineering values and the software for the monitoring of the payload.

Figure 2: EUSO-SPB on the launch pad, in Wanaka. The payload is on the left, suspended from the crane which launched it.

Figure 3: Mini-EUSO installed in the Zvezda module of the ISS. The velocity vector is usually toward bottom, in the side marked as '1' on Mini-EUSO.

The flight uses the NASA Super Pressure Balloon (SPB) technology. This is the only science flight of 2017 using the SPB, which employs a sealed balloon and allows long observation periods. This telescope employs a 1m^2 optics (11 deg field of view) with two Fresnel lenses and a focal surface of 2304 channels (36 Multi-anode Photomultipliers, MAPMTs, both realized in RIKEN). The duration of the flight, improved optics design and manufacturing, electronics and trigger system allows to detect UHECR with E>10^{18} eV. Launch occurred on April 25th 2017 from Wanaka, New Zealand and lasted for 12 days until 7/5/2017. The optical system was realized and tested in RIKEN and shipped to USA for integration and calibration in EUSO-TA site. It was then transferred to Wanaka Balloon Launch Facility. The whole payload weights 2 tons. Data analysis is currently in progress: preliminary results show the correct functioning of the detector.

(2) MINI-EUSO

Mini-EUSO telescope was installed on board the International Space Station (Figure 3). This project has been approved by ASI (Italian Space Agency) and the Roscosmos (Russian Space Agency). The telescope consists of two double sided, 25 cm diameter Fresnel lens optical system (realized by RIKEN), and a 2304-pixel focal surface detector similar to that of EUSO-SPB. Field of view is 40°. The telescope was first turned on on October 7th 2019 (Figure 3). As already mentioned, the detector is designed to operate in night-time conditions.

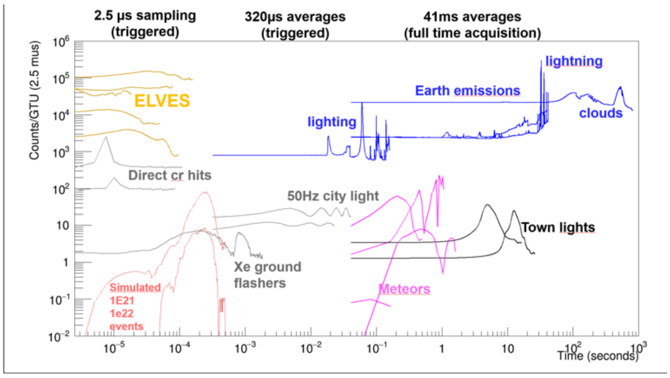

Figure 4; Temporal profile of various signals observed by Mini-EUSO.

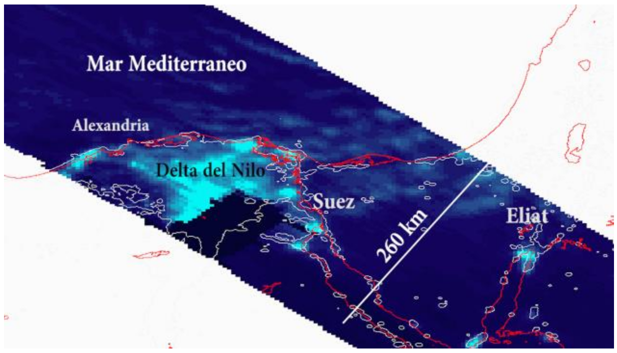

Figure 5: Night time emissions of the Earth from North Africa region.

The CPU handles cycling between day and night based on the measurements performed by the UV sensors located in the focal surface. The UV sensor is currently used for this purpose, although for redundancy reasons all three sensors (two photodiodes and one SiPM) can be used. To avoid spurious fluctuations between the two states at the night/day terminators,

two thresholds are used. At the start of each session, the detector is taken from storage, the lens cover removed and is placed in position on the UV transparent window in the Zvezda module. UV map of night-time Earth is acquired during the observation time (Figure 5). Figure 6 shows a sample image of an ELVE (transient luminous event). Figure 4 shows the total signal of the FS as a function of time for signals of various time scales, from the faster 2.5µs sampling (D1) to the 128 frame average of D2 (320µs) to the 128*128 frame average of D3 (40.96ms). The D1 and D2 are triggered acquisitions, D3 is continuous readout. On the long time frame, the gradual increase is due to the passage over a clouded area, whereas the sharp spikes are due to lightning. Large lightning triggers the safety system of the detector, resulting in the temporary deactivation of the high-voltage power supply to the EC unit (16*16 pixels) which is hit by lightning.

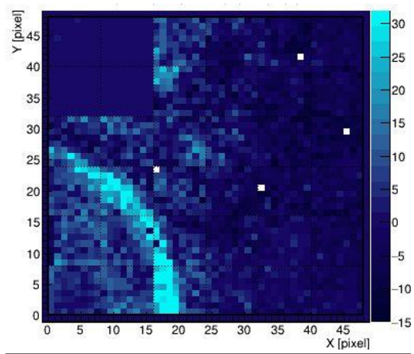

Figure 6: Ring-like structure of an ELVE (Transient luminous event)

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５．主な発表論文等

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3．雑誌名 Advances in Space Research	6．最初と最後の頁 1188～1198
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1016/j.asr.2019.06.017	査読の有無 有
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

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