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The JEM-EUSO Program for UHECR Studies from Space

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Abstract. To take up the challenge of understanding the origin of the ultra-high-energy cosmic rays (UHECRs), new observational means appear necessary. The JEM-EUSO Collaboration has undertaken to open the space road to UHECR studies. For more than a decade, it has been developing a realistic program to measure the UHECRs from space with unprecedented aperture, together with complementary scientific objectives in a broader multidisciplinary context. Several intermediate missions have already been completed (on the ground: EUSO-TA; under stratospheric ballons: EUSO-Balloon and EUSO-SPB1; in space: TUS, and on-board the ISS: MINI-EUSO), and others are in preparation for flight (EUSO-SPB2), under review (K-EUSO: currently on hold), or proposed for the next decade (POEMMA). We report on the general status of the JEM-EUSO program, underlining that its technology has now reached operational maturity, and is ready for actual cosmic-ray shower detection from above.

1 Introduction

Despite intense observational efforts and a series of important results in the last two decades, the study of ultra-high-energy cosmic rays (UHECRs) remains one of the most challenging in astronomy, both because their flux is extremely low (one particle per m^2 per billion year at the highest known energies) and because their macroscopic energies (tens of Joules) still remain insufficiently large to allow quasi-rectilinear propagation in the Galactic (and extragalactic) magnetic fields. As a consequence, no direct detection of their sources has been possible thus far, and their astrophysical origin as well as their acceleration mechanism remain unknown. A broad and detailed summary of the current status and observational situation in the field, as well as a presentation of the interactions with other fields in high-energy physics and astrophysics can be found in a recent white paper, which involved and was endorsed by a large research community worldwide [1]. It also examines the perspective for progress in the next two decades. One of its conclusions it that new observational means will be necessary, notably to increase the statistics of the UHECR datasets at the highest energies.

As an alternative to building more and more detectors spread over larger and larger areas on the ground (beyond the thousands of km^2 currently instrumented), one way to reach significantly larger instantenous apertures with a single instrument has been identified several decades ago [2]: it consists in going to space and looking down to the Earth atmosphere with a large field-of-view telescope, to detect the fluorescence light of UHECR-induced extensive air showers (EAS) over a very large volume. This is of course challenging from the instrumental point of view, given the large distance at which the showers must be observed with sufficient precision to allow a reconstruction that is reliable enough. However, such an achievement appears accessible with current technology, and this is indeed what the JEM-EUSO Collaboration (Joint Experiment Missions for

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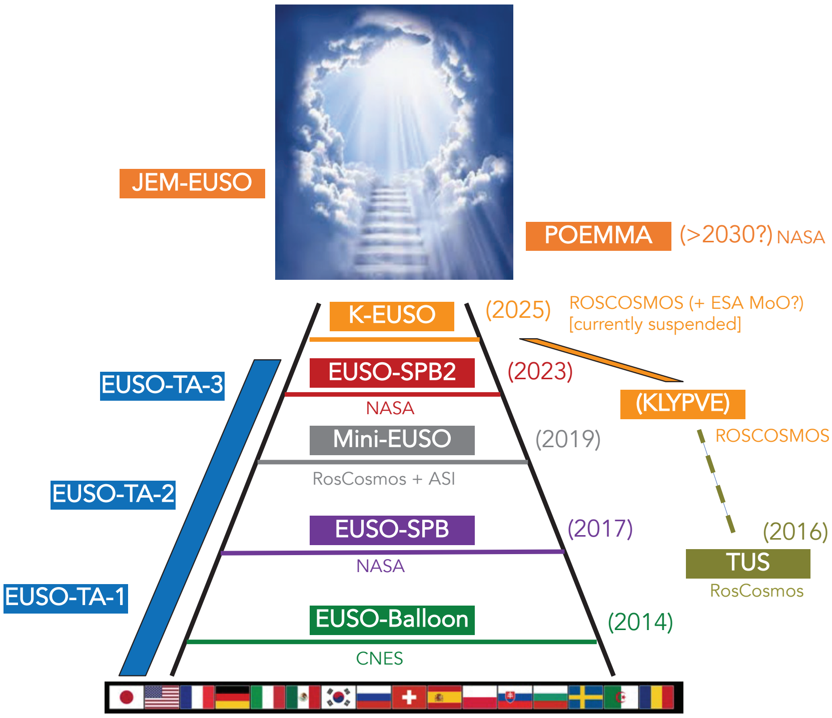

Figure 1. Summary of the JEM-EUSO "stairway to Heaven" development program. (Details in the text.)

an Extreme Universe Space Observatory) has undertaken to demonstrate and realise.

Following earlier work in the context of the Orbiting Wide-angle Light-collector (OWL) [3] and Extreme Universe Space Observatory (EUSO) [4] mission projects, the JEM-EUSO Collaboration endeavoured to develop a major space mission to study UHECRs, also allowing the detection of very high energy neutrinos and additional scientific objectives. Its strategy has been to proceed via a series of intermediate missions, each time achieving new technical and scientific milestones, thus climbing step by step what may be loosely referred to as the UHECR "stairway to heaven" (or at least to space!), as summarized in Fig. 1. After a decade of innovative technological developments and successful missions, as briefly summarized below, the JEM-EUSO Collaboration appears ready for a major UHECR mission from space. With the help of concommitant progress in other parts of astrophysics, such as a reliable mapping of the Galactic magnetic field and new progress in the modelling of potential sources, this may indeed lead to a long-awaited breakthrough in the understanding of the origin.

2 UHECR state of the art

The current understanding of the UHECR phenomenology is the result of decades of intense activity in the field, which is currently dominated by the two largest observatory ever built: the Pierre Auger Observatory (Auger: 3000 km^2; e.g. [5] and Berat, these Proceedings) and the Telescope Array (TA: currently being extended up to 2800 km^2; e.g. [6, 7] and Kido, these Proceedings). Very broadly, it may be summarized as follows:

- As expected from simple and solid theoretical considerations, it is clearly established [8, 9] that the spectrum of the UHECRs shows a GZK-like cutoff [10, 11], above a few tens of EeV.
- As generically expected from astrophysical particle acceleration models for which the maximum energy of protons at the source hardly reaches 10^{19} EeV, the UHECR composition is getting heavier and heavier above a few EeV [12].
- As expected from simple considerations linking the sources of UHECRs with ordinary matter, the distribution of the UHECR arrival directions is not isotropic. By order of decreasing significance, departure from isotropy has been established through: i) a significant first-order angular modulation coefficient (dipole) above 8 EeV, [13] ii) a correlation with large scale cosmic matter distribution (using catalogs of galaxies as a proxy), [14] and iii) warm spots showing flux excesses on relatively large angular scales, both in the Southern and Northern hemispheres. [15, 16]

In addition, significant signals for a composition anisotropy [17] and a declination-dependent energy spectrum [18] have been reported by the Auger and TA collaborations, respectively.

While these results are important milestones and come as the crowning achievement of years of intense observational efforts, they have not allowed, so far, to discover the origin of the UHECRs. We still do not know what the sources are, nor which physical mechanism is responsible for the acceleration of such high-energy particles. In addition, the experimental situation is still partly confused, primarily by lack of statistics, but also because the two main detectors in operation observe different parts of the sky, with different levels of exposure and limited overlap.

3 Forward through space

The main reason why the current generation of detectors were not able to discover the sources of UHECRs, despite their very large aperture and excellent quality data, can be understood from the data themselves. Contrary to what had been (somewhat naively) expected two decades ago, the highest energy particles appear not to be protons, but heavier nuclei, with higher charges and thus larger deflections in the intervening magnetic fields. This makes direct pointing astronomy with cosmic rays essentielly impossible. A better knowledge of the Galactic magnetic field than currently available will be needed to infer the distribution of arrival directions before they enter the Galaxy, which would provide a much clearer view on the location of the sources. In addition, a relatively low rigidity cutoff at the sources (as strongly suggested by the composition [19, 20]) makes the acceleration of the UHECRs less challenging than had been thought, which increases considerably the number of sources potentially contributing to the observed flux. More sources with larger deflections leads to source confusion and overlap, which makes it difficult to exploit the measured anisotropies, especially at the current level of significance, which does not allow to discriminate between competing astrophysical models.

Since we cannot change the phenomenology of UHECRs, we must try and develop strategies to overcome the above problems. This is where a space mission can be of remarkable value, in complement to ground based observatories, by providing much larger statistics at the highest energies as well as near-uniform full sky coverage with one single instrument deployed in Low Earth Orbit (LEO).

Even an intermediate space mission of moderate size, say providing an exposure comparable to that of current ground-based observatory, would be of great value to draw the first full-sky map in UHECR with a single instrument (thus with the uniform systematics), characterise the large scale anisotropies with greater precision, and address the potential discrepancies or differences in the UHECR flux in the Northern and Southern hemispheres. It would also increase by one order of magnitude the instantaneous aperture, and by the same amount the fluorescence aperture, providing a direct measurement of the average of the depth of the maximum shower development ($\langle X_{\max}\rangle$) up to the highest energies. This will help characterising the evolution of the UHECR composition, and its possible non uniformity.

The JEM-EUSO experimental concept has also been enriched by the addition of direct Cherenkov detection capability, which will take effect with the EUSO-SPB2 mission in Spring 2023. This allows to search for high-energy neutrino showers, by looking at the limb of the Earth, either to detect the diffuse cosmogenic flux or by pointing towards targets of opportunities as part of a global multi-messenger strategy [21] (see also Cummings, this conference, and Krizmanic, this conference, and references therein).

In addition, a space-based shower detector allows to target new types of cosmic-ray events, inaccessible from the ground, in particular high-altitude, "atmosphere-skimming" showers, whose entire development takes place in very low density medium [22]. These may provide important information about the physics of the showers, as the balance between the decay of instable particles and the production of new particles, which is the key parameter driving the shower development, directly depends on the ambient density.

Finally, a UHECR space mission will collect a large amount of data that are valuable for other scientific domains, such as planetary science, fundamental physics, atmospheric physics and Earth observation in general. Among the complementary science objectives of current and future missions based on the JEM-EUSO technology, one may cite the study of meteors, transient luminous events (ELVES), putative anitons, ionospheric phenomena, bioluminescence, or the search for nuclearites and strange quark matter.

4 The JEM-EUSO program and technology

4.1 JEM-EUSO collaboration

The JEM-EUSO Collaboration gathers about 300 physicists and engineers from 12 member countries (Algeria, Czech Republic, France, Germany, Italy, Japan, Mexico, Poland, Russia, Slovakia, Sweden, USA) and 4 associated countries (Republic of Korea, Romania, Spain, Switzerland). It is engaged in an ambitious, consistent experimental project aiming at advancing the understanding of UHECRs through the observation of EAS from space. Taking up this challenge required the establishing of a full program composed of intermediate missions (see Fig. 1), whose progressive development allowed to acquire, optimise and validate the appropriate technology, demonstrate the viability of the experimental and instrumental concepts, and assess the performance that can be realistically expected from a full scale JEM-EUSO mission (cf. Bertaina, this conference).

4.2 JEM-EUSO instrumentation

The JEM-EUSO Collaboration has developed technology to operate a *fluorescence telescopes* (FT) from LEO, for the detection of the isotropically emitted fluorescence light and the diffused Cherenkov emission from extensive air showers. The nadir-pointing FT provides the large instantaneous exposure for UHECR detection, which can be further increased by tilting the optical axis to observe larger volumes of atmosphere. In addition, for the forthcoming mission EUSO-SPB2 (see below), a new type of telescope has been added, namely a *Cherenkov telescopes* (CT) for the detection of the direct Cherenkov light emitted (roughly) along the direction of the showers. The CT requires a different pointing configuration, to detect upward going showers from Earth skimming neutrinos (or exotic events) emerging from below the limb of the Earth,

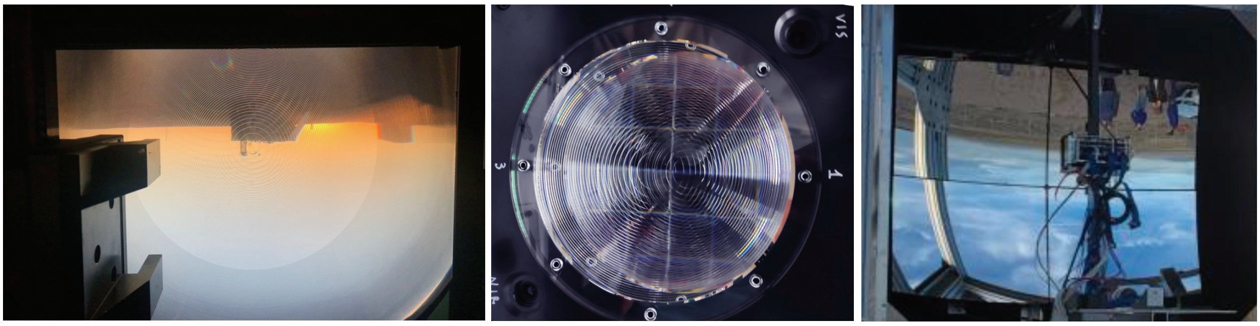

Figure 2. JEM-EUSO optics. Left: view through the EUSO-TA refractive Fresnel optics system. Center: front view of the MINI-EUSO Fresnel lens system. Right: side view of the EUSO-SPB2 mirrors.

or horizontal showers developing at high altitude from above the limb.

Operating from space implies specific requirements for the instrumentation. Since the atmospheric showers are observed from a large distance (typically 400 km on the ISS or a bit more for free flyers in LEO), the geometric attenuation of the light intensity is very large. Thus, ensuring an energy threshold compatible with a satisfying overlap with ground-based observatories requires both very sensitive detectors, able to operate in photon counting mode, and very large optics, to collect as much light as possible and allow efficient detection down to a few 10^{19} eV.

The JEM-EUSO collaboration has developed two types of large field-of-view optics: refractive optics using large polymethyl methacrylate (PMMA) Fresnel lenses (contributed by Japan) and Schmidt telescope with large segmented spherical mirrors (contributed by Czech Republic). Examples can be seen on Fig. 2, which shows the refractive optics of EUSO-TA (left) and MINI-EUSO (center) and the reflective optics of EUSO-SPB2 (right; NB: a front corrective lens is not visible).

Regarding the photodetectors, the FT uses 64-pixels multi-anode photomultiplier tubes (MAPMT) from Hamamatsu, allowing single photon detection with very high efficiency (~30%). BG3 UV filters are used to narrow the detection window around the N_2 fluorescence lines in the UV. A modular focal surface allows to adapt the developed technology to missions of different sizes. The smallest detection unit consists of 4 MAPMTs, gathered into a so-called elementary cell (EC, contributed by France). Three successive generations of ECs have been developed, culminating in the fully integrated EC version 3, used for the K-EUSO prototype and the EUSO-SPB2 mission. It integrates the front-end electronics based on the dedicated ASIC SPACIROC3 (contributed by France), and a specially developed low consumption Cockroft-Walton high-voltage power supply (HVPS) board (contributed by Poland). The EC is then potted to be able to operate in the 3 mbar environment of the JEM-EUSO balloon missions (see Fig. 3). For the CT, the photodetectors are Silicon photomultipliers (SiPM) matrices from Hamamatsu, also assembled into modular elements including the front-end electronics using a Music chip, power supply, amplifier board and microcontroller (contributed by the USA).

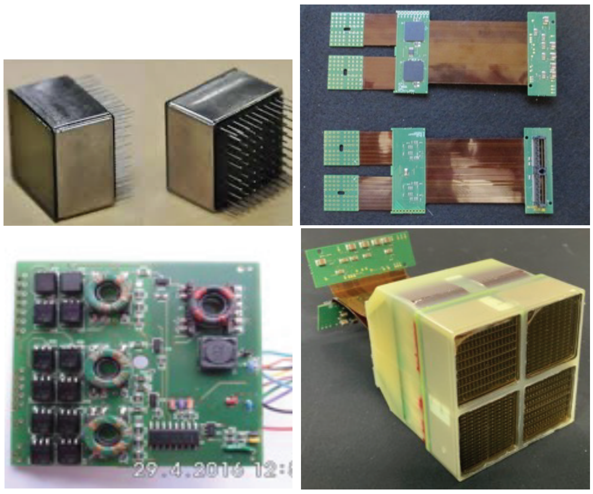

Figure 3. JEM-EUSO FT detection unit. Top left: 64 pixel MAPMTs used by all JEM-EUSO missions. Top right: ASIC boards using SPACIROC 3. Middle left: Cockroft-Walton (CW) high-voltage power supply. Middle right: 4 MAPMTs, 2 ASIC boards and 1 CW board assembled into a potted elementary cell of the third generation for the EUSO-SPB2 mission.

Figure 4 shows additional elements of JEM-EUSO's last generation FT electronics, namely the Zynq board ensuring data acquisition and trigger (contributed by Russia), the HVPS DC-DC control board (contributed by Poland) and the Data Processor (contributed by Italy). All these elements, except the latter, are integrated together into a so-called Photo-Detection Module, or PDM, which is the largest FT building block of all JEM-EUSO missions, composed of 9 ECs in a square matrix, i.e. 36 MAPMTs, with a total of 2304 pixels. Its last version, implemented in the EUSO-SPB2 mission, is shown on Fig. 5 with the ECs facing towards the left of the picture.

4.3 JEM-EUSO missions

As mentioned above, the JEM-EUSO experimental program has been developed through a series of intermediate balloon and space missions, in parallel with the operation

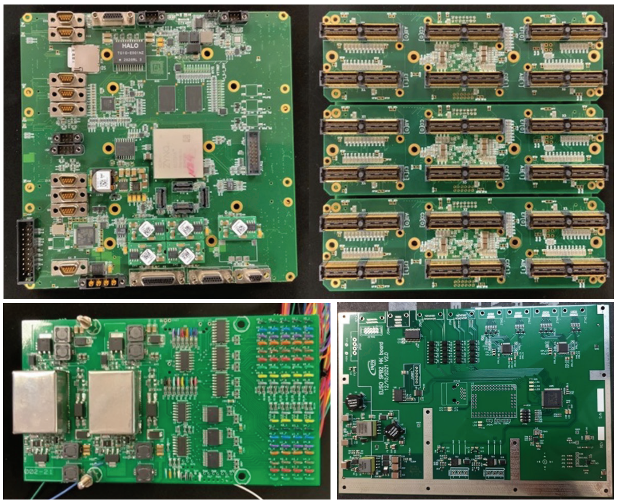

Figure 4. JEM-EUSO electronics. Top: Zynq board with FPGA for data acquisition and trigger. Bottom left: HVPS DC-DC control board. Bottom right: data processing and control board.

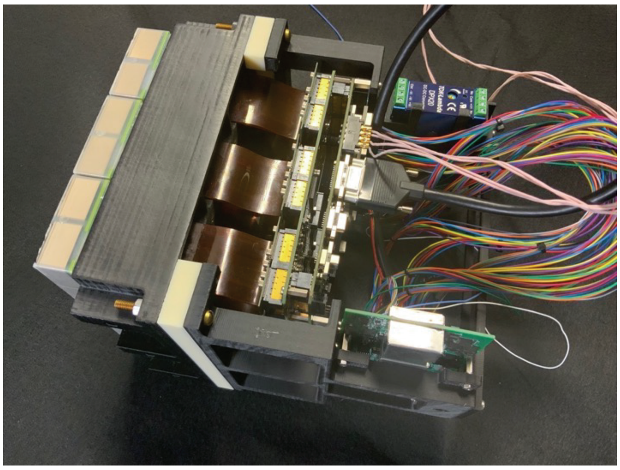

Figure 5. JEM-EUSO's last generation PDM.

of the EUSO-TA facility, benefiting from the installation of the TA collaboration at Black Rock Mesa (Delta, Utah, USA). This facility proved very useful for tests, measurements and data taking with the succesive versions of the instrumentation [23].

4.3.1 EUSO-Balloon

The first JEM-EUSO mission to fly was the EUSO-Balloon mission [24], a one-night mission of the French space agency, CNES, under a stratospheric balloon launched from the joint CNES-CSA facility in Timmins (Canada). The main innovations of the EUSO-Balloon instrument were the Fresnel optics and the first generation PDM using of dedicated ASIC (SPACIROC) for the front-end electronics and a low-consumption HVPS board implementing an automatic switch of the high-voltage scheme in case of a sudden increase of the background light, to protect the MAPMTs from luminous events (such as lightning), as well as efficient data processing.

The mission had a successful flight in August 2014, demonstrating the validity of the experimental concept and the robustness of the instrumentation to operate at 3 mbar. EUSO-Balloon also provided important results for the following steps of the JEM-EUSO program, namely the first imaging measurement of the UV emissivity of the Earth at night, both with and without clouds, which also allowed to demonstrated the anticorrelation between the UV and IR luminosities (using an IR camera contributed by Spain). EUSO-Balloon also demonstrated the serendipitous detection of unexpected flashers on the ground (most probably of artificial origin).

Finally, and most importantly, EUSO-Balloon was able to detect CR-like tracks, produced by laser pulses shot from a helicopter flying below the balloon, crossing the field of view of the telescope. The scattered light from the laser pulse was properly detected for several tens of laser shots, and the reconstruction of the trajectory showed an accuracy of the order of 2 degrees (from the known laser orientation).

4.3.2 EUSO-SPB

After the success of this first flight, the JEM-EUSO collaboration undertook to develop a second balloon mission with upgraded instrumentation and a much longer flight, so as to be able to detect cosmic-ray showers from above for the first time in fluorescence. This led to the NASA mission EUSO-SPB [25], where SPB stands for Super Pressure Balloon, a closed, pressurised balloon allowing to stay afloat for up to 100 days in principle. The instrument was designed to detect and reconstruct several CR events during such a flight, thanks to an energy threshold around 10^{18} eV and a field-of-view similar to that of EUSO-Balloon ($\sim 11^\circ \times 11^\circ$). The focal surface consisted again of 1 PDM, but with several important improvements. Among them a new version of the ASIC, SPACIROC-3, and a new generation of ECs, more compact and stable. These were integrated in the second version of the PDM, shown in Fig. 6 (left picture). The optics performance was also improved compared to EUSO-Balloon, and a new power supply scheme was added, using solar panels, as required for a long duration flight. Finally, the EUSO-SPB instrument had a complete scheme of data acquisition, processing and transmission, implementing an autonomous trigger for showers or other types of events.

Pre-flight tests on the ground at the TA site allowed to assess the performances of the instrument, with a reconstruction of laser shots with $\sim 1^\circ$ accuracy and an energy threshold at 50% detection efficiency at ~ 3 EeV, so that one or two events per month could be expected.

EUSO-SPB was successfully launched from the NASA balloon facility in Wanaka (New-Zealand) in April 2017. The instrument proved to be working nominally. Unfortunately, because of a leak in the balloon, the flight was cut short after 12 days, which did not allow to detect an actual cosmic ray shower (nor to recover the instrument). A total of 25.1 hours of data could be downloaded. They contain very useful information about the in-flight

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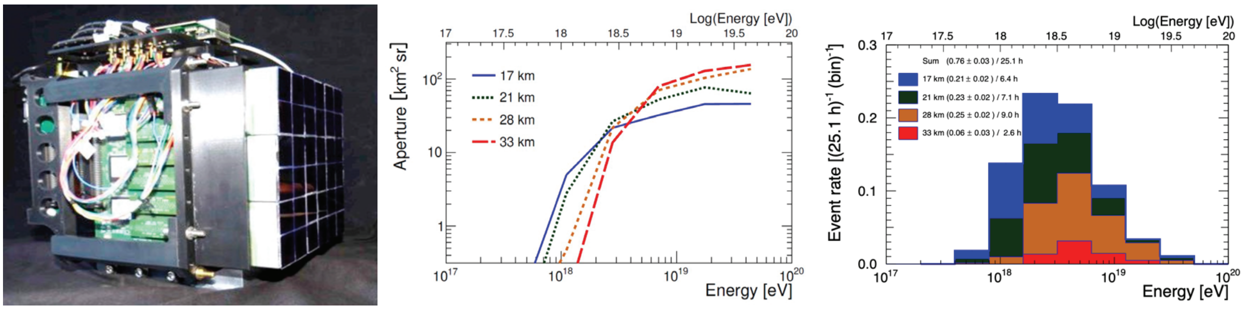

Figure 6. Left: JEM-EUSO's second generation PDM, used in the EUSO-SPB mission. Center: EUSO-SPB realised aperture. Right: EUSO-SPB expected event rate. See [25] for details.

performance of the instrument, attesting a photometric stability within ±5%. The UV emissivity of the Earth, which constitutes a background for the EAS detection, could be measured over different types of background: land, ocean, clouds of various types and altitude. Moreover, the effective exposure could be estimated as a function of energy, for different altitudes of the balloon, as shown in Fig. 6 (middle panel). This could in turn be used to derive the expected event rate in different energy bins (right panel). The resulting, integrated number of events expected on average during the entire flight is ~ 0.7 events, which is reduced to 0.4 events when taking clouds into account. Although this is of order unity, in line with the expactations from the mission design, none were actually detected.

Finally, the data collected during the flight allowed to identify various types of events corresponding to direct hits of cosmic rays on the instrument. A classification of such hits (depending on their shape and appearance in the data) was proposed, which will be useful for future missions. Their rate is low enough for the associated dead time to be acceptable, so no veto needs to be implemented to get rid of these undesired events.

4.3.3 MINI-EUSO

MINI-EUSO (Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory, also known as *UV atmosphere* in the Russian Space Program) is the currently active orbital mission of the JEM-EUSO Collaboration [26]. It was precedented in space by the TUS mission [27], launched in 2016, which was subsequently inserted into the JEM-EUSO program both for technology and scientific results and analyses [28]. MINI-EUSO is a joint mission of the Italian (ASI) and Russian (ROSCOSMOS) space agencies, installed inside the International Space Station (ISS) in the Russian Zvezda module. The design of the focal surface is close to that of EUSO-SPB, with 1 PDM using the second generation of ECs. However, the optics is different and consists of two circular Fresnel lenses of 25 cm diameter, to fit in front the UV transparent window of the Zvezda module. The field of view is also much larger, namely ~44°×44°, with a projected size of the individual pixels on the ground of ~6.3×6.3 km^2, so that the typical background is similar to that of the other missions, including the future major JEM-EUSO missions, i.e. ~1 photon per pixel per so-called *Gate Time Unit*, or GTU, whose value is 2.5μs.

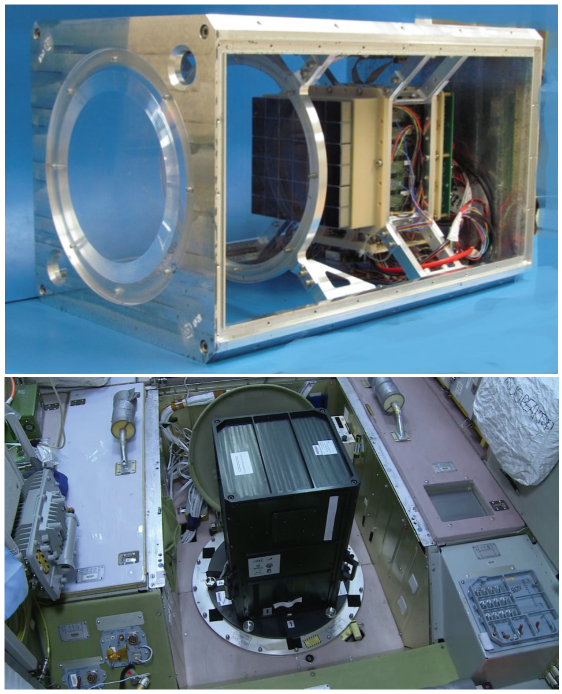

Figure 7. Top: open MINI-EUSO instrument, showing the circular Fresnel lens, as well as the second generation PDM and its electronics at the focal surface. Bottom: MINI-EUSO locked onto the UV transparent window of the Zvezda module in the ISS.

MINI-EUSO was successfully launched in August 2019, and saw its first light in October 2019. It operates nominally since then, when cosmonauts position it in front of the quartz window and turn it on for 12h sessions, i.e. ~8 orbits. More than 70 sessions have taken place so far, producing data of which a small fraction is downloaded after each session, while the main part if brought back to Earth physically on solid state disks every ~12 months.

Because of the small entrance pupil, the collected light from UHECR showers or other atmospheric phenomena is much reduced, compared to what will be the case for a full-scale mission. As a consequence, the detection threshold of MINI-EUSO for UHECR events is around 3 10^{21} eV, as

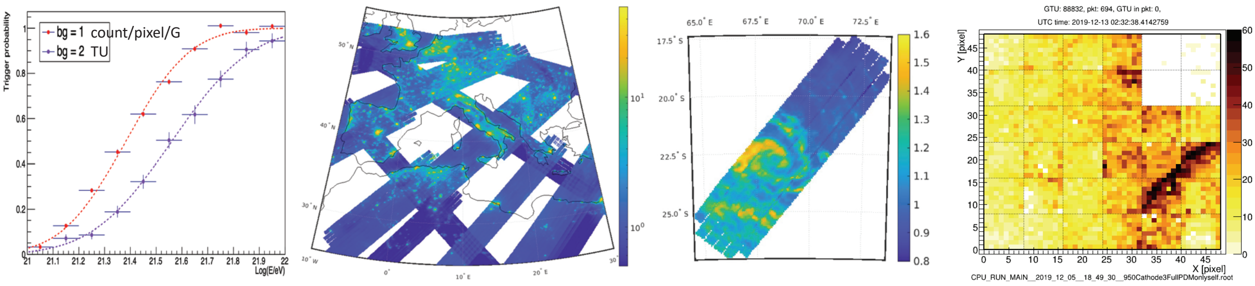

Figure 8. Left: trigger efficiency of MINI-EUSO as a function of energy. Center left: UV map of the nightly Earth (the bands correspond to different passages of the ISS with the instrument turned on by the cosmonauts). Center right: UV map of a cyclone. Right: ring of an ELVES (with apparent luminal motion in the field of view).

shown in Fig. 8 (left panel) for two typical levels of background. Given the extremely low flux of particles at such an energy (if there are some at all!), MINI-EUSO is not expected to detect UHECR showers. However, it did already demonstrate its ability to detect such events, by triggering on various signals with similar properties, including artificial UV flashers as well as unidentified events, which are currently under investigation and remain an important target for the mission. Also, the in situ measurements already provided key information allowing to determine the performance of a scaled-up fluorescence telescope for UHECR detection from space, confirming the previous analyses and simulations of the JEM-EUSO collaboration (see Bertaina, this conference).

MINI-EUSO addresses a variety of additional scientific objectives, thanks to a key feature of its electronics and data acquisition system, namely the ability to operate on 3 different timescales in parallel. The first level uses the basic time resolution, namely 1 GTU. This is best suited for rapid transient phenomena, such as man-made flashers, or moving signal in the field of view of the instrument, such as ELVES, potential relativistic grains, and of course UHECR events, above the energy threshold. On the second level, the light integration time is 128 GTU, i.e. 320μs. This allows to measure emissions from other types of transient luminous events, cities and various anthropogenic signals. Finally, a third level of integration has a time unit of 128×128 GTU, i.e. 40.96 ms, which provides continuous monitoring of clouds, ionospheric waves, lightning, or other natural or non natural emissions.

In addition to the information relevant for future large-scale JEM-EUSO missions, MINI-EUSO provided for the first time UV maps of the Earth at night (Fig. 8). It also detected thousands of meteors down to magnitude 6.5, with full efficiency above magnitude 5. It also allowed unprecedented imaging of ELVES, thanks to its unique sensitivity and spatial resolution, which led to the discovery of new internal feature (paper in preparation).

4.3.4 EUSO-SPB2

The next mission of the JEM-EUSO Collaboration will be EUSO-SPB2 [29]), a NASA mission under a stratospheric super pressure balloon. Compared to the previous EUSO-SPB mission (now renamed EUSO-SPB1), EUSO-SPB2 has been scaled up with the inclusion of three PDMs instead of one (for a total of 6912 pixels), and the addition of the above-mentioned Cherenkov telescope (CT), whose SiPM-based focal surface is shown in Fig. 9 (see also Cummings, this conference). Moreover, it benefits from several important improvements of the PDM, with new electronics and a third generation of ECs, more compact and more efficient, identical to those developed for the K-EUSO prototype [30]. The length of the GTU has also been reduced compared to previous JEM-EUSO missions, down to 1 μs instead of 2.5 μs. This is optimised with respect to the average time it takes a shower to cross the field of view of a pixel, thereby increasing the detection efficiency.

In addition, EUSO-SPB2 will be the first JEM-EUSO mission using reflective optics, with the adoption of a Schmidt camera design for both the FT and the CT. The FT aperture has a diameter of 1 m, and its field of view is ~12°×36°, corresponding to a projected area of ~36 km^2 on the ground. The CT also has 1 m diameter aperture, with a field of view of ~6.4°×12.8° covered by 512 SiPM-based pixels. A key feature of its optics is the use of a bi-focal mirror, coupled with a trigger scheme requiring signal on 2 conjugate pixels, to reduce the noise from direct cosmic-ray hit on the focal surface or single pixel fluctuations.

EUSO-SPB2 has been approved for a launch from Wanaka (New-Zealand) in April 2023. Its performances have been tested on the ground, at the TA site in Utah. They confirmed the numerical simulations and validated the different aspects of the instrumental and experimental concept. Based on these results, EUSO-SPB2 is expected to detect and reconstruct several high-energy CR showers, with typical energies around 2 10^{18} eV, thereby completing the development phase of the JEM-EUSO program. The right panel of Fig. 9 shows the expected trigger efficiency as a function of energy, and the resulting number of events per hour of clear sky observation in the different energy bins.

As for the CT, its orientation can be adjusted both in elevation and azimuth. Tilting in elevation allows to chose the position of the limb of the Earth in its ~6.4°×12.8° field of view, to measure the yet unknown UV luminosity both above the limb (as a background for high-altitude,

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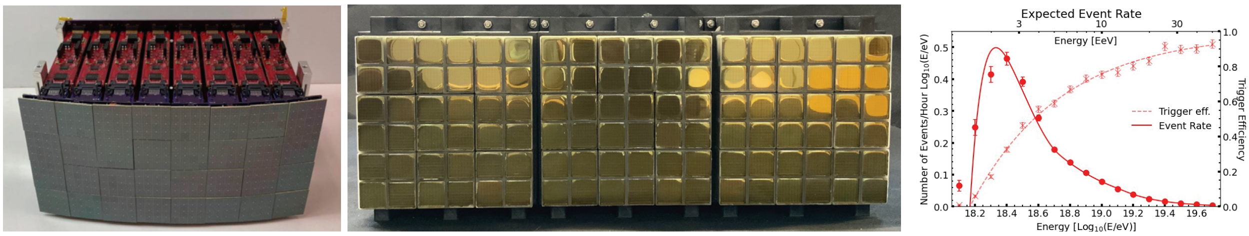

Figure 9. Left: SiPM and electronics modules of the CT camera of EUSO-SPB2. Center: focal surface of the FT of EUSO-SPB2, with 3 PDMs for a total of 6912 pixels. Right: expected trigger efficiency for cosmic-ray events in the FT of EUSO-SPB2 and the corresponding event rate.

horizontal CR showers and other fast atmospheric events) and below the limb (as a background for neutrino shower detection). Complementarily, tilting in azimuth allows to point the CT towards specific targets of opportunity, searching for neutrino counterparts as a response to multi-messenger alerts that may be issued during the flight. While an actual neutrino detection is not likely, the detection of direct Cherenkov light from CRs above the limb is expected to be on the order of ~100 per hour of live time, because of the low energy threshold around 10^{15} eV. This should provide a useful benchmark for the Cherenkov method applicable to neutrinos. Additionally, the measurements from the CT towards the limb will be of great important in preparation of a future major neutrino experiment from space, such as POEMMA [31].

5 Conclusion

Although the current generation of detectors has collected extremely rich information and high-quality data about the UHECR phenomenology in the last two decades, the current consensus among the interested research community is that a new generation of detectors will be needed to reach a global understanding of the phenomenon and discover the sources of the UHECRs and their acceleration mechanism. A very important step forward will be to significantly increase the statistics and achieve full sky coverage with roughly uniform exposure. This is what a space-based UHECR observatory could naturally provide, and this is the vision that drove the international JEM-EUSO Collaboration in its endeavour to develop suitable and operational technology for a large instrument looking down towards the Earth to detect extensive atmospheric showers from a low Earth orbit.

As summarized above, after one and a half decades of intense instrumental activity, the JEM-EUSO Collaboration has demonstrated its ability to develop efficient technology and meaningful instruments for balloon and space missions of increasing complexity and scientific scope, with the support of many space agencies and research institutes around the globe. All the missions have been experimentally successful, and provided crucial information and results for the development of the future steps.

In this incremental adventure, EUSO-Balloon and EUSO-TA first demonstrated the relevance of the JEM-EUSO technology. The EUSO-SPB1 mission further demonstrated the scalability of the concept with new generations of detectors and electronics, and was able to assess the performance and the robustness of the instruments in flight. With MINI-EUSO, the JEM-EUSO collaboration confirmed the long-term operation of its technology in space, and demonstrated the full potential of complementary and interdisciplinary science accessible with its versatile technology, operating on different timescales in parallel. Finally, EUSO-SPB2 gathered all the past experience in a scaled-up mission. With its improved performance obtained from a third generation of detectors, upgraded electronics and the addition of a Cherenkov telescope targeting high-altitude showers and neutrinos, it will explore the multi-messenger potential of the field.

Most of all, EUSO-SPB2 should be the first mission to detect the fluorescence light of high-energy cosmic-ray showers from above, which will mark the crowning achievement of this preparatory phase, vouching for the maturity of the technology and validating the entire JEM-EUSO program.

From then on, the JEM-EUSO Collaboration can move forward, as it is now ready for the success of a major UHECR space mission, along the lines proposed for the (currently suspended) K-EUSO mission [30] or the POEMMA mission [31].

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