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Overview of the JEM-EUSO Program

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Since 2010, the international JEM-EUSO (Joint Exploratory Missions for Extreme Universe Space Observatory) Collaboration has been developing an ambitious program with the support of major International and National Space Agencies and research funding institutions, to enable Ultra-High-Energy Cosmic Ray (UHECR) and High-Energy (HE) neutrino observations from space. Its main objective is to develop a large mission with dedicated instrumentation looking down on the Earth atmosphere from space, both towards nadir and/or towards the limb, to detect the Extensive Air Showers (EAS) initiated by such particles in the atmosphere. This strategy is intended to complement the observations made with ground-based observatories, by allowing a significant increase in the exposure at the highest energies, and achieving near-uniform full sky coverage, as part of the global effort to better characterize the phenomenology of UHECRs, discover their sources and understand their acceleration mechanism. In the last decade, the JEM-EUSO Collaboration successfully developed five intermediate missions: one ground based (EUSO-TA), three balloon-borne (EUSO-Balloon, EUSO-SPB1, EUSO-SPB2) and one space-based (Mini-EUSO), and also benefited from the experience gained by the space mission TUS. Important studies for a full-scale mission have also been carried out, namely K-EUSO and the stereo double telescope Probe Of Extreme Multi-Messenger Astrophysics (POEMMA), to be considered for a NASA Probe Mission in the next decade. The technical and scientific achievements of this rich and manifold program are reported on, as well as the scientific objectives updated in the light of the knowledge gained from the previous missions, and additional scientific objectives accessible to such unique technology. Finally, the near-future developments of the JEM-EUSO Program are briefly presented, with the continuation of the Mini-EUSO observations and the new balloon-borne mission PBR.

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1. The JEM-EUSO Science Case

Since 2010, the international JEM-EUSO (Joint Exploratory Missions for Extreme Universe Space Observatory) Collaboration (URL: https://www.jemeuso.org), around 170 researchers, 60 institutions and 16 countries has been developing an ambitious Program with the support of major International and National Space Agencies (ASI, CNES, ESA, JAXA, NASA, ROSCOMOS) and research funding institutions, to enable Ultra-High-Energy Cosmic Ray (UHECR) (E> 100 PeV) and High-Energy (HE) neutrino (E>1 PeV) observations from space. Its main objective is to develop a large mission with dedicated instrumentation looking down on the Earth's atmosphere from space, both towards nadir and/or towards the limb, to detect the Extensive Air Showers (EAS) initiated by such particles in the higher atmosphere. This strategy is intended to complement the observations made with ground-based observatories (Pierre Auger Observatory, Telescope Array), by allowing a significant increase in the exposure at the highest energies, and achieving near-uniform full sky coverage, as part of the global effort to better characterize the phenomenology of UHECRs. The open questions still alive about the nature of UHECRs, the identification of their sources and the origin of the observed flux suppression will be addressed as primary scientific goals, adding the detection of HE neutrinos, with precise measurements and unprecedented statistical accuracy by means of a single instrument with highly increased statistics and minimized systematics, using a target volume far greater than from the ground, at energies beyond the human-made accelerators. Such indirect measurements from space could be devoted also to study atmospheric and space-weather sciences (measurement of the night-glow and transient luminous events, meteors and meteoroids, tracking of space debris), as secondary scientific goals, and to open a new window of the Unknown (searching for physics Beyond the Standard Model at the energy frontier and probing Relativity and quantum gravity effects). Currently, the international UHECR community is addressing the problem of aiming at such researches in the next two decades with most effective approach by fostering a farseeing road map [1]. The next-generation large experiments or missions (GCOS, GRAND, and POEMMA) will provide complementary information needed to meet the scientific goals in the UHECR field. They should proceed through their respective next stages of planning and prototyping. To this end, next generation experiments should be space-based or multi-site. In such scientific context, the JEM-EUSO Collaboration completely places itself pursuing a Program [see Sec.3] of intermediate missions by a necessary step-by-step approach.

2. Basic concepts and the genesis of the JEM-EUSO Program

In the so-called current hybrid technique for the indirect detection of UHECRs, the EAS are three-dimensionally reconstructed by the combined use of a giant array of Cherenkov or scintillator detectors, measuring secondary charged particles (mainly electrons) at ground, surrounded by fluorescence telescopes, detecting the fluorescence light produced in the atmosphere, primarily due to the interaction of secondary electrons with N_2 molecules. The key innovative idea consists in reconstructing EAS by measuring the Ultra Violet (UV) (290 ÷ 430 nm) fluorescence and/or Cherenkov light produced in the atmosphere by means of space-based detectors based on an UV wide-field telescope flying at low-Earth orbits looking at nadir (0°) direction and/or *tilted* (30°) mode, towards the limb, during the night, using the whole Earth atmosphere as 10^{12} tons target

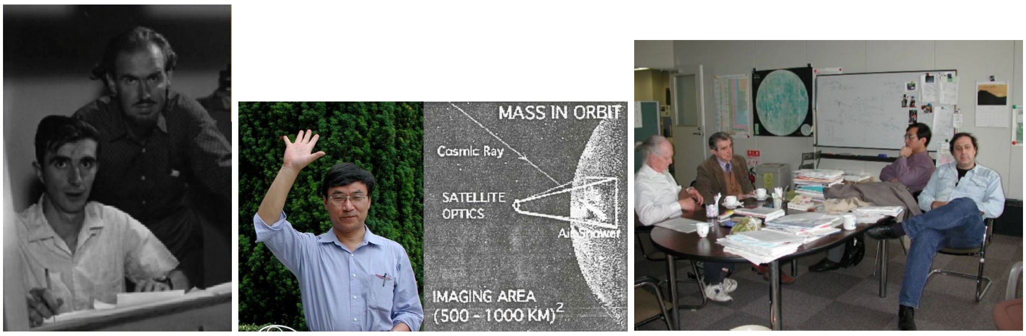

Figure 1: Left: J. Linsley and L. Scarsi collaborating at the pioneering UHECR grund-based Volcano Ranch experiment. Middle: Y. Takahashi and its MASS Proposal. Right: first EUSO meeting in RIKEN (Japan): Linsley, Scarsi, Takahashi and O. Catalano in round table discussion.

volume [2]. This challenging technique presents relevant advantages: very large instantaneous observational areas ($A \approx 2 \times 10^5$ km^2 in nadir and $A \approx 7 \times 10^5$ km^2 in *tilted* mode); highly uniform exposure ($4\,\pi$ coverage) across the Nord and South skies; large and well constrained distances toward showers; clear and stable atmospheric transmission in the above half troposphere [3]. The futuristic concept for novel EAS detection from space was developed thanks to the effort of three visionary scientists: John Linsley, Yoshuyuki Takahashi and Livio Scarsi [3] (see Fig.1, left and middle). The first (1979) original idea was conceived by J. Linsley and submitted in 1981 in the form of SOCRAS (Satellite Observatory of Cosmic Ray Showers) Project, included in Field Committee Report of NASA "Call for Projects and Ideas in High Energy Astrophysics for the 1980s". Nevertheless, it was not actualized due to the not mature technological level for that time period. Only in 1995 Y. Takahashi proposed a new imaging technology, denominated MASS (Maximun-energy Auger (Air-)Shower Satellite) Approach, related to the original Linsley's idea. Soon Takahashi contacted Linsley, who was collaborating in Palermo (Italy) with L. Scarsi and, in the meantime, organized a first Workshop in Huntsville (USA) (August 1995). As a result of that meeting, in U.S.A. the OWL (Orbiting Wide angle Light concentrators) Proposal was born, included and selected in NASA SEU Mid-term Strategic Plan (2010). At the same time, Scarsi and Linsley named the MASS Approach as *Airwatch* and organized the first Symposium for *Airwatch* Project in Catania (Italy) in 1996, interesting many Italian and Russian colleagues that merged in the EUSO (Extreme Universe Space Observatory) concept, under the leadership of Scarsi. In 2000 the EUSO Proposal was submitted to the ESA Call for the F2/F3 Missions and selected for accommodation study onto International Space Station (ISS). In 2001, the first EUSO Collaboration meeting took place at RIKEN (Japan) under guidance of Linsley, Scarsi, Takahashi and the significant contribution of O. Catalano (see Fig.1, right) [2]. In March 2001, EUSO was approved for a Phase-A study, as an external payload for the ISS European Columbus module, that was successfully completed in 2004. However, due to the awful Columbia disaster (2003), the start of Phase-B was postponed indefinitely. In a timely manner, Takahashi re-defined EUSO as a mission attached to the ISS Japanese Experiment Module/Exposure Facility (JEM/EF), joined Japanese and U.S. teams and re-named the mission as JEM-EUSO under a new Phase-A study led by JAXA for a possible launch in 2013. The Kick-Off meeting of the renewed JEM-EUSO mission was held at RIKEN in 2006. At the same time, Russian researchers flowed into other projects (TUS and KLYPVE) for detecting

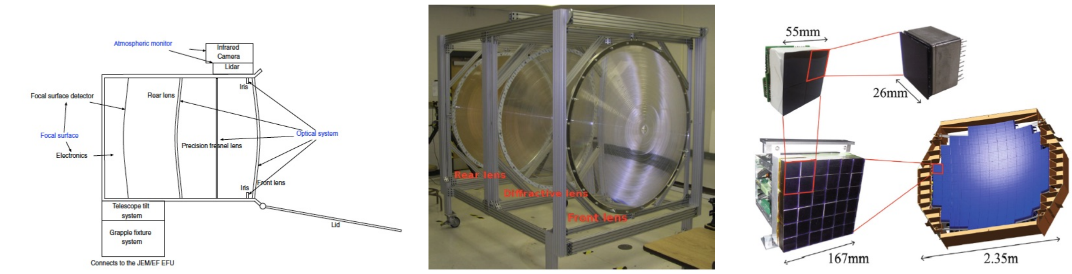

Figure 2: The schematic design of the JEM-EUSO detector (left); the 1.5 m diameter 3 Fresnel lens optics (middle); the FS consisting in 137 PDMs: each PDM is a (3×3) set of Elementary Cells (EC). Each EC is a (2×2) array of MAPMTs for a total of 315648 pixels (right).

EAS from space using the Fresnel optics. The Phase A/B1 study intensively and successfully continued achieving a good enhancement of the Technology Readiness Level (TRL). Basically, as result of that Phase, the conceptual design (see Fig.2, left) of the JEM-EUSO detector [4] was based on a Fresnel-optics refractive telescope that would orbit the Earth every 90 minutes at an altitude of $330 \div 400$ km, making observations in the dark part of the Earth, about 40 minutes per orbit. The UV light from the EAS is focused through a wide ($\pm 30°$) Field of View (FoV) diffractive optics employing Fresnel lenses (see Fig.2, middle) . The light is detected by a 3×10^5 pixel spherically (2.5 m in diameter) curved Focal Surface (FS) of about 5×10^3 Multi-Anode Photomultiplier Tubes (MAPMTs, Hamamatsu R11265-M64), each with 64 pixels (see Fig.2, right), which records the EAS track with a 2.5μs time resolution and a $0.074°$ angular resolution. Following the terrible Fukushima nuclear disaster (2011), the JAXA was obliged to dismiss its leadership and mission was put on hold status. The JEM-EUSO Collaboration was redirected towards a rich and manyfold pathfinder Program under a renewed acronym (Joint Exploratory Missions for Extreme Universe Space Observatory).

3. The JEM-EUSO Program

In the last decade, the JEM-EUSO Collaboration effectively developed five intermediate missions: one ground based (EUSO-TA), three balloon-borne (EUSO-Balloon, EUSO-SPB1, EUSO-SPB2) and one space-based (Mini-EUSO), described to follow, and also benefited from the experience gained by the Russian space mission TUS (Tracking Ultraviolet Setup) [5].

3.1 Ground-based intermediate mission: EUSO-TA (2014-)

EUSO-TA [6], [7] is a ground-based telescope, installed at the Telescope Array (TA) site in Black Rock Mesa, Utah, USA. This is the first detector to successfully use a Fresnel lens based optical system and MAPTs for UHECR detection: two 1 m^2 Fresnel lenses with $(10.6° \times 10.6°)$ FoV, a (17.3 cm $\times$ 17.3 cm) FS consisting in 1 PDM (36 MAPTs Hamamatsu, 2304 pixels), a Front-End (FE) read-out electronics based on ASIC-SPASIROC1, upgraded to ASIC-SPACIROC3 in 2018. The telescope is located in front of one of the fluorescence detectors of the TA experiment. Since its installation in 2013, and during five observational campaigns in the course of time, the detector has observed some UHECR events and, in addition, meteors, stars and laser light events. Measurements of the UV night sky emission in different conditions and moon phases and positions have been completed. In 2016 the EUSO-TA was employed for test and calibration campaign of EUSO-SPB1 payload and in 2022 of EUSO-SPB2 payload.

3.2 Balloon-born intermediate missions

The stratospheric balloons flights present significant merits in the range of intermediate missions of the JEM-EUSO Program (see *This Conference* [8]): they are technology demonstrators and allow to advance the TRL, they permit studies of background and data acquisition in realistic environmental and operational conditions, they are precursors of the future full-size space-based missions.

• **EUSO-Balloon (2014)** [9] was launched (see Fig.3, left) by the CNES from the Timmins base in Ontario, Canada, on the moonless night between August 24th and 25th, 2014. After reaching its floating altitude of about 38 km, EUSO-Balloon measured the UV intensity in the ~ (290 ÷ 500) nm wavelength range for more than 5 hours and a 100 km path before descending to ground level by splashing down in a solitary local lake. The EUSO-Balloon refractor telescope consists of two Fresnel lenses of ~ 1 m^2 area and $(6^\circ \times 6^\circ)$ FoV, the FS with 1 PDM (36 MAPTs, 2304 pixels). The spatial and temporal resolutions at floating altitude are ~130 m and 2.5 μs, respectively. The FE read-out electronics uses SPACIROC1-ASIC. During 2.5 hours of the EUSO-Balloon flight, a helicopter circled under the balloon to operate UV flashers and a UV laser to simulate the optical signals from UHECRs, to calibrate the apparatus, and to characterise the optical atmospheric conditions. The EUSO-Balloon flight allowed for the first time a full scale end-to-end test of most of the key technologies and instrumentation on air and a detailed study of its response to cosmic rays events and artificial light sources. A first accurate measurement of the UV intensity in different atmospheric and ground conditions was achieved. The detection of laser events proved the feasibility of the observation of EAS-like events [10].

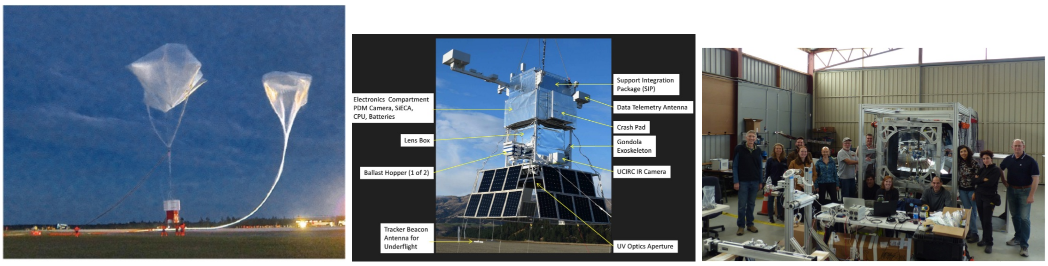

Figure 3: Left: launch of EUSO-Balloon from the CNES Timmins base in Canada. Middle: layout of the EUSO-SPB1 detector. Right: the EUSO-SPB2 team during the final stage of completion.

• **EUSO-SPB1 (2017)** (EUSO-Super Pressure Balloon 1) [11] was launched in 2017 April from Wanaka (NASA balloon base) New Zealand. The plan of this mission of opportunity on a NASA super pressure balloon test flight was to circle the southern hemisphere. The primary scientific goal was to make the first observations of UHECR-induced EAS by looking down on the atmosphere with an UV fluorescence telescope from suborbital altitude (33 km). After about 12 days, the flight was terminated prematurely landing in the South Pacific Ocean due to an unexpected helium leak in the balloon. For the telescope on-board, two 1 m^2 Fresnel lenses $(6^\circ \times 6^\circ)$ FoV, 1 PDM (36 MAPTs, 2304 pixels) (II Generation) and FE SPACIROC3-ASIC read-out system was assembled (see Fig.3, middle). Although the EUSO-SPB1 mission did not yield any cosmic-ray EAS events, most of the valid data were downloaded (25.1 hours) and analyzed. The data showed that the instrument performed well and that the instrument photometric stability was stable within 5%. The upgraded triggers, new development of data acquisition system and a real-time monitoring in ground stations via NASA contributed effectively in raising of TRL.

• **EUSO-SPB2 (2023)** (EUSO-Super Pressure Balloon 2) [12] [13] (see *This Conference* [14]) flew on May 13th, 2023 from Wanaka (NASA balloon base), New Zealand and landing May14th, 2023 in South Pacific Ocean after 37 hours, due to a hole in the envelope of the balloon, flying at about 33 km of altitude. Consisting of two novel optical telescopes, the payload utilized next-generation instrumentation: one Fluorescence Telescope (FT) based on 1 m Schmidt optics with ($36° \times 12°$) FoV searching for UHECRs by recording the atmosphere below the balloon in the near-UV with a 1.5 μs time resolution, using 3 PDM (108 MAPTs, 6912 pixels) and one Cherenkov Telescope (CT) based on 1 m Schmidt optics with ($6.4° \times 12.8°$) FoV searching for HE neutrinos by pointing towards 10°, below the Earth's limb, in the near-UV with a 10 ns time resolution, using 512 Hamamatsu Silicon PhotoMultipliers (SiPMs). Consistent with the expectation, no UHECR candidate events have been found. Nevertheless, the flight was an excellent opportunity to test a new technology based on two different telescopes that nominally worked (see Fig.3, right).

3.3 Space-based intermediate mission: Mini-EUSO (2019-)

Mini-EUSO [Mini-(Multiwavelength imaging new instrument)-EUSO] [15], (see *This Conference* [16]) is a telescope observing the Earth in the UV band from the ISS and detecting artificial showers generated with lasers from the ground with a 6.3 km spatial resolution and a 2.5 μs time resolution, through a nadir-facing UV-transparent window in the Russian Zvezda module.

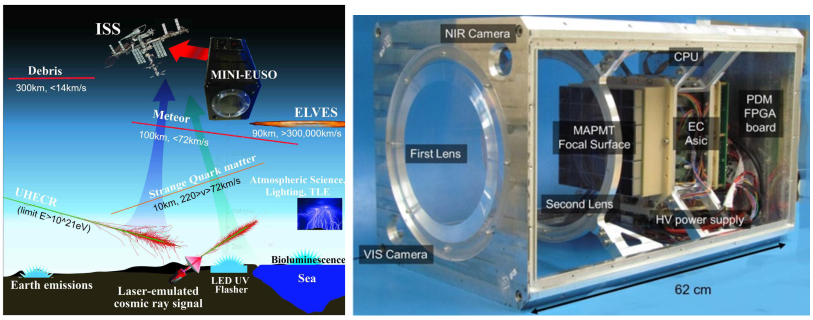

Figure 4: Left: an artistic view about the collection of events, corresponding to different scientific goals, studied by MiniEUSO mission. Right: details of the MiniEUSO detector.

The instrument was successfully launched on 2019 August 22nd from the Baikonur Cosmodrome and has been successfully collecting data since October 6th, 2019 so far operating nominally. The detector is based on an optical system employing two Fresnel lenses and a FS composed of 36 MAPTs (2304 pixel in total) with a 44° FoV (see Fig.4, right). Other main scientific objectives of the mission are the search for nuclearites and strange quark matter, the study of atmospheric phenomena such as transient luminous events, meteors, and meteoroids, the observation of sea bio-luminescence and of artificial satellites and man-made space debris (see Fig.4, left). Five years of collected data demonstrate that Mini-EUSO measures the Earth UV background with unprecedented accuracy and is capable to detect a large range of natural events of great interest to atmospheric and space-weather sciences.

4. Near-future developments and the next full-size space-based missions

All the relevant and extensive efforts of the JEM-EUSO Collaboration to develop the science case as well as the experimental, technological, and engineering aspects of such a challenging pioneer intermediate missions pave the way for the near-future developments, the next balloon-born mission and the future medium/large size space-based mission. As a matter of fact, a new balloon-borne flight has been already approved and funded by NASA for a launch planned in Spring 2027 from the Wanaka base. This next intermediate mission, named PBR (POEMMA Balloon with Radio) (see *This Conference* [17]), will be the real precursor of the large-size space-based POEMMA (Probe Of Extreme Multi-Messenger Astrophysics) mission [18], a stereo double telescope to be considered for a NASA Probe Mission in the next decade. Important studies for a full-scale mission have also been carried out in case of K-EUSO (KLYPVE-EUSO) [19], a medium-size space-based mission led by the ROSCOMOS together with the JEM-EUSO Collaboration to place an UHECR detector on board the Russian segment of the ISS.
A summarizing collection [20] of the main parameters of the JEM-EUSO Program, starting from original JEM-EUSO design and including intermediate missions and future full-size space-based missions is reported in conclusion (see Fig.5).

Experiment	JEM-EUSO	K-EUSO	POEMMA	Mini-EUSO	TUS	EUSO-Balloon	EUSO-SPB1	EUSO-SPB2	EUSO-TA
Optics type	Lenses	Lenses	Mirror	Lenses	Mirror	Lenses	Lenses	Mirror	Lenses
Optics aperture (m^2)	~ 4.5	~ 3	~ 6	~ 0.05	~ 2	~ 1	~ 1	~ 1	~ 1
Height (km)	400	400	525	400	~ 500	~ 38	~ 33	~ 33	~ 0
FoV (°)	$\sim 64 \times 45$	$\sim 20 \times 15$	~ 45	~ 44	~ 9	~ 11	~ 11	12×36	~ 11
Area at ground (km^2)	1.4×10^5	4.8×10^4	1.5×10^5	$\sim 8 \times 10^4$	$\sim 6.4 \times 10^3$	~ 54	~ 40	~ 150	–
PDMs	137	44	55	1	1	1	1	3	1
Pixels	3.2×10^5	1×10^5	1.3×10^5	2304	256	2304	2304	6912	2304
Spatial ang. resolution (°)	~ 0.074	~ 0.1	~ 0.084	~ 0.9	~ 0.7	~ 0.2	~ 0.2	~ 0.25	~ 0.2
Pixel size at ground (km)	~ 0.5–0.6	~ 0.6–0.7	~ 0.8	~ 6.3	~ 5.0	~ 0.13	~ 0.12	~ 0.14	–
GTU (μs)	2.5	2.5	1.0	2.5	0.8	2.5	2.5	1.0	2.5
Bckg level (cts/pix/GTU)	1.1	0.6	1.5	~ 1.0	~ 18.0	~ 0.5–1.0	1–2	~ 1	1–2
Reference	[9,10]	[19]	[20,38]	[18,39]	[17,29]	[14,33]	[15]	[16,37]	[13]

Figure 5: Main parameters of different configurations [20] of the JEM-EUSO Program. Note: the references present in the table refer to those ones reported in [20].

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