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The JEM-EUSO program

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The JEM-EUSO mission, onboard the International Space Station (ISS), is currently being designed to unveil the nature and the origin of the ultra high energy (UHE) cosmic rays, at energies from a few $E \sim 10^{19}$ eV up to the decade of $E \sim 10^{20}$ eV. JEM-EUSO also addresses basic problems of fundamental physics at energies $E \sim 10^{20}$ eV, unachievable by man-made accelerators. The instrument is designed to measure the arrival direction, the energy and, possibly, the nature of UHE particles. The mission basically consists of a wide field UV telescope that points along nadir from the ISS at night-time to detect the UV tracks associated to the propagation of the extended air showers induced by UHE primaries in the earth's atmosphere. The main goal is to identify the individual sources of the UHE cosmic rays and their association with known nearby astronomical objects. An infrared camera and a LIDAR improve the performance of the instrument. The program is proceeding in different steps. While the JEM-EUSO mission is being improved to allow the use of Space-X Dragon, the K-EUSO mission, an advanced version of the KLYPVE mission, already approved by ROSCOSMOS, modified with EUSO technology, and attached to the Russian module of the ISS, is in the stage of final definition. Two pathfinders have already been developed and operated: the first, the EUSO-Balloon flew on board a stratospheric balloon on August 2014; the second, EUSO-TA on ground, is in operation at the Telescope Array site. A third pathfinder, the Mini-EUSO mission, is approved by ASI and ROSCOSMOS, and will be installed inside the ISS. More short and long duration balloon flights are in addition envisaged.

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1. Introduction

The Extreme Universe Space Observatory on-board the Japanese Experiment Module of the ISS (JEM-EUSO) is an innovative mission designed to observe from space the UHE cosmic rays with energies from a few $E \sim 10^{19}$ eV up to the decade of $E \sim 10^{20}$ eV [1], [2], [3].

It was John Linsley who, back in the late 70s, first proposed the use of space-based devices, looking downward to the earth's atmosphere at night, to observe UHE cosmic rays [4]. Linsley's idea was simple and visionary: to observe the fluorescence light produced, in near UV, by extensive air showers (EAS) propagating at relativistic speed in the atmosphere. The idea was unfortunately not implementable with the imaging and space technology of the 80s. In 1995, Linsley's original idea was rediscovered by Yoshiyuki Takahashi, who proposed MASS, the Maximum-energy Auger (Air)-Shower Satellite. The key breakthrough in the imaging technology was the use of light-weight, segmented, double Fresnel lenses optics to enlarge the field of view (fov) to about 60° keeping a reasonable size of the instrument [5].

Under the leadership of John Linsley, Yoshi Takhashi and Livio Scarsi, the MASS idea evolved in the US, into the Orbiting Wide Angle Light Concentrator (OWL), whose mission study was accepted by NASA in 1996 and entered NASA's Structure and Evolution of the Universe Mid-Term strategic plan in 2010 [8]. OWL consists of two UV telescopes, each based on a Schmidt camera with a 45° full fov and 3.0 meter entrance aperture, observing in stereo configuration. The mission's orbit is initially at about 1000 km that reduce to 550 km at the end of operations. The mission has not yet been implemented. In Europe, it was started the AIRWATCH program, which, after a few years, led to EUSO. The *Extreme Universe Space Observatory*- EUSO was originally an ESA lead international mission designed for the Columbus module of the ISS [6], [7]. The phase-A study for the feasibility of EUSO, started in 2001, and was successfully completed in March 2004. EUSO was found technically ready to proceed into phase B, but ESA did not continue the program mainly because of financial constrains and because of the programmatic uncertainties of the ISS related to the Columbia accident.

In 2006, the Japanese and U.S. teams reoriented the mission as an observatory attached to KIBO, the Japanese Experiment Module (JEM) of ISS. JEM-EUSO started a new phase-A study in the framework of the second phase utilisation of JEM/EF utilisation [1]. In 2010 the EUSO mission was also included in ESA's European Life and Physical Sciences in Space Programme (ELIPS). The Phase A/B1 study of JEM-EUSO, led by JAXA, included extensive simulations, as well as design, and prototype hardware developments that have significantly improved the original EUSO mission profile [9], [10], [11].

2. Science objectives

JEM-EUSO will pioneer UHECR science from space, allowing a significant jump in the statistics of the UHE events. It will clarify the origin of the UHECRs and probe particle interactions, possibly discovering new physics at energies well beyond those attainable by man-made accelerators. The main science goal of the mission is the study of the sources of the UHECRs. An update view of the science case at the core of the mission is discussed in [12]. The main science objectives of the mission can be summarised as:

- the identification of UHE sources
- the measurement of the energy spectra of individual sources
- the measurement of the spectrum above the GZK energy

In addition to the main objectives, several *exploratory objectives* will be pursued by the mission:

- the study of the UHE neutrinos flux and potentially the discovery of UHE neutrinos
- the study of the UHE photons flux and potentially the discovery of UHE photons
- the study of the galactic and local extragalactic magnetic field through the study of the magnetic spread functions of the events
- Fundamental physics studies: the study of the *Top-Down* scenario, the search for nuclearites, monopoles, and strangelets, limits to Lorentz Invariance at factors of 10^{11}

The JEM-EUSO science program is completed by a series of objectives related to phenomena occurring in the atmosphere:

- the study of the UV background and of the Nightglow
- the study of the Transient Luminous events, and of the UV counterpart of Terrestrial Gamma Ray Flashes
- the study of meteors and meteoroids
- the study of the distribution and of remediation techniques for space debris polluting the terrestrial atmosphere.

The last item is indeed a recent interesting development of the potentiality of JEM-EUSO. Ebisuzaki et al. (2015) ([13]) proposed that the EUSO telescope can be used to detect and determine the position and velocity of space debris, and to implement a deorbiting operation by a high intensity laser inducing a reaction force via plasma ablation. Space debris are widely recognized as one of the growing threads against space operations. Detailed studies on the capability of JEM-EUSO on UHE neutrino and photon detection can be found in [14], [15].

3. Technique and baseline instrument

JEM-EUSO uses -from space- the well established fluorescence technique. The main instrument images the $\sim 290-430$ nm UV tracks produced by the relativistic propagation of EAS in the earth's atmosphere, and due to the decay of nitrogen molecules excited by collisions. Typically, for a 10^{20} eV EAS, a few thousand photons reach the instrument.The telescope can in addition observe the signal of the forward-beamed Cherenkov radiation diffusively scattered from the earth's ground or form the cloud's tops, which marks the core location of the shower. JEM-EUSO measures the time development of the EAS, imaging the track with a resolution of 2.5 μs. From the recorded image the energy and the arrival direction of the UHE primary are determined. Details on the observation technique, on the exposure, on the expected angular and energy resolution, can be found in [3], [16], [17], [18]. The current baseline of the instrument is described in [19]. The UV images of EAS are captured by a highly-pixelized high-speed camera. The camera focal plane is covered with 3×10^5 pixels, each 3 mm wide, reaching a $\sim 0.07^\circ$ resolution per pixel, corresponding to ~ 0.5 km on the earth's surface (for the ISS height of 400 km). The wide fov UV telescope ($\sim 60^\circ$) is assisted by an atmospheric monitor system, a LIDAR associated to a wide fov Infrared Camera [20], [21]. The optics uses a complex system of three Fresnel double-sided curved circular lenses with 2.65 m maximum diameter, and f number $\sim$1.00. The minimum diameter of the lenses is 1.9 m. This shape is referred to as *side-cut* and is required by the use of the H-IIB Transfer Vehicle (HTV) to deliver the instrument to the ISS. The focal surface consists of about 5,000 Multi-anode Photomultiplier Tubes (MAPMTs, Hamamatsu R11265-M64), each with 64 pixels, organised in 137 Photo-Detector Modules (PDMs), each comprising a 3×3 set of Elementary Cells (ECs). Each EC is formed by a 2×2 array of MAPMTs. The focal plane is completed by the read-out electronics based on the ASIC SPACIROC chip, and by an FPGA based digital electronics which has the challenging task of triggering the good events while rejecting the fake triggers to allow a reduction of the data rate from ~ 142 GB/s on the focal surface to the ~ 3 GB/day allowed by telemetry.

Several are the advantages of space-based observations of UHECRs. Since the EAS track length, $\sim 10-20$ km, is small when compared with the height (~ 400 km) of the ISS, a clear advantage is the far and almost constant distance between the detector and the shower. In addition, for most of the observed showers, the entire profile is contained in the field of view. Third, space-based observatories can observe in cloudy conditions, since in most cases the maximum of the shower occurs above the cloud-top. In addition the fluorescence signal received by the space-based UV telescope is marginally affected by scattered Cherenkov light, or by Rayleigh scattering. The most relevant advantage of space-based observations of UHECRs is however the extremely large area that can be monitored from space. The instantaneous observational area is $\sim 2 \times 10^5$ km^2 in nadir mode, which implies a target mass of more than $\sim 10^{12}$ ton, and can reach $\sim 7 \times 10^5$ km^2 when the observation axis is tilted with respect to nadir. These figures are almost two orders of magnitude larger than what achievable by ground based observatories. e.g. $\sim 3 \times 10^3$ km^2 for the Pierre Auger Observatory. Another key advantage is the highly uniform exposure over the full sky. JEM-EUSO and in general UHECRs space observatories naturally provide a 4π sky coverage, in contrast to ground-based observatory that can observe only the South or North Hemisphere.

4. The JEM-EUSO program: the main mission

The JEM-EUSO program consists of the development of the main mission and of a series of pathfinder experiments. According to the JAXA's study, JEM-EUSO is transferred to the ISS by the HTV (H2 transfer vehicle). To accommodate JEM-EUSO in the HTV, a contractible/extensible structure has been adopted. After the HTV docks in the ISS Docking Port, the Space Station Remote Manipulator System takes out JEM-EUSO and pass it to the JEM Remote Manipulator System. JEM-EUSO is planned to be attached to the Exposed Facility Unit #2 of the JEM and then expanded to the operational configuration using the deploying mechanism. Unfortunately the JEM-EUSO mission in its baseline configuration, as emerged from the phase A/B1 study, has been frozen by JAXA due to the restructuring of the space station program of Japan. In addition the

HTV launch program will most likely be reduced. The US team is currently pursuing, together with the European teams, the goal of reorienting the mission using the Space-X Falcon 9 launcher and Dragon transport vehicle to accommodate the mission onto the JEM module. To accommodate JEM-EUSO in the Dragon trunk several modifications have been investigated [22]. The so called *Dragon option* positively impacts on the design of the instrument, since a circular optics and focal surface can now be used, instead of the side-cut design. A series of simulations have been recently conducted to assess the performance of the mission in the new configuration. The expected exposure of JEM-EUSO with Dragon is reported in [23]. These preliminary investigation show that an annual exposure of up 10 times higher than the one of the ground-based experiment, above an energy $E > 6 \times 10^{19}$ eV, can be reached and set as a goal for the mission requirements. Studies on the angular resolution achievable are reported in [24], while the observational capabilities for different UHE primaries are summarised in [15]. The mission will be formally submitted to NASA by the US team in early 2017, targeting launch in 2020.

A different parallel approach is also actively studied by the JEM-EUSO collaboration: an improved version of the Russian KLYPVE mission, defined as K-EUSO. The KLYPVE project, included into the ROSCOSMOS long term programme of experiments onboard the ISS, uses a compound mirror concentrator, instead of Fresnel lenses, reaching a better efficiency but a significantly smaller fov. To eliminate, however, severe off-axis aberration, and reduce the spot-size, a corrective Fresnel lens is included in the telescope system. The thickness of the lens should be sufficiently small, around 1 cm. The lens has a radial Fresnel structure with groove depth of ~ 1 mm. In the current baseline system the diameter of the reflector and the lens-corrector are 3.4 m and 1.7 m respectively. The total length of the system ~ 4 m, while the distance from the lens to the focal surface is ~ 70 cm. In this configuration the field of view reaches up to $\pm 14°$, with a granularity of $\sim 0.058°$, equivalent to a scale of ~ 0.4 km on ground. The focal surface utilises a design similar to that proposed for the JEM-EUSO detector, and it is based on 1,900 Hamamatsu R11265-103-M64 MAPMTs, for a total of $\sim 120,000$ pixels. K-EUSO will be located on the external facility of the Russian MRM-1 module of the ISS. It will be delivered to the ISS by the Progress-TM vehicle, implying that the various instrument's elements have to pass through a cylindrical lock of 70 cm diameter and 120 cm length. This requires segmentation of all the major components of the system, including the lens, the mirror and the photodetector, and implies deployment and assembly in space, which requires Extravehicular activity (EVA). The annual exposure will be a factor of two that of Pierre Auger Observatory, about 20% the one of JEM- EUSO, amounting to $\sim 1.2 \times 10^4$ km^2 sr yr/yr. The threshold will be lower than that of JEM- EUSO thanks to the larger collection efficiency of the reflective optics. Details can be found in [25], [26], [27]. The mission is planned to be launched in 2020.

5. The JEM-EUSO program: pathfinders

The pathfinder program of the JEM-EUSO collaboration currently includes: i) the EUSO Balloon mission; ii) the ground based EUSO-TA experiment; iii) the MINI-EUSO mission. The *EUSO-Balloon* has been and is developed by the JEM-EUSO collaboration as a demonstrator of the key technologies and methods at the core of JEM-EUSO. The mission was proposed by the French laboratories involved in JEM-EUSO and is led by the balloon division of CNES. The instrument has been built by the JEM-EUSO collaboration. EUSO-Balloon is an imaging UV telescope, a scaled version of the JEM-EUSO telescope, pointing towards the nadir from ~ 40 km, monitoring an area of ~ 50 km^2. Using Fresnel optics and a PDM, a prototype of that designed for the main mission, the instrument monitors a $12^\circ \times 12^\circ$ wide fov in the 290 and 430 nm range, at a rate of 400,000 frames/s [28]. An Infrared Camera (IRcam), needed to monitor the cloud coverage and to estimate the cloud top, observes the field of view of the main instrument. The first flight was performed on August 25, 2014 from the Timmins base in Canada, in the framework of a CNES balloon campaign [29]. The objectives of the Euso-Balloon program are threefold: a) perform a full end-to-end test of a JEM-EUSO prototype; b) image the UV background originating from the earth surface, with a spatial and temporal resolution relevant for JEM-EUSO; c) detect tracks of ultraviolet light from near space for the first time. The first flight was indeed very successful. The background was measured under several conditions and although no cosmic rays tracks were detected, the instrument detected UV tracks induced by a laser beam shouted from an helicopter flying in the field of view of the balloon. The main features of the instrument and mission, together with several results of the first flight are summarised in [29] and references therein. To reach the breakthrough of the first measurements of an UHECR from near space, preparations are under way for an EUSO super pressure balloon (SPB) flight of several week duration, for an estimated total of 118 hours dark observations. The proposed launch site of the EUSO SPB flight is Wanaka in New Zealand. The EUSO-SPB instrument is an updated version of the first EUSO-Balloon instrument. It will include an update optical system, that uses the third fresnel lens originally designed to provide chromatic focusing over the UV spectrum of the track, and an improved version of the trigger, to try to catch the 10-20 events predicted to be observed during the mission. The proposed launch date for EUSO-SPB is March 2017 [30]. The EUSO-SPB will also record UV backgrounds over the ocean and will observe faint pulses in the atmosphere of man-made or natural origin. A precursor short duration flight from Aire-sur-l'Adour is also envisioned to test an improved instrument.

The *EUSO-TA*, where TA stands for Telescope Array, is a ground-based precursor of the main mission developed by the JEM-EUSO Consortium in collaboration with the Institute Cosmic Ray Research in Tokyo and the Telescope Array collaboration. A downscaled but fully functional prototype of JEM-EUSO has been built and installed at Black Rock Mesa, in Utah, at the site of the Telescope Array observatory. EUSO-TA has already successfully observed artificial tracks produced by the electron light source and the central laser facility of the TA calibration system, and by the mobile UV laser facility of Colorado School of Mines. EUSO-TA is also designed to observe tracks induced by cosmic rays, simultaneously with TA, that provides the external trigger. The first UHECR event of $E \sim 10^{18}$ eV traversing at ~ 2.5 km distance was indeed recently observed. This allows a deeper understanding of the EUSO response and systematics. EUSO-TA will also perform studies of the transversal profile of the shower with spatial resolution better than that of the TA fluorescence detector (TA-FD). Details are found in [31].

The JEM-EUSO collaboration is also developing and actually building a new pathfinder mission: *Mini-EUSO*. Mini-EUSO, included in the ISS science programs of ROSCOSMOS and ASI, is a small, compact UV telescope to be installed inside the Russian Module of the ISS, to measure the UV background from earth. Mini-EUSO will be placed at the transparent nadir looking UV window inside the ISS. In addition to the key objective of measuring and fully characterising the UV emission of night-time earth, at different inclinations and for different moon phases, Mini-EUSO will study a variety of UV atmospheric and bioluminescence phenomena, including TGFs, TLEs and meteors. Launch is foreseen for 2017 [32]. We wish eventually to mention that the collaboration is also involved in a series of technology developments. In particular the option of using SiPM as the active detection element is currently vigorously explored by several groups of the collaboration. The goal is to achieve the construction of a prototype of a SiPM based elementary cell to be tested in the soon to come ballon flights and on Mini-EUSO [33]. As of today the JEM-EUSO collaboration consists of more 300 scientists in 16 Countries, from 80 institutions in four continents.

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