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The JEM-EUSO mission: a space observatory to study the origin of Ultra-High Energy Cosmic Rays

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Abstract

The Extreme Universe Space Observatory (EUSO) onboard the Japanese Experiment Module (JEM-EUSO) of the International Space Station (ISS) is an innovative space-based mission with the aim of detecting Ultra-High Energy Cosmic Rays (UHECRs) from the ISS, by using the Earth's atmosphere as a calorimeter viewed by a fluorescence telescope. An observatory able to produce an arrival direction map with more than several hundreds events above 5×10^{19} eV would give important information on the origin of the UHECRs and identify structures in the sky map that contain information about the source density and/or distribution. This is likely to lead to an understanding of the acceleration mechanisms with a high potential for producing discoveries in astrophysics and/or fundamental physics. The scientific motivations of the mission as well as the current development status of the instrument and its performance are reviewed.

Keywords: cosmic rays, neutrino, International Space Station, JEM-EUSO, extensive air showers.

1. Introduction

The Extreme Universe Space Observatory - EUSO (Fig. 1) is the first space mission devoted to the exploration of the Universe through the detection of Extreme Energy (E > 60 EeV) cosmic rays (EECR) and neutrinos [1]–[4]. EECRs are observed by looking downward from the International Space Station (ISS). The main science objective of JEM-EUSO is to reveal the cosmic accelerators that produce the highest energy particles in the Universe. JEM-EUSO will make the first all-sky survey of EECRs with a significant increase in sensitivity compared to ground-based observatories. By identifying the positions of EECR sources in the sky, JEM-EUSO will open a new field of astronomy through the charged particle channel. JEM-EUSO will also search for extreme energy neutrinos and gamma-rays, monitor atmospheric phenomena in ultraviolet, and extend the energetic reach of fundamental physics probes by studying interactions of the highest energy particles ever observed.

The cosmic ray spectrum spans over 11 orders of magnitude in energy and reaches energies well beyond the energy of the most powerful man-made accelerators, such as the Large Hadron Collider (LHC). Above 1 EeV=10^{18} eV these particles are called ultrahigh energy cosmic rays. The mysterious sources of UHECRs are likely to be the most powerful accelerators in the Universe.

John Linsley discovered UHECRs over 50 years ago, but their sources remain a great mystery. These mysterious sources most probably involve extreme physical processes in extreme extragalactic environments as very few known astrophysical objects can reach the requirements imposed by the observed spectrum, composition, and lack of strong anisotropies [5, 6]. In particular, the lack of anisotropies towards the Galactic plane implies an extragalactic origin for protons above ~ 1 EeV and above $\sim Z$ EeV for nuclei with charge Z, based on Pierre Auger Observatory limits on the dipole anisotropy amplitude [7], and reasonable models of Galactic magnetic fields (see e.g. [8]).

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At these extreme energies, the interaction of cosmic ray protons or nuclei with the cosmic background photons causes the production of pions or the dissociation of nuclei. These processes are known as the Greisen-Zatsepin-Kuz'min (GZK) effect [9, 10]. The GZK effect changes the shape of the spectrum above ∼ 30 EeV and limits the distances of UHECR sources to less than 100 Mpc from Earth, named the GZK sphere . Since the distribution of matter within the GZK sphere is anisotropic, the GZK effect opens the possibility of observing clear anisotropies in the sky at extreme energies indicative of the nearest sources.

The difficulty for ground-based experiments to accumulate data at extreme energies is due to the fact that the flux of EECRs at $E > 60$ EeV is around 1 particle/km^2/sr/century and decreases to 1 particle/km^2/sr/millennium for $E > 100$ EeV. This challenging extreme energy region is the scope of JEM-EUSO. With hundreds of events above 60 EeV, JEM-EUSO can reveal the hidden sources of UHE and EECRs.

Although extremely large (covering area $3,000$ km^2 in case of Pierre Auger Observatory [11] in the Southern Hemisphere and 700 km^2 for Telescope Array [12] in the Northern Hemisphere), current observatories are not large enough to study EECRs with the necessary statistics to unveil their sources. The expected anisotropy signal has been elusive and not a single source of UHECRs has been identified so far. The observed distribution of arrival directions shows no departure from isotropy below about 50 EeV. Above 60 EeV a low amplitude dipole anisotropy was reported by Auger, while the test for anisotropies based on correlations with active galactic nuclei continues to show a departure from isotropy at the $\sim 3\sigma$ level but with a large background of isotropic events.

The path to solving this puzzle is clear, a large increase in statistics above the anisotropy energy scale of about 60 EeV to be able to accumulate tens of events per source. There are no ground-based plans to reach this goal in the next decade. These many events can be more easily collected from space, where the detector volume can far exceed that of current and future ground-based experiments. Increasing the statistics of events at the highest energies over the whole sky to discover the first sources of UHECRs is the main goal of JEM-EUSO.

2. Main Science Objective: Identification of EECR sources

JEM-EUSO is a pioneering mission that will lead the next generation of EECR experiments. JEM-EUSO will have an annual exposure of over 4×10^4 km^2 sr yr above 60 EeV and above 100 EeV, where it reaches full aperture, it will accumulate 6×10^4 km^2 sr yr every year, an order of magnitude above the annual exposure of ground based observatories. JEM-EUSO will accumulate 3×10^5 km^2 sr yr in 5 years in "Nadir mode" while in "Tilt mode" it can reach significantly larger exposures but with a higher energy threshold. In addition to the needed increase in statistics at extreme energies, JEM-EUSO will make a full sky map of the events it observes due to the ISS orbit. Having the same instrument cover the whole sky will make able to assess possible differences between EECRs from the results in the North and South.

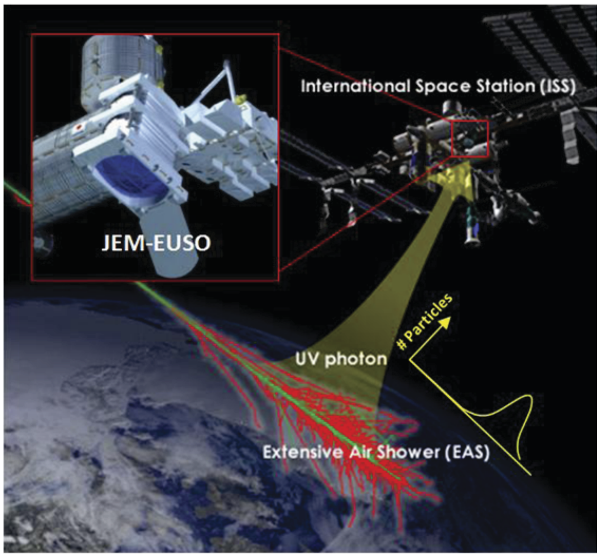

Figure 1: Principle of the JEM-EUSO mission to detect EECRs.

The discovery of EECR sources will rely on the power of large statistics at the highest energies. In addition to the ability to circumvent the bending effects of cosmic magnetic fields, extreme energy events will come mostly from the few cosmologically nearby extragalactic sources. The GZK effect limits both protons and iron nuclei of 60 EeV from originating beyond about 100 Mpc from Earth. The attenuation length for intermediate nuclei between proton and iron is even shorter. The volume of the universe sampled by UHECRs, regardless of their composition, is local in cosmological terms and encompasses a region where the matter distribution is inhomogeneous. Therefore, the sky maps observed by JEM-EUSO will be anisotropic and dominated by the few nearby sources.