Science objectives of the JEM-EUSO mission

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Abstract: JEM-EUSO is a space telescope proposal, devoted to the observation of the ultraviolet fluorescence light emitted by extreme energy cosmic ray (EECR) atmospheric cascades [1]. The fluorescence technique has proved to be extremely successful from the ground and JEM-EUSO will be the first detector to use it from space. The telescope possesses an innovative wide field of view Fresnel optics which, combined with a highly sensitive focal surface and an observation altitude in excess of 360 km, will allow it to reach an unprecedented exposure of $10^{6}$ km\(^2\) sr yr at $3 \times 10^{20}$ eV. These capabilities go far beyond what can be practically achieved by ground observatories. The large number of expected events will allow the identification of relatively nearby individual sources of EECR and determine their spectra. Point spread function analysis will also be used to study the Galactic magnetic field. Furthermore, baryons, photons and neutrino primaries can be discriminated with considerable accuracy, and upper limits to the fluxes of the last two will be improved by at least a factor of 10 beyond present experiments. Moreover, the mass target inside the field of view is $\sim 10^{12}$ ton which, depending on the actual astrophysics scenario, makes very likely the observation of up to a few cosmogenic neutrinos per year. Other exploratory objectives include the observation of atmospheric phenomena, like night-glow, high altitude plasma discharges and meteors.

Keywords: Extreme Energy Cosmic Rays, space detection, fluorescence technique

1 Introduction

Cosmic rays (CR) at the highest energies may be messengers of the most extreme environments in the universe. This challenging extreme energy region, at the frontier of present scientific knowledge, is the scope of the JEM-EUSO mission. JEM-EUSO is intended to address basic problems of fundamental physics and high energy astrophysics by investigating the nature and origin of extreme energy cosmic rays (EECR). JEM-EUSO will pioneer the observation from space of EECR-induced extensive air showers (EAS), making accurate measurements of the energy, arrival direction and identity of the primary particle using a target volume far greater than which is possible from the ground. The corresponding quantitative jump in statistics will clarify the origin (sources) of the EECR and, possibly, the particle physics mechanisms operating at energies well beyond those achievable by man-made accelerators. Furthermore, the spectrum of scientific goals of the JEM-EUSO mission also includes as exploratory objectives the detection of high energy gamma rays and neutrinos, the study of cosmic magnetic fields, and testing relativity and quantum gravity effects at extreme energies. In parallel, all along the mission, JEM-EUSO will systematically survey atmospheric phenomena over the Earth surface.

2 Main objectives

The CR can be considered as the Particle channel complementing the Electromagnetic one of conventional astronomy. The main objective of JEM-EUSO is to initiate a new field of astronomy and astrophysics that uses the extreme energy particle channel ($10^{19.5}$ eV < $E$ < $10^{21}$ eV).
JEM-EUSO is designed to achieve more than $10^5 \text{ km}^2 \text{ sr} \text{ yr}$ above $7 \times 10^{19} \text{ eV}$ during its first three years of operation which, given current uncertainties, amounts to the detection of between 500 and 800 events with energy above $5.5 \times 10^{19} \text{ eV}$ [2]. Such a number of events makes possible the following targets: (a) identification of sources by high-statistics arrival direction analysis; (b) measurement of the energy spectra from individual sources to constrain acceleration or emission mechanisms.

A remarkable characteristic of the EECR flux is that few astrophysical candidates are known which can attain such energies with the acceleration mechanisms we are presently aware of [3, 7]. This fact makes imperative the identification of both, those sources and of the powering mechanisms at play.

Given that a correlation between the arrival directions of EECR and the Galactic plane has never been observed, not to mention the relative calmness of the Milky Way, it is broadly accepted that the particles have an extragalactic origin. Furthermore, in all the most conservative models, the sources either follow the distribution of luminous matter or that of the associated dark matter. In either case, at large enough energies, anisotropies in the arrival directions is expected in the form of an enhanced correlation with nearby luminous matter, as data from the Pierre Auger Observatory presently implies [4]. To complicate the picture even further, the particles are widely thought to be predominantly baryons and, therefore, to possess charge during at least a significant portion of their transit through the intergalactic medium. Magnetic fields of poorly known intensity and topology are likely widespread throughout the universe, blurring any correlation between arrival directions and source position on the sky.

Particles also interact with the CMBR and the IR background. At the energies of JEM-EUSO the dominant target is the CMB which leads, in the case of HE protons, to photo-pair and photo-pion production. Above $\sim 10^{19.6} \text{ eV}$ the latter dominates and can effectively decelerate particles to below the threshold for photo-pion production in few tens of Mpc, strongly suppressing the EECR energy spectrum (the GZK cut-off), and effectively setting a horizon at $\sim 100 \text{ Mpc}$. Nuclei, on the other hand, lose energy mainly by photo-disintegration. The end result is a similar attenuation length for Fe, but shorter for intermediate nuclei. Therefore, the volume of universe sampled by EECR, regardless of their mass, is local in cosmic terms and encompasses a region where the large scale matter distribution (LSMD) is inhomogeneous. Thus, under general assumptions and given enough statistics, the footprint of the source distribution should emerge from the EECR flux.

The identification of the sources can follow different paths. First, a statistical identification can be attempted. In this case, arrival directions and source positions from candidate astrophysical catalogues are globally compared and the corresponding correlation is quantified. This has been attempted many times in the literature for the various experiments for a variety of astronomical catalogues and, most
notably, recently for Auger [4] and HiRes [5] data. However, the results are always severely bounded by the low available statistics at the highest energies and, to a lesser extent, by the small observed fraction of the sky and the strong exposure dependence on declination. JEM-EUSO, with its full sky coverage, low declination dependence of the exposure and large aperture, can significantly improve this kind of analysis.

There are several approaches to infer the density of nearby sources of EECR. If magnetic deflections are not too large, a low density of sources implies a relatively high EECR luminosity per source and, therefore, a smaller number of large multiplicity clusters of events is expected, while the opposite should occur in a large density scenario. The degree of clustering over the celestial sphere should also be dependent on the large scale spatial distribution of the sources. However, in practice, the number of parameters involved when trying to explore this avenue leads to ambiguous results due to the present limited data set [6]. Again, JEM-EUSO will have a strong impact in this arena, since its increased statistics will allow the discrimination of source densities in the interval \( n_s \sim 10^{-7} - 10^{-3} \) Mpc\(^{-3} \) at more than 99% confidence level, as it is shown in Figure 2 in comparison to the present statistics of Auger above 55 EeV.

The energy dependent distortions of the sources’ point spread functions as a result of the Galactic magnetic field can be clearly seen as a function of the position on the sky (top panel in Fig.). This pattern of distortions, over the celestial sphere can be used to infer the large scale structure of the Galactic magnetic field (GMF).

3 Exploratory objectives

Gamma rays at extreme energies are a natural consequence of \( \pi_0 \) production during EECR proton propagation through the CMB. A gamma-ray flux higher than expected from this secondary production would signify a new production mechanism, such as top-down decay/annihilation, or a breaking of Lorentz symmetry. Nuclei, on the other, would produce a much smaller gamma background. Therefore, the flux of gamma rays in extreme energy is a key parameter to discriminate origin models. Figure 3 summarizes existing limits on the gamma-ray flux and shows the sensitivity of gamma rays by five years operation of the JEM-EUSO Mission. The Auger Observatory reported the upper limit on gamma ray flux as a few percent of EECR flux above 10 EeV [12]. Under the null gamma ray assumption, JEM-EUSO is capable of putting more stringent upper limit by an order of magnitude at overlapping energies. To give the constraint on origin models or their parameters, the gamma ray flux above 100 EeV is essential and will be constrained in an unprecedented way after five years operation of JEM-EUSO.

During proton propagation through the CMB, \( \nu \) are produced. These cosmogenic neutrinos constitute a guaranteed
flux at Earth and contain extremely valuable information on the redshift evolution of the sources. Besides the cosmogenic flux there may also be contributions from hadronic interactions at the acceleration sites and from top-down processes. JEM-EUSO can detect neutrinos evolving deep in the atmosphere or, in the case of bursts of upward-going neutrinos interacting inside the outermost layers of the crust, as expected form GRB, through direct Cherenkov.

Figure shows the flux sensitivity of JEM-EUSO detecting 1 event/energy-decade/yr. An observational efficiency of 25% is assumed. Thick blue and red curves show the case of nadir and tilted modes, respectively. Adapted from [11]

**References**