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JEM-EUSO Science capabilities

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Abstract: JEM-EUSO is a space telescope to be installed at the International Space Station to observe extensive air showers (EAS) in the Earths atmosphere produced by cosmic rays of energies above 50 EeV. JEM-EUSO will reach the unprecedented annual exposure at the highest energies of more than 6×10^4 km^2 sr yr with very nearly uniform dependence on declination over the Celestial Sphere. These capabilities go far beyond what can be practically achieved by ground-based observatories and enable an all sky study of anisotropies above 60 EeV where hints of anisotropies have been reported. The decrease in attenuation length of UHECRs with increasing energy implies that the extreme energy cosmic ray sky must be dominated by very few, relatively nearby sources. The full sky analysis of JEM-EUSO anisotropy patterns should unveil the closest of these extreme sources of the highest energy particles ever observed. These anisotropy patterns as a function of energy can also set constraints on the particle charge and the effects of Galactic and extragalactic magnetic fields. The higher statistics measurement of the spectrum at extreme energies (above 100 EeV) can test if the maximum energy of these extreme accelerators reaches well beyond the GZK feature or if it coincides with the GZK effect further constraining the source characteristics. JEM-EUSO will also study transient light events in the atmosphere related to meteors and atmospheric phenomena. In addition, JEM-EUSO will set limits on Lorenz Invariance violation and will search for nucleates and extreme energy photons and neutrinos that could lead to ground-breaking discoveries in fundamental physics.

Keywords: JEM-EUSO, UHECR, EECR, space instrument, fluorescence

1 Introduction

Although the study of ultrahigh energy cosmic rays (UHECRs), from 1 to 100 EeV (1 EeV = 10^{18} eV), has progressed considerably over the last decade, *not a single source* of these extreme events has been identified thus far. Current data indicates that only a significant increase in the exposure at the highest energies (above about 60 EeV) will allow a clear source identification [1]. Increasing the statistics of events at the highest energies to discover the first sources of UHECRs is the main goal of the Extreme Universe Space Observatory (EUSO) to be deployed on the Japanese Experiment Module (JEM) of the International Space Station (ISS) [2].

JEM-EUSO will observe the ultraviolet fluorescence light emitted by atmospheric nitrogen excited by extensive air showers (EAS) through the use of an innovative wide field of view Fresnel optics telescope with a highly sensitive focal surface, complemented by an extensive real time atmospheric monitoring system[3]. The mission will reach the unprecedented annual exposure at the highest energies of more than 6×10^4 km^2 sr yr [4], which is about 9 times the annual exposure of the largest observatory ever built, the Pierre Auger Observatory [5]. This order of magnitude increase in annual exposure is reached in the nadir configuration leaving open the possibility of a further increase in exposure at the highest energies in the tilted configuration. The unprecedented exposure is also nearly uniform over the Celestial Sphere [4] enabling a full sky survey of possible sources.

Recent progress in UHECR science is due to observations by giant ground arrays culminating with the 3,000 km^2 Auger Observatory in Mendoza, Argentina [6], the largest observatory worldwide, and the 700 km^2 Telescope Array (TA) in Utah, USA [7], the largest in the northern hemisphere. These two leading observatories have made precise measurements of the spectrum over a wide range of energy, each in their own hemispheres. Both observatories report spectra which are consistent in normalization and shape after an absolute energy scaling of about 20% is applied (which is within the quoted systematic uncertainties). The reference spectrum where Auger and TA energy scales are averaged can be described by a triple power law fit where below the *ankle* at about 4.8 EeV, the spectrum is $E^{-\gamma}$ with $\gamma = 3.3$ followed by a hardening with $\gamma = 2.7$ from the ankle up to a suppression at about 38 EeV when the spectrum softens to $\gamma = 4.2$ [8]. The ankle may be due to the transition from Galactic to extragalactic cosmic rays or possibly due to losses of cosmic ray protons producing electron-positron pairs in the cosmic microwave background (CMB). The suppression is consistent with the Greisen-Zatsepin-Kuzmin effect [9] which is due to photopion production for protons interacting with the CMB or photo-dissociation of heavier nuclei on cosmic backgrounds (from microwave to ultraviolet). These energy losses limit the volume from which UHECRs can originate to be observed at Earth. The horizon for 60 EeV protons and iron

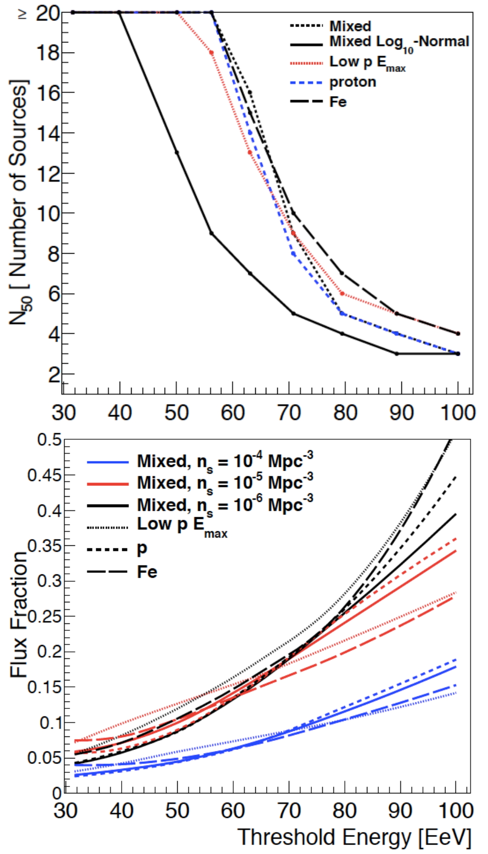

Figure 1: Dominance of the UHECR sky by a few individual sources due to horizon effects. Top: Plotted are the number of sources contributing 50% of the flux as function of energy. Bottom: fraction of the flux contributed by the 3 brightest sources as a function of threshold energy. Several models and source densities are shown as in [12].

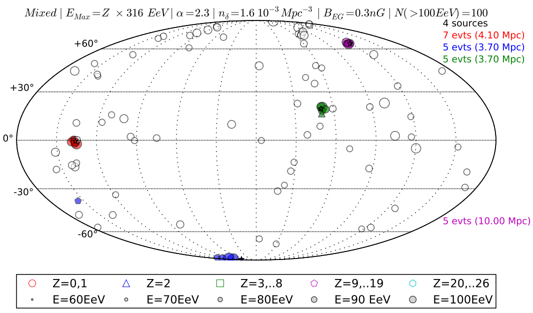

Figure 2: Example of a sky map of 100 UHECR events with energies above 100 EeV (using the Auger energy scale) obtained for total exposure of $300,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$ (5 years of JEM-EUSO). The proton dominated composition model assumes a maximum energy $E_{Z,\max} = Z \times 316$ EeV, an injection spectrum of $\alpha = 2.3$ and a source density of $10^{-3}\,\mathrm{Mpc}^{-3}$. The 4 sources contributing the largest fraction of events are color coded [12].

are similar at ~ 100 Mpc. The attenuation length for intermediate nuclei between proton and iron is shorter. Therefore, the volume of universe sampled by UHECRs, regardless of their composition, is local in cosmological terms and encompasses a region where the large scale matter distribution is inhomogeneous. The suppression may also be explained by the maximum energy of the accelerator, $E_{\max}$.

As theoretical models attempt a fit to the spectrum together with composition measurements, the GZK effect is the main cause of the observed suppression for proton dominated models. For mixed composition models that fit the Auger composition, $E_{26;\max}$ of iron (or $E_{p;\max}$ of protons divided by 26) is chosen to coincide with the suppression energy while the GZK effect still affects all components up to iron. In this sense, the maximum energy is the main driver for the suppression, although the GZK effect is still present [1].

Auger observes a trend toward heavier nuclei above about 5 EeV (or a change in hadronic interactions) while TA reports a proton dominated spectrum throughout their sensitivity range [10]. (It is possible that the change in shower properties observed by Auger is not due to a change in composition but instead to a change in the properties of particle interactions.) Finding the first sources with JEM-EUSO can help determine the composition with studies of source shape distortions at the highest energies while a high statistics measurement of the spectrum at 100 EeV can help select between a GZK effect and $E_{\max}$ cause of the suppression. In particular, the spectrum will display a significant recovery if the suppression is produced by the GZK effect and the sources have $E_{\max} \gg 100$ EeV.

The observed sky distribution of arrival directions show tantalizing hints of anisotropies above about 60 EeV. Both Auger and TA observe partial sky distributions (from the South by Auger and the North by TA) that show hints of the nearby large scale structure distribution above about 60 EeV, but the departure from isotropy continues to be at the low significance level. This is where JEM-EUSO can make significant contributions by increasing by an order of magnitude the exposure to cosmic rays with energies between 60 and 100 EeV, sometimes called extreme energy cosmic rays (EECRs).

JEM-EUSO will pioneer UHECR observations from space with a far greater exposure than any experiment on the ground. The 60 degree field of view will instantly monitor several 10^6 km^3 volume of the atmosphere, an order of magnitude larger than any current observatory. The corresponding quantitative jump in statistics will clarify the origin of the UHECRs and probe particle interactions at energies well beyond those achievable by man-made accelerators. Furthermore, the JEM-EUSO mission will make important contributions to atmospheric phenomena including meteors by monitoring the Earth's atmosphere in the ultraviolet with the main telescope and in the infrared with the telescope's atmospheric monitoring system. Among the exploratory objectives of JEM-EUSO are the search for high energy gamma rays and neutrinos that would be groundbreaking if detected. In addition, JEM-EUSO will set limits on the violation of Lorentz Invariance at relativistic factors up to 10^{11} and search for exotic events that may be caused by nucleorites and monopoles traversing the atmosphere.

2 Main science objectives

The main objective of JEM-EUSO is to begin the new field of particle astronomy and astrophysics by identifying the first sources of UHECRs. To reach that goal a 5 year mission will achieve an exposure of 3×10^5 km^2 sr yr at 100 EeV [4]. Each additional year of operation will add the equivalent of nine years of operation of a ground detector as large as Auger at extreme energies. Such exposure makes possible unprecedented anisotropy studies including the possible identification of individual nearby sources by high-statistics arrival direction analysis. It will also allow a higher statistics measurement of the energy spectrum at 100 EeV over the whole sky and the study of atmospheric and meteor phenomena. A number of additional exploratory goals will be discussed in the next section.

The mysterious sources of UHECRs most certainly 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 [1]. 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, as discussed by [11] based on Auger limits on the dipole amplitude and reasonable models of Galactic magnetic fields.

As they traverse cosmological distances, UHECRs lose energy through interactions with cosmic photon backgrounds limiting the observable horizon to about 100 Mpc for energies above 60 EeV. The horizon effect limits the number of sources contributing to the observed flux for proposed source models as shown in Figure 1. This decrease in source number translates into an increase in anisotropies at the highest energies making source identification easier above energies of about 80 EeV. Thus, JEM-EUSO can discover the closest sources by a significant increase in statistics at extreme energies.

The expected sky map of events that will be observed by JEM-EUSO depends strongly on the primary composition and the number density of sources in addition to other model parameters such as the injected spectrum and $E_{\max}$. An extensive study of predicted sky maps with JEM-EUSO statistics that are consistent with current data on spectrum, composition, and lack of strong anisotropies is found in [12]. Figure 2 shows the sky map of a proton dominated case where 100 UHECR events are shown with energies above 100 EeV (using the Auger energy scale) obtained for an exposure of $300,000\,\mathrm{km^2\,sr\,yr}$ (i.e., 5 years of JEM-EUSO in Nadir mode). This model assumes a maximum energy $E_{Z,\max} = Z \times 316$ EeV, where Z is the charge of nuclei between proton and iron. With such a large maximum energy, the spectrum is dominated by protons. The other model parameters are an injection spectral index of $\alpha = 2.3$ and a source density of $10^{-3}\,\mathrm{Mpc}^{-3}$ to be consistent with the lack of strong anisotropies in current observations. The 4 sources contributing the largest fraction of events are color coded and the clustering of events around the sources is clear. This proton case can be easily identified by JEM-EUSO. In this case, the change in observed shower properties reported by Auger should be interpreted as due to changes in particle interactions at the highest observed energies instead of due to composition changes. Also in this case, the observed suppression of the spectrum is due to the GZK cutoff, not $E_{\max}$, and JEM-EUSO may observe the recovery of the spectrum if $E_{\max}$ extends beyond 300 EeV.

To fit the composition trend observed by Auger together with the spectrum and lack of strong anisotropies, mixed composition models are needed in which $E_{\max}$ for iron is close to the observed highest energy events. Figure 3 shows such a mixed composition model in which the maximum energy $E_{Z,\max} = Z \times 15$ EeV, the injection spectral index is $\alpha = 1.6$, and the source density is $10^{-5}\,\mathrm{Mpc}^{-3}$ [12]. In this case, 4 sources contribute $\sim 70\%$ of events and generate significant anisotropies as shown by the distribution of 250 events above 80 EeV displayed in the figure. Identifying the sources in such a scenario will only be possible with an increase of statistics such as planned for JEM-EUSO. In this case, the observed suppression of the spectrum is due to the maximum energy reached by the accelerators, $E_{\max}$, instead of the GZK effect and the spectrum of these sources should not display a recovery.

In addition to the significant increased exposure, an advantage of an orbiting observatory, such as JEM-EUSO, with respect to a ground observatory is the full sky coverage. An all-sky survey offers access to large scale multipoles such as dipoles and quadrupoles which are challenging for observations with partial sky coverages [13]. For example, a partial sky map may be unable to distinguish a dipole from a quadrupole depending on the orientation, while a full sky survey can distinguish the two cases with the same statistics. An example of the power of the combined statistics and full sky coverage of JEM-EUSO in extracting a high significance dipole is discussed in [14] where a 5σ dipole detection is within reach of JEM-EUSO assuming the Auger anisotropy hint towards Centaurus A generates a dipole.

As shown by current experiments, there are a number of possible tests for anisotropies that can be applied when significant anisotropies are present. One possible such measurement is the variation due to cosmic variance of the spectrum at the highest energies. Large exposure over the full sky will allow the measurement of the spectrum variation as the sky is partitioned into different regions. As the energy increases, data from different hemispheres are dominated by different sources causing a detectable ensemble fluctuations. The superior sensitivity of JEM-EUSO as compared to current ground observatories to ensemble fluctuations based on various assumptions about the CR source properties and distributions is discussed in [15]. The size and fine details of the variance are sensitive to and therefore yield information about the density of sources, the proximity to the nearest source or source populations, and the composition of the highest energy CRs.

In addition to searching for the mysterious sources of UHECRs, JEM-EUSO will monitor the Earth's dark atmosphere to observe atmospheric transient light events and meteor events. For example, meteor observations by JEM-EUSO will help derive the inventory and physical characterization of the population of small solar system bodies orbiting in the vicinity of the Earth. After decades of ground-based activities, JEM-EUSO mission may become the first space-based platform to the observe meteor events which are eminently slow events when compared to UHECR showers.

3 Exploratory objectives

In addition to studying the highest energy cosmic rays, JEM-EUSO is also capable of observing extreme energy cosmic photons and neutrinos [16]. EECR propagation through the cosmic background radiation produces extreme energy gamma-rays (EEGRs) and neutrinos (EEνs) as a natural consequence of π^0 and charged π production respectively (usually called cosmogenic photons and neutrinos). The attenuation length for EEGRs is very short depending on

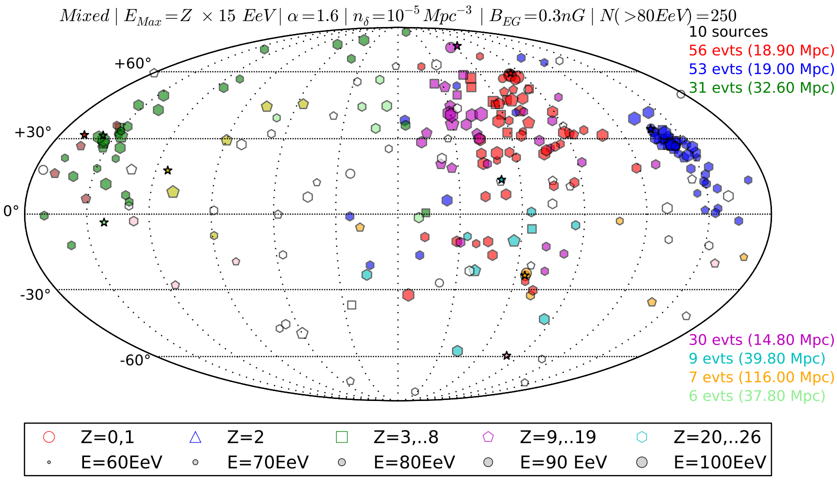

Figure 3: Example of a sky map of 250 UHECR events with energies above 80 EeV (using the Auger energy scale) obtained for total exposure of $300,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$ (i.e., 5 years of JEM-EUSO. This mixed composition model assumes a maximum energy $E_{Z,\max} = Z \times 15$ EeV, an injection spectrum of $\alpha = 1.6$, and a source density of $10^{-5}\,\mathrm{Mpc}^{-3}$. The 10 sources contributing the largest fraction of events are color coded [12].

the cosmic radio background. The expected flux of EEGRs on Earth is small and highly model dependent, (e.g., nuclei primaries produce much fewer gamma-rays than proton primaries). JEM-EUSO will search for EEGRs events and place stronger constraints on their flux [16]. A detection of a higher than expected flux can be due to a new production mechanism such as top-down decay or annihilation [17] or the breaking of Lorentz Invariance.

Similarly to EEGRs, the detection of EEνs is another exploratory objective of the JEM-EUSO mission. The flux of cosmogenic neutrinos around 100 EeV is highly dependent on $E_{\max}$ of cosmic rays. For high enough $E_{\max}$, a flux of cosmogenic neutrinos is within reach of the JEM-EUSO mission [14]. A neutrino flux from extremely energetic sources may also be observed by JEM-EUSO. The acceptance for EEν events is well above current ground detectors. In addition, an order of magnitude larger acceptance results for Earth-skimming events transiting ocean compared to transiting land is discussed in [18]. Since ground-based observatories cannot observe ocean events, only space-based missions can realize the advantage of this possible enhancement of the acceptance over the ocean.

The observing strategy developed for JEM-EUSO to detect atmospheric and meteor events will also be sensitive to other hypothetical slow velocity events such as nuclearites or massive strangelets (quark nuggets with a fraction of strange quarks similar to up and down quarks). JEM-EUSO is sensitive to nuclearites with mass $m > 10^{22}$ GeV/c^2 . A null observation of these events will set strong limits on their flux, reaching one order of magnitude more stringent limits than current ones in only one day of observations [19]. This search is a great example of the multi-disciplinary capabilities of the JEM-EUSO mission.

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