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JEM-EUSO Science

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The Extreme Universe Space Observatory (EUSO) to be accommodated in the Japanese Experiment Module (JEM) of the International Space Station (ISS), JEM-EUSO, is designed to discover the origin of ultrahigh energy cosmic rays by observing extremely energetic extensive airshowers from space. The JEM-EUSO design is based on a wide field of view (60°) refractor with an ultra-fast 0.3M pixel UV camera that records the extensive airshower fluorescence and backscattered cherenkov. The main science goal of JEM-EUSO is to accumulate significantly higher number of events than available from ground-based observatories at the highest energies. The ISS orbit guarantees full sky coverage and its altitude provides the ability to monitor two orders of magnitude more atmosphere when compared to fluorescence telescopes on the ground. The large number of observed extremely energetic events will provide a sky map of the relatively nearby sources. The increase in statistics will also provide a measurement of the spectral shape around the GZK feature, which may have a recovery depending on the maximum energy of UHECR sources. Extremely energetic neutrinos may also be observed as well as fast atmospheric phenomena and meteoroid emission in the UV. JEM-EUSO will also test physics beyond the standard model by searching for the decay products of super-heavy dark matter and tracks produced by strangelets.

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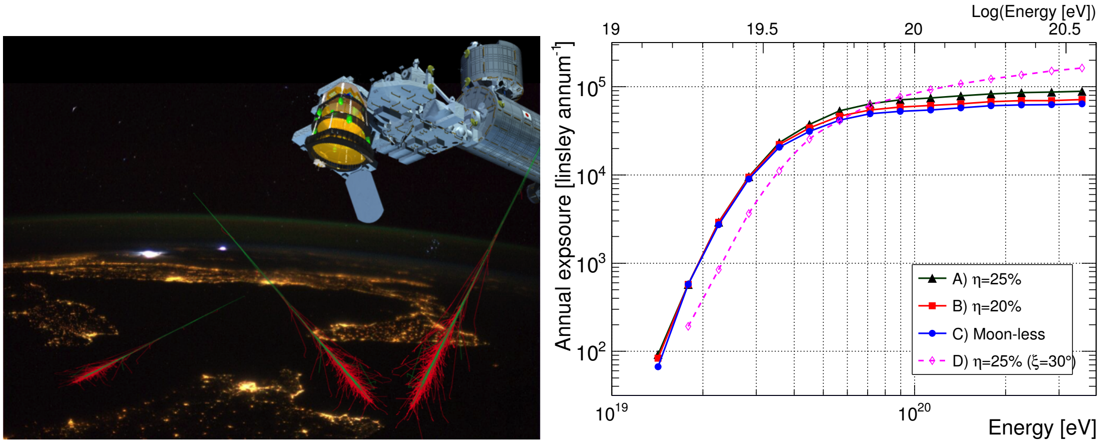

Figure 1: [Left] A model of JEM-EUSO delivered by Space-X Dragon to the ISS. [Right] JEM-EUSO annual exposure for the Dragon delivery design [4]. Shown are curves for duty cycle estimates for different criteria with η = 25%; 20%; and moonless condition in (C) all for nadir pointings. In (D) the case of a tilt $\xi = 30^\circ$ is shown.

1. Introduction

The Extreme Universe Space Observatory (EUSO) accommodated in the Japanese Experiment Module (JEM) of the International Space Station (ISS), JEM-EUSO, is designed to discover the sources of ultrahigh energy cosmic rays (UHECRs) by observing extremely energetic extensive air-showers from space [1, 2]. JEM-EUSO consists of an innovative wide field of view (60°) Fresnel optics refractor with a highly sensitive ultrafast 0.3M pixel UV camera. It will record fluorescence and back-scattered cherenkov light generated by extremely energetic cosmic ray airshowers. An number of JEM-EUSO prototypes are currently operating and under development by the collaboration as described in [2].

The main science goal of JEM-EUSO is to accumulate a significantly higher number of events than attained by ground-based observatories at the highest energies (above 60 EeV, with 1 EeV = 10^{18} eV). Figure 1 shows a model of the JEM-EUSO telescope delivered by a Space-X Dragon [3]. The mission is designed to reach unprecedented geometrical apertures above 4×10^5 km^2 sr yr which after duty cycle corrections corresponds to an annual exposure of more than 5×10^4 km^2 sr yr at the highest energies as shown on the right panel of figure 1 from [4]. In the figure the different lines correspond to the JEM-EUSO aperture for nadir observations and three duty cycle estimates for different criteria and the exposure for tilt ξ of 30° .

The unprecedented JEM-EUSO exposure of is also nearly uniform over the Celestial Sphere as shown in figure 2. The ISS orbit guarantees a full sky coverage and its altitude (of about 400 km) provides the ability to monitor two orders of magnitude more atmosphere when compared to fluorescence telescopes on the ground and about one order of magnitude when compared to ground arrays of particle detectors. The large number of observed extreme energy cosmic rays (EECRs, cosmic rays above 60 EeV) will provide a complete sky map of the relatively nearby sources (within about 100 Mpc). The increase in statistics will also provide a measurement of the spectral shape around the Greisen-Zatsepin-Kuzmin (GZK) [5] feature, which may have a recovery depending on the maximum energy of UHECR sources or display the signature of higher energy cosmological relics.

The delivery of JEM-EUSO to the ISS by the Space-X Dragon allows for a cylindrical redesign of the telescope and the focal surface. This new design improves the telescope's performance relative to the HTV delivery option as discussed in [4]. In particular, the energy and angular resolution of event reconstruction is improved as discussed in [6, 7] allowing for more accurate anisotropy studies and better discrimination of primaries as discussed in [8].

JEM-EUSO will pioneer UHECR science from space and allow a quantitative jump in statistics to 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 the study of meteors by monitoring the Earth's atmosphere in the ultraviolet with the main telescope and ultrafast camera as well as the infrared camera of the telescope's atmospheric monitoring system (see [9, 10]). Among the exploratory objectives of JEM-EUSO are the search for high energy gamma rays and neutrinos that would be ground-breaking if detected (see [11, 12]). In addition, JEM-EUSO can 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 strangelets or nuclearites and monopoles traversing the atmosphere. It will also probe the parameter space of super-heavy dark matter candidates (see, e.g., [13]).

2. JEM-EUSO main science

The main objective of JEM-EUSO is to begin the new field of particle astronomy and astrophysics by identifying the sources of UHECRs. The study of UHECRs, from 1 to about 60 EeV, has progressed considerably over the last decade due to observations by giant ground arrays culminating with the 3,000 km^2 Auger Observatory in Mendoza, Argentina [14], the largest observatory worldwide, and the 700 km^2 Telescope Array (TA) in Utah, USA [15], 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.

The joint working group between Auger and TA produced a combined spectrum [16], shown in figure 2, where the Auger energy was adjusted by using the TA fluorescence yield (TA FY) and invisible energy (E_{inv}) correction and the TA energy scale shifted by 7% overall towards the Auger energy scale. Both experiments see a clear ankle, between $10^{18.6}$ and $10^{18.8}$ eV, and the suppression at the highest energies. The suppression is consistent with the effect predicted by Greisen, Zatsepin, and Kuzmin [5] whereby ultrahigh energy protons interacting with the CMB lose energy through photo-pion production and heavier nuclei photo-dissociate by interacting with cosmic backgrounds (from microwave to ultraviolet). The supression can also be due to the maximum energy reached by accelerators, E_{max}.

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 (see, e.g., [17]). 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

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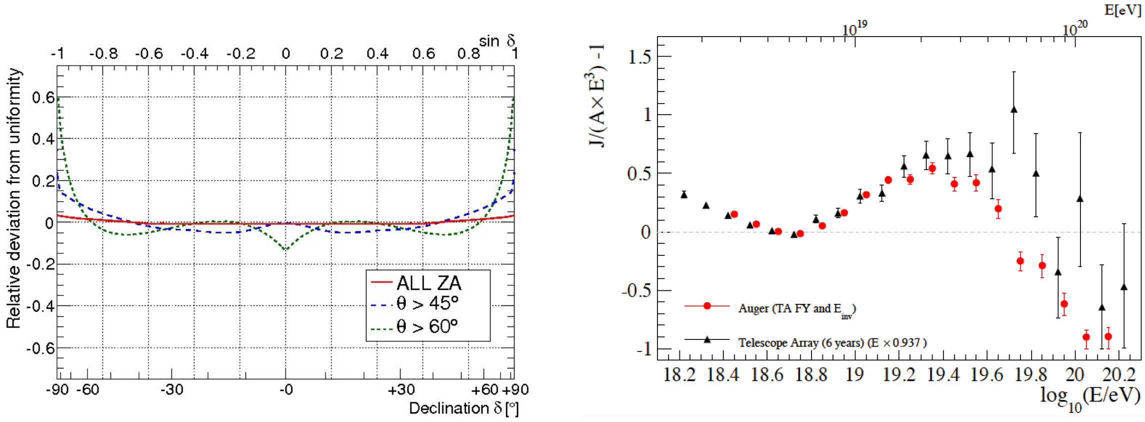

Figure 2: [Left] Deviation from uniformity of the aperture as a function of sine of declination δ. Solid line for all zenith angles and dashed curves for zenith angles greater than 45° and 60°. (Isotropic exposure is defined as 0) [1]. The horizontal axis on the bottom denotes corresponding declination. [Right] Auger and TA spectrum combined by working group with 7% energy normalization shift of TA data and adjustment of Auger data with TA fluorescence yield and invisible energy [16].

[18] 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 (GZK effect) limiting the observable horizon for protons and iron to about 100 Mpc for energies above 60 EeV. The attenuation length for intermediate nuclei between proton and iron is shorter. Therefore, the volume of the 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 possibility of observing many events from the nearest sources and the anisotropic distribution of sources within a few 100 Mpc is what drives the need to increase significantly the statistics above 60 EeV.

Hints of anisotropies in the sky distribution of events above around 60 EeV have been reported by Auger [19] and most recently by TA [20]. The TA collaboration published a tantalizing finding that among the 72 events above 57 EeV (and incident zenith angle less than 55°) accumulated over 5 years a hotspot of about 20° in the sky includes 19 events (26.4%) instead of the expected 4.5 events (the region has 6.25% exposure). The hotspot centered at R.A. = 146°.7, Dec. = 43°.2 has a Li-Ma statistical significance of 5.1σ (pre-trial) with a chance probability of 3.7×10^{-4} or 3.4σ of this enhancement being a fluctuation of an isotropic distribution. With an additional year of data the same excess is observed, of the 15 new events above 57 EeV, 4 events (26.7 %) are in the hotspot region increasing the Li-Ma significance to 5.55σ and a chance probability of 3.1×10^{-5} or 4.0σ [21].

These tantalizing findings by TA may signal the first source of UHECRs to be located. The annual exposure of the TA ground array for events with incident zenith angle less than 55° should be about $(7/30)(1 - cos(55°) + cos(60°))\text{Exp}_{\text{Auger}}(60°)$, where $\text{Exp}_{\text{Auger}}(60°)$ is the Auger ground array exposure which down to 60° zenith is geometrically estimated to be 7,000 km^2 sr annually and after reconstruction efficiency comes down to just below 6,000 km^2 sr annually [22]. To compare with expectations from JEM-EUSO we use the geometrical estimate which gives an annual exposure for TA of about 1,513 km^2 sr.

Of the 87 events above 57 EeV observed by TA in 6 years, 23 (26.4%) are located in the hotspot region which encompasses only 6.25% of the exposed sky, therefore about 69 events are from the isotropic background while 18 from the hotspot. With 5×10^4 km^2 sr annual full sky exposure, JEM-EUSO will observe 33 times more events from the isotropically distributed flux than TA annually, which corresponds to about 380 isotropically distributed events per year throughout the sky. In addition, about 49 events will be observed per year from the hotspot (assuming that it is visible over half of the sky), adding to a total of 429 events/yr. In sum, a 5 year JEM-EUSO mission will collect 245 events from the TA Hotspot and a total of about 2,145 events above 57 EeV.[1] This significant increase in statistics will sharpen the EECR image of the TA hotspot allowing for a multi-messenger campaign to identify the nature of the first UHECR source.

The TA collaboration should be enlarging the area covered by its observatory fourfold. TAx4, as the project is known, will cover the same area as the Auger observatory but in the northern hemisphere. Depending on deployment cadence of TAx4 and the launch of JEM-EUSO the annual increase in the global accumulated statistics of EECR events will differ. If operating in 2022, JEM-EUSO will match the accumulated number of events of TAx4 after less than 1 year of observations given the planned deployment for TAx4. Subsequent years would double and triple the number of events at the interesting energy region in the northern hemisphere. The increase in statistics by JEM-EUSO will be over the complete sky which enables the identification of other regions of higher flux from the direction of other sources.

In terms of UHECR composition, Auger observes a trend towards heavier nuclei at the highest energies starting above about 5 EeV [23]. (This trend can also signify a change in hadronic interactions at the extreme interaction energies.) TA reports a proton dominated spectrum throughout their sensitivity range and the data between the two experiments is consistent within errors [24]. Identifying the sources with JEM-EUSO can help determine the composition with studies of source shape distortions at the highest energies. In addition, the two orders of magnitude increase in fluorescence data from JEM-EUSO will enable good determination of the shower maximum for a good fraction of the events, helping to determine the composition above 60 EeV.

In addition to the significant increase in 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 with the same instrument offers access to large scale multipoles such as dipoles and quadrupoles which are challenging for observations with partial sky coverages. In addition, discrepancies between the spectra reported by Auger and TA (shown in 2) can be settled by JEM-EUSO. This spectral difference may be due to different systematics in energy or exposure determinations or a real difference in the flux between northern and southern hemisphere. The northern hemisphere

[1]These estimates are based on the TA energy scale and reported event number. A different estimate can be made using the Auger detection rates and the Auger energy scale which should be applicable to the southern hemisphere. Given that it is currently not clear if the differences between the two spectra at the highest energies is a systematics issue or an actual difference, we chose here to do these simple estimates based on TA only. A more thorough study will be forthcoming.

may be dominated by the Hotspot region of increased flux, which could explain the difference in spectra. JEM-EUSO will be able to observe with the same instrument both hemispheres and with increased sensitivity at the highest energies. This will settle the question of the difference in spectra and the possibility of a spectral recovery at the highest energies.

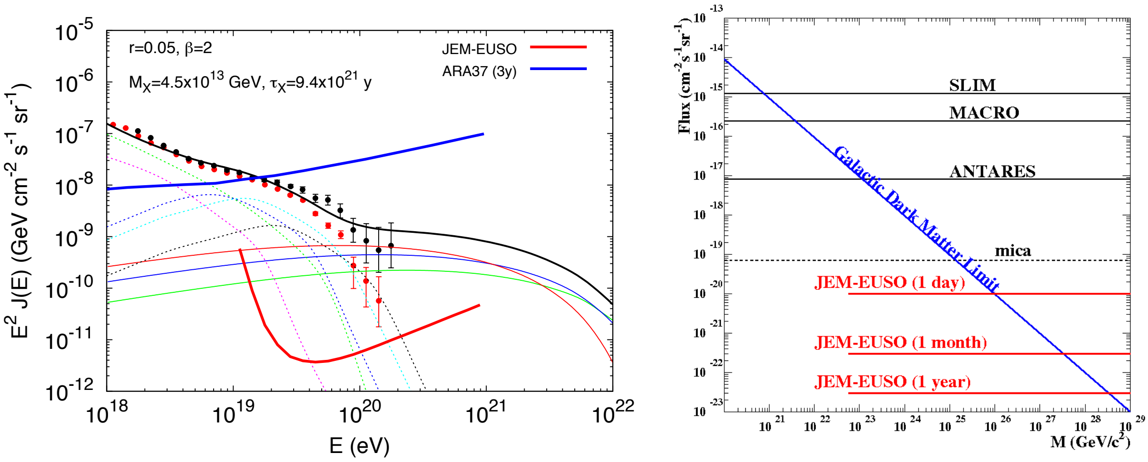

Figure 3: [Left] Sensitivity to SHDM decay products of JEM-EUSO for UHECRs (thick red solid line) and ARA observatory for UHE neutrinos (thick blue solid line) from [13] (with $r = 0.05$, $\beta = 2$). [Right] The JEM-EUSO 90% confidence level upper limit on the flux of nuclearites resulting from null detection over 24 hours, 1 month and 1 year of JEM-EUSO operations from [34].

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 [25]. 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 (often called cosmogenic photons and neutrinos [26]). The attenuation length for EEGRs is short compared to EECRs and neutrinos depending on the cosmic radio background. (The expected flux of EEGRs on Earth is highly dependent on the UHECR source characteristics, see e.g., [27]). JEM-EUSO will search for EEGRs events and place stronger constraints on their flux [25]. A detection of a higher than expected flux can be due to a new production mechanism such as top-down decay or annihilation [28] or the breaking of Lorentz Invariance.

An example of top-down models is the idea that the dark matter may be produced through gravitational processes around the inflationary epoch of the early universe. These super-heavy dark matter (SHDM) models received renewed interest given the announcement by BICEP2 of the detection of B-mode polarization consistent with a substantial contribution of tensor modes to the CMB fluctuations [29]. More recent results by Planck on polarized dust show that the observed tensor modes signal is compatible with pure foreground dust emission [30]. Forthcoming measurements of CMB polarization experiments will open the possibility of determining the energy scale for inflation (and SHDM models) by the fundamental measurement of CMB tensor modes. SHDM particles are long lived and the best way to constrain their lifetime is through UHECR observations. Super-heavy dark matter can be discovered by a precise measurement of CMB tensor modes combined with high statistics measurements of cosmic rays above the GZK cutoff. JEM-EUSO will have unprecedented sensitivity to these models as shown in figure 3.

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 the $E_{\rm max}$ of UHECR sources. For high enough $E_{\rm max}$, a flux of cosmogenic neutrinos is within reach of the JEM-EUSO mission [31]. A neutrino flux from extremely energetic sources may also be observed by JEM-EUSO. The acceptance for EEν events is well above current detectors. In addition, an order of magnitude larger acceptance results for Earth-skimming events transiting ocean compared to transiting land as discussed in [32]. 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.

JEM-EUSO will also monitor the Earth's dark atmosphere to observe atmospheric transient light events and meteors. 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. JEM-EUSO may become the first space-based platform to monitor meteor events, which are eminently "slow" when compared to UHECR showers.

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 [33] (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 as shown in figure 3. A null observation of these events will set strong constraints on their flux, reaching one order of magnitude more stringent limits than current ones in only one day of observations [34]. This search is a great example of the multi-disciplinary capabilities of the JEM-EUSO mission.

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