A giant natural TPC (500 km)$^3$ to observe extremely high energy cosmic particles - JEM EUSO telescope on International Space Station

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Abstract. An idea of a remote sensing, Time Projection Chamber (TPC) type of detector can be found in the planned cosmic ray experiments, Extreme Universe Space Observatory (EUSO). It uses a huge volume of earth's night sky in which an extremely energetic cosmic ray particle ($E > 10^{19}$ eV) generates a straight-line $N_2$ fluorescence signals of a track of cascade shower moving at the speed of light for a length of 10 - 100 km depending on the incident angle. The space-time resolved calorimetry of showers is designed with a large-aperture Fresnel lens optics and a large-area focal surface of detectors. Such a system in space is capable of detecting thousands of events with energy above $10^{20}$ eV ($>1000$ super-LHC) in a few years of operation on orbit, allowing a particle channel of astronomy and a research of fundamental physics in universe. Neutrino interaction cross-section at such high energies is expected to increase in the Standard Model, and EUSO expects a reasonable chance of observing the cosmogenic neutrino events among those detectable showers, because the atmospheric target mass of the EUSO TPC exceeds 1 trillion tons. This experiment JEM-EUSO is currently considered by the Japan Aerospace Exploration Agency (JAXA) for a possible payload on the Japan Experiment Module (JEM) of the International Space Station (ISS).

1. Largest Gas Detector: Earth’s atmosphere

JEM-EUSO (Extreme Universe Space Observatory on Japanese Experiment Module) is a new type of observatory that uses the whole earth as a detector including the International Space Station (ISS) where a remote sensor is located. It observes transient luminous phenomena taking place in the earth’s atmosphere caused by particles and waves coming from space. The sensor is a super wide-field telescope that detects extremely high-energy cosmic ray (EHECR) particles with energy above $10^{20}$ eV. This remote-sensing instrument orbits the earth every ~ 90 minutes on board International Space Station (ISS) at the altitude of ~ 430km (Figure 1). An EHECR collides with a nucleus in the earth’s atmosphere and produces an Extensive Air Shower (EAS) that consists of numerous electrons, positrons, and photons. JEM-EUSO captures the moving track of the fluorescent UV photons and reproduces the calorimetric development of EAS.

The JEM-EUSO telescope has a super-wide Field-of-View ($\pm30^\circ$) with two double sided curved Fresnel lenses and records the track of an EAS with a time resolution of 2.5$\mu$s and a spatial resolution of about 0.75 km (corresponding to 0.1 degrees). These time-segmented images allow to determine the energies and directions of the primary particles. The focal surface of the JEM-
EUSO telescope is formed by about 6,000 multi-anode photomultipliers. The number of pixels is about two hundred thousands.
JEM-EUSO instrument can reconstruct the incoming direction of the EHECRs with accuracy better than several degrees. Its observational aperture of the ground area is a 250 km radius and its atmospheric volume above it with a 60-degree field-of-view is about 1 tera-tons or more. The target volume for upward neutrino events exceeds 10 tera-tons. The instantaneous aperture of JEM-EUSO is larger than the Pierre Auger Observatory by a factor of 56 - 280 (Figures 1 and 2) when attached to ISS (Figure 3).

JEM-EUSO has two possible modes of operations on board ISS, namely, the nadir and the tilted modes (Figure 3). The latter mode gives up to 5 times larger aperture of the former mode.

Figure 1 JEM-EUSO Telescope

Figure 2 The Area-size that JEM-EUSO observes

Figure 3 JEM-EUSO telescope attached to ISS (artist’s view).
2. Science Objectives: Extremely high energy Astronomy in particle channel

JEM-EUSO is designed to detect more than 1,000 events with energy higher than $7 \times 10^{19} \text{eV}$ in a few years of operation. This number of events exceeds the critical value to observe all the sources at least once within several hundred Mpc even when the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1] is at work. Hence, JEM-EUSO may initiate a new astronomy with these particles ($10^{19} \text{eV} < E < 10^{21} \text{eV}$). This experiment can

- possibly identify the particle and energy sources using the arrival direction, and study acceleration mechanisms with the observed events;
- clarify the trans-GZK intensity profile [2] of distant sources and make a systematic survey of nearby sources; and
- separate gamma-rays and neutrinos from nucleons and nuclei, which allows testing of the Super-Heavy-Particle (SHP) models that assume long-lived particles produced in the early era of the universe.

The spectrum region with energy above $10^{20} \text{eV}$ is a regime where SHP ($m \sim 10^{22-25} \text{eV}/c^2$) is speculated to produce EHECRs without acceleration. SHPs are certainly CDM (Cold Dark Matter) and can be broadly distributed with an enhancement toward the galactic center. It could show small clumps, too, in the outer halo region where theses clumps would not be destroyed by the gravitational frictions and tidal effects in the Galaxy [3].

The EHECR particles can be traced back to the origin in the measured arrival direction with accuracy better than a few degrees. AGASA experiments [4] reported small-scale anisotropy (cluster) and some correlation existed in the arrival direction of EHECR with AGNs/Blazars. Hi-Res [5] also indicated such a point-source correlation with AGNs. If they come from isotropically-distributed point sources in three-dimensional space, several dozen clusters would be found with the statistics expected for JEM-EUSO. Nearby point sources can bear several dozens of events (Figure 4).

Figure 4 Arrival Direction expected from JEM-EUSO.

In a global anisotropy analysis, arrival directions are integrated for spherical harmonics. Such an analysis should reveal the source distributions of EHECRs. For the best analysis, the exposure must be uniform over all sky. ISS has an inclination of 51.6 degree, and JEM-EUSO on it can observe both north and south sky equally and would offer a nearly uniform exposure for all sky.

If the EHECRs come from cosmological distances as those of gamma-ray bursts and active galactic nuclei, these point sources might indicate global isotropy. Decay or annihilation of a super-heavy particle (SHP) can also produce EHECR particles. If EHECR source is such a SHP dark matter, it could be concentrated in our Milky Way Galaxy and might show an enhancement in the direction of Sagittarius, too. If they belong to galaxy clusters, they may show the enhancement at nearby clusters such as Virgo, Pisces, Peruses, and Heracles [6].
When the point sources are seen for events above $10^{20}\,\text{eV}$, other member events of these sources at different energies could also be identified. Changes in apparent point-spread-function depending on energy, magnitude and direction, and they can help determining the galactic magnetic field [7]. Galactic magnetic field is poorly known so far due to the limited data only from Faraday rotation of polarized radio sources. Independent direct measurement of galactic magnetic field performable by high-energy particle deflections will provide new information.

Auger experiment has some difficulty to make a comprehensive analysis of the arrival direction due to the very high galactic magnetic fields in the southern sky dominated by the galactic center and galactic plane. If one uses lower energy events, for example, at $4 \times 10^{19}\,\text{eV}$, the deflection by magnetic field ($\sim 5$ higher) is as large as 10 degrees: that is more than enough to erase possible signatures of any small angle anisotropy. Since Auger aperture is 20 times smaller than that of JEM-EUSO per year, the statistics it can obtain is also significantly limited to less than 100 events above $10^{20}\,\text{eV}$ even by 10 years of operation.

Furthermore, observations from the ground have other problems in the energy region above $3 \times 10^{20}\,\text{eV}$, even if a large area for observation becomes possible. An air shower at such high energies in dense atmosphere develops quite differently from the scaled Nishimura-Kamata-Greisen (NKG) function [8] due to the Landau-Pomeranchuk-Migdal (LPM) effect [9]. The lateral distribution method being used for energy determination by ground array experiments ceases to be usable for individual LPM showers due to large fluctuations. JEM-EUSO is relatively free from these problems of the ground-based experiments: in particular, far more immune from uncertainties of the LPM effects for longitudinal calorimetry method of the multi-peaked LPM showers. Moreover, many showers observable from space develop at high altitudes (above 20km) and at low densities, whose longitudinal shower developments suffer much less LPM uncertainties.

3. Exploratory Objectives

JEM-EUSO has several exploratory objectives in addition to the major science objectives of extremely high-energy astronomy in particle channel.

3.1 Detection of extreme energy neutrino can constrain the extra-dimension theory

Cosmogenic neutrinos may steadily be produced in universe in the GZK process in which an extreme energy proton looses its energy through the collisions with 2.7K microwave backgrounds. Many authors already pointed out the possibility that they are also produced during acceleration at high-energy objects such as AGNs or gamma-ray bursts. Neutrinos have such a small interaction cross-section with matter that they can directly convey the information of the acceleration site. They escape the source region without blacking the matter. They do not suffer from deflections by magnetic fields and can propagate many times the cosmological distance.

Neutrino-hadron cross-section data at the highest accelerator energy was given by the Electron Positron collider experiments at HERA, $\sigma_{\nu n}^{CC} \sim 2 \times 10^{-14}\,\text{cm}^2$ at $\sqrt{s}=314\,\text{GeV}$. This corresponds to $52\,\text{TeV}$ of such fixed target collision as that of cosmic-ray experiments. According to the standard QCD predictions and cosmogenic GZK neutrino flux calculations, JEM-EUSO is predicted to observe 1-10 neutrino events [10]. Extra-dimensional models [11] predict varieties of cross-sections. The predicted event rate is at least 100 times larger than the Standard QCD rate, and it is testable by JEM-EUSO.

Neutrino events can clearly be distinguished by JEM-EUSO from those of gamma-ray, protons and nuclei in terms of the shower maximum $X_{\text{max}}$: Neutrino events will be recognized as EAS that interacted deep in the atmosphere with nearly horizontal direction (HAS) or as upward-going air showers (UAS) [12]. UAS is produced by the decay of a tau-particle emitted by the interaction in the earth’s crust by the interaction of an earth-skimming or earth-penetrating tau-neutrino. By its three-years of operation of the tiled mode, JEM-EUSO can set an upper-limit of neutrino flux significantly lower than the Waxman-Bahcall limit [13] in the energy range of $10^{20}\,\text{eV}$ and above (Figure 5). Cosmogenic neutrinos are expected to be observed at least for a few events in JEM-EUSO. If top-down scenario for super-GZK particles (blue and green lines) is the valid case, at least several events are expected in a year. On the other hand, if JEM-EUSO does not observe
significant neutrino events exceeding a few events, it would exclude most of the top-down models, as well as the extra-dimensional models.

Figure 5 The flux-sensitivity of JEM-EUSO of 1 event/energy-decade/year; an observational efficiency of 25% is assumed. Red Thick Line: ESA-EUSO (min); Blue Thick Line: JEM-EUSO Nadir; Green Thick Line: JEM-EUSO-Tilt. As for Ice cube (Pink line), a few events/energy-decade/10years is assumed. Black Line denotes the Waxman-Bahcall limit.

Figure 6 Cosmogenic Neutrinos are expected by the GZK mechanism in vacuum.

3.2 Exploratory Objective 2 Super-LHC Physics
The center of mass energy of an extreme energy particle and a target nucleus interaction in the atmosphere exceeds the energy reachable by Large Hadron Collider (LHC) more than three orders of magnitudes. In this extreme energy frontier, many new physics that may change around the trans-GZK energies have been proposed and seriously discussed. JEM-EUSO can examine the Lorentz Invariance at very high Lorentz factors ($\gamma \sim 10^{11}$). Special relativity has been undoubtedly
firm at lower energies so that the GZK cutoff is expected to be imminent. Gamma ray mean free path in vacuum is shorter than 100 kpc by interactions with CMB unless strong quantum gravity effect prohibits $\gamma\gamma\rightarrow e^+e^-$ process. Hence, no gamma ray events are expected as EHECRs in standard physics. However, if GZK-process itself would not appear as expected [14], it could imply some limitations of local Lorentz Invariance in the presence of external fields. These EHECRs offer a unique way of experimental testing of the theory of relativity and quantum gravity. The standard quantum physics also predicts that EAS suffers large fluctuations of cascading from Landau-Pomeranchuk-Migdal (LPM) effect. It becomes considerable from $5\times10^{20}$ eV for protons and from $5\times10^{21}$ eV from iron nuclei. JEM-EUSO can observe this fluctuation with a high statistics. Furthermore, existence of super heavy dark matter particles can be tested if they decay or annihilate into EHECRs delivering photons and neutrinos as well as nucleons.

3.3. Exploratory Objectives

3. Global Earth Observation

JEM-EUSO will also observe atmospheric luminous phenomena such as lightning, nightglow, and meteors. In the upper atmosphere of the thunderstorm, many luminous transient events have been observed, such as, sprite, blue jet, and elves. These are believed to be a secondary discharge caused by the electric field from the redistribution of electric charge of the lightning. Gamma rays were also observed associated with lightning [15]. These are explained by streamer discharge [16]. If this is the case, streamer formation must be preceded by the main discharge. Furthermore, some satellites detected several gamma-ray bursts probably associated with lightning from the earth [17]. Such runaway electrons produced by cosmic-rays might be accelerated by the quasi-static electric field of the discharge associated with lightning. JEM-EUSO would keep monitoring both EHECR tracks and runaway phenomena to see whether there is any recognizable relationship. Other atmospheric phenomena that would be observable by JEM-EUSO have been included in the mission studies.

4. Conclusions

The very large TPC-type detector described here could be in operation in space in early 2010s when JEM-EUSO gets deployed on ISS. Its expected versatile performances on orbit for several years to a decade will be helpful in observing extremely high energy universe and exploring fundamental physics beyond the LHC energies.

5. Acknowledgments

This work is supported by RIKEN and JAXA of Japan, and by 8 other countries of the JEM-EUSO Collaboration, namely, USA, France, Italy, Germany, Korea, Mexico, Russia and Switzerland. This paper is represented by the Author for the JEM-EUSO Collaboration. The author is grateful to the organizers of the “Third Symposium On Large TPCs for Low Energy Rare Event Detection” for kind hospitality and useful discussions.

References

[1] Greisen K, 1966, Phys. Lett. 16 148; Zatsepin G T and Kuz'min V A 1966 JETP Phys. Lett. 4 78.
[2] Berezinsky V, Kachelrie M, and Vilenkin A.1997 Phys.Rev. Lett. 79 4302; Berezinsky V, and Kachelrie M. 2001 Physical Review D. 63 034007; Berezinsky V, Blasi P. and Vilenkin A. 1998 Phys. Rev. D 58:103515; Berezinsky V, Mikhailov A A 1998 Phys. Rev. D. 58 10315.
[3] Navarro J F, Frenk C S and White S D M 1996, Astrophys. J. 462 563; Moore B. et al. 1999 Adtrphys. J. Lett. 524 L19; Fukushima T, Kawai A and Makino J 2004 Astrophys. J. 606 625.
[4] Uchihori Y, eu al. 2000 Astropart. Phys. 13 151; Hayashida N. et al, 1999. Astrophys. J. 522, 225; Tinyakov P G and Tkachev I I 2000, JETP 74 445.
[5] Abassi R U, Abu-Zayyad T et al. 2005; Astrophys. J. 623 164.
[6] Medina-Tanco G, Teshima M and Takeda M 2003 Proc. 28-th ICRC Tokyo, 747; Takami H, Yoshiguchi H and Sato K 2004, Astrophys. J. 639 803.
[7] Medina-Tanco G and Watson A 1999 Astropart. Phys. 12, 25; Medina-Tanco G 2006 arXiv:astro-ph/0607543v1.

[8] Kamata, K, and Nishimura J 1958 Prog. Theor. Phys. Supple 6 9; Greisen K 1956 Prog. Cosmic Ray Physics III ed. J G Wilson (North Holland, Amsterdam).

[9] Landau, L D and Pomeranchuk,I J 1935 Dokl.Akad.Nauk SSSR, 92 535; Migdal, A B 1956 Phys. Rev. 103 1811.

[10] Palimares-Ruiz S, Irimia A. and Weiler T J 2006 Physical Rev. D 73 083003 2006.

[11] Randall L 2000 JHEP 06 014; Kisselev A V 2004 Eur.Phys.J. C34 513; arXiv:hep-ph/0412376v1; Kachelriess M and Plumacher M 2000 astro-ph/0005309; Emparan R etAl. 2002 hep-ph/0109287; Ilana J I et al 2004 hep-ph/0402279; Barbot M et al 2003 Phys. Lett. B 555 22; Anchordoqui L A, Feng L J, Goldberg H and Shapere A D 2002 Phys. Rev. D65 124027; Anchordoqui L, Goldberg H and Nath P 2004 hep-ph/0403115.

[12] Ringwald A and Wong Y Y Y 2004 J. Cosmol. Astropart. Phys. 12, 005, 2004.

[13] Waxman E and Bahcall J. 1999 Phys. Rev.. D 59, 23002.

[14] Sato H and Tati T 1972 Prog. Theor. Phys. 47 1788; Amelio-Camelia G. et. al. 1998 Nature 393 763; Coleman, S. and Glashow, S.L., 1999, Phys. Rev. D. 59 116008; Ellis, J., Mavromatos N E. and Nanopoulos D V. 2001 Phys. Rev. D, 63 124025; Yamaguchi Y 2003 Prog. Theor. Phys. 110 611; Yamaguchi Y 2004 Prog. Theor. Phys 111 545.

[15] Pasko V P and George J J 2002 Journal of Geophysical Research 107 A12 1458.

[16] Zong J et al. 2002 Photogrammetric engineering & remote sensing 68 821.

[17] Fishman G J et al.1994 Science 264 131.