Imaging the Extreme Universe
Solid-state cameras for Astroparticle Physics

May 9-10, 2013 - CHICAGO, USA

KIOP

The University of Chicago
JEM-EUSO Mission

Extreme Universe Space Observatory (EUSO) in the Japanese Experiment Module (JEM) of the International Space Station (ISS)
JEM-EUSO Mission

Japanese Experiment Module (JEM)

きぼう, Kibo = Hope
JEM-EUSO Mission

Japan, USA, Korea, Mexico, Russia, Europe: Bulgaria, France, Germany, Italy, Poland, Slovakia, Spain, Switzerland

13 Countries, 73 Institutions, 250 researchers
Leading institution: RIKEN

PI: Piergiorgio Picozza
JEM-EUSO goals

- pioneer the study of EECR from Space
- increase exposure to EECR by 1 order of magnitude
- discover the nearby sources of UHECRs
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- increase exposure to EECR by 1 order of magnitude
- discover the nearby sources of UHECRs

EECR: Extreme Energy CRs > 60 EeV
UHECR: Ultrahigh Energy CRs > 1 EeV = 10^{18} \text{ eV}
Cosmic Ray Flux $\times E^2$

$E^2 dN/dE$ (eV m$^{-2}$ s$^{-1}$ sr$^{-1}$)

- ATIC
- Proton
- RUNJOB
- Tibet AS-$\gamma$ (SIBYLL 2.1)
- KASCADE (QGSJET 01)
- KASCADE (SYBILL 2.1)
- KASCADE-Grande 2009
- HiRes I
- HiRes II
- Auger 2010

LHC ($p-p$)

Ultrahigh Energy

Extreme Energy = Particle Astronomy

GZK?

Koteran, AO 2011
Current Observatories of Ultrahigh Energy Cosmic Rays

Telescope Array
Utah, USA
(5 country collaboration)
700 km² array
3 fluorescence telescopes

Pierre Auger Observatory
Mendoza, Argentina
(19 country collaboration)
3,000 km² array
4 fluorescence telescopes
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC

Auger Anisotropy limits: rule out Galactic protons to CNO as dominant CR component E > 1 EeV and Fe above 20 EeV

Giacinti et al '11
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC

Implies a GZK* feature in the spectrum

(*Greisen-Zatsepin-Kuzmin)
Greisen-Zatsepin-Kuzmin effect

Proton energy loss lengths [Mpc] vs. energy [eV]

- Photo-pion production
- Energy loss length
- Interaction length
- Interaction length, IR
- Pair production
- Cosmological expansion
UHECR 2012
CERN

Tsunesada et al.
CERN WG ’12
Recent Results

$E_{\text{>20 EeV}}$ Cosmic Rays are EXTRAGALACTIC

$E_{\text{>40 EeV}}$ GZK-like feature in the spectrum
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC

E>40 EeV GZK-like feature in the spectrum or end of the injected spectrum, $E_{\text{max}}$?
GZK vs $E_{\text{max}}$

![Graph showing $E^3 dN/dE$ vs. log $E$ with different components and models.](image)

Fang, Kotera, AO '13
Recent Results

E > 20 EeV Cosmic Rays are EXTRAGALACTIC

E > 40 EeV GZK-like feature in the spectrum or end of the injected spectrum, $E_{\text{max}}$?

E > 10 EeV Composition may be changing!
Auger Composition

Consistent within quoted errors!

HiRes Composition

TA Composition
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC

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or maybe the HE interactions are changing!
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How to sort out this conundrum?
Recent Results

E>20 EeV Cosmic Rays are EXTRAGALACTIC

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or maybe the HE interactions are changing!

How to sort out this conundrum? Find the Sources!
EECR Anisotropy Hints

\( E > 60 \) EeV

Mild anisotropy - still dominated by isotropic background at 55 EeV

>100 EeV Auger/TA doublet

TA 25 events above 57 EeV - consistent with LSS
How to find the Sources?

GET A LOT MORE DATA above 60 EeV!!!!
How to find the Sources?

GET A LOT MORE DATA above 60 EeV!!!!

OVER THE WHOLE SKY !!!!
How many EECRs $> 60$ EeV?

Before we see a source?
1,000 is a good o.o.m. estimate

Dipole from direction of Cen A in Auger $>60$ EeV: (a posteriori) right ascension harmonic analyses

Anchordoqui, Goldberg & Weiler ‘11

$$\alpha_d \hat{d} = \frac{3}{N} \int J(\hat{u}) \, \hat{u} \, d\Omega$$

$\alpha_d = 0.25$

5$\sigma$ discovery requires 1,000 events (with whole sky coverage)
Population Separation: need 1,000 events above 60 EeV

Kalli, Lemoine, Kotera ‘10

\[ X_C = \frac{\sum_{i=1}^{N_{\text{tot}}} \frac{(N_i^T - \langle N_{i,LSS} \rangle)(\langle N_{i,iso} \rangle - \langle N_{i,LSS} \rangle)}{\langle N_{i,LSS} \rangle}} \]
Current Observatories of Ultrahigh Energy Cosmic Rays

Telescope Array
Utah, USA
(5 country collaboration)
700 km² array
3 fluorescence telescopes

The Atmosphere as a Detector

Pierre Auger Observatory
Mendoza, Argentina
(19 country collaboration)
3,000 km² array
4 fluorescence telescopes
How many EECRs > 60 EeV?

Auger w/ 3,000 km²
~20 events > 55 EeV/yr

Telescope Array w/ 700 km²
~4.6 events > 55 EeV/yr

Auger + TA ~30 events/yr
How many EECRs > 60 EeV?

Auger w/ 3,000 km²
~20 events > 55 EeV/ yr
Telescope Array w/ 700 km²
~4.6 events > 55 EeV/ yr

Auger + TA ~30 events/yr
30+ years to reach 1,000

Earth - surface ~ 5 \(10^8\) km²
~3.4 \(10^6\) events/yr
How many EECRs > 60 EeV?

- Auger w/ 3,000 km²: ~20 events > 55 EeV/yr
- Telescope Array w/ 700 km²: ~4.6 events > 100 EeV/yr
- Auger + TA: ~30 events/yr
- Earth surface: ~5 × 10⁸ km²
- ~3.4 × 10⁶ events/yr

5 o.m. to go!
Go to SPACE!
To look down on the Atmosphere!
How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

JEM-EUSO

~200 events > 60 EeV/yr

Earth - surface ~ 5 $10^8$ km$^2$

~3.4 $10^6$ events/yr
How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

JEM-EUSO
~200 events > 60 EeV/yr

Earth surface ~ $5 \times 10^8$ km$^2$

~$3.4 \times 10^6$ events/yr
JEM-EUSO Mission

Extreme Universe Space Observatory (EUSO) in the Japanese Experiment Module (JEM) of the International Space Station (ISS)
Huge Exposure Area

Tilt-mode ($\sim 7 \times 10^5 \text{km}^2$)

Nadir-mode ($\sim 2 \times 10^5 \text{km}^2$)

AGASA ($\sim 100 \text{km}^2$)

Auger ($\sim 3000 \text{km}^2$)

3000 Gton – for EHE neutrinos
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch date</td>
<td>2017</td>
</tr>
<tr>
<td>Mission Lifetime</td>
<td>3+2 years</td>
</tr>
<tr>
<td>Rocket</td>
<td>H2B (or Falcon9)</td>
</tr>
<tr>
<td>Transport Vehicle</td>
<td>HTV (or Dragon)</td>
</tr>
<tr>
<td>Accommodation on JEM</td>
<td>EF#9</td>
</tr>
<tr>
<td>Mass</td>
<td>1938 kg</td>
</tr>
<tr>
<td>Power</td>
<td>926 W (op.) 352 W (non op.)</td>
</tr>
<tr>
<td>Data rate</td>
<td>285 kbps (+ on board storage)</td>
</tr>
<tr>
<td>Orbit</td>
<td>400 km</td>
</tr>
<tr>
<td>Inclination of the Orbit</td>
<td>51.6°</td>
</tr>
<tr>
<td>Operation Temperature</td>
<td>-10° to +50°</td>
</tr>
</tbody>
</table>
H-II Transfer Vehicle (HTV)

HTV is 4m across ~10 m long
Full Sky Coverage
with nearly uniform exposure

Inclination: 51.6°
Height: ~400km

The ISS ORBIT
JEM-EUSO
Sky Coverage

![Image of sky coverage diagram]

- JEM-EUSO (ISS) / 64,000 km²-sr
- Auger (φ = 35.5°S) / 7,000 km²-sr
- TA (φ = 39.1°N) / 1,800 km²-sr
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Field of View</td>
<td>±30°</td>
</tr>
<tr>
<td>Monitored Area</td>
<td>&gt;1.3×10^5 km^2</td>
</tr>
<tr>
<td>Telescope aperture</td>
<td>≥2.5 m</td>
</tr>
<tr>
<td>Operational wavelength</td>
<td>300-400 nm</td>
</tr>
<tr>
<td>Resolution in angle</td>
<td>0.075°</td>
</tr>
<tr>
<td>Focal Plane Area</td>
<td>4.5 m^2</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>&lt;3 mm</td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>≈3×10^5</td>
</tr>
<tr>
<td>Pixel size on ground</td>
<td>≈560 m</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>2.5 μs</td>
</tr>
<tr>
<td>Dead Time</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>Photo-detector Efficiency</td>
<td>≥20%</td>
</tr>
</tbody>
</table>
Science Instrument on HTV

Stowing configuration to carry by HTV

Side view

H2B Transfer Vehicle (HTV)
Science Instrument

Side view

Deployment Mechanism

JEM-EUSO Telescope will be deployed after it is attached at the ISS

Atmospheric Monitoring System

Focal Surface Detector and Electronics

Focal Surface

Rear Lens

Middle Lens

Optics

Front Lens

Pallet
Focal Surface Detector

4932 MAPMTs (8x8 pixels)

Focal Surface detector
137 PDMs = 0.3M Pixels

Photo-Detector Module
(3x3 ECs = 2,304 pixels)
1 High Voltage / PDM

Y. Kawasaki, ID 0472
M. Ricci, ID 0335
FAST SIGNAL

duration 50 - 150 $\mu$s

a) Fluorescence
b) Scattered Cherenkov
c) Direct (diffusively reflected Cherenkov)

1 GTU gate time units = 2.5 $\mu$s

Background: 500 $\text{m}^2 \text{sr ns}$
Result of end-to-end simulation

F. Fenu, ID 0829
K. Higashide, ID 1240
T. Mernik, ID 0633

Simulated air shower image on the focal surface detector.

$2 \times 10^{20}$ eV

$65 \degree$

$3 \times 10^5$ pixels

Detected photoelectrons are recorded every Gate Time Unit (GTU) of $2.5\mu$s continuously.
Result of end-to-end simulation

F. Fenu, ID 0829
K. Higashide, ID 1240
T. Mernik, ID 0633

Num. of Photons
- On Pupil: 8617
- On FS: 4819
- Detected: 1134
annual exposure = 10 x Auger
6 $10^4$ km$^2$ sr yr
Serendipity: ZeV neutrinos

diffuse $\nu_e + \nu_\mu + \nu_\tau$ limits
JEM-EUSO in USA

Institutions on NASA APRA Proposal:
University of Chicago, PI Institution
University of Alabama in Huntsville
Marshall Space Flight Center
University of Wisconsin-Milwaukee
Colorado School of Mines
Vanderbilt University

Other US Institutions in the Collaboration
University of California, Berkeley
University of California, Los Angeles
Fermilab
University of Kansas, Wichita
others interested in joining
JEM-EUSO in USA

Global Light System
<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Elevation</th>
<th>Location</th>
<th>Latitude</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jungfraujoch (Switzerland)</td>
<td>47° N</td>
<td>3.9 km</td>
<td>Chacaltaya (Bolivia)</td>
<td>16° S</td>
<td>5.3 km</td>
</tr>
<tr>
<td>Mt. Washington (NH, USA)</td>
<td>44° N</td>
<td>1.9 km</td>
<td>La Reunion (Madagascar)</td>
<td>21° S</td>
<td>1.0 km</td>
</tr>
<tr>
<td>Alma-Ata (Kazakhstan)</td>
<td>44° N</td>
<td>3.0 km</td>
<td>Cerro Tololo (Chile)</td>
<td>30° S</td>
<td>2.2 km</td>
</tr>
<tr>
<td>Climax (CO, USA)</td>
<td>39° N</td>
<td>3.5 km</td>
<td>Sutherland (South Africa)</td>
<td>32° S</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Frisco Peak (UT, USA)</td>
<td>39° N</td>
<td>2.9 km</td>
<td>Pierre Auger (Argentina)</td>
<td>35° S</td>
<td>1.4 km</td>
</tr>
<tr>
<td>Mt Norikura (Japan)</td>
<td>30° N</td>
<td>4.3 km</td>
<td>South Island (New Zealand)</td>
<td>43° S</td>
<td>1.0 km</td>
</tr>
<tr>
<td>HAWC Site (Mexico)</td>
<td>19° N</td>
<td>&gt;3.0 km</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EUSO Balloon - pathfinder

EUSO-BALLOON

PI: P. von Ballmoos Phase C/D
Testing EUSO-Balloon (US NASA APRA)
Fly one aircraft equipped with two types of calibrated pulsed UV light sources.

Point Test: Fly airplane in field of view and fire flash lamp. Light travels directly from lamp to detector.

Track Test: Fly airplane outside field of view and shoot a UV pulsed laser across field of view. Light scatters out of the beam to the detector.
(5 mJ Laser ~100 EeV Cosmic Ray)

Fly aircraft at altitudes between 2,000 and 10,000 feet.
JEM-EUSO goals

- pioneer the study of EECR from Space
- increase exposure to EECR by 1 order of magnitude
- discover the nearby sources of UHECRs
Exposure History

Exposures ($L = km^2 s^{-1}$)

- Fly's Eye
- AGASA
- HiRes
- Auger
- TA
- JEM-EUSO (tilt, nadir)

Year:
- 1990
- 2000
- 2010
- 2015
- 2020
- 2025
- 2030
In a decade, we can discover the first sources of EECRs from Space!!!