極高宇宙線測定の現状：ICRCよりの報告

宇宙線研究所・福島正己
Status of UHECR

1. Energy Spectrum
2. Composition
3. Source and Anisotropy
The Auger Observatory in the Southern Hemisphere
Now fully deployed in Argentina

1600 water Cherenkov stations
24 fluorescence telescopes (30°x30°)

 Highlight talk of P.Sommers
Auger SD: 08 vs 09

Energy [eV]

$E^3 J(E)$ [km$^2$ yr$^{-1}$ sr$^{-1}$ eV$^{-2}$]

- $\varepsilon = 12790$ km$^2$ sr yr (PRL: 7000 km$^2$ sr yr)
- energy calibration with full statistics

C. DiGiulio (0142), this conf.
Auger SD (θ: 60°-80°)

Graph showing data points for angle θ and energy E (in eV) for Recon. A and Recon. B, with error bars. The data points are differentiated by symbols and colors: squares for angle θ < 60°.
Auger-09

![Graph showing energy spectra and data points for different elements: Auger combined 2009, Proton, $\beta=2.6$, $m=0$, Proton, $\beta=2.3$, $m=5$, Iron, $\beta=2.4$, $m=0$. The graph includes a logarithmic scale for energy and a linear scale for the integral of the flux. The systematic uncertainty is noted as $\sigma_{sys}(E)=22\%$.](Image)
Auger SD, resolution effect

\[ E^3 J(E) \text{ [km}^2 \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^{-2}] \]

\[ 10^{37} \]

\[ 10^{19} \]

\[ 10^{20} \]

Energy [eV]

Auger SD 2009 (raw)

Auger SD 2009

F. Schuessler
Auger-09 vs HiRes-stereo

$J / (B \times E^{2/3}) - 1$

- HiRes Stereo ($k_E = 0.75$)
- Auger ($k_E = 1.25$)

Energy [arb. units]

F. Schuessler
TA Mono  (HiRes transfer)
Auger, Xmax

Raw $X_{\text{max}}$ distribution above 1 EeV

Example of bad geometries for sampling the Xmax distribution

The red line indicates the slant depth range for expected $X_{\text{max}}$ values.

maximum detection distance for the corresponding shower energy.
Conclusions

* The data favor a break in the $X_{\text{max}}$ Vs energy curve at:

$$E_b = 10^{18.25 \pm 0.05} \text{ eV}$$

This energy is close to the ankle in the energy spectrum.

* At energies above $E=2 \times 10^{18} \text{ eV}$ the small elongation rate,

$$D_{10} = 24 \pm 3 \text{ g cm}^{-2} / \text{ decade}$$

and the decreasing trend of the RMS($X_{\text{max}}$) suggest a composition change towards a heavier composition.
Indications from Auger SD

Statistical approach

- Timing Asym.
- Muon content

\[ \tau(R, \Theta) = a + b \cos(\zeta) \]

asymmetry factor = \(b/a\)

H. Wahlberg
A. Castellina

(Study of had. Int. Model)
HiRes $X_{\text{max}}$: Data vs MC (QGSJET-2)

- $X_{\text{max}}$
- $\sigma_{\text{age}}$
- $p$
- $Fe$
HiRes X_{\text{max}}: Data vs MC (QGSJET-2)

\begin{align*}
X_{\text{max}} & \quad \sigma_{X_{\text{max}}} \\
\text{HiRes/MIA} & \quad \text{HiRes 2005} & \quad \text{HiRes 2009} \\
\text{QGSJET2 Proton} & \quad \text{QGSJET2 Iron} \\
\log_{10}E (\text{eV}) & \quad \sigma_z (\text{g/cm}^2) \\
550 & \quad 18 & \quad 18.25 & \quad 18.5 & \quad 18.75 & \quad 19 & \quad 19.25 & \quad 19.5 & \quad 19.75 & \quad 20
\end{align*}
AUGER vs HiRes

$X_{\text{max}}$

$\sigma_{X_{\text{max}}}$

HiRes: acceptance corrected
Auger: no accept. corr. necessary

HiRes: acceptance not corrected
Definition of “width” differs.
### Composition: $10^{18}$ eV – $10^{19.7}$ eV

<table>
<thead>
<tr>
<th>HiRes</th>
<th>Auger</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD Stereo</td>
<td>FD/SD Hybrid</td>
</tr>
<tr>
<td>Strict comparison of Data &amp; MC</td>
<td>Little reliance on MC</td>
</tr>
<tr>
<td>Acceptance correction estimated by MC</td>
<td>Event geometry selected such that “no” acceptance correction is necessary</td>
</tr>
<tr>
<td>Data consistent with constant elongation rate, and Xmax fluctuations consistent with QGSJET2 protons, slight tendency towards heavier primaries within QGSJET1 model. (J.Beltz)</td>
<td>A change towards a heavier composition suggested (J.Bellido)</td>
</tr>
<tr>
<td>Stay with PROTON</td>
<td>Change to IRON</td>
</tr>
<tr>
<td>Northern hemisphere</td>
<td>Southern hemisphere</td>
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</tbody>
</table>
South : Iron
North : Proton
Are we really happy with it?

A careful examination of experimental problem is necessary.
Energy shift by $10^{0.25}$
Xmax shift by 17 gr/cm$^2$
鉄と陽子のXmax分布の概念図
Auger AGN correlation

27 events as of November 2007

55 EeV
3.1 deg.
VCV catalog
Correlation update

Correlated / TOT.  9 / 14  →  9 / 13  →  8 / 31

Not consistent with ISOTROPY with 99% CL
Correlation with Galaxy catalogues persists

(1) 22 Months SWIFT-BAT Catalogue
(2) 2MRS Catalogue* (~23000 galaxies)
(3) HIPASS Catalogue* (~3000 galaxies):
(4) HIPASS* High Luminosity Catalogue (HIPASS HL):
(2’) 2MASS Redshift Survey
(5) Cen-A (within 18°, 12/2.7 event, 2% prob.)

J.D.Hague
J.Aublin
G.Farrar
CEN-A からの separation angle 分布
Trans-GZK composition is simpler

Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

Cosmic magnetic fields should make highly charged nuclei almost isotropic.
Hires stereo Sky Plots

Expectation from 2MRS CATALOGUE (x HiRes acceptance)

Correlation with 2MRS for $\theta_s < 10^0$ and $E \geq 40$ EeV excluded by 95% CL.
First Skymap of TA for $E > 10^{19.5}$ eV and $\theta < 45^0$

Data: May 11 2008 → Nov. 30 2008 (204 days)
Exposure: $2.0 \times 10^{16}$ m$^2$ sr sec

N.Sakurai
31st ICRC@Lodz の時点で

（スペクトル）・到来方向・粒子種、についての観測データに矛盾あり

UHECRの「標準的解釈」は液状化

TAは独自の地点から正しい測定を行う
Iron, “Cutoff,” LSS correlation...

A simple (+happy) paradigm of UHECR may be forced to change.

• UHECR is extra-galactic proton
• It creates GZK cutoff and $e^+e^-$ dip
• in collision with CMB
• It originates from AGNs in GZK horizon or, at least, it follows LSS.
• Universe is north/south symmetric
Recent Reviews

- M. Nagano, New J. Phys. 11 065007
- J. Bluemer, R. Engel and J. R. Hoerandel
  arXiv: 0904.0725

Energies are rescaled in Nagano’s spectra plot;

AGASA 2003 x 0.75, Auger 2008 x 1.2, Yakutsk 2004 x 0.625
Akeno 1984 x 0.85, Akeno 1992 x 0.85, RUNJOB 2005 x 1.2,
Blanca 1999 x 1.1, CASA-MIA 1999 x 1.1, HiRes 2008 = 1.00
Telescope Array
Hybrid detector

TA wide area network:
Talk by T. Nonaka ID=977

3 communication towers

507 Plastic Scintillator Detectors
cover ~700 km² (1.2 km spacing)

3 Fluorescence Telescope
Stations overlook the array.

Utah, USA
39.3° N, 112.9° W
alt. 1400 m

TA overview: poster by
J.N. Matthews ID=138
H. Sagawa
TA SD stable and well calibrated

Available SDs: (communication status)

- (05/17~)
- Running time:
  - LR: 97%
  - SK: 96%
  - BR: 97%

Available SD: > 98%

T. Nonaka
Progress of AS simulation

(1) Make fully simulated AS data base

- Cosmos, ~130 events for $10^{17} - 10^{19}$ eV, $-10^{20}$ eV (qF)
- Corsika, ~100 events for $10^{18.5} - 10^{19.5}$ eV
TA Triple Hybrid Event

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<tbody>
<tr>
<td>MD</td>
<td>51.43</td>
<td>73.76</td>
<td>7.83</td>
<td>-3.10</td>
</tr>
<tr>
<td>BR mono</td>
<td>51.50</td>
<td>77.09</td>
<td>7.67</td>
<td>-4.14</td>
</tr>
<tr>
<td>Stereo  (BR&amp;LR)</td>
<td>50.21</td>
<td>71.30</td>
<td>8.55</td>
<td>-4.88</td>
</tr>
</tbody>
</table>

Zenith > 45deg

D. Ikeda
Event Top View

number = MeV energy deposit (av U+D)
~ 2.5 MeV for vertical mu

Event “Side” View
Wave Form Example

- **upper layer**
- **lower layer**

Central hit

Surrounding soft e / γ hits

peak ~ 230
Integ. ~ 4700 [VEMs]

peak ~ 5
Integ. ~ 30 [VEMs]

1 μs
Reconst. Accuracy: core position & angle

MC by dt-Corsika

rms = 63m
X

\[ X_{\text{rec}} - X_{\text{gen}} \] [1200m]

rms = 67m
Y

\[ Y_{\text{rec}} - Y_{\text{gen}} \] [1200m]

rms = 1.2°
\( \theta \)

\[ \theta_{\text{rec}} - \theta_{\text{gen}} \] [degree]

rms = 1.3°
\( \phi \)

\[ \sin \theta_{\text{gen}} \left( \phi_{\text{rec}} - \phi_{\text{gen}} \right) \] [degree]
$\theta$ and $\phi$ distributions

Data
MC

MC by dt-Corsika
S(800) distribution

**MC spectrum:**
- $E^{-2.81}$ above ankle
- $E^{-3.25}$ below ankle
- Ankle @ $10^{18.65}$ eV
- QGSJET2, proton
dt-Corsika
- # ev norm. to data

**Data:**
- May~Nov, 2008
- $\sim 1.0 \times 10^{16}$ m$^2$ sr s
Prospects and Summary

• Check with two “full” Air Shower simulations
• Test reconstruction methods
  (1) average S(800)
  (2) LDF ( r, E, θ, φ )
• Estimate systematics from
  (a) had. models, (b) p/Fe, (c) reconstruction
• Improve calibration < ~3%
• Improve efficiency at E ~ 10^{19} eV or less
• Check energy scale by SD / FD coin. event
• Wait for more data:
  AGASA total exposure (13y) reached by spring 2010