 Recent Studies of Ultra High Energy Cosmic Rays

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Current Situation: (re-UHECR)

The “Conservative” AGN (Black Hole!) Bottom-Up scenario has observational Problems that are difficult to dismiss.

The Top-Down (Big Bang Relics) is also constrained but is still flexible enough to be quite viable.

NEED MORE DATA!!

Note: Top-Down(Big Bang Relics) \( \Rightarrow \) TOE (New Fundamental Physics)
Outline:

• Present Status of Detectors - Auger

• The Issues:
  i Changes to Hadronic Interaction Models
      - inferences for mass composition
  
  ii Energy Spectrum
      – is there a GZK-effect?
  
  iii Arrival Directions
      - Clusters? BL Lac associations?

• Summary
### Exposure and Event Numbers from various Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>km² sr year</th>
<th>Approximate rate &gt; 10 EeV (km² sr year)^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGASA: closed in January 2004:</td>
<td>1600</td>
<td>827</td>
</tr>
<tr>
<td>Scintillator array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HiRes I: monocular</td>
<td>~5000</td>
<td>403</td>
</tr>
<tr>
<td>Fluorescence Detector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HiRes: stereo (PRELIMINARY)</td>
<td>~2500</td>
<td>~500</td>
</tr>
<tr>
<td>Yakutsk:</td>
<td>~900</td>
<td>171</td>
</tr>
<tr>
<td>Scintillator plus air-Cherenkov light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auger: data taking since Jan 2004</td>
<td>1750</td>
<td>444</td>
</tr>
<tr>
<td>Fluorescence plus water-Cherenkov</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hybrid Approach of Auger Observatory

Fluorescence in UV $\rightarrow$ AND

Water-Cherenkov detectors respond to muons, $e^\pm, \gamma$
1056 surface detector stations deployed with 919 taking data (2 Dec 2005)

Three fluorescence buildings complete each with 6 telescopes

First tri-oculars in August
$\theta \sim 48^\circ$, $\sim 70$ EeV

18 detectors triggered

Typical flash ADC trace
Detector signal (VEM) vs time (ns)

Threshold

PMT 1
PMT 2
PMT 3

Lateral density distribution
$\theta \sim 60^\circ, \sim 86$ EeV

35 detectors triggered

Flash ADC Trace for detector late in the shower

Much sharper signals than in more vertical events leads to $\nu$-signature

PMT 1
PMT 2
PMT 3

Lateral density distribution

ID 787469
FD reconstruction

Signal and timing
Direction & energy

Pixel geometry
shower-detector plane
~4 \times 10^{19}\text{eV}
355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy
Geometrical Reconstruction
Angular and Spatial Resolution from Central Laser Facility

- Angle in laser beam /FD detector plane
  - Mono/hybrid rms 1.0°/0.18°

- Laser position – Hybrid and FD only (m)
  - Mono/hybrid rms 566 m/57 m
A Big Event - *One that got away!*

Shower/detector plane

Fluorescence Mirror

Energy Estimate

\[ \theta = 47^\circ \]

\[ R_p = 28 \text{ Km} \]

\[ \chi_0 = 130^\circ \]

\[ > 140 \text{ EeV} \]

19 April 2004
(ii) Muon Content of Showers:

\[ N_{\mu} (>1 \text{ GeV}) = A B (E/A)^{\varepsilon \pi} \]

(\text{depends on mass/nucleon and model})

\[ N_{\mu} (>1 \text{ GeV}) = 2.8 A (E/A)^{0.86} \sim A^{0.14} \]

So, more muons in Fe showers.

(i) Variation of Depth of Maximum with Energy

Methods of Inferring the Primary Mass

HADRONIC MODELS REQUIRED - NEW MODEL, QGSJET II, DISCUSSED AT ICRC

Limiting bound = 2.3 X_0 g cm^{-2} per decade (Linsley 1977)
FIG. 7: Pseudorapidity distributions of charged particles (upper panel) and of the energy flow (lower panel) for $pp$ collisions at LHC [121].
New hadronic model: QGSJETII   Heck and Ostapchenko ICR 2005

Multiplicity vs. Energy

\[ \langle N_{ch} \rangle \]

QGSJET 01
QGSJET II
SIBYLL 2.1

\[ p-^{14}N \text{ collisions} \]

\[ E_{\text{lab}} \text{ (eV)} \]
$X_{\text{max}}$ vs. Energy for different models compared with data

- Fly's Eye
- HiRes-MIA
- HiRes 2004
- Yakutsk 2001
- Yakutsk 2005
- CASA-BLANCA
- HEGRA-AIROBICC
- SPASE-VULCAN
- TUNKA
- DICE

$E_{\text{lab}}$ (eV)

- QGSJET 01c
- QGSJET II
- SIBYLL 2.1

Heck and Ostapchenko: ICRC 2005
Assumption: Fe with $E^{-2}$ with sharp cut-off at $10^{22}$ eV
1: SURFACE DETECTOR ARRAYS (e.g. AGASA, Yakutsk)

APERTURE:
- relatively easy to determine

ESTIMATION OF PRIMARY ENERGY:
- mass assumption required
- hadronic interaction model must be assumed for which systematic uncertainty in UNKNOWABLE
- QGSJETII model will lead to revisions
2. FLUORESCENCE DETECTOR (e.g. HiRes):

**ENERGY ESTIMATES** depend only weakly on assumptions about models and mass

**BUT** determination of energy requires
- atmospheric corrections for each event
- Cherenkov light subtraction (< 25% used)

**APERTURE** is difficult to measure
- does not saturate
- depends on atmosphere
- mass of primary
- models
- spectral shape

so, aperture can be systematically uncertain
3. Hybrid Detectors (e.g. Auger)

**ENERGY CALIBRATION** of size parameter measured by surface detectors is made with fluorescence detectors on carefully selected sample of events:

- long tracks in atmosphere: > 350 g cm\(^{-2}\)
- Cherenkov light contamination: < 10%  
  (Auger criteria)

**HIGH STATISTICS** from surface array

**APERTURE:** well-defined
Ratio of total energy to electromagnetic energy for fluorescence detector

$E_{\text{tot}}/E_{\text{cal}}$

$\log_{10} E_{\text{tot}}$ (eV)

Pierog et al. ICRC 2005
The HiRes group have yet to release a stereo spectrum. It will have hour-by-hour atmospheric corrections using monitoring data. Should also help to resolve the aperture uncertainties - at least at small distances.

Choice of data used in the fit is entirely subjective and no propagation of E errors into y-direction.

\[
\chi^2/DOF=34.7/34
\]
\[
\gamma=-3.25(3)
\]
\[
\log_{10}E=18.46(3)
\]
\[
\gamma=-2.88(3)
\]
\[
\log_{10}E=19.75(5)
\]
\[
\gamma=-5.1(6)
\]

\[
\chi^2/DOF=63.3/NA
\]
\[
N_{exp}=42.8
\]
\[
N_{obs}=15
\]
\[
P(15,42.8)=8.9 \times 10^{-7}
\]
Auger Energy Determination: Step 1

The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

The detector signal at 1000 m from the shower core

- called the ground parameter or S(1000)

- is determined for each surface detector event using the lateral density function.

S(1000) is proportional to the primary energy.

Zenith angle ~ 48°
Energy ~ 70EeV
Auger Energy Determination: step 2

Hybrid Events with STRICT event selection:
- aerosol content measured
- track length > 350 g cm\(^{-2}\)
- Cherenkov contamination <10%
Spectrum measured with Auger Observatory

The function is

\[ F = (30.9 \pm 1.7) \times \left( \frac{E}{\text{EeV}} \right)^{-1.84 \pm 0.03} \]

with \( \chi^2 = 2.4 \) per degree of freedom

Issues of aperture, mass and hadronic interactions under control – systematic uncertainties being assessed

\[ S(1000) \]

Fluorescence Yield

Absolute FD calibration

\[ S(1000) \text{ to energy} \] – and limited statistics
Percentage Deviation from the Power-Law Fit

\[
\frac{100}{F} \times \left( \frac{dI}{d \ln(E)} - F \right)
\]
Summary Spectrum above 2 EeV

- Auger (3525)
- AGASA (7000)
- HiRes I (1616)
- Yakutsk (1303)
Deviations of data from $E^{-3}$ line through first point of Auger data.
HiRes stereo events > 10 EeV plus AGASA events above 40 EeV

Candidate Cluster

\[ \alpha = 169.0 \quad \delta = 56.2 \]

NB: Previously, Finley and Westerhoff had shown previously that AGASA clustering was statistically unconvincing

- Clustering is very far from being established

Analysis uses likelihood ratio method:

\[ p = 43\% \text{ for } 271 \text{ HiRes and } 47 \text{ AGASA events} \]

HiRes does see correlations with BL Lacs:
Veron 11th Catalogue:
178 objects with magnitude < 18

Claim: excess number of BL Lacs seen near HiRes events > $10^{10}$ GeV, consistent with the HiRes angular resolution ~ 0.6º

GOOD ANGULAR RESOLUTION
see 11 pairs < 0.8º and expect ~ 3,
⇒ probability ~ $5 \times 10^{-4}$

But these BL Lacs are hundreds of Mpc distant!

Few % of primaries must be neutral @ $10^{10}$ GeV!!
### Summary of BL Lac Searches

<table>
<thead>
<tr>
<th>Source Sample (# Obj.)</th>
<th>All Energies</th>
<th>$E &gt; 10^{10}$ EeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>“BL” (157)</td>
<td>$2 \times 10^{-4}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>“BL”+“HP” (204)</td>
<td>$5 \times 10^{-4}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>TeV Blazars (6)</td>
<td>$10^{-3}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 2. Combined HiRes — BL Lac Correlations: Fraction $\mathcal{F}$ of simulated HiRes sets with stronger correlation signal. All samples include the $m_i < 18$ cut. The samples overlap and are *not* independent.

Group is awaiting independent data set recorded post January 2004 up to closure in March 2006 before making any claims. They have concerns about ‘over tuning’.
Auger Observations show NO concentration of events along
Galactic or Super-Galactic Plane

A: 1 – 5 EeV:
Galactic Plane

B: > 5 EeV:
SGP

C: > 10 EeV:
SGP

A) GP 1 - 5 EeV  (L ± 10°) 5077 / 5083.3
B) SGP > 5 EeV  (L ± 10°) 241 / 232.8
C) SGP > 10 EeV  (L ± 10°) 68 /67.4

(Antoine Letessier-Selvon, ICRC 2005)
If highest energy particles were protons, and there is no anisotropy, exotic origin ideas have to be invoked

- Decay of super-heavy relics from early Universe (or top-down mechanisms)
  - Wimpzillas/Cryptons/Vortons

**Predictions:**
- *dominance of neutrinos and photons*

- New properties of old particles or new particles

- Breakdown of Lorentz Invariance
On-set of LPM effect

$\gamma + B \rightarrow e^+ + e^-$
... the highest energy particles seem NOT to be dominantly photons

(Risse for Auger Collaboration, ICRC 2005) 26% upper limit (95% CL) on cosmic-ray photon fraction
Ideas to explain the Enigma

• Decay of super heavy relics from early Universe (or top down mechanisms)
  \textbf{Wimpzillas/Cryptons/Vortons}
  Few photons: <26\% at $10^{19}$ eV (Auger claim)
  Model predictions have changed

\textbf{Is there need for exotic explanations?}
or is it ‘simple’?

• Are the UHE cosmic rays iron nuclei at source?
• Are magnetic field strengths really well known?
Summary: I

• **Arrival Directions:**
  No convincing evidence for anisotropy
  Possibility of BL Lac associations could
  be clarified in ~ 2 years

• **New Hadronic Interaction Model:**
  suggests that there could be a heavier mass > 10 EeV
  than has been supposed by many in the past

  **Heavier mass** would ease acceleration, isotropy
  and spectrum issues

  **BUT – Nature may have surprises to show at the LHC**
Energy Spectrum:

**Auger**: ~ 5 to 7 X AGASA by 2007
Spectrum that is largely mass and model independent

AGASA/HiRes/Auger differences could – possibly – be understood through combination of improved understanding of HiRes aperture (composition/spectrum/hadronic model and stereo data) AND different models and mass assumptions by AGASA

ALL GROUPS HAVE REPORTED EVENTS ABOVE 100 EeV

**QUESTION**: WHAT IS THE DETAILED SHAPE OF THE SPECTRUM?
Thanks to all of my Auger colleagues

Czech Republic       Argentina
France               Australia
Germany              Brasil
Italy                Bolivia*
Netherlands          Mexico
Poland               USA
Slovenia             Vietnam*
Spain                
United Kingdom       

~250 PhD scientists from 63 Institutions and 15 countries

*Associate Countries
Electromagnetic Acceleration

- **Synchrotron Acceleration**
  \[ E_{\text{max}} = Z e B R \beta c \]

- **Single Shot Acceleration**
  \[ E_{\text{max}} = Z e B R \beta c \]

- **Diffusive Shock Acceleration**
  \[ E_{\text{max}} = k Z e B R \beta c, \text{ with } k < 1 \]

Shocks in AGNs, near Black Holes……
Magnetars?  
GRBs?

Hillas 1984
ARA&A
B vs R
Some properties of 20 highest energy events:

- Curvature
- Core Distance (m)
- Fall-off of signal size with distance from axis
- Slope of LDF ($\beta$)
- Thickness of shower disc

Showers of 30 EeV are just like showers at 1 EeV – but bigger.
Resolution of Core Position

Hybrid – SD only core position

Hybrid Data

Laser Data

-500 < distance to axis [m] < 500

Laser position – Hybrid and FD only (m)
rms spread ~ 570 m for monocular fit

Core position resolution:
Hybrid: < 60 m
Surface array: < 200 m
Angular Resolution

Surface array Angular resolution (68% CL)
- <2.2° for 3 station events (E< 3EeV, θ < 60°)
- < 1.7° for 4 station events (3<E<10 EeV)
- < 1.4° for 5 or more station events (E>10 EeV)

Hybrid Angular resolution (68% CL)
- 0.6 degrees (mean)

Entries 168
- Monocular
  - Mean 0.5°
  - RMS 1.0°
- Hybrid
  - Mean -0.02°
  - RMS 0.18°

Entries 269
- σ(ψ) ~ 1.24°

4 stations - θ ∈ (30, 50)

Angle in laser beam /FD detector plane

Hybrid-SD only space angle difference

Resolution using a centrally positioned laser

Hybrid Data
Sensitivity of HiRes II aperture to shower model

More statistics needed and updated model needs to be used.

Mass assumption has only been explored at ± 5% of an assumed proton fraction

Arrival Direction Studies

AGASA ANISOTROPIES ON 20° SCALES \( (10^{18} - 10^{18.4} \text{ eV}) \)

\[
\frac{\text{observed}}{\text{expected}} = \frac{506}{413.6} \quad (+4.5\sigma)
\]

at \( (\delta, \alpha) = (-15,280) \)

(22% excess)

SUGAR galactic center search \( (10^{17.9} - 10^{18.5} \text{ eV} \) )

\[
\frac{\text{observed}}{\text{expected}} = \frac{21.8}{11.8} \quad (+2.9\sigma)
\]

(85% excess)

5.5° cone around \( (\delta, \alpha) = (-22,274) \)
In numbers:

**AGASA**

Original Cuts (1.0 – 2.5 EeV)

- top hat 20°: 1155 / 1160.7, ratio = 1.00 ± 0.03

(22% excess would give 1415 and a 7.5 σ excess)

Enlarge energy range (0.8 – 3.2 EeV)

- top hat 20°: 1896 / 1853.06

**SUGAR (0.8 – 3.2 EeV)**

- top hat 5°: 144 / 150.9, ratio = 0.95 ± 0.08

(85% excess would give 279 and a 10.5 σ excess)

Also looked for as a point source, no signal.
Galactic center search (point source)

SD only:
Gaussian filtering 1.5 degree
exp/obs 24.3/23.9
if $\phi_S \propto \phi_{CR}$ then for $0.8 \text{ EeV} < E < 3.2 \text{ EeV}$:

$\phi_S < 2.5 \xi \varepsilon \times 10^{-15} \text{ m}^{-2} \text{ s}^{-1} @ 95 \%$
• Fit to power law.
• Single index gives poor $\chi^2$.
• Evidence for changing index.

Springer et al. ICRC 2005
Association with BL Lacs?

Initial claims by Tinyakov et al. – but disputed by Evans et al and others

217 HiRes Stereo events above 10 EeV

$\sigma = 0.4 \text{ deg}$, so that 68% of events would lie within $\theta = 1.52 \sigma$

This is an impressive angular accuracy

Tinyakov et al. conclusion for $m<18$ confirmed – but same data set of events and same 157 BL Lacs

BUT for $E> 40$ EeV, HiRes shows a deficit in the correlation

Presumably primaries are neutral because of anticipated magnetic field deflections – worth looking at lower energies.
Hybrid events are equivalent to stereo-events and superior to monocular events.

Observations with real showers confirm the results from Central Laser Facility.
10% reduction in predicted muon number leads to ~ x 2 increase in the average mass – depending on model details
Original Claim (2003):

“Consistent with proton dominant component” — must be revised

Muon measurements with the AGASA array
Stereo-Hybrid Event

$\sim 4 \times 10^{19}$ eV
Surface Array
1600 detector stations
1.5 km spacing
3000 km²

Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total
HiRes I and HiRes II
Geometrical Reconstruction