New Results on the Highest Energy Cosmic Rays

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6. Summary ...
1. Background ... highest energy cosmic rays

![Schematic of extensive air shower cascade](image)

- **Energy scale:** $10^{20}$ eV $\approx$ 16 Joules ... **well** above future collider energies.

  1. cosmic rays are *observed* via the extensive air shower produced when they reach the earth’s atmosphere
  2. 16Joules/$\sim$ 16$\mu$sec (typical shower time) $\approx$ 1 MW!
1. Background (con’t) ...

Schematic of air shower measurements

- **Measurement of $10^{20}$eV air showers:**
  1. km’s *wide* at ground level ... sparse sampling OK!
  2. Composition of *primary* cosmic rays from depth of shower maximum, $X_{\text{max}}$, and/or from $\mu/e$ ratio.
  3. $\sim 50$ppm of shower energy is re-emitted as nitrogen *fluorescence* light (290 $\sim$ 440nm) ... thus a 1-MW shower appears as a 50W relativistic *light bulb*!
1. Background (con’t) ...

Cosmic ray energy spectrum

- **Rate:** - low (~ 1/km²/century) ... so need large experiments ... about the area of Rhode Island! Fluorescence based experiments need dry (desert) air with good visibility.
1. Background (con’t) ...

Cosmic ray flux scaled by $E^3$

- **Structure in a power law spectrum:**
  1. *knee* at $\sim 4 \times 10^{15}$eV
  2. second *knee* at $\sim 4 \times 10^{17}$eV
  3. *ankle* $\sim 4 \times 10^{18}$eV
  4. *cutoff* at $\sim 10^{20}$eV ... or not!
1. Background (con’t) ...

(One) possible source of $10^{20}$ eV cosmic rays

- Why (... just a couple of reasons):
  1. At these energies extra-galactic cosmic rays probably dominate local (galactic) sources.
  2. At the same time the GZK cutoff predicts an end to the cosmic ray spectrum ... except for nearby ($< 50$Mpc) sources
1. Background (con’t) ...

Energy loss attenuation length, $\Lambda_{\text{atten}}(z = 0)$

- Greisen-Zatsepin-Kuz’min (GZK) cutoff:
  1. Cosmic rays interact with the cosmic micro-wave background (CMB) radiation; after a distance, $d$:
     \[ E = E_0 \cdot e^{-d/\Lambda_{\text{atten}}} \]
  2. Steep drop of $\Lambda_{\text{atten}}$ near $10^{20}\text{eV}$ from the onset of $\pi$ photo-production: $\gamma_{\text{CMB}} \ p \rightarrow \pi \ X$. 
1. Background (con’t) ...

![Proton energy spectrum versus source red-shift, z](image)

- **GZK simulation** (*proton primary*):
  1. (Assumed) source spectrum: \( \text{Flux}(E) \propto E^{-2} \)
  2. *Observed* spectrum scaled by \( E^3 \) ...
  3. Only sources with red-shift \( z \leq 0.03 \) (about 150Mpc) should have any flux above \( \sim 10^{20}\text{eV} \).
2. Status ... highest energy cosmic rays

**AGASA detector layout**

- **Experiments probing $10^{20}$eV cosmic rays:**
  1. **Haverah Park**, UK, 12km$^2$ ground array area
  2. **AGASA**, Japan, 100km$^2$ ground array area
  3. **HiRes**, Utah, $\sim 300$km$^2$ (equivalent)
  4. Pierre Auger, Argentina, 3000km$^2$ (building)
2. Status (con’t) ...

AGASA spectrum above $10^{18}\text{eV}$

- **AGASA flux *versus* energy:**
  1. (Published) experiment with the largest *exposure*
  2. *GZK* model: uniform distribution of extra-galactic sources, proton primary, source flux $J(E) \propto E^{-2}$, plus detector resolution
  3. Two events well above $10^{20}\text{eV}$!
  4. Number of events above $10^{20}\text{eV}$ *inconsistent with the curve*!
2. Status (con’t)...

(Preliminary) HiRes spectrum above $10^{17}$ eV

- (Preliminary) HiRes flux *versus* energy:
  1. Similar data *exposure* to AGASA
  2. Fewer (2 *versus* 10) events above $10^{20}$ eV!
  3. One event well above $10^{20}$ eV!
2. Status (con’t) ...

AGASA arrival directions above $4 \times 10^{19}\text{eV}$

- AGASA arrival directions:
  1. Primary cosmic ray direction measured to $\sim 1^\circ$
  2. red squares (events $> 10^{20}\text{eV}$) and green dots ($4 - 10 \times 10^{19}\text{eV}$) are consistent with large-scale source uniformity
  3. Six $2.5^\circ$ clusters of events: 5 doublets and 1 triplet
  4. Two of the clusters lie in the super-galactic plane (blue line)
Simulated proton trajectories: $10^{18}, 10^{19}$ and $10^{20}$eV in $2\mu$G fields ... $\geq 4 \times 10^{19}$eV protons are deviated little by local (galactic) magnetic fields.
2. Status (con’t) ...

Cosmic ray composition

- **Average depth of shower maximum** ($X_{max}$) **is sensitive to primary cosmic ray composition**:
  1. *light* (p,He) dominate near $3 \times 10^{15}$eV
  2. *intermediate* (C,N,O) to *heavy* (Si,Fe) dominate near $10^{17}$eV!
  3. *light* appear to dominate at the highest energies!
3. New results ... highest energy cosmic rays

Comparison of latest spectra

- Possible differences in energy scales:
  1. (Preliminary) HiRes data are consistent with the earlier Fly’s Eye experiment
  2. Re-analyzed Haverah Park data [not shown] are consistent with HiRes.
  3. AGASA data lie higher ... consistent with relative energy scale differences of 20 ~ 30%
3. New results (con’t) ...

Unfolding of cosmic ray spectra near the knee
Note: horizontal-axis units are GeV where 1 GeV = 10⁹eV

- **KASKADE results ... astro-ph/0201109:**
  1. **Confirm** Casa-Blanca result: composition is light (p,He) near 3 × 10¹⁵eV (3 × 10⁶GeV) changing to intermediate near 3 × 10¹⁶eV (3 × 10⁷GeV).
  2. **Extends** previous studies to show that intermediate (C,N,O) to heavy (Si,Fe) dominate near 10¹⁷eV!
  3. **Data are consistent with rigidity-dependent breaks in flux for different element groups.**
3. New results (con’t) ...

![Graph showing cosmic ray composition](image)

- Cosmic ray *composition* including new results

- **Average depth of shower maximum** ($X_{\text{max}}$) is sensitive to primary cosmic ray *composition*:
  2. *orange* - Haverah Park (re-analyzed): astro-ph/0203150, consistent with *mixed* composition [34%-light (p), 66%-heavy (Fe)]
3. New results (con’t) ...

Simulations evolve to describe the data better ...
Note: horizontal-axis units are GeV where 1 GeV = 10^9 eV

- **Simulations are needed to link e.g. depth of shower maximum (X_{max}) with composition:**
  1. Two Monte Carlo (hadronic interaction) models (QGSJet and SIBYLL) are used to interpret the data; e.g. D. Heck et al astro-ph/0103073; J. Alvarez-Muniz et al astro-ph/0205302
  2. (Systematic) uncertainties remain ...
4. Emerging model ... highest energy cosmic rays

![Graph showing the energy spectrum of cosmic rays]

Conceptual model for cosmic ray flux ...

- **Consider a 2-component model:**
  1. KASKADE data consistent with *one* component for CR-I and CR-II (*e.g.* galactic super-novas ... )
  2. **Spectrum steepening**, at 1\textsuperscript{st} and 2\textsuperscript{nd} knee, from acceleration or lifetime/retention limitations
  3. **Spectrum flattening**, at the ankle, consistent with a new (2\textsuperscript{nd}) component
4. Emerging model (con’t) ...

Theoretical model for cosmic ray flux ...

Note: horizontal-axis units are GeV where 1 GeV = 10^9 eV

1. Slope breaks at the 1<sup>st</sup> and 2<sup>nd</sup> knee follow constant rigidity physics observed by KASKADE ... i.e. energy features scale in atomic charge: \( E_{Fe} \equiv 26 \times E_p \).

2. 2<sup>nd</sup> break, \( E_p \approx 4 \times 10^{17} \text{eV} \), proton Larmor-radius:
   \[
   \left( \frac{R_p}{1 \text{kpc}} \right) \approx \left( \frac{E_p}{10^{18} \text{eV}} \right) \cdot \left( \frac{1 \mu \text{G}}{B} \right) \approx \text{galaxy thickness.}
   \]
4. Emerging model (con’t) ... *Simple* summary

Cosmic ray (> $4 \times 10^{19}$ eV) arrival directions ...

1. 1*st* component: broad *composition* light (p,He) to heavy (Si,Fe,..); may extend to energies $\sim 10^{19}$ eV

2. 2*nd* component: lighter (significant proton) composition; possibly measurable implications to below $10^{18}$ eV

3. **Primary motivations for the 2*nd* component**: flattening of the flux above the ankle ($\sim 4 \times 10^{18}$ eV) and a change to lower mass composition at the highest cosmic ray energies: above $\sim 10^{18}$ eV

4. The primary motivation for identifying the 2*nd* component as extra-galactic is the *isotropy of the highest energy cosmic rays* (strengthened if *light* (p,He))
4. Emerging model (con’t) ... EXTRA-galactic(I)

![Graph showing log_{10} E vs log_{10} E, eV]

**Theoretical model for EXTRA-GALACTIC flux ...**

V. Berezinsky et al, astro-ph/0204357

1. Several *conventional* astro-physical models studied: uniform sources, local *over-dense* sources, with GRB or AGN constraints

2. Figure shows “local *over-dense*” case: over-dense region size, \( R_{overdense} = 30\text{Mpc} \), and 4 over-densities: \( n/n_0 = 1, 2, 10, 30 \) for curves 1 - 4

3. Actual \( n/n_0 \approx 2 \), thus **cannot describe the highest energy events**; models well to \( \leq 10^{18}\text{eV} \)!
4. Emerging model (con’t) ... EXTRA-galactic(II)

Theoretical model for EXTRA-GALACTIC flux ...
G. Sigl et al, astro-ph/9806283

1. Model assumes local (~ 10Mpc Virgo cluster) source with turbulent, super-galactic magnetic fields (~ 0.1µG) ... sensitive to field parameters!

2. Figure shows case with source at 10Mpc, $B_{rms} = 0.1\mu G$, proton (injection) spectrum $\propto E^{-2.4}$

3. Model describes the (AGASA, Fly’s Eye and Haverah Park) data above $10^{19}$eV ... but single source, tuning of source distance and field parameters!
4. Emerging model (con’t) ...

**HiRes stereo event with** $E \approx 2.5 \times 10^{20}$ eV

- **We can’t resolve the** $10^{20}$ eV **puzzle today!**

  1. AGASA, Fly’s Eye and HiRes observe (a few) events well above $10^{20}$ eV
  2. What is the detailed shape of the spectrum?
  3. What is the *composition*?
  4. What are the arrival directions (and clustering)?
5. Next step ... highest energy cosmic rays

Pierre Auger (south) experiment ... Malargüe, Argentina

- **Biased opinion** ... high quality (hybrid) data are needed from $< 10^{18}\text{eV}$ ($10^{17}\text{eV}$?) to a few $\times 10^{20}\text{eV}$:
  
  1. need to link with galactic source(s) measurements
  2. need to remove (reduce) the model dependence of the significance of the *big* events $> 10^{20}\text{eV}$
  3. need to tune the Monte Carlo (hadronic interaction) models
5. Next step (con’t) ...

Detection method

Pierre Auger hybrid detection ...

1. Hybrid detection: simultaneous measurement of the air shower by a ground array and by fluorescence telescopes

2. Hybrid events cross-check and cross-calibrate the two types of detectors and provide the best composition measurement

3. Ground array (only) events provide most statistics (i.e. highest energy events)
5. Next step (con’t) ...

Typical Pierre Auger ground array detector ...
10m², 1.2m deep, water cherenkov detector
Solar powered, radio communication to central trigger
Site environment very similar to Albuquerque ...

1. > 30 of 1600 ground array detectors installed and running (initial *engineering array* test)
2. ~ 100 ground array detectors and 12 of 24 fluorescence telescopes scheduled to be operational by spring 2003
5. Next step (con’t) ...

Biggest Pierre Auger hybrid event ... \( \sim 3 \times 10^{19} \text{eV} \)

\( \sim 70 \) hybrid events observed during recent 5-month run

1. Event triggered 11 ground array detectors
2. Event was observed (simultaneously) by 1 fluorescence telescope
3. Hybrid events are already helping to tune both detector subsystems.
5. Next step (con’t) ... some “perspective”!

John Linsley ... a little NW of the Abq. convention center

- **February 1962:** 1\(^{st}\) \(10^{20}\)eV event (Volcano Ranch)
  1. Event triggered 14 ground array detectors
  2. Event was about as un-expected then as it would be today!
6. Summary ... highest energy cosmic rays

- Cosmic rays are observed by three experiments: AGASA, Fly’s Eye and HiRes to energies above $10^{20}$eV.

- AGASA energy scale may be $20 \sim 30\%$ higher than Fly’s Eye, Haverah Park and HiRes. **IF AGASA energies scaled down then fewer events $> 10^{20}$eV but biggest events remain.**

- Sources of the events above the cosmic microwave background **GZK cutoff “must”** be (relatively) nearby ... but are still unknown!

- New data are consistent with light (p,He) primaries at the highest energies. Hadronic interaction uncertainties weaken this conclusion.

- Arrival directions of events $> 4 \times 10^{19}$eV are isotropic supporting the extra-galactic source of these cosmic rays. AGASA clusters interesting ... but could be a statistical fluctuation.

- New data increase the support for (predominantly) 2-component model of cosmic rays above $10^{15}$eV. However limited data, particularly at the highest energies, often provide little constraint to theoretical models.