The trouble with UHECRs

Seeming contradictions have interesting Implications...

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With special thanks to J. Allen, A. Berlind, R. Jansson, C. Lage, I. Zaw and members of the Pierre Auger Collaboration.
Contradictions?

- Experimental?  Interpretational?

- Consider:
  - Composition
  - Correlations

- HiRes versus Auger

- “Auger versus Auger” – Is there any consistent interpretation of all the data?
Can both HiRes and Auger be right about composition?

Yes!....
Both see the “Auger break”

- X-max distributions have same shapes:
  - become consistent, when shift HiRes by -0.1 in log E, and systematic shift in Xmax.
  - => break and flattening in Elongation Rate from (astro)physics
But could HiRes and Auger be seeing different compositions?

* In principle yes, because see different sky:
  * Intermediate mass nuclei ⇔ nearby source
  * Distant sources only ⇒ bimodal composition (heavy & light)
* Only Auger sees Cen A (4 Mpc)
* Nearest obvious source for HR is Virgo (20 Mpc)
* But doesn’t fit other evidence...
Most straightforward interpretation of $X_{\text{max}}$ data:

- Both HiRes and Auger see the “Auger break”

$\Rightarrow$ either

1) Composition is becoming heavier at higher energy
2) Or, particle physics is changing at higher energy…
3) (or both!)

- Correlation data favors 2)
## Correlations

<table>
<thead>
<tr>
<th></th>
<th>AGASA*</th>
<th>HiRes</th>
<th>Auger</th>
</tr>
</thead>
<tbody>
<tr>
<td>multiplets</td>
<td>yes</td>
<td>no</td>
<td>some</td>
</tr>
<tr>
<td>BL-Lacs</td>
<td>no</td>
<td>yes</td>
<td>[no]@</td>
</tr>
<tr>
<td>AGNs</td>
<td>....</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Ursa Major Cluster</td>
<td>3</td>
<td>2</td>
<td>can't see</td>
</tr>
<tr>
<td>Large Scale Structure</td>
<td>??</td>
<td>??</td>
<td>yes</td>
</tr>
</tbody>
</table>

Need more data to clarify correlations
COSMIC VARIANCE in SCAN METHOD is large (GRF et al in prep)

*AGASA angular resolution much worse than HiRes or Auger => AGASA correlation studies are less sensitive
@ Auger angular resolution insufficient to exclude BL-Lac correlation with photon-like events, at the HiRes level.
Ursa Major Cluster

* 4 events in AGASA + HiRes (94 total)
  Same position within < 1°,
  Chance probability: $2 \times 10^{-3}$
  Not in Auger field of view!

* SDSS => foreground empty!
  Extragalactic magnetic deflection low
  “confusion” problem reduced
  $\text{GRF, Berlind, Hogg 06}$

* Galactic magnetic deflection

  $\Delta \theta \sim 1° \frac{Z}{E_{100}}$

  Evidence for proton composition
Time development of CRs from bursting source, with GZK

GRF 07 & in prep

**Spectrum** (E^{-2} at source)

**Arrival Directions**

<table>
<thead>
<tr>
<th>Time (kyr)</th>
<th>CR Energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=0-3</td>
<td>38, 53, 55, 77 EeV</td>
</tr>
<tr>
<td>T=30-31</td>
<td>+ 1 event in HiRes</td>
</tr>
<tr>
<td>T=60-61</td>
<td>&lt; 30 EeV</td>
</tr>
<tr>
<td>T=90-91</td>
<td></td>
</tr>
</tbody>
</table>

**UM CR Energies:**
- E_{UHECR} \approx 10^{49} \text{ erg } (D_{200})^3 f_{GZK}
- Too low for GRB

UM Cluster FAVORS BURSTING SOURCE, but not so powerful as GRB

7/11/09
UHECR correlation with Large Scale Structure

- X-correlate with nearby galaxies
- Traditional method in cosmology
- Application to published UHECRs: A. Berlind + GRF ICRC09 & in prep (presented here)
- Application to Auger data: presented by C. Lage for the Auger Collaboration, Washington APS Feb, 2010
Significance = Fraction of 10,000 mock datasets where $\chi^2 >$ real dataset.

Cross-correlation between 2MRS and Real Data $\Rightarrow \sum \chi^2$ for fit to zero correlation, out to some $\Theta_{\text{max}}$

Do the same for each mock data set $\Rightarrow$ 1-sigma range
Impact of galaxy sample depth and angular separation

- Broad minimum with respect to Galaxy depth
- Relatively insensitive to $\Theta_{\text{max}}$
Conclusions from UHECR-galaxy cross-correlation (A. Berlind & GRF using published events)

- UHECR arrival directions are inconsistent with an isotropic distribution at the 3σ level, and appear correlated with locations of nearby galaxies.

- Strongest correlations are seen at UHECR energies of \( E > 55 \) EeV, and galaxy depths \( D \leq 70 \) Mpc.

- The observations are consistent with external galaxies as the source of UHECRs, moderate deflections and the GZK model.

- See C. Lage, for the Auger Collaboration, Washington APS, Feb. 2010 for results with full dataset.
Cen A & Galactic deflections
R. Jansson, GRF, I. Feain & B. Gaenssler, in prep
Fit Galactic magnetic field
R. Jansson, GRF, Waelkens, Ensslin 09

WMAP5 22.8 GHz, Q&U + RMs

Figure 2. Polarized synchrotron intensity (color), overlaid with a texture showing the magnetic field directions (i.e., the observed polarization angle rotated by 90°). Image created using the line integral convolution code, ALICE, written by Dan Larson.
Dedicated Cen A study of GMF

RJ, GRF, I Feain, B Gaensler in prep

* 166 new RM$s$ surrounding lobes (Feain & Gaensler)
* New GMF model (RJ+GF) adding
  * Random and striated fields
  * Out-of-plane component
* Gives MUCH BETTER fit to Q,U & RM$s$
  * Global fit, with halo and disk

Reduced $\chi^2$ for various models
Interpretation of Cen A excess requires good GMF model!

27 Auger events with $18^\circ$ circle @ CenA

Deflection depends on GMF

Need global GMF fit to constrain CenA deflections

$B_\perp$ and $B_\parallel$
5 of 27 published Auger CRs are most likely protons from Cen A

- Define Cen A locus
- Contains 5 events
- Fraction of Auger exp in locus = 0.009
- 27 events => expect 0.25
- Probability to find \( \geq 5 \) by chance = \( 7 \times 10^{-6} \)
- No scan penalty… what “idea penalty”???

\[
 f_{\text{CenA}} = 0.18^{+0.07}_{-0.08}
\]
Implication of Correlations

- Protons are a major component of UHECRs even above 50 EeV
- Reconciliation with Auger-HiRes “X-max break”
  - Requires $\sigma_{\text{tot}}$ increases faster with E than in models, hint of some break or acceleration
- But, need to get consistency also with ground signal!
Simulated versus observed ground signal, with proton composition

- Robust evidence that observed SD signal is too strong compared to model predictions
  - The “excess-muon problem”
  - Seen using many approaches, in both SD and Hybrid datasets
  - More info in next talk by M. Unger

- Present models have factor-2 deficiency with protons
  - Fe only increases muons by ~ 1/3, so
  - Factor-1.7 deficiency with Fe

- Hadronic models matter (Ulrich et al 0906.0418)
How can the “muon excess” be explained?

- Problem severe -- not solved by heavy composition
- Jeff Allen & GRF campaign to explore options:
  - Use QGSJet-2, Sybill, and EPOS
  - Vary total cross section, multiplicity distribution, photon fraction
  - “Accept” combos giving observed X-max distribution and strength and zenith average LDF
  - Are Golden Hybrid events well-described?
The Axe (1) -- Multiplicity

- Method: selective choose events generated by QII
- Make a multiplicity cut, only keep a fraction, $\kappa$, that fall below cut
  - Cut at the 90% threshold to see maximum effect possible
  - Cut is energy dependent
- Maximum effect of the “axe”
  - 10% reduction of EM signal
  - 25% increase in number of muons
  - Right direction, need more muons
The axe (2) -- $\pi^0$ Conversion

- Convert $\pi^0$'s of QII events into baryons
- $f$ is fraction of $\pi^0$ to convert at 10 EeV, with logarithmic $E$ dependence
- Maximum effect:
  - 10% increase in EM signal
  - 60% increase in muonic signal
  - Still need more muons
$\pi^0$-Multiplicity Combination

- Multiplicity cut
  - 90% threshold
  - $K = 0.0$
- $\pi^0 \mod f = 100$
- Maximum effect
  - No change in EM
  - 80% increase in muons
  - 8% reduction in LP
  - $<X_{\text{Max}}>$ dramatically reduced
- Still not enough muons!
- Still too much EM ground signal!
- Getting a doubling of number of muons is non-trivial
Drastic increase in multiplicity improves LDF muon signal

Drastic conversion of pi-0’s to other hadrons improves LDF

VERY hard to get observed muon and EM signals

Modification of total cross section fixes X-max distribution but doesn’t impact muon problem

Evidence of new physics?
Conclusions (very personal)

- UHECRs are perplexing, but not daunting.

- Present evidence favors predominantly proton composition, and drastic modifications to final states of hadronic collisions at energies $>\text{EeV}$.

- Promising directions:
  - bursting sources -- produce correlations with large scale structure but not individual source classes.
  - Improve GMF modeling for better-constrained reconstructions; use more sophisticated reconstruction methods.
  - Improve astro source catalogs; start combining HiRes/TA and Auger data for all-sky correlation studies.