Ultra High Energy Cosmic Rays in the North Some results from the High Resolution

Fly's Eye (HiRes) Experiment

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University of Utah Cosmic Ray Pioneer Gene Loh Dies at 72

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He Oversaw Contruction, Operation of Famed Fly's Eye Cosmic Ray Observatory

May 24, 2006 – Eugene Loh, University of Utah distinguished professor emeritus of physics, has died of kidney cancer at age 72 after a career in which he pioneered the university's world-renowned effort to determine the mysterious source of ultrahigh-energy cosmic rays, the most energetic particles in the universe.



UHECR Subjects:

- Spectrum
- Chemical Composition
- Anisotropy
- proton-air Cross-section
- Neutrinos / Exotics



HiRes

 HiRes is located on the U.S. Army's Dugway Proving Ground, ~2 hours SW of The University of Utah

 The two fluorescence detector sites are located 12.6 km apart at Little Granite Mountain and Camel's Back Ridge







Typical HiRes Event



~2×10¹⁹ eV event seen in 1999 (3× vertical scale)







Measured Shower Profile





Measured shower parameters.

/S

Event by event:

- X_{max} in g/cm²;
- Total energy of the primary particle:
- Arrival direction

Statistically:

- Mass composition
- *p*-air inelastic cross-section

Data vs MC(proton): Rp Distribution



Photoelectrons per degree of track



Physics with HiRes Data

- HiRes-1 monocular data began ~3 years earlier: largest statistics,
- HiRes-2 monocular: can reach down to as low as 10^{17.2}eV,
- Stereo data: best resolution, optimized for E>3×10¹⁸eV







5σ Observation of the GZK Suppression

Broken Power Law Fits

- No Break Point
 - χ²/DOF = 162/39
- □ One BP
 - χ^2 /DOF = 68.2/37
 - BP = 18.63
- Two BP's
 - χ^2 /DOF = 34.7/35
 - 1st BP = 18.63
 - 2nd BP = 19.75
- □ Two BP with Extension
 - Expect 51.1 events
 - Observe 15 events
 - Poisson probability: P(15;51.1) = 3x10⁻⁹ (5.8σ)
- Independent statistics:
 P(14;44.9)=7x10⁻⁸ (5.2σ)





Confidence Building Tests:

- Geometry/Energy Reconstruction
- Atmosphere
- Aperture
- High Energy Aperture



Mono versus Stereo Energy Measurements



The HiRes monocular energy is in excellent agreement with stereoscopic measurements !



ATM and the Aperture



Ratio of Apertures:

numerator: MC w/ATM database Reconstruction w/ database <u>denominator:</u> MC gen w/database Reconstruction using Average ATM



Aperture Check



HiRes-2 Data:

Artificially cut the data so that you are certain of the aperture.

Cut data with an impact parameter > 15 km

>10 km

Excellent agreement! Confidence in aperture calculation





Preliminary Stereo Spectrum

- Fit to power law.
- Single index gives poor χ²
- Evidence for changing index near ~10^{19.8} eV











HiRes and Other Experiments



Composition: X_{max} Distribution Width Predictions





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Composition: All-Energy X_{max} Distribution



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Stereo HiRes Elongation Rate



Width is constant from ~10¹⁸ eV up

<u>Width</u> and <u>Xmax</u> (elongation) imply constant composition in this energy range

- QGSjet (1) prefers 80% "protons"

- Sybil prefers 60%

Application of radio-sonde data will move the HiRes X_{max} up ~10 gm/cm² on average, thus lighter

Model-independent break in slope at about 10¹⁸ eV.

Heavy (galactic) nuclei decrease, give way to light (extragalactic) composition. Galactic/extragalactic transition is complete by about 10¹⁸ eV.



Astrophysical Journal 622 (2005) 9th 9.926 challenges Hanoi

Additional Data - Thru May 2005

- Previous result runs out of statistics near 30 EeV
- Analyze "golden events" above 8 EeV to increase statistical reach
- "golden events" are events where Xmax is clearly observed by HR 2 as determined by manual scan
- 80% of data above 10 EeV falls into this category
- Scan bias is believed to be small





 Open circles: previous HiRes publication

 Filled circles: new HiRes "golden events"

Fitting tail of X_{max} Distribution & Deconvoluting



 1348 out of 3346 stereo events pass the quality cuts (data:12/1999-3/2003)



HiRes Measurement



■ **HiRes:** $\sigma_{in}^{p-Air} = 456 \pm 17 (stat) + 39 (sys) - 11 (sys) mb$ at $10^{18.5} eV$

"Solid link between cosmic ray and accelerator measurements for the very first time!" – M.Block.



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Hot Sources?

- Performed an autocorrelation study using HiRes Stereo data with excellent (~0.6 deg. resolution.... Consistent with isotropy at all angular scales...
- However....
- There are six widely discussed "clusters" containing 13 events in the AGASA data
- Assume that these represent the six brightest sources in the sky
- Test this hypothesis



Maximum Likelihood Point Source Search

Scan over a fine grid of locations in the sky, treating each as a potential source position, to identify the single spot with highest deviation from null source hypothisis. The significance is determined by scanning over Monte Carlo data sets and counting the fraction with $ln(R_{MC}) > ln(R_{data})$.



No significant point source is found in the combined set of HiRes and AGASA events above **4x10¹⁹ eV**.



Maximum Likelihood Point Source Search

If the HiRes threshold is lowered to 3×10^{19} eV, one more event lands near the triplet. There are now 57 AGASA events and 40 HiRes events.

The fraction of MC sets with higher ln(R) is 0.5%

This result contains some biases:

- the clustered AGASA events which were originally used to *establish* the 4x10¹⁹ eV threshold are still included in the sample
- the HiRes energy threshold has to be *changed* to include an event that contributes to the cluster

These biases imply that 0.5% is a *lower bound* on the chance probability.



Abbasi et al., Astrophys.J. 623 (2005) 164.



Stereo Anisotropy: Good for Point Sources

- Note the effect of the better angular resolution of the HiRes detector. That one point (blue circle) dominates the uncertainty in the potential source location.
- Angular resolution is VERY important to anisotropy
- This "Quartet" could be first point source (Ursa Major).
- Needs confirmation!!





BL Lac Correlation: Previous Claims

Searching for potential correlations with AGASA and Yakutsk events... We tested each claim with HiRes data:

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (9 th Ed.) BL Lacs			22	AGASA >48 EeV Yakutsk >24 EeV	65	2.5°	8	< 10 ⁻⁴
m < 18	z > 0.1 or unknown	S _{6cm} > 0.17 Jy	22	HiRes > 24 EeV	66	2.5 °	0	1.00
Catalog: Veron (10 th Ed.) BL Lacs correlated with EGRET sources			44	AGASA >48 EeV Yakutsk >24 EeV	65	2.9 °	8	10 ⁻⁴
no cut	no cut	no cut	14	HiRes > 24 EeV	66	2.9 °	1	.70
Catalog: Veron (10 th Ed.) BL Lacs			450	AGASA > 40 EeV	57	2.5°	12	.02
m < 18	no cut	no cut	156	HiRes > 40 EeV	27	2.5 °	2	.78

Tinyakov & Tkachev, JETP 74 (2001) 445. Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165. Gorbunov et al., ApJ 577 (2002) L93.

No previous correlations confirmed In HiRes data

BL Lac Correlation: New Correlation

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (10 th Ed.) BL Lacs			450	HiRes > 10 EeV	271	0.8°	10	10 ⁻³
m < 18	no cut	no cut	150	Need to test w				

Gorbunov et al., JETP Lett. 80 (2004) 145.

The fraction of isotropic MC sets with stronger signal: $F = 2 \times 10^{-4}$.

The 0.8° angular bin size was estimated by Gorbunov *et al.* to be optimal for the HiRes angular resolution of 0.6°. **However**, correlations on the scale of the HiRes angular resolution imply that primary must be **neutral** (at least over most of its path). Neutrons and photons have a very short mean path (~ few Mpc) at this energy...

In addition this recent claim is based upon published HiRes data for which limited information was publicly available. It uses a new 10¹⁹ eV threshold and thus it represents a new claim which must itself be tested.

Use current sample to decide *a priori* what will be tested with "new data" collected January 2004 – April 2006. (# events ~70% previous data set)

- TA Phase-1 is a funded experiment (13M\$ equivalent from Japan, US 2.4M\$ start-up recently approved). Construction underway – complete 2007
 - Main ground array of 576 Scintillators
 - 3 Fluorescence Sites
- Located west of Delta, UT.
 ~2.5 hrs South of SLC
- Japan-Korea-PRC-ROC-US Collaboration.

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TN*/MN /13½°

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Telescope Array

- 150/576 Scintillator Detectors (SDs) exist at Delta, more enroute from Japan. Deployment of SDs begins in September, 2006
- BRM Fluorescence Detector: building complete, currently installing the fluorescence detector cameras, test data by September
- LR FD: building complete, begin installation of detectors in October. (Japanese construction complete by April 2007
- MD FD: building construction begins in September, HiRes detectors begin moving from Dugway to Delta in January, 2007. Site Complete June 2007.





Telescope Array

- Telescope Array: The main US contribution is the TA Low-energy Extension. Bring the operational range down to ~10^{16.5} eV
- Add two additional fluorescence sites including a tower of telescopes looking up to 75 deg
- Add an "infill array", SDs with closer spacing
- TALE will also make TA into a fully stereo-hybrid detector





- Recently Approved: US proposal to add HiRes detectors, infill ground array (fluorescence stereo and hybrid down to 3x10¹⁶ eV). The PRC group also recently received funding approval
 - Apertures:
 - \Box High energy aperture: 3000 km² ster(time avg), 3x HiRes
 - □ 10x HiRes stereo aperture at 10^{18} eV.
 - □ 10x HiRes/MIA hybrid aperture, $E < 10^{18}$ eV.
 - \Box Extend E_{min} down to 10^{16.5} eV.
- Measure all three spectral features in one experiment "flat aperture".



Take Home:



- Spectrum clearly shows structure (ankle, GZK suppression) – galactic/extra-galactic cosmic rays
- Xmax AND Width important to measuring composition
- Point Sources/BL Lacs tantalizing need verification
- p-air cross-section connects to accelerator data
- More to come
 - □ HiRes data taking concluded 4 April 2006
 - Analysis will continue for another year or two
- Future: The Telescope Array Project is under construction in central Utah data in 2007!!





HiRes Operations

- Continuous operation of HiRes-1 detector since 1997 with 4 major down periods (7 months off after anthrax episode)
- Has been operating at 10% duty cycle since 2001-2002 shutdown



X_{max} and Energy Resolution– detector MC.



Measuring Cross-Section using cosmic rays. Deconvolution.

Point of first interaction distribution. Exponential index reflects inelastic Cross-section

Atmospheric part of air shower fluctuations

X_{max} distribution





Energy Distribution * E



Ankle clearly observed in raw energy distribution (before aperture correction)



Ratios





10km Aperture





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15 km Aperture





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Mono & Tandem Stereo Spectra





















HiRes Composition Measurement





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Filled triangles, Stereo Fly's Eye result, scaled up by 13 gm/cm2 (average shift above 10 EeV)



