TASI 2008:

Particle Astro, Cosmic Rays, ...

Tom Weiler
Vanderbilt University
Many thanks to Gustavo Medina-Tanco, Luis Anchordoqui, Haim Goldberg, Masahiro Teshima, Etienne Parizot, and anyone else whose slides I have “borrowed”...
The Cosmic Ray Timeline

1912  Hess (Austrian) balloons to 5km, his sparks increase; also sees no change during solar eclipse
1929  Cloud chambers, and the birth of particle physics:
1933  Anderson’s positron; Kunze’s muon (Rostock)
1937  Anderson’s muon
1938  Auger’s remarkable PeV air-shower
1949-54 Fermi’s “Doppler” acceleration via magnetized shocks
1966  3K CMB discovered; GZK predict cutoff at $5 \times 10^{19}$ eV
       (But Linsley already reported (PRL) event at $10^{20}$ eV)
1987  IMB/Kamiokande neutrinos from SN87a
AUGER’s key discovery

Auger, in 1938, separated two particle counters by nearly a km high in the Swiss Alps (Jungfrau, near Bern). He discovered coincident signals.

He calculated $E_{TOT}$ to be about $10^{15}$ eV. His inference was correct.

His energy was $10^7$ times the prior record event, and now thought to be typical of emission from a SN remnant.
1991  Fly’s Eye reports $3 \times 10^{20}$ eV, with proton-like profile;
        Akeno/AGASA Xpt begins
mid-90s  DUMAND taken off life-support; Baikal continues
90s  SuperK neutrinos from the sun (directional astro)
1996  AGASA reports event clustering within 2.5$^0$ ang. res’n
        and: $F(E \geq 10^{20}$ eV) $\sim 1$/km$^2$/century,
        with shower diameter $\sim 5$km, $N(e\pm) \sim 10^{11}$
2000  20 events at and above $10^{20}$ eV
2001  HiRes withdraws 7 events; AGASA adds 6 (from $\theta_z > 45^o$);
        And the **controversy** has begun!
        Importantly, Auger gets first “light”
2002  AMANDA pushes to $10^{14}$ eV thru-Earth neutrinos
2005  Auger Observatory data expected
2008  Extreme Universe Space Observatory (EUSO) ?
Cosmic Photon- Proton-Spectra

(after Ressell & Turner ‘90)
Power-laws are definitely not thermal exponentials
Any particle Rx we will ever make, CERN and beyond, was done many times by CRs.

BB: CoM calculation

![Graph](image)

Fig. 1: The spectrum of ultra-high-energy cosmic rays, as measured by several experiments [5]. Every cosmic ray with an energy shown in this plot, namely above $10^{22}$ eV, liberates in its collision with the atmosphere more energy in its centre-of-mass frame than does a proton-proton collision at the LHC.
LHC is “safe”, because CRs say so:

Review of the Safety of LHC Collisions

LHC Safety Assessment Group(*)

lsag@cern.ch

Summary

The safety of collisions at the Large Hadron Collider (LHC) was studied in 2003 by the LHC Safety Study Group, who concluded that they presented no danger. Here we review their 2003 analysis in light of additional experimental results and theoretical understanding, which enable us to confirm, update and extend the conclusions of the LHC Safety Study Group. The LHC reproduces in the laboratory, under controlled conditions, collisions at centre-of-mass energies less than those reached in the atmosphere by some of the cosmic rays that have been bombarding the Earth for billions of years. We recall the rates for the collisions of cosmic rays with the Earth, Sun, neutron stars, white dwarfs and other astronomical bodies at energies higher than the LHC. The stability of astronomical bodies indicates that such collisions cannot be dangerous. Specifically, we study the possible production at the LHC of hypothetical objects such as vacuum bubbles, magnetic monopoles, microscopic black holes and strangelets, and find no associated risks. Any microscopic black holes produced at the LHC are expected to decay by Hawking radiation before they reach the detector walls. If some microscopic black holes were stable, those produced by cosmic rays would be stopped inside the Earth or other astronomical bodies. The stability of astronomical bodies constrains strongly the possible rate of accretion by any such microscopic black holes, so that they present no conceivable danger. In the case of strangelets, the good agreement of measurements of particle production at RHIC with simple thermodynamic models constrains severely the production of strangelets in heavy-ion collisions at the LHC, which also present no danger.

(*) John Ellis, Gian Giudice, Michelangelo Mangano, Igor Tkachev(**) and Urs Wiedemann

Theory Division, Physics Department, CERN, CH 1211 Geneva 23, Switzerland

(**) Permanent address: Institute for Nuclear Research of Russian Academy of Sciences, Moscow 117312, Russia
$3 \times 10^{20} \text{ eV} = \text{macroscopic 50 Joules}$

Clemens does this with $10^{27}$ nucleons; Nature does this with one nucleon, $10^{27}$ times better pitcher!

You might say, Nature is Clemens on steroids.
CR Spectrum above a TeV

from Tom Gaisser

AGASA
Akeno
CASA-BLANCA
CASA-MIA
DICE
Fly’s Eye (mono)
Fly’s Eye (stereo)
Grigorov
Haverah Park
HEGRA
JACEE
KASCADE
MSU
Tibet
Tien Shan
Yakutsk

fixed target

VLHC (100 TeV)^2

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The CR **record energy** is $3 \times 10^{20}$ eV (0.3 ZeV).

Found by Fly’s Eye a decade ago (they got lucky!).

This is truly a macroscopic energy:

$3 \times 10^{20}$ eV = 50 Joules

equivalent to a Roger Clemens fastball,
   a Tiger Woods tee shot,
   a Pete Sampras tennis serve,
   Or a speeding bullet.

(Also to 12 Calories, which heats a gram of water by 12°C)
Fly’s Eye $3 \times 10^{20}$ eV event (1992)  
The Big One that didn’t get away!

This longitudinal profile is consistent with a primary proton, but not with a primary photon; Disfavors “local” top-down sources such as massive Particle DK, topo-defects, Z-bursts, etc.

Fluorescence detectors see real-time shower development

100 billion e+e- pairs at $x_{\text{max}} \sim 800 \text{ g/cm}^2$
Inter-galactic space is not “nothing”:

**Photon background**

<table>
<thead>
<tr>
<th>Band</th>
<th>eV/cm³</th>
<th>Ph/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>$5 \times 10^{-8}$</td>
<td>1</td>
</tr>
<tr>
<td>Microwaves</td>
<td>0.3</td>
<td>550</td>
</tr>
<tr>
<td>IR 0.025-0.0625 eV</td>
<td>$2 \times 10^{-2}$</td>
<td>(?)</td>
</tr>
<tr>
<td>Optic</td>
<td>$\sim 2 \times 10^{-3}$</td>
<td>$\sim 10^{-3}$</td>
</tr>
<tr>
<td>UV</td>
<td>?</td>
<td>$\sim 10^{-5}$ (?)</td>
</tr>
<tr>
<td>X-rays</td>
<td>$7.5 \times 10^{-5}$</td>
<td>$3 \times 10^{-9}$</td>
</tr>
<tr>
<td>γ-rays</td>
<td>$2.5 \times 10^{-6}$</td>
<td>$3 \times 10^{-12}$</td>
</tr>
</tbody>
</table>
Energy-losses on the Cosmic Radiation Background (CRadB)

GZK process

Nuclear Photo-dissociation

Berezinsky’s favorite

Energy loss mechanisms for protons:

\[ p + \gamma_{2.7K} \rightarrow n + \pi^+ \]
\[ \rightarrow p + \pi^0 \]
\[ \rightarrow p + e^+ + e^- \]

Dominant:
\[ \lambda \sim 6 \text{ Mpc} / E\text{th} \sim 10^{19.6} \text{ eV} \]
\[ \Delta E \sim 20\% \text{ per interaction} \]

\[ \lambda \sim 1 \text{ Mpc} / E\text{th} \sim 10^{18} \text{ eV} \]
\[ \Delta E \sim 0.1\% \text{ per interaction} \]

Energy loss mechanisms for nuclei:

\[ A + \gamma_{\text{IR}} \rightarrow (A-1) + N \]
\[ \rightarrow (A-2) + 2N \]
\[ \rightarrow A + e^+ + e^- \]

\((\gamma,n)\) \hspace{1cm} \((\gamma,p)\)

Dominant

One order of magnitude below

Energy loss mechanisms for gammas:

\[ \gamma + \gamma_{2.7K} \rightarrow e^+ + e^- \]

and \((e^+e^-)^2\)
Double pair production has huge t-channel log at HE.
Greisen-Zatsepin-Kuzmin, and the Cosmic-Ray Wall

Photo-pion production off CMB

\[ p^+\gamma_{\text{cmb}} \rightarrow \Delta \rightarrow p/n+\pi \]

Figure 9: The nucleon interaction length (dashed line) and attenuation length (solid line) for photo-pion production and the proton attenuation length for pair production (thin solid line) in the combined CMB and the estimated total extragalactic radio background intensity shown in Fig. 10 below.
The “GZK sphere”:

Too generous, imho;
AND, about the size of the BAO length!!
(Dan, let’s write.)
But AGASA Spectrum, pre-2003: EeV to ZeV

AGASA, July 2002
Super-GZK events - yes?

What does the absence of the GZK-cut-off mean?

Either:

- Nearby sources
  - Particles don’t interact with photons
  - EHE 2nd. Component (bump in the energy spectrum)

- GZK-sphere dominates
- Other sources are too far away

- Neutrinos
- Light SUSY hadrons
- Violation of Lorentz invariance

- Decay of topological defects
- Some neutrino models (e.g., Z-bursts)
Super GZK events - no?

What the presence of the GZK-cut-off does not mean?

That trans-GZK UHECR do not exist

-- Auger has many more events above $10^{20}$ eV that do not make their stringent tank cuts;

-- one awaits the “GZK recovery”, due to nearby sources, or Z-bursts or TDs or SMHPs or ... (coming tomorrow)
Composition signatures: X-max, and muon richness
Energy determination/estimation

At AGASA, from lateral particle distribution:

\[
\rho(r) \propto \left( \frac{r}{R_M} \right)^{-1.2} \left( 1 + \frac{r}{R_M} \right)^{-(\eta - 1.2)} \left\{ 1 + \left( \frac{r}{1000} \right)^2 \right\}^{-0.6}
\]

\[R_M = 91.6 \text{ m @ Akeno level}\]

\[\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62) (\sec \theta - 1)\]

\[
E = 2.21 \times 10^{17} \cdot S_0(600)^{1.03} \text{ eV}
\]

Takeda et al.: astro-ph/0209422
Fluctuations, dangerous or no?

Fluctuations

Difference between showers produced from the same initial conditions

\[ X_0 \text{ has uncertainty of the order of the interaction length} \quad \Rightarrow \quad X_{\text{max}} \text{ has an intrinsic fluctuation } \sim \text{few } \times 10 \text{ g cm}^{-2} \text{ (decreasing with } A) \]

LDF = \( f(X) \) and is also affected by the initial fluctuation

But there is a distance from the core, \( r^* \), where the dependence on the fluctuation of \( X_0 \) is minimal: < 10%

\[ h=0 \text{ (ground)} \& 10 \text{ EeV} \Rightarrow r^* \sim 1000 \text{ m} \]

Unfortunately, fluctuations also mimic “Zoo”-events
EAS detector types:
Pierre Auger Observatory

38° South, Argentina, Mendoza, Malargue

1600 water Cherenkov detectors, 1.5 km grid, 3000 km², 4 x 6 fluorescence telescopes

Expected events per year
- Energy (eV)
  - > 10^{18}
    - SD only
      - 180000
    - SD > 1 FD
      - 15000
  - > 10^{17}
    - 5150
    - 515
  - > 10^{16}
    - 103
    - 10

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Tom Weiler, Vanderbilt University
GZK suppression established (more or less)

The High Resolution Fly’s Eye (HiRes) experiment has observed the Greisen-Zatsepin-Kuzmin suppression (called the GZK cutoff) with a statistical significance of five standard deviations. HiRes’ measurement of the flux of ultrahigh energy (UHE) cosmic rays shows a sharp suppression at an energy of $6 \times 10^{19}$ eV, consistent with the expected cutoff energy. We observe the “ankle” of the cosmic-ray energy spectrum as well, at an energy of $4 \times 10^{18}$ eV. We describe the experiment, data

Feb 2008

Confirmed by Auger
Auger anisotropy:

Fig. 2. Aitoff projection of the celestial sphere in galactic coordinates with circles of 3.2° centred at the arrival directions of 27 cosmic rays detected by the Pierre Auger Observatory with reconstructed energies $E > 57$ EeV. The positions of the 442 AGN (292 within the field of view of the Observatory) with redshift $z \leq 0.017$ ($D \leq 71$ Mpc) from the 12th edition of the catalogue of quasars and active nuclei [11] are indicated by asterisks. The solid line draws the border of the field of view for the southern site of the Observatory (with zenith angles smaller than 80°). The dashed line is, for reference, the super-galactic plane. Darker colour indicates larger relative exposure. Each coloured band has equal integrated exposure. Centaurus A, one of the closest AGN, is marked in white.

Fig. 3. Probability for the null hypothesis (isotropic distribution) vs. maximum angular distance $\psi$ (left), maximum AGN redshift $z_{\text{max}}$ (centre), and threshold cosmic-ray energy $E_{\text{th}}$ (right). In each case the other two parameters are held fixed at the values that lead to the absolute minimum probability ($\psi = 3.2°, z_{\text{max}} = 0.017, E_{\text{th}} = 57$ EeV).
AGASA hot-spots -- Data

red: \( E > 4 \times 10^{19} \) eV

green: \( E > 10^{20} \) eV

Cluster Component
\(~ E^{-1.8 \pm 0.5}\)

Neutrinos will point better
AGASA hot-spots -- numbers

Within 2.5 degree circles, AGASA identifies six doublet, one triplet, Out of 57 events;

Opening the angle to just 2.6 degrees, AGASA identifies seven doublets, two triplets;

Source number \( \sim \frac{N_1^2}{2N_2} \sim 270 \) to 50%, weighting with GZK suppression, \( \rightarrow \sim 10^{-5} \) /Mpc\(^3\) for source density

Haverah Park contributes two more paired events in AGASA directions.

NOT corroborated by HiRes.
Size matters

EUSO ~ 300 x AGASA ~ 10 x Auger
EUSO (Instantaneous) ~ 3000 x AGASA ~ 100 x Auger
JEM-EUSO: Extreme Universe Space Observatory
“clear moonless nights”

Or New York State power blackout
Orbiting Wide-angle Lens (OWL), or “Super-EUSO”

3000 events/year above $10^{19.7}$ eV

and UHE Neutrinos!
E > 10^{19.5} eV protons are not so much deflected by GMF

= Particle Astronomy
**Expected number of events (GZK-case)**

<table>
<thead>
<tr>
<th>Log(E)</th>
<th>Nadir</th>
<th>Tilt 30°</th>
<th>Tilt 35°</th>
<th>Tilt 38°</th>
<th>Integral /year</th>
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<tbody>
<tr>
<td>19.7</td>
<td>1317.3</td>
<td>1394.0</td>
<td>1575.4</td>
<td>2421.9</td>
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<tr>
<td>19.8</td>
<td>570.5</td>
<td>653.7</td>
<td>790.8</td>
<td>1235.3</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>74.7</td>
<td>86.4</td>
<td>111.7</td>
<td>157.9</td>
<td></td>
</tr>
<tr>
<td>20.2</td>
<td>14.1</td>
<td>20.4</td>
<td>24.1</td>
<td>33.7</td>
<td></td>
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<td>20.4</td>
<td>5.7</td>
<td>9.9</td>
<td>11.7</td>
<td>15.5</td>
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<td>20.8</td>
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<td>1.8</td>
<td>2.2</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>21.0</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>
Clustering with EUSO

- > 1,000 events: E>7x10^{19}\text{eV}
- Several dozen clusters are expected
- All sky coverage