Possible physical significance of new measurements in the energy region from the “Knee” to the “Ankle”.

Paolo Lipari
Workshop for LHAASO
Roma 20th July 2011
Project Overview

Large High Altitude Air Shower Observatory
Yangbajing, 4300m a.s.l., 606g/cm²

ED: 5137, 1m×1m×2cm
15m spacing

MD: 1161, 6m×6m×2cm
30m spacing

WFCA: 3×8, 16×16 pixels
130m spacing

SCDA: 5000m² (φ80m)

WCDA: 4×900
φ170m×4m
300m spacing

IACT: 2
100m spacing

A ≈ 8 × 10⁵ m²
“Bubble” of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field.

Space extension and properties of this “CR bubble” remain very uncertain.
\[
\phi_j(E) = \frac{c}{4\pi} n_j(E)
\]

\[
N_j(E) = \int d^3x \ n_j(E, \vec{x})
\]

\[
N_j(E) = Q_j(E) \times T_j(E)
\]

\(p, \text{ nuclei}(Z, A)\)

\(\bar{p}, e^-, e^+\)

Different particles

Injection of cosmic rays

Containment time

Galactic Cosmic Rays
Injection of cosmic rays

Containment time

\[ N_j(E) = Q_j(E) \times T_j(E) \]

\[ L_j = \int dE \ E \ Q_j(E) \]

LARGE Power Requirement

Spectral Shape
[Dynamics of acceleration process]

Source Identification!

Maximum Energy of the Galactic CR sources
“PeV-atrons” (10^{15} \text{ eV})
“EeV-atrons” (10^{18} \text{ eV})
\[ N_j(E) = Q_j(E) \times T_j(E) \]

Competition of different times:

\[ T_{\text{int}}^{p,A} (E) \propto [\sigma_j(E)]^{-1} \sim \text{slowly varying} \]

\[ T_{\text{diffusion}} \left( \frac{p \cdot c}{Z} \right) \propto \left( \frac{p \cdot c}{Z} \right)^{-\delta} \]

\[ T_{\text{loss}}^{(e^\mp)} (E) \propto \frac{1}{E} \]

Injection of cosmic rays

Containment time

Interaction (hadrons)

Escape from Galaxy

Energy losses (electrons/positrons)
\[ r_L = \frac{1.08 \text{ Kpc}}{Z} \left[ \frac{E}{10^{18} \text{ eV}} \right] \left[ \frac{\mu\text{Gauss}}{B} \right] \]

\[ r_{Larmor}^p(100 \text{ GeV}) \simeq 3.6 \times 10^{-8} \text{ Kpc} \]

\[ r_{Larmor}^p(10^{20} \text{ eV}) \simeq 36 \text{ Kpc} \]

\[ r_{Fe Larmor}^p(10^{20} \text{ eV}) \simeq 1.4 \text{ Kpc} \]
Propagation as isotropic diffusion

Observable CR populations:

\[ n_j(E, \Omega, \vec{r}) \]

Injection:

\[ q_j(E, \vec{r}, t) \]

CR escape

\[ D(p/Z, \vec{r}) \]

Extra galactic particle
Piece of extragalactic space: Non MilkyWay-like sources
Piece of extragalactic space: Non MilkyWay-like sources

\[ Q_{\text{Milky Way}}(E) \]

\[ Q_{\text{extra galactic}}(E) \]

Extragalactic CR Injection Power density

Extragalactic Magnetic Field

AGN

Galaxy

Milky Way
The Galactic to Extragalactic Transition is emerging as a crucial problem for CR science.
Power Law Injection (No Cosmic Evolution)

Remarkable “coincidence” (?!)

Berezinski et al. “DIP Model” Transitions at $E = 10^{18}$ eV
CAS A
(1667)

The SuperNova Paradigm
“Fireball” of an Supernova explosion

MAXIMUM ENERGY?

Interstellar Gas

Strong Shock

Fermi $1^{st}$ order acceleration

$q(E) \propto E^{-(2+\varepsilon)}$
FERMI Telescope work:

Detection of Starburst galaxies

Gamma Ray Luminosities (> 100 MeV)

\[ p + p_{\text{ISM}} \rightarrow \pi^0 \]
\[ \pi^0 \rightarrow \gamma\gamma \]

The Acceleration of CR is correlated to the Star Formation Rate (and therefore Star “Death” Rate) Compatible with the “standard scenario”.
GAMMA RAY BURSTS (GRB's)

Proposed source of the CR
GRB: associated with a subset of SN Stellar Gravitational Collapse
1. Energy Spectrum

- Clear identification of a high energy suppression [the “END” (... well the “suppression”) of exotic/fundamental physics modeling for UHECR].

- Good agreement between experiments [“small” but important question about the energy scale].

- Physical interpretation strongly coupled to (2., 3.) (anisotropy + composition). [proton GZK ?]
About 20% energy scale difference!

HiRes/ TA – Auger observe the GZK suppression

But: problem on the energy scale
HiRes/TA/Auger observe a High energy Suppression
That could be the GZK suppression
[or photo-disintegration of Iron]
[or Source Cutoff]

HiRes/ TA – Auger observe the GZK suppression

But: problem on the energy scale
UHECR

1. Energy Spectrum
2. Anisotropy
3. Composition

Crucial Problem:
Galactic Extragalactic Transition

Significant Experimental Discrepancies
Auger/Hires/TA
Confusing situation.
$E \propto \int (\frac{dE}{dX}) \, dX$

$E_{\text{ionization}} = \int dX \, N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$

Area $\propto$ Energy

Shape depends on:
- Primary Identity
- Interaction Model
$E \approx 10^{20} \text{ eV}$
Mass Composition becoming heavy at very high energy?

Significance would be very important!

Constraints on the structure and properties of the astrophysical sources.

Observational controversy NON confirmation of HiRes

Correlation with sources
Small deviation in magnetic Fields (Z < 3?)
- Detailed measurements of the Energy Spectrum
  [Identification of features]

- Evolution with energy of the Chemical Composition

- Anisotropies of the flux
PAMELA

Proton/Helium CR fluxes
1 GV - 1.2 TV

Science in press
(march 2011)
Surprising and important result.

Broken power law fits to spectra.

Break at same rigidity $p/Z$

Surprising and important result.
Broken power law fits to spectra.

“Ankle” at same rigidity $p/Z$

Surprising and important result.
We report precision measurements of the proton and helium spectra in the rigidity range 1 GV-1.2 TV performed by the satellite-borne experiment PAMELA. We find that the spectral shapes of these two species are different and cannot be well described by a single power law. These data challenge the current paradigm of cosmic-ray acceleration in supernova remnants followed by diffusive propagation in the Galaxy. More complex processes of acceleration and propagation of cosmic rays are required to explain the spectral structures observed in our data.
CREAM  (calorimeter on balloon)
(5 flights in Antartica. Total of 156 days)

Cream 5  trajectory
37 days 12/2009-01/2010
TeV spectra are harder than spectra < 200 GeV/n

*Claim of “break” hardening in CR spectra*

*Helium overtakes protons (!)*
Discrepant hardening

Flux $\times E^{2.75} \, (m^2 \, s^{-1} \, sr^{-1} \, (GeV/n))^{1.75}$

Energy (GeV/n)

He $\times 10^{-1}$

O

HeAO3

CRN

TRACER

AMS

BESS-TeV

JACEE

RUNJOB

ATIC-2

CREAM-I

CREAM-II

Ne $\times 10$

Mg $\times 10$

Si $\times 10$

Fe $\times 10$

Balloons & Satellites

Eun-Suk Seo
Tibet AS Gamma Air Shower

Tibet III Air Shower Array (2003)  \( A_{\text{internal}} = 36,900 \, \text{m}^2 \)

Spacing 7.5 meters (interior)

150 meters

A(internal)  
\[= 36,900 \, \text{m}^2 \]
Tibet Air Shower Energy Spectrum

\[ E^{2.5} \times \frac{dJ}{dE} (\text{GeV}^{1.5} / \text{sr}/\text{m}^2/\text{s}) \]

- \( \text{JACEE} \)
- \( \text{RUNJOB} \)
- \( \text{Grigorov} \)

- \( \text{KASCADE}(\text{QGSJET}) \)
- \( \text{KASCADE}(\text{SIBYLL}) \)
- \( \text{CASA-MIA} \)
- \( \text{AKENO}(1984) \)
- \( \text{Tibet-III}(\text{ICRC2003}) \)
- \( \text{This work}(\text{QGSJET}+\text{HD}) \)
- \( \text{This work}(\text{QGSJET}+\text{PD}) \)
- \( \text{This work}(\text{SIBYLL}+\text{HD}) \)

Energy (GeV)
TIBET AS-gamma CR spectra

![Graph showing CR spectra with a peak labeled "KNEE". The x-axis represents energy (PeV) on a logarithmic scale, ranging from 0.1 to 10^5 PeV, and the y-axis represents the differential flux times energy cubed (\(\phi(E)/E^3\)) in units of \(10^6 \text{ PeV}^2 \text{ m}^2 \text{ s}^{-1} \text{ sr}^{-1}\). The graph shows data points and error bars.]
TIBET AS-gamma CR spectra
HIRES spectrum

2\textsuperscript{nd} "Knee"?

Ankle
TIBET AS-gamma CR spectra
HIRES spectrum
AUGER spectrum Energy scale discrepancy.
\[ [A \, t \, \Omega] = \pi \left[ 10^6 \text{ m}^2 \right] \left[ 1 \text{ yr} \right] \]

\[
\Phi \left[ 10^{15} \text{ eV}, E_{\text{knee}} \right] \quad [A \, t \, \Omega] \approx 1.4 \times 10^8
\]

\[
\Phi \left[ E_{\text{knee}}, 10^{16} \text{ eV} \right] \quad [A \, t \, \Omega] \approx 1.2 \times 10^7
\]

\[
\Phi \left[ 10^{16} \text{ eV}, 10^{17} \text{ eV} \right] \quad [A \, t \, \Omega] \approx 1.9 \times 10^6
\]

\[
\Phi \left[ 10^{17} \text{ eV}, 5 \times 10^{17} \text{ eV} \right] \quad [A \, t \, \Omega] \approx 1.4 \times 10^4
\]

\[
\Phi \left[ \geq 5 \times 10^{17} \text{ eV} \right] \quad [A \, t \, \Omega] \approx 5 \times 10^2
\]
KASCADE Results

Model Dependence!
Progress in hadronic interaction modeling?

7 + 7 TeV PP collider
### Table

<table>
<thead>
<tr>
<th>Model</th>
<th>QGSJET01</th>
<th>QGSJETII</th>
<th>SIBYLL 2.1</th>
<th>EPOS 1.99</th>
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</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (TeV)</td>
<td>0.9, 2.36, 7</td>
<td>0.9, 2.36, 7</td>
<td>0.9, 2.36, 7</td>
<td>0.9, 2.36, 7</td>
</tr>
<tr>
<td>$dN_{ch}/d\eta</td>
<td>_{\eta=0}$</td>
<td>✓ ✓ ✓</td>
<td>✓ ✓ ✓</td>
<td>✓ ✓ ✓</td>
</tr>
<tr>
<td>$\langle p_{T} \rangle$</td>
<td>over over ✓</td>
<td>over over over</td>
<td>✓ under under</td>
<td>✓ ✓ ✓</td>
</tr>
<tr>
<td>$P(N_{ch} &lt; 5)$</td>
<td>over over under</td>
<td>over over over</td>
<td>over over over</td>
<td>✓ ✓ ✓</td>
</tr>
<tr>
<td>$P(N_{ch} &gt; 30)$</td>
<td>✓ under under</td>
<td>✓ ✓ over</td>
<td>over ✓ over</td>
<td>under under under</td>
</tr>
</tbody>
</table>
LHC and Ultra-High Energy Cosmic Rays

Total pp Cross Section

![Graph showing total pp cross section vs. √s (GeV)]
KASCADE-GRANDE

\[ A \approx 1.7 \times 10^5 \text{ m}^2 \]
KASCADE-GRANDE energy spectrum

Systematic uncertainty in flux at $10^{17}$ eV
(QGSJET II/FLUKA)

- $N_{ch} - N_{\mu}$: 12% (incl. composition)
- $N_{ch}$: 21%, 17% (for H, Fe)
- $N_{\mu}$: 7%, 13% (for H, Fe)
Comparison with KASCADE & EAS–TOP

Data

- ○ KASCADE QGSjet01
- ▼ EAS–TOP
- ● KASCADE–Grande QGSjet2

primary energy [Log(E/GeV)]

$\frac{I}{(A \times 10^{3.015})^{-1}}$
"Shape of the Knee" (?!)

Kascade Grande
(Karlsruhe KIT)
"Steepening"
KASCADE-GRANDE spectrum
KASCADE-GRANDE spectrum

3 knees ??
COSMIC RAY ANISOTROPIES
Tibet ASγ (verified by ARGO + IceCube)

M. Amenomori et al. Science, 2006
Fig. 3. Celestial CR intensity map for different representative CR energies. (A) 4 TeV; (B) 6.2 TeV; (C) 12 TeV; (D) 50 TeV; (E) 300 TeV. Data were gathered from 1997 to 2005. The vertical color bin width is $2.5 \times 10^{-4}$ in [(A) to (D)] and $7.25 \times 10^{-4}$ in (E) for different statistics, all for the relative CR intensity.
MILAGRO data (10 TeV hadrons).

Milagro “hot spots”

0.05 % effect

0.5 % effect

Right ascension

Argo

-7.6  11.4 s.d.
Observation of the CRs large scale anisotropy

There have been several observations of large-scale, part-per-mille anisotropy in cosmic ray arrival directions between 0.1 and 100 TeV.

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**Northern Sky**

- **Milagro**
- **SuperK**
- **Argo-YBJ**
- **Tibet-III**

**Southern Sky**

- **IceCube**

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**References**

- **Milagro** A. Abdo et al., Astrophys. J. 698 (2009) 2121
- **ARGO-YBJ** S. Vernetto, Proc. 31st ICRC, 2009

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S. Toscana for the IceCube collaboration - RICAP II - 05/25/2011
Relative Intensity

Equatorial sky maps in HEALPix with NSide=16, pix resol ~ 3°

No energy selection

20 TeV

400 TeV

Preliminary

S. Toscano for the IceCube collaboration - RICAP 11 - 08/25/2011
Energy dependence of the Solar dipole

* IceCube observes the Solar dipole in both energy bins. The observed amplitude is compatible with the expectations within the stat. and sys. uncertainties.
* The observation of the solar dipole supports the observation of the sidereal anisotropy in cosmic ray arrival direction.

relative intensity Vs. \((\alpha[^\circ] - \alpha_{\text{SUN}}[^\circ])\)

\(20\,\text{TeV}\)

\(400\,\text{TeV}\)

Preliminary
Small scale anisotropy

Several experiments have discovered anisotropies on scales of about 10°.

- Milagro observes two localized regions with significance > 10σ in the total data set of 2.2 × 10¹¹ events recorded over 7 years. The “hot” regions have fractional excesses of order several times 10⁻⁴ relative to the background.

- Same structures observed by ARGO-YBJ.

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A. Abdo et al., PRL 101 (2008) 221101

S. Vernetto, Proc. 31st ICRC, 2009

Milagro
Median Energy: 1 TeV

ARGO-YBJ
Median Energy: 2 TeV
\[ \delta I(\alpha, \delta) = m_0 + p_x \cos \delta \cos \alpha + p_y \cos \delta \sin \alpha + p_z \sin \delta + \frac{1}{2} Q_1 (3 \cos^2 \delta - 1) + Q_2 \sin 2\delta \cos \alpha + Q_3 \sin 2\delta \sin \alpha + Q_4 \cos^2 \delta \cos 2\alpha + Q_5 \cos^2 \delta \sin 2\alpha \]

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Fit Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_0 )</td>
<td>0.320 ± 2.264</td>
</tr>
<tr>
<td>( p_x )</td>
<td>2.435 ± 0.707</td>
</tr>
<tr>
<td>( p_y )</td>
<td>-3.856 ± 0.707</td>
</tr>
<tr>
<td>( p_z )</td>
<td>0.548 ± 3.872</td>
</tr>
<tr>
<td>( Q_1 )</td>
<td>0.233 ± 1.702</td>
</tr>
<tr>
<td>( Q_2 )</td>
<td>-2.949 ± 0.494</td>
</tr>
<tr>
<td>( Q_3 )</td>
<td>-8.797 ± 0.494</td>
</tr>
<tr>
<td>( Q_4 )</td>
<td>-2.148 ± 0.200</td>
</tr>
<tr>
<td>( Q_5 )</td>
<td>-5.268 ± 0.200</td>
</tr>
</tbody>
</table>

\( \chi^2/\text{ndf} = 14743.4/14187 \)

\( \text{Pr}(\chi^2|\text{ndf}) = 5.5 \times 10^{-4} \)
Identification of significant structures

<table>
<thead>
<tr>
<th>region</th>
<th>right ascension</th>
<th>declination</th>
<th>optimal scale</th>
<th>peak significance</th>
<th>post-trials</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>(122.4$^0^{-4.4}_{4.7}$)</td>
<td>($-47.4^0^{-7.3}_{3.2}$)</td>
<td>22$^0$</td>
<td>7.0$\sigma$</td>
<td>5.3$\sigma$</td>
</tr>
<tr>
<td>2</td>
<td>(263.0$^0^{-3.8}_{3.7}$)</td>
<td>($-44.1^0_{-5.1}$)</td>
<td>13$^0$</td>
<td>6.7$\sigma$</td>
<td>4.9$\sigma$</td>
</tr>
<tr>
<td>3</td>
<td>(201.6$^0_{-3.8}$)</td>
<td>($-37.0^0_{-2.3}$)</td>
<td>11$^0$</td>
<td>6.3$\sigma$</td>
<td>4.4$\sigma$</td>
</tr>
<tr>
<td>4</td>
<td>(332.4$^0_{-7.6}$)</td>
<td>($-70.0^0_{-7.0}$)</td>
<td>12$^0$</td>
<td>6.2$\sigma$</td>
<td>4.2$\sigma$</td>
</tr>
<tr>
<td>5</td>
<td>(217.7$^0_{-10.2}$)</td>
<td>($-70.0^0_{-8.8}$)</td>
<td>12$^0$</td>
<td>$-6.4\sigma$</td>
<td>$-4.5\sigma$</td>
</tr>
<tr>
<td>6</td>
<td>(77.6$^0_{-8.4}$)</td>
<td>($-31.9^0_{-5.2}$)</td>
<td>13$^0$</td>
<td>$-6.1\sigma$</td>
<td>$-4.1\sigma$</td>
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<td>7</td>
<td>(308.2$^0_{-7.7}$)</td>
<td>($-34.5^0_{-6.9}$)</td>
<td>20$^0$</td>
<td>$-6.1\sigma$</td>
<td>$-4.1\sigma$</td>
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<tr>
<td>8</td>
<td>(166.5$^0_{-4.5}$)</td>
<td>($-37.2^0_{-5.0}$)</td>
<td>12$^0$</td>
<td>$-6.0\sigma$</td>
<td>$-4.0\sigma$</td>
</tr>
</tbody>
</table>
Models:

- **A/S =** gal. models $\rightarrow$ GMF with $\neq$ symmetries
- **Gal =** gal. origin up to few tens of $10^{19}$ eV $\rightarrow$ turb. GMF predominant
- **C-G Xgal =** extra-gal. model $\rightarrow$ CMB dipole
Need measurements [and understanding] of Large Scale anisotropy in all energy range from TeV to UHECR
AMIGA
Auger Muons & Infill for the Ground Array

- 1500 m grid stations
- 750 m grid stations (infill stations)
- infill stations just installed
- associated muon detectors
- 8 missing infill stations

Total area: 23.5 km²
Near future:
+24 stations in a 433 m grid ~ 5.9 km²

Data taking since August 2008

Water Cherenkov detectors: electromagnetic component + muons
Muon detectors: muons
Final Remarks:

New measurements of the CR fluxes in the broad energy region “from the knee to the ankle” have the Potential to give very valuable information on the “high energy universe”.

The Optimization of the design of a shower detector for this purpose is a non trivial problem that requires careful discussion.

Uncertainties in the shower modeling due to our imperfect Understanding of hadronic interactions remain an important issue. LHC is a great opportunity for improvement.

The study of anisotropies is of great importance.
The idea of constructing an instrument that is at the same time:

- **Gamma Ray Telescope**
- **High Energy Cosmic Ray Detector**

is natural and very attractive.

There is space for significant improvement over existing measurements.

[but a more detailed study is required to estimate the impact of the current LHAASO project as CR detector.]