Cosmic Rays and Extensive Air Showers

Paolo Lipari, INFN Roma “Sapienza”

Multi-Messenger Astrophysics in the era of LHAASO

Online meeting  28th  July  2020
Outline:

1. Introduction.
2. Spectral structures below the Knee
3. Measurements of the spectra around the Knee
4. Hadronic Interactions
5. The potential of LHAASO
6. Relation to UHECR
7. Conclusions.
1. INTRODUCTION

Cosmic-Rays in the context of Multi-messenger Astrophysics
Space and time integrated average of particles generated by many sources in the Galaxy and in the universe, also shaped by propagation effects.

Spectra nearly perfectly isotropic $\phi(E, \Omega) \sim \phi(E)$

Single point, and (effectively) single time.
[slow time variations, geological record carries some information]

A “Local Fog” that is a terrible nuisance but also carries very important information
MILKY WAY

Solar system

High energy sources

GALACTIC COSMIC RAYS
ExtraGalactic Space

Milky Way
ExtraGalactic Space

Milky Way
Formation of the Cosmic Ray flux: divided into two phases:

Injection
[in interstellar (or intergalactic) space]

Propagation
[from the injection point to the Sun]

Q: is this division really valid?
A: in most scenarios this is a good subdivision, but this is a critical point
Very important ambiguity:

Any feature in the shape of the energy spectrum can be attributed to the injection or to propagation.

Most prominent spectral feature the “Knee” [or better the “Knees”]:

Is it created by Injection or Propagation?
Galactic Cosmic Rays: have their origin in sources inside the Milky Way

Extra-Galactic Cosmic Rays gave their origin in sources outside the Milky Way

Natural to expect that:

- Galactic particles dominate the flux at Low energy
- Extra-galactic particles dominate the flux at High energy

\[ \phi_{\text{galactic}}(E^*) = \phi_{\text{extra galactic}}(E^*) \]
Fundamental “Boundary Condition” for High Energy Astrophysics:

Some sources are capable to accelerate particles to very high energy:

\[ E \sim 10^{20} \text{ eV} \]

Maximum energy for Galactic sources

\[ E \sim \text{few} \times 10^{15} \text{ eV} \]

[but perhaps much higher transition at the “Ankle”]
Fundamental “Boundary Condition” for High Energy Astrophysics:

Some sources are capable to accelerate particles to very high energy:

\[ E \sim 10^{20} \text{ eV} \]

Extragalactic sky dominated by Blazars
Do they generate the highest energy particles?

Maximum energy for Galactic sources

\[ E \sim \text{few} \times 10^{15} \text{ eV} \]

[but perhaps much higher transition at the “Ankle”]

Supernova “Paradigm”
Are they the Pevatrons?
Measurements of the Cosmic Ray Fluxes at the Earth:

\( \phi_p(E, \Omega) \), \( \phi_{\text{He}}(E, \Omega) \), \ldots, \( \phi_{\{A,Z\}}(E, \Omega) \)

protons + nuclei

electrons

\( \phi_{e^-}(E, \Omega) \)

anti-particles

\( \phi_{e^+}(E, \Omega) \)

\( \phi_{\overline{p}}(E, \Omega) \)

Interpretation in terms of sources and propagation
Cosmic Ray Spectra

AMS02

CREAM p data

angle averaged diffuse Galactic gamma ray flux (Fermi)
1. The spectra of electrons

Understand CR p/e- co-acceleration in the sources

2. The spectra of positrons and anti-protons.

essential to understand CR propagation.

[In my view] finding the solution to
the "positron anomaly" problem
is a crucial problem with deep and broad implications.
2. CR Spectral “Features”

The description of Cosmic Ray Spectra below the “Knee” as simple power laws is not valid.

Discovery of spectral features below the “Knee"
Ultrahigh Energy Cosmic Rays

$E^{2.6} F(E) \text{[GeV}^{-1.6} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$E \text{[eV]}$

Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly’s Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger

PDG 2017
Pamela Hardening of the proton and Helium spectra
CREAM Measurements of the proton and Helium spectra

“Hint” of a softening at $10^4$ GeV
DAMPE telescope

Clear Observation of the softening in the proton spectrum
DAMPE telescope

Clear Observation of the softening in the proton spectrum

\[ 2.60 \pm 0.01 \]

\[ 13.6^{+4.1}_{-4.8} \text{ TeV} \]

\[ -0.25 \pm 0.07 \]
P.L. and Silvia Vernetto,
“The shape of the cosmic ray proton spectrum,”
Astropart. Phys. 120, 102441 (2020)
[arXiv:1911.01311 [astro-ph.HE]].
Global Fit

$2.80 \pm 0.03$

$2.87^{+0.15}_{-0.10}$

$2.57^{+0.04}_{-0.06}$

P.L. and Silvia Vernetto,
“The shape of the cosmic ray proton spectrum,”
Astropart. Phys. 120, 102441 (2020)
[arXiv:1911.01311 [astro-ph.HE]].
Extrapolation to the region of EAS observations
“unorthodox” speculation

CR spectrum formed by components that have different (log—parabola) form

Paolo Lipari,
“The origin of the power-law form of the extragalactic gamma-ray flux,”
ARGO "light component" Knee
3. Measurements around the “Knee”

*Very large*

*systematic uncertainties*
KASCADE Collaboration,
“KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems,”
[astro-ph/0505413].

KASCADE-Grande Collaboration,
“KASCADE-Grande measurements of energy spectra for elemental groups of cosmic rays,”

IceCube Collaboration,
“Cosmic ray spectrum and composition from PeV to EeV using 3 years of data from IceTop and IceCube,”
Phys. Rev. D 100, no.8, 082002 (2019)
The Kascade detector
Unfolding [Model dependent]

Sibyll-2.1 model
KASCADE-Grande data (full efficiency)
0°-18°
c. 78000 events

rec. number of charged particles $\log_{10}(N_{\text{ch}})$

reconstructed number of muons $\log_{10}(N_{\mu})$

$10^{18}$ eV
$10^{17}$ eV

electron-rich ridge
(light primaries)

electron-poor ridge
(heavy primaries)

number of showers

$10^3$
$10^2$
$10$
$1$
KASCADE-GRANDE Collaboration
“The spectrum of high-energy cosmic rays measured with KASCADE-Grande,”

KASCADE-GRANDE Collaboration
[arXiv:1304.7114 [astro-ph.HE]].

KASCADE-GRANDE Collaboration
“Kneelike structure in the spectrum of the heavy component of cosmic rays observed with KASCADE-Grande,”
\[ \gamma_1 = -3.25 \pm 0.05, \gamma_2 = -2.79 \pm 0.08, \log_{10}(E_{\text{break, light}}/\text{eV}) = 17.08 \pm 0.08 \]
T. Abu-Zayyad et al.,
“The Knee and the Second Knee of the Cosmic-Ray Energy Spectrum,”
Main results of the observations
[Kascade, Kascade-GRANDE, IceTop/IceCube]

[1.] Composition that becomes gradually “heavier”

Simple hypothesis:
*Rigidity dependent spectral shapes*

\[
\phi_Z(E_p, Z) \propto \phi_p(E_p)
\]

This is consistent with the data but not clearly established. Should be verified experimentally.

Shape of the spectra should be accurately measured (to allow an understanding of its origin).

[2.] Emergence of a light (proton rich) component

[Auger, TA] \( E \approx 10^{18} \text{ eV} \) composition proton rich
Systematic Uncertainties
in the measurement of the Cosmic Ray Spectra

1. Understand the detector performances

2. Algorithms of analysis

2. Modeling of Shower Development

Hadronic Interactions

“The Dark Side of the
(Particle Physics) Standard Model”
4. Hadronic Interactions

QCD
PDF's
Parton Distribution Functions

Multiple Interactions

\[ Q^2 = 10 \text{ GeV}^2 \]
\[ E_0 = 10^{15} \text{ eV} \]
\[ \sqrt{s} = 1.37 \text{ TeV} \]

No need for extrapolation in energy, but systematic uncertainties remain large.
Phase space coverage
[very forward region crucial for CR showers and poorly measured in accelerator experiments]

Nuclear effects
[Little/no data on interactions on nuclear targets at high energy]

Meson Interactions
[Limited to fixed target interactions]

Lower energy (deeper in the shower development) interactions known with limited precision
[often old data]

Theoretical understanding remain (very) poor.
How can we improve?

1. Program of experimental studies at accelerators (including “lower energy”)

2. Theoretical efforts (Deeper understanding) (Development of better Montecarlo codes)

5. LHAASO CR observations
Cosmic ray spectral measurement around the knee with LHAASO experiment

Lingling Ma for LHAASO Collaboration
2020.01 Nanjing
Hybrid observations of LHAASO

- High Altitude: 4400m
- Multi-type detectors

<table>
<thead>
<tr>
<th></th>
<th>WCDA</th>
<th>WCDA++</th>
<th>KM2A</th>
<th>WFCTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO. of detector</td>
<td>3120cells</td>
<td>5195</td>
<td>1171</td>
<td>20</td>
</tr>
<tr>
<td>Area</td>
<td>3120X25m²</td>
<td>1km²</td>
<td>1km²</td>
<td>0.06X20Sr</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>10TeV - 10PeV</td>
<td>100TeV - 100PeV</td>
<td>100TeV - 100PeV</td>
<td>15TeV - 100PeV</td>
</tr>
</tbody>
</table>
Discrimination variables for composition studies by MC

- Length/Width
- Dist (related to $X_{\text{max}}$)
- Particle numbers near the shower core
- Number of muons

$$P_c = \left(\frac{\text{Length}}{\text{Width}}\right)_{\text{normalized}}$$

Core resolution: $\leq 3\text{m}$
Multi-Component observations of EAS

Cherenkov Telescopes (WFCTA)

\[ N_{p.e.}^{\text{tel}} \quad X_{\text{max}} \quad \text{Length, Width} \]

Water Detectors (WCDA)

\[ N_{p.e.}^{\text{water}} \quad N_{\text{core}}^{\text{water}} \]

Km2A detector

\[ S_{\text{em}}^{\text{km2}} \quad N_{\mu}^{\text{km2}} \]

e.m. signal          Muon signal
6. Connection to the UHECR
Interpretation in terms of Composition
TELESCOPE ARRAY [8.5 Years of Hybrid observations]
Auger ICRC-2019

$E \sim 10^{18}$ eV

“Light” composition (rich in protons). Measurements of the proton-air cross section

Understand the “emergence” of this light component
Important "theoretical" uncertainty
The “Muon problem” in UHECR

Auger number of muons in inclined showers
\[ E_{\text{cal}} = \int \frac{dE}{dX} \, dX \]

\[ S_{1000} \propto E \]
Pierre Auger Collaboration
“Testing Hadronic Interactions at Ultrahigh Energies with Air Showers Measured by the Pierre Auger Observatory,”
[arXiv:1610.08509 [hep-ex]].

\[
S(1000)
\]

\[
\begin{align*}
\text{Energy: } & (13.8 \pm 0.7) \text{ EeV} \\
\text{Zenith: } & (56.5 \pm 0.2)^\circ \\
X_{\text{Max}}: & (752 \pm 9) \text{ g/cm}^2 \\
\chi^2/\text{dof (p)} & = 1.19 \\
\chi^2/\text{dof (Fe)} & = 1.21
\end{align*}
\]

\[
R = \frac{\text{data}}{\text{sim}}
\]

(Average size hadronic shower)
(Montecarlo prediction)

\[
1.33 \pm 0.16 \quad \text{EPOS-LHC}
\]

\[
(1.61 \pm 0.21) \quad \text{(QGSJetII-04)}
\]
Telescope Array Collaboration,
“Study of muons from ultrahigh energy cosmic ray air showers measured with the Telescope Array experiment,”
\[ z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu p}^{\text{det}})}{\ln(N_{\mu \text{Fe}}^{\text{det}}) - \ln(N_{\mu p}^{\text{det}})} \]

Energy dependence of the “muon anomaly”

This type of studies can receive a great boost from the (multi-component) data of LHAASO.
Conclusions

New measurements of the cosmic ray spectra in the energy range from direct-observations up to the “UHECR” region, with better control of systematic uncertainties can be of great value to develop our understanding of the “High Energy Universe”.

LHAASO with its capabilities of multi—component observations has a great potential to provide very important measurements.

To fully exploit this potential it is very desirable (in fact in my opinion necessary) to invest in an effort to improve our understanding of hadronic interactions.

(1) Accelerator Data, (2) Theoretical work, (3) CR data “Self-Consistency” [“Bootstrap”] with the measurements of different shower components (and different experiments)