Energy spectrum of Primary Cosmic Rays in the range of 10 GeV – 10 TeV

Hari Haran Balakrishnan

On behalf of
GRAPES-3 Collaboration
Cosmic Ray Laboratory, TIFR, Ooty, India
GRAPES-3 (Gamma Ray Astronomy at PeV EnergieS – 3)

- 400 scintillation detectors (1 m² each)
- Area covered 25000 m²
- Hexagonal layout 8m inter-detector separation
- Measures density, arrival time of particles to estimate primary energy and direction

- 16 muon modules (35 m² each) = 560 m²
- EAS trigger rate ~33 Hz
- Records muon flux (>1 GeV) spread over solid angle of 2.3 Sr in 13x13=169 directions
• Muon rate in each module ~ 3000 Hz.

• ~4 billion muons/day from 169 directions, 0.002% of statistical accuracy.

• Angular distribution of muons to very high precision.

• Successfully corrected for efficiency variation of detector.

• Variation in muon rate due to various atmospheric and solar phenomena can be studied.
Motivation

• Muon angular distribution calculated using CORSIKA simulations shows dependence on assumed hadronic interaction models.

• However, before comparing an experimentally measured muon angular distribution with expectations from Monte Carlo simulations using different hadronic interaction models, it is necessary to have access to precise energy spectrum of cosmic rays.

• Muons detected in GRAPES-3 are produced by primary cosmic rays largely in 10 GeV to 10 TeV energy range.
Present work

- Recent direct measurement of energy spectrum and composition of cosmic rays in the relevant energy range of 10 GeV to 10 TeV responsible for production of >1 GeV muons in GRAPES-3 have been used.
- Dominant components are proton and helium.
- We have used results from balloon and satellite experiments.
  - Balloon experiments (BESS, CREAM, CAPRICE)
  - Satellite experiments (PAMELA, AMS)
- The main components used in satellite and balloon experiments are
  - Magnetic spectrometer - Rigidity
  - Calorimeter - Energy measurements
- Since, these experiments have used different techniques of measurements (energy, rigidity), therefore, energy spectrum is reported in different units.
- For our simulations total energy spectrum is required which have been generated from above measurements.
\[
\frac{dN}{dE_{k.e/n}} (m^2 \text{ sr s GeV n}^{-1})^{-1} = \phi_0 E_{k.e/n}^{-\gamma} (m^2 \text{ sr s GeV n}^{-1})^{-1}
\]

\[
\frac{dN}{dE_{k.e}} (m^2 \text{ sr s GeV})^{-1} = \frac{1}{n} \phi_0 E_{k.e/n}^{-\gamma} (m^2 \text{ sr s GeV n}^{-1})^{-1}
\]

\[
\frac{dN}{dE_{k.e}} (m^2 \text{ sr s GeV})^{-1} = \phi_0 E_{k.e}^{-\gamma} (m^2 \text{ sr s GeV})^{-1}
\]

\[
\frac{dN}{dE_{k.e}} = \phi_0 (E_T - m_0 c^2)^{-\gamma} = \phi_0 E_T^{-\gamma} \left(\frac{E_T - m_0 c^2}{E_T}\right)^{-\gamma}
\]

\[
\frac{dN}{dE_{k.e}} = \frac{dN}{dE_T} (E_{k.e})^{-\gamma}
\]

\[
\frac{dN}{dE_T} (m^2 \text{ sr s GeV})^{-1} = \frac{1}{n} \left(\frac{E_{k.e}}{E_T}\right)^\gamma \frac{dN}{dE_{k.e/n}} (m^2 \text{ sr s GeV n}^{-1})^{-1}
\]
\[
\frac{dN}{dE_{k.e/n}} = \Phi_0 E_{k.e/n}^{-\gamma} (m^2 \text{ sr s GeV } n^{-1})^{-1}
\]

\[
\frac{dN}{dR} = \Phi_0 R^{-\gamma} (m^2 \text{ sr s GV})^{-1}, \text{where } R = \frac{pc}{|z|e}
\]

\[
\frac{dN}{dE_{k.e}} = \frac{dN}{dR} \frac{dR}{dE_{k.e}} \text{ and } R = \frac{\sqrt{E_{k.e}(E_{k.e} + 2mc^2)}}{|z|e}
\]

\[
\frac{dN}{dR} (m^2 \text{ sr s GV})^{-1} = \frac{|z|\sqrt{(E_{k.e}(E_{k.e} + 2mc^2))}}{n(E_{k.e} + mc^2)} \frac{dN}{dE_{k.e/n}} (m^2 \text{ sr s GeV } n^{-1})^{-1}
\]

\[
\frac{dN}{dE_T} (m^2 \text{ sr s GeV})^{-1} = \frac{(E_{k.e} + mc^2)}{|z|\sqrt{E_{k.e}(E_{k.e} + 2mc^2)}} \left(\frac{E_{k.e}}{E_T}\right)^\gamma \frac{dN}{dR} (m^2 \text{ sr s GV})^{-1}
\]
### BESS
(Balloon-borne Experiment with a Superconducting Solenoid for TeV)

#### Kinetic Energy per nucleon

<table>
<thead>
<tr>
<th>Type</th>
<th>K.E (GeV/n)</th>
<th>Reported</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>20 – 540</td>
<td>2.732 ± 0.011</td>
<td>2.725 ± 0.010</td>
</tr>
<tr>
<td>Helium</td>
<td>20 – 250</td>
<td>2.699 ± 0.040</td>
<td>2.697 ± 0.040</td>
</tr>
</tbody>
</table>

#### Rigidity

<table>
<thead>
<tr>
<th>Type</th>
<th>Rigidity (GV)</th>
<th>Reported</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>21 – 541</td>
<td>-</td>
<td>2.766 ± 0.011</td>
</tr>
<tr>
<td>Helium</td>
<td>42 - 502</td>
<td>-</td>
<td>2.763 ± 0.041</td>
</tr>
</tbody>
</table>

**Graphs:**
- Graph a: Proton K.E
- Graph b: Helium K.E
- Graph c: Proton Rigidity
- Graph d: Helium Rigidity
# CREAM
*(Cosmic Ray Energetics And Mass experiment)*

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>(2.5 – 250) x 10^3</td>
<td>2.66 ± 0.02</td>
<td>2.671 ± 0.034</td>
</tr>
<tr>
<td>Helium</td>
<td>(0.63 – 63) x 10^3</td>
<td>2.58 ± 0.02</td>
<td>2.588 ± 0.032</td>
</tr>
</tbody>
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<td>Helium</td>
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<td>-</td>
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### CAPRICE
*(Cosmic AntiParticle Ring Imaging Cherenkov Experiment)*

#### Proton

<table>
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<th>Calculated</th>
</tr>
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<tbody>
<tr>
<td>Proton</td>
<td>20 – 350</td>
<td>2.75 ± 0.02</td>
<td>2.753 ± 0.017</td>
</tr>
<tr>
<td>Helium</td>
<td>15 – 150</td>
<td>2.67 ± 0.06</td>
<td>2.674 ± 0.055</td>
</tr>
</tbody>
</table>

#### Helium

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<th>Reported</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>21 - 341</td>
<td>-</td>
<td>2.808 ± 0.018</td>
</tr>
<tr>
<td>Helium</td>
<td>32 - 302</td>
<td>-</td>
<td>2.756 ± 0.058</td>
</tr>
</tbody>
</table>

#### Kinetic Energy per nucleon

![Graphs showing the comparison between reported and calculated kinetic energy per nucleon for Protons and Helium.]

- **Proton**
  - $\chi^2 / \text{ndf} = 7.13 / 9$
  - $E_{KE} = 2.753 ± 0.017$
- **Helium**
  - $\chi^2 / \text{ndf} = 3.684 / 5$
  - $E_{KE} = 2.674 ± 0.055$

#### Rigidity

- **Proton**
  - $\chi^2 / \text{ndf} = 5.311 / 9$
  - $E_{KE} = 2.808 ± 0.018$
- **Helium**
  - $\chi^2 / \text{ndf} = 2.68 / 5$
  - $E_{KE} = 2.756 ± 0.058$
### PAMELA
(Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)

#### Kinetic Energy per nucleon

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</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>30 - 1000</td>
<td>2.782 ± 0.003</td>
<td>2.793 ± 0.011</td>
</tr>
<tr>
<td>Helium</td>
<td>15 – 600</td>
<td>2.712 ± 0.010</td>
<td>2.703 ± 0.012</td>
</tr>
</tbody>
</table>

#### Rigidity

<table>
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<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>30-1000</td>
<td>-</td>
<td>2.820 ± 0.010</td>
</tr>
<tr>
<td>Helium</td>
<td>30-1000</td>
<td>-</td>
<td>2.740 ± 0.010</td>
</tr>
</tbody>
</table>

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![Graphs showing kinetic energy and rigidity distributions](image-url)
Combined transformed total differential energy spectrum for protons and helium

Protons fitted in the range of 10 GeV – 10 TeV
\[ \gamma_p = 2.651 \pm 0.001 \]

Helium fitted in the range of 20 GeV – 20 TeV
\[ \gamma_{He} = 2.494 \pm 0.001 \]
Conclusions

- Combined cosmic ray spectrum from satellite and balloon experiments is obtained after transforming those measurements into a single unit.

- Combined differential energy spectrum can be used for further simulation studies, which are relevant to the energy range of $10 \text{ GeV} - 10 \text{ TeV}$ for proton and $20 \text{ GeV} - 20 \text{ TeV}$ for helium primaries.

- The transformation relations derived here may be used by others for conversion into other units of energy spectrum.
Thank You