Direct Cosmic-ray Measurement below knee

Presented by Nahee Park
(University of Chicago)
What are Cosmic Rays?

High energy charged particles, originating in outer space

- Mostly nuclei of atoms (85% proton, 12% helium, 2% heavy nuclei & 1% leptons at $10^9$eV)
- Spectrum follows a smooth power-law distribution over wide energy range
  - Notable spectral features
    - Knee ($\sim 4 \times 10^{15}$eV)
    - Ankle ($\sim 10^{18}$eV)

Scientific Goals:

- What is the origin of CRs?
- How do they get their energies?
- How do they propagate to us?
Galactic Cosmic Rays

Cosmic Ray sources

Tycho's SNR

CR nuclei

CR nuclei

Propagation

(diffusion + spallation + decay + energy loss + convection)

Earth
knee (1 particle per m²-year)

ankle (1 particle per km²-year)

2nd knee

1 particle per m²-sec
What direct measurement can provide

Direct composition measurements

- Can study the composition of the source site of CRs
  - e.g. Super-bubble origin of CRs
What direct measurement can provide

Primary & secondary elemental spectrum

- Important data set to understand the propagation of CRs

Leaky box model (Cowsik et al. 2014)

Nested Leaky box model

Comparison with measurements from 0.5 GeV/n to 3 TeV/n
What direct measurement can provide

Elemental spectrum

- Can study the elemental dependency in acceleration and propagation of CRs

\[ \begin{align*}
&\text{He} \times 10^{-2} \\
&\text{C} \times 10^{-4} \\
&\text{O} \times 10^{-6} \\
&\text{Ne} \times 10^{-8} \\
&\text{Mg} \times 10^{-10} \\
&\text{Si} \times 10^{-12} \\
&\text{Fe} \times 10^{-14}
\end{align*} \]
What direct measurement can provide

Elemental spectrum

- Can study the elemental dependency in acceleration and propagation of CRs
  - e.g. Cut-off energy differences around knee region per each element

![Diagram showing the elemental spectrum and cut-off energy differences around the knee region.](Horandel2007)
What direct measurement can provide

**Elemental spectrum**

- Can study the local accelerators with leptonic spectrum studies
- Multi-TeV electron flux will reflect the local accelerators (<1kpc)

\[ E_{c} = 20\text{TeV}, \tau = 0 - 1 \times 10^{4}\text{yr} \]
\[ D_{0} = 2 \times 10^{29} (\text{cm}^{2}\text{s}^{-1}) \]

Distant component excluding
\[ T \leq 1 \times 10^{5}\text{yr} \text{ and } r \leq 1\text{kpc} \]

- Rockstroh et al. (Radio) 1978
- Golden et al. 1984
- Tang 1984
- Golden et al. 1994
- Kobayashi et al. 1999
- Boezio et al. 2000
- DuVernois et al. 2001
- Torii et al. 2001
- Aguilar et al. 2002

Kobayashi 2004
What direct measurement can provide

**Isotopic flux measurement**

- Measurement of isotopes w/ known half life can provide “time scale” for propagation and acceleration
  - Propagation clock: life time of CRs in our Galaxy
    - Secondary isotopes which decay by $\beta^\pm$ decay
      - e.g. $^{10}$Be: half life of 1.5 Myr
  - Acceleration clock: time delay between nucleosynthesis to acceleration
    - Primary isotopes which decay by electron capture
      - e.g. $^{59}$Ni: half life of $7.6 \times 10^4$ yr
  - Re-acceleration clock: probe potential re-accelerating during the propagation
    - Secondary isotopes which decay solely by electron capture
      - e.g. $^{51}$Cr: half life of 28 days
Recent Experiments

- **ATIC**
- **TRACER**
- **BESS-polar**
- **CREAM**
- **CREST**
- **(Super)-TIGER**
- **PAMELA**
- **ACE-CRIS**
- **AMS-02**
- **CALET**

Timeline from 2003 to 2016:

- **ATIC**
- **TRACER**
- **BESS-polar**
- **CREAM**
- **CREST**
- **(Super)-TIGER**
- **PAMELA**
- **ACE-CRIS**
- **AMS-02**
- **CALET**

Experiments:

- **BACUS/ISS-CREAM**
- **TIGER**
- **S-TIGER**
- **AMS-02**
- **CALET**

Timeline:

- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016

Research periods:

- **ATIC**
- **TRACER**
- **BESS-polar**
- **CREAM**
- **CREST**
- **(Super)-TIGER**
- **PAMELA**
- **ACE-CRIS**
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- **CALET**
Recent Experiments

- **ATIC**
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### Fluxes of Cosmic Rays

- **ATIC** $1 \leq Z \leq 30$
- **PAMELA** $1 \leq Z \leq 6$
- **AMS-02** $1 \leq Z \leq 28$
- **Super-TIGER** $14 \leq Z \leq 42$
- **ATIC** $1 \leq Z \leq 26$
- **TRACER** $4 \leq Z \leq 26$
- **BESS** $1 \leq Z \leq 3$
- **CREST** (leptonic)
- **CREAM** $1 \leq Z \leq 26$
- **CALET** $1 \leq Z \leq 28$

### Flux Calculations

- **ATIC**
  - 43 days (3 flights) $\times 0.25\,\text{m}^2\text{sr}$
  - $=11\,\text{m}^2\text{sr day}$
  - 19 days (2 flights) $\times 5\,\text{m}^2\text{sr}$
  - $=95\,\text{m}^2\text{sr day}$
  - 33 days (2 flights)

- **CREAM**
  - 161 days (6 flights) $\times 0.4\,\text{m}^2\text{sr}$
  - $=64\,\text{m}^2\text{sr day}$
  - 10 days (1 flight)

- **CREST**
  - 105 days (3 flights)
  - 10 years $\times 0.002\,\text{m}^2\text{sr} = 7.2\,\text{m}^2\text{sr day}$
  - 17 years

- **BESS-polar**
  - 5 years $\times 0.05\,\text{m}^2\text{sr} = 91\,\text{m}^2\text{sr day}$

- **(Super)-TIGER**
  - 1 year $\times 0.1\,\text{m}^2\text{sr} = 37\,\text{m}^2\text{sr day}$
  - 10 days (1 flight)

- **AMS-02**
  - 10 years $\times 0.25\,\text{m}^2\text{sr}$
  - $=11\,\text{m}^2\text{sr day}$
  - 105 days (3 flights)

- **CALET**
  - 1 year $\times 0.002\,\text{m}^2\text{sr} = 7.2\,\text{m}^2\text{sr day}$
  - 10 days (1 flight)
Hardening of spectra

Light nuclei spectra measured by PAMELA & AMS-02

- Proton, helium & lithium show spectral break
- Propagation effect?
- Source population?
- Acceleration mechanism?

![Graphs showing flux vs. rigidity and kinetic energy for protons and helium.](image)
Hardening of spectra at heavy nuclei?

Hint of elemental spectra hardening at 200 GeV/n by CREAM?

- w/ ~ 70 days of exposure time (2 flights)

No break observed for preliminary AMS-02 Carbon spectrum?

Ahn et al (2010)
Difference between Proton & Helium

Measured by PAMELA & AMS-02

- Different acceleration? Source population? Propagation effect?

Aguilar et al (2015)
Rise of positron fraction

Measured by PAMELA, AMS-02 & Fermi-LAT

- More positrons than classical propagation estimated
  - Additional sources? (pulsar? SNR? PWN? exotic particle?)
  - Propagation?
No bump in HE leptonic spectrum

AMS-02’s leptonic flux is consistent with a single power-law above 30 GeV
Flattening anti-proton-proton ratio

Including the hardening of CRs, current measurement of anti-proton-proton ratio is consistent with secondary origin of anti-proton
First measurement of primary CR clock - $^{60}$Fe

$^{56}$Fe detected over 16.8 yr of data

- $^{60}$Fe/$^{56}$Fe = $(4.6 \pm 1.7) \times 10^{-5}$
- Half life of $^{60}$Fe : $2.62 \times 10^6$ yr
- Mostly primary particles from core collapse SN

Time between nucleosynthesis to acceleration:
10$^5$ yr < $T$ < several Myr

- Lower bound comes from lack of $^{59}$Ni (half-life $7.6 \times 10^4$ yr)
- $^{60}$Fe has to be accelerated relatively in short time after nucleosynthesis → accelerated by other SNRs nearby
- Source site distance order of kpc
Heavy Nuclei Abundance

Better ordering of refractory & volatiles by mass assuming 20% ejecta from massive stars + 80% Solar system

- Origin of GCR in OB associations
- Refractory elements (dust, grain) are more effectively accelerated than volatile ones (gas)
Summary

Hardening of light nuclei (P, He, Li) spectra at ~ 250 GV
- Will this continue to heavier elements?
  - CREAM data show weak evidence for this
  - No clear hardening of preliminary Carbon spectrum by AMS-02

Different spectral index between Proton & Helium

No clear feature in preliminary B/C ratio

Rise of positron fraction

Issues on CR propagation and local sources
- Kfir Blum

Pulsars as local electron-positron sources
- Matt Kistler

Astrophysical electron-positron factories
- Norita Kawanaka
knee (1 particle per m²-year)

ankle (1 particle per km²-year)

2nd knee?
<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e^+e^-$</th>
<th>CR</th>
<th>UHGCR</th>
<th>gamma</th>
<th>Type</th>
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<td>100 GeV-3 TeV</td>
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<td>p-Fe 10 GeV-1 PeV</td>
<td>26$&lt;Z$$\leq$40 GeV/n</td>
<td>10 GeV-10 TeV X-ray 7-20 MeV</td>
<td>ISS</td>
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<td>ISS-CREAM</td>
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<td>proposal</td>
</tr>
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</table>
Better data set for the propagation studies

Updates on $^{10}\text{Be}$ measurement (by HELIX)

Updates on B/C measurements (by ISS-CREAM, CALET)
Good elemental measurements

Good elemental spectrum measurement of ~ 100 GeV/n - few tens of TeV/n (CALET - 5 yr, ISS-CREAM - 3 yr)

Not good enough to reach knee region?
Study of nearby sources w/ electron HE electron measurement by CALET
Multiwavelength Approach

Cosmic Ray sources

Gamma-ray & neutrino can point to the source!

Earth
Multiwavelength Approach (2)

Galactic diffusive emission
- Gamma-ray
  - Fermi, HESS, ...
- Neutrino?

Anisotropy
- Large scale
- Smaller scale
- HAWC, Ice-top, Tibet,...
Multiwavelength Approach (3)

Source observation in gamma-ray & neutrino

- **SNR**
  - Understanding the acceleration, local diffusion, source population, ...

- Other sources?

- Neutrino sources?

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Galactic neutrinos (from ANTARES to KM3Net)  Veronique Van Elewyck