High Resolution Cosmic Ray Measurements using Next Generation Ground-based Gamma Ray Observatories

David Kieda
University of Utah
Department of Physics
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Outline

• Cosmic Ray Origin
• Existing Origin Signatures
  At Source
  At Earth
• Potential Contributions of Next Generation γ-Ray Observatories
• New Possibilities
Energy Spectrum and Fluxes

Cosmic Ray Acceleration

- Canonical SNR Shock acceleration model
  - Simplified Rigidity dependent acceleration limitation $E_{\text{max}} \sim Z \times 10^{14}$ eV
  - Spectral Steeping with no bump (Knee)
  - Increasing Energy $\rightarrow$ Increasing Mass
γ-Ray Pulsar acceleration

Acceleration of nuclear material from neutron star surface by outer gap electric field of pulsar magnetosphere.

Heavy nuclei injected into medium of expanding Supernova Remnant.

May explain CR origin $10^{15} - 10^{17}$ eV


Propagation/Escape

“Leaky Box” model

- Galactic Magnetic Field
  - Charged Particle Trapping
- Rigidity-dependent escape
- Modifies the power law energy spectrum
- Measurable through energy dependence of secondary B/primary C ratio
- Interstellar Particle density ~ 1 atom/cm$^3$
- CR has to at least pass out of disk then back in again
  - Energy Dependent pathlength with fixed minimum

\[
\lambda_r = \lambda_0 \left( \frac{r}{R_0} \right)^{-\delta'} + \lambda_r \quad \text{gm cm}^{-2}
\]

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B/C ratio and Propagation

Decreasing B/C implies continually decreasing pathlength with increasing energy.


Minimum Pathlength

Pathlength minimum forces higher mass nuclei to breakup into lighter secondary fragments.

Can exact value be extracted from higher energy CR flux normalization w.r.t low energy flux?
“Bump” on the Knee

Toy leaky Box Propagation model
Common Spectral Cutoff

Normalized to JACEE/CRN/HEAO-3 fluxes ~ TeV

Tsao-Silberberg cross-sections (Kieda & Swordy 2001)

Almost no nuclei broken up

Indirect Experimental Evidence

No Direct Evidence of origin due to diffusive propagation of charged CR to earth

Emission of Radio/X-Ray/γ-rays by SNR (at source)

Cosmic Ray Energy spectrum, composition measurements (at Earth)
TeV $\gamma$-ray SNR Observations

SN1006 SNR detection
CANGAROO collaboration
Tanimori et al
Consistent with IC emission
Hadronic $\pi^0$ production/decay not necessary

RXJ1713.7-3946


$e^\pm$ synchroton
IC

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Energy Spectrum

• Location of the Knee?
• Bump on the knee?

(C.G. Larsen et al, Proc. 27th ICRC, Hamburg (2001))

Nuclear Composition

Extensive Air Shower development profile
- depth of shower maximum -> primary mass
Nuclear Composition

- Mixed Composition
- Insufficient resolution to examine propagation effects
- New CR source appears above the knee

Ground Based Systematics

- Poor Charge/Energy Resolution
  Only coarsest origin features barely discernable
- Energy Dependence of Composition Parameter
  Error in energy -> error in charge measurement
- Interaction Model Dependency
  Clouds any astrophysical interpretations
Direct Cherenkov Light

- Emitted before primary CR nuclear interaction
- Narrow angle emission (0.25 degree), distinct from main EAS Cherenkov
- Light arrives 3-6 nsec late compared to main EAS Cherenkov
- Distinct from main Cherenkov emission out to radius of ~100m from shower core
  - Proportional to Z^2, independent of energy
- 0.25 degree gap between DC emission and main EAS Cherenkov

At balloon height

At Ground

100 TeV Z=26 Vertical
5 TeV Z=4 Vertical

DC Light Emission Threshold

- Lower limit set by Minimum Lorentz factor
- Maximum Energy set by Obscuration by Secondary Cherenkov light
- Measurement window expands with increasing Z
**Expected Charge Resolution**

Factors:
- Core Location Error
- Secondary Cerenkov Light
- First Interaction Fluctuations
- Mie/Rayleigh Scattering
- Angular Trajectory Error
- Night Sky Background
- Photostatistics

**Existing IACT Array Data**

- 7 Telescope Array (ICRR)
- HEGRA Telescopes (Max Planck)
7 Telescope Array Data

Pixel size approaches resolution to possess sensitivity to DC light : (0.25 degree)

Mirror area is small : ~ 10 sq m

Stereo Reconstruction : available

Best chance for success:
   Look for Iron nuclei or heavier
   Direct Cherenkov Threshold > 10 TeV

Selection criteria:
   • Two or more telescopes
   • Core distance to each telescope different
   • Core distance to each telescope 50-120 m
   • High energy showers (E > 10 TeV)
   • DC light pixel has large excess (> 2 \sigma) in geometry predicted location
   • DC light pixel has gap to main (secondary) Cherenkov light from EAS
   • Ratio of light at two core distances consistent with expectations from Monte Carlo Simulation

~1000 hours stereo Data:
Reconstruct Core position, direction from stereo imaging

Simple Cuts:
   a) 40 m < Core < 150 m
   b) 1 pixel with > 70 photons
      & surrounding pixels < 20 photons
      or
   2 adjacent pixel sum > 70 photons
      & surrounding pixels < 20 photons each
   c) More than 10 pixels/telescope over 10 photons/pixel
   d) More than 2 telescopes in event

Cuts 60,000 stereo events -> 10 events
Have not yet exploited additional DC light geometrical constraints
IACT Detection rate

Typical IACT aperture:

1) Require shower to hit within $2^\circ$ telescope axis
   -> $10^{-3}$ sr
2) Require core to hit between 60-120 m from central telescope: 8400 m$^2$
3) 800 hours operation/year
4) Flux of Iron > 20 TeV ~ 1/m$^2$/day

-> typical IACT telescope array
(VERITAS, HESS, CANGAROO)
will detect 0.012 iron/hour
or
~ 10 high resolution iron nuclei/year in stereo mode

(Factor of 2x more if telescope pairs point in different directions).
High Resolution Charge Measurements: UH nuclear fluxes

- UH nuclei: r, s in SN Nucleosynthesis
- SNR accelerates swept-up ISM material in vicinity of SNR (concentrated strongly in OB associations)
- Common spectral features between UH nuclei and light nuclei?
  Common Acceleration process?
- UH nuclei inherently fragile (compared to Fe).
  Can UH nuclei survive the acceleration process?
- Fe to UH ratio probes acceleration process
  short, fast (superbubbles of multiple SNRs).
  long, slow (isolated SNR expansion into ISM)
- Probe of acceleration region environment
  photodissociate UH nuclei but not light nuclei

UH nuclear fluxes
PeV UH nuclear measurements

counts / bin

Cherenkov slope


500 TeV Z=100 45 degree zenith

runsum_500TeV_45deg_100_80m
DC Light Emission Threshold

- Low flux of PeV UH nuclei requires extremely large detection area (>20,000 m² sr)
- Impossible for satellite/balloon (<100 m² sr)
- Only ground based, wide FOV instrument has sufficient aperture

Schematic DC Observatory

- Fixed mount, vertical
- Wide Field of View: 45-60 degree
- Multiple stations separated by ~80 m spacing
  - Detect several 1000 Fe/year at knee with 5% charge resolution
  - Detect several UH/year around 1 PeV with 5% charge resolution
  - Wide FOV TeV transient γ-ray monitor
  - Measure Nuclear/Particle Interactions with tagged Z cosmic beam
All Sky \(\gamma\)-Ray Monitoring
(3m diameter prototype)

CPAX Proposal (NSF 2002) Center for Particle Physics

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Quark Matter Stars: A new Form of Matter?

Chandra X-ray Image of RXJ1856.5-3754
Is RXJ1856.5-3754 a Quark Star? (Drake et al. AP. J 2002) astro-ph/0204159

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Summary

- **Cosmic Ray Origin Signatures**
  - At Source: Particle acceleration observed
    - Lepton acceleration certainly present
    - Hadronic acceleration controversial
  - At Earth: Definitive conclusions are limited by experimental sensitivity, resolution

- **Next Generation Gamma Instruments**
  - Probe origin at Source (with radio, x-Ray)
  - New Potential for High resolution charge measurement at Earth
  - Explore nuclear/particle fragmentation, cross sections with tagged nuclear beam
  - Electron/Proton rejection (17m+ mirror)

- **Future Dedicated Wide FOV Observatory**
  - Unknown PeV UH nuclei (Z > 30) flux
  - Common origin/acceleration with lighter nuclei?
  - Can UH nuclei survive acceleration speed/environment?
  - All sky gamma monitor for episodic TeV flares/GRBs
  - Probe existence of unusual charge states in Cosmic Ray Flux