Cosmic Rays in large air-shower detectors

2. The cosmic-ray spectrum from Galactic to Extra-galactic
Cascade equations

For hadronic cascades in the atmosphere

\[ \frac{dN_i(E, X)}{dX} = - \left( \frac{1}{\lambda_i} + \frac{1}{d_i} \right) N_i(E, X) + \sum_j \int \frac{F_{ji}(E_i, E_j) N_j(E_j)}{E_i} \frac{N_j(E_j)}{\lambda_j} dE_j, \]

\( X = \) depth into atmosphere \hspace{1cm} \( d = \) decay length

\( \lambda = \) Interaction length

Boundary conditions at top of atmosphere:

Primary spectrum:

\[ N(E, 0) = N_0(E) = \frac{dN}{dE} \approx 1.8 E^{-2.7} \text{ nucleons} \frac{\text{cm}^2 \text{ sr s GeV/A}}{\text{cm}^2 \text{ sr s GeV/A}} \]

Single nucleus

\[ N(E, 0) = A \delta(E - \frac{E_0}{A}), \]
Inclusive flux  EAS
\( \pi^\pm \) in the atmosphere

\[
\frac{d\Pi}{dX} = -\Pi(E, X) \left( \frac{1}{\Lambda_\pi} + \frac{\epsilon_\pi}{EX \cos \theta} \right) + \frac{Z_N \pi}{\lambda_N} N_0(E) e^{-X/\Lambda_N}.
\]

Solution for power-law boundary condition:
secondary spectrum proportional to primary \( N_0(E) \)

\[
\Pi(E, X) = e^{-(X/\Lambda_\pi)} \frac{Z_N \pi}{\lambda_N} N_0(E) \int_0^X \exp \left[ \frac{X'}{\Lambda_\pi} - \frac{X'}{\Lambda_N} \right] \left( \frac{X'}{X} \right)^{\epsilon_\pi/Ex \cos \theta} dX'.
\]

(3.30)

\[ Z_{ac} \equiv \int_0^1 (x_L)^{\gamma-1} F_{ac}(x_L) \, dx_L, \quad \frac{1}{d_\pi} = \frac{m_\pi c^2 h_0}{E c \tau_\pi X \cos \theta} \equiv \frac{\epsilon_\pi}{E X \cos \theta}. \]

\( \pi \) decay or interaction more probable for \( E < \epsilon_\pi \) or \( E > \epsilon_\pi = 115 \text{ GeV} \)
$\mu$ and $\nu_\mu$ in the atmosphere

- To calculate spectra of $\mu$ and $\nu$
  - Multiply $\Pi(E,X)$ by pion decay probability
  - Include contribution of kaons
    - Dominant source of neutrinos
  - Integrate over kinematics of $\pi \rightarrow \mu + \nu_\mu$
  - Integrate over $K \rightarrow \mu + \nu_\mu$
  - Integrate over the atmosphere ($X$)
  - Good description of data
Solution for air showers

• Same set of equations subject to
  – \( N(E,0) = A \delta( E – E_0/A) \)
  – \( \Pi(E,0) = K(E,0) = 0 \)

• Analytic approximate solutions possible
  – Compare Rossi & Greisen (1941) e-m cascades

• In practice need Monte-Carlo simulations
  – SIBYLL 2.1 R. Engel et al., 26th ICRC (199) & E-J Ahn et al. 0906.4113
Structure of EAS

• Primary nucleus interacts
  – Core of energetic hadrons
    • $\pi^\pm$, K interact; feed core
    • $\pi^0$ decay at production, generate e-m subshowers
    • $\pi^\pm$, K with $E < \varepsilon_{\text{critical}}$ decay
      – $\rightarrow \mu$ and $\nu$
      – TeV $\mu$ and $\nu$ produced with lower probability $\sim 1 / E$
  – $e^\pm$ in e-m cascade dissipate most energy
  – $\sim 2.2$ MeV per g/cm$^2$ per charged particle ionizes the air

• Measure $dE/dX$ via atmosphere fluorescence (Fly’s Eye technique)

• Measure $e^\pm$ and $\mu$ at the ground
  – Relate to energy via simulations

Seattle, July 2, 2009

Tom Gaisser

“Knock-Knock” a sculpture by Eva Rothschild, Tate Britain
UHE shower detectors

Hi-Res stereo fluorescence detector in Utah

AGASA (Akeno, Japan)
100 km² ground array

Sketch of ground array with fluorescence detector – Auger Project realizes this concept

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Hi-Res / AGASA circa 2003

- Where is the “end” of the cosmic-ray spectrum?
- Expect suppression for $E > 5 \times 10^{19}$ eV from energy loss in the CMB
  - $p \gamma \rightarrow N \pi X$ and
  - $A \gamma \rightarrow A' +$ nucleons
Akeno-AGASA / HiRes: comparison of what is measured
5σ Observation of the GZK Suppression (mono)

- Broken Power Law Fits (independent data)
  - No Break Point
    - $\chi^2$/DOF = 162/39
  - One BP
    - $\chi^2$/DOF = 63.0/37
    - BP = 18.63
  - Two BP's
    - $\chi^2$/DOF = 35.1/35
    - 1st BP = 18.65 +/- .05
    - 2nd BP = 19.75 +/- .04
  - BP with Extension
    - Expect 43.2 events
    - Observe 13 events
    - Poisson probability: $P(15; 51.1) = 7 \times 10^{-8} (5.3 \sigma)$
Auger spectrum compared to HiRes

M. Roth, Socor 2009

With a cosmological evolution of the source luminosity of \((z + 1)^m\)
(de) constructing the extra-galactic spectrum

Doug Bergman et al. (HiRes), Proc 29th ICRC, 7 (2005) 315
Energy loss in CMB + radio

Particles with $E > 50$ EeV come from $< 100$ Mpc
--Look for point sources

FIG. 10. The energy attenuation lengths for cascade photons and for protons as a function of energy assuming the radiation background photon spectrum shown in Fig. 2. These curves were obtained by running the code over small distances and ignoring the production of non-leading particles, which corresponds to the CEL approximation.
Active Galactic Nuclei as cosmic accelerators

Auger Collaboration:

20 of 27 events with E > 57 EeV are within 3.1 degrees of an AGN less than 75 Mpc away. Centaurus-A (4 Mpc, white dot) is especially prominent.

( 57 EeV = 0.01 Joule )
( 1 Mpc = 3 million light years )

• AGN are cosmic accelerators
• Accelerated protons may (or may not) interact in or near the sources to produce neutrinos
• Neutrinos could discriminate
Auger AGN correlation – ICRC 2009

• Data to 31 August 2007 (Science, 9 November 2007)
  – Control sample: 14 events used to define cuts
  – After control sample, 9 of 13 with $E > 55$ EeV events fell within $3.1^\circ$ of a nearby ($z < 0.018$) AGN in the VCV catalog

• Data from 01 Sept 2007 – 31 March, 2009
  – 8 of 31 events satisfy criteria

• Total data after control sample
  – 17 of 44 events satisfy pre-determined criteria
  – Chance probability < 1% from an isotropic distribution

• Note prominence of area around Cen-A
  – Could see $\gamma$ from first generation $p + \text{CMB} \rightarrow p + \pi^0$
    • Taylor et al., arXiv:0904.3903
The “Hillas Plot” (1984)

- $E_{\text{max}} \sim \beta_{\text{shock}} (\text{ZeB}) R$
- Plot shows B, R to reach $10^{20}$ eV
- Two more candidates since 1984
- Active Galaxies, Gamma-ray Bursts favored
A common phenomenon on both stellar & galactic scales:
Matter falls onto black hole or neutron star driving collimated, relativistic jets perpendicular to the disk
Acceleration can occur both at remote termination shocks and at internal shocks near the central engine

VLA image of Cygnus A
An active galaxy

Seattle, July 2, 2009
Tom Gaisser

M. Urry, astro-ph/0312545
Where is the transition from galactic to extra-galactic CR?

- Model galactic component
- Subtract from observed to get extragalactic

Transition predicted:

$10^{16.5}$ to $10^{17.5}$ eV

Berezhko & Völk
Or start with a model of the extra-galactic component

Subtract it from the observed spectrum to get the galactic component

Allard, Olinto, Parizot,

3 x 10^{17} eV

3 x 10^{18} eV

What is power needed for extra-galactic CR?
Energy content of extra-galactic component depends on location of transition

- Composition signature: transition back to protons

**Uncertainties:**
- Normalization point: $10^{18}$ to $10^{19.5}$ used
  Factor 10 / decade

- Spectral slope
  Steeper spectrum requires more power ($\alpha=2.3$ for rel. shock
  But $E_{\text{min}} \sim m_p (\gamma_{\text{shock}})^2$)
Power needed for extragalactic cosmic rays assuming transition at \(10^{19}\) eV

- **Energy density in UHECR**, \(\rho_{CR} \sim 2 \times 10^{-19}\) erg/cm\(^3\)
  - Such an estimate requires extrapolation of UHECR to low energy
  - \(\rho_{CR} = (4\pi/c) \int E\phi(E) \, dE = (4\pi/c)[E^2\phi(E)]_{E=10^{19}\text{eV}} \times \ln\{E_{max}/E_{min}\}\)
  - This gives \(\rho_{CR} \sim 2 \times 10^{-19}\) erg/cm\(^3\) for differential index \(\alpha = 2\), \(\phi(E) \sim E^{-2}\)

- **Power required** \(\rho_{CR}/10^{10}\) yr \(\sim 1.3 \times 10^{37}\) erg/Mpc\(^3\)/s
  - Estimates depend on cosmology and assumed spectral index:
    - \(3 \times 10^{-3}\) galaxies/Mpc\(^3\) \(\sim 5 \times 10^{39}\) erg/s/Galaxy
    - \(3 \times 10^{-6}\) clusters/Mpc\(^3\) \(\sim 4 \times 10^{42}\) erg/s/Galaxy Cluster
    - \(10^{-7}\) AGN/Mpc\(^3\) \(\sim 10^{44}\) erg/s/AGN
    - \(\sim 1000\) GRB/yr \(\sim 3 \times 10^{52}\) erg/GRB
Power for “B” component

\[ E_{\text{max}} = Z \times 1 \text{ PeV} \]

Depends on

- diffusion model, \( \tau(E) \)
- \( \gamma \) of source acceleration
- onset of extra-galactic

Galactic “B” component
Power needed for knee B-component

- Integrate to $E > 10^{18}$ eV assuming
  - $\tau_{\text{esc}} \sim 2 \times 10^7$ yrs $\times E^{-1/3}$
  - Source spectral index $\sim 2.1$
  - $V_{\text{galaxy}} \sim \pi (15 \text{ kpc})^2 \times 200 \text{ pc} \sim 3 \times 10^{66} \text{ cm}^3$
  - Total power for “B” component $\sim 2 \times 10^{39}$ erg/s

- Possible sources
  - Sources may be nearby
  - E.g. $\mu$-quasar SS433 at 3 kpc has $L_{\text{jet}} 10^{39}$ erg/s
  - Eddington limited accretion $\sim 2 \times 10^{38}$ erg/s
  - Neutron source at GC $\sim 10^{38}$ erg/s

- Speculations call for more experiments
Model dependence of composition in galactic-extragalactic transition

Allard, Olinto, Parizot, astro-ph/0703633

- Model extragalactic component
- Subtract from observed to get galactic component
Composition with air showers

- Proton penetrates deep in atmosphere
  - Shower max deeper
  - $(\mu/e)$ smaller
  - Muons start deeper

- Heavy nucleus cascade starts high
  - Shower max higher up
  - $(\mu/e)$ larger
  - Muons start higher
$X_{\text{max}}$ for composition

- $\langle X_{\text{max}} \rangle = \text{const} + \Lambda \log(E / A)$
- Interpretation depends on comparison to simulations of cascade development
  - Different models give different results
  - Extrapolations to high-energy differ
    - Need minimum bias data outside central region
    - LHCf can help
- Distributions of $X_{\text{max}}$ less model-dependent
- Also look at $\mu / e$ with ground arrays
Depth of maximum via air
Cherenkov or fluorescence

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Fluorescence Detector: Longitudinal Shower Profiles

M. Unger, Socor 2009

- event 3262296, LM
- event 7294424, LM
- event 4871069, CO

- event 4742735, LM
- event 2694024, LL
- event 5153530, CO
Auger Depth of Maximum

Auger, HiRes Comparison
M. Unger, Socor 2009

Fluctuations suggest transition to significant fraction of heavy nuclei
HiRes Xmax results consistent with protons $> EeV$

Pierre Sokolsky, Socor, June 2009

Fig. 28.— Results of fitting HiRes stereo data $X_{\text{max}}$ distribution to Gaussian truncated at $2 \times$ RMS (black points). Superimposed are curves representing expectations based on QGSJET1 and QGSJET2 proton and iron Monte Carlo. Gaussian-in-age parametrization used in reconstruction.

Fig. 25.— Comparison of current HiRes stereo $X_{\text{max}}$ results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).
Xmax: comparison to simulations

Summary of Xmax and comparison to simulations: Klaus Werner, Paris June 09
Muon density AUGER

\[ \log_{10} \rho_{\mu} (1000 \text{ m}) \text{ [m}^{-2}] \]

\[ \log_{10} E_{\text{CIC}} \text{ [eV]} \]

- AUGER - LAL method
- proton
- iron
- SIBYLL 2.1
- QGSJet II-3
- EPOS 1.6

PRELIMINARY
Why more muons in EPOS?

... because EPOS produces more baryons

Baryon = no $\pi^0 \rightarrow$ no EM cascade

$\rightarrow$ chance to make muons
Searching for the Origins of Cosmic Rays, Trondheim, June 2009
KASCADE-Grande

Composition results promised for ICRC  Andreas Haungs, Socor2009
Plans to decrease the thresholds of Auger and TA

• Auger SD threshold 3 EeV, FD is 1 EeV
  – Goal: lower threshold to 0.1 EeV = 10^{17} \text{ eV}
  – HEAT consists of 3 FTs viewing 30° to 60°
  – AMIGA is an in-filled surface array

• TA threshold 3 EeV
  – Goal: lower threshold to 3 \times 10^{16} \text{ eV}
  – TALE FD: 3 FDs including higher viewing angle
  – Overlooking a graded infill array
Layout of Auger enhancements. White and black lines show the six original and three enhanced telescopes FOVs, respectively. Grey, white and black dots indicate SDs plus buried muon counters placed 433, 750, and 1500 m apart, respectively. In this area a further enhancement of radio detection of extensive air showers will start its R&D phase [3].

A. Etchegoyen et al., ICRC2007 #1307
Seattle, July 2, 2009

Tom Gaisser

125 m

IceCube:
Neutrino telescope & cosmic-ray detector

Seattle                                      Tom Gaisser

Photo: James Roth 17-12-2007
Cosmic-ray physics with IceCube

- Goal:
  - Composition, & spectrum
  - $10^{15}$ – $10^{18}$ eV
  - Use coincident events
  - Look for transition to extra-galactic cosmic rays

Seattle, July 2, 2009  Tom Gaisser  IceTop 40

(plus 19 stations planned for 08/09)
Cross checks

• Kascade-Grande, IceCube, TALE and Auger infill ground arrays
  – Include separate detectors for $\mu$ and e-m components
  – $\mu / e$ and $X_{\text{max}}$ depend on composition in different ways
  – In principle allows breaking degeneracy between composition and hadronic interactions
High-energy cosmic rays: key questions

• What is the composition through the knee region?
  – Need more direct measurements for calibration

• How to make a complete picture of galactic cosmic rays?
  – Isotropy / propagation problem
  – Non-linear acceleration $\rightarrow$ hard source spectrum
  – How many sources?

• What interaction model to use?

• Where is transition to extra-galactic population?
  – Is there a Galactic component “B”?
  – Are there nearby extra-galactic sources of UHECR?

• What are the sources of the highest energy particles?
  – Do they accelerate primarily protons or a mixture of nuclei?
  – Heavy component of $>50\text{EeV}$ particles cannot point to sources because of bending locally in galactic magnetic field

• Look for cosmogenic neutrinos (a.k.a. GZK neutrinos)
neutrinos from GZK interactions

Slide by Francis Halzen