Charged Cosmic Rays and Neutrinos

Michael Kachelrieß

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Outline of the talk

1. Introduction  ⇒ talk by F. Halzen

2. SNRs as Galactic CR sources

3. Extragalactic CRs
   - transition
   - anisotropies
   - composition measurements

4. Astrophysical source models  ⇒ talks of S. Ando & F. Halzen

5. Cosmogenic neutrinos

6. Summary
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HE neutrinos and HE photons are unavoidable byproducts of HECRs

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- **top-down models:**
  - large fluxes with $I_\nu \gg I_p$
  - ratio $I_\nu/I_p$ fixed by fragmentation
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- prizes to win:
  - astronomy above 100 TeV
  - identification of CR sources
  - determine galactic–extragalactic transition of CRs
  - test/discover new particle physics
Diffusive shock acceleration in test particle picture:

- energy spectrum \( dN/dE \propto 1/E^2 \)
- escape flux \( dN/dr \propto \exp\left(-\left(r - R_{sh}\right)/x_0\right) \) for \( r > R_{sh} \)
SNR: Leptonic versus hadronic models

SNRs as CR sources

Test the SNR CR acceleration paradigm through SNR’s particle radiation:

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SNR: Leptonic versus hadronic models

- combining Fermi and IACT contrains models tightly
Maximal energy of SNR: Lagage-Cesarsky limit

- acceleration rate

\[ \beta_{\text{acc}} = \frac{dE}{dt}_{\text{acc}} = \frac{3E \nu_{sh}^2}{\zeta D(E)} , \quad \zeta \sim 8 - 20 \]
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\[
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- assume Bohm diffusion \( D(E) = cR_L/3 \propto E \) and \( B \sim \mu G \)
SNRs as CR sources

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- assume Bohm diffusion \( D(E) = cR_L/3 \propto E \) and \( B \sim \mu G \)

\[ \Rightarrow E_{\text{max}} \sim 10^{13} - 10^{14} \text{ eV} \]
Maximal energy of SNR:

- (resonant) coupling CR $\leftrightarrow$ Alfven waves
Maximal energy of SNR:

- (resonant) coupling CR ↔ Alfvén waves
- non-linear non-resonant magnetic field amplification
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- observational evidence for $B \sim 0.1 - 1 \text{ mG}$ in young SNR rims
changes on $\delta t \sim 1\,\text{yr}$ imply $B \sim 1\,\text{mG}$

$\Rightarrow \ E_{\text{max}} \sim 10^{16}\,\text{eV}$ for protons
SNRs as CR sources

Tycho observations by VERITAS

\[ \Gamma = 1.95 \pm 0.51_{\text{stat}} \pm 0.30_{\text{sys}} \]
Tycho observations by VERITAS
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- CRs escape before Sedov phase
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- $E_{\gamma,\text{max}} > 10$ TeV requires:
  - protons with $E > 100$ TeV
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  - electrons, ICS on CMB

\[
E_\gamma = \frac{4 \varepsilon_\gamma E_e^2}{3 m_e^2} \approx 3 \text{ GeV} \left( \frac{E_e}{1 \text{ TeV}} \right)^2
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\]

electrons with $E > 50$ TeV
Tycho: Leptonic versus hadronic models

[Morlino, Capriolo '11]
Why is there a universal CR spectrum?

- age-limited
  - CRs are advected down-stream, released at end of Sedov phase
  - adiabatic losses, reduced $E_{\text{max}}$, no $B$ amplification
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- CRs escape up-stream:
  - standard approach: homogeneous field & free escape boundary
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[Reville, Bell '11]
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[Reville, Bell ’11]
Transition – KASCADE Grande data
Transition from Galactic to extragalactic CRs

Nuclear composition

Transition – KASCADE Grande data

rising proton fraction $E \gtrsim 10^{17}$ eV?
PAO result on dipole anisotropy:

\[ \text{Amplitude} \]

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 1 \]

\[ \text{E [EeV]} \]

Rayleigh Analysis
East/West Analysis
PAO result on dipole anisotropy:

Phase [°] vs. E [EeV]

- **East/West analysis**
- **Rayleigh analysis**

- **Graph**
  - X-axis: E [EeV]
  - Y-axis: Phase [°]
  - Data points with error bars
  - Trend line

- **Data Points**
  - East/West analysis: Blue circles with error bars
  - Rayleigh analysis: Red squares with error bars

- **Axis Labels**
  - X-axis: E [EeV] from 0.3 to 20
  - Y-axis: Phase [°] from 180 to 0

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Anisotropy of protons at $E = 10^{18}$ eV

protons excluded for all reasonable parameters

⇒ measuring protons at $E = 10^{18}$ eV means fixing transition energy
Energy spectrum

- PAO confirmed the “GZK-suppression” seen first by HiRes
Energy spectrum

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- Interpretation:
  - $E_{\text{max}}$ of sources?
  - does not fix composition: proton GZK, Fe photo disintegration
Determining nuclear composition: $X_{\text{max}}$ and $\text{RMS}(X_{\text{max}})$

- Bethe-Heitler model: $N_{\text{max}} \propto E_0$ and $X_{\text{max}} \propto \ln(E_0)$
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$\Rightarrow X_{\text{max}} \propto -\ln(A)$ and $\text{RMS}(X_{\text{max}})$ reduced
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$\Rightarrow X_{\text{max}} \propto -\ln(A)$ and $\text{RMS}(X_{\text{max}})$ reduced

- $\text{RMS}(X_{\text{max}})$ has smaller theoretical error than $X_{\text{max}}$
Nuclear composition via $X_{\text{max}}$:

![Graph showing nuclear composition via $X_{\text{max}}$.](image-url)
Nuclear composition via $\text{RMS}(X_{\text{max}})$ from Auger:

\[
\begin{align*}
\text{RMS}(X_{\text{max}}) \text{ [g/cm}^2\text{]} & \quad \text{E [eV]} \\
\text{proton} & \quad 10^{18} \quad 10^{19} \\
\text{iron} & \quad 10^{18} \quad 10^{19}
\end{align*}
\]
Mixed composition:

\[ \sigma^2 = \sum_i f_i \sigma_i^2 + \sum_{i<j} f_i f_j (X_{\text{max},i} - X_{\text{max},j})^2 \]
What goes wrong?

- internal discrepancy in PAO:
  - AGN correlations favor protons
  - $\text{RMS}(X_{\text{max}})$ favors heavy
  - energy spectrum, $X_{\text{max}}$ and $\text{RMS}(X_{\text{max}})$ difficult to fit

- experimental discrepancy: HiRes/TA ⇔ Auger
  - $X_{\text{max}}$
  - $\text{RMS}(X_{\text{max}})$

- discrepancy experiment ⇔ theory:
  - energy ground array/fluorescence $\sim 1.2$
  - muon number exp/MC $\sim 1.2 - 2$
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Comparison of MCs to LHC data: Energy flow

PYTHIA as typical HEP model

Cosmic ray interaction models
Fermi-LAT limit for cosmogenic neutrinos:

$z_{\text{max}} = 2$, $E_{\text{max}} = 10^{21}\text{eV}$

[Berezinsky et al. '10, ...]
Fermi-LAT limit for cosmogenic neutrinos: 

$z_{\text{max}}=2; E_{\text{max}}=10^{21}\text{eV}; m=0$

HiRes II

HiRes I

$\Sigma \nu_i$

$E, \text{eV}$

$E^3J(E) \text{eV}^2\text{m}^{-2}\text{sec}^{-1}\text{ster}^{-1}$
Fermi-LAT limit for cosmogenic neutrinos: \[\text{[Berezinsky et al. '10, ...]}\]
Cosmogenic neutrinos

Limit from EGRB

Fermi-LAT limit for cosmogenic neutrinos:

\[\nu : \nu_e : \nu_\tau = 1:1:1\]

- Auger diff.
- ANITA
- BAIKAL
- Auger
- ANITA-lite
- RICE
- JEM-EUSO
- IceCube 5yr
- \(E^2 \text{cascade}\)

\(E, \text{ eV}\)

\(E^2 J(E), \text{ eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\)
Fermi-LAT limit for cosmogenic neutrinos:

\[ \text{[Berezinsky et al. '10, ...]} \]

\[ E^2 J(E), \text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

\[ 0.01 \text{ nG} \]
\[ 1 \text{ nG} \]

\[ m=0, \alpha_g=2.0, z_{\text{max}}=2, E_{\text{max}}=10^{21} \text{eV} \]
Cosmogenic neutrinos: proton vs. Fe

\[ \text{Anchordoqui et al. '07} \]

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Summary

- **Galactic CRs:** *Tycho:* room left for *leptonic* models marginal

- **UHECRs:**
  - understanding differences PAO vs. TA and MC vs. experiment
  - extensions (HEAT, Amiga, infill array) allow cross checks
  - test of MC models against LHC data
  - proton dominance at $10^{18}$ eV fixes transition energy

- *cosmogenic neutrino flux is low,* because of Fermi limit

- 2 Icecube events: start of neutrino astronomy?
New TA data for $X_{\text{max}}$: 

![Graphs showing $X_{\text{max}}$ data for HiRes and TA.](image)
Zenith angle dependence, TA scintillator:

Data/MC Comp. (TA-SD, Zenith angle)

QGSJET-II p, E > 10^{18.0} eV

QGSJET-II Fe, E > 10^{18.0} eV
Zenith angle dependence, TA scintillator:

**Data/MC Comp. (TA-SD, Zenith angle)**

**QGSJET-II p, E > 10^{19.0} eV**

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<th>$\chi^2$/ndf</th>
<th>9.516 / 7</th>
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<td>const</td>
<td>0.8639 ± 0.0996</td>
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<tr>
<td>slope</td>
<td>0.004327 ± 0.00334</td>
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**QGSJET-II Fe, E > 10^{19.0} eV**

<table>
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<tr>
<th>$\chi^2$/ndf</th>
<th>11.08 / 7</th>
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<tbody>
<tr>
<td>const</td>
<td>0.574 ± 0.088</td>
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<tr>
<td>slope</td>
<td>0.0152 ± 0.0032</td>
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</tbody>
</table>
Icecube events

- 2 cascade events close to $E_{\text{min}} = 10^{15} \text{ eV}$, bg = 0.14
Icecube events

- 2 cascade events close to $E_{\text{min}} = 10^{15} \text{ eV}$, bg = 0.14
- **Glashow resonance**
  - very narrow
  - if $W^- \rightarrow \bar{q}q$, detected energy too low
Icecube events

- 2 cascade events close to $E_{\text{min}} = 10^{15} \text{ eV}$, bg = 0.14
- Glashow resonance
- cosmogenic neutrinos: $\lesssim 1$ events/yr

[Anchordoqui et al. '07]
Icecube events

- 2 cascade events close to $E_{\text{min}} = 10^{15}$ eV, bg = 0.14
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- extragalactic sources: extension to higher energies? if yes, then diffuse flux
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- Glashow resonance
- cosmogenic neutrinos: $\lesssim 1$ events/yr
- extragalactic sources: extension to higher energies?
  if yes, then diffuse flux
- **Galactic point sources**: SNR with $d \sim 50$ pc