Energy-Dependent Composition of UHECRs and the Future of Charged Particle Astronomy.
Outline

• The cosmic ray spectrum

• The current hunt for possible sources

• The Pierre Auger Observatory (PAO) and its energy-dependent chemical composition

• Diffusion

• The role of galactic sources, anisotropy, and spectral features
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- The cosmic ray spectrum
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- The Pierre Auger Observatory (PAO) and its energy-dependent chemical composition
- Diffusion
- The role of galactic sources, anisotropy, and spectral features

[AC, Kusenko, Nagataki]
- $E < 1\text{ GeV}$ solar modulation make studies of the primary cosmic ray spectrum very complex

- $1\text{ GeV} < E < 10^9\text{ GeV}$
  - galactic origin
  - $E > 10^5\text{ GeV}$ supernova explosion into stellar wind
  - Spectral feature around $3 \times 10^6\text{ GeV}$: "knee"
  - Rigidity dependent transition
  - Probe of the magnetic spectrum
  - Second spectral break around $10^{8.6}\text{ GeV}$: "second knee"?
• $E > 10^9$ GeV Ultra High Energy Cosmic Rays (UHECRs)
  – Transition from galactic to extragalactic sources: "ankle"
  – "Pair production dip", consistent with proton primary and galactic to extragalactic transition at the second knee
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• Lack of galactocentric anisotropy

These reasons seem compelling, but are they supported by the latest data?
Auger Anisotropy Study

Auger PRL 104 (2010) 091101
Auger Anisotropy Study

- Correlation with AGNs originally confirmed at $>99\%$
- Signal has decreased over time but still disfavors the null hypothesis
HiRes Anisotropy Study
Auger energy-dependent chemical composition

[Auger PRL 104 (2010) 091101]
The change in composition is corroborated by the Yakutsk experiment, but not by the HiRes experiment!
Could there be another explanation?

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  - Collapsars
  - Unusual Supernovae
  - GRBs
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- **Gyroradius incompatible with particle confinement** *unless* $Z$ *is large*

- **Lack of galactocentric anisotropy compatible with large $Z$**
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Are we probing a different mode of the magnetic spectrum?
Two different regimes depending on the energy of the particle
**Diffusion**

**Critical energy** $E_0$ where $r_L = l_c$

For $E < E_0$, we get $l_c >> r_L$

- mean free path $\sim l$
- $D = \frac{l}{3} \equiv D_0$

For $E > E_0$, we get $l_c \sim r_L$

- random walk
- mean free path $>> l$
- $D = D_0 \left( \frac{E}{E_0} \right)^2$
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$E_0$ depends on the charge of the nuclei
For a particle with charge $q_i = eZ_i$, we get a critical energy $E_{0,i}$ with $r_{L,i} = l_c$:

- $r_{L,i} = \frac{E}{Bq_i}$

- $E_{0,i} = eBl_cZ_i$

- $E_{0,i} = Z_i \times (10^8 \text{ eV}) \left( \frac{B}{3 \times 10^{-6} \text{ G}} \right) \left( \frac{l_c}{0.3 \text{ kpc}} \right)$
Diffusion with Non-Unit Charge

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The diffusion coefficient is therefore:

$$D_i(E) = \begin{cases} 
D_0 \left(\frac{E}{E_{0,i}}\right)^{\delta_1} & E \leq E_{0,i}, \\
D_0 \left(\frac{E}{E_{0,i}}\right)^{(2-\delta_2)} & E > E_{0,i}
\end{cases}$$
**Diffusion Equation**

For a **point-like source**:

\[ Q_i(E, \vec{r}) = Q_0 \xi_i \left( \frac{E}{E_{0,i}} \right)^{-\gamma} \delta(\vec{r}) \]

We solve the following differential equation:

\[
\frac{\partial n_i}{\partial t} - \vec{\nabla}(D_i \vec{\nabla} n_i) + \frac{\partial}{\partial E}(b_i n_i) = Q_i(E, \vec{r}, t) + \sum_k \int P_{ik}(E, E') n_k(E') dE'
\]
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Below GZK energies, energy losses are negligible thus we only consider diffusion terms.
Solution

The flux is:

\[ n_i(E, r) = \frac{Q_0}{4\pi r D_i(E)} \left( \frac{E}{E_{0,i}} \right)^{-\gamma} \]

with diffusion time \( t_D \):

\[ t_D \sim \frac{R^2}{D_i} \sim 10^7 \text{yr} \left( \frac{R}{10 \text{ kpc}} \right)^2 \left( \frac{Z_i}{26} \times \frac{10^{19} \text{ eV}}{E} \right)^{2-\delta_2} \]
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  Diffusion times for nuclei are longer than for protons of the same energy

- The flux drops for protons at lower energies than heavy nuclei
Energy-dependent composition due to diffusion
protons, C, Fe
The Source Problem (with some overlap)

Galactic sources are likely to exist, and more pertinently, *to have existed*:
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- Hypernovae
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GRBs as Possible Galactic Candidates

- GRBs have been proposed as sources of extragalactic UHECRs [Vietri; Waxman; Dermer]

- Galactic GRBs have been considered as sources of UHECRs [Dermer et al., Biermann et al.]

- Past Galactic GRBs have been considered as the explanation of 511 keV line from the Galactic Center [Bertone, et al.; Parizot et al.; AC, Kusenko], as well as the electron excess of PAMELA/Fermi [Ioka; AC, Kusenko]
What are GRBs

- **Long GRBs:**
  - associated with core-collapse supernovae
  - correlation with star-forming metal-poor galaxies

- **Short GRBs:**
  - probably mergers of compact stars or black holes
  - likely less beamed

- Both should have happened in our own Galaxy in the past, at a combined rate of one per $10^4 - 10^6$ years
Nuclei Acceleration in GRBs

**Internal Shock**

The nuclei can survive if:

- Internal shock radius is large
- Large Lorentz factor of the relativistic jets
- (And/Or) In the presence of a synchrotron self-absorption break

**External Shock**

- Large dissipation radii item Nuclei can easily survive
Distribution of GRBs in the Milky Way

Supernovae or long GRBs, assuming they follow star counts [Bahcall et al.]

Short GRBs, based on observed distribution in other galaxies [Cui, Aoi, Nagataki]

We generate 1000 GRBs separated in time with $\bar{\Delta}t = 10^5$ years (note that average time is irrelevant as long as $t_{diff} > t_{rep}$)
Comparison with Pierre Auger data

Protons, Fe, Overall Spectrum

$E^3 \times dN/dE (\text{GeV}^2 \text{km}^2 \text{s}^{-1} \text{sr}^{-1})$

[AC, Kusenko, Nagataki]
Comparison with Pierre Auger data

- Spectrum fairly insensitive to diffusion spectral indices; here \( D(E < E_0) \propto E^{0.3} \) and \( D(E > E_0) \propto E^2 \)
- \( B = 4 \mu \text{G} \), consistent with current observation of the galactic magnetic field
- Index of the injection spectrum \( \gamma = 2.3 \): relativistic shock acceleration
- 10% iron and 90% proton
- \( l_c = 200 \text{ pc} \)
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**Dramatic change in the spectral slope of the magnetic energy $E_B(k)$ around**
$\sim 0.1 \text{ kpc}$
Composite Magnetic Energy Spectrum

[Han, Ferriere and Manchester, ApJ. 610, 820 (2004)]
Comparison with Pierre Auger data

Protons, Fe, Overall Spectrum
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Protons, Fe, Overall Spectrum

Energy requirement only $10^{46}$ erg compared to $10^{50}$ erg for extragalactic GRBs
Galactocentric anisotropy (sources follow stars)

\[ \frac{\Delta}{ Total \ Fe \ p} \times 10^{8,5,10} \]

[AC, Kusenko, Nagataki]
Clusters of events from recent/closest GRBs

supernovae/long GRBs

short GRBs
Extragalactic Component
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Since the protons leak out of other galaxies as well Extragalactic protons must also contribute to the overall spectrum above $10^{18}$ eV, and any anisotropy would be diluted by magnetic fields
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Sources within $\sim 100$ Mpc:

- extragalactic GRBs
- AGNs [Essey, Kusenko]

These contribution should not be significant until $\sim 3 \times 10^{10}$ GeV where energy losses for the galactic component become significant.
Implications for charged-particle astronomy
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- Correlations with extragalactic sources are expected for protons at the highest energies:
  - The ability to separate protons from nuclei is essential for observing such correlations
  - The realization that IGMFs are as small as femtogauss further improves the prospects of observing distant sources [Ando, Kusenko, ApJ 722, L39]
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• Galactic component (nuclei) can be used to understand the power spectrum of galactic magnetic fields

• Hot spots in galactic nuclei can point to the locations of the recent/closest GRBs. Can they be connected with some mass extinctions on Earth?
The Future

Improvement we are in the process of making:

- Inclusion of coherent component of the magnetic field
- Treatment of more realistic source models
- Improve propagation model at high energy to include energy losses
- Include extragalactic sources
- Investigate neutrino signal
Summary

The energy-dependent composition observed by PAO motivates alternative solutions to the origin of UHECRs: **Galactic Sources**
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- Energy dependent diffusion coefficient offers a solution to the dominance of nuclei at $10^{18} - 10^{19}$ eV

- The diffusion process within galactic magnetic fields maintains the galactocentric anisotropy below a few percents

- Many possible source exist within the Milky Way
  
  As long as event rate exceeds $1/10^8$ year

- The apparent clustering could be the result of the most recent event
Extra Slides