Arrival distribution of ultra-high-energy cosmic rays and implications to their sources

Hajime Takami
KEK, JSPS Fellow
Ultra-high-energy cosmic rays

- Highest-energy particles ever detected
  - up to $3 \times 10^{20}$ eV
- Extremely low flux
  - ~ $1$ km$^{-2}$ millennium$^{-1}$ @ $10^{20}$ eV
  - huge detectors are required to study
- None of their origin is not identified yet.

Source identification of UHECRs is an important first step to understand physics on the production of such extremely energetic particles.
UHECR Source Candidates

Hillas Criterion
Larmor radius < Source size

Only extreme phenomena or objects in the universe can produce the highest energy cosmic rays.
Estimated Composition of UHECRs

**Auger**: heavy elements are mixed

**Telescope Array**: consistent with protons

The recent results are significantly inconsistent within the quoted systematic errors.

A joint working group of Auger and TA is collaborating to solve this problem.
Cosmic magnetic fields deflect the propagation trajectories of UHECRs and make it difficult to identify sources by UHECR experiments.
Mean Free Paths of UHECRs in Intergalactic Space

The mean free path of UHECRs rapidly decreases above $\sim 10^{20}$ eV

Sources of UHECRs detected with $>\sim 10^{20}$ eV are dominantly located within several tens Mpc.
Hints of anisotropy have been reported, but no clear evidence of point-like sources so far.

**Statistical approach**

Hajime Takami | KICP workshop “High-Energy Messenger”, KICP, the university of Chicago, USA, June 10, 2014
Anisotropy and UHECR Source Number Density

Experimental result

$n_s = 10^{-5} - 10^{-4} \text{ Mpc}^{-3}$
for $E > 5.5 \times 10^{19} \text{ eV}$

Simulations under assumed $n_s$

Assuming steady sources

<table>
<thead>
<tr>
<th>Objects</th>
<th>$n_s$ (Mpc$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bright galaxy</td>
<td>$1.3 \times 10$</td>
</tr>
<tr>
<td>Seyfert galaxy</td>
<td>$1.25 \times 10$</td>
</tr>
<tr>
<td>Dead Quasar</td>
<td>$5 \times 10$</td>
</tr>
<tr>
<td>Fanaroff-Riley I</td>
<td>$8 \times 10$</td>
</tr>
<tr>
<td>Bright quasar</td>
<td>$1.4 \times 10$</td>
</tr>
<tr>
<td>Colliding galaxies</td>
<td>$7 \times 10$</td>
</tr>
<tr>
<td>BL Lac objects</td>
<td>$3 \times 10$</td>
</tr>
<tr>
<td>Fanaroff-Riley II</td>
<td>$3 \times 10$</td>
</tr>
</tbody>
</table>

HT & Sato 2009

Cuoco+ 2009

HT & Sato 2009
UHECR Source Candidates

Only extreme phenomena or objects in the universe can produce the highest energy cosmic rays.

Hilllas Criterion

$R_L < R$

Active Galactic Nuclei

Gamma-ray Bursts

Newly Born Magnetars

Clusters of galaxies

Hajime Takami | KICP workshop “High-Energy Messenger”, KICP, the university of Chicago, USA, June 10, 2014
Propagation of UHECRs from a Transient Source

Observational features are different among energies.

- Random deflections by cosmic magnetic fields
- Stochastic nature of photomeson production

- Arrival time is delayed, and depends on energies.
- Intrinsic burst duration < apparent CR-burst duration
- Apparent duration also depends on energies.
Apparent Source Number Density of UHECRs

A stronger anisotropy appears at higher energies (even without considering the GZK mechanism).

\[ \rho_s \gtrsim \frac{n_s(E)}{\tau(E)} \]

\[ \rho_s = 10^2 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

\[ \rho_s = 1 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

\[ n_s(E) \approx \frac{n_s(E)}{\tau(E)} \]

<1 source within \( D_{\text{max}}(E) \)

Higher energy CRs

- Shorter apparent duration
- Smaller probability to observe a UHECR burst
- Smaller number of “point source”-like features
- + GZK mechanism
- Stronger anisotropy (smaller \( n_s(E) \))

The dependence of \( n_s(E) \) is evidence of transient generation of UHECRs.

\[ n_s(E) \text{ should be estimated in at least two energy ranges.} \]
Evolution of anisotropy

\[ E_p > 6 \times 10^{19} \text{ eV}, n_s = 10^{-5} \text{ Mpc}^{-3} \]
Constraints on $\rho_s$ and Energy Budget

$$\rho_s \approx \frac{n_s(E)}{\tau(E)}$$

$$\frac{n_s(E)}{\tau_{\text{max}}(E)} \lesssim \rho_s \lesssim \frac{n_s(E)}{\tau_{\text{min}}(E)}$$

- $\tau_{\text{min}}$: GMF, EGMF surrounding sources
- $\tau_{\text{max}}$: GMF, EGMF surrounding sources, IGMF

\[ E^2 dN_{\text{CP}}^i dE (10^{19} \text{ ev}) \text{ [erg]} \]

\[ n_s [\text{Mpc}^{-3}] @ 10^{20} \text{ ev} \]

\[ \rho_s \text{ [Gpc}^{-3} \text{ yr}^{-1}] \]

HT & Murase 2012

\begin{tabular}{|l|c|}
\hline
Source & Typical Rate $\rho_0$ (Gpc$^{-3}$ yr$^{-1}$) \\
\hline
HL GRB & $\sim 0.1$ \\
LL GRB & $\sim 400$ \\
Hypernovae & $\sim 2000$ \\
Magnetar & $\sim 12000$ \\
Giant Magnetar Flare & $\sim 10000$ \\
Giant AGN Flare & $\sim 1000$ \\
SNe Ibc & $\sim 20000$ \\
Core Collapse SNe & 120000 \hline
\end{tabular}

$n_s(E)$ from huge UHECR experiments and $\tau(E)$ from understanding cosmic magnetic fields allows us to constrain transient UHECR sources by comparing their restricted properties with parameters of known astrophysical objects.
Anisotropy in a heavy-nuclei-dominated case

Anisotropy studies may be doable in the future.

Hajime Takami | KICP workshop “High-Energy Messenger”, KICP, the university of Chicago, USA, June 10, 2014
Summary

- The origin of ultra-high-energy cosmic rays is still unknown, but some hints have appeared in their arrival distribution.

- Anisotropy indicates source number density: \( n_s \sim 10^{-4} \text{ Mpc}^{-3} \) for steady sources in the cases of light composition / weakly magnetized universe. This value is much larger than blazars, radio galaxies, and clusters of galaxies.

- An anisotropy study in narrow consecutive energy bins can reveal the transient generation of UHECRs.

- Conservative estimation of the UHECR generation rate and related energy output can be achieved by independent studies on extragalactic magnetic fields.
Filament
\[ B \sim 10^{-nG} \] (e.g., Ryu et al. '08),
assuming turbulence with \( \lambda_c \sim 100 \text{ kpc} \)

Cluster
\[ B \sim 1 \mu G, \beta\text{-model} + \]
turbulence with \( \lambda_c \sim 100 \text{ kpc} \) (e.g., de Marco et al. '06),

Void
\[ B, \lambda_c^{1/2} < (10 \text{ nG})(1 \text{ Mpc})^{1/2} \] (e.g., Ryu et al. '98, Blasi et al. '99)
\[ B > 10^{-17} \sim -18 G \] (e.g., Dolag et al. '11, Dermer et al. '11,
Takahashi et al. '12, see also Ando & Kusenko '10 and Neronov et al. '11)