The Origin of the Highest Energy Cosmic Rays

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Ultra High Energy Cosmic Rays (UHECRs): Energies and Origins

- $\lesssim 10^{15}$ eV: possible for particles to be accelerated to these energies by:
  - solar and planetary magnetic fields
  - binary star systems
  - supernovae

- $\gtrsim 10^{18}$ eV: acceleration methods unknown, but possible progenitors include:
  - active galactic nuclei (AGNs)
  - gamma ray bursts
  - new physics

Interested in ultra high energy cosmic rays (UHECRs) ($\gtrsim 10^{18}$ eV).

Credit: W. Hanlon, Utah
The Greisen Zatsepin Kuzmin (GZK) effect affects UHECRs with energies $\gtrsim 5 \times 10^{19}$ eV.

Highly relativistic particles:
- see cosmic microwave background (CMB) photons blueshifted.
- lose energy by interacting with CMB.

Protons with $E \gtrsim 5 \times 10^{19}$ eV:
- interact via: $p + \gamma \rightarrow p + \pi$
- lose $\sim 0.2E$ per interaction.
- have mean free path $\sim 4$ Mpc.

GZK effect places limit on plausible distances to UHECR progenitors of $\sim 100$ Mpc.

Achterberg et al. 1999

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The Pierre Auger Observatory (PAO) South covers 3000 km$^2$ near Malargue, Argentina.

PAO detects shower of secondary particles created after CR hits atmosphere.

1600 surface detectors (SDs, Cerenkov tanks) observe the extent of the halo.

4 fluorescence detectors (FDs) look at the trajectory of core of shower ($\sim$ CR).

*Credit: Pierre Auger Collaboration*
Data and Current Results

Sky map of PAO UHECR events (black) and VCV AGNs (red).

- We use the same data as used by Pierre Auger Collaboration (PAC) 2007:
  - 27 UHECR events detected by PAO.
  - Veron-Cetty & Veron (VCV) 2006 catalogue of AGN.

- Current results:
  - Varying correlations between UHECR arrival directions and AGN positions (PAC 2007, 2010).
  - Statistical methodologies used ignore information and introduce problematic fine-tuning.
Bayesian Approach and Model Used

- Bayesian approach has advantage of taking account of more of the available information…

- Model:
  - Progenitors: UHECRs emitted from either AGNs ('sources' with initial power-law spectrum \( \frac{dN(E_{\text{emit}})}{dE_{\text{emit}}dt} \propto E_{\text{emit}}^{-\alpha} \) where \( \alpha \sim 3.6 \)) at a rate 's’, or a uniform background at a rate 'b’.

- Propagation: 1. GZK attenuation of the source (AGN) signal of form:
  \[ E_{\text{rec}} = E_{\text{emit}}(1 - f_{\text{GZK}})^{D/L_{\text{GZK}}} \]
  where \( f_{\text{GZK}} \sim 0.2E, L_{\text{GZK}} \sim 4 \text{ Mpc} \).

  2. received flux \( F \propto \frac{1}{4\pi D^2} \)

- Detection: 1. known detector acceptance as a function of sky location \( \epsilon(\theta, \phi) \)

  2. magnetic angular deflection and experimental uncertainty → Gaussian smearing \( G \) with \( \sigma = 3^\circ \)
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- **Posterior:** \[ P(s, b|\hat{n}_p) = \frac{P(\hat{n}_p|s,b)P(s,b)}{P(\hat{n}_p)} \]

- **Prior:** uniform in source and background rates, s and b: \( P(s, b) = \text{const.} \)

- **Likelihood:** Poisson pdf: \[ P(\hat{n}_p|s, b) = \prod_p \frac{\hat{n}_p^p e^{-\hat{n}_p}}{\hat{n}_p} \]

with mean \( \bar{n}_p = [(\sum_{\text{AGN}} \frac{(1-f_{\text{GZK}})(\alpha-1)D/L_{\text{GZK}}}{4\pi D^2} Gs) + b] \epsilon(\theta, \phi) \)
Bayesian Analysis of Simulated Data

Background only simulation:

Posterior recovers simulation input parameters:

\[ s \rightarrow \overline{N}_s = 0 \]
\[ b \rightarrow \overline{N}_b = 27 \]
Bayesian Analysis of Simulated Data

VCV AGN only simulation:

Posterior recovers simulation input parameters:

\[ s \rightarrow \bar{N}_s = 27 \]
\[ b \rightarrow \bar{N}_b = 0 \]
Bayesian Analysis of PAO Data

PAO data:

Mean expectation values of numbers of cosmic rays received (with uncertainties forming 68% confidence levels) are:

\[
\overline{N}_s = 8.7^{+3.3}_{-4.9}, \\
\overline{N}_b = 20.3^{+4.5}_{-6.2}
\]

Posterior probability density as a function of UHECR background and VCV AGN rates

Contours enclose 68%, 95% and 99.7% of the posterior probability.
Bayesian Analysis of PAO Data

Mean fraction of UHECRs from AGNs (uncertainties from 68% confidence levels):

$$F_{AGN} = 0.30^{+0.13}_{-0.16}$$
Conclusions and Future Work

Bayesian analysis provides:

- clear advantages over other statistical methodologies.
- encouraging results so far.

Further work:

- better data - e.g. 56 PAO UHECRs, Swift/BAT AGN catalogue.
- improve modelling - e.g. better representation of GZK effect.
- use more information - e.g. measured UHECR energy.

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Bayesian Approach and Model Used

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Model:
- background rate $b$, source rate $s$ and initial source power spectrum $\frac{dN(E_{\text{emit}})}{dE_{\text{emit}} dt} \propto E_{\text{emit}}^{-\alpha}$
- received energy $E_{\text{rec}} = E_{\text{emit}}(1 - f_{\text{GZK}})^{D/L_{\text{GZK}}}$ and received flux $F \propto \frac{1}{4\pi D^2}$
- detector acceptance $\epsilon(\theta, \phi)$ and Gaussian smearing $G$

Posterior: $P(s, b|\hat{n}_p) = \frac{P(\hat{n}_p|s,b)P(s,b)}{P(\hat{n}_p)}$

Prior: uniform in source and background rates, $s$ and $b$: $P(s, b) = \text{const}$.

Likelihood: Poisson pdf: $P(\hat{n}_p|s, b) = \prod_p \frac{\hat{n}_p e^{-\hat{n}_p}}{\hat{n}_p}$

with mean $\bar{n}_p = [(\sum_{\text{AGN}} \frac{(1-f_{\text{GZK}})(\alpha-1)D/L_{\text{GZK}}}{4\pi D^2} Gs) + b] \epsilon(\theta, \phi)$