Multi-$\nu$ search for astrophysical sources of Auger UHECR events

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Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects
The Pierre Auger Collaboration, et al.
Science 318, 938 (2007);
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Veron-Cetty-Veron AGN
($\Theta_{\text{correlation}} = 3.1^\circ$)

X-ray Swift-BAT AGNs
HI (HIPASS) galaxies
VCV2001 + NED
NED
IRAS galaxies

George et al. 2008. Mostly Sy1, Sy2 galaxies, LINERS

Ghisellini et al. 2008. Spiral galaxies / Magnetars association

Moskalenko et al. 2008. No complete nearby AGN catalogue

Gureev & Troitsky 2008. Proton acceleration: hard to get Intermediate mass nuclei from CenA

Can we say something more on the astrophysical sources of UHECRs? ...some steps ahead...
Spatial constraints
- Energetic sources (galactic + extragalactic) associated with Auger Events
- AGNs, RGs, Galaxies, Clusters, PSRs, SNRs, MCs

Spectral constraints
- Synchrotron emission ... @ high $\nu$
- X-ray emission ... hard X-rays
- Gamma-ray emission ... MeV $\rightarrow$ GeV $\rightarrow$ TeV

Horizon constraints
- $z < 0.02$
Correlating UHECRs with WMAP

High-E particles

\[ \nu \approx 3.7 \text{MHz} \quad B_\mu \left( \frac{E_e}{\text{GeV}} \right)^2 \]

High-frequency radio
Synchrotron emission

[Colafrancesco et al. 2008-9]
Multiple events

DEFLECTION OF CHARGED PARTICLES
IN GALACTIC MAGNETIC FIELDS

If Galactic B field (and composition) were known, one could correct the arrival direction to search for the source.

\[
\delta_{\text{reg}} \approx 5^\circ \frac{10 \text{ EeV}}{E/Z} \frac{\int_0^D d\vec{x} \times \vec{B}}{\text{kpc} \, \mu G}
\]

\[
\delta_{\text{ran}} \approx 10^9 \frac{10 \text{ EeV}}{E/Z} \frac{B}{10^{-9} \text{ G}} \sqrt{\frac{L_c}{1 \text{ Mpc}}} \sqrt{\frac{D}{10 \text{ Mpc}}}
\]

Consistent with the angular separation of doublets and triplets of Auger events.
WMAP5yr – Q band image and candidate sources around Event 3

ESO 444- G 046
CD-RG in A3558

NGC 5140
Liner

ESO 443- G 024
RG in A3557

IC 4296
RG in A3556
WMAP 185

ESO 383- G 035
Sy 1.2
WMAP5yr – Q band image and candidate sources around Event 8

Q-spot 8

-0.500 0.500 mK

-0.4 -0.3 0.0 0.3 0.4

IC 4518
RG

ESO 273-IG 004
Sy 2

SN 1006
SNR
WMAP5yr – Q band image and candidate sources around Events 5, 6, 7
WMAP5yr – Q band image and candidate sources around Event 10

Q – spot 10
Statistical confidence

Every Auger event with $E > 57$ EeV can be associated to a cosmic accelerator with appropriate properties for UHECR production (Colafrancesco et al. 2008-9)

Observed distribution

Random rotated pattern

Random pattern
Some statistics

Table 1. Auger events: statistics.

<table>
<thead>
<tr>
<th></th>
<th>BLLac</th>
<th>Radio galaxies</th>
<th>Seyfert galaxies</th>
<th>Liner</th>
<th>SN SNR</th>
<th>Other sources</th>
<th>Radio Sources</th>
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<td><strong>Observed</strong></td>
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<tr>
<td><strong>Rotated random</strong></td>
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<td>4</td>
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<td>4</td>
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<td>9</td>
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</tbody>
</table>

No evident association with galaxy clusters
(with accretion shocks and with no RG / AGN)
5,6,7
CenA

IC 4518

9 [HB91] 1739-126

0 4C -04.49

11 WKK 2031

1

2 TOLOLO 00020

3 IC 4296

10

17 NGC 6967

19 MRK904

18 CGCG403-019

15-16 PKS2203-18, NGC 6407

12 CenB

26 2MASXJ01115114-4045426

NGC 7130

21

NGC 7674

NGC 7562

20

NGC 6967

23

MRG -02-09-040

24

NGC 1358

13

IRAS06483-1955

14

NGC 7130

16
Large deflection angles: $Z$ & $B$

**$Z > 1$ The case of CR nuclei**

\[
\delta_{\text{reg}} \approx 5^\circ \frac{10 \text{ EeV} \int_0^P d\vec{x} \times \vec{B}}{E/Z \text{ kpc } \mu \text{G}}
\]

\[
\delta_{\text{ran}} \approx 10^\circ \frac{10 \text{ EeV} \text{ B}}{E/Z \times 10^{-9} \text{ G} \sqrt{L_c \text{ 1 Mpc}} \sqrt{D \text{ 10 Mpc}}}
\]

**Association of UHECR events to few sources**

Fraction of observed UHECR events vs. their deflection angle (Das et al. 2008)

**IGM & ICM B-fields**

\[\log [df(\theta)/d\theta] \]

$E > 60 \text{ EeV}$
A minimal set of UHECR sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>CenA</td>
<td>RG</td>
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<tr>
<td>CenB</td>
<td>RG</td>
</tr>
<tr>
<td>IC4518</td>
<td>RG</td>
</tr>
<tr>
<td>ESO 565- G 019</td>
<td>BLLac</td>
</tr>
<tr>
<td>NGC 6407</td>
<td>Sy2</td>
</tr>
<tr>
<td>NGC 6967</td>
<td>Sy2 + radio jets</td>
</tr>
<tr>
<td>NGC 1358</td>
<td>Sy2 + AGN radio emission</td>
</tr>
<tr>
<td>NGC 5506</td>
<td>Sy1.9 + radio jets</td>
</tr>
</tbody>
</table>

“Good” UHECR source conditions:

- **Energy injection rate:** $(0.7–20) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$
- **Number of sources:** $n_s \sim 10^{-4} \text{ Mpc}^{-3}$
- **Arrival time delay of UHECRs:** $\langle \tau_{\text{delay}} \rangle \equiv \tau_5 \times 10^5 \text{ yr} \approx 10^5 \text{ yr}$
UHECR source conditions

Conventional long-lived AGN jets (Blazars, BLLacs, RGs) cannot be the primary site of UHECR acceleration.

\[ L_{\text{bol}} \geq 10^{45} E_{20}^2 \text{ erg s}^{-1} \]

... unless extreme conditions are met:
• gyroresonant interaction with a magnetic turbulence [Fraschetti & Melia 2008]
• giant AGN flares [Farrar & Gruzinov 2008]

No longer conventional description of AGN jets

The Cen-A jet

Composite image of Chandra X-ray (blue) and VLA radio (red) observations showing the inner 4,000 light years of a magnetized jet in Centaurus A.
Purple regions are bright in both radio and X-ray.
PKS 0637-752
A 20.1-GHz Compact Array image (pixels) overlayed with contours of X-ray emission

[D.C.Homan et al. 2009]


(a) 22.2 GHz

3C 273 jet  VLA  Spitzer*  Hubble Chandra  (* deconvolved)

I'
high-energy emission  low-energy emission
Blazar: multiple components (blobs)

Stationary component:
p1=1.7; p2=4.2
\( \gamma_b = 1.8 \times 10^3 \)
N=631 cm\(^{-3}\)
R=0.01 pc

Additional component:
p1=1.1; p2=4.05
\( \gamma_b = 3.9 \times 10^3 \)
N=8.91 cm\(^{-3}\)
R=0.005 pc

S50716+714 during the Oct. 2007 bright flare
(Giommi, Colafrancesco et al. 2008)
Centaurus A / CenA Group

Th. bremsstrahlung

CenA RG core

ICS

Diffuse Radio emission

Bremsstrahlung

[Colafrancesco et al. 2009]
Centaurus A / CenA Group

Th. bremsstrahlung

CenA / CenA group

CenA RG core

ICS

Diffuse Radio emission

Bremsstrahlung

[Colafrancesco et al. 2009]
... a plausible scenario !?

\[ \gamma_0 = \frac{1}{\sqrt{1 - \beta^2}} \]

**HECRs**

\[ E'_p = \gamma_0 m_p \]

**HE electrons**

\[ E'_e = \gamma_0 m_e \]

*Magnetic isotropization of relativistic e*^\(-^*\)
... a plausible scenario !?

\[ \gamma_0 = \frac{1}{\sqrt{1 - \beta^2}} \]

UHECRs

\[ E_p = \gamma_0^2 m_p \]

VHE radiation

- Synch.
- IC (SSC)
- IC (EC)
- IC (CMB-C)
$E_{\text{max}} + \text{AGN SEDs:}$

$$E_{\text{max}} = eZ \frac{1}{\gamma \delta} R \nu_{\text{synch}}$$

$$\nu_{\text{IC}} \approx \gamma^2 \nu_{\text{synch}}$$

$$\nu_{\text{synch}} \approx \gamma^2 B \delta$$

Hillas-plot
(candidate sites for $E=100$ EeV and $E=1$ ZeV)

$$E_{\text{max}} = \gamma eZRB$$

$E_{\text{th}}$
...some conclusions

A minimal set of viable UHECR sources is found

These sources are RG-like objects

Production of UHECRs in jets:
  non-canonical acceleration
  acceleration by high-$\gamma$, B-confined plasmoids

E_max condition related to observational properties
  $\nu_{\text{synch}}$, $\nu_{\text{IC}}$
  NT-AGN class

UHECR cut-off:
  astrophysical origin
  GZK (only for extreme $\nu_{\text{synch}}$)

... towards an astrophysical study of UHECR sources
THANKS

for your attention!