Ultra-high energy cosmic rays and the strongest AGN flares.

M.S. Pshirkov, B.A. Nizamov
Sternberg Astronomical Institute

Quarks XX
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Cosmic rays spectrum

Nagano, 2009
Cosmic rays spectrum – EAS part

The graph shows the energy spectrum of cosmic rays with a focus on the EAS part. The x-axis represents the energy $E$ in eV, while the y-axis represents the number of events per unit area, time, and solid angle ($E^{2.6} F(E)$) in units of $[\text{GeV}^{1.6} \text{ m}^{-2} \text{s}^{-1} \text{ sr}^{-1}]$. The plot includes data points from various experiments such as Grigorov, JACEE, MGU, Tien-Shan, Tibet07, Akeno, CASA-MIA, HEGRA, Fly’s Eye, Kascade, Kascade Grande, IceTop-73, HiRes 1, HiRes 2, Telescope Array, and Auger, each represented by different markers.

Key features of the spectrum include:
- **Knee**: around $10^{15}$ eV
- **2nd Knee**: around $10^{17}$ eV
- **Ankle**: around $10^{19}$ eV

PDG, 2015
UHECR spectrum

$E^{2.6} F(E)$ [GeV$^{1.6}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$]

- **Telescope Array**
- **Auger**

$E$ [eV]

PDG, 2015
GZK cut-off

- Dramatic energy loss at $\log(E) > 19.7$ due to $p$-CMB collisions
- Horizon shrinks to $\sim 100$ Mpc

$$p + \gamma_{\text{CMB}} \rightarrow n + \pi^+$$

$$\rightarrow p + \pi^0$$

Hooper et al., 2007
'Hillas plot'

\[ \mathcal{E} \leq \mathcal{E}_H = qBR \]

Ptitsyna & Troitsky, 2010
Luminosity threshold

- We take the limiting case of protons.
- Hillas criterion can be written out explicitly, taking into account possible relativistic bulk motion:

\[ RB \gtrsim 3 \times 10^{17} \Gamma^{-1} E_{20} \]

- In certain case of relativistic jets that allows to estimate corresponding magnetic (Poynting) flux:

\[ L \sim \frac{1}{6} c \Gamma^4 B^2 R^2 \gtrsim 10^{45} \Gamma^2 E_{20}^2 \text{ erg/s} \]

- In AGN \( \Gamma \sim 10 \), so we are talking about \( 10^{47} \text{ erg/s} \)!
Problems

- Summing up, there are two effects interplaying in the end of the spectrum:
  - Progressively smaller active volume, $V_{\text{GZK}}$
  - Increasing degree of 'extremeness' of the sources
- Still, we do observe UHECRs at these energies, thus there must be some sources
- NO steady astrophysical sources in $V_{\text{GZK}}$
- The only way out – HE transients.
• Successful candidate shall simultaneously:
  i) Satisfy luminosity (or Hillas) criterion
  ii) Meet total energetics condition – there should be enough energy to accelerate observed UHECRs, at the very least

• Benchmark (observed emissivity at $E>10^{20}\,\text{eV}$):
  $\mathcal{L}(\text{TA}) = 8 \times 10^{43} \, \text{erg s}^{-1} \, \text{Mpc}^{-3}$
  or
  $\mathcal{L}(\text{PA}) = 1.5 \times 10^{43} \, \text{erg s}^{-1} \, \text{Mpc}^{-3}$
Transients. GRB

- Gamma-ray bursts – natural candidate
- Easily pass the luminosity test
- The second point could be problematic, because $\mathcal{L}_{\text{GRB}} \sim 5 \times 10^{43}$ erg s$^{-1}$ Mpc$^{-3}$
- Need some other mechanism (or LLGRBs?)
Transients. AGNs

- AGNs are highly variable

- Flares with $L > 10^{50}$ erg/s were observed, so it is possible to fulfill the first criterion

- The crucial question is – whether there is enough luminous flares in the GZK volume?

- The idea is straightforward – take some fiducial volume $V_0 >> V_{GZK}$ ($z_0 = 0.3$, $R_0 \sim 1.5$ Gpc, $R_{GZK} * \sim 150$ Mpc)

  *$R_{GZK}$ is the mean attenuation length of the proton with the initial energy of $10^{20}$ eV.
Sample

- We tried to construct a full sample of candidate flares using the Fermi LAT observations.
- Advantages: long time span and uniform coverage of the celestial sphere with high (3h) cadence → there's no chance to miss a flare at these distances.
- On the other hand, there is no way to directly measure the Poynting luminosity, we estimate it assuming equipartition and that the jets radiate effectively.
- In this case $L_{\text{mag}} \sim L_{\text{bol}}$
• Luckily, $\gamma$-luminosity in 0.1–100 GeV energy range is a good proxy for the bolometric one

$$L_{\text{bol}} \sim 2L_\gamma$$
Aperture photometry

- It is rather difficult to find luminosity for full 0.1-100 GeV energy range
- Proxy again, now it is 1-100 GeV. As the Fermi-LAT angular resolution improves, we can employ the easiest way to build the needed lightcurves – aperture photometry
Aperture photometry

- AP – it is just photon counts in 2 deg circle divided by an actual exposure in the time bin (week)
- PRO: simple and robust. Makes possible to investigate all the lightcurves of Fermi sources
- CONTRA: too rough. Inevitably include background and photons from another sources, so great care should be taken when dealing with AGNs at low galactic latitudes and/or in the vicinity of some strong sources.
- NEVERTHELESS: we set high luminosity threshold and the sources are not too far away, so they'll dominate over the bckg. Eventually candidate flares was checked using more precise ML method (gtlike).
TABLE I. The list of the analyzed AGNs. $z$, $l$, $b$ are the redshift and galactic longitude and latitude, $N_{\text{flare}}$ is the number of flares, $L_{\text{max}}$ is the maximum isotropic equivalent bolometric luminosity in the observation period, in units of $10^{45}$ erg $s^{-1}$.

<table>
<thead>
<tr>
<th>Name</th>
<th>$z$</th>
<th>$l$</th>
<th>$b$</th>
<th>$N_{\text{flare}}$</th>
<th>$L_{\text{max}}$</th>
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<tbody>
<tr>
<td>PKS 0556-572</td>
<td>0.02</td>
<td>300.9</td>
<td>-60.1</td>
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<td>179.8</td>
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<td>0</td>
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<tr>
<td>Mkn 501</td>
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<tr>
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<td>NVSS J223708-392137</td>
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<td>S5 0716+71</td>
<td>0.30</td>
<td>144.0</td>
<td>28.0</td>
<td>42</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Kinetic energy

• We can select 13 candidate sources

• Next step – we calculate corresponding kinetic energy deposited in this flares, using correlation from (Nemmen et al, 2012)

• The obtained energetics corrected for the beaming effects is $10^{45}$ erg s$^{-1}$ Mpc$^{-3}$

• Correction ($2\Gamma^2$) implies that we need effective isotropisation
Isotropisation & anisotropy

- We need effective isotropisation. There are several possible sites:
  - Immediate vicinity of AGNs. Strong MFs
  - Host galaxy
  - Intercluster medium
  - (least likely) EGMF

- Also we need to solve the problems of anisotropy and steady flux – there were observed 13 candidate sources in 7.4 years of observations in 1000 $V_{\text{GZK}}$ volume. That gives $\mathcal{R}=0.2 \, \text{yr}^{-1}$ (with beaming correction) in the $V_{\text{GZK}}$.
- Delay due to the MF $\tau \sim d\theta_s^2/2$ greatly increase the number of 'active' UHECR sources at any given time, because $\tau$ could exceed $10^6$ years and we observe CRs from $10^5$ flares simultaneously.
Spectrum in the sources

• Even in the case of isotropisation the UHECRs with \( E > 10^{20} \) eV consume a significant fraction of AGN kinetic energy, \( 1.5(PA)-7.5(TA)\)%.

• That makes possible to put strong constraints on the allowed shape of the spectrum. It should be hard and/or narrow. This shape is predicted in a large number of different models of acceleration in relativistic shocks.
Spectrum in the sources

- **PAO spectrum**
- **TA spectrum**

The graph shows the relationship between the spectral index $\alpha$ and $\log_{10}(E_{\text{min}}(\alpha))$. The PAO spectrum is represented by the red line, and the TA spectrum is represented by the blue line. The x-axis represents the spectral index $\alpha$, while the y-axis represents $\log_{10}(E_{\text{min}}(\alpha))$.
Conclusions

- Fermi LAT observations show that it is possible that the strongest AGN flares can be sources of UHE protons of even the highest energies, $E > 10^{20}$ eV, if effective isotropisation takes place.

- A significant part of kinetic energy of flares is still needed for that, this fact allows to strongly constrain shape of the CR spectrum in the sources – it must be hard (sp.index $\sim -2$) and/or narrow.
Thank you!
FIG. 2. Deviations of the energy flux computed in the assumption of a flat spectrum from the actual value as a function of “known” spectral index.