WHICH ASTROPHYSICAL SOURCES CORRELATE WITH ULTRA-HIGH-ENERGY COSMIC RAYS? A COMPARATIVE STUDY

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- THEORETICAL SPECULATIONS
  ⇒ POSSIBLE ASTROPHYSICAL SOURCES (18 CATALOGS)
- TEST THE CATALOGS AGAINST THE DATA:
  - one procedure for all catalogs
  - no a posteriori cuts
  - AGASA, Yakutsk, HiRes

  ⇒ more probable sources

- DETAILED STUDY OF SELECTED CLASSES OF SOURCES

⇓

which of them are possible emitters?

⇓

predictions for future experiments

CHOICE OF ASTRONOMICAL CATALOGS:

similar acceleration mechanisms

$$\Downarrow$$

potential correlations = the best way to distinguish

many solutions suggested

- extragalactic
  (no Galactic anisotropy found at $E > 10^{19}$ eV)
- persistent (not GRBs...)
  (hard to compare)

CHOICE OF ASTRONOMICAL CATALOGS:

NO A POSTERIORI CUTS

WHAT WE DO NOT DO in this study:

- to maximize the signal
- to compensate by a penalty factor

[to simulate many random sets and to maximize the signal in each of them; how often the signal may be obtained by making cuts in parameters?]

CHOICE OF ASTRONOMICAL CATALOGS:

A PRIORI CUTS INEVITABLE...

- brightness
- identification

$\Rightarrow$ inclusion into a catalog

Any choice of a catalog is a cut

In our study:

- no a posteriori cuts
- a priori cuts from original theoretical studies only
- exception: "extragalactic" unidentified gamma-ray sources, $|b| \geq 10^\circ$ (results without this cut given for comparison)

CHOICE OF ASTRONOMICAL CATALOGS:

Flat spectrum radio quasars

Farrar, Biermann

Catalog 1: Kuehr FSRQs

Original catalog: Kuehr et. al., 1981.

Cuts: class=QSO, spectral index $\alpha > -0.5$.

Number of objects: 201.

Catalog 2: Véron FSRQs

Original catalog: Véron-Cetty and Véron 2003, Table 1 (quasars).

Cuts: 6 cm flux $F_6 > 1$ Jy, spectral index $\alpha > -0.5$
(calculated from fluxes at 6 and 11 cm).

Number of objects: 211.

Seyfert galaxies

Uryson

Catalog 3: Lipovetsky Seyferts

Original catalog: Lipovetsky et. al.

Cuts: $z < 0.01$.

Number of objects: 136

Catalog 4: Véron Seyferts

Original catalog: Véron-Cetty and Véron 2003, Table 3 (active galaxies)

Cuts: classification starts with S (all Seyferts), $z < 0.01$.

Number of objects: 190.

BL Lac type objects

Tinyakov, Tkachev

Uryson

Catalog 5: Confirmed Véron BL Lac's

Original catalog: Véron-Cetty and Véron 2003, Table 2 (BL Lac type objects).

Cuts: classification=BL (confirmed BL Lac's).

Number of objects: 491.

Catalog 6: HP Véron BL Lac's

Original catalog: Véron-Cetty and Véron 2003, Table 2 (BL Lac type objects).

Cuts: classification=HP (high-polarization BL Lac's)

Number of objects: 68.

Radio galaxies

Bierman, Strittmater

Catalog 7: FR I radio galaxies

Original catalog: Zirbel and Baum, Table 11.

Cuts: classification=I or Ig (confirmed FR I).

Number of objects: 73.

Catalog 8: FR II radio galaxies

Original catalog: Zirbel and Baum, Table 11.

Cuts: classification=II, IIg, IIn, or IId (confirmed FR II).

Number of objects: 116.

Colliding galaxies

AGASA

Catalog 9: Colliding galaxies

Original catalog: Vorontsov-Velyaminov et. al.

Cuts: classification starts with PK (pair in contact).

Number of objects: 454.

Starburst and luminous infrared galaxies

Smialkowski, Giller and Michalak; Bednarek; Torres et.al.

Catalog 10: PDS starbursts

Original catalog: The Pico dos Dias Survey, Table 1.

Cuts: no.

Number of objects: 203.

Catalog 11: HCN luminous infrared galaxies

Original catalog: HCN survey, Table 1.

Cuts: no.

Number of objects: 53.

Catalog 12: Selected luminous galaxies

Original catalog: HCN and PDS surveys.

Cuts: calculated in Torres et.al. expected gamma-ray flux exceeds the GLAST sensitivity.

Number of objects: 16.

Dead quasar candidates in luminous nearby galaxies.

Boldt, Ghosh

Torres et.al.

1) absolute magnitude $M_{\text{abs}} < -21$;

2) redshift $z < 0.01$;

3) morphological type $t < -3$ (elliptical);

4) galactic latitude $|b| > 20^\circ$;

5) the object belongs to a group with richness not exceeding 50.

Catalog 13: dead QSO candidates

Original catalog: LEDA database.

Cuts: $M_{\text{abs}} < -21$, $z < 0.01$, $t < -3$, $|b| > 20^\circ$.

Number of objects: 20.

Gamma ray sources

Catalog 14: EGRET blazars

Original catalog: The 3rd EGRET catalog.

Cuts: identification=A (confirmed AGN).

Number of objects: 67.

Catalog 15: Possible EGRET BL Lac's

Original catalog: Véron-Cetty and Véron 2003, Table 2 (BL Lac type objects).

Cuts: classification=BL (confirmed BL Lac), angular distance to the nearest source from the 3EG catalog less than $2r_{95}$, where r_{95} is the angular radius of the circle containing the same solid angle as the 95% confidence contour of that EGRET source.

Number of objects: 30.

Catalog 16: Unidentified EGRET sources outside the Galactic plane

Original catalog: The 3rd EGRET catalog.

Cuts: identification void, galactic latitude $|b| > 10^\circ$.

Number of objects: 96

Catalog 17: GeV sources outside the Galactic plane

Original catalog: Lamb, Macomb.

Cuts: galactic latitude $|b| > 10^\circ$.

Number of objects: 26

Catalog 18: extragalactic TeV sources

Original catalog: List of confirmed TeV sources presented at ICRC2003

Cuts: identification with extragalactic objects.

Number of objects: 10.

THE COSMIC-RAY DATA SETS:

- AGASA, $4 \cdot 10^{19} < E < 10^{20}$ eV (49)
- AGASA + Yakutsk, $4 \cdot 10^{19} < E < 10^{20}$ eV (59)
- $E > 10^{20}$ eV, all Northern experiments (13)
- HiRes stereo, $E > 10^{19}$ eV (271) (energies unknown)

determined by availability of data

METHOD OF CALCULATION:

Monte-Carlo simulation of cosmic rays

n_r cosmic rays in the experimental dataset

Real data $\Rightarrow$ ν_r pairs "CR – source" within the angle δ

$N \times n_r$ cosmic rays in mock sets $\Rightarrow$ ν_i in each

$$\mathcal{P} = \frac{\text{number of mock sets with } (\nu_i(\delta) \geq \nu(\delta))}{N}.$$

WHY TO SIMULATE COSMIC RAYS, NOT SOURCES?

- distribution of sources known poorly
- acceptance of cosmic-ray experiments known quite well

A subtle point: choice of δ

Our study: fix a priori $\sim 1.4*$ angular resolution

(simulations by Tinyakov and Tkachev)

(does not maximize the signal in real interesting cases)

Difficult to be compensated by a penalty factor:

1 source inside the angular resolution circle of $2°$:

$\delta = 2°$, $\mathcal{P} = 1$

$\delta = 0.2°$, $\mathcal{P} = \left(\frac{0.2}{2}\right)^2 = 10^{-2}$

important: GALACTIC MAGNETIC FIELD (GMF)

At least a significant part of cosmic rays:

electrically charged particles

deflections by several degrees

extragalactic magnetic field: smaller deflections, poorly known

GMF: try to compensate

Tinyakov, Tkachev

Energies should be known:

not applicable to HiRes at the moment

Catalog	A	A	A+Y	A+Y	20+	H
		*		*		
1	0.23	1.00	0.20	0.88	0.73	0.69
2	0.95	0.98	0.96	0.92	1.00	0.28
3	0.70	**0.013**	0.45	**0.038**	1.00	0.60
4	0.69	0.62	0.79	0.78	0.74	0.40
5	0.17	**0.024**	0.29	$\mathbf{2.9 \cdot 10^{-3}}$	0.98	**0.040**
6	0.59	0.56	0.44	0.77	0.48	0.078
7	0.56	0.56	0.58	0.46	0.49	1.00
8	0.89	0.34	0.95	0.48	0.68	0.63
9	0.27	0.15	0.069	0.099	0.50	0.55
10	0.089	0.47	0.18	0.27	0.22	0.80
11	0.11	0.87	0.18	0.11	0.41	0.30
12	0.086	0.18	0.13	0.090	1.00	0.24
13	0.41	1.00	0.50	1.00	0.13	1.00
14	0.24	0.68	0.14	0.80	0.48	0.20
15	$\mathbf{7.4{\cdot}10^{-3}}$	0.20	$\mathbf{2.9{\cdot}10^{-3}}$	**0.027**		0.35
16	0.10	$\mathbf{5.1{\cdot}10^{-3}}$	0.16	$\underline{\mathbf{1.2{\cdot}10^{-3}}}$		0.62
16a	0.24	**0.015**	0.37	$\mathbf{5.8{\cdot}10^{-3}}$	0.61	0.82
17	0.27	0.31	0.34	1.00		0.42
17a	0.19	0.39	0.095	0.50	1.00	0.52
18	1.00	1.00	1.00	1.00	1.00	1.00

Catalog	A	A	A+Y	A+Y	20+	H
		*		*		
1	0.23		0.20			
2						0.28
3		**0.013**		**0.038**		
4						
5	0.17	**0.024**	0.29	$\mathbf{2.9\cdot10^{-3}}$		**0.040**
6						0.078
7						
8						
9	0.27	0.15	0.069	0.099		
10	0.089		0.18	0.27	0.22	
11	0.11		0.18	0.11		0.30
12	0.086	0.18	0.13	0.090		0.24
13					0.13	
14	0.24		0.14			0.20
15	$\mathbf{7.4\cdot10^{-3}}$	0.20	$\mathbf{2.9\cdot10^{-3}}$	**0.027**		
16	0.10	$\mathbf{5.1\cdot10^{-3}}$	0.16	$\underline{\mathbf{1.2\cdot10^{-3}}}$		
16a	0.24	**0.015**		$\mathbf{5.8\cdot10^{-3}}$		
17	0.27	0.31				
17a	0.19		0.095			
18						

Catalog	A	A *	A+Y	A+Y *	20+	H
1						
2						
3		**0.013**		**0.038**		
4						
5		**0.024**		$\mathbf{2.9{\cdot}10^{-3}}$		**0.040**
6						
7						
8						
9						
10						
11						
12						
13						
14						
15	$\mathbf{7.4{\cdot}10^{-3}}$		$\mathbf{2.9{\cdot}10^{-3}}$	**0.027**		
16		$\mathbf{5.1{\cdot}10^{-3}}$		$\underline{\mathbf{1.2{\cdot}10^{-3}}}$		
16a		**0.015**		$\mathbf{5.8{\cdot}10^{-3}}$		
17						
17a						
18						

RESULTS:

- $E > 10^{20}$ eV ⇒ nothing (small statistics)
- AGASA, AGASA+ Yakutsk (consistent) (GMF important):
  - Unidentified 3EG sources
  - BL Lac's
  - Seyferts
- HiRes
  - BL Lac's
    - GMF not accounted
    - angular resolution less than deflections
    - $\sim 4\%$ correlate ⇒ $5 \ldots 10\%$ of primaries neutral??

particular samples

- Sample maximizing the signal in AGASA+ Yakutsk, without GMF (22 BL Lac's) of Tinyakov and Tkachev
- sample of Torres et.al.

Catalog	A	A *	A+Y	A+Y *	H
BL	$3.5 \cdot 10^{-3}$	0.035	$4.9 \cdot 10^{-3}$	0.046	1.00
Torres	$1.0 \cdot 10^{-4}$	1.00	$1.0 \cdot 10^{-3}$	1.00	1.00

PREVIOUSLY SELECTED SMALL SAMPLES OF BL LAC'S

GIVE NO SIGNAL IN HIRES WITHOUT GMF

BUT

BL LAC'S DO CORRELATE WITH HIRES!!!

A DETAILED STUDY: WHICH BL LAC'S CORRELATE?

(TO MAKE PREDICTIONS)

Set of all BL Lac's with known optical and X-ray fluxes (338 out of 491)

(Note: generally, they are brighter and correlate strongly!)

DEPENDENCE ON MAXIMAL ENERGY OF THE COSMIC RAYS:

AGASA, GMF, $4 \cdot 10^{19} < E < E_{max}$

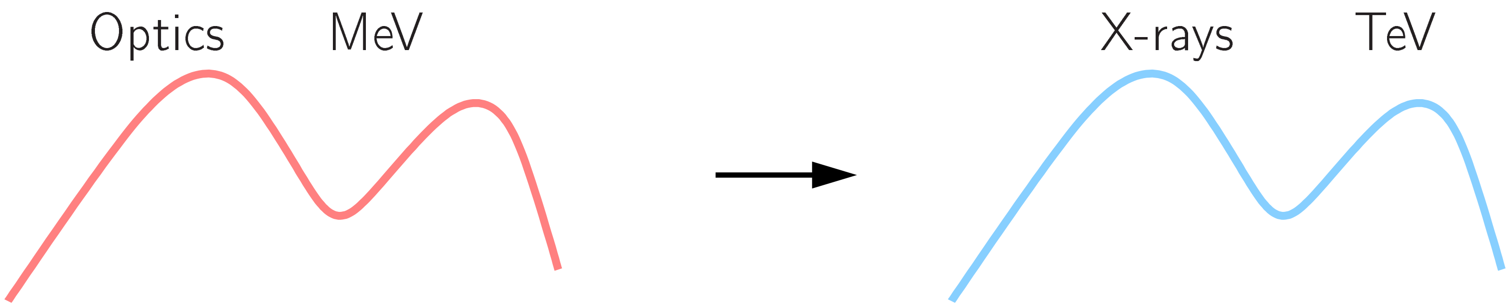
GMF accounted $\Rightarrow$ protons, below GZK (consistent)

BRIGHTER OBJECTS — STRONGER COSMIC-RAY SOURCES

for the sample of BL Lacs with $m < 18$, $\mathcal{P} = 6 \cdot 10^{-4}$

LESS TRIVIAL: PHYSICAL PROPERTIES OF BL LAC'S

A sequence of BL Lac's



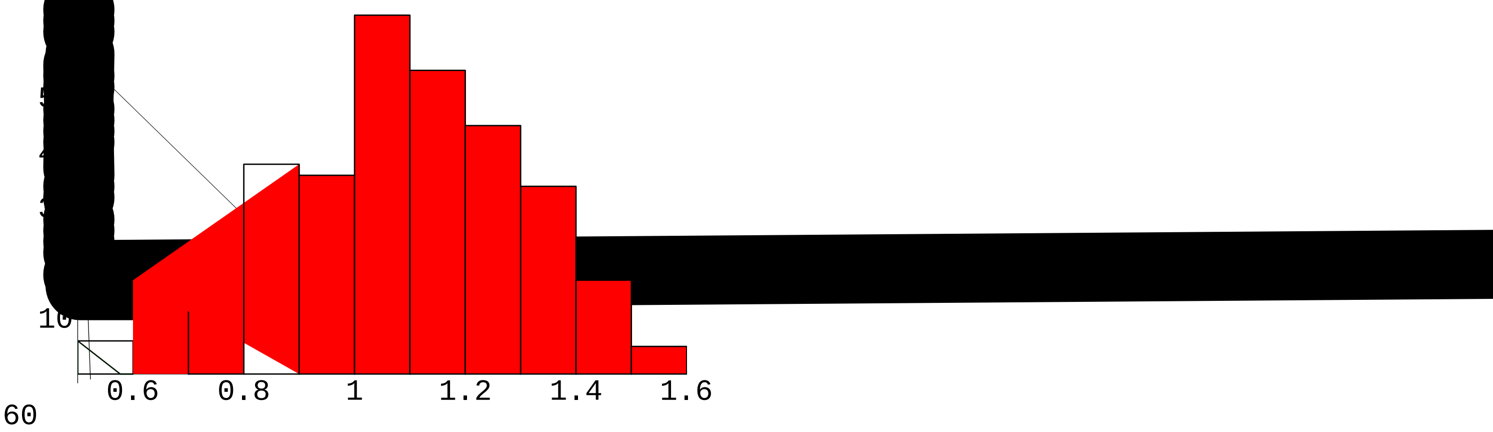
"LOW-ENERGY PEAKED" → "HIGH-ENERGY PEAKED"

higher luminosity → lower luminosity

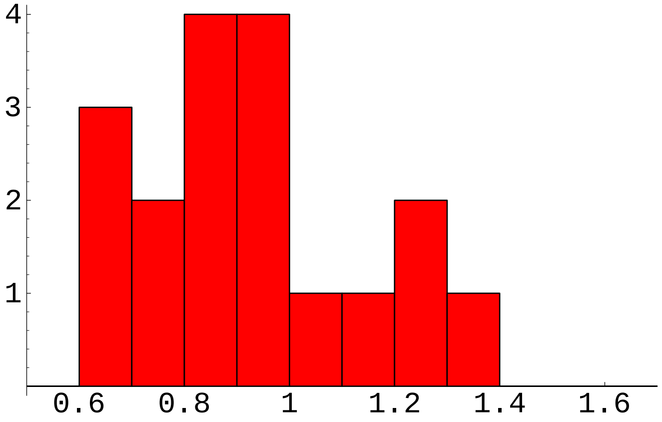
Parameter which governs the sequence:

X-ray to optical spectral index α

ALL BL LAC'S WITH KNOWN OPTICAL AND X-RAY FLUXES



CORRELATING WITH HIRES $E > 10^{19}$ eV



Kolmogorov-Smirnov probability: 0.0013

$\alpha < 1.0 \Rightarrow \mathcal{P} = 3 \cdot 10^{-4}$

- CONSISTENT WITH PREVIOUS STUDIES:

  LBLs HAVE STRONG OPTICAL AND X-RAY EMISSIONS

- PREDICTIONS FOR PIERRE AUGER:

  A CATALOG OF SOUTHERN OBJECTS WITH $m < 18$ and $\alpha < 1.0$

CONCLUSIONS:

- TEST OF CORRELATIONS PERFORMED
- AGASA, YAKUTSK:
  - UNIDENTIFIED EGRET
  - BL LAC's
  - SEYFERT

  GMF IMPORTANT; STRONGER CORRELATIONS AT LOW ENERGIES CONSISTENT WITH PROTONS
- HIRES
  - BL LAC's

  (NO GMF)
- AT LEAST $5 \ldots 10\%$ OF NEUTRAL PRIMARIES AT $E > 10^{19}$ eV (HIRES SCALE)

MORE CONCLUSIONS:

- ENERGIES, PROFILES, ARRIVAL TIMES WANTED!
- ULTRA-HIGH-ENERGY ASTRONOMY STARTED

  (HIRES STEREO ANGULAR RESOLUTION BETTER THAN EGRET)
- WHICH BL LAC'S? BRIGHT LBLs

  (STRONG IN OPTICAL AND SUB-GEV, WEAK IN X AND TEV)
  - TEST WITH PIERRE AUGER
  - DEVELOP MODELS (LBL + NEUTRAL PRIMARIES)