Origin of the highest energy cosmic rays

Peter L. Biermann[1,2,3], J. Becker [4], P. Gina Isar [5,6], Ioana C. Mariş[5], Faustin Munyaneza[1], Todor Stanev[7], & Oana Taşcău[8]

[1]Max-Planck Institute for Radioastronomy, Bonn, Germany
[2]Department of Physics and Astronomy, University of Bonn, Bonn, Germany,
[3]Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA
[4] Dept of Physics, Univ. Dortmund, Dortmund, Germany
[5] FZ Karlsruhe, and Dept. of Physics, Univ. of Karlsruhe, Germany
[6] Institute of Space Science, Bucharest, Romania
[7] Bartol Research Institute, University of Delaware, Newark, DE, USA
[8] Dept. of Physics, University of Wuppertal, Wuppertal, Germany

Sources

- Our Galaxy/galaxies: Supernovae (Wolf Rayet star supernovae!), OB star wind bubbles, Microquasars, Pulsars, Gamma Ray Bursts
- Galaxies: Active Galactic Nuclei, Black hole mergers
- Galaxies: Cluster of galaxies, accretion shocks, large scale structure shockwaves
- Particle decay, correlated with halos or large scale structure, or uncorrelated

Remember: Almost every galaxy has an active nucleus, observed or observable
Remember: Almost every galaxy has supernovae and most form stars
(e.g., Elvis et al. ApJ 1984, Pérez-Fournon & Biermann AAL 1984, Faber et al. AJ 1997, Bower et al. ApJL 2002, Greene et al. NewAR 2006, Véron-Cetty & Véron AA 2006)

Sources: Gamma Ray Bursts

- Gamma Ray Bursts (GRBs) explosions of Wolf Rayet stars, into supernovae type Ic
- Wolf Rayet stars end product of evolution of all very massive stars
- Of order one percent of all very massive stars explode as Gamma Ray Bursts
- Due to beaming of a highly relativistic jet, only about 1/300 of all GRB like explosions actually perceived as a GRB
- In analogy to radio galaxies (see below) believed to be possible sources of ultra high energy cosmic rays
- Correlates with a high star formation rate, and so with a high FIR flux - flux density at 60 micron

Source NGC	Dist Mpc	$S_{60\mu}$ Jy	E_{max} eV	F_{cr} units (M82)
6946			3×10^{20}	
253			3×10^{20}	
M101			3×10^{20}	
M51a			3×10^{20}	
M51			3×10^{20}	
M31			3×10^{20}	
M94			3×10^{20}	
M33			3×10^{20}	
IRAS02421+6233			3×10^{20}	
2146			3×10^{20}	
Maffei 2			3×10^{20}	
4102			3×10^{20}	
IC342			3×10^{20}	
891			3×10^{20}	
M82			3×10^{20}	1.0
660			3×10^{20}	
3690			3×10^{20}	
4631			3×10^{20}	
1569			3×10^{20}	
2403			3×10^{20}	
3079			3×10^{20}	
2MAJ0456+3557			3×10^{20}	
M77			3×10^{20}	
2MAJ0530+3347			3×10^{20}	
2903			3×10^{20}	
1097			3×10^{20}	
1365			3×10^{20}	
3628			3×10^{20}	
1808			3×10^{20}	
M66			3×10^{20}	
3256			3×10^{20}	
LMC			3×10^{20}	
SMC			3×10^{20}	
4945			3×10^{20}	
ESO173-G015			3×10^{20}	
5128 = Cen A			3×10^{20}	
Circinus gal.			3×10^{20}	
M83			3×10^{20}	
55			3×10^{20}	
7582		5	3×10^{20}	
7552			3×10^{20}	

Table 1: Ultra high energy cosmic rays from GRBs; sample selected by > 50 Jy at 60 micron; work done by Alina Istrate

Sources: Gamma Ray Bursts, injection

- The rate of GRBs is proportional to the supernova rate, so to the star formation rate, and hence to the FIR luminosity
- Injection from each event at one single time; maybe mostly neutrons, in beam
- Neutrons at top energy (maybe 10^{21} eV), can travel 10 Mpc before they decay back to protons
- So at lower energy they are influenced by magnetic fields earlier in their path (as protons), so get to Earth later
- Critical energy E_{wind}, when the path could be deflected in a possible galactic magnetic wind around the parent galaxy, perhaps many 10^{19} eV

Sources: Gamma Ray Bursts, propagation

- So source region, below E_{wind}, summing over many GRBs in one galaxy, is a cloud around the parent galaxy, with a size proportional to energy
- Above this critical energy E_{wind}, source region again star burst region scale inside parent galaxy
- This may imply that the effective proton injection, summing over many galaxies, is from a highly distributed region of space, mimicking isotropy
- Therefore testable prediction: Below the critical energy E_{wind} sources highly distributed, above conversion to nearly straight-line path outside our Galactic wind

Sources: Radio galaxies

- 10^{21} eV proton energy in M87 required from ubiquituous cutoff near $\nu^\star \simeq 3\,10^{14}$ Hz in jet (Biermann & Strittmatter ApJ 1987)
- This translates to loss limit

$$E_{p,max} \simeq \; 1.4\,10^{20}\text{eV}\,(\frac{\nu_e^\star}{3.10^{14}\,\text{Hz}})^{1/2}\,B^{-1/2} \qquad (1)$$

- B typically 10^{-2} to 10^{-4} Gauß; spatial limit near $10^{21}\,L_{46}^{1/2}$ eV (Falcke et al. AA 1995)
- Independent of all the detailed assumptions about intensity of the turbulence, shock speed; the dependence via magnetic field on parameters with the 1/7-power
- Radiogalaxies confirmed source candidates for protons at energies $> \; 10^{20}$ eV!
  for other energies all jet-sources: gamma ray bursts, microquasars, jet-supernovae, ..

Sources: Radio galaxies: Maximal energy

- In jets $B(r) \sim 1/r$, analogy to the Solar wind (Parker 1958)
- This implies loss limit scales with $r^{1/2}$
- If one knot, or shock, where the flow goes from relativistic supersonic to subsonic (probably knot A in the M87 jet): source
- The distance along the jet, where this happens scales with power
- So lower power sources have weaker magnetic field, implying larger maximal energy; but shorter jets, so higher magnetic field at the end-point
- However, if the maximal energy from the loss limit above the size limit, then the size limit applies, independent of r

Positional correlations?

Work with Ioana Mariş, expanding on earlier work, in recent years with Todor Stanev and Glennys Farrar
see Tinyakov, Tkachev, Semikoz, ..

- Take samples, complete samples and irregular samples of active galactic nuclei, starving and active, starburst and normal galaxies, clusters of galaxies, ... heureka!
- formal probability very small that this is random, using 5 degrees diameter, with radio sources from the Condon Radio survey in positional coincidence with far infrared sources
- Since we tried many times to get such a result we do not assign any physical meaning to this result at this time

Positional correlations? Toy model

- Liberation of sequestered GUT particles in the squeeze of a merger of two black holes (work with Paul Frampton, astro-ph/0512188, in Phys. Lett. B March 2006):
- Particles in 5 dimensions. About 1 percent of dark matter is sequestered DM particles:
- Decay time reduced drastically only for decay into the direction of the spin of the resulting spinning black hole!
- The new particles do not interact with the MWBG, again due to sequestering.
- The second particle generation then decays along the line of sight to hadrons.
- These hadrons are observed. Test: relatively flat spectrum, pointed to AGN, and all AGN flat spectrum radio sources.

Alternate approach: V. Berezinsky

- Dip in range 10^{18} to 4 10^{19} eV due to pair creation interaction (V.B.)
- Dip near 3 10^{18} eV due to due to transition to Galactic cosmic rays (P.L.B.)
- Transition to Galactic cosmic rays near 10^{18} eV (V.B.)
- Injection spectrum spectral index 2.55 - 2.75, fitting the spectrum of extended radio lobes (V.B.)
- Injection spectrum spectral index 2.0 - 2.2, fitting the spectrum of radio hot spots (P.L.B.)

Sources: Recent spin-flips of black holes

Work with László Á. Gergely, Gopal-Krishna, Christian Zier

- Galaxies merge; almost all galaxies have central black hole; black holes merge
- Then orbital spin can win over intrinsic spin: Spin-flip
- Observed: Z-shaped radio galaxies: just before merger
- Observed: Super-disk radio galaxies: Merger of black holes imminent
- Observed: X-shaped radio galaxies: Merger of black holes recently
- Jet new direction: Super-strong shock, particle acceleration, interaction region, beam-dump: 3C147 example

Sources: Integration over cosmic history

Work with Faustin Munyaneza, Sorin Roman, Gordon Thompson,

- Galaxies merge: Stirring up of all dark matter, powerlaw radial distribution
- Core region degenerate for keV Fermions
- Formation of degenerate dark matter star: Eaten by stellar black hole
- Black hole mass distribution indeed observed, power-law from about $3\,10^6$ solar masses to 10^8 solar masses, and steeper power-law to $3\,10^9$ solar masses
- Then activity from mergers, highly intermittent, gives cosmological source distribution of high energy cosmic rays

Sources: Nearby Black Holes: spin-down power

Work with Ioana Duţan, Todor Stanev

- All quiescent black holes produce radio emission
- Using concept that spin down of black holes dominates jet power and emission
- Estimate of maximum particle energy, and maximum cosmic ray flux contribution
- Many weaker sources dominate between $3\,10^{18}$ eV and $5\,10^{19}$ eV
- **M87** dominates the flux near maximum particle energy,
  Cen A and NGC1068 dominate at lower energy

Source NGC	Dist Mpc	BH Mass $M_\odot$	S_{core} mJy	E_{max} eV	$F_{cr}/$ $F_{cr}(M87)$
315	69*	1×10^8	305	2.09×10^{19}	1.33
383=3C31	69.8*	1×10^8	48	2.09×10^{19}	0.14
821	22	5×10^7	0.5	1.48×10^{19}	0.00062
1068	15	1.5×10^7	650	8.11×10^{18}	6.77
1167	66.1*	1×10^8	243	2.09×10^{19}	0.99
1399	20	1×10^8	5.1	2.09×10^{19}	0.0059
2778	22.9	1.4×10^7	0.6	7.83×10^{18}	0.00192
2787	13	4.1×10^7	11.4	1.34×10^{19}	0.02472
3031=M81	3.7	1.8×10^7	120	8.88×10^{18}	0.44853
3245	20.9	2.1×10^8	3.3	3.03×10^{19}	0.00215
3377	9.9	1.45×10^9	< 0.5	7.97×10^{19}	< 0.00004
3379	10.6	1×10^8	0.7	2.09×10^{19}	0.00042
3384	11.6	1.6×10^7	< 0.5	8.38×10^{18}	< 0.00107
3608	22.9	1.1×10^8	< 0.5	2.19×10^{19}	< 0.00036
3516	40	2.3×10^7	15.5	1.00×10^{19}	0.08398
4168	20	1.2×10^9	3.1	7.25×10^{19}	0.00057
4203	14.1	1.2×10^7	8.9	7.25×10^{18}	0.044
4239	15.3	3.37×10^8	< 0.5	3.84×10^{19}	< 0.00014
4258=M106	7.3	4.1×10^7	3	1.34×10^{19}	0.00395
4278	9.7	5.2×10^7	87.7	1.51×10^{19}	0.21542
4291	26	1.9×10^9	< 0.5	9.13×10^{19}	< 0.00005
4342	15.3	3×10^8	< 0.5	3.62×10^{19}	< 0.00015
4365	22	2.14×10^8	< 0.5	3.06×10^{19}	< 0.00022
4374=M84	18.4	1.6×10^9	183	8.38×10^{19}	0.06111
4395	3.6	1.18×10^5	9	7.19×10^{17}	0.66
4434	15.3	1.17×10^9	< 0.5	7.16×10^{19}	< 0.00005
4458	15.3	1.78×10^9	< 0.5	8.83×10^{19}	< 0.00004
4459	16.1	7×10^7	0.8	1.75×10^{19}	0.00076
4472	16.8	5.2×10^7	4.1	1.51×10^{19}	0.0067
4473	15.7	1.1×10^8	2	2.19×10^{19}	0.00165
4486=M87	16.1	3×10^9	2835	1.14×10^{20}	1
4564	15	5.6×10^7	< 0.5	1.56×10^{19}	< 0.00049
4596	16.8	7.8×10^7	< 0.5	1.85×10^{19}	< 0.00040
4760	57	1×10^8	35.4	2.09×10^{19}	0.0931
4783	57	1×10^8	34.5	2.09×10^{19}	0.0903
5127	66.5	1×10^8	11.1	2.09×10^{19}	0.0246
5128=Cen A	5	1×10^8	6 980	2.09×10^{19}	19.97
NGC 5141	72 *	1×10^8	150	2.09×10^{19}	0.57
5845	25.9	2.4×10^8	< 0.5	3.24×10^{19}	< 0.00022

Table 2: Ultra-High energy cosmic rays from active black holes in the spin-down model; work done by Ioana Duţan. Here VLA or VLBI; the black hole mass is derived from observations, or assumed to be 10^8 solar masses

Sources: Nearby Black Holes: accretion power

Work with Oana Taşcău, Ralph Engel, Heino Falcke, Ralf Ulrich, Todor Stanev

- All quiescent black holes produce radio emission (see Pérez-Fournon & Biermann AAL 1984)
- Tested with with Heino Falcke, {Nijmegen}; Sera Markoff, {Amsterdam}; Feng Yuan, {Shanghai}; Marina Kaufman-Bernardó, {now Bonn}) item Many weaker sources dominate between
  $3\,10^{18}$ eV and $5\,10^{19}$ eV
- **M87** dominates the flux near maximum particle energy,
  Cen A dominates at lower energy

Source NGC	Dist Mpc	BH Mass $M_\odot$	S_{core} mJy	E_{max} eV	F_{cr} F_{cr} units (M87)
315	69*	1×10^8	305	1.1×10^{20}	0.09
383=3C 31	69.8*	1×10^8	92	7.8×10^{19}	0.04
821	22	5×10^7	1.1	4×10^{18}	<0.0051
1068	15	1.5×10^7	1.55	1.07×10^{19}	0.7
1167	66.1*	1×10^8	243	1.04×10^{20}	0.08
1399	20	1×10^8	5.1	1.3×10^{19}	0.01
2778	22.9	1.4×10^7	0.6	9.7×10^{17}	0.002
2787	13	4.1×10^7	11.4	5.2×10^{18}	0.029
3031=M81	3.7	1.8×10^7	120	2.16×10^{18}	0.324
3245	20.9	2.1×10^8	3.3	2.41×10^{19}	0.01
3377	9.9	1.45×10^9	< 0.5	$< 5.4 \times 10^{19}$	< 0.004
3379	10.6	1×10^8	0.7	4.37×10^{18}	0.01
3384	11.6	1.6×10^7	< 0.5	$< 6.63 \times 10^{17}$	<0.004
3608	22.9	1.1×10^8	< 0.5	$< 7.1 \times 10^{18}$	<0.002
3516	40	2.3×10^7	15.5	$< 6.7 \times 10^{18}$	<0.017
4168	20	1.2×10^9	3.1	1.31×10^{20}	0.01
4203	9.7	1.2×10^7	8.9	$< 1.15 \times 10^{18}$	0.03
4239	15.3	3.37×10^8	< 0.5	$< 1.85 \times 10^{19}$	<0.003
4258-M106	6.8	4.1×10^7	3	$< 2.16 \times 10^{18}$	0.018
4278	9.7	5.2×10^7	87.7	1.07×10^{19}	0.14
4291	26	1.9×10^9	< 0.5	$< 1.34 \times 10^{20}$	<0.002
4342	15.3	3×10^8	< 0.5	$< 1.49 \times 10^{19}$	<0.003
4365	22	2.14×10^8	< 0.5	$< 1.35 \times 10^{19}$	<0.002
4374=M84=3C 272.1	16.8	1.6×10^9	180	6×10^{19}	0.16
4395	3.6	1.18×10^5	9	2.7×10^{15}	0.012
4434	15.3	1.17×10^9	< 0.5	$< 5.86 \times 10^{19}$	<0.003
4458	15.3	1.78×10^9	< 0.5	$< 8.87 \times 10^{19}$	< 0.003
4459	16.1	7×10^7	0.8	4.22×10^{18}	0.004
4472	16.8	5.2×10^7	4.1	5.56×10^{18}	0.01
4473	15.7	1.1×10^8	2	8.85×10^{18}	0.008
4486=M87	16.1	3×10^9	2835	2.75×10^{21}	1
4564	15	5.6×10^7	< 0.5	$< 2.75 \times 10^{18}$	<0.003
4596	16.8	7.8×10^7	< 0.5	$< 4.13 \times 10^{18}$	< 0.003
4760	57	1×10^8	35.4	5×10^{19}	0.23
4783	57	1×10^8	34.5	5×10^{19}	0.22
5127	66.5	1×10^8	11.1	1.1×10^{19}	0.01
5128=Cen A	5	1×10^8	6 980	5.7×10^{19}	3.9
5141	72 *	1×10^8	150	9.3×10^{19}	0.05
5845	25.9	2.4×10^8	< 0.5	$< 1.7 \times 10^{19}$	<0.002

Table 3: Ultra-High energy cosmic rays from active black holes in the jet-disk symbiosis model. Work done by Oana Taşcău. VLA or VLBI; the black hole mass is derived from observations, or assumed to be 10^8 solar masses

Conclusions

- Open question, whether GRBs have a sufficient rate in the nearby universe, and whether their intermittent injection can explain a smooth spectrum and sky distribution
- In the **accretion dominated** relativistic jet: Beyond the GZK cutoff **M87** and **Cen A**. Weaker sources low maximum particle energy, and small flux. The arrival directions on the sky smooth around 30 EeV, patchy at higher energies. At the highest energies only directions cluster around the real sources
- In the **spin-down dominated** relativistic jet: Many sources with high particle energy, but each low flux. But difference between Cen A, NGC1068 and M87 is even more extreme

- Critical accretion rate accretion powered jet and acceleration, and below critical accretion rate spin-down powered jet and acceleration; so competition between many weak sources, and a few strong sources
- The total spectrum should be accounted for with just these sources: possible in accretion powered jet model

Radio galaxy 3C147 testbeds for fundamental physics - CERN / Stanford / FermiLab in the sky

Acknowledgements

Support for PLB is coming from the AUGER membership and theory grant 05 CU 5PD 1/2 via DESY/BMBF.

References

[1] "Ultra high energy cosmic rays from sequestered X bursts [rapid communication]", P.L. Biermann & P. Frampton 2006, *Physics Letters B*, **634**, p. 125-129 (2006); astro-h/0512188

[2] "Cosmic-ray protons and magnetic fields in clusters of galaxies and their cosmological consequences", Torsten A. Enßlin, Peter L. Biermann, Philipp P. Kronberg, and Xiang P. Wu, *Astrophys. J.* **477**, 560 (1997); astro-ph/9609190