Origin, interaction and propagation of energy cosmic rays

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Students, postdocs and visiting professors

- Students, postdocs and visiting professors from/in: China, Korea, Japan, Australia, India, Israel, Ruanda, Armenia, Iran, Russia, Turkey, Bulgaria, Romania, Hungary, Poland, Greece, Italy, Switzerland, Germany, Great Britain, Norway, France, Netherlands, Spain, Argentina, Mexico, Canada, USA
- Former students and postdocs involved in teaching at the level of professor in the US in and/or from: China, Australia, India, Bulgaria, Romania, Germany, Netherlands, Spain, Mexico, Canada, USA

There are more...

Sources of high energy cosmic ray particles

- Our Galaxy/galaxies: Supernovae, OB star wind bubbles, Pulsars
- Correlates with FIR emission
- Wolf Rayet star supernovae (Gabriela Păvălaş, Adrian Popescu, Ana Vasile), Gamma Ray Bursts (Valeriu Tudose)
- Microquasars
- Galaxies: Active Galactic Nuclei (Alina Donea, Fanel Donea), black hole mergers
- Galaxies: Cluster of galaxies, accretion shocks, large scale structure shockwaves
- Particle decay, correlated with halos or large scale structure, or uncorrelated
- Particles in 5 dimensions, squeezed

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		4	3×10^{20}	
7552			3×10^{20}	

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

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

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

- 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, ..

Positional correlations?

Work with Ioana C. 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

Sky distribution

- At 3 10^{19} eV the sky is homogeneous, as far as the data go.
- So many sources (Sorin Roman): However, all possible astronomical sources are not homogeneous, if the distance is given by the GZK distance.
- Sky is only homogeneous for distances far beyond GZK. Possible solution new particle physics (e.g., Biermann & Frampton 2006).
- Sources that are homogeneous within GZK volume are also new physics, like the Z-burst mechanism (e.g., Weiler), or defect decay (e.g., Sigl et al.).

Method to identify source candidates

- First step: Complete sample, at 5 GHz, 60 microns, 2 microns, optical, X-rays, gamma-rays: e.g. IceCube collaboration and Biermann (astro-ph/0609534); (Alina Istrate) to flux density limit, to redshift limit
- Second step: Other criteria, flat radio spectrum, radio + far infrared, flat radio spectrum + GeV emission (critical catalogue: Véron-Cetty & Véron 2006):
- Starbursts versus AGN hypotheses
- Develop null hypothesis: homogeneous sources, or distributed as matter (Galaxy, supergalactic plane, large scale structure)
- Develop null hypothesis for the magnetic field of the Galactic halo wind: Events from homogeneous source distribution can be all mangled up by Galactic magnetic fields

Magnetic Fields: Galactic Winds

- Many galaxies have winds, visible in radio polarization data (Cracow group).
- All galaxies which make stars also have magnetic fields.
- The origin of the magnetic fields is the battery mechanism in rotating stars; a dynamo acting in the stars; the spreading by wind and explosion of stars. Then dynamo in the galaxy.
- The cosmic ray driven dynamo implies galactic wind, fast enough (Cracow group).
- Unsolved question: Why the magnetic field well correlated around galaxies (Cristina Galea, Valentin Curtef)?
- Conclusion: All galaxies which make stars have a magnetic wind.

Magnetic Fields: Galactic Magnetic Field

- Galaxy has wind (confirmed by Westmeier et al. AA 2005), driven by cosmic rays, then magnetic field topology as in Solar Wind
- Magnetic fields start tangentially to minimize angular momentum transport (Laurenţiu Caramete)
- $B_{\phi} \sim \sin\theta / r$ dominant
- turbulence spectrum k^{-2} in wavenumber for adopted isotropy in wave number phase space, since shock driven
- Plots: Sky distribution for strong and weak turbulence (Alex Curuţiu)

Sources: Recent spin-flips of black holes

Mihaela Chirvasa, László Á. Gergely, Gopal-Krishna, Rodica Roman, 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: Nearby Black Holes: spin-down power

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 (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})
- 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 (Oana Taşcău). VLA or VLBI; the black hole mass is derived from observations, or assumed to be 10^8 solar masses

Conclusions

- Magnetic fields around galaxies in winds can disperse the injection locations
- Magnetic fields in the wind of our Galaxy can disperse the arrival directions
- Magnetic fields can delay the arrival of intermittent sources for lower energies
- At highest energies propagation should be closer to a near straight line path, both in source region, and in our Galaxy
- 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. Sum of nearby sources adds up to best spectrum derived by Venya Berezinsky

- 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 as well as spin-down model

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

To be measured by
AUGER, LOPES and LOFAR
P. Gina Isar, Ioana C. Mariş, Oana Taşcău!

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