arXiv:0811.1848v3 [astro-ph] 18 Dec 2008

Active Galactic Nuclei: Sources for ultra high energy cosmic rays?

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The origin of ultra high energy cosmic rays promises to lead us to a deeper understanding of the structure of matter. This is possible through the study of particle collisions at center-of-mass energies in interactions far larger than anything possible with the Large Hadron Collider, albeit at the substantial cost of no control over the sources and interaction sites. For the extreme energies we have to identify and understand the sources first, before trying to use them as physics laboratories. Here we describe the current stage of this exploration. The most promising contenders as sources are radio galaxies and gamma ray bursts. The sky distribution of observed events yields a hint favoring radio galaxies. Key in this quest are the intergalactic and galactic magnetic fields, whose strength and structure are not yet fully understood. Current data and statistics do not yet allow a final judgement. We outline how we may progress in the near future.

1. Introduction

In the quest of understanding the fundamental structure of matter the physics community has built the Large Hadron Collider (LHC) at CERN in Geneva, which will have particle energies up into the TeV region. In the universe, as we know from direct observation (first Linsley 1963), we have particles up to 300 EeV ($= 3 \cdot 10^{20}$ eV); even in the center of mass collision with an identical particle (proton or heavier) this yields energies in the center of mass frame of $5 \cdot 10^{14}$ eV, so more. If we could identify the sources and interaction regions of these extreme energy particles (see the books by Ginzburg & Syrovatskii 1964, Berezinsky et al. 1990, Gaisser 1991, Stanev 2004, and recent reviews by Gaisser & Stanev 2006, Biermann et al. 2003, 2006, as well as Nagano & Watson 2000) we may be able to learn some of the physics at such energies, so perhaps go beyond the LHC.

In this short review we will discuss the latest trends in the quest to understand where the extremely high energy particles come from, and how we might be able to test our ideas. For lack of space we only give a small fraction of all references.

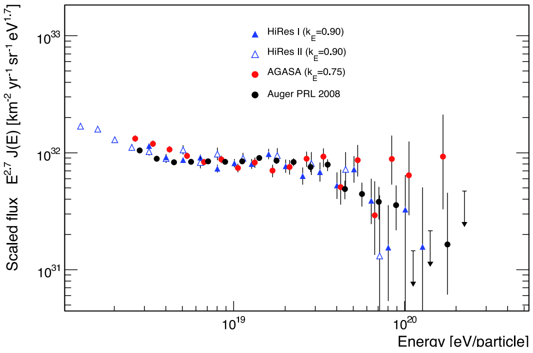

Figure 1. This overlay spectrum shows the public data, as of summer 2008, of AGASA, HiRes and Auger (Abbasi et al. (HiRes) 2008; Auger 2008b). The AGASA event energy has been scaled down by 25 %, and the HiRes event energy has been scaled down by 10 %. The spectra are adjusted to show a common flux near 10^{19} eV. The main problem here is the energy estimate of the different detectors.

2. Source candidates

While very many ideas exist based on detailed physical models for possible sources of ultra high energy cosmic ray particles, the best bet candidates to explain them are radio galaxies (Ginzburg & Syrovatskii, Blandford, Biermann, et multi al.) and gamma ray bursts (Mészáros, Piran, Rees, Vietri, Waxman, et multi al., with a recent summary, e.g., Waxman 2006). As gamma ray bursts are special cases of very massive star explosions, their occurrence should correlate with galaxies, which have a current starburst, so are strong in the far infrared, such as, e.g., M82 (e.g. Kronberg et al. 1985), NGC253, NGC2146 and the like; the early models (Biermann 1976, Biermann & Fricke 1977) already allowed the prediction of far-infrared from radio fluxes from starburst galaxies, such as NGC2146 (Kronberg & Biermann 1981), and so gave a prediction of the supernova rate (today perhaps equivalent to a prediction of the gamma ray burst rate). At present the statistics of the arrival directions do not support a correlation with starburst galaxies. On the other hand, the arrival directions do seem compatible with the nearest radio galaxy, Cen A = NGC5128, a source long suspected to emit cosmic rays (Ginzburg & Syrovatski 1963). However, this radio galaxy has so little power, it presents a special challenge to understand how it could accelerate particles to 10^{20} eV, and beyond.

For another nearby radio galaxy, M87 in the Virgo cluster (Ginzburg & Syrovatski 1963, Cunningham et al. 1980), the synchrotron spectrum of the knots in the jet has been used to argue that it requires protons at 10^{21} eV to initiate the cascade in the plasma for scattering the non-thermal electrons in order to yield a parameter-free cutoff frequency of near $3 \cdot 10^{14}$ Hz, as observed in many knots, hot spots and nuclei (e.g. Rieke et al. 1976) of radio emitting active galactic nuclei (Biermann & Strittmatter 1987). This is in fact the only argument based on observations which implies the existence of these ultra high energy particles in the source. However, it has to be noted, that this does not necessarily imply that the particles we observe come from such sources; it is just plausible for lack of many alternatives.

2.1. Complete samples

In order to test the idea that radio galaxies are source candidates, we have developed the jet-disk symbiosis concept (papers by Falcke et al. 1995a, b, Markoff et al. 2001, Yuan et al. 2002, Massi & Kaufman Bernardo 2008, etc.). Therefore we need a complete sample of steep spectrum radio sources (e.g. teams led by Witzel, see Kühr et al. 1981). Table 1 presents such a complete list, differentiated in two sets in redshift range; the complete sample takes all extragalactic steep spectrum sources down to a flux density limit, which are not already known as predominantly starburst galaxies from their far-infrared/radio flux density ratio, and that are within the redshift specified. Table 2 extends the list to slightly higher redshift.

2.2. Particle energy and particle flux predictions

The main indefinite parameter in the jet-disk symbiosis picture is the anchoring of the magnetic field at the base of the jet. Spin-down powered jets emanating from very near supermassive black holes (Blandford & Znajek 1977, Blandford & Koenigl 1979, Boldt & Ghosh 1999) are one possibility to do this: The jet power is roughly proportional to the total radio luminosity (Enßlin et al. 1997), especially if we include low power sources in the crude fit. If we identify the jet power as an upper limit to the Poynting flux, and use the relationship between Poynting flux and maximal particle energy (Lovelace 1976, see below), we obtain an expression for the maximal particle energy. Furthermore we can assume that the cosmic ray flux is a fraction of the total jet power, and so obtain a simple proportionality. Calling the mass of the black hole M_{BH}, the observed compact radio flux density S_{rad} or extended total flux density at 2.7 GHz $S_{2.7,tot}$, the luminosity distance D_L to the radio galaxy, the maximal particle energy E_{max}, and the maximal cosmic ray flux F_{CR}, we then have here and below:

$$E_{max} \sim D_L \, S_{2.7,tot}^{1/2} \tag{1}$$

and

$$F_{CR} \sim S_{2.7,tot} \tag{2}$$

This flux corresponds to distance attenuation only with D_L^{-2}. Interestingly, the mass of the black hole does not even enter here due to the simplicity of the Poynting flux argument. Following the argument below we might have to multiply the maximum particle energy by 6 - 8 or so to simulate the seeding with heavier nuclei from a weak starburst, indicated by a relatively large FIR/radio ratio as given in Table 1; this ratio is still far below that of a pure starburst, for which it is of order 300. However, the numbers given for the maximal energy do not include this extra factor. In Table 2 this is indicated by an asterisk.

Accretion powered jets are the other alternative, which works well for relatively high current accretion rates (Falcke et al. 1995a, b, Taşcău 2004, Taşcău et al. 2008):

$$E_{max}^{\dagger} \sim S_{rad}^{1/3} \, D_L^{2/3} \, M_{BH} \tag{3}$$

and

$$F_{CR}{}^{\dagger} \sim S_{rad}^{2/3} \, D_L^{-2/3} \tag{4}$$

For distances < 50 Mpc usually NGC5128 = Cen A, possibly NGC1316 = For A, and a group around M87 = Vir A dominate in predicted UHECR flux (Ginzburg & Syrovatskii 1963). The first five in flux density of the extended flux are ESO137-G006, NGC1316, NGC4261, NGC4486=M87, and NGC5128.

An early attempt to fit older data is shown in Fig. 2.

These two approaches allow to understand the huge range in radio to optical flux ratios from active galactic nuclei (Strittmatter & Witzel et al., 1980), and the ubiquity of low flux densities of compact radio emission from basically all early Hubble type galaxies (e.g. Perez-Fournon & Biermann 1984). As soon as the accretion rate drops below some critical level, spin-down takes over from accretion as the powering mode. As pointed out by Blandford the decay time of spin-down powered activity is very long, and may allow to understand the appearance of "inverse evolution"

Table 1
Properties of the complete sample selected in passband 6cm (5 GHz), redshift $z \leq 0.018$ and $z \leq 0.0125$ flux density brighter than 0.5 Jy, steep spectrum and no starburst, sample of 21 and 14 candidate sources (Caramete et al. 2008). The distances are corrected for the local cosmological velocity field. The FIR/radio ratio can readily distinguish radio galaxies from normal galaxies and pure starbursts (Kronberg et al., Chini et al.).

Name	Morphological type	Redsh.	Dist. Mpc	M_{BH} $10^8 M_\odot$	Core flux density mJy	B-V mag	FIR/Radio ratio
NGC 5128	S0 pec Sy2	0.001825	3.4	2	133361	0.88	3.39
NGC 4651	SA(rs)c LINER	0.002685	18.3	0.4	700	0.51	8
MESSIER 084	E1;LERG;LINER Sy2	0.003536	16	10	2094.18	0.94	0.17
MESSIER 087	E+0-1 pec;NLRG Sy	0.00436	16	31	9480.75	0.93	0.01
NGC 1399	cD;E1 pec	0.004753	15.9	3	342	0.95	0.04
NGC 1316	(R')SAB(s)00 LINER	0.005871	22.6	9.2	5651.61		0.06
NGC 2663	E	0.007012	32.5	6.1	628.56		0.08
NGC 4261	E2-3;LINER Sy3	0.007465	16.5	5.2	2662.69	0.97	0.02
NGC 4696	BCG;E+1 pec LINER	0.009867	44.4	3	518.28		0.08
NGC 3801	S0/a	0.011064	50	2.2	300.25	0.9	0.3
IC 5063	SA(s)0+: Sy2	0.011348	44.9	2	321.14	0.93	11.08
NGC 5090	E2	0.011411	50.4	7.4	488.13	..	0.1
NGC 5793	Sb: sp Sy2	0.011645	50.8	1.4	51.5	0.79	12.76
IC 4296	BCG;E;Radio Galaxy	0.012465	54.9	10	442.22	0.95	0.08
NGC 0193	SAB(s)0-:	0.014657	55.5	2	285.93	0.98	0.76
VV 201	Double galaxy	0.015	66.2	1	450.09		0.05
UGC 11294/4	E0?;HSB	0.016144	63.6	2.9	254.52		0.33
NGC 1167	SA0-;LINER Sy2	0.016495	65.2	4.6	393.09		0.13
CGCG 114-025	SA0-	0.016885	67.4	1.9	443.39		0.01
NGC 0383	BCG;SA0-: LERG	0.017005	65.8	5.5	414.25		0.21
ARP 308	Double galaxy WLRG	0.018	69.7	1	88.54		0.09

for flat spectrum radio sources: It just may be the growing number of "old" central activity since the activity per comoving starburst and central activity in galaxies peaked in the redshift range 1.5 to 2. The activity decreased by about a factor of 30 since then, and so we have an increasing population of early Hubble type galaxies, which had their prime activity years some long time ago. If all central black holes stay active - as observations suggest, albeit at a very low level - then a subset of the population of these black holes will aim their jet at Earth, and so give rise to a weak, but dominant flat radio spectrum. One consequence is that most central supermassive black holes should have close to maximal spin.

All these weakly active galactic nuclei will also accelerate particles to high energy, but have a flux, which is generally extremely low. Such particles would have to be injected from the interstellar medium of the early Hubble-type host galaxy, and can be argued to be mostly protons, with some Helium. Their maximal energy will be relatively low.

Table 2 gives the predictions.

2.3. Scattering model

Basic questions on the effect of intergalactic and galactic magnetic fields on the propagation of ultra high energy charged particles are whether a) is there (almost) no effect, b) is a systematic bending of orbits key or c) is there a general scattering (see, e.g., Das et al. 2008). Any systematic shift is not apparent at the present time with the sparse data, while a general scattering seems required. There may be a general systemic shift, which would provide a location-dependent change

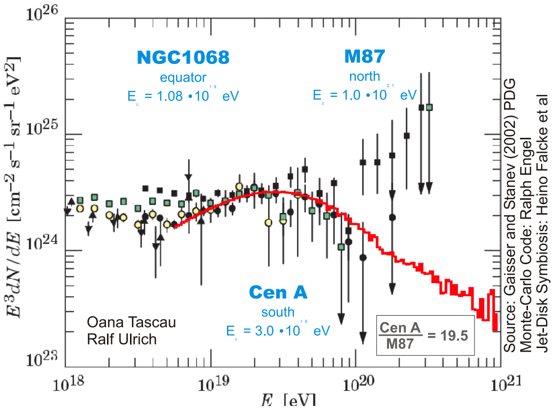

Figure 2. This spectrum shows a best fit, including only three sources, NGC1068, Cen A, and M87. The fit was achieved by setting the ratio of the flux of Cen A relative to M87 to 19.5 at 10^{19} eV; key to the match was the lower maximal energy of Cen A - at highest energy M87 is still the strongest: The cutoff is due to source limits, not due to GZK-interactions. The flux of NGC1068 is at 0.7 relative to M87, and its maximal energy is only 10^{19} eV; relative to Cen A, this is insignificant here. This is quoted from the M.Sc. thesis of O. Taşcău (2004).

of direction for the least scattered events from anyone source. For lack of strong evidence we ignore such a plausible shift for the moment.

Since the data suggested a near isotropic sky distribution in 1995 (Stanev et al. 1995), and a more correlated distribution with more and homogeneous data (Auger-Coll. 2007, 2008a) a scattering model is suggested which spreads arriving events almost evenly; an alternative would have been to have many sources, but no such model is currently plausible. A simple single scattering plasma physics approximation suggests a scattering model of θ^{-2} in scattering angle θ per solid angle, which spreads events evenly into logarithmic rings $\Delta\theta/\theta = const$ (Curuţiu et al. 2008). The detailed magneto-hydro-dynamic (MHD) simulations of Das et al. (2008) support a description as a simple such power-law at high energy, while at low energy the spreading is smoother and broader, corresponding to multiple scattering. For simplicity we use here θ^{-2} with a core of 3 degrees, and a maximum of 90 degrees; the core is to reflect what happens in the galactic disk (Beuermann et al. 1985, Snowden et al. 1997), while the general scattering distribution may reflect either scattering in the cosmological magnetic fields as in Das et al. (2008), or scattering in a galactic magnetic wind halo (Parker 1958, Simard-Normandin & Kronberg 1980, Parker 1992, Ahn et al. 1999, Hanasz et al. 2004, Westmeier et al. 2005, Chyży et al. 2006, Breitschwerdt 2008, Kulsrud & Zweibel 2008, Caramete et al. 2008). The main difference in these two sites of scattering is that only for scattering by cosmological magnetic fields we obtain appreciable delay times, changing the spectrum (Stanev et al. 2003, Das et al. 2008). We neglect here the possibility that the source itself might be appreciably extended, as Cen A is, with a 10 degree size already in sensitivity limited data (Junkes et al. 1993). We also do not take into account the effect of the local shear flow, dragging magnetic fields along (Kulsrud et al. 1997, Ryu et al. 1998, Enßlin et al. 1998, Kronberg et al. 1999, Gopal-Krishna et al. 2001, Ryu et al. 2008), in the cosmological filament around Cen A; the shear flow is expected to be parallel to the outer shape of the radio source. This shear flow can be expected to scatter particles, making the sites of origin appear correlated with the large scale filament.

With such a simple prescription we can turn a source list with predicted cosmic ray fluxes into probable sky distributions (Caramete et al. 2008). We used sets of 100 simulated events each, and performed 10^6 such Monte-Carlo runs, for a total of 10^8 simulated events: Using the predicted fluxes, and the scattering distribution we sample the entire list of Table 2 out to a given redshift (we used 0.0125, 0.018, and 0.025) not taking here into account the GZK-attenuation. Including the sky sensitivity for both Auger and HiRes we again generate detected simulated sets of events of 100 each, and we then find with the predictions listed above, that using the Véron-catalogue (Véron-Cetty & Véron 2006) as procedure (Auger-Coll. 2007, 2008a) in searching for correlations we get a broad probability distribution around 50 percent of correlated events in the Auger sky, and about 30 percent in the HiRes sky (Curuţiu & Caramete 2008). We also find a relatively large ratio between the number of simulated events in the Auger-sky versus the HiRes-sky. We find a larger predicted number of events in the HiRes-sky versus the Auger-sky only for galaxies selected to represent a parent population of gamma ray bursts (i.e. selected at 60 μ). All this just reflects the well-known fact, that the sky is not homogeneous in the nearby universe.

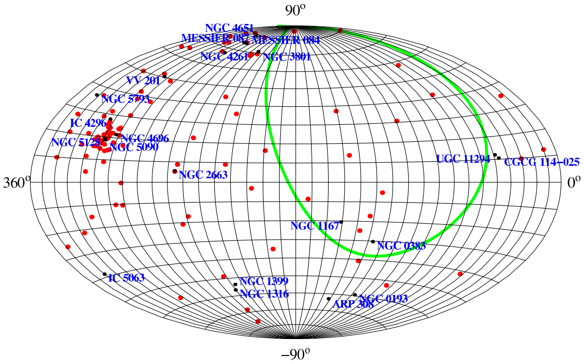

Figure 3. Aitoff projection in galactic coordinates of the selection from the NASA/IPAC Extragalactic Database (NED) in passband 6cm (5 GHz), redshift $z \leq 0.0125$ flux density brighter than 0.5 Jy, steep spectrum and no starburst, sample of 14 candidate sources and 100 virtual events from these sources (Curuţiu & Caramete 2008) using the core of 3 degrees distribution of scattering and weighted contribution from the accretion model (O. Taşcău). The green line highlights the area of the sky not visible from the Auger site.

We note that gamma ray bursts have been predicted to show only protons (Rachen & Mészáros 1998), as end-products from decaying neutrons, the only particles that may escape from magnetic confinement before adiabatic losses set in; the neutrons are believed to be created in proton-γ collisions, so arise from regions of very high photon density. The HiRes data on air-fluorescence are consistent with such a picture (Talk by Sokolsky 2008, ISVHECRI meeting).

However, this does not easily explain the cloud of events in the Auger data around the obvious radio galaxy Cen A, of which 5 at least are directly confined within the outlines of the radio emission (Junkes et al. 1993, Rachen 2008).

2.4. Determining anisotropy

One major question with the sparsity of data is how to determine a measure of anisotropy quantitatively. The astronomical sky shows two extreme measures directly: The microwave background, once corrected for the dipole anisotropy to to our peculiar velocity is as perfect as one could imagine (Komatsu et al. 2008). On the other hand, the nearby distribution of galaxies, out to at least 300 Mpc shows anisotropy. Different classes of galaxies have different measures of anisotropy, and the most anisotropic are the galaxies which harbor very large super-massive black holes, giant elliptical galaxies.

Therefore, clearly the best measure of anisotropy is to determine for a given set of ultra high energy cosmic ray arrival directions, where in the range from perfect isotropy to maximal anisotropy, the set of nearby very large super-massive black hole host galaxies, these events lie. Clearly, as demonstrated already, the arrival directions are somewhere in between - assuming of course, that they relate to astrophysical and known object classes.

3. Problems with radio galaxies

3.1. The Poynting flux limit

As Lovelace (1976) has originally shown, the Poynting flux is a lower limit to the energy flux along a relativistic jet, and can be written as basically proportional to the maximal particle energy containable squared. The numbers are such, that for particles reaching 10^{21} eV, 10^{47} erg/s is a conservative lower limit:

$$L_P \, = \, \frac{B^2}{4\pi} \pi \theta^2 z^2 c \tag{5}$$

and

$$E_{max} \, = \, ZeB\theta z \tag{6}$$

which implies

$$L_P \, = \, 10^{47} \, \mathrm{erg/s} \left(\frac{E_{max}}{Z \, 10^{21} \, \mathrm{eV}} \right)^2 \tag{7}$$

M87 and Cen A have energy flows along the jet of order $< \, 10^{45}$ erg/s, $< \, 10^{43}$ erg/s (Whysong & Antonucci 2003), respectively. This implies that it is completely impossible for the Cen A jet to supply the environment to accelerate protons to $> \, 10^{20}$ eV, but allowing $Z \, > 1$ changes this conclusion. A shock in upstream flow with shock Lorentz facor γ_{sh} (Gallant & Achterberg 1999) adds another factor, and finally intermittency $f_{flare} < 1$ also helps, so visible directly in Her A (Gizani & Leahy 2003, and Nulsen et al. 2005). We finally obtain

$$L_P \, = \, \frac{c}{4\pi} \, f_{flare} \left(\frac{E_{max}}{e \, Z \, \gamma_{sh}} \right)^2 \tag{8}$$

The discrepancy is so large, that perhaps all three elements, heavy elements, relativistic shocks, and intermittency or flaring, are required; only pure Fe at the highest particle energies has a chance for Cen A to do it all by itself. In Cen A there is clearly a starburst happening, a phase of strongly enhanced star formation and supernova activity, in which the local cosmic rays can be expected to be substantially increased. The heavier elements as seeds of ultra high energy cosmic rays are therefore perhaps plausible, since it is much faster to accelerate particles from the knee of cosmic rays, where Carbon, Oxygen, Neon to Sulfur are important (Stanev, Biermann, & Gaisser 1993), as was shown by Gallant & Achterberg in a different context (1999).

Let us consider the approach of Gallant & Achterberg (1999) in more detail so understand, what it would lead to: A young starburst has injected a strong population of galactic cosmic rays, still in the spectral injection limit, and now a very powerful highly relativistic shock driven by a jet plows right through this environment. The starburst was visibly triggered by a merger between two galaxies, probably both with super-massive central black holes, and when the two black holes finally also merge, orbital spin wins and induces a spin-flip of the final black hole relative to the spin direction of the previously more massive single black hole (e.g. Gergely & Biermann 2007, 2008, also see below). Therefore the newly powered jet plows through material untouched by the previous older jet, and just filled with interstellar medium, highly excited by the all the explosions of very massive stars, most importantly Wolf-Rayet stars. Wolf-Rayet stars render all the heavy element and Helium cosmic ray particles (Stanev et al. 1993). Therefore we are considering the energy gains of a highly relativistic particle of energy E_1, going back and forth across a relativistic shock, with shock Lorentz factor Γ_{sh}, gaining energy each cycle time (e.g., Drury 1983). Gallant & Achterberg show that the initial energy jump is by a factor of Γ_{sh}^2, and all subsequent energy jumps are just by about a factor of 2.

$$E_2 \, = \, E_1 \, \Gamma_{sh}^2 \, 2^n \tag{9}$$

where n is the number of subsequent cycles. This can be rewritten with $\epsilon \, = \Gamma_{sh}^2 \, 2^n \, >> 1$ as

$$E_2 \, = \, E_1 \, \epsilon \tag{10}$$

which turns a spectrum of

$$N_0 \left(\frac{E}{E_0} \right)^{-p} dE \tag{11}$$

into

$$\frac{N_0}{\epsilon} \left(\frac{E}{E_0 \, \epsilon} \right)^{-p} dE \tag{12}$$

which implies that a spectrum is shifted in flux down by a factor of ϵ, and also over in energy by the same factor.

Considering then the seed population of energetic particles at the knee (Stanev, Biermann, & Gaisser 1993) this implies, that the spectral differentiation by Z at the knee of cosmic rays is shifted over, and down by another factor of ϵ, so reproducing the spectral structure in Z. So, given the spectral bending of the various elements at the knee, we can readily predict the spectral shapes of the spectrum in energy per particle, with the elements like Carbon, Oxygen etc first, shifting ultimately to Iron.

We can obviously check whether the energy jump required, by about 1000 to 3000, is sensible. For the shock Lorentz factor we can take some value between 10 and 50 (Begelman et al. 1994, 2008, Gopal-Krishna et al. 2004, Miller-Jones et al 2004, Ghisellini & Tavecchio 2008, et multi al.), and we then estimate the number of subsequent cycles required:

$$1000 \,\mathrm{to}\, 3000 \, = \, \Gamma_{sh}^2 \, 2^n \tag{13}$$

For a shock Lorentz factor of 10 this requires n from 3 to 5, and for a shock Lorentz factor of 50 it requires no extra jump at all. Obviously, $n = 0$ would minimize the smearing in energy during the shift up in energy.

In this speculative model the knee structure (Stanev et al. 1993) in chemical composition and spectrum is preserved at very high energy. Superluminal shocks can squeeze this overall spectral structure (Hoffmann & Teller 1950), and may deplete it at lower energies, but will basically still preserve it (Meli 2008, see below). As only a small fraction of all Wolf-Rayet stars turn into gamma ray bursts, the cosmic ray contribution from gamma ray bursts to the seed population is likely to be small (Pugliese et al. 2000). As was noted by Biermann (1993) and Stanev et al. (1993), there is an accentuation at the knee, the polar cap component with a E^{-2} spectrum, now probably detected in its loss limit of cosmic ray electrons by the ATIC experiment (Chang et al. 2008). This polar cap component sharpens the knee features of each element; during the strong jump in energy from the knee up there will be some inevitable smearing, but this polar cap component will help keep the features visible.

Of course, very much later in the evolution of an activity episode these seeds will be replaced by the normal average chemical abundances, normal for an elliptical galaxy as typical host for a radio galaxy with perhaps inflow from the local intergalactic medium.

3.2. Magnetic fields in jets

The radio polarization data (e.g. Bridle & Perley 1984) strongly suggest that the magnetic field decreases with distance squared from the central black hole, just as in the Solar wind along the rotational symmetry axis (Parker 1958). A magnetic field decaying as distance squared along the jet would never allow enough space for ultra high energy particles to be accelerated. However, highly oblique shocks could mimick such a pattern (Becker & Biermann 2008) even for a basic magnetic field oscillating around a inverse linear decay along the jet. In such a case, the magnetic field could be strong enough far along the jet to allow the acceleration of ultra high energy particles (Hillas 1984).

3.3. Spectral limit

All these suggestions above lead to another discrepancy, considering the likely spectrum of energetic particles: the radio data suggest a typical spectrum of $E^{-2.2}$ (Bridle & Perley 1984), and only rarely a spectrum as flat as $E^{-2.0}$, while fitting the lower energies of the ultra high energy cosmic ray spectrum suggests possibly even $E^{-2.7}$ (Berezinsky et al. 2006). On the other hand, the observed flux of ultra high energy particles is already so high, that a simple straight continuation of the spectrum $E^{-2.2}$ versus $E^{-2.0}$ would imply an extra factor of about 200 in required energy flux.

However, the phenomenon of incomplete Comptonization (Katz 1976) leads us to ask, whether an analogy of relativistic particles to photons might be possible: Photons can show a diminished low energy spectrum in cases, when the number of photons is constrained independently of its energy content, leading to a finite chemical potential describing what might be called a starved spectrum. Such spectra were crucial to understand the X-ray spectra of active X-ray binary stars (see also Katz, Lightman, Sunyanev, et multi al.). It appears that starved cosmic ray spectra are also possible, as first explorations (Meli 2008) show, that the combination of a subluminal shock with a superluminal shock (Hoffmann & Teller 1950, Drury 1983), a natural reconfinement shock arrangement (Mach 1884-1898, R. Sanders 1983, M. Norman et al., T. Jones et al.), would indeed lead to spectra with a dearth of low energy particles. This would lower the energy requirement considerably. This may actually be required for spectra as steep as $E^{-2.2}$ or steeper.

3.4. Neutrons

In analogy to gamma ray bursts Rachen (2008) has suggested also for radio galaxies to accelerate protons to high energy, then transforming them in p-γ-collisions to neutrons (Puget et al. 1976, Rachen & Mészáros 1998) to get them out at high energy without adiabatic losses. Given that the jet in Cen A is apparently not close to the line of sight, this could be tested for consistency, if the arriving events interpreted as original neutrons were linearly arranged sorted by particle energy, with about 16 degrees in the plane of the sky at 100 EeV, or less. The sparse data do not contradict this; however, as noted above, this environment may not be conducive to the acceleration of protons to extremely high energy. It has to be noted that neutrons at 300 EeV (the observed maximum energy, Fly's Eye 1993) could travel straight from Cen A to Earth, a distance of 3.4 Mpc, with only a small fraction decaying back to protons.

3.5. The three horizons

Observed protons which come from large distances are diminished in energy by interaction with the microwave background (Greisen 1966, Zatsepin & Kuzmin 1966) for energies beyond about $6 \cdot 10^{19}$ eV; nuclei suffer from photo-dissociation (Rachen 1996, Stecker, & Salamon 1999, Hooper et al. 2007, 2008, Allard et al. 2008). This leads to the GZK-horizon, which is strongly dependent on the energy of the particle arriving at Earth; if protons at $> \ 6 \cdot 10^{19}$ eV, about half of the events should come from less than 50 Mpc, and close to 90 percent should come from less than 200 Mpc. Enhancing this line of reasoning, there is obviously for each element and isotope separately a horizon, from which this specific element has a good chance of surviving photo-dissociation. It could be interesting to investigate the paths in the charge-mass (Z, A)-diagram, the nuclei take, and how often they just disintegrate on their own, sowing the environment with decay products; this is a concept just the reverse of the nuclear element build-up (Burbidge et al. 1957). Another query is to understand to what degree these processes might already happen inside the relativistic radio jet. And a third investigation might center on the spallation products among the seed population resulting from the ubiquitous nuclear collisions happening in the dense environments of Wolf-Rayet stars after they blow up, and before they get hit by the relativistic jet; do we have a chance to discern these spallation products, like the sub-Fe elements or the Li, Be, B nuclei, among the ultra high energy cosmic ray particles?

These particles may not come from arbitrarily large distances due to magnetic scattering (Stanev et al. 2003, Das et al. 2008). This is the magnetic horizon. In the MHD simulations of Das et al. (2008) this is at 100 Mpc at $>$ 60 EeV for protons. Due to the chain of photo-dissociation and the ensuing modification of the nuclear charge, this horizon is strongly dependent on the path, the nuclei take upon interaction.

In the search for directional correlations on the sky we require the large scale structure scales, and this is $\geq$ 300 Mpc (Peebles 1989, Rudnick et al. 2007). So directional correlations are expected (see Tinyakov et al., Tkachev et al., & Finley & Westerhoff 2004, Mariş 2004, Caramete et al. 2008, et multi al.) up to the corresponding redshift to be far more common than by chance. This is the correlation horizon.

3.6. The HiRes vs. Auger discrepancy

The HiRes collaboration (2008b) has disputed the Auger (2007, 2008a) result that the arrival directions of ultra high energy cosmic rays are correlated with active galactic nuclei in the Véron catalogue (Véron-Cetty & Véron 2006). The authors emphasize that this catalogue is incomplete, and so we are using it only in the exact sense in which the original Auger publication is using it, as an instrument of comparison. HiRes finds less than random correlations. We noted already above, that there are fewer such correlations expected in the North from a simple simulation of arriving events from radio galaxies (on average 1/3 vs. 1/2); since we are using here very small number statistics, we may not have to look any further. Another effect might play an additional role: As magnetic scattering increases rapidly with lower particle energy (Das et al. 2008), one might speculate that in the HiRes sample the uncertainty of energy determination at the low energy threshold might be large enough to add additional smearing of directions due to magnetic fields, and so decreasing any coincidental directional correlation. Obviously also, the final energy calibration of HiRes versus Auger is a remaining serious issue.

As already noted, just using a simple scattering model and the notion that radio galaxies are the sources predicts that about half the events should be correlated in the procedural sense for the Auger sky, in the limit of large numbers.

3.7. Application to Cen A

Taking all these ideas together suggests that maybe we require all of the four concepts mentioned above at the same time, relatively heavy elements (perhaps Carbon and Oxygen at somewhat lower energies, and Iron at higher energies), flaring, starved particle spectra, and weakly relativistic shocks. And in addition there may be a subset of pure protons from neutron decay at the lower energies.

However, using Cen A as the main source engenders another problem: The MHD simulations of Das et al. (2008) suggest strongly a scattering distribution of a power-law at high energy, for protons only. If we argue that heavier elements are the key, then these magnetic fields are either much weaker, or much more structured (more structure weakens the scattering, for a given total energy per large volume). In the magnetic field data in our galaxy (Beck et al. 2003) there is already strong evidence for small scale substructure, since different measures of the magnetic field yield very different numbers: linear measures such as Faraday Rotation Measures indicate much lower strengths of the magnetic field than quadratic measures such as synchrotron emission. This is typical for small scale substructure (H. Lee at el. 2003, Avillez & Breitschwerdt 2004), where for a given total energy content high intensity sheets can hold all the energy for a small volume fraction; in such a picture linear measures give a much smaller number than quadratic measures, as is well known from mathematically isomorphic arguments in thermal emission. Of course we should be comparing the proper integrals, also involving the spatial distribution of thermal electron density and cosmic ray electron density; we ignore all this in our simple didactic exercise.

We can quantify this by integrating along a long thin cylinder of unit length; we refer to the magnetic field as B_0, when it is homogeneous, and for the inhomogenous case the magnetic field is B_1 over most of the length, and enhanced by a factor $1/x$ in a region of length x: This then gives for the integrated energy density

$$B_1^2 \times \frac{1}{x} + B_1^2 \times (1-x) \;=\; B_0^2 \qquad (14)$$

where we keep the integrated energy content B_0^2 constant. The linear measure of the magnetic field is then given by

$$B_1 \times \frac{1}{x} \times x + B_1 \times (1-x) \;= B_1 \times (2-x) \qquad (15)$$

We now vary x to see how the linear measure varies with x, keeping the entire energy content fixed.

Combining the first equation with the second yields

$$\sqrt{\frac{x}{1-x}} \times (2-x) \qquad (16)$$

for the ratio of linear measure versus quadratic measure. In the limit of small x this is simply $\sqrt{x}$. The observations suggest that this ratio is of order 1/5, and so $x = 0.04$ by order of magnitude. This implies that most of the magnetic energy is contained in shells of a volume a few percent, possibly as low as 1 percent. Since the linear measure is proportional to the bending of ultra high energy cosmic rays, this implies that the bending is reduced by a factor between 5 and

10 over what we might reasonably expect otherwise.

Using the approach of Cox (1972) with the environment of the tenuous hot phase of the interstellar medium (Snowden et al. 1997) the cooling stage of an expanding shell of a supernova remnant might lead to such a configuration, of a very thin shell at large distances, with strong magnetic fields. In such a picture this stage would encompass most of the supernova's energy dissipation, and so similar considerations may apply to the interpretation of the X-ray data (Snowden et al. 1997).

Begelman (1995) has shown that an analogy of supernova remnants to radio galaxies can be illuminating, and so might also lead to thin shells of high magnetic fields, in turn decreasing the scattering of ultra high energy particles in intergalactic space.

If both of these applications were realized in Nature, magnetic scattering of nuclei of $Z >> 1$ might appear similar to scattering of protons in environments without allowing for such fine substructure (Stanev 1997, Stanev et al. 2003, Armengaud et al. 2005, Dolag et al. 2005a, b, Ryu et al. 1998, 2008, Takami & Sato 2008, Das et al. 2008); taking the interstellar medium data literally and also the power-law scattering found by Das et al. (2008), would suggest very tentatively, that $Z \gtrsim 6$ is quite plausible. This implies that protons would be scattered very little. And so, the fact that very few events directly point to plausible sources, except at Cen A (protons are energetically not plausible from this source, see above), implies under these assumptions, that the proton fraction among the events must be small.

However, such considerations on the small scale structure of magnetic fields both in the interstellar as well as intergalactic medium must remain speculation at this time.

3.8. Merging black holes

There is evidence that each episode of an active galactic nucleus is triggered by the merger of the host galaxy with another galaxy. In a major merger the second galaxy will also have a central super-massive black hole, and so the merger of the two black holes will follow, leading to a spin-flip: The spin axis of the final merged black hole will differ from the spin axis of the preceding more massive black hole. For the characteristic mass ratio range $3 \div 30$ of the merging super-massive black holes (inferred from the Press-Schechter mass distribution of galaxies, Press & Schechter 1974, as well as observations) the occurrence of the spin-flip was shown to be caused by the superposition of the spin-orbit precession and energy dissipation due to gravitational radiation (Gergely & Biermann 2007, 2008). This effect can be observed through first a sweeping of the jet (Gopal-Krishna et al. 2003), and then a switch in jet direction (Rottmann 2001; Zier & Biermann 2001, 2002; Merritt & Ekers 2002). In this context it is an unsolved question, how it is possible that super-massive black holes undergo many mergers and keep their spin high at the same time, as typically a merger reduces the spin (Hughes & Blandford 2003, Berti & Volonteri 2008). However, differential dynamical friction during the spiraling down of an incoming black hole and its accompanying core of its host galaxy may lead to a partial alignment, if the receiving more massive core is co-rotating with its black hole (Gergely & Biermann).

3.9. High energy neutrinos

Following a spin-flip the jet has to carve out a new channel in the surrounding material, strongly enhanced possibly due to the preceding merger. This will result in powerful shock waves, as the jet plows through this environment. This in turn will lead to extreme particle acceleration, and strong interaction, as the molecular clouds become the near-perfect beam-dump. Furthermore, the first strong shock in the jet can accelerate particle in an environment with fairly high photon density, either from the accretion disk, or from the emission of the jet itself, and so produce lots of high energy neutrinos. The last strong shock in the jet, where it goes subsonic, or sub-Alfvénic, or stops altogether, will produce the high energy particles, that can most readily escape, and so perhaps make up those particles which we observe (Becker & Biermann 2008). The very rare but most powerful sources, the Fanaroff-Riley class II radio galaxies will be sources of ultra high energy cosmic rays and high energy neutrinos, but none seems close enough to our Galaxy to be a detectable source at high energy for particles. In summary we predict that most neutrinos will be detected from flat spectrum radio sources such as BL Lac type sources (just those Fanaroff-Riley class I sources aiming at us with their relativistic jets), while the observed ultra high energy cosmic rays may come predominantly from Fanaroff-Riley class I radio galaxies as well as BL Lac type AGN.

However, there is a difficulty, should it be true, that some, perhaps many, of the ultra high energy cosmic ray particles are nuclei such as Carbon, Oxygen, or even heavier, as conclusively argued above for the case of Cen A (see, e.g., Anchordoqui et al. 2008). In that case, any interaction of nuclei with a photon field yields just a photo-dissociation, and a reduced flux of neutrinos. We obtain neutrinos only in a second interaction, with the nucleon split off in this first interaction again interacting with the photon field. So, in this case, the combined probability for such an interaction is the product of the optical depth for photo-dissociation τ_1 with the further optical depth for p-γ-interaction τ_2. Now, we have also argued and demonstrated with an example, Her A, above, that active galactic nuclei do most of their interesting activity in a flaring mode. In a flaring mode, it is readily expected (applying the equations and numbers in Becker & Biermann 2008), that both optical depths attain values above unity, and so from nearly no neutrinos we predict in strong flares a huge flux of neutrinos. If this expectation is borne out, the detection would also be much easier against the atmospheric neutrino background.

4. Future

Since the chemical composition enters here at four points of reasoning, we probably require a “principal component analysis”, fitting at once 1) the air fluorescence data, 2) the scattering distribution (note that scattering angles of more than 90 degrees are plausible even for sources as near as Cen A: Das et al. 2008), including a possible systematic shift of the core of the distribution, 3) the delay time distribution, which enters the microwave background interaction for protons and in photo dissociation for nuclei, and 4) the magnetic horizon, out to which we can receive ultra high energy particles from sources.

The task is to predict a chemical composition and associated spectrum for a source, then propagate all nuclei and the protons through another prediction of the cosmic web of magnetic fields with all its un-known fine-structure, include the delay time distribution, and the changing scattering properties, as nuclei slide lower in charge, to arrive a predicted chemical composition and spectrum at Earth.

This type of “principal component analysis” will have to be repeated for each source class, for which we have quantitative predictions using a complete sample, as above. It is to be expected that different sources have different chemical composition of their ultra high energy cosmic rays, and could appear as extremely different in such an analysis. Given sufficient statistics it might be possible to invert the procedure by assigning to each event a most probable source, and then adding up to obtain both the source spectrum, and the scattering distribution; this would have to be consistent with what we know about the source, its plausible chemical composition contribution, and magnetic fields. One obvious further consequence is that at very high energy the northern and southern sky should be different.

This will only be possible with an all-sky survey with matching sensitivity and observing procedures.

5. Conclusion

Gamma ray bursts are not yet ruled out, but would require very much higher fluxes from nearby sources such as M82 or NGC2146 and the like than expected based on gamma ray burst statistics (Pugliese et al. 2000). The predictions are not sufficiently reliable to completely rule out or confirm such an idea. However, the cloud of events around Cen A would suggest in such a picture, that the starburst in Cen A actually produces a sufficiently large number of gamma ray bursts so as to dominate the sky distribution. This would be quite compatible with the Das et al. (2008) scattering simulations, and also the air fluorescence data from HiRes (Sokolsky 2008). If so, the air fluorescence data obtained within Auger should confirm a pure proton composition. On the other hand, if it is true, that a subset of Wolf-Rayet stars explode as gamma ray bursts, could it be that gamma ray bursts also pick up the abundances from the wind shells, as supernovae are believed to do? Such a picture would lead to a very similar high energy spectral behaviour of the different chemical elements; two problems, however, appear for this line of thinking: 1) Gamma ray bursts have a rapidly decreasing Lorentz factor with time, and so a final spectrum will be extremely smeared. 2) The Lorentz factor in gamma ray bursts is so high, of order 300, that acceleration from the knee region would go far beyond 30 EeV, and then there would be no spectral downturn, at least if the main sources are just 3 Mpc or so distant. This might deserve a dedicated test simulation.

Radio galaxies still provide the best bet to explain the data, but do face a number of serious difficulties. We have shown how to overcome such problems in the physics interpretation, and have suggested how to deal with the coming data. In a speculative approach we suggest strong substructure in the interstellar medium, and also the intergalactic medium, and also suggest the chemical composition spectral structure at very high cosmic ray energies in the context of a starburst (Biermann & Fricke 1977) model: The chemical composition at the knee of galactic cosmic rays, derived from exploding Wolf-Rayet stars (Stanev, Biermann, & Gaisser 1993) is reproduced at the highest energies, with just a factor-shift in energy and flux for all particles (Gallant & Achterberg 1999); this leads to a sequence in energy from lighter towards heavier nuclei, just as at the knee. We furthermore strongly predict, that given Cen A as the adopted source, the observed cosmic ray particle at high energy must be heavier nuclei, such as Carbon, Oxygen and heavier. We suggest a global strategy to deal with complexity of photo-dissociation, delay times, angular scattering, and range of possible sources detectable at Earth; the only way to overcome these difficulties is to use a 4π sky survey with matching procedures and sensitivity.

In terms of ultra high energy cosmic rays radio galaxies come in two classes, those with an associated starburst with exploded Wolf-Rayets stars as feeding source such as Cen A, and those with just the inter-stellar/-galactic medium as a feeding source such as M87. Right now much of the known data suggest that Cen A could be the single dominant source. The two different classes of radio galaxies will look very different in arriving cosmic rays, and will also likely look different in TeV γ-emission and high energy neutrinos.

The future promises to be exciting in this field.

6. Acknowledgements

Collaborations and discussions with Eun-Joo Ahn, Rainer Beck, John Belz, Johannes Blümer, Silke Britzen, Alex Curuţiu, Ioana Duţan, Carlos Escobar, Tom W. Jones, Hyesung Kang, Marina Kaufman, Timo Kellmann, Gopal Krishna, Phil Kronberg, Sera Markoff, Gustavo Medina-Tanco, Joao de Mello-Neto, Faustin Munyaneza, Biman B. Nath, Giovanna Pugliese, Jörg P. Rachen, Gustavo Romero, Markus Roth, Dongsu Ryu, Vitor de Souza, and Arno Witzel are gratefully acknowledged. Work with PLB was supported by contract AUGER 05 CU 5PD 1/2 via DESY/BMB and by VIHKOS via FZ Karlsruhe; by Erasmus/Sokrates EU-contracts with the universities in Bucharest, Cluj-Napoca, Budapest, Szeged, Cracow, and Ljubljana; by the DFG, the DAAD and the Humboldt Foundation; and by research foundations in Korea, China, Australia, India and Brazil. Support for JKB comes from the DFG grant BE-3714/3-1 and from the IceCube grant BMBF (05CIPE1/0). This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research also made use of the ViZier system at the Centre de Donneés astronomiques de Strasbourg (CDS) (Ochsenbein et al. 2000).

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Table 2

UHECR predictions: Using core flux-density at 5 GHz for the complete sample of 29 steep spectrum sources (Kühr et al., 1981). Col. 4: (*) Core flux density estimated from the total flux density by using $\log(P_{core}) = 11.01 + 0.47\log(P_{tot})$, cf. Giovannini 1988; Col. 5 & 6: Relative values of the particles maximum energy and UHECR flux by using spin-down (equations above). Col. 7 & 8: (†) Relative values of the particles maximum energy and UHECR flux by using accretion (O. Taşcău). These predictions do not take into account losses, these numbers just reflect the spatial limit, and the flux reduction with distance squared. Energies with an asterisk may have to be increased due to weak starburst seeding of heavier elements; this could be an order of magnitude)

Source (1)	D (Mpc) (2)	M_{BH} ($\times 10^9 M_\odot$) (3)	S_{5GHz} (mJy) (4)	E_{max}/E_{max}^{M87} (5)	F_{CR}/F_{CR}^{M87} (6)	$E_{max}/E_{max}^{M87\dagger}$ (7)	$F_{CR}/F_{CR}^{M87\dagger}$ (8)
ARP 308	69.7	0.1	88.53*	0.72	0.027	0.03	0.04
CGCG 114-025	67.4	0.19	2260	0.80	0.036	0.15	0.33
ESO 137-G006	76.2	0.92	631.32*	1.79	0.12	0.51	0.13
IC 4296	54.9	1	214	0.49	0.026	0.31	0.08
IC 5063	44.9	0.2	321.15*	0.23 *	0.0067	0.06	0.12
NGC 0193	55.5	0.2	285.93*	0.34	0.010	0.07	0.09
NGC 0383	65.8	0.55	414.25*	0.70	0.029	0.24	0.11
NGC 1128	92.2	0.2	280.2*	1.1	0.036	0.1	0.07
NGC 1167	65.2	0.46	393.1*	0.42	0.011	0.2	0.1
NGC 1316	22.6	0.92	26	1.3	0.82	0.08	0.03
NGC 1399	15.9	0.3	10	0.11	0.012	0.01	0.02
NGC 2663	32.5	0.61	160	0.22	0.012	0.12	0.09
NGC 3801	50	0.22	635	0.25	0.0063	0.09	0.17
NGC 3862	93.7	0.44	1674	0.97	0.027	0.39	0.21
NGC 4261	16.5	0.52	390	0.34	0.11	0.09	0.26
NGC 4374	16	1	168.7	0.18	0.033	0.13	0.15
NGC 4486	16	3.1	2875.1	1	1	1	1
NGC 4651	18.3	0.04	15	0.12 *	0.012	0	0.03
NGC 4696	44.4	0.3	55	0.37	0.018	0.05	0.04
NGC 5090	50.4	0.74	268	0.50	0.026	0.23	0.1
NGC 5128	3.4	0.2	6984	0.43*	4.0	0.04	3.63
NGC 5532	104.8	1.08	194.58*	0.98	0.023	0.5	0.05
NGC 5793	50.8	0.14	95.38*	0.27 *	0.0072	0.03	0.05
NGC 7075	72.7	0.25	20	0.34	0.0054	0.04	0.01
UGC 01841	84.4	0.1	365.46*	1.2	0.053	0.05	0.08
UGC 02783	82.6	0.42	541	0.40	0.0058	0.23	0.11
UGC 11294/4	63.6	0.29	314	0.35	0.0075	0.11	0.09
VV 201	66.2	0.1	450.1*	0.82	0.040	0.04	0.11
WEIN 045	84.6	0.27	321.6*	0.98	0.034	0.13	0.08