SF2A 2008
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ON THE RESULTS OF THE PIERRE AUGER OBSERVATORY

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Abstract. This paper discusses the correlation recently reported by the Pierre Auger Observatory (PAO) of the arrival directions of the highest energy cosmic rays with active galactic nuclei (AGN) located within 75 Mpc. It is argued that these correlating AGN do not have the power required to be the sources of those particles. It is further argued that the current PAO data disfavors giant radio-galaxies (both Fanaroff-Riley type I and II) as sources of ultra-high energy cosmic rays. The reported correlation with AGN should thus be understood as follows: the AGN trace the distribution of the local large scale structure, in which the actual sources of ultrahigh energy cosmic rays camouflage. The most promising theoretical candidates for these sources are then gamma-ray bursts and magnetars. One important consequence of the above is that one will not detect counterparts in gamma-rays, neutrinos or gravitational waves to the sources of these observed ultrahigh energy cosmic rays, since the cosmic rays are delayed by extragalactic magnetic fields on timescales $\sim 10^4 - 10^5$ yrs much larger than the emission timescale of these sources.

1 Introduction

The Pierre Auger Observatory has become the largest cosmic ray detector ever built. Among the first results published so far, the announcement of a correlation of 20/27 arrival directions of the highest energy events ($E > 5.7\times10^{19}\,$eV) with nearby ($d < 75\,$Mpc) active galactic nuclei (Abraham *et al.* 2007, 2008) has triggered a surge of interest in AGN models of ultrahigh energy cosmic ray origin as well as forecast studies of neutrino and gamma-ray expected signals from these objects. However, the fact that the correlating AGN are intrinsically weak seems to have been ignored or gone unnoticed (for exceptions, Moskalenko et al. 2008, George et al. 2008, Ghisellini et al. 2008). The term “AGN” stands for a broad class of galaxies and covers a huge range of luminosities $\sim 10^{40} - 10^{48}\,$erg/s. Whereas the typical model of ultrahigh energy cosmic ray origin in AGN refers to strongly beamed Fanaroff-Riley II (FR II) sources with giant radio lobes (e.g. Rachen & Biermann 1993), 19 out of 20 correlating AGN in the PAO dataset belong to the Seyfert or LINER class, only one being a Fanaroff-Riley I (FR I) radio-galaxy.

As emphasized in the PAO papers, one cannot exclude that actual sources of ultrahigh energy cosmic rays are distributed as the correlating AGN. As argued in Section 2, this interpretation is most likely the correct one. This has strong implications for the sources of ultrahigh energy cosmic rays, as discussed in Section 3. The present discussion, which draws heavily from the arguments presented in Lemoine & Waxman (2008), concludes that, quite ironically, the current data actually disfavors the acceleration of the highest energy cosmic rays in AGN, be they powerful or not, but instead point to bursting sources such as gamma-ray bursts (Vietri 1995, Waxman 1995) or spinning down magnetars (Arons 2003).

2 On AGN as sources of ultrahigh energy cosmic rays

The Hillas criterion gives a phenomenological bound to the maximal energy $E_{\rm max}$ that can be produced by a source of size R and magnetic field B (Hillas 1984). It relies on the statement that the particle must spend at least a Larmor time in the source, leading to: $E_{\rm max,20} = 11\, ZB_0R_0$, with $E_{\rm max,20} \equiv E_{\rm max}/10^{20}\,$eV, $B_0 \equiv B/1\,$G and $R_0 \equiv R/1\,$pc (Z denotes the charge of the accelerated particle). The above inequality can actually be recast as a lower limit on the magnetic luminosity of the source (Norman *et al.* 1995), which for spherical symmetry and non-relativistic motion with speed βc reads: $L_{\rm B} \simeq B^2R^2\beta c/2 \geq 1.2\times10^{45}\,\beta Z^{-2}E_{20}^2\,$erg/s.

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One can actually obtain a more stringent bound on L_B by considering the acceleration process in more detail (Lyutikov & Ouyed 2005, Waxman 2005, Lemoine & Waxman 2008). To this effect, one writes the acceleration timescale as: $t_{\rm acc} = \mathcal{A} t_{\rm L}$, and assumes an outflow with bulk Lorentz factor γ and half-opening angle Θ. In the comoving frame, the maximal energy is limited by the condition $t_{\rm acc} < t_{\rm dyn} = R/(\gamma\beta c)$, with R the distance to the origin the outflow, the quantity $t_{\rm dyn}$ defining the dynamical timescale. This can be rewritten as a lower bound on $L_B = R^2\Theta^2\gamma^2\beta c B^2/4$ (L_B is calculated in the laboratory or source frame):

$$L_B \geq 0.65 \times 10^{45}\, \Theta^2\gamma^2\mathcal{A}^2\beta^3 c^2 Z^{-2} E_{20}^2\,\mathrm{erg/s}\ , \tag{2.1}$$

with E_{20} the observed energy in units of 10^{20} eV. This bound is more severe than that derived from the Hillas criterion for several reasons. First of all, one must expect $\mathcal{A} > 1$ (and possibly $\mathcal{A} \gg 1$). For instance, non-relativistic Fermi acceleration leads to $\mathcal{A} \sim \alpha/\beta_{\rm sh}^2$ for Fermi-I at a shock of velocity $\beta_{\rm sh}c$ or $\alpha/\beta_{\rm A}^2$ for Fermi-II (with $\beta_{\rm A}c$ the Alfvén velocity), and $\alpha > 1$ is the ratio of the scattering timescale in the magnetic turbulence to the Larmor time (see Casse et al. 2002). Ultra-relativistic shock acceleration has been shown to be inefficient at ultrahigh energies in the sense that $\mathcal{A} \propto r_{\rm L}$ (see Pelletier et al. 2008 for a recent discussion). Moderately relativistic shock acceleration seems to be the most efficient acceleration process, but still one expects $\mathcal{A} \sim \alpha$, so that $\mathcal{A} \sim 1$ can be seen as a limiting regime of maximally efficient acceleration, for moderately relativistic shocks and assuming a Bohm diffusion regime $\alpha = 1$.

In these respects, Eq. (2.1) is very restrictive because very few sources are capable of emitting such magnetic power. One can check that the bound remains robust in the limit $\beta \to 0$, since $\mathcal{A}^2 \propto \beta_{\rm sh}^{-4}$ then more than compensates for this term. Similarly, as $\Theta \to 0$, lateral escape losses become prominent and one obtain a very similar bound albeit with a slightly different dependence on parameters (see Lemoine & Waxman 2008). It is furthermore natural to expect $Z \sim 1$ in regards of the tiny cosmic abundance of iron and other heavy nuclei.

Even then, this does not suffice. One should also require that the acceleration timescale be smaller than the energy losses timescales. The comparison does not directly depend on L_B but also on the magnetic field and radiation energy densities, so that additional parameters are to be considered. Such constraints allow to rule out acceleration of particles in the central regions of the powerful AGN (Norman et al. 1995, Henri et al. 1999).

This discussion shows that Seyfert galaxies (and more generally, radio quiet AGN) do not have the power to accelerate particles up to 10^{20} eV since their bolometric luminosities lie below 10^{45} ergs/sec. In the dataset of the Pierre Auger Observatory released so far, only one of the correlating AGN is a radio-galaxy possessing a large scale radio jet (Centaurus A), all others are Seyfert galaxies (with a few possible LINERs). Extending the search for counterparts to deeper distances (130 Mpc) or larger radii, Moskalenko et al. (2008) and Nagar & Matulich (2008) have noted a correlation of eight out of the twenty seven events with the lobes of extended radio-galaxies.

Centaurus A had been previously considered as a possible source of ultrahigh energy cosmic rays, even though it is classified as a low power BL Lac: its bolometric luminosity $L_{\rm bol} \sim 10^{43}$ erg/s and its jet kinetic power $L_{\rm jet} \simeq 2\times10^{43}$ erg/s. Through the modelling of the spectral energy distribution of the nucleus, Chiaberge et al. (2001) find $L_B \sim 10^{42}$ ergs/sec, which misses the above bound by three orders of magnitude. Note that the paper of Romero et al. (1995), which argues that acceleration can take place in the X-ray knots of the inner jet contains flawed estimates for the maximal energy. These authors match the acceleration timescale with the energy loss timescale, but do not compare it to the escape timescale; and yet, this comparison would yield a maximal energy $\sim 10^{18}$ eV, in agreement with the inferred magnetic luminosity and Eq. (2.1).

More generally, FR I radio-galaxies, TeV blazars and BL Lac objects do not seem to possess significant power to accelerate particles up to 10^{20} eV, since their inferred magnetic luminosities are of order $L_B \sim 10^{42} - 10^{44}$ ergs/s (Celotti & Ghisellini 2008). According to this study (done in the framework of leptonic models), only flat spectrum radio quasars (i.e. the most powerful FR II sources) seem capable of producing jets with $L_B > 10^{45}$ ergs/s.

In proton blazar models, the magnetic field in the blazar zone is typically one order of magnitude larger than in leptonic models. In this case, acceleration might occur to ultrahigh energy in the blazar zone. However, in order to escape further expansion losses in the magnetized jets, the accelerated protons would have to be converted into neutrons, which would decay back to protons on a distance scale $\sim 0.9E_{20}$ Mpc, i.e. outside the jet. One should therefore observe a correlation of the arrival directions with blazars, not with radio-galaxies seen offside (Rachen 2008). Since the Pierre Auger Observatory reports no correlation with blazars, and since blazars are too rare objects to be able to explain the number of events observed, this scenario fails.

Hence, in the class of radio-galaxies, only the most powerful FR II could potentially accelerate particles to ultra-high energies. However, in the sample of radio-galaxies that correlate with some events of the Pierre Auger dataset, constructed by Nagar & Matulich (2008), there is no FR II source, only three radio-galaxies of an intermediate FR I/FR II type. Furthermore, the highest energy PAO event, with $E = 1.48 \pm 0.27 \times 10^{20}\,$eV, lies 28° away from the closest FR II (NGC 4261) within 130 Mpc in the catalog of Massaglia (2007). The closest blazar located closer than 150 Mpc lies 115° away from this event. At energies above $10^{20}\,$eV, magnetic deflection should not exceed a few degrees (see Kotera & Lemoine 2008, Kashti & Waxman 2008 for a recent analytical discussion, and Dolag et al. 2004, Sigl et al. 2004 for numerical simulations). Large deflection angles at such energy are also disfavored from a purely empirical point of view since they would imply isotropic arrival directions of particles above $6 \times 10^{19}\,$eV, in direct contradiction with the PAO results.

All in all, the PAO data argue against the origin of ultrahigh energy cosmic rays in AGN, be they powerful or not. Intriguingly, a fraction of events seem to cluster in the direction to Cen A, with a small probability of chance coincidence (Gorbunov et al. 2008). However, one must keep in mind that Cen A lies in front of the Centaurus supercluster (at 50 Mpc) and the Shapley supercluster (200 Mpc), which represent some of the most important concentrations of matter in the local Universe. As discussed in Lemoine & Waxman (2008), the small occurence probabilities are not conclusive because they are calculated a posteriori, and because the significance fluctuates strongly with the assumptions made on the distribution and distance scale of the sources.

3 Discussion

The correlation of the Pierre Auger Observatory is thus mostly accidental, in the sense the correlating AGN trace the matter distribution, hence the source distribution. It is useful to note at this stage that the HiRes experiment does not confirm the correlation seen by the Pierre Auger Observatory (Abbasi et al. 2008). Kotera & Lemoine (2008) have observed that the distance scale of these correlating AGN (75 Mpc) is too small when compared to the expected source distance scale ($\sim$ 150 Mpc) and have suggested that the apparent correlation may be imaging the last scattering surface of ultrahigh energy cosmic rays rather than the source distribution. If the PAO energy scale had been underestimated by $\sim$ 30%, the two distance scales would agree (Abraham et al. 2007). Independently of this issue of the energy scale, Kashti & Waxman (2008) have shown that the PAO arrival directions are consistent with a source population tracing the large scale structure, with a preference for a source population biased towards dense regions of the intergalactic medium.

This discussion leads us to the conclusion that the sources of ultrahigh energy rays are invisible. The lack of clear counterpart, together with the hint of correlation of the arrival directions with the large scale structure suggest that these sources camouflage in more common galaxies and that they are of the bursting type. Given an expected deflection angle $\delta\theta \sim 3°$, the time delay suffered by ultrahigh energy protons is $\delta t \simeq \delta\theta^2 d/4c \simeq 10^5\,$yrs (Waxman & Miralda-Escudé 1996), which sets an upper bound on the source activity timescale. Theoretical models which fall in this class are gamma-ray bursts (Vietri 1995; Waxman 1995), and magnetar spin-down (Arons 2003).

One fundamental consequence of bursting sources is that no counterpart, be it gamma-rays, X-rays, neutrinos or gravitational waves, should be found in the arrival directions of the highest energy events since these particles have passed by us δt ago and these sources are non-repeating. In order to confirm the origin of the highest energy cosmic rays in such sources, one must now collect more ultrahigh energy events at the highest energies possible, in order to search for specific signatures of bursting models, notably the departure from a continuous power law spectrum associated with a smaller number of contributing sources, or the energy clustering of events from a same source (Miralda-Escudé & Waxman 1996, Waxman & Miralda-Escudé 1996).

Quite certainly, much work also remains to be done on a theoretical level in order to improve our understanding of acceleration processes in these objects, and on the observational level, using multi-messenger astronomy.

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