Nearby quasar remnants and ultra-high energy cosmic rays

Diego F. Torres[1], Elihu Boldt[2], Timothy Hamilton[2,3], and Michael Loewenstein[2,4]
[1]Physics Department, Princeton University, NJ 08544, USA
[2]Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[3]National Research Council Associate
[4]Department of Astronomy, University of Maryland, College Park, MD 20742

May 13, 2002

Abstract

As recently suggested, nearby quasar remnants are plausible sites of black-hole based compact dynamos that could be capable of accelerating ultra-high energy cosmic rays (UHECRs). In such a model, UHECRs would originate at the nuclei of nearby dead quasars, those in which the putative underlying supermassive black holes are suitably spun-up. Based on galactic optical luminosity, morphological type, and redshift, we have compiled a small sample of nearby objects selected to be highly luminous, bulge-dominated galaxies, likely quasar remnants. The sky coordinates of these galaxies were then correlated with the arrival directions of cosmic rays detected at energies > 40 EeV. An apparently significant correlation appears in our data. This correlation appears at closer angular scales than those expected when taking into account the deflection caused by typically assumed IGM or galactic magnetic fields over a charged particle trajectory. Possible scenarios producing this effect are discussed, as is the astrophysics of the quasar remnant candidates. We suggest that quasar remnants be also taken into account in the forthcoming detailed search for correlations using data from the Auger Observatory.

PACS number(s): 98.70.Sa, 98.54.-h

1 Introduction

Different experiments over the past few decades have detected several giant air showers, confirming the arrival of cosmic rays (CRs) with energies up to a few hundred EeV (1 EeV $\equiv 10^{18}$ eV)[1]. The nature and origin of these energetic particles remain a mystery [2]. CRs, however, can not travel unaffected through inter-galactic space. The thermal photon background becomes highly blueshifted for ultra-relativistic protons, and the reaction $p\gamma \to \Delta^+ \to \pi^0 p$, and similar others, effectively degrade the primary proton energy. This provides a strong constraint on the proximity of CR-sources, discovered early on by Greisen, and by Zatsepin & Kuz'min, and referred to as the GZK cutoff [3]. Specifically, fewer than 20% of 300 EeV (100 EeV) protons can survive a trip of 18 (60) Mpc. For nuclei and photons the situation is, in general, more drastic [4].

The possible solutions to this puzzle appear to fall into three broad categories, viz: 1) There are many nearby sources (e.g., based on a substantial present-epoch population of galaxies hosting core supermassive black holes). 2) There are only a few nearby sources (e.g. [5]) and particles are isotropized by strong deflections in Galactic and/or extragalactic magnetic fields of micro-Gauss strength, close to existing upper limits (e.g., see [6], also [7]). 3) The particles somehow travel relatively unhindered through the Cosmic Microwave Background radiation field, either by virtue of being some exotic new kind of weakly photon-interacting entity, or by violating the Lorentz symmetry of special relativity (e.g. [8]), or by an as yet unknown other effect.

The arrival directions of the primary particles could be a useful source of information about the origin(s) of CRs. However, due to the small number of events, particularly at the highest energies, correlation studies are to be considered preliminary. For instance, the first five events observed with $E > 80$ EeV did in fact point toward high redshift radio-loud quasars, astrophysical environments that could well accelerate CRs above the GZK energies via shock mechanisms (see Farrar and Biermann, in Ref. [8]). However, with the inclusion of subsequent data, this association now seems to have disappeared [9].

In this communication we explore whether UHECRs can be in any way related to present-epoch supermassive black holes. To that end, we analyze what we can learn from the arrival directions of cosmic rays concerning their possible correlation with nearby massive dark objects, candidate QRs (quasar remnants), and their underlying astrophysics.[1] The compact dynamo model has been proposed as a natural mechanism for accelerating cosmic rays in such environments [10]. In this model UHECRs are produced in nearby dead quasars harboring spinning supermassive black holes. The required emf is generated by the black hole induced rotation of externally supplied magnetic field lines threading the horizon. The observed flux of CRs would apparently drain only a negligible amount of energy from the black hole dynamo, and particles up to at least 100 EeV are expected. It is then interesting to ask if we are able to see any correlation between the sky position of these QRs and those of the highest energy CRs, assuming different simple configurations for the intervening magnetic field.

2 Quasar remnant candidates

The Nearby Optical Galaxy (NOG) catalog of Giuricin et al. [12] is a complete magnitude-limited (corrected blue total magnitude $B \leq 14$), distance-limited (redshift $z \leq 0.02$) sample of several thousand galaxies of latitude $|b| > 20°$, with their morphology T also provided [14]. We shall impose very restrictive selection criteria, those necessary for obtaining candidate objects providing the most favorable setting for a black hole based compact dynamo model of UHECR production [10]. The key goal of our strategy is to select *a priori* an NOG subsample of galaxies that are likely to be quasar remnants. Therefore, we are seeking optically bright galaxies whose luminosities are bulge dominated (e.g., giant ellipticals). Imposing a GZK-related horizon of ~ 50 Mpc assures that there are no quasars in our sample. We already know that the best determined (and most massive) black hole nuclei tend to be associated with bulge luminosities corresponding to $M_B \sim -21$ and brighter (for tables, see Kormendy's website at http://chandra.as.utexas.edu/~kormendy/wwwbhtable-tech or the second reference in [27]).

Firstly, then, we shall impose a cutoff in redshift, requiring all galaxies in our sample to be within $z \leq 0.01$, which for $H_0 = 75$ km/s/Mpc corresponds to 40 Mpc. Since the CRs detected are mostly in the northern hemisphere (except those coming from SUGAR, which are not used in the present analysis), we shall impose the restriction that all QRs have equatorial latitudes north of -10 deg. We further require the absolute blue magnitude to be brighter than $M_B = -21$ (for $H_0 = 75$ km/s/Mpc) and an RC3 (*Third Reference Catalog of Bright Galaxies*) morphological type $T < -3$. A more negative T indicates greater bulge prominence. In order to correlate the UHECR arrival directions with their putative QR origins, we require that these candidate QRs not lie within rich clusters (those having more than 50 members). Some of the most massive QRs could reside in rich clusters of galaxies (e.g., all four QRs considered by Boldt and Loewenstein in Ref. [10] are in rich clusters), but the magnetic field strength in those clusters is presum-

[1] The term "quasar remnants" was introduced by Chokshi and Turner [11] to describe the present-epoch population of dead quasars harboring supermassive black hole nuclei.

Table 1: Sample of QR candidates, columns are the B1950 coordinates (α, δ), name of the galaxy, richness of the group to which the galaxy pertains (number of members), galactic longitude and latitude, mean redshift, corrected redshift (against Hubble distortions, using models of the peculiar velocity fields Marinoni et al. [15]), morphological type code (RC3), and absolute magnitude (for H_0 =75). This table is based on data from the NOG catalog of Giuricin et al. provided to us by C. Marinoni [12].

α	δ	Name	#	l	b	$\langle cz \rangle$ [km/s]	cz [km/s]	T	M_B
108.938	85.808	NGC 2300	8	127.708	27.809	2214	2559	-3.6	-21.17
136.937	60.244	NGC 2768	5	155.492	40.563	1469	2063	-3.1	-21.68
161.296	12.846	NGC 3379	24	233.490	57.634	732	1217	-4.0	-21.07
168.880	59.060	NGC 3610	5	143.540	54.462	1816	2467	-3.9	-21.24
168.926	58.274	NGC 3613	4	144.338	55.099	2072	2733	-4.1	-21.32
181.407	65.450	NGC 4125	4	130.187	51.341	1536	2109	-4.6	-21.94
182.431	13.484	NGC 4168	9	267.668	73.337	2092	2811	-4.2	-21.04
187.227	26.049	NGC 4494	7	228.618	85.316	1160	1882	-4.5	-21.59
188.871	74.469	NGC 4589	1	124.234	42.898	2131	2617	-4.1	-21.38
191.502	-5.5282	NGC 4697	30	301.632	57.064	1168	1476	-4.1	-21.33
206.895	60.438	NGC 5322	4	110.279	55.494	1947	2505	-4.4	-21.89
225.987	1.7986	NGC 5846	13	000.427	48.797	1577	1894	-4.2	-21.27

ably several micro-Gauss [13]; hence, UHECRs originating in such QRs would be extremely deflected away from their sources. In addition, there are only a handful of galaxies within large clusters in the Giuricin et al.'s sample that survive all other constraints in order to be declared plausible quasar remnant candidates. Using these selection criteria, we obtain a sample of 12 candidate QRs. These candidate QRs are listed in Table 1, and their astrophysical properties are analyzed below.

The UHECR sample used is that obtained with AGASA above 40 EeV [18]. There are 38 such events at $|b| > 20°$; the angular precision of their arrival directions was estimated as a circle of radius 1.6 degrees. For energies > 100 EeV we also consider the 7 events observed at $|b| > 20°$ compiled by Sigl et al. [9], 4 of which were obtained with AGASA.[2] We note that the statistical test we shall report was blind, i.e. we did not know beforehand if any of the QR galaxies were coincident with high energy cosmic rays. The simulation technique is the same as that used in Refs. [9, 20, 21].

Looking for superposed QRs in the cosmic ray error circles, we find the results reported in Table 2. When we consider the AGASA sample with $E > 40$ EeV, there is an excess in the real result which approaches 3σ. This could argue in favor of a correlation between our sample of QRs and UHECRs at small angular scales. This is not the case for the CRs with energies above 100 EeV, for which we found only an apparent excess for the nominal error circles, not significant enough to give to it any confidence. A summary of these results is given in Figure 1. There we show the number of real coincidences in rings surrounding the position of the central QR as a function of the internal radius of the ring, A. Each ring has an angular width of 1.6 deg, and the number of coincidences is shown with angular offsets between A and $A + 1.6$. An excess of coincidences is clearly evident for the innermost radii. At larger radii, the real superpositions are compatible with the random coincidences. This result stands disregarding the value chosen for the size of the ring.

[2] See Table 1 in [9] for this compilation and the associated error estimates.

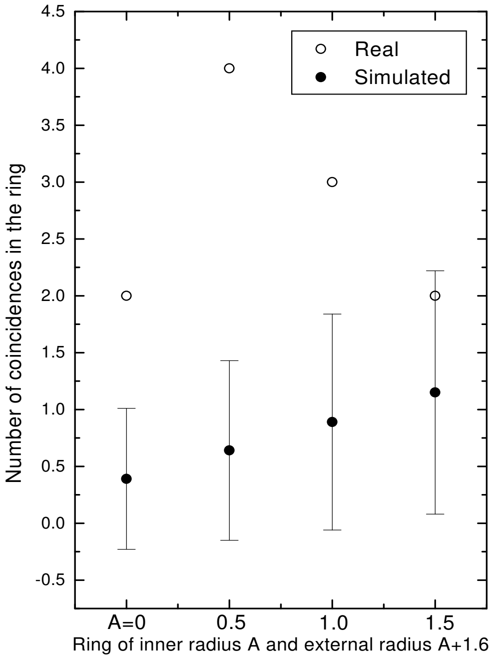

Figure 1: Real coincidences in rings surrounding the position of the central QR as a function of the internal radius. In black we show the random result expectation, whereas in light colour we show the real result. x-axis is given in degrees. Error bars are 1σ.

Note that when increasing the error circles, no additional QRs are involved in the coincidences, but instead, there are new CRs involved. This is what makes the real result increase. Details of the coinciding pairs are given in Table 3. *It is risky, of course, to evaluate the level of significance that we should attribute to this correlation, especially when so few events/objects constitute the samples involved.* The 12 galaxies, however, are selected *a priori* on a restrictive physical basis, aimed at identifying QRs harboring super-massive black holes. Furthermore, we can see that the correlated pairs identify an apparently preferred region of the sky, as Figure 2 shows. The expected number of random coincidences decreases from 0.40 to 0.14 when the region of the sky is restricted to an area given roughly by $160 < \alpha < 200$ and $50 < \delta < 80$. This is $\sim 5\sigma$ below the real result of 2 coincidences. This latter result, however, is obtained *a posteriori*, and its importance is thereby reduced.

If we consider that charged particles (protons) are accelerated in these QRs and then travel through the intergalactic and Galactic magnetic fields towards the Earth, we expect their trajectories to be deflected. When the Larmor radius of a particle ($r_{\rm L} \simeq 10^2$ Mpc E_{20}/B_{-9}) is much larger than the coherence length of the magnetic field $\ell_{\rm coh}$, the characteristic deflection angle θ from the direction of the source, located at a distance D, can be estimated assuming that the particle makes a random walk in the magnetic field (see e.g. [16])

$$\theta(E) \simeq 3.8^\circ \left(\frac{D}{50\text{ Mpc}}\right)^{1/2} \left(\frac{\ell_{\rm coh}}{1\text{ Mpc}}\right)^{1/2} \left(\frac{B_{-9}}{E_{20}}\right) , \tag{1}$$

where E_{20} is the energy of the particle in units of 10^{20}eV, and B_{-9} is the magnetic field in units of 10^{-9} G. We can see that scattering in large scale magnetic irregularities $\mathcal{O}$ (nG) [17] are enough to bend the orbits of trans-GZK protons by about 4 deg in a 50 Mpc traversal. As exhibited in Table 3, the CR angular offsets observed for these QRs are much smaller than θ. For a variety of assumed magnetic field scenarios,

Table 2: Coincidences with the 34 AGASA CRs with energies of $E > 40$ EeV and the given constraints in both δ and b. The 12 QRs given in Table 1 are considered. The second panel shows similar results, but in this case, we consider the coincidences with 7 UHECR with $E > 100$ EeV in the same latitude range. A real result equal to 2 means that there are 2 different cosmic rays coinciding with the quoted QRs.

Error considered	Real Result	Random Result	Poisson Prob.	Galaxies involved
Nominal	2	0.40±0.60	0.04 (2.7σ)	NGC 3610, 3613, 5322
Nominal + 0.5 deg	3	0.68±0.82	0.02 (2.8σ)	NGC 3610, 3613, 5322
Nominal + 1.0 deg	4	1.06±1.03	0.01 (2.9σ)	NGC 3610, 3613, 5322
Nominal	1	0.23±0.45	0.17 (1.7σ)	NGC 4589
Nominal + 0.5 deg	1	0.30±0.52	0.22 (1.1σ)	NGC 4589
Nominal + 1.0 deg	1	0.40±0.61	0.26 (1.0σ)	NGC 4589

Table 3: Superposed pairs of QRs and CRs. Nominal errors are considered. $\theta(E)$ is given for the nominal values in its definition. The offset angles for NGC 3610 and NGC 3613 refer to the same CR, which lies within both error circles.

Galaxy	CR Energy 10^{19} eV	Experiment	$\theta(E)$	Angular offset
NGC 3610	7.7	AGASA	3.7	1.3
NGC 3613	7.7	AGASA	3.9	0.7
NGC 5322	4.4	AGASA	6.6	0.8

θ is often substantially larger than the estimated AGASA measurement error of 1.6 degrees. If, in fact, due to the value of the inter-galactic magnetic field, such is the case, it would then indicate that

1. the number of apparent QR/UHECR associations is no longer above random expectations (see Figure 1 for large value of A), and
2. the *a priori* probability is relatively very small for offset angles as little as those actually observed (Table 3).

Should the apparent clustering of correlated pairs be supported by future data, what are the viable scenarios under which this could occur? One possibility is to consider that the intergalactic medium between Earth and the three apparently 'clustered' QRs is sufficiently different from the intergalactic medium in front of the remaining nine objects that are much more uniformly distributed on the accessible sky. For the deflection of an energetic (60 EeV, the mean of the two CR energies in Table 3) proton in traversing 34 Mpc (the mean of the 3 QR distances in Table 3) to be less than a degree, we would need $B < 2 \times 10^{-10}\ \ell_{\rm coh}^{-0.5}$ G, which appears to be not as drastic a difference from the canonical nano-Gauss B field and coherence length of 1 Mpc that are usually assumed. Indeed, the IGM B field is likely to be an order of magnitude less than a nano-Gauss in voids comparable in size to the GZK horizon (Peter Biermann; 2002, personal communication). Independent estimates of the Intergalactic Medium (IGM) magnetic field towards these galaxies would prove very useful in assessing this explanation.

It is important to note that, in some directions, the magnetic field of our own galaxy could well lead to a deflection of up to several degrees for primaries with energies below 60 EeV; see, for instance, Table 1 of Ref. [22]. A recent study of this issue was presented by Alvarez-Muñiz et al. [23]. However, it is important to realize that the possible filamentary topology of the Galaxy's magnetic field (Gerrit Verschuur; 2002, personal communication) would likely allow some directional windows, albeit narrow, where the deflection

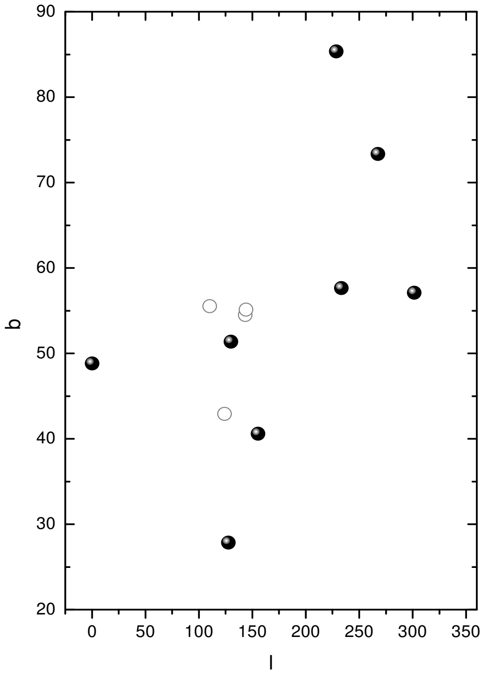

Figure 2: Sky distribution (galactic coordinates) of the selected QRs. The lighter dots stand for those QRs which exhibit superposition with UHECRs. Two closely neighboring QRs (in projection) are actually almost indistinguishable in this plots (NGC 3610 and NGC 3613).

of an UHECR could be much less than typical. Deflections due to the magnetic fields would of course be avoided if the primary were a photon, generated in the neighborhood of the QR via an accelerated charged particle interaction. A photon primary is ruled out for the highest cosmic ray energy event detected with Fly's Eye [5], but there is yet some discussion of the likelihood of having some photons as primaries in the AGASA sample [24]. Protheroe and Johnson (see second reference in [4]) have studied the propagation of ultra-high energy gamma rays in the intergalactic magnetic field in detail. They have shown that if the intergalactic magnetic field is low enough, say $B \sim 10^{-10}$ G, a photon can survive a distance comparable to those of the QRs in our sample and be a plausible primary for the observed showers. A new neutral hadron could obviously be another extreme possibility. However, as we have seen, the involved QRs are all within a relatively small region of the sky; their angular separation is clearly less than the average angular separation between neighbors in the remaining sample of nine. Why would sources of neutral hadronic CRs be restricted to a limited angular region of the sky? Albeit suggestive, we warn the reader that the effect observed here might be no more than an artifact resulting from the small number statistics available at this time. It is, however, interesting to study the underlying astrophysics of our candidates as possible cosmic rays emitters.

3 Underlying Astrophysics

Table 4 exhibits the physical attributes of our sample of QR candidates, viz: morphological type, mass of supermassive black hole nucleus ($M_{\rm BH}$), galactic bulge mass ($M_{\rm GB}$), black hole accretion rate $\dot{m}$ (in

Eddington units), the maximum resulting proton energy ($E_{\max}$) expected, and lower limits to the proton's radiation length (Λ) for losses arising from photo-pion production in ultra-relativistic collisions with the ambient electromagnetic radiation (photon) field. That the nuclei of these galaxies are indeed dark as well as massive may be appreciated by noting that the radio luminosity (νL_ν at 6 cm) within a 5 arcsec beam [25] is in no instance greater than 10^{-8} (in Eddington units); the ROSAT obtained X-ray luminosity [26], within a broader beam that extends beyond the nucleus, is in every case already less than 10^{-5} (in Eddington units). The four QRs that appear to be correlated with UHECRs (> 40 EeV) are identified here by their offset angles relative to the measured arrival direction of the primary particle initiating the associated air shower; this offset is never greater than the estimated experimental error in determining this arrival direction. For the worst case, NGC 4589, the associated Haverah Park UHECR direction measured has an angular uncertainty radius of 5.6 degrees.

Along with the six published values cited in Table 4, we estimate the black hole mass (M_{BH}) for all twelve QRs from the velocity dispersion of stars [27] within the bulge. The galactic bulge mass ($M_{\rm GB}$) is derived from its stellar luminosity using the mass–luminosity formula $(M/M_\odot)\,/\,(L/10^{10}L_\odot)^{0.15}$ [28]. For the S0 galaxy NGC 2300, we assume a typical S0 bulge–to–disk ratio of $m_V(\text{bulge}) - m_V(\text{total}) = 0.60$ [29]. We note that the bulge mass loss rate in giant elliptical galaxies is $\sim [M_{\rm GB}/(10^{12}M_\odot)]\,M_\odot/\text{year}$ [30] and assume that the rate of accretion onto the central black hole is an order of magnitude less, as typically found for the Bondi rate [31]; based on this, we estimate that the accretion rate is $\mathrm{d}M/\mathrm{d}t \approx 0.1 M_{12}\,(M_\odot/\text{year})$, where $M_{12} \equiv [(M_{\rm GB})/(10^{12}M_\odot)]$. In Eddington units, this rate is then

$$\dot{m} \equiv c^2(\mathrm{d}M/\mathrm{d}t)/L_{\rm Edd} \approx 0.45(M_{12}/M_8), \tag{2}$$

where $M_8 \equiv [(M_{\rm BH})/(10^8 M_\odot)]$, and $L_{\rm Edd} = 1.3\times 10^{46} M_8$ ergs/s is the Eddington luminosity limit.

From equations 2—4 in the last paper of Ref. [10], we obtain that, for losses dominated by curvature radiation, the maximum proton energy expected via the dynamo action considered is

$$E_{\max} = 77\,(\mathrm{d}M/\mathrm{d}t)^{1/8}\ (M_8)^{1/4}\,\text{EeV} \ \approx\ 58\ (M_{12})^{1/8}\ (M_8)^{1/4}\,\text{EeV}. \tag{3}$$

We note that the values of $E_{\max}$ for all 12 galaxies in Table 4 lie above 40 EeV, the lower limit characterizing the AGASA sample considered.

A lower limit to the radiation length ($\Lambda_{\min}$) for proton energy loss associated with photo-pion production is estimated by considering the population of target photons within the source region $[R(\text{source radius}) \geq 2GM/c^2]$ at radio frequencies $\nu \geq 360(\gamma/10^{11})^{-1}$ GHz [10], where γ is the Lorentz factor given by $\gamma = (E_{\max})/(938\text{MeV})$. The radio estimates required are extrapolated from data at lower frequencies [32]. Those QRs with $\Lambda_{\min} > R$ are expected to successfully accelerate protons up to $\sim E_{\max}$.

Apart from their apparent correlation with UHECRs, there is no obvious systematic difference between the first four QR candidates listed at the top of Table 4 and the eight remaining ones at the bottom. However, it's important to note that we do not as yet know the spin states of the supermassive black holes associated with the nuclei of these galaxies; this key parameter might differ substantially among them. In each instance, the present state of spin depends on the specific prior history involved (e.g., accretion evolution, merger interactions, and earlier activity). Since the galactic nuclei considered here are X-ray dark, as are most (see first Ref. in [31]), they are not viable candidates for black hole spin determination by means of the accretion disk iron K-line x-ray florescence that appears to be so promising a spectroscopic tool for active galactic nuclei, particularly Seyferts [33]. We emphasize that a black hole state of near maximal spin is a necessary condition for the realization of a compact black hole dynamo of the sort

Table 4: Physical attributes of quasar remnant candidates. Col. (1), catalog number. Col. (2), morphological type. Col. (3), distance, D, corresponding to the corrected redshift in Table 1 (for $H_0 = 75$). Col. (4), galactic bulge mass, $M_{\rm GB}$, in units of $10^{12} M_{\odot}$. Col. (5), black hole mass, $M_{\rm BH}$, in units of $10^8 M_{\odot}$. Col. (6), accretion rate, $\dot{m}$, in Eddington units. Col. (7), maximum proton energy, $E_{\rm max}$. Col. (8), minimum radiation length, $\Lambda_{\rm min}$, relative to source size, R. Col. (9), offset angle between the putative QR and the most nearly aligned UHECR observed (> 40 EeV).

NGC	Type	D Mpc	$M_{\rm GB}$ M_{12}	$M_{\rm BH}$ M_8	$\dot{m}$	$E_{\rm max}$ EeV	$\Lambda_{\rm min}/R$	UHECR Offset degrees
3610	E5	33	0.43	0.51	0.39	44	2.9	1.3
3613	E6	36	0.47	1.56	0.14	59	5.8	0.7
4589	E2	35	0.50	2.57 (4.71†)	0.05	67 (78)	0.23 (0.38)	4.7
5322	E3	33	0.85	2.63 (12.4†)	0.03	72 (107)	0.36 (1.3)	0.8
2300	S0	34	0.19	4.28	0.02	68	14	
2768	E6	28	0.68	1.56	0.20	62	0.5	
3379	E1	16	0.36	1.71 (1.53‡)	0.11	58 (57)	23 (21)	
4125	E6	28	0.90	2.79	0.15	74	15	
4168	E2	37	0.35	0.984 (7.29†)	0.02	51 (84)	0.45 (2.3)	
4494	E1	25	0.62	0.484 (8.58†)	0.03	46 (94)	4.5 (49)	
4697	E6	20	0.47	0.866 (2.9‡)	0.07	51 (69)	10 (27)	
5846	E0	25	0.44	4.1	0.05	75	2.6	

Note—Black hole masses in the table are normally calculated from stellar velocity dispersions. Those black hole masses taken from the literature are shown in parentheses, as are the quantities derived from them. A † symbol stands for masses taken from van der Marel 1999, whereas a ‡ symbol, for masses taken from Kormendy & Gebhardt 2001 [35]. These literature masses are corrected for our assumed distances.

envisaged for accelerating UHECRs [10]. In this sense, if confirmed, the correlation of UHECRs and QRs might well signal the introduction of a new means for identifying those nearby isolated non-active galactic nuclei that harbor highly spun-up black holes [34].

4 Concluding remarks

As recently suggested, quasar remnants are plausible sites of black-hole based compact dynamos that could be capable of accelerating protons up to ultra-relativistic energies. We have found that nearby quasar remnant candidates present an above-random positional correlation with the sample of UHECRs. The correlation appears on closer angular scales than those expected when taking into account the deflection caused by typically assumed intergalactic or Galactic magnetic fields. Possible scenarios producing this effect were discussed; if real, the plausible fine structure of the Galactic field may ultimately provide the basis for the most natural explanation. In order to substantiate and further investigate the apparent correlation reported here between QR candidates and CR arrival directions, we need a large, reliable sample of the most energetic UHECRs, those of the very highest magnetic rigidity. It is hard to claim a definitive correlation with few objects and CRs constituting the samples. Future experiments, such as the Pierre Auger observatory [36], EUSO [37] and the NASA space-borne OWL (Orbiting Wide-angle Light-collectors) mission [38], should vastly increase the availability of UHECRs ≥ 100 EeV. As we have already noted, however, CR sources in rich galactic clusters (those with pervasive micro-Gauss fields) are not well suited for our present kind of correlative investigation, even though the nearest QR candidates of interest reside in such systems. We suggest that QR candidates located within the relatively nearby Virgo and Fornax clusters [10] might be best studied by means of the TeV curvature radiation expected from the putative compact black-hole dynamos associated with these objects (see second paper in [10]). This work suggests that QRs should also be taken into account when analyzing coincidences in the forthcoming Auger Observatory.

Acknowledgments

DFT acknowledges L. Anchordoqui and G. Sigl for discussions and criticism, and support from Fundación Antorchas, CONICET, and Princeton University. Much appreciated questions posed by the referee have led to substantial improvement of our paper.

References

[1] S. Yoshida, and H. Dai, J. Phys. G **24**, 905 (1998); M. Nagano and A. A. Watson, Rev. Mod. Phys. **72** (2000) 689.

[2] P. Bhattacharjee, and G. Sigl, Phys. Rep. **327**, 109 (2000), and references therein.

[3] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin, and V. A. Kuz'min, Pis'ma Zh. Éksp. Teor. Fiz. **4**, 114 (1966) [JETP Lett. **4**, 78 (1966)].

[4] J. L. Puget, F. W. Stecker and J. H. Bredekamp, ApJ **205**, 638 (1976); R. J. Protheroe and P. Johnson, Astropart. Phys. **4**, 253 (1996); F. W. Stecker and M. H. Salamon, ApJ **512**, 521 (1992) [arXiv:astro-ph/9808110].

[5] J. W. Elbert and P. Sommers, ApJ **441**, 151 (1995).

[6] J. Wdowczyk, and A. W. Wolfendale, Nature **281**, 356 (1979); G. Sigl, M. Lemoine, and P. Biermann, Astropart. Phys. **10**, 141 (1999); M. Lemoine, G. Sigl, and P. Biermann, [arXiv:astro-ph/9903124]; G. R. Farrar and T. Piran, Phys. Rev. Lett. **84**, 3527 (2000); P. Blasi, S. Burles, and A. V. Olinto, ApJ **514**, L79 (1999);L. A. Anchordoqui, H. Goldberg and T. J. Weiler, Phys. Rev. Lett. **87**, 081101 (2001) [arXiv:astro-ph/0103043]; L. Anchordoqui, H. Goldberg, S. Reucroft and J. Swain, [hep-ph/0107287].

[7] C. Isola, and G. Sigl [arXiv:astro-ph/0203273].

[8] G. R. Farrar, and P. L. Biermann, Phys. Rev. Lett. **81**, 3579 (1998); A. Virmani, S. Bhattacharya, P. Jain, S. Razzaque, J. P. Ralston, and D. W. McKay, [arXiv:astro-ph/0010235]; P. G. Tinyakov, and I. I. Tkachev, [arXiv:astro-ph/0102476]; L. A. Anchordoqui et al., Mod. Phys. Lett. A**16**, 2033 (2001); T. J. Weiler, Astropart. Phys. **11**, 303 (1999); *ibid* **12**, 379E (2000); D. Fargion, B. Mele and A. Salis, ApJ **517**, 725 (1999); Gonzales-Mestres, in Proceedings of the 25th ICRC, Durban, So. Africa, 1997, edited by M.S. Polgieter, B.C. Raubenheimer, and D.J. van der Walt (World Scientific, Singapore, 1997); S. Coleman and S.L. Glashow, Phys. Rev. D59, 116008 (1999); C. Tyler, A. V. Olinto and G. Sigl, Phys. Rev. D **63**, 055001 (2001) [hep-ph/0002257]; L. Anchordoqui, H. Goldberg, T. McCauley, T. Paul, S. Reucroft and J. Swain, Phys. Rev. D **63**, 124009 (2001) [hep-ph/0011097].

[9] G. Sigl, D. F. Torres, L. A. Anchordoqui and G. E. Romero, Phys. Rev. D **63**, 081302 (2001) [arXiv:astro-ph/0008363].

[10] E. Boldt, and P. Ghosh, Mon. Not. Roy. Astron. Soc. **307**, 491 (1999); A. Levinson Phys. Rev. Lett. **85**, 912 (2000); E. Boldt and M. Loewenstein, Mon. Not. Roy. Astron. Soc. **316**, L29 (2000).

[11] A. Chokshi and E. L. Turner, Mon. Not. Roy. Astron. Soc. **259**, 421, 1992.

[12] G. Giuricin, C. Marinori, L. Ceriani, and A. Pisani, ApJ **543**, 178 (2000).

[13] T. E. Clarke, P. P. Kronberg, ApJ **547**, L111 (2001).

[14] C. Marinoni, private communication.

[15] C. Marinoni et al. ApJ **501**, 484 (1998).

[16] E. Waxman and J. Miralda-Escudè, ApJ **472**, L89 (1996).

[17] See, for instance, L. A. Anchordoqui and H. Goldberg, [hep-ph/0106217] and references in [6] above.

[18] M. Takeda et al., ApJ **522**, 225 (1999) [arXiv:astro-ph/9902239]; [arXiv:astro-ph/0008102].

[19] N. Sasaki et al., Proceedings of the ICRC 2001, in press.

[20] G. E. Romero, P. Benaglia and D. F. Torres, Astron. Astrophys. **348**, 868 (1999) [arXiv:astro-ph/9904355].

[21] G. E. Romero, D. F. Torres, I. Andruchow, L. A. Anchordoqui and B. Link, Mon. Not. Roy. Astron. Soc. **308**, 799 (1999) [arXiv:astro-ph/9904107].

[22] T. Stanev, ApJ **479**, 290 (1997).

[23] J. Alvarez-Muñiz, R. Engel, and T. Stanev, [arXiv:astro-ph/0112227].

[24] K. Shinozaki et al., Proceedings of the ICRC 2001, in press.

[25] Nagar, N. M., Wilson, A. S. & Falcke, H., ApJ **559**, L87 (2001).

[26] E. O'Sullivan, D. A. Forbes, & T. J Ponman, [arXiv:astro-ph/0108181].

[27] D. B. McElroy, ApJS **100**, 105 (1995); D. Merritt, & L. Ferrarese, ApJ **547**, 140 (2001).

[28] S. M. Faber, et al., AJ **114**, 1771 (1997); A. Wandel, ApJ **519**, L39 (1999).

[29] F. Simien & G. de Vaucouleurs, ApJ **302**, 564 (1986).

[30] A. Athey, et al. [arXiv:astro-ph/0201338].

[31] M. Loewenstein, et al. ApJ **555**, L21 (2001); T. Di Matteo, et al. [arXiv:astro-ph/0202238].

[32] M. Birkinshaw, & R. L. Davies, ApJ **291**, 32 (1985); T. Di Matteo, C. L. Carilli, & A. C. Fabian, ApJ **547**, 731 (2001); P. B. Eskridge, G. Fabbiano, & D-W. Kim, ApJS **97**, 141 (1995); E. Hummel, J. M. van der Hulst, & J. M. Dickey, A&A **134**, 207 (1984); J. M. Wrobel, AJ **101**, 127 (1991); J. M. Wrobel, & D. S. Heeschen, AJ **101**, 148 (1991).

[33] K. Nandra, et al. ApJ **477**, 602 (1997).

[34] E. Boldt, A. Levinson, and M. Loewenstein, Classical and Quantum Gravity, 19, 1317 (2002).

[35] R. van der Marel, AJ **117**, 744 (1999); J. Kormendy & K. Gebhardt (2001) [arXiv:astro-ph/0105230].

[36] J. Cronin, Rev. Mod. Phys. **71**, S165 (1999); J. Cronin, in Unsolved Problems in Astrophysics, edited by J.N. Bahcall & J.P. Ostriker (Princeton Univ. Press, Princeton, 1997), p. 325.

[37] EUSO web pages: http://ifcai.pa.cnr.it/euso.html

[38] R. Streitmatter, in Workshop on Observing the Highest Energy Particles From Space, AIP Proc. 433, edited by J. Krizmanic, J. Ormes, & R. Streitmatter (Am. Inst. Phys., New York, 1998), p. 95.