

Cosmic rays from remnants of quasars?

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ABSTRACT

Considerations of the collision losses for protons traversing the 2.7-K blackbody microwave radiation field have led to the conclusion that the highest energy cosmic rays, those observed at $\geq 10^{20}$ eV, must come from sources within the present epoch. In light of this constraint, it is here suggested that these particles may be accelerated near the event horizons of spinning supermassive black holes associated with presently inactive quasar remnants. The required emf is generated by the black hole induced rotation of externally supplied magnetic field lines threading the horizon. Producing the observed flux of the highest energy cosmic rays would constitute a negligible drain on the black hole dynamo. Observations with upcoming air shower arrays and space missions may lead to the identification of candidate dormant galaxies that harbour such black holes. Although the highest energy events observed so far are accounted for within the context of this scenario, a spectral upper bound at $\sim 10^{21}$ eV is expected since the acceleration to higher energies appears to be precluded, on general grounds.

Key words: acceleration of particles – black hole physics – cosmic rays – galaxies: nuclei.

1 INTRODUCTION

The highest energy cosmic ray induced atmospheric air shower yet observed (Bird et al. 1995) corresponds to initiation by a 3.2×10^{20} eV particle. Owing to energy degrading ‘GZK’ interactions with the pervasive microwave background (Greisen 1966; Zatsepin & Kuz’min 1966), however, such a baryonic particle (e.g. proton) that energetic could not have originated from a distance beyond 50 Mpc; for sources beyond 100 Mpc all proton energies are less than 10^{20} eV upon arrival here, regardless of their initial energy. As pointed out by Elbert & Sommers (1995), accelerating such particles by powerful radio sources, the presumed best candidates for achieving these energies, is not possible for this particular event since there are no appropriate radio objects in the correct general direction that are within an acceptable distance. What other population, one adequately represented locally, should be considered as an alternative candidate? Although quasars are not a local phenomenon, the *present* epoch is in fact the *preferred* one for *dead* quasars (Schmidt 1978). The prospect of such apparently inactive quasar remnants serving as sources of the highest energy cosmic rays is explored within the context of their putative underlying supermassive black holes. If the generator driving the high-energy

particle accelerator is a spinning supermassive black hole, the system involved must in all other respects look relatively dormant (e.g. no obvious jets). If not a dead quasar then what other astronomical object could possibly satisfy this requirement? Considering the apparently plausible (albeit speculative) conditions here identified, this ‘bottom-up’ scenario appears to provide a unique basis for a potential explanation that is remarkably well matched to the puzzle. The more speculative, highly interesting ‘top-down’ possibility disregarded in this present discussion would have the primary particles produced at ultra-high energies in the first instance, typically by quantum mechanical decay of some supermassive elementary particles related to grand unified theories (Sigl et al. 1995; Kuz’min & Tkachev 1998).

2 HIGH-ENERGY ACCELERATORS

In the present epoch, there is a drastic paucity of quasars such as the extremely luminous ones ($L \geq 10^{47}$ erg s⁻¹) evident at large redshifts, those with putative black hole nuclei having masses $\geq 10^9 M_{\odot}$. Nevertheless, the expected local number of *dead* quasars associated with the same parent population (Schmidt 1978; Small & Blandford 1992; Richstone et al. 1998) is expected to be relatively large. Studies of the X-ray sky indicate a pronounced extragalactic cosmic background that arises mainly from accretion-powered active galactic nucleus (AGN) emission at previous epochs (Boldt 1987; Fabian & Barcons 1992). The present-epoch mass density that has thereby been built up in the form of supermassive black holes must now be substantially more

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than represented by currently active galactic nuclei (Boldt & Leiter 1995). The black hole mass spectrum for the nuclei of active Seyfert galaxies only extends up to $\sim 5 \times 10^7 h^{-2} M_{\odot}$ (Padovani, Burg & Edelson 1990), where $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Considering a radiative efficiency of 10 per cent for the accretion-powered bolometric luminosity of AGNs, Chokshi & Turner (1992) have calculated the mass built up over all earlier epochs and thereby estimated that the expected local mass density of compact galactic nuclei is two orders of magnitude greater than that accounted for by Seyfert galaxies. They conclude that more than half of this local density is contributed by inactive quasar remnants which are now black holes of mass $> 10^8 h^{-2} M_{\odot}$; over 10 per cent of this density is associated with black holes of mass $> 6 \times 10^8 h^{-2}$. As emphasized by Chokshi & Turner (1992), the local Universe is expected to be well populated by currently inactive remnants of quasars. Based on the mass function described by them we have estimated that, for $h \approx 0.5$, the minimum number of black holes within 50 Mpc having a mass $> 4 \times 10^8 M_{\odot}$ is ~ 40 , and that there should be about a dozen or more quasar remnant black holes of mass $> 10^9 M_{\odot}$ in this volume. These quasar remnant expectations are consistent with being lower limits to the number of corresponding supermassive black holes inferred from a recent comprehensive study of massive dark objects (MDOs) at the centres of 32 nearby galaxy bulges (Magorrian et al. 1998). In this connection we note that the number of MDOs within 50 Mpc identified in their sample as being more massive than $10^9 M_{\odot}$ is already eight, comparable to the total number of Seyfert 1 AGNs out to that distance. This is a lower limit to the total number of such supermassive objects within this volume since their sample of MDOs at the centres of nearby galaxy bulges is incomplete, albeit sufficiently large for the correlations sought by them (Magorrian, private communication). Using the luminosity function for field galaxies (Efstathiou, Ellis & Peterson 1988) to estimate the incompleteness of their sample suggests that the corrected number of present-epoch supermassive MDOs could well be an order of magnitude greater than that so far observed.

We use the appellation ‘dead’ for the quasar remnants considered here in a more complete sense than that which is customary in the conventional description of radio galaxies as starved/dead quasars (see e.g. Rees et al. 1982). The latter merely implies that the nuclear luminosity of the object is small, whereas the objects to which we are referring are inconspicuous as regards jets as well. Although local dead quasar remnants are manifestly underluminous, their underlying supermassive black holes are likely to be sufficiently spun-up (i.e. after their many ‘Salpeter’ time units of accretion history: see Thorne 1974; Rees 1997) possibly to serve as high-energy accelerators of *individual* particles. In this scenario (cf. Blandford & Znajek 1977), externally produced magnetic field lines threading the event horizon of such black holes would, by virtue of the induced rotation, generate an effective electromotive force (emf) characterized by $\text{emf} \propto cBR$, where B is the magnetic field strength and R is the effective range over which the concomitant electric field is applicable. Scaling to the magnitude for this impressed B field considered by Macdonald & Thorne (1982) and taking $R \approx R_g (\equiv GM/c^2)$, the gravitational radius, the expected value for the emf is then here estimated as

$$\text{emf} \approx 4.4 \times 10^{20} B_4 M_9 \text{ V}, \quad (1)$$

where $B_4 \equiv B/(10^4 \text{ G})$ and $M_9 \equiv M/(10^9 M_{\odot})$. As described by

Znajek (1978) and Blandford (1979), the massive black hole in their model behaves as a battery with an emf of up to 10^{21} V , comparable to our estimate. We note that radiative losses for particles accelerated in such a dynamo are very much larger for electrons than protons. Proton energy losses during the phase of acceleration up to $\sim 10^{17} \text{ eV}$ are due principally to pair production in collisions with ambient photons (Blumenthal 1970). For the low-luminosity objects considered here [i.e. $L \leq 10^{-4} L$ (Eddington)], however, the associated radiation length is larger than the gravitational radius ($R_g = 1.5 \times 10^{14} M_9 \text{ cm}$) of the black hole, for any plausible emission spectrum from the accretion disc. Hence radiative cascades (basic to the Blandford–Znajek mechanism), such as could attend the process of electron acceleration, would not necessarily constitute a comparable limiting factor in the present scenario for the acceleration of the relatively few (favourably disposed) *protons* that need to achieve an energy close to that of exploiting the full voltage. The dominant energy loss mechanism for protons during the final acceleration phase involves photomeson production (Blumenthal 1970; Hill & Schramm 1985). Although the total cross-section for this increases somewhat with energy, its value is always < 200 microbarns at the highest energies of interest (Caso et al. 1998). For the low-luminosity objects considered here, then, the mean free path for such inelastic collisions is larger than R_g . Thus proton energy losses are not expected to be significant in this scenario. This proton accelerator might be an intrinsic feature of an underlying dynamo (non-jet-producing) somewhat different from that of the Blandford–Znajek model or, alternatively, a subsidiary aspect of that mechanism. The situation that we envisage, therefore, is one in which the accelerator is not operational in the mode in which quasi-steady conversion of the rotational energy of the hole into that of luminous radio jets is possible, but where acceleration of individual protons to the full voltage may occur, perhaps sporadically, at those episodes (possibly of brief duration) when the emf is *not* shorted out.

3 REQUIREMENTS

The air shower events observed at $\geq 10^{20} \text{ eV}$ (Cronin 1997) correspond to an equivalent omnidirectional cosmic ray flux of about one such energetic particle per [(kilometre)² decade]. Assuming that this flux arises from a local random distribution of dead quasars associated with black hole masses $\geq 10^9 M_{\odot}$ implies that their average luminosity is $< 10^{42} \text{ erg s}^{-1}$ in these energetic particles. In contrast to the full electromagnetic process discussed by Blandford & Znajek (1977) for effectively extracting much energy (up to a rate $\geq 10^{45} \text{ erg s}^{-1}$ for a $10^9 M_{\odot}$ object), the particle accelerator aspect considered here for sustaining this cosmic ray output ($\geq 10^{20} \text{ eV particle}^{-1}$) would constitute, by itself, a relatively negligible power drain on the rotational kinetic energy reservoir provided by the putative underlying supermassive ($\geq 10^9 M_{\odot}$) canonical Kerr hole. Replenishing the particles ejected at high energies ($> 10^{20} \text{ eV}$) would only require a minimal mass input; a luminosity of $10^{42} \text{ erg s}^{-1}$ in such particles (if protons) corresponds to a rest mass loss $< 10^{-5} M_{\odot}$ in a Hubble time. Since the energy source in this model derives from the black hole itself, no further mass input is needed; the principal input requirement for the ambient plasma is to generate the magnetic field. The ejection of the energetic protons considered in this model would constitute a leakage of electric charge at a rate amounting to less

than 0.01 per cent of the total effective current flow associated with the Blandford–Znajek dynamo.

4 DISCUSSION

What are the environmental circumstances of the black hole nuclei in dead quasars, and are they conducive to sustaining the magnetic fields needed for this model? We appear to encounter a variety of different situations that can account for the low luminosity of such systems. Why are they so quiescent? As emphasized by Rees (1997), their environment could be almost free of gas, so that very little gets accreted; in this case the accretion rate is inefficient, in that the cooling is so slow (because of the low densities) that only a small fraction of the binding energy gets radiated before the gas is swallowed, a regime of advection-dominated accretion flow (Narayan 1997). The unusually low luminosities associated with the supermassive black holes at the centres of nearby bright elliptical galaxies (Fabian & Canizares 1988; Fabian & Rees 1995; Loewenstein et al. 1998) have been explained in terms of advection-dominated flow (Mahadevan 1997; Narayan 1997), even when there is ample ambient gas. Rather than attempting to address the parameter space for the potential applicability of this model to all dead quasars or to study possible alternative models for the microphysics of low-luminosity AGNs, we have considered in some detail the phenomenology of the specific MDOs in the large sample recently reported by Magorrian et al. (1998), and have investigated the quite general constraints that they impose on our proposed scenario. Of the 32 nearby galaxies with MDOs considered by Magorrian et al. (1998), 14 have compact central masses $M_{\text{MDO}} > 10^9 M_{\odot}$. In order to obtain absolute upper limits on the emf that could be generated by each of these putative supermassive black holes, we assume that the maximum magnetic field possible near the event horizon would correspond to pressure equilibrium between it and the infalling matter, whereby

$$(B_4)^2 \leq 3.7\dot{m}/M_{\odot}, \quad (2)$$

where \dot{m} is the accretion rate in Eddington units ($L_{\text{Edd}} = 1.26 \times 10^{47} M_{\odot} \text{ erg s}^{-1}$), defined as

$$\dot{m} \equiv c^2(dM/dt)/L_{\text{Edd}}. \quad (3)$$

The galaxy bulge mass (M_{Bulge}), as described by Magorrian et al. (1998), constitutes the ultimate reservoir fixing the maximum accretion rate possible into the central black hole, namely

$$\dot{m} \leq 4.6 \times 10^{-4} \mu/x, \quad (4)$$

where μ is the galaxy bulge mass-loss rate ($M_{\odot} \text{ yr}^{-1}$) per $10^{12} M_{\odot}$ and

$$x \equiv M_{\text{MDO}}/M_{\text{Bulge}}. \quad (5)$$

Typically, $\mu \gtrsim 1$ (Renzini & Buzzoni 1986; Mathews 1989). The maximum possible magnetic field is obtained from equations (2) and (4) as

$$B_4 \leq 4.1 \times 10^{-2} (\mu/x)^{1/2} M_{\odot}^{-1/2}. \quad (6)$$

The largest possible emf, that corresponding to the maximum magnetic field, is then obtained from equations (1) and (6) as

$$(emf)_{20} \leq 0.18(\mu/x)^{1/2} M_{\odot}^{1/2}, \quad (7)$$

where $(emf)_{20} \equiv emf / (10^{20} \text{ V})$.

The limits on \dot{m} , magnetic field and emf obtained from equations (4), (6) and (7) are listed in Table 1 for the 14 most massive nearby MDOs studied by Magorrian et al. (1998). The average maximum magnetic field is $2.3 \times 10^3 \mu^{1/2} \text{ G}$. For $\mu \approx 1$ this is substantially less than the magnetic field strength previously considered by Macdonald & Thorne (1982), but comparable to more recent estimates of the likely strengths of magnetic fields threading the horizons of accretion disc fed black holes (Ghosh & Abramowicz 1997). The average limiting emf ($4.9 \times 10^{20} \mu^{1/2} \text{ V}$) is remarkably consistent with what would be required to accelerate the highest energy cosmic ray yet observed. What is the prospect of actually achieving something close to these limiting values for several supermassive MDOs? While a well-defined specific accretion model that is clearly compatible with the constraints and requirements is still to be identified, we find that the possibility of such cannot be excluded at this stage, on quite general grounds. We anticipate that some version of the current standard view of advection-dominated flow (Mahadevan 1997) could be adequate in this respect for many of the MDOs considered here. Exploring the possibly relevant parameter space for such models is beyond the scope of this discussion. However, the margins associated with satisfying the constraints listed in Table 1 could well be suggestive of what sort of modification of the theory would be needed should the more standard models prove inadequate. Based on the 14 MDOs listed in Table 1, it appears that the generation of cosmic rays more energetic than $\sim 10^{21} \text{ eV}$ is precluded; to a precision commensurate with the statistics of this sample, such a spectral cut-off can then be taken as a prediction of our proposed scenario.

5 OUTLOOK

The Akeno Giant Air Shower Array (AGASA), currently the world's largest, has during 1990–97 accumulated an extensive collection of cosmic ray events above $10^{18.5} \text{ eV}$, 461 of which correspond to more than 10^{19} eV (Takeda et al. 1998). Although only six of these exceed the critically important threshold of

Table 1. Upper limits for cosmic ray generation by nearby massive ($>10^9 M_{\odot}$) dark objects.^a

Galaxy	M_{\odot}	$\log x$	\dot{m}/μ \leq	$B_4/\mu^{1/2}$ \leq	$(emf)_{20}/\mu^{1/2}$ \leq
n1399	5.2	-1.785	0.028	0.14	3.2
n1600	11.6	-2.046	0.051	0.13	6.5
n2300	2.7	-2.161	0.067	0.30	3.6
n2832	11.4	-1.935	0.040	0.11	5.7
n4168	1.2	-2.356	0.105	0.57	3.0
n4278	1.6	-1.959	0.042	0.31	2.2
n4291	1.9	-1.807	0.029	0.24	2.0
n4472	2.6	-2.509	0.145	0.46	5.2
n4486	3.5	-2.377	0.110	0.34	5.3
n4649	3.9	-2.143	0.063	0.25	4.2
n4874	20.8	-2.000	0.045	0.09	8.3
n4889	26.9	-1.678	0.021	0.06	6.5
n6166	28.4	-1.767	0.027	0.06	7.4
n7768	9.1	-1.991	0.044	0.14	5.3
average	9.3		0.06	0.23	4.9

^aBased on table 2 in Magorrian et al. (1998). Here, $M_{\odot} \equiv M_{\text{MDO}}/(10^9 M_{\odot})$, $x \equiv M_{\text{MDO}}/M_{\text{Bulge}}$, $\dot{m} \equiv [c^2(dM/dt)]/L_{\text{Edd}}$, $\mu \equiv$ galaxy bulge mass-loss rate ($M_{\odot} \text{ yr}^{-1}$) per $10^{12} M_{\odot}$, $B_4 \equiv B/(10^4 \text{ G})$, $(emf)_{20} \equiv (emf)/(10^{20} \text{ V})$.

10^{20} eV, the overall data base already provides evidence, albeit still statistically limited, which suggests that the observed spectrum is most compatible with a scenario in which sources of ultra-high-energy protons trace the inhomogeneous distribution of luminous matter in the ‘local’ present-epoch Universe, well within 100 Mpc (Medina-Tanco 1999). If more data at the highest energies were to confirm this preliminary indication, it would strongly support models based on cosmic ray proton acceleration by present-epoch supermassive black holes, and preclude the need for invoking cosmologically remote sources of extremely energetic exotic hadrons whose special properties would allow them to traverse large distances (≥ 1000 Mpc) without their energy falling below 10^{20} eV (Chung, Farrar & Kolb 1998; Farrar & Biermann 1998). The sample of about 100 extraordinary events with energy $\geq 2 \times 10^{20}$ eV expected with the upcoming Pierre Auger array (Cronin 1997) will come from nearby sources and, if protons, will point accurately to the directions of origin (i.e. owing to the correspondingly large particle Larmor radius in the weak intergalactic magnetic field). Candidate galaxies within the acceptable pixels would then be searched for stellar-dynamical evidence for central supermassive black hole nuclei [such as the MDOs discussed by Kormendy & Richstone (1995); Kormendy et al. (1997); Magorrian et al. (1998)], here taken to be indicative of the dead quasar sources of the highest energy cosmic rays. If such a correlation were clearly established, and the lack of correlation with strong radio sources were to persist, it would imply that the existence of a black hole dynamo is not a sufficient condition for the presence of pronounced jets. The *OWL (Orbiting Wide-angle Light-collectors)* space-borne NASA mission planned for observing, from above, those air showers induced by the highest energy cosmic rays is anticipated to have the sensitivity to accumulate an order of magnitude more such events than expected with the Auger array (Streitmatter 1998).

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