Cosmic Ray Generation by Quasar Remnants: Constraints and Implications

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ABSTRACT

The quasar remnant cores of nearby giant elliptical galaxies NGC 4486 (M87), NGC 1399, NGC 4649 and NGC 4472 are the sites of supermassive ($>10^9$ M$_\odot$) black holes. These objects are investigated as to the viability of the conjecture that they could harbor compact dynamos capable of generating the highest energy cosmic rays. For an accretion process involving an equipartition magnetic field near the event horizons of the underlying putative spun-up black holes, the energy achievable in accelerating protons could well be $\geq 10^{20}$ eV for all these when only considering the drag induced by curvature radiation. Estimates of the SED (spectral energy distribution) of ambient core photons lead to the conclusion that the energy losses arising from photopion production in proton collisions with these target photons are relatively small for all but M87. For M87, the ambient photon field is likely to be a limiting factor. Accretion rates of $\sim 1$ M$_\odot$ yr$^{-1}$, comparable to the Bondi rates and to the stellar mass loss rates, are associated with ($>10^{20}$ eV) cosmic ray generation in the other (electromagnetically dark) galactic core sites. If these sites are found to be sources of such cosmic rays, it would suggest the presence of a global inflow of interstellar gas all the way into the center of the host galaxy.

\textbf{Key words:} acceleration of particles – black hole physics – cosmic rays – galaxies: nuclei – accretion.

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1 INTRODUCTION

The massive dark objects (MDOs) at the centers of present-epoch giant elliptical galaxies appear to be the supermassive black hole remnants of earlier quasar activity (McLure et al. 1999; McLeod, Rieke & Storrie-Lombardi 1999; Salucci et al. 1999; Richstone et al. 1998; Boldt & Leiter 1995; Chokshi & Turner 1992). It has been proposed that the highest energy cosmic ray particles, those above the ‘GZK’ limit (Greisen 1966; Zatsepin & Kuz’min 1966), could be accelerated by the effective electromotive force (emf) generated near the event horizon of spinning supermassive ($\gtrsim 10^9 M_\odot$) black holes at the apparently dormant quasar remnant cores of nearby massive elliptical galaxies (Boldt & Ghosh 1999). While an emf up to $10^{21}$ volts or somewhat greater would appear to be possible, the drag arising from curvature radiation (Levinson 2000) limits the energy to be attained by a charged particle accelerated by this field; for the four cases considered here (i.e., NGC 4486, NGC 1399, NGC 4649 & NGC 4472) the suppression factor for a proton is estimated to be $\sim 6 - 9$. Acceleration to energies $\geq 10^{20}$ eV would then still be feasible. However, during the final phase of the acceleration process energy losses due to inelastic collisions with ambient photons, those dominated by photo-pion production, must be considered. Therefore, we address in some detail the major concern that recent radio data on low-luminosity AGNs could imply a photon number density at the nuclear core that is so high as to preclude ultra-relativistic processes of particle acceleration and escape, particularly as they pertain to the immediate vicinity of the putative supermassive black hole (Blandford 2000).

Since $\gamma = 10^{11}$ for a $10^{20}$ eV proton, ambient photons at $h\nu > 15 \times 10^{-4}$ eV (i.e., $\nu > 360$ GHz; $\lambda < 0.83$ mm) would appear in the nucleon’s proper frame as $\gamma$-rays $> 150$ MeV, above the critical threshold for energy losses via inelastic collisions involving pion production (cf., Stecker 1968; Hill & Schramm 1985; Stecker & Salamon 1999). Using recent estimates of the SED (spectral energy distribution) at the core of M87 (NGC 4486), the central (and dominant) giant elliptical galaxy in the Virgo Cluster (Reynolds et al. 1996; Ho 1999; Di Matteo et al. 2000), we find that the corresponding radiation length of such energetic protons might well be significantly smaller than the Schwarzschild radius, thereby precluding the acceleration to such a high energy. Hence, if M87 is indeed found to be a source of the highest energy cosmic rays, as commonly conjectured (Biermann & Strittmatter 1987; Biermann 1999; Farrar & Piran 2000), the underlying accelerator would then have to be other than the compact dynamo considered here. However, for other nearby giant
elliptical galaxies harboring apparently dormant supermassive (> $10^9 M_\odot$) black holes, in particular for the remaining three such objects addressed by Di Matteo et al. (1999, 2000), the radiation lengths are estimated to be larger than their Schwarzschild radii. These include NGC 1399, the central giant elliptical in the Fornax Cluster and two other giant elliptical galaxies in Virgo (i.e., NGC 4649 and NGC 4472). The dynamo characteristics expected for the associated compact cores (i.e., $B$-field, achievable energy) are derived from independent estimates of the black hole mass, Bondi accretion rate and SED environment. It has been pointed out that TeV $\gamma$-ray curvature radiation is a necessary consequence of cosmic ray generation by such black hole dynamos (Levinson 2000); these giant elliptical galaxies would be worthwhile targets for the observation of such electromagnetic radiative signature.

2 DYNAMO CHARACTERISTICS

The dynamo’s emf ($V$) is generated by the black hole induced rotation of externally supplied magnetic field lines threading the horizon (Blandford & Znajek 1977). If $B$ is the ordered poloidal field near the hole, $V \sim aB$, where $a$ is the hole’s specific angular momentum; for a hole mass $M$, $a \leq M$ (e.g., $a = M$ for an extreme Kerr hole). In astrophysical units (Znajek 1978):

$$V = 9 \times 10^{20} (a/M) B_4 M_9 \text{ volts,}$$

where $B_4 \equiv B/(10^4 G)$ and $M_9 \equiv M/(10^9 M_\odot)$.

The energy density of the magnetic field near the event horizon is expected to be in equipartition with the rest mass energy density of accreting matter (Krolik 1999). In terms of an Advection Dominated Accretion Flow (ADAF) model (cf., Di Matteo et al. 1999) this is to be identified with the regime where the gas pressure is half the total (i.e, $\beta = 1/2$). Under this assumption,

$$B_4 = 1.33 M_9^{-1} \dot{M}^{1/2},$$

where $\dot{M}$ is the accretion rate $dM/dt$ in $M_\odot \text{ yr}^{-1}$.

The magnetic field ($B$) to be associated with the nuclei of those elliptical galaxies considered here is obtained via equation 2 using the Bondi accretion rates $\dot{M}_{\text{Bondi}}$ estimated by Di Matteo et al. (2000) and the black hole masses determined by Magorrian et al. (1998).
Noting that the hole’s radius is fixed by its mass, the emf given by equation 1 may be expressed directly in terms of the accretion rate. The maximum emf \( V \), that corresponding to \( a/M \) close to unity, is then given by:

\[
V = 1.2 \times 10^{21} \dot{M}^{1/2} \text{ volts.}
\]  

(3)

Except where noted, we take \( \dot{M} = \dot{M}_{\text{Bondi}} \).

The energy \( (E) \) to be attained in this electric field is limited by the drag arising from curvature radiation induced by the magnetic field (Levinson 2000). From equation 5 in Levinson (op. cit.), we obtain that, for a proton (charge \( e^+ \)), the suppression ratio is given by:

\[
E/[e(V)] \approx [(50M_9)^{-1/2}B_4^{-3/4}]r^{1/2},
\]  

(4)

where \( r \) is the magnetic field curvature in units of the Schwarzschild radius. For \( r \approx 1 \) and \( \dot{M} \approx (0.1 - 10) \ M_\odot \ \text{yr}^{-1} \), we note (from equations 2–4) that \( E = (1.0 - 1.8) \times 10^{20} M_9^{1/4} \text{ eV} \). Although the energy possible for a heavier nucleus could be substantially greater, such a particle (e.g., Fe) launched at \( \geq 10^{21} \text{ eV} \) would be disrupted into its constituent nucleons after traveling only 20 Mpc (e.g. Cronin 1997). By contrast, a proton starting with \( 10^{21} \text{ eV} \) would maintain about one-third of its initial energy after traversing the same distance.

During the final phase of the acceleration process energy loss due to photo-pion production in collisions with ambient photons becomes a relatively important effect. The associated radiation length \( (\Lambda) \) relative to \( R \) (the radius of core emission) is given by

\[
\Lambda/R = c\pi R/[(K\sigma)Q]
= \left(278/(K\sigma')\right)(R/R_S)M_9(Q/10^{53} \text{ s}^{-1})^{-1},
\]  

(5)

where \( \sigma \) is the proton photo-pion production cross-section, \( \sigma' \) its value in microbarns \( (10^{-30} \text{ cm}^2) \), \( R_S \) is the Schwarzschild radius, \( K \equiv \langle E(\text{loss})\rangle/E(\text{initial}) \) is the inelasticity in a single collision (Stecker 1968) and \( Q \) is the core emission rate (photons s\(^{-1}\)) for electromagnetic radiation at \( \nu > 360 \text{ GHz} \), given by

\[
Q = h^{-1} \int \nu^{-1}L_\nu d\nu
\]  

(6)

where \( h \) is the Planck constant and \( L_\nu = 4\pi D^2 F_\nu \) for a source of spectral density \( F_\nu \) at distance \( D \). We note (Caso et al. 1998) that, for the regime of interest here,

\[
\langle K\sigma' \rangle \equiv \left[ \int (K\sigma'(dQ/d\nu)d\nu \right] / Q < 120 \text{ microbarns.}
\]  

(7)
Table 1. Black Hole Galactic Nuclei: Candidate Cosmic Ray Sources

| Host Galaxy | NGC 4486 | NGC 1399 | NGC 4649 | NGC 4472 |
|-------------|----------|----------|----------|----------|
| Host Cluster | Virgo | Fornax | Virgo | Virgo |
| Distance ($D$) (Mpc) | 18 | 29 | 18 | 18 |
| Black Hole Mass ($M$) ($10^9 M_\odot$) | 3.6 | 5.2 | 3.9 | 2.6 |
| $M_{\text{Bondi}}$ ($M_\odot$ yr$^{-1}$) | 1.5 | 3 | 1.4 | 0.7 |
| Stellar Bulge Mass ($M_{\text{Bulge}}$) ($10^{12} M_\odot$) | 0.82 | 0.32 | 0.54 | 0.84 |
| $L_{\text{Obs}}/L_{\text{Bondi}}$ | $10^{-5}$ | $2 \times 10^{-6}$ | $3 \times 10^{-5}$ | $10^{-5}$ |
| Magnetic Field ($B$) (10$^4$ G) | 0.45 | 0.44 | 0.40 | 0.43 |
| emf ($V$) ($10^{20}$ volts) | 15 | 21 | 14 | 10 |
| $r^{-1/2}E$ ($10^{20}$ eV) | – | 2.4 | 2.0 | 1.7 |
| Obs. Radio Freq. ($\nu_{\text{obs}}$) (GHz) | 100 | 43 | 43 | 43 |
| $\nu L_\nu(\nu_{\text{obs}})$ ($10^{38}$ erg s$^{-1}$) | 32 | 6.7 | 2.0 | 3.3 |
| $\langle \nu L_\nu(360 \text{ GHz}) \rangle$ ($10^{38}$ erg s$^{-1}$) | 47 | 13 | 3.8 | 6.2 |
| $\nu L_\nu(7 \times 10^8 \text{ GHz})$ ($10^{38}$ erg s$^{-1}$) | – | < 13 | – | – |
| $\langle Q(\lambda < 0.83\text{ mm}) \rangle$ ($10^{21}$ photon s$^{-1}$) | $\sim 28$ | < 7.7 | < 2.3 | < 3.7 |
| $(R_S/R)\Lambda/R$ | $\sim 0.3$ | > 2 | > 4 | > 2 |

The black hole and galactic bulge masses are from Magorrian et al. (1998). The distances, Bondi accretion rates and $L_{\text{Obs}}/L_{\text{Bondi}}$ ratios are taken from Di Matteo et al. (2000). Radio observations are at 0.3 cm for NGC 4486/M87 (Reynolds et al. 1996; Bäath et al. 1992) and 0.7 cm for the three other sources (Di Matteo et al. 1999, 2000). X-ray observations with the Chandra Observatory at $\nu > 3$ keV (Loewenstein 2000) correspond to $\nu = 7 \times 10^8$ GHz.

3 CONSTRAINTS

The key characteristics of the four dynamo candidates investigated here are summarized in Table 1. The tabulated values for $\nu L_\nu$ at $\nu = 360$ GHz were obtained from $F_\nu$ measurements at lower frequencies under the assumption that $F_\nu \propto \nu^{-0.7}$, consistent with the radio spectra observed in the vicinity of 43 GHz (Di Matteo et al. 1999, 2000; Reynolds et al. 1996). The core emission rate ($Q$ photons s$^{-1}$) at $\lambda < 0.83$ mm ($\nu > 360$ GHz) from the accretion flow associated with each of the four supermassive black holes is estimated via equation 6 under the assumption that $F_\nu \propto \nu^{-0.7}$ at higher frequencies as well. For M87 this is based on a high resolution ($10^{-4}$ arcsec) VLBI measurement at 100 GHz (Reynolds et al. 1996; Bäath et al. 1992). For the other three sources we rely on VLA measurements at 43 GHz (Di Matteo et al. 1999, 2000). Because these latter measurements allow more of a contribution from the underlying galaxy and weak jets, and two (NGC 4472 & NGC 4649) do show some extended emission, they are taken to be upper limits to the flux from the compact cores of these galaxies. Comparisons of these extrapolated spectra with the observed limits shown in
Figure 2 of Di Matteo et al. (2000) are consistent with these estimates being upper limits to $L_\nu$ at $\nu \geq 360$ GHz, although less clear for M87. The presence of inner jets associated with any of these potential dynamos would imply vacuum breakdown if created by the mechanism suggested by Blandford & Znajek (1977). In this situation, the feasibility of our compact cosmic ray generator demands that such a jet ejection process be episodic.

The magnetic field ($B$) is obtained from the Bondi accretion rate and black hole mass via equation 2. The emf is calculated from the Bondi accretion rate via equation 3. Considering the drag arising from curvature radiation (Levinson 2000) the energy ($E$) to be attained by a proton accelerated by this emf is estimated via equation 4. During the final phase of the acceleration process energy losses due to collisions with ambient photons are dominated by photo-pion production. The associated radiation length ($\Lambda$) relative to $R$ listed in Table 1 is obtained from equation 5, where $R$ is the radius of core emission and $R_S$ is the Schwarzschild radius.

Lack of microwave data for these sources prevents any direct confirmation that our power-law extrapolation from the radio (centimeter) band does in fact provide an upper limit to their emission in the entire relevant submillimeter band at $\lambda < 0.83$ mm. As a result, we depend on the ADAF models prescribed by Di Matteo et al. (2000) to provide us with the template needed for evaluating our power-law extrapolation. For M87 our extrapolation equals or exceeds $L_\nu$ expected for all their models except the ‘no-wind’ ADAF; see Figure 2a in their paper. For the three other sources our power-law definitely exceeds what is expected for all models except the ‘no-wind’ ADAF; see Figures 2b, 2d & 2e. Radio data exhibited by Di Matteo et al. (2000) at longer wavelengths, at least for NGC 4649 and NGC 4472, appear to rule out the no-wind ADAF model in favor of models with winds that have less emission at frequencies $> 360$ GHz than those based on the simple extrapolations presented in Table 1. Moreover, analysis of Chandra X-ray Observatory data for NGC 1399 (see below, and Loewenstein et al. 2000) places an upper limit on $\nu L_\nu$ at 3 keV ($\sim 7 \times 10^{17}$ Hz) of $1.3 \times 10^{39}$ erg s$^{-1}$ (where, for consistency, we adopt the distance to NGC 1399 of 29 Mpc used by Di Matteo et al. 2000) with comparable limits throughout the 0.3–3.0 keV X-ray energy range. A preliminary estimate of the detected UV flux from a nuclear point source yields a comparable value of $\nu L_\nu$ at $\nu \sim 2 \times 10^{15}$ Hz (O’Connell 2000). Simply extrapolating the highest energy radio point (at 43 GHz) through the X-ray upper limit reduces the value of the photon emission rate $Q$ in Table 1 by about a factor of 3 for NGC 1399, thereby increasing the associated lower limit to $\Lambda/R$ threefold.
4 IMPLICATIONS

The vicinities of spun-up supermassive black holes in dormant elliptical galaxy nuclei can provide an acceleration mechanism sufficient to explain observations of the highest energy cosmic rays, and meet the further criterion of being numerous in the nearby (< 50 Mpc) universe defined by the GZK cutoff for the highest energy particles. Since few, if any, other astrophysical sites in the present-epoch are as feasible, the comparison of the following predictions with cosmic ray data of improved spatial and spectral statistics could determine whether models invoking new particles or topological defects need be considered more carefully. Conversely, confirmation of the present model has far-reaching astrophysical implications; e.g., it would indicate continued spin-up and growth of supermassive black holes via accretion.

The angular distribution of ultra-high energy (UHE) cosmic ray sources provides the cleanest test of a supermassive black hole origin, as the most massive black holes lie in the nuclei of elliptical galaxies. Scattering by intrACLuster fields (microgauss $B$) may destroy this association for galaxies in clusters; however, TeV $\gamma$-rays created via curvature radiation (Levinson 2000) would preserve the correlation. Also, one would not expect otherwise active galaxies, with their higher central photon densities, to produce these cosmic rays. Finally, under the equipartition assumption the emf should be proportional to the square root of the rate of accretion into the nucleus, which should be well approximated by the Bondi rate (Brighenti & Mathews 1999; Quataert & Narayan, 2000), i.e., $V \propto \rho_{\text{gas}}^{1/2}T_{\text{gas}}^{-3/4} M$, where $\rho_{\text{gas}}$ and $T_{\text{gas}}$ at the accretion radius are measurable using the Chandra X-ray Observatory.

The estimates of the radiation lengths in Table 1 rest on the extrapolation of the radio spectrum through 360 GHz assuming a $\nu^{-0.7}$ energy spectrum. A significantly flatter (or inverted) slope would imply a photon number density that is prohibitively high for particle acceleration to > $10^{20}$ eV; and, indeed this seems to be the case for many low-luminosity AGN (Ho 1999). However, with the exception of M87, the galaxies considered here may not be members of the same population, as they lack detectable optical emission lines (Ho, Filipenko & Sargent 1997).

The Chandra limit on the 3 keV nuclear emission for NGC 1399 is derived using the extracted spectrum in a 3.5 arcsec diameter aperture. Two-component models including thermal (hot ISM) and power-law components are fit to the data and 90% confidence upper limits to the power-law flux derived. This upper limit is robust as it accounts for all the...
observed emission above 2 keV, and is conservative since image analysis strongly suggests an even lower upper limit to the flux originating in any nuclear point source (Loewenstein 2000). The hard component attributed by Di Matteo et al. (2000) to an ADAF associated with the nuclear supermassive black hole has now been resolved with Chandra into an extended distribution of discrete sources (Angelini et al. 2000). The VLA radio observations of NGC 4649, NGC 4472, and NGC 1399 correspond to a similar angular resolution as that of Chandra and should be regarded as upper limits as well since there may be contributions from inner-jet emission [the spectra in Ho (1999) are derived from higher resolution VLBI observations]. Thus these galaxies are quiescent even relative to LINERS and other low luminosity AGN, and it is plausible that cosmic ray energy losses by ambient photons are unimportant for these three galaxies. We note that M87, a likely exception, displays more powerful activity at all energies.

If the Chandra results for NGC 1399 are generalizable, the nuclear X-ray emission from elliptical galaxies is well below that predicted by models of ADAFs accreting at the Bondi rate. However, for the specific cases considered in this paper the Bondi accretion rate that provides sufficient compression of the magnetic field to generate an emf corresponding to the most energetic cosmic rays is of the same order as the integrated stellar mass loss rate. $\frac{\dot{M}_{\text{Bondi}}}{M_{\text{Bulge}}} = 1.8, 9.4, 2.6$ and $0.83 \times 10^{-12}$ yr$^{-1}$ for M87, NGC 1399, NGC 4649 and NGC 4472, respectively (Table 1). These are comparable to the specific mass return rate calculated for the stellar population in elliptical galaxies (e.g., Mathews 1989), suggesting the presence of a global inflow of interstellar gas that persists from large galactic radii all the way into the very center of the galaxy. Thus while (hot) protogalactic gas may be the source for the initial rapid growth and quasar–epoch fueling of massive black holes (Nulsen & Fabian 2000), the stellar population of the galaxy at large may be responsible for ‘feeding the monster’ (Gunn 1979) during the present era: an era where the quieter power output may very well be characterized by high energy particles and their associated gamma radiation.

5 OUTLOOK

Comprehensive investigations of nearby giant elliptical (& S0) galaxies indicate that most harbor a massive dark object (MDO) at their centers (Magorrian et al. 1998). Studies of AGN evolution (Chokshi & Turner 1992; Fabian & Iwasawa 1999; Salucci et al. 1999) and the X-ray background of accretion-powered radiation (Boldt & Leiter 1995) conclude that the
largest of these MDOs are associated with supermassive black holes which are the apparently dormant remnants of previously active quasars. It has been proposed that these accretion-fed spinning dark objects are latent dynamos, sufficient for producing the highest energy cosmic rays (Boldt & Ghosh 1999). The accretion rate for such a dynamo is no greater than the mass loss rate estimated for giant elliptical galaxies (Mathews 1989). The scatter and uncertainty in the ratios of black hole to bulge mass and of bulge mass to optical luminosity, and the inhomogeneity of the galaxy distribution within 50 Mpc, make it virtually impossible to precisely quantify the expected underlying number of UHE cosmic ray sources. However, we note that the number of galaxies within 50 Mpc that have bulges sufficiently luminous \((L_{\text{Bulge}} > 10^{10}L_{\odot})\) to be potential sites of \(> 3 \times 10^8 \ M_\odot\) black holes is on the order of \(10^3\) (Magorrian 1999, Marinoni et al. 1999). Assuming an IGM B field of coherence length \(\sim 1\) Mpc and magnitude \(\sim 1\) nanogauss, a UHE proton \(> 10^{20}\ eV\) originating within 50 Mpc would have an arrival direction aligned sufficiently well with its origin for avoiding confusion among candidate sources (Medina-Tanco, de Gouveia Dal Pino, & Horvath 2000), although it has been suggested that the relevant B field could be larger than a nanogauss (Farrar & Piran 2000). For a UHE proton \(< 10^{21}\ eV\) originating from a source deep within a rich cluster of galaxies the Larmor radius (for the associated microgauss B field) is much less than the cluster radius (Saikia & Salter 1988); hence the emerging protons would appear to be coming from an extended source the size of the cluster. Fortunately, most suitably massive giant elliptical galaxies reside outside of clusters (Magorrian et al. 1998; Burstein 1999). If the ‘local’ extragalactic magnetic field is much less than a microgauss, then an angular resolution of about a degree should be good enough for the OWL/Airwatch air-shower observatory (Streitmatter 1998) to establish a correlation between candidate ellipticals and UHE cosmic ray events, at least two-thirds of the time (the remainder would be cluster associated). Those in clusters would then be located via their TeV \(\gamma\)-ray curvature radiation. In particular, of the six such giant ellipticals addressed by Di Matteo et al. (2000) we find that, after considering principal constraints, at least half could well be harboring supermassive black hole dynamos capable of producing cosmic rays more energetic than \(10^{20}\ eV\) and be identifiable via their TeV \(\gamma\)-radiation, e.g., with the Whipple Observatory at an angular resolution sufficient for isolating specific galaxy emission (Weekes et al. 1996).
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Cosmic Ray Generation by Quasar Remnants

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