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GIANT RADIO GALAXIES AND COSMIC-RAY ACCELERATION

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ABSTRACT

Giant radio galaxies (GRGs) are prime and unique laboratories for constraining the plasma processes that accelerate relativistic electrons within large intergalactic volumes. The evidence for short radiative loss times rules out certain scenarios for energy transport within their very large dimensions. This, combined with their high energy content, large ordered magnetic field structures, the absence of strong large-scale shocks, and very low upper limits on their internal thermal plasma densities, points to a direct and efficient conversion of force-free magnetic field to particle energy. This is underlined by the evidence in GRGs that their internal Alfvén speeds are higher than the lobe expansion speeds. We discuss these constraints in the context of models in which the central black hole energy is initially extracted as electromagnetic Poynting flux that injects large amounts of magnetic flux into the lobes. Recent advances in the theory of collisionless magnetic reconnection make this a favored mechanism to explain the particle acceleration in these systems. The energy reservoir is likely to be force-free fields, which is independently consistent with recent models of initial electromagnetic energy transfer from the parent galaxy's supermassive black hole. Such a scenario has wide-ranging astrophysical consequences: it implies that space-distributed magnetic reconnection or some other highly efficient field-to-particle energy conversion process likely dominates in *all* extended extragalactic radio sources.

Subject headings: acceleration of particles — intergalactic medium — magnetic fields — plasmas — radio continuum: galaxies

1. INTRODUCTION

The energy content in magnetic fields and relativistic particles in the giant radio galaxies (GRGs) are collectively the largest seen in a single galaxy-associated astrophysical system. This makes GRGs the best calorimeters of central black hole (BH) energy release in the sense that they retain more of the BH-released energy in a visible form than other systems. Their typical "visible" energy content, 10^{60}–10^{61} ergs, is possibly even conservative by a factor of a few (Kronberg et al. 2001, hereafter Paper I). This requires a very high conversion efficiency of the central BH's infall energy into magnetic fields and cosmic-ray (CR) particles. Typically, GRGs are morphologically "relaxed" and apparently free of significant energy input from the lobe–intergalactic medium (IGM) interface.

About a dozen GRGs have been imaged and analyzed in great detail at multiple radio frequencies, giving distributions of the CR particle energy index and/or Faraday rotation within their radiating volumes (Willis & Strom 1978; Strom & Willis 1980; Willis et al. 1981; Kronberg, Wielebinski, & Graham 1986; Subrahmanyan, Saripalli, & Hunstead 1996; Mack et al. 1998; Schoenmakers et al. 1998; Feretti et al. 1999; Lara et al. 2000; Palma et al. 2000).

In this Letter, we focus on the detailed properties of seven of the best-studied GRGs, combined with pertinent results from other, collective radio source analyses. Detailed studies of these GRGs indicate very high intralobe Alfvén speeds, and we argue that they provide important constraints on particle acceleration processes. Recent advances in understanding collisionless reconnection (Birn et al. 2001; Hanasz & Lesch 2003), and in reconnection-induced particle acceleration (Nodes et al. 2003), make this a favored mechanism in GRGs, especially in the context of electromagnetic energy transfer from the central BH accretion disk.

2. PHYSICAL CONSTRAINTS PROVIDED BY OBSERVATIONS OF RADIO SOURCES OF THE LARGEST SIZE

2.1. *Central Black Hole Accretion as the Primary Power Source of Radio Lobe Energy*

Global studies of radio galaxies suggest that their power and energy content is correlated with the energy output of the central galactic BH. A recent study of radio galaxies up to $z = 1$ by Best et al. (1999) finds that, over a large radio source size range (extending to well below the GRG dimensions), the radio core/lobe luminosity *ratio* is nearly constant and only weakly depends on radio power. This result strongly indicates that the CRs in the radio lobes are energized by an energy flow path that is coupled closely to the galaxy nucleus.

Another, UV-radio study based mostly on low-luminosity BHs, by Falcke, Malkan, & Biermann (1995), finds that the jet power correlates with the accretion disk luminosity as revealed by the UV flux. This is another signature of a direct connection between the central accretion-power source and the radio-visible CR particles.

We interpret the above analyses, especially that of Best et al. (1999), as further evidence that the source-IGM interaction in GRGs does not play a significant role in energizing the GRG radio lobes. In particular, the outer radio "hot spots" of GRGs (where they exist), which have been proposed as prime CR particle acceleration sites in the past, are insufficient to energize the radio lobes on megaparsec scales.

2.2. *Polarization Structure, Faraday Rotation, and Constraints on Field, Densities, and Alfvén Speeds*

The highly ordered intralobe magnetic field geometry, often on scales $\gtrsim$100 kpc, appears largely free of magnetic discontinuities that would be expected within large-scale lobe internal shocks. This high degree of field alignment also suggests that particle transport is unlikely to be super-Alfvénic. At the lobe/

IGM interface, the field orientation is consistently perpendicular to the local direction of lobe expansion. This applies both to 100 kpc scales and down to ∼20 kpc, as revealed in high-resolution subimages of outer hot spots that exist for some GRGs. The latter can be seen, e.g., in Kronberg et al. (1986; 0634−20, 3C 445).

The GRGs' large sizes and relatively low redshifts also permit detailed imaging of the synchrotron emissivity, spectral index, Faraday rotation, and polarization structure within the GRG lobes. The favorable combination of the megaparsec-scale dimensions and a large λ^2 "baseline" gives the most accurate differential Faraday rotation determinations at the low values that are typical of GRGs. The local $\delta\mathrm{RM}(x, y)$ over the projected lobe surface can usually be determined to $\lesssim 2$ rad m^{-2}, close to image noise errors. Upper limits to $\mathrm{RM}(x, y)$ at these levels give very sensitive limits to the lobe internal thermal electron density, n^L_{th}, and that for the ambient IGM, $n^{\mathrm{IG}}_{\mathrm{th}}$ (Willis & Strom 1978; Strom & Willis 1980; Kronberg et al. 1986; Schoenmakers et al. 1998; Palma et al. 2000),

$$\Delta\chi = 0.81 \frac{\Delta\lambda^2}{\mathrm{m}^2} \frac{n_{\mathrm{th}}}{\mathrm{cm}^{-3}} \frac{B_{\parallel}}{\mu\mathrm{G}} \frac{L}{\mathrm{pc}} \ \mathrm{rad}. \tag{1}$$

A remarkable observational fact is that $\delta\mathrm{RM}(x, y)$ within the projected area of each approximately megaparsec-sized lobe often appears close to or below the threshold of measurability. The fact that some foreground contribution is included in $\delta\mathrm{RM}(x, y)$ implies even lower limits on the lobe internal rotation measure (RM) of GRGs. Consequently, lower limit estimates of the Alfvén velocity, v^L_{A} are more stringent than in any other extragalactic system.

In our analysis, we have used seven of the most comprehensively observed giant FR II sources: 0313+683, 8C 0821+695, 3C 326, 3C 236, 3C 445, 0634−20, and 2146+82. For these sources, a typical equipartition field in the lobes is 5 μG. This estimate uses the same parameters adopted in Paper I, which include a lobe volume filling factor of 0.1 and a relativistic proton/electron ratio, $k = 100$. These parameters lead to estimates of n^L_{th} and B^L, hence estimates of the lobe internal Alfvén speeds of

$$v^L_{\mathrm{A}} \simeq 6300 \ \mathrm{km\ s}^{-1} \frac{B^L_{5\times10^{-6}}}{\sqrt{n^L_{\mathrm{th},\,3\times10^{-6}}}}. \tag{2}$$

The value of v^L_{A} is comparable to the lobe expansion speed, as noted by Subrahmanyan et al. (1996), and may sometimes be greater, given that n^L_{th} are more likely upper limit estimates from the RM data; v^L_{A} significantly exceeds the GRGs' typical lateral expansion velocity of ∼1000 km s^{-1}. Our estimates for v^L_{A} would be further raised if the magnetic field strengths in the filaments, $|B^L_F|$, are locally higher. For example, if $|B^L_F|$ were to reach 5 times the smoothed-out equipartition value, and if n^L_{th} were not to scale with $|B^L_F|$, then v^L_{A} would become ∼0.1c.

The stringent RM-constrained limits to n^L_{th} within the lobe volume gives $M^L_{\mathrm{th}} = n^L_{\mathrm{th}} m_p V^L \lesssim 10^9\ M_{\odot}$, which can be compared with the total baryonic rest mass of the relativistic plasma, $M^L_{\mathrm{rel}} \sim 10^5 E^T_{61}\ M_{\odot}$. Comparison of these two numbers is of interest for two reasons: (1) It implies that even at these low values of n^L_{th}, the lobes still contain an adequate reservoir of thermal protons and electrons that are available to be accelerated to relativistic energies. (2) At the same time, it leaves "room" for a particle energy spectrum modification due to reconnection acceleration, in which only a fraction of the thermal gas is accelerated to relativistic energies.

Whereas $\delta\mathrm{RM}(x, y)$ within GRG radio lobes is typically an upper limit $\lesssim 2$ rad m^{-2}, $\delta\mathrm{RM}$ *between* lobes is detected up to (but often less than) ∼10 rad m^{-2} $= 0.81 n^{\mathrm{IG}}_e \zeta B^{\mathrm{IG}} D/\sqrt{2}$, where D is the true average lobe 1–lobe 2 separation. We assume an average 45° projection away from the sky plane, and ζ is a geometrical factor, of order 0.5, that allows for fluctuations of magnetic field direction. With these assumptions, $5 \times 10^{-5}\ \mathrm{cm}^{-3} \gtrsim n^{\mathrm{IG}}_e \gtrsim 2 \times 10^{-6} \mathrm{cm}^{-3}$ assuming $B^{\mathrm{IG}} \sim (8\pi n^{\mathrm{IG}}_e kT)^{1/2}$, i.e., an intergalactic plasma $\beta \sim 1$. Given these numbers, the thermal matter density within the GRG lobes could be slightly lower than the ambient IGM value—as is the case in galaxy cluster–embedded lobes.

2.3. *Particle Acceleration at the Lobe/IGM Interface?*

There is at best weak evidence for highly energized outer termination shocks in GRGs. The linear polarization of the synchrotron radiation typically indicates a highly ordered magnetic field structure around the lobe periphery, while the surface brightness tapers off slowly, especially at the lateral peripheries. There is also evidence for radio spectral index steepening transverse to the long axis of some GRGs (Klein et al. 1994; Kronberg et al. 1986), which argues against fresh particle acceleration at the lateral lobe peripheries.

GRG lobe volumes are typically 10^2 times those of their outer hot spots, and they have comparably higher total luminosities $L_L \gg L_{\mathrm{HS}}$, so that the total energy content of the relativistic plasma in the hot spots (when they exist in GRGs) is a few percent or less of that in the lobes. This means that if the relativistic magnetoplasma in the lobes is fed by the hot spots, the latter would need to be reenergized at least ∼10^2 times *and* transported over several hundred kiloparsecs (see also § 2.4). This conclusion is independent of whether the mechanism of hot spot energization is by an outer bow shock or some other direct deposition by the energy "pipe" or jet. Either scenario has difficulties with particle transport over their very large dimensions. Global studies of the lobe length/width ratio of FR II–type radio sources (Best et al. 1999; Subrahmanyan et al. 1996) show that this ratio is roughly constant over a large range of sizes (extending well below the GRG class) and radio power. That is, radio lobes tend to expand quasi-homologously (and overpressured) into the ambient IGM with little evidence for outer boundary shocks along the source sides. This behavior has an interesting similarity to that of an expanding spheromak (Bellan 2000), which is a highly scalable system.

The (quasi-homologous) expansion of the GRG radio lobes can be modelled as (1) quasi-free expansion into a rarified IGM having $B \lesssim 1\ \mu$G, and gas density $n \lesssim 10^{-5}$ to 10^{-6} cm^{-3}, consistent with the observed lobe-lobe RM differences, or (2) a spheromak-like expansion (also overpressured) that is constrained by the internal tension of highly organized (as observed), mostly force-free fields.

The latter scenario is an attractive possibility, in that it "matches" to mechanisms for the collimated electromagnetic extraction of the BH accretion energy, by which the BH–accretion disk system initially and efficiently converts gravitational accretion energy into magnetic field energy (Lovelace 1976; Blandford & Znajek 1977; Colgate et al. 2001; Li et al. 2001; Koide et al. 2002; Lovelace & Romanova 2003).

2.4. *Particle "Aging" and Transport Constraints*

The large particle transport distances within the GRGs can be matched to synchrotron and inverse Compton radiative loss times to place constraints on distances that particles have traveled from their sites of last acceleration. Here too, the *largest* radio sources are uniquely useful as limit testers when radio lobes are imaged over a decade in frequency and over megaparsec dimensions. Spectral index distributions over a wide frequency range have emerged in a series of papers, e.g., 0.6–5 GHz (Willis & Strom 1978; Strom & Willis 1980); 1.4–10.6 GHz (Kronberg et al. 1986); 0.33–10.6 GHz (Mack et al. 1998); 0.3–8.5 GHz (Palma et al. 2000).

The results often show spectral index flattening within the "bridge" zones at $\gtrsim$300 kpc away from the outer advancing "head." That is, the zones having the flattest (most recently accelerated) spectrum are not always located near the outer hot spot (if it exists), as would be expected in a lobe/IGM interface shock acceleration scenario in which they passively backflow-propagate from the outer hot spot shock into the inner bridge toward the host galaxy.

We can quantitatively compare electron radiative lifetimes at 10.6 GHz, the highest observed frequency of detailed GRG images so far, with plausible transport times within the giant radio lobes. The former is

$$\tau_{\rm rad} = \frac{5.4 \times 10^7 B_{3.3\,\mu{\rm G}}^{1/2}}{[B_{{\rm cmb}(3.3)}^2(1+z)^4 + B_{3.3\,\mu{\rm G}}^2]\nu_{10.6\,{\rm GHz}}(1+z)^{1/2}}\ {\rm yr}, \quad (3)$$

where the cosmic microwave background energy density equivalent $B_{{\rm cmb}(3.3)}^2 \equiv 1$; $\tau_{\rm rad}$ is an upper limit, since (1) $B \gtrsim 3\ \mu$G in GRG lobes for $k \gtrsim 50$, (2) the highest synchrotron turnover frequency in intralobe volumes could be greater than 10.6 GHz, and (3) even at $z = 0.2$, $\tau_{\rm rad}$ is reduced by 1.7 for $B_L = 3.3\ \mu$G. Images of giant sources at frequencies as high as 10.6 GHz (Kronberg et al. 1986; Mack et al. 1998) suggest that particle radiative ages in parts of GRG lobes are at most a few times 10^7 yr. By contrast, the transport time from the hot spot is

$$\tau_T \sim 5 \times 10^8 \frac{d}{500\ {\rm kpc}} \frac{1000\ {\rm km\ s^{-1}}}{v_T}\ {\rm yr}, \quad (4)$$

where we scale to a transsonic transport velocity $v_T = 1000$ km s^{-1}. The large dimensions of many GRG lobe regions dictate that $\tau_{\rm rad} \ll \tau_T$. The radiating relativistic electrons must therefore somehow be accelerated in situ, a fact first recognized over 25 years ago by Willis & Strom (1978).

2.5. *The Emissivity Contrast in the GRG 2147+816*

We have considered the emissivity contrast within the lobes of GRGs in order to estimate the ratio of magnetic field strengths in presumptive energy source and sink zones. We use the giant source 2147+816 to show a representative calculation.

Regions of enhanced surface brightness that are just visible in Figure 1 have volume emissivity variations (in units of ergs s^{-1} Hz^{-1}) of a factor $\sim$2 or less above the lobe internal level. Similar emissivity contrasts are obtained for the southern lobe of this source (not shown). Generally, emissivity contrast ratios in GRG lobe internal zones (excluding hot spots) are small, $\lesssim$5. This mild contrast is not indicative of strong intralobe shocks.

If the shock were strong and propagated perpendicular to the field, the emissivity contrast across the shock would be proportional to $(B_1/B_2)^2(\gamma_1/\gamma_2)^2$, where subscripts 1 and 2 indicate ahead of and behind the shock. A parallel shock, on the other hand, need not compress the field significantly, $\leq \times 2$ (Vainio & Schlickeiser 1999), but an efficient acceleration of electrons requires large Alfvén wave scattering and a localization of the shock to $\Delta R \leq 10(c/v_s)R_{{\rm L},e} \simeq 2.5 \times 10^{16}$ cm,

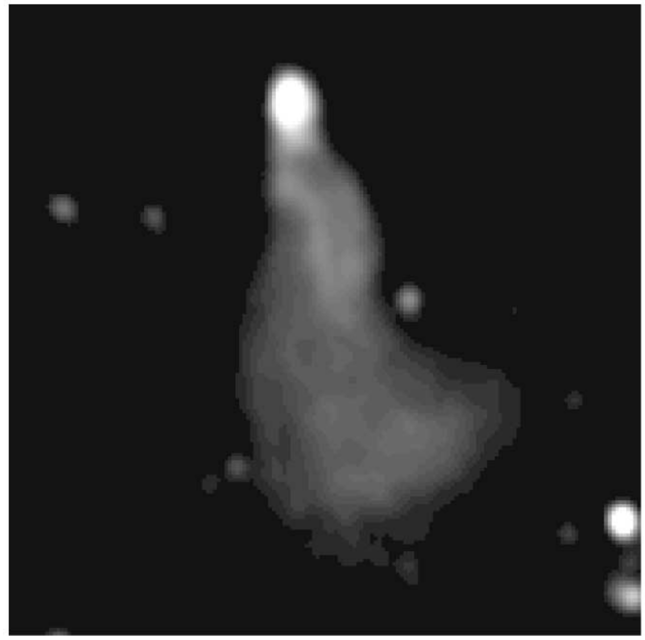

FIG. 1.—Very Large Array image of the northern lobe of the GRG 2147+816 ($z = 0.146$) at 1.4 GHz. The figure is 1.1 h_{75}^{-1} Mpc on a side. (Adapted from Palma et al. 2000.)

where $R_{{\rm L},e}$ is the Larmor radius of the relativistic electrons, and hence a sharp jump in luminosity, which is not observed.

2.6. *Possible Mechanisms for Highly Efficient Particle Acceleration*

Radio lobe energization in which the initial energy carrier is a collimated electromagnetic jet from the central BH naturally leads to the requirement that most of the particle acceleration will come from the dissipation of magnetic energy. This *Ansatz*, combined with the requirement that relativistic leptons must be accelerated in situ, and with high efficiency (Paper I), leads us to suggest intralobe collisionless reconnection as an attractive mechanism for direct magnetic to particle energy conversion.

It is instructive to begin in the resistive MHD limit, even though we do not expect this regime to be valid for GRG lobes, given their low density and small resistivity. In this case, ordinary magnetic field diffusion will not be fast enough to account for the magnetic energy conversion. For example, in a filament with size of $\sim$1 kpc and resistivity of $\eta \sim 10^4$ cm^2 s^{-1} (using an electron temperature of 10^6 K), the diffusion time will be $L^2/\eta \sim 9 \times 10^{38}$ s, much longer than a Hubble time.

A very different situation obtains, however, by realizing that as the fluids carry the frozen-in fields and move them around, steep field gradients could be generated. These result in thin sheetlike current structures and hence greatly reduce the diffusion times. In the Sweet-Parker reconnection picture, the current layer width is $\Delta_\eta \sim (\tau_{\rm A}\eta)^{1/2}$, where $\tau_{\rm A} \sim L/v_{\rm A}$, the typical MHD timescale, and $v_{\rm A} \sim 6.3 \times 10^8 B_{5\times10^{-6}}/n_{3\times10^{-6}}^{1/2}$ cm s^{-1} (see § 2.2). Now the rate of energy dissipation is related to the rate of convection of magnetic flux into and out of the reconnection region. This timescale is $\tau_{\rm SP} \sim (\tau_{\rm A}\tau_\eta)^{1/2} \sim 6 \times 10^{26}$ s, but it is still much too long to be relevant to GRG lobes.

The physical conditions in the GRG lobes are, rather, more consistent with the so-called fast collisionless reconnection scenario, which has recently been studied in the context of hot fusion laboratory plasmas (e.g., tokamaks) and magnetospheric plasmas (e.g., Earth's magnetotail). This is because for radio lobes, the ion skin depth (which is understood to be closely related to kinetic effects in reconnection), $d_i = c/\omega_{pi} \sim 1.3 \times 10^{10} n_{3\times10^{-6}}^{-1/2}$ cm (where ω_{pi} is the ion plasma frequency), is significantly larger than the resistive Sweet-Parker layer width:

$$\Delta_{\rm SP} \sim 1.5 \times 10^8 L_{\rm kpc} n_{3\times10^{-6}}^{1/4} \eta_4^{1/2} B_{5\times10^{-6}}^{-1/2}\ {\rm cm}. \tag{5}$$

In this limit, reconnection is mediated by the kinetic physics to break the flux frozen-in condition. It has been shown that the reconnection rate is then independent of the resistivity (e.g., Shay & Drake 1998), although its exact dependence on various parameters (especially d_i) is currently under debate (Shay et al. 1999; Wang, Bhattacharjee, & Ma 2001; Fitzpatrick 2003).

Another recent study by Li et al. (2003) on a fully force-free system using particle-in-cell simulations has shown that collisionless reconnection that is facilitated by the full kinetic physics can indeed proceed at a very fast rate, with flow speeds that are a fraction of the Alfvén speed. The above scale estimates strongly favor the idea that collisionless reconnection in radio lobes will be Alfvénic and thus could play an important role in converting the magnetic energy to particles at a fast rate, given the high Alfvén speeds within GRGs. This may therefore be the main mechanism of the in situ particle acceleration that is demanded by the GRG radio spectral index distributions (§ 2.4).

An alternative efficient process, particle acceleration by MHD turbulence/waves, has also been studied in some detail as a possible mechanism of CR acceleration. A recent comprehensive summary can be found in Schlickeiser (2002). The basic idea is that magnetized plasma systems usually support a broad spectrum of waves (high-energy particles can excite waves as well), and when particles are in gyroresonance with these waves, strong interactions can occur, causing pitch-angle scatterings of the particles and stochastic particle acceleration. One difficulty, however, is that the level of turbulence/waves is typically unknown, which makes it difficult to apply to radio lobes at the present time.

3. WIDER IMPLICATIONS FOR ALL BH-POWERED RADIO SOURCES

The similarity of GRGs to their smaller radio galaxy counterparts implies that if reconnection is the primary acceleration mechanism in the GRGs, it is reasonable to conclude that it, or some other process associated with very high Alfvén speeds relative to the lobe expansion speed, is a universal and primary process in all extended active galactic nucleus–powered extragalactic radio sources. The reservoir of magnetic flux can only come from the gravitational infall energy, probably by an accretion disk dynamo (Colgate et al. 2001).

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