JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
37: 501 ∼ 507, 2004

BLACK HOLE-IGM FEEDBACK, AND LINKS TO IGM FIELDS AND CR'S

PHILIPP P. KRONBERG
Los Alamos National Laboratory, IGPP, Los Alamos NM 87545, USA
E-mail: kronberg@lanl.gov

ABSTRACT

The uniquely large dimensions of Giant radio galaxies (GRGs) make it possible to probe for stringent limits on total energy content, Faraday rotation, Alfvén speeds, particle transport and radiation loss times. All of these quantities are more stringently limited or specified for GRG's than in more "normal" FRII radio sources. I discuss how both global and detailed analyses of GRG's lead to constraints on the CR electron acceleration mechanisms in GRG's and by extension in all FRII radio sources. The properties of GRG's appear to rule out large scale Fermi-type shock acceleration. The plasma parameters in these systems set up conditions that are favorable for magnetic reconnection, or some other very efficient process of conversion of magnetic to particle energy. We conclude that whatever mechanism operates in GRG's is probably *the* primary extragalactic CR acceleration mechanism in the Universe.

Key words : cosmic rays – intergalactic medium – radio galaxies

I. INTRODUCTION

It has been known since several decades ago that a single galaxy releases a very large magnetic energy (Burbidge 1956)– up to $\sim 10^{61}$ ergs, and that gravitational energy is the only feasible source (Hoyle et al. 1964, Burbidge & Burbidge 1965).

A strong case can be made for the accretion on the central supermassive black holes as the energy engine for the powerful radio sources (e.g. Begelman, Blandford, & Rees 1984). Colgate & Li 1999; 2000; Colgate, Li, & Pariev 2001 have argued that such sytems can provide a strong feedback effect on the dynamics of the intergalactic medium (IGM). A significant fraction of the energy released during the formation of galactic black holes appears to have been directly converted into magnetic field energy and magnetic flux. Observations confirm that these are "directly" injected into extragalactic space, even before subsequent CR diffusion into the IGM continues this process further.

The fact that extragalactic radio sources are seen in synchrotron radiation enables an approximate calculation of the minimum energy contained in the sources' magnetic fields and relativistic particles. The jet-lobe morphology and commonly high polarization degree confirm, respectively, that the energizing source is at the host galaxy/quasar nucleus, and that the largest field ordering scales are comparable to, or greater than a galactic dimension. This latter fact sets constraints on the magnetic field generation process. The energy content in magnetic fields and relativistic particles in the giant radio galaxies (GRG's) are collectively the largest seen in a single galaxy-associated astrophysical system. This makes GRG's 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 system (Kronberg *et al.* 2001). Their typical "visible" energy content, $10^{60} - 10^{61}$ ergs, is possibly even conservative by a factor of a few (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, GRG's are morphologically "relaxed" and apparently free of significant energy input from the lobe-intergalactic medium (IGM) interface.

About a dozen GRG's have been imaged and analysed 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 *et al.* 1996, Mack *et al.* 1998, Schoenmakers *et al.* 1998, Feretti *et al.* 1999, Lara *et al.* 2000, Palma *et al.* 2000).

I will focus here on an analysis of the detailed plasma parameters for seven of the best studied FRII GRG's, along with pertinent results of other collective radio source analyses. Following Kronberg et al. (2004), I show why they provide important constraints on particle acceleration processes, and the probable importance of magnetic reconnection, or a similar highly efficient process. The importance of GRG's for understanding of the origins of intergalactic magnetic fields in the mature universe and possible implications for extragalactic CR acceleration are discussed.

Proceedings of The 3rd Korean Astrophysics Workshop on
Cosmic Rays and Magnetic Fields in Large Scale Structure

II. THE GLOBAL ENERGETICS OF LARGE FRII RADIO SOURCES

(a) Radio Source Samples Analysed

We have analysed ~ 100 powerful extragalactic radio galaxies consisting of two main categories, having extremes of external ambient pressure, and extremes of radiating volume on the other. These are (Kronberg et al. 2001):

(i) sources with large projected linear size, $\geq 670\, h_{75}^{-1}$ kpc, most of which are likely to be in a rarefied IGM environment. They are referred to as "giant" sources and are taken from a substantial list of ~ 70 such sources, largely from the Northern Hemisphere, that are currently known and well imaged.

(ii) ~ 30 sources located in the *densest* known IGM environment — within ~ 150 kpc of the cores of rich clusters. We refer to them as "cluster sources" in this paper.

It is intructive to estimate the total energy content of the synchrotron radiating lobes for both categories of source, and plot them against the linear size, volume and luminosity. Figure 1, adapted from Kronberg et al. 2001, shows plots for these two source samples, plus a third set (see caption), in which we compare total energy content with linear size, luminosity and volume.

(b) Global Flow Paths of the Galactic BH Energy

The GRG's have globally the largest energy content, even though they do not, as a group, represent the most luminous extragalactic radio sources. The cluster-embedded sources, presumably powered by similar supermassive black holes have 10 % or less of the energy content of GRG's. This discrepancy can be understood in terms of an energy release path which is a combination of PdV work against the hot intercluster gas, and cluster ICM heating associated with both the expansion and turbulent heating in consequence of the buoyant rise of the lobes in the ICM environment. The former can be quantitatively verified from X-ray images that reveal temperature and pressure of the ambient gas that is displaced by the radio lobes. It is interesting to note that when these two components are added to the energies in Fig. 1, the energy supplied to the cluster sources becomes comparable to that in the giant sources. The upper envelope of the GRGs' total energy content is higher than for any other class of extraglactic radio source. In this sense GRG's constitute the best "calorimeters" for the *minimum* amount of magnetic energy that galactic black holes have injected into intergalactic space.

Though the upper envelope in Figure 1 represents the best approximation of galactic BH energy release from a limited range of radio observations, does it really estimate the total energy deposited in relativistic particles and magnetic fields over the formation time of the radio lobes? That is, how much additional energy could our estimates have possibly missed?

Each item in the following list would, or could lead to an underestimate of the radio sources' energy content as measured "now", at a mature stage of the GRGs' evolution. They are:

1. Synchrotron and inverse Compton cooling losses.
2. Due to deprojection the true source volume, hence E_{min}^{tot}, is even larger than we infer.
3. Particle escape into the IGM will have occured at some rate.
4. PdV work on the ambient medium, which is measurable in X-ray imaged clusters, but not (yet) against the lower density IGM.
5. Free expansion energy loss (independent of Ep)
6. Given that *in situ* particle acceleration occurs (see below), synchrotron radiation could occur at frequencies well above the cm radio range, e.g. possibly up to X-rays, which would lead us to larger lobe energy content estimates if all other parameters are the same.
7. The "final" infall radius may be larger than the BH's Schwarzschild radius R_s, which we use here as the fiducial size of the central Black Hole. If most of it were extracted at some $\mathrm{r} \succ \mathrm{R}_s$, it would further narrow the gap between the gravitational energy reservoir and the GRG measured energies.

The sum of items $1 - 6$, though very difficult to quantify with current instrumental capabilities, could easily give factor of ~ 10 increase in the total AGN energy release into magnetic fields and particles, over and beyond the energy estimates in Figure 1.

This consideration forces us into an intriguing situation when we compare the upper envelope of the GRG energy contents in Figure 1(b), (c), or (d) with the gravitational energy reservoir of supermassive galactic black holes. The infall energy of the latter, using the Schwarzschild radius R_s as a fiducial final infall radius, is

$$E_{\mathrm{infall}} = M_{BH}c^2 = 1.8 \times 10^{62} \frac{M_{BH}}{10^8 M_\odot} \mathrm{ergs} \quad (1)$$

Point 7 above tells us that the available gravitation energy might be less than this. That would further narrow the "gap" between the energy available in the AGN and the actual energy released in CRs and magnetic fields.

(c) Magnetic Energy as "Captured" Energy Release from Galactic Black Holes

It follows from the above discussion that a substantial fraction of the energy stored in extended extragalactic radio sources is probably in the form of

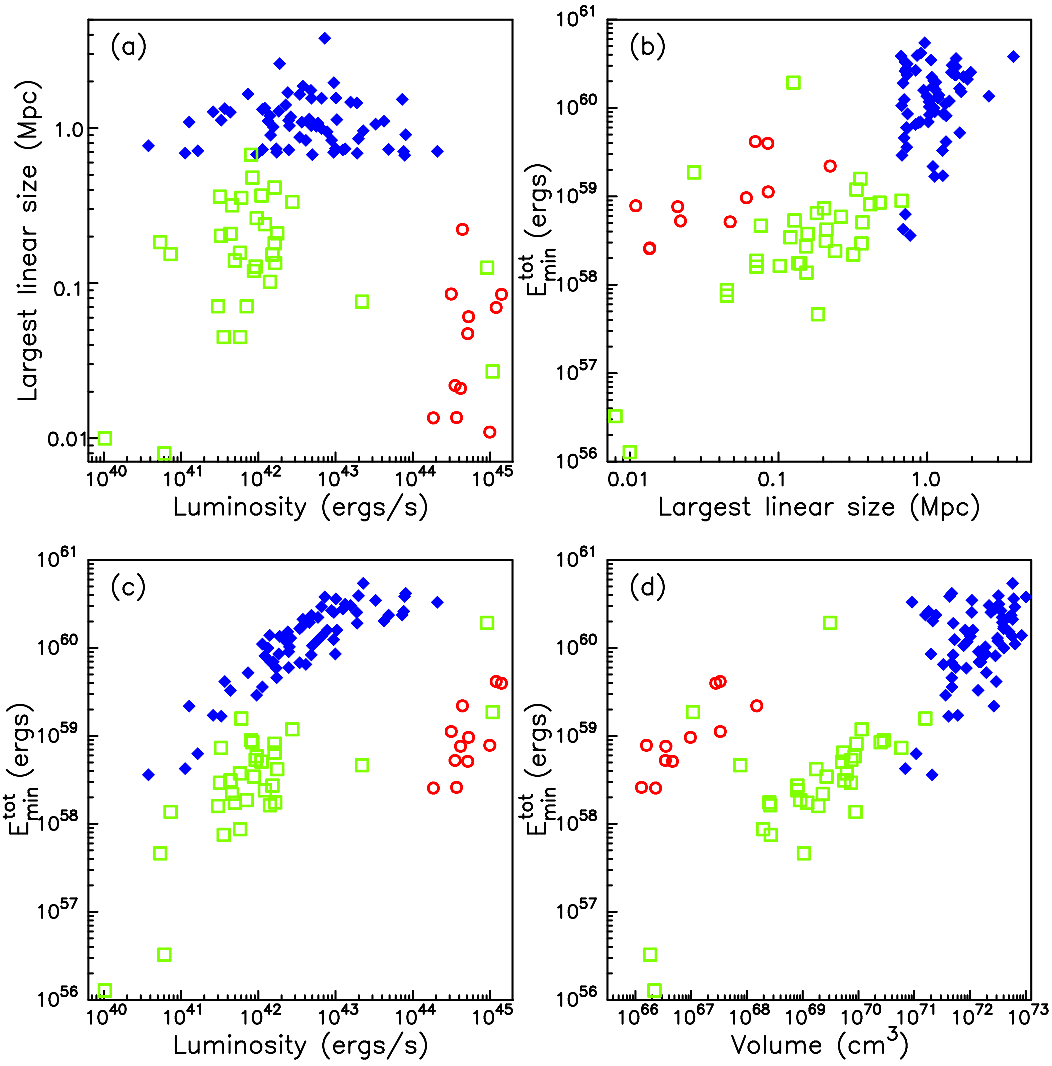

Fig. 1.— Comparisons of total energy content, source size, luminosity, and volume. GRG's are represented in the four panels by the blue diamond points, and cluster members by the open green squares. The data are taken from Kronberg Dufton, Li and Colgate (2001). Open red circles show, for comparison, an additional sample of the highest luminosity extended sources.

magnetic energy. This is different from other forms of energy release, such as the radiation from AGNs. The photon energy quickly loses its dynamical impact when the surrounding medium becomes optically thin, at which point it is carried away at $v = c$. The magnetic energy, by contrast, gets retained/confined within a much smaller volume (large compared to the "engine" size but much smaller than what the radiation will fill) for a significant fraction of cosmic time (Kronberg et al. 2001). Gopal-Krishna and Wiita (2001) and Furlanetto and Loeb (2001) have produced calculations to show that the global IGM filling factor of radio lobes is a significant fraction of unity. Similar IGM filling factors were estimated by Kronberg, Lesch and Hopp (1999), who calculated the minimum IGM magnetic field volume filling factor using only models of starburst halos for primeval galaxies beginning at z ∼10. They arrived a similar conclusion, namely that star-driven outflows by themselves would fill a significant fraction of the IGM filament volume by z ∼7.

An important consequence of outwardly transported magnetic fields is that they can remain *dynamically* important, perhaps for most of a Hubble time, because they will interact more strongly with the surrounding IGM than will the radiation. Wiita et al. (2001), and Gopal-Krishna Wiita & Osterman (2003) consider the triggering of star formation by AGN-powered radio jets and lobes and their consequences for the magnetization of the Universe.

III. WHY THE GRG'S ARE INTERESTING MAGNETO-PLASMA LABORATORIES

(a) Comparison of Particle Transport and Loss Times

The uniquely large dimensions of GRG's set limits on the ratio of the transport times of accelerated CR particles to their radiative loss times. A small number of the largest GRG's have been imaged near 10 GHz, where the CR electron radiative loss times are only a few million years. If they were transported, e.g. from an acceleration site in an outer hotspot ~ 500 kpc away is virtually impossible since highly supersonic or super-Alfvénic transport speeds would be required. This is also consistent with the absence of large scale intra-lobe shocks in the GRG's (Kronberg et al. 2004). It requires, as originally pointed out by Willis and Strom (1978) some *in situ* acceleration mechanism within the lobes must take place, consistent also with recent GRG spectral index analyses by Mack *et al.* (1998). Some global analyses of extragalactic radio sources, including those smaller than GRG's, have produced independent evidence that the lobe energization is more directly associated with the jet power or the AGN luminosity (Falcke, Malkan & Biermann 1995, Best et al. 1999). The physics of this energy transport remains to be clarified.

(b) Internal Faraday Rotation and Intra-Lobe Alfvén Speeds

Over the past 2 decades, a small number of FRII GRG's have been imaged in linear polarization over a large baseline in λ^2 with a large ratio of source size to angular RM resolution. The former permits a high accuracy in the RM determination, approaching $\sim$1 rad m^{-2}. This is close to the limit set by ionospheric effects. Inspection of the Faraday rotation law, with n_{TH}, B, and L normalized to the approximate dimensions and densities appropriate to GRG's (equation (2)), shows that such measurements on GRG's have the unique ability to probe thermal plasma densities in a régime so low that it is close to the ambient IGM gas density in the field.

Indeed, the GRG lobe-internal Faraday rotations are often very small, close to the limits of measurability at $\sim$1 rad m^{-2} as shown for example by Willis & Strom (1978), Strom & Willis (1980), Kronberg *et al.* 1986, Subrahmanyan *et al.* (1996).

$$\Delta\chi \;=\; 0.81\times10^{6}\frac{\Delta\lambda^2}{m^2}\cdot\frac{n_{th}}{cm^{-3}}\cdot\frac{B_{\|}}{\mu G}\cdot\frac{L}{Mpc}radians \quad (2)$$

Faraday RM limits near 1 rad m^{-2} combined with the large dimensions of GRG's and the lobe - internal magnetic fields of $1-5$ μG require thermal gas densities in the range 10^{-5} to 10^{-6} cm^{-3}. This, combined with the equipartition magnetic fields in the lobes, a few μG, implies that the lobe-internal Alfvén speeds are very high.

$$v_A^{lobe} \;\simeq\; 6300km/s\frac{B^{lobe}_{5\cdot10^{-6}}}{\sqrt{n^{lobe}_{th}{}_{\;3\cdot10^{-6}}}} \qquad (3)$$

A brief digression at this point is useful, to examine the scaling parameters for B_{lobe} that were assumed in Figure 1, since these also scale the Alfvén speed estimated above. We recall that n_{th}^{lobe} in equation (3) also scales by the estimate of B

$$B_{minE} = (6\pi)^{2/7}(1+k)^{2/7}\,\mathcal{C}^{2/7}(\phi V)^{-2/7}L^{2/7}\ \mathrm{G}, \quad (4)$$

Here I follow the terminology of Pacholczyk (1970), in which L denotes total synchrotron luminosity, and C is a slowly varying "constant". v_A^{lobe} in equation (5) therefore scales as $(1\text{+k})^{3/7}$. The energy content calculations of E_{min}^{tot} and B_{minE} in Figure 1 assumed a global relativistic proton/electron ratio $k = 100$ and $\phi = 0.1$, the former being close to that measured for Galactic cosmic rays. The estimated E_{min}^{tot} and B_{minE} will be reduced by a factor of ~ 14 and ~ 4, respectively, if $k = 0$ is used. Furthermore, using $\phi = 1$ will increase E_{min}^{tot} by a factor of 2.7 but decrease B_{minE} by 2.

The parameter k glosses over differing energy spectra of the CR protons and electrons, including their low - and high energy cutoff energies. Ideally, if we could quantify these as yet uncertain effects, we would calculate a k_{eff}, which could differ from k by a factor of a few due to these effects alone (See Pfommer & Enßlin 2004, Beck & Krause 2004 for a discussion of this and related issues). It is of course also subject to the various scaling factors discussed above.

The conclusion is nonetheless that the Alfvén speeds in the GRG's are very high, $\gtrsim 1000$ kms^{-1}. To the extent that some of the measured RM's are only *upper* limits near 1 rad m^{-2}, v_A in equation (3) is a *lower* limit.

This range of lobe-internal Alfvén speeds is comparable to the global expansion speed of the GRG lobes. Another important consequence of high v_A is that it is a key condition for making fast magnetic reconnection possible as a particle acceleration mechanism. Reconnection on these large scales is still poorly understood (see the contribution by Alex Lazarian in this volume), but the acceleration process must be very efficient, as required by the small energy "gap" between the GRG lobe internal energy content and the putative gravitational energy reservoir that energized the GRG's.

(c) Emissivity Contrast as a Test for Large Scale Conventional Shocks in the Lobe Plasma

We have considered the emissivity contrast within the lobes of GRG's in order to estimate the ratio of magnetic field strengths in the presumptive energy

Fig. 2.— VLA image of the Northern lobe of the GRG 2147+816 ($z = 0.146$) at 1.4 GHz. The figure is $1.1h_{75}^{-1}$Mpc on a side. (Adapted from Palma *et al.* 2000)

source and sink zones within the lobes. We use the giant source 2147+816 as an example.

Regions of enhanced surface brightness that are just visible in Figure 2 have volume emissivity variations (in units of erg $\mathrm{s}^{-1}\mathrm{Hz}^{-1}$) of a factor ~ 2 within most of the lobe volume. Similar emissivity contrasts are obtained for the southern lobe of this source (not shown). Generally, emissivity contrast ratios in GRG lobe-internal zones (excluding hotspots) are small, $\lesssim 5$. This mild contrast is not indicative of strong intra-lobe shocks.

If the shocks were strong and propagated perpendicular to the field, the emissivity contrast across the shock would be proportional to $(B_1/B_2)^2 \cdot (\gamma_1/\gamma_2)^2$, 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, $\lesssim \times 2$ (Vaino and Schlickeiser 1999), but an efficient acceleration of electrons requires large Alfvén wave scattering and a localization of the shock to $\Delta R \lesssim 10(\mathrm{c/v}_s)\ \mathrm{R}_{Le} \simeq 2.5 \times 10^{16}$ cm, where R_{Le} is the Larmor radius of the relativistic electrons, and hence a sharp jump in luminosity. This is not observed.

IV. 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, leads us to suggest intra-lobe collisionless reconnection as an attractive mechanism for direct magnetic to particle energy conversion (Kronberg *et al.* 2004).

Following Kronberg at al. (2004), we begin with the resistive MHD limit, even though we do not expect this régime to be valid for GRG lobes, given the low density and small resistivity of the latter. 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 ~ 1 kpc, and resistivity of $\eta \sim 10^4$ cm^2/s (using an electron temperature of 10^6 K), the diffusion time will be $L^2/\eta \sim 9\times10^{38}$ sec, 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 sheet-like current structures, and hence greatly reduce the diffusion times. In the Sweet-Parker reconnection picture, the current layer width is $\Delta_\eta \sim (\tau_A\eta)^{1/2}$, where $\tau_A \sim L/v_A$, the typical MHD time-scale, and $v_A \sim 6.3 \times 10^8 B_{5\cdot10^{-6}}/(n_{3\cdot10^{-6}})^{1/2}$ cm/s (see Sec.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 time scale is $\tau_{sp} \sim (\tau_A\tau_\eta)^{1/2} \sim 6 \times 10^{26}$ sec, but it is still much too long to be relevant to GRG lobes.

The physical conditions in the GRG lobes seem 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), $d_i = c/\omega_{pi} \sim 1.3 \times 10^{10} n_{3\cdot10^{-6}}^{-1/2}$ cm (where ω_{pi} is the ion plasma frequency) is significantly larger than the resistive Sweet-Parker layer width (see Kronberg *et al.* 2004 and references therein).

$$\Delta_{sp} \sim 1.5 \times 10^8\, L_{kpc}\, n_{3\cdot10^{-6}}^{1/4}\, \eta_4^{1/2}\, B_{5\cdot10^{-6}}^{-1/2}\, cm \qquad (5)$$

In this limit, reconnection is modified 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, Li *et al.* 2003), although its exact dependence on various parameters (especially d_i) is currently under debate (Shay et al. 1999; Wang et al. 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 GRG's. 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).

Another efficient particle acceleration process, by MHD turbulence/waves, has also been studied in some detail as a possible mechanism. A 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 gyro-resonance 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 make detailed comparisons with radio lobes at the present state of observational capability.

V. CONCLUDING REMARKS AND WIDER IMPLICATIONS FOR ALL EXTRAGALACTIC RADIO SOURCES

The similarity of GRG's 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 analyses discussed in this presentation put a focus on some new questions: One is, is there some new, efficient magnetic field to particle energy conversion mechanism that is not reconnection, but another as yet unrecognized particle acceleration mechanism. Other plasma processes have recently been suggested, for example in some special situations of plasma kinetics such as simulations by (Schlickeiser 2004) in which colliding electron clouds can generate electrostatic waves, which can lead to electron acceleration. Also collisionless shocks could also locally accelerate particles instantaneously in Weibel-like two stream instabilities that are produced in collisionless shocks as proposed by Hededal *et al.* (2004). In comparing these models with observations, the GRG's still impose constraints, not yet explored in detail, that are set by the low intra-lobe emissivity contrast on kpc scales and the high Alfvén speeds.

The ultimate reservoir of magnetic flux can only come from the gravitational infall energy, e.g. by an accretion disk dynamo (Colgate *et al.* 2001). The GRG's provide increasingly stringent tests on the combination of AGN-BH energy conversion processes, jet dissipation processes, and the particle spectrum of both relativistic protons and electrons in the lobes. As measurements improve, the narrow gap between the available gravitational energy reservoir and that injected into the GRG lobes merits close attention. For example we are close to limiting the CR proton energy component in the lobes – which may be forced by the GRG energy budget to be much smaller than our assumed $k = 100 \times E_e$. Definitive answers to questions like these are thinkable when our physical understanding is more complete and when future, better instrumentation and methods are sufficiently developed. The model of jet production near or within the BH accretion disk is a particularly important piece of physics to understand in detail. Independent optical and X-ray estimates of M_{BH} for the same GRG's that have been studied in detail count among the next observational advances needed.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Energy, the Laboratory Directed Research and Development Program and the Institute of Geophysics and Planetary Physics at Los Alamos National Laboratory, and by the Natural Sciences and Engineering Research Council of Canada. Special acknowledgement is also due to my colleagues Stirling Colgate, Hui Li and Quentin Dufton. I also thank Peter Biermann, Gopal Krishna, Alex Lazarian and Reinhard Schlickeiser for helpful discussions, and Phyllis Orbaugh for comments on the manuscript.

REFERENCES

Beck, R., & Krause M. 2004, A&A, in press

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, RMP, 56, 255

Best, P. N., Eales, S. A., Longair, M. S., Rawlings, S., & Röttgering, H. J. A. 1999, MNRAS, 303, 616

Burbidge, G. R. 1956, ApJ, 124, 416

Burbidge, G. R., & Burbidge, E. M. 1965, in The Structure and Evolution of Galaxies, Proc. 13^{th} (Solvay) Conf. on Physics, Bruxelles, New York: Interscience, Wiley, 137

Colgate, S. A., & Li, H. 1999, Astrophys. Space Sci., 264, 357

Colgate, S. A., & Li, H. 2000, in IAU Symp. No. 195 "Highly Energetic Physical Processes and Mechanisms for Emission from Astrophysical Plasmas", eds. P. C. H. Martens, S. Tsurta, M. A. Weber, p.255

Colgate, S. A., Li, H., and Pariev, V. 2001, *Physics of Plasmas*, 8, 2425

Falcke, H., Malkan, M. A., & Biermann, P. L. 1995, A&A, 298, 375

Fitzpatrick, R. 2003, Phys Plasmas, 10, 1702

Furlanetto, S. R., & Loeb, A. 2001, ApJ, 556, 619

Gopal-Krishna & Wiita, P. J. 2001 ApJ, 560, L115

Gopal Krishna, Wiita, P. J., & Osterman, 2003 ASP Conf ser. 290, 319

Hededal, C. B., Haugbolle, J., Fredreriksen, j. T., & Nordlund, Å. 2004, ApJ, in press

Hoyle, F., Fowler, W. A., Burbidge, G. R., & Burbidge E. M. 1964, ApJ, 139, 909

Kronberg, P. P., Lesch, H., & Hopp, U. 1999, ApJ, 511, 56

Kronberg, P. P., Colgate, S. A., Li, H., & Dufton, Q. W. 2004, ApJ, 604, L77

Kronberg, P. P., Dufton, Q. W., Li, H., & Colgate, S. A. 2001, ApJ, 560, 178

Lara, L., Mack, K.-H., Lacy, M., Klein, U., Cotton, W. D., Feretti, L., Giovannini, G., & Murgia, M. 2000, A&A, 356, 63

Li, H. et al. 2003, Phys Plasmas, 10, 2763

Mack, K.-H., Klein, U., O'Dea. C. P., Willis, A. G., and Sarapelli, L. 1998, A&A, 329, 431

Nodes, C., Birk, G. T., Lesch, H., and Schopper, R. 2003 Phys Plasmas, 10, 835

Pacholczyk, A. G. 1970, Radio Astrophysics (San Francisco: Freeman)

Palma, C., Bauer, F. E., Cotton, W. D., Bridle, A. H., Majewski, S. R., & Sarazin, C. L. 2000, AJ, 119, 2068

Pfrommer, C., & Enßlin T. E., 2004 MNRAS, 352, 76

Shay, M. A., & Drake, J. F. 1998, Geophys. Rev. Lett., 25, 3759

Shay, M. A., Drake, J. F., & Rogers, B. N. 1999, Geophys. Rev. Lett., 26, 2163

Schlickeiser, R. 2002, "Cosmic Ray Astrophysics" Springer Verlag

Schlickeiser, R. 2004, Physics Letters A, **330**, 384

Strom, R. G., and Willis, A. G. 1980, A&A, 85, 36

Subrahmanyan, R., Sarapelli, L., & Hunstead, R. W. 1996, MNRAS, 279, 257

Vaino, R., & Schlickeiser, R. 2001, A&A, 343, 303

Wang, X., Bhattacharjee, A., & Ma, Z. W. 2001, PRL, 87, 265003

Wiita, P. J., Gopal-Krishna, Kulkarni, V. K., & Osterman, A. 2001 Bull. AAS, 33, 1483

Willis, A. G., and Strom, R. G. 1978, A&A, 62, 375

Willis, A. G., Strom, R. G., Perley, R. A., & Bridle, A. H. 1982, in IAU Symp. 97, Extragalactic Radio Sources, ed. D. S. Heeschen & C. M. Wade (Dordrecht: Reidel), 141