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Low-Level Radio Emission from Radio Galaxies and Implications for the Large Scale Structure

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ABSTRACT

We present an update on our proposal that during the 'quasar era' ($1.5 \lesssim z \lesssim 3$), powerful radio galaxies could have played a major role in the enhanced global star-formation, and in the widespread magnetization and metal pollution of the universe. A key ingredient of this proposal is our estimate that the true cosmological evolution of the radio galaxy population is likely to be even steeper than what has been inferred from flux-limited samples of radio sources with redshift data, when an allowance is made for the inverse Compton losses on the cosmic microwave background which were much greater at higher redshifts. We thus estimate that a large fraction of the clumps of proto-galactic material within the cosmic web of filaments was probably impacted by the expanding lobes of radio galaxies during the quasar era. Some recently published observational evidence and simulations which provide support for this picture are pointed out. We also show that the inverse Compton x-ray emission from the population of radio galaxies during the quasar era, which we inferred to be largely missing from the derived radio luminosity function, is still only a small fraction of the observed soft x-ray background (XRB) and hence the limit imposed on this scenario by the XRB is not violated.

Key Words : galaxies: active — galaxies: formation — galaxies: jets — large-scale structure of universe — radio continuum: galaxies — x-rays: background

I. Introduction

(a) Some Key Observational Results

• Powerful radio galaxies (RGs) have a steep evolution of their comoving number density up to the 'quasar era', at $z \sim 1.5 - 3$ when $\rho \sim 100$–$1000\ \rho(z = 0)$; this is followed by a possible decline at $z > 3$, (e.g., Willott et al. 2001; Grimes et al. 2004). A similar trend for the quasar era is exhibited by powerful active galactic nuclei (AGN) seen at optical and soft x-ray bands (e.g., Silverman et al. 2004).

Interestingly, observations of distant galaxies indicate that the stellar birthrate, too, peaked at similarly high redshifts and has declined by about an order-of-magnitude, since $z \sim 1$ (e.g., Archibald et al. 2001). Likewise, from the spectra of a large sample of nearby SDSS galaxies, it has been deduced that the star formation activity in massive galaxies with $M > 10^{12} M_{\odot}$, which typically host powerful radio sources, peaked at $z > 2$ (Heavens et al. 2004). Also, recent highly complete deep multi-color surveys with secure redshifts have revealed an unexpectedly high abundance of massive galaxies at $z > 1$ (Glazebrook et al. 2004).

• The formation of massive galaxies could have been accelerated by even modest levels of metal enrichment (e.g., Scannapieco & Broadhurst 2001). Indeed, QSO absorption line studies have revealed substantial quantities of heavy elements to be present already by $z = 3 - 5$ (e.g., Songaila 2001; Pinchon et al. 2003). Not yet fully accepted claims for substantial enrichment have been made even for underdense regions of the universe (e.g., Ellison et al. 2000; Schaye et al. 2000).

• Faraday rotation measurements of quasars provide a nominal upper bound on intergalactic magnetic fields of $B_{\rm IGM} < 10^{-9}$G (e.g., Kronberg et al. 1999). But if the magnetic field is preferentially distributed in the cosmic sheets and filaments where the relevant intergalactic medium (IGM) is concentrated, then fields within those filaments ranging up to $\sim 10^{-6}$G are allowed by these observations (Ryu et al. 1998).

(b) Important, but Usually Ignored, Points

• Statistical properties of radio sources (Blundell et al. 1999, hereafter BRW), x-ray activity in AGN (Barger et al. 2001), SDSS optical studies of active galaxies (Miller et al. 2003) and black hole demographics arguments (e.g., Marconi et al. 2004), all indicate that an AGN activity lifetime of $\sim$ 500 Myr (also, McLure & Dunlop 2004). Even with this lifetime, around four generations of radio galaxies could have occurred within the quasar era, which lasted $\sim$ 2 Gyr.

• Due to severe adiabatic and inverse Compton losses during the quasar era, the RGs undergo a rapid fading, and most of them become excluded from the flux-limited complete samples of radio sources with spectroscopic redshifts. This is the "youth–redshift degeneracy" (e.g., BRW; also Gopal-Krishna, Wiita & Saripalli 1989) and the derived radio luminosity functions (RLFs) for powerful RGs need an upward correction for this effect. This correction factor is estimated to be very large, (~ 50 for the quasar era, §IIIa; Gopal-Krishna & Wiita 2001, 2003; hereafter GKW01, GKW03).

• Recent numerical models of the evolution of ΛCDM universes indicate that at $z \sim 0$, roughly 70% of baryons are within a cosmic web of filaments of gas and embedded galaxies and clusters that together occupy only about 10% of the volume of the universe (e.g., Cen & Ostriker 1999; Davé et al. 2001). But at $z \sim 2.5$ the growing network of filaments contained only about 20% of the baryonic mass, and a quite small fraction, $\eta \simeq 0.03$, of the total volume.

As discussed below in some detail, the above considerations, taken together, lead us to conclude that a very large portion of the cosmic filaments (hosting most of the proto-galactic clouds) was probably pervaded by radio lobes during the quasar epoch, and this may have important implications for the evolution of the universe (GKW01, GKW03; Gopal-Krishna, Wiita & Osterman 2003, hereafter GKWO).

II. A Larger Role for Radio Galaxies

Several interesting processes can follow from the inferred high volume coverage of the filaments (which is the *relevant universe* in which new galaxies will form) by the RG lobes at high redshifts:

1) Triggering of extensive star formation in a two- (or multi-)phase (clumpy) medium. (But see Rawlings & Jarvis 2004, who agree that RG lobes will penetrate much of the universe, but argue they may often shut off star formation by expelling gas from protoclusters; however, they implicitly assume a single phase medium.)

2) Seeding the IGM with the magnetic fields generated in the AGN.

3) Rapid spreading of metals produced in early stellar generations throughout the cosmic web, and possibly into the voids. This, in turn, would accelerate global star formation.

Below, we discuss these points quantitatively.

III. Cosmic Evolution of the RLF

We use the RLF derived by Willott et al. (2001) using the 3CRR, 6CE and 7CRS surveys. This is an excellent RLF because their combined sample has essentially complete redshift information (96%), offers fairly good coverage of the redshift-luminosity plane, and is practically free from orientation bias because of a low selection frequency (~ 0.15 GHz).

The work of Willott et al. (2001), as well as the very recent update by Grimes et al. (2004), shows that by $z \sim 2$, the co-moving density of powerful radio sources (FR II type with high excitation lines) was $2 - 3$ dex above the local RLF, and then changes little out to the beginning of the quasar era at $z \sim 3$. It perhaps declines at higher z but the data are still too sparse to allow a firm determination of the RLF at such high z's.

The weaker RGs (FR I and FR II with low excitation lines) are substantially more abundant at $z < 1$, but their densities are comparable around $z = 2$ and appear to fall quickly at higher redshift, though again statistics are very poor for $z \gtrsim 1.5$ for these weaker sources. Recently, Clewley & Jarvis (2004) have examined a larger sample of predominantly weaker radio sources with photometric redshifts from SDSS and concluded that there is little evolution of the FR I RLF for $z \lesssim 0.8$. Here we only consider the powerful sources (which for convenience we will refer to as FR II's) whose lobes are expected to grow substantially larger than those of the weaker ones; by doing so we arrive at a conservative estimate of the volume coverage of radio lobes.

(a) Correcting the RLF for the Youth–Redshift Degeneracy

Using a sophisticated semi-analytical model, based on the dynamical RG evolution model of Kaiser & Alexander (1997), BRW computed radio-power – projected linear size ($P-D$) tracks for FR II radio sources of different beam powers and redshifts. By employing the following assumptions they were able to fit these tracks to the data for the 3CRR and 7CRS samples:

1) The typical lifetime of nuclear activity, T, is around 5×10^8yr (§Ib above).

2) The probability distribution of beam power, Q_0, is $\mathcal{P}(Q_0) \propto Q_0^{-2.6}$ between appropriate upper and lower limits.

3) There is no good evidence for a cosmological evolution of the ambient medium through which the jets propagate (e.g., Mulchaey & Zabludoff 1998). At small z, x-ray observations have indicated a radial dependence of the ambient gas density to be:

$$n(r) \simeq n_0 \left(\frac{r}{a_0}\right)^{-\beta}, \tag{1}$$

with $n_0 = 1.0 \times 10^{-2}\mathrm{cm}^{-3}$, $a_0 = 10$ kpc, and $\beta = 1.5$ (Mulchaey & Zabludoff 1998).

The total linear size of the RG is given by

$$D(t) = 3.6 a_0 \left(\frac{t^3 Q_0}{a_0^5 m_p n_0}\right)^{1/(5-\beta)}. \tag{2}$$

The $P-D$ tracks published by BRW show that for most RGs, especially at $z > 2$, the active lifetime of the central engine, T, is much longer than the phase up to which they will remain above the flux limits of their samples [which they used to compute the RLF (z)]. Such missed RGs will nonetheless continue to be fed by the jets and will continue to grow to large dimensions (typically $D(T) > 1\,\mathrm{Mpc}$). From the $P-D$

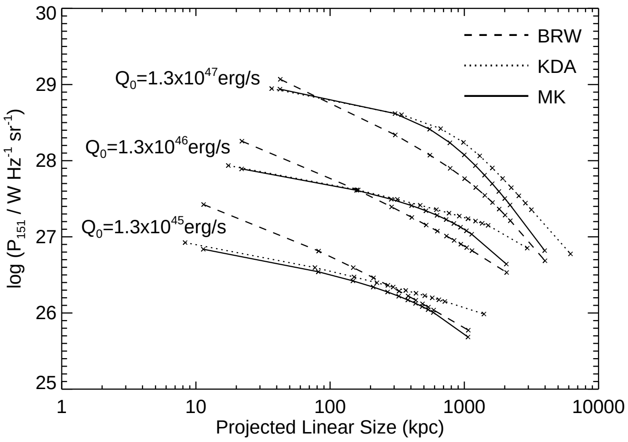

Fig. 1.— Radio power, linear size ($P-D$) tracks predicted by three models, BRW (*dashed*), KDA (*dotted*) and MK (*solid*), of three sources with beam powers as labeled in each case and at redshifts of $z = 2.0, 0.5$ and 0.2, *upper to lower*, respectively. Small crosses on the tracks indicate source ages of 1, 10, 20, ..., 100, 200 Myr.

tracks computed by BRW, we find the mean visibility duration, τ, to scale as $\tau \propto Q_0^{1/2}$ (GKW01). By convolving this with the estimated beam power function $\mathcal{P}(Q_0) \propto Q_0^{-2.6}$, we computed the mean value of the correction factor τ/T to be $\sim 1/50$ for powerful RGs (GKW01). Thus, in order to find the actual co-moving density of powerful radio sources, the observed RLF needs to be divided by this factor.

As part of a project to obtain more accurate values of this key correction factor, and to determine its sensitivity to various model parameters (Barai et al., in preparation), we have been comparing the results from three recent sophisticated RG evolution models: Kaiser et al. (1997; KDA), Blundell et al. (1999; BRW), and Manolakou & Kirk (2002; MK). While all of these models adopt the formula for linear size evolution given by Eq. (2), albeit with somewhat different ambient medium parameters in the case of KDA, they differ significantly in their treatment of the expansion of radio plasma from the hotspot acceleration region into the lobes; we refer the reader to the original papers for discussions of those details. We have computed $P-D$ tracks for all these RG models using their default parameters, and have displayed results corresponding to a wide range of FR II type beam powers in Figure 1. The key point is that all of these tracks show significant decays of P with D (or, of course, t), which become more pronounced at higher z as adiabatic and inverse Compton losses set in. The KDA and MK tracks are very similar at earlier times, but with increasing age the MK tracks become steeper. The BRW tracks start at higher values of P than do the others, but they fall more steeply, so that by late times their fluxes are usually lower. Details are in Barai et al. (in preparation).

Detection of such a putative, huge population of faded or fossil radio lobes of high-z RGs poses a large challenge for low frequency radio telescopes, such as *LOFAR* (which will need to be backed up by spectroscopy with large optical telescopes in order to get properly identified samples). This difficulty is underscored by the example of the radio 'bubbles' of the nearby radio galaxy M87, whose rather late discovery required exceptionally skillful analysis of the sensitive VLA observations (Owen et al. 2000).

An interesting possibility of detecting faded radio lobes of high-z RGs is exemplified by the $z = 1.786$ RG 3C 294. Its *CHANDRA* image has revealed extended x-ray lobes located *beyond* the radio lobes; These outer, presumably older, lobes appear to shine by emitting inverse Compton x-rays from relativistic electrons whose energy losses have pushed their synchrotron radio emission below the detection limit (Fabian et al. 2001).

An even more tantalizing possibility has emerged from the recent *SCUBA* sub-mm imaging of several high$-z$ RGs, revealing megaparsec-scale star forming regions significantly aligned with the radio jets of the respective host galaxy (Stevens et al. 2003).

(b) Corrected Number Density of RGs

As noted above, the densities of FR II type radio sources are 2–3 dex above the local RLF by $z \sim 2$, and their RLF varies little out to the beginning of the quasar era at $z \sim 3$ (e.g., Willott et al. 2001). The RLF for those redshifts is nearly flat for over a decade in radio power above $P_{151} \geq 10^{25.5}$ W Hz^{-1} sr^{-1}, which is where the FR II sources are most numerous.

Combining these results with the density correction factor discussed above, we find that at $z = 2.5$ the actual proper density of powerful radio sources energized for a duration T is

$$\rho \simeq 4 \times 10^{-5} \mathrm{Mpc}^{-3}\ (1+z)^3 T_5\ (\Delta \log P_{151})^{-1}, \quad (3)$$

where $T_5 \equiv T/(5 \times 10^8 \mathrm{y})$. To obtain a number density we next integrate this RLF over the roughly 1.25 dex of the peak of the RLF. Finally, we take into account the fact that several generations of RGs will be born and die within the ~ 2 Gyr duration of the quasar era.

This procedure leads to a total proper density, Φ, of intrinsically powerful radio sources: $\Phi = 7.7 \times 10^{-3}$ Mpc^{-3}, which is independent of the assumed value of T, and nearly independent of cosmological model parameters (GKW01).

IV. Fractional Volume Filled by Radio Lobes

(a) Average Lobe Volumes

The volume of each radio source can be approximated by (GKW01)

$$V(t) = \left(\frac{\pi D(t)^3}{4 R_T^2}\right); \quad (4)$$

$R_T \sim 5$ is the typical length to width ratio of a RG.

Integrating over the distribution of beam powers and using the growth rate, $D(t)$, for each source power given by our Eq. (1), Eq. (4) yields the mean volume of a powerful RG during the quasar era (GKW01)

$$\langle V(T)\rangle \simeq 2.1\, T_5^{18/7}\ \mathrm{Mpc}^3. \qquad (5)$$

(b) The Cosmic Web; the Relevant Universe

Recent numerical models of the evolution of ΛCDM universes indicate that at $z \sim 0$, a substantial majority of baryons are in a cosmic web of filaments of multiphase gas and embedded galaxies and clusters that together occupy merely $\sim 10\%$ of the volume of the universe (e.g., Cen & Ostriker 1999; Davé et al. 2001). But at $z \sim 2.5$ the growing network of filaments comprised only about 20% of the baryonic mass, and a quite small fraction, $\eta \simeq 0.03$, of the total volume.

The massive galaxies that harbor super-massive black holes large enough to energize RGs at early times would very likely have formed in the densest regions of those filaments, usually at their intersections. The radio lobes ejected from them would thus mostly remain within the filaments. Since it is in this relatively small, '*relevant* universe', where new galaxies formed out of the extant denser gas clumps, we really only need to be concerned with what fraction of this *relevant* universe was impacted and permeated by the radio lobes. In other words, we do not need to have the radio lobes filling substantial fractions of the *entire* universe for them to have a significant role in the development of the large-scale structure.

In our simplest model (GKW01) we found that the volume fraction of the relevant universe which radio lobes born during the quasar era cumulatively permeated was

$$\zeta = \Phi\ \langle V(5\times 10^8 \mathrm{yr})\rangle\ \left(\frac{1}{\eta}\right)\left(\frac{5}{R_T}\right)^2 \simeq 0.5, \qquad (6)$$

where we have conservatively ignored the volume filled by the lobes of the weaker FR I source population.

If the average age is $T_5 \simeq 1$, this is a substantial volume fraction of the relevant universe. But if $T_5 \simeq 0.2$ then it drops to only a few percent; even then RGs will have some important, albeit more localized, effects.

(c) Cosmologically Evolving Ambient Medium

Our earlier work assumed no cosmological evolution in the ambient gas density, following BRW (GKW01). This is reasonable as long as the galactic halo or ICM is the predominant confining gas, but at high enough z, $\rho_{\mathrm{IGM}} \propto (1+z)^3$ will dominate for large enough D ($\gtrsim$1 Mpc).

To test the robustness of the claim that a significant volume fraction of the relevant universe is indeed filled by radio lobes we have considered a simple implementation of cosmological evolution of the ambient

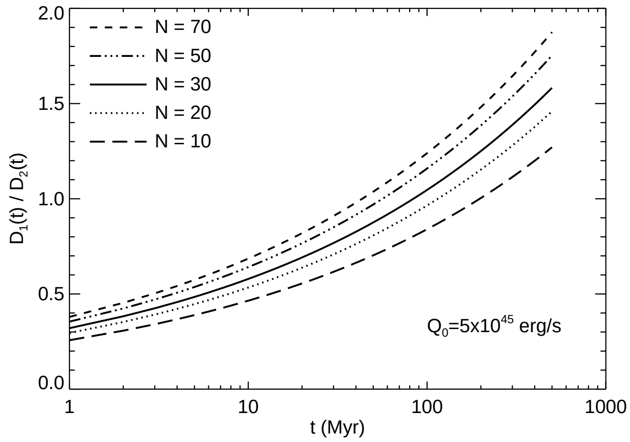

Fig. 2.— Ratios of source size for power-law ambient density (Case 1), to constant density (Case 2), as functions of source age for a typical FR II RG, with labeled Q_0, for several values of overdensity factor, N; $R = 5$ Mpc is assumed.

gas density (Barai et al. 2004). As Case 1, the standard power law ambient density (Eq. 1) is assumed. As an alternative model we consider a limiting Case 2; this assumes propagation into a constant density ambient medium where the total mass contained within a sphere of R Mpc is N times larger than that within the standard $z = 0$ halo with power-law density profile.

For $z = 2.5$, near the peak of the quasar era, $N = 30$ is reasonable (since the relevant volume fraction is 0.10 and about 50% of the mass is in the filaments at $z = 0$), but we have considered quite a wide range of this parameter. We find that at early times the power-law propagation distance (D_1) is roughly 1/3 of the constant density propagation distance (D_2), but for long-lived ($t > 10^8$ yr) sources $D_1 > D_2$ is still likely, as shown in Fig. 2. Figure 3 gives the volumes filled for a variety of jet powers under the Case 1 or Case 2 assumptions (V_1, V_2) for $z = 2.5$, and we see that for $T > 300$ Myr even weaker FR II type jets will fill volumes $\mathcal{O}(1\ \mathrm{Mpc}^3)$. So our key conclusion that much of the cosmic web was filled by radio lobes is not likely to be affected by any reasonable cosmological evolution of ambient medium properties (Barai et al. 2004).

V. Triggering Extensive Star Formation

The discovery of the alignment effect between extended UV continuum and radio lobe direction (e.g., McCarthy et al. 1987; Chambers et al. 1988) quickly led to calculations indicating that the supersonic jets and the associated expanding overpressured radio lobes can trigger star formation in a clumpy ambient medium (e.g., Rees 1989; Begelman & Cioffi 1989). Evidence for a young stellar component in the extended optical emission has come from the HST observations of high -z RGs (e.g., Dey et al. 1997; Best et al. 1996; Bicknell et al. 2000). This scenario is strongly supported by the recent hydrodynamical (and magnetohydrodynamical)

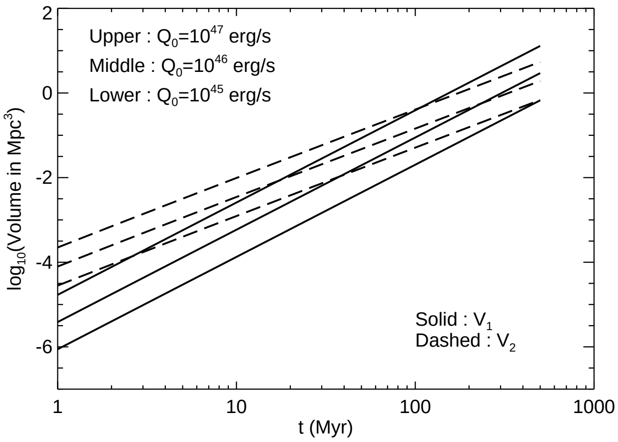

Fig. 3.— Total radio lobe volumes for the two ambient density models against source age for several beam powers as labeled. For Case 2, $N = 30$ and $R = 5$ Mpc are taken.

simulations which employ the cocoon of an extragalactic jet to drive a fast shock ($V \gtrsim 10^3$ km s^{-1}) into denser ambient clouds; this shock simultaneously displaces, compresses, and triggers fragmentation in those clouds (e.g., Mellema et al. 2002). The very important new result is that if radiative cooling within the clouds is taken into account, even quite small sized ($r_{\rm cloud} > 0.2$ pc) dense clouds cool and condense and can be followed a goodly way along their path to forming stars on a cooling time scale ($\sim 10^2$ yr) much shorter than the cloud collapse time ($\sim 10^6$ yr) (Mellema et al. 2002; Fragile et al. 2004a). If the lobe material contains significant magnetic fields (as is expected in our scenario, §VI) then this process is even more efficient (Fragile et al. 2004b).

Some well-known nearby examples of ongoing star formation within radio lobes are: Cen A (Oosterloo & Morganti 2004); Minkowski's object (van Breugel et al. 1985) and 3C 285 (van Breugel & Dey 1993). Additional recently discovered examples include the cooling flow cluster Abell 1795 (McNamara 2002) and the giant radio galaxy DA 240 (Peng et al. 2004).

At high redshifts ($z > 3$), some prominent examples of this phenomenon are the radio galaxy 4C 41.17 (Dey et al. 1997; Bicknell et al. 2000), and the more recently discovered set of six quasars in which the associated CO emission is extended along the radio lobes and kinematically as well as spatially offset from the host galaxy (Klamer et al. 2004).

To test if the lobes we have considered are indeed capable of triggering extensive star formation on larger scales we (GKW01; GKWO) used the models of Falle (1991) and BRW to find the lobe pressure decline with distance: $p_{\rm lobe} \propto t^{(-4-\beta)/(5-\beta)}$, but $D \propto t^{3/(5-\beta)}$, so $p_{\rm lobe} \propto D^{(-4-\beta)/3}$. For $\beta < 2$ (as observations indicate) the decline in the external pressure is slower, since $p_{\rm ext} \propto D^{-\beta}$. Therefore, $p_{\rm lobe}/p_{\rm ext} \propto D^{(-4+2\beta)/3}$, and for our usually assumed $\beta = 3/2$, $p_{\rm lobe}/p_{\rm ext} \propto D^{-1/3}$, a quite slow drop-off of overpressure with distance.

The values of Q_0, ρ_0 and a_0 appropriate for FR II sources produce overpressures at $D = 50$ kpc amounting to factors of 10^2–10^4, corresponding to Mach numbers of 10–100 for the bow shock. But, once the source expands to ~ 1 Mpc, even though the jets may remain significantly supersonic near the hotspots, the lobes may become transonic, producing only weak shocks in the transverse directions. On the other hand, it is expected that, through hierarchical clustering, a substantial fraction of the baryonic clumps will have gravitated to within a few hundred kpc of the central dominant host galaxy (e.g., Bode et al. 2001). These clumps are likely to be triggered into collapse by the passage of the strong bow-shock associated with relatively young, and hence strongly supersonically expanding, radio lobes (and thereafter continue to condense within the overpressured radio lobe).

VI. Radio Galaxies Spread Magnetic Fields

An exciting implication of this scenario is that RGs can inject a substantial amount of magnetic energy into the IGM at $z \sim 2-3$. As noted above, Faraday rotation measurements of quasars provide a nominal upper bound on intergalactic magnetic fields of $B_{\rm IGM} < 10^{-9}$G (e.g., Kronberg et al. 1999). But, for a more realistic scenario, Ryu et al. (1998) showed that these same measurements would translate into typical limits of up to 10^{-6}G, if the fields were mainly confined to the cosmic web and did not pervade the voids.

From the energy injected into the RGs we have found that energy densities $u \sim 10^{-16} - 10^{-15}$ erg cm^{-3} are typical of the fully expanded radio lobes. Assuming equipartition, this translates into magnetic fields of $\sim 10^{-8}$ Gauss pervading the cosmic web of filaments during the quasar era (GKW01, GKWO). It is worth recalling that fields of $\approx 1\mu$G are known to exist even within the megaparsec-scale lobes of giant RGs (e.g., Ishwara-Chandra & Saikia 1999; Kronberg et al. 2001), so our estimates seem quite reasonable.

Arguing independently from the consideration of energetics of giant RGs, Kronberg et al. (2001) have proposed that the plasma ejected by AGN would have sufficient magnetic energy to magnetize the universe to the level similar to its thermal energy density, provided the radio lobes can expand to fill up the IGM. From our analysis, this seems to be a real possibility (GKW01, GKWO). One may also recall an earlier suggestion by Kronberg et al. (1999), according to which a substantial fraction of the IGM even may have been permeated by magnetized stellar outflows from galaxies.

The tentative detection of magnetic fields in high-z galaxies (Oren & Wolfe 1995) poses considerable difficulties for the standard dynamo models, since amplification in galactic disks requires many dynamical times (e.g., Furlanetto & Loeb 2001). Thus, it may be less likely that sufficient magnetic fields can be generated from ordinary galaxies and then transported into the IGM. Advancing essentially orthogonal arguments to ours (GKW01), Furlanetto & Loeb (2001) suggested that the quasar population is capable of polluting $\sim$ 10% of the *entire* universe with magnetic fields at high redshifts. Their computation is based on the evolution of isotropized magnetized bubbles fed by quasars (mostly radio-quiet), and is motivated by very different considerations from our study.

The possibility of jets in radio galaxies magnetizing the IGM has in fact been considered for more than a decade, but the earlier investigations concluded that either only minute magnetization levels or insignificant volume coverage would be attained (e.g., Daly & Loeb 1990; Rees 1994). It is worth stressing that all three recent studies of this phenomenon, which approached the question from different datasets and using different methods, came to similar conclusions about the efficacy of RGs spreading magnetic fields through the cosmos (Furlanetto & Loeb 2001; Kronberg et al. 2001; GKW01).

VII. RGs as Vehicles for Metal Pollution

The issue of transporting metals from their production sites, namely the ISM of galaxies, to the Mpc-scale IGM with a mean density $< 10^{-4}$ as much (e.g., Gnedin 1998; Shchekinov 2002), and perhaps even farther into the voids (Theuns et al. 2002) is much debated. Lyman-break galaxies at $z > 3$ often have metalicities around 0.1 solar and damped Lyman-α clouds have metalicities $\sim 10^{-2.5}$ solar (e.g., Steidel et al. 1999; Pettini et al. 2001). The problem is further accentuated by the apparent detection of O VI absorption at $z \sim 2-3$ from under-dense regions $(\rho/\langle\rho\rangle < 1)$ representing the true IGM (Schaye et al. 2000).

Unfortunately, the obvious way to drive this transport, supernova explosions in star-forming galaxies, are found to fail by at least an order-of-magnitude to pollute the whole IGM to the metalicity levels observed within the available time (e.g., Gnedin & Ostriker 1997; Ferrara et al. 2000). A possible alternative is mergers of protogalaxies in the process of hierarchical clustering (Gnedin & Ostriker 1997; Gnedin 1998). Alternatively, we have suggested (GKW03) that the sweeping of the ISM of star-forming galaxies by the expanding giant radio lobes during the quasar era, or even earlier, can distribute metals both widely and rapidly.

The outflowing radio jets will drag along a significant fraction of the gas in their host galaxy, most of it compressed into a shell along the bow shock just outside the lobes (e.g., Hooda & Wiita 1998). This enriched gas can then be spread over distances exceeding 1 Mpc over the course of $\sim 10^8$ years. This picture is consistent with the ~ 2 Mpc clustering length for IGM metals recently found by Pinchon et al. (2003). Note that the morphology of the line-emitting gas surrounding the radio bubbles of M87 indeed suggests that much of this material has been excluded from the cocoon (Bicknell & Begelman 1996).

When this expanding gaseous shell interacts with denser clouds in the ICM or IGM, not only will extensive star formation be triggered, but it also will be accelerated since this star-forming region will have been contaminated with a fraction of the swept-up enriched gas. In that much of it is likely to have remained in the bow-shock region, the dilution will not be as severe as it would have been if the enriched gas were spread throughout the immense volume of the radio lobes. Moreover, individual AGN may go through several generations of nuclear activity that yield radio jets and lobes. The first such episode could trigger extensive star formation, or even new galaxy formation, in relatively nearby clouds. Any subsequent lobes impacting that newly formed galaxy a few hundred Myr later could sweep out most of the enriched gas it had already produced, thereby propagating these newer metals into yet more distant regions. These metals could then contribute to the metal enrichment of additional clouds whose collapse is triggered by this second round of activity.

VIII. An Observational Check: the X-ray Background

It is imperative to check if the combined inverse Compton (IC) losses from the electrons in all the putative non-detected RGs against the CMBR photons violates the stringent result that most of the soft x-ray background (XRB) can be accounted for in terms of emission from AGN cores (Miyaji et al. 2000; Hasinger 2002). This constraint is most severe around 1 keV where roughly 90% of the XRB has been resolved into discrete sources (e.g., Worsley et al. 2004). Above 5 keV, this fraction drops to roughly 50%, leaving much more room for the IC contributions from RG lobes.

Recently, Celotti & Fabian (2004) have determined the x-ray luminosity function (XLF) at 1 keV of RGs with z up to 2, by transforming the RLF of Willott et al. (2001), defined at 151 MHz. Radio emission at such low frequencies mainly arises from the extended lobes, and so the assumptions of roughly uniform and weak magnetic field used in their simple model of IC production seem realistic (e.g., Gopal-Krishna et al. 1989). Another reasonable simplifying assumption made by Celotti & Fabian is that the magnetic field and CMBR maintain a rough equipartition of energy density.

We have performed an integral over the XLF in a fashion similar to that GKW01 used for the RLF (also see Marconi et al. 2004), using the relation

$$I_{\nu=1\mathrm{keV}} \simeq \frac{T}{\tau} \int \int P_{\nu'} \rho(P_{\nu'}, z) \frac{(1+z)}{4\pi} \frac{dV(z)}{d^2(z)} d\log P_{\nu'} dz; \qquad (7)$$

here $\rho(P_{\nu'}, z)$ is the number density of x-ray emitters, $dV(z)$ is the cosmological volume element and $d(z)$ is the luminosity distance.

This yields a rough estimate of the total IC contribution from RGs between redshifts of 1.5 and 3 of 0.1 keV cm^{-2} s^{-1} sr^{-1} at 1 keV. To arrive at this estimate we assumed a conservative (in the sense of probably overpredicting) mean correction factor $T/\tau = 50$ for the number of missing RGs vs. those counted in the RLF derived from the low frequency samples (§IIIa). The measured XRB at 1 keV is 10 ± 1 keV cm^{-2} s^{-1} sr^{-1} (Urry 2004; Worsley et al. 2004). If 90% of it is identified with AGN, as claimed, that leaves $\sim$1 keV cm^{-2} s^{-1} sr^{-1} to be accounted for. We suggest that a non-negligible fraction of this remainder of the XRB could be contributed by the fading RGs at high z.

Recent simulations estimating the x-ray emission produced by fast jets propagating through a hot ICM show a modest increase in flux from shock heated gas (Zanni et al. 2003). But these same simulations also show that there is frequently a comparable reduction in flux due to the displacement of the hot ICM by the lobes, so that the combined effect of these two processes is unlikely to modify our above conclusion.

It is also quite conceivable that the IC X-rays from some faded RG lobes on the arcmin scale may be misidentified as AGN emission, since the ROSAT/PSPC beam is not narrow enough to resolve such high z RGs, particularly the fainter ones, as extended sources.

IX. Observational Challenges

For this RG expansion scenario to have substantial impact on extensive starbursts or galaxy formation it is necessary that the massive host galaxies for the FR II type RGs and quasars form quite rapidly. While this may not fully accord with the standard hierarchical structure formation paradigm, the recent discoveries of old, massive galaxies at high z lend support to our picture (Glazebrook et al. 2004; Cimatti et al. 2004).

We expect to see enhanced 3-point correlation functions for galaxies around RGs because the extended lobes advance in the directions of the jet, compressing gas clouds. Unfortunately, by the time much of the star formation triggered by the jets or lobes has become apparent, the radio lobes would have frequently faded away. Thus, testing this prediction is not straightforward. Nonetheless, it would be interesting to make a deep search for an excess of galaxies or starbursts in the vicinities of RGs in the directions of the jets, using large samples, particularly at high z.

Once deeper radio surveys (e.g., *FIRST, NVSS, WENSS*) are more fully identified optically, more examples of the older and faded RGs are likely to be found, (especially using *LOFAR* in coming years). Thus, the correction factor estimated here for the 'missing' RG population could be determined empirically.

X. Conclusions

The scenario presented here invokes a well known mechanism, the expansion of RG lobes, to explain the widespread magnetization in the cosmic web of baryonic material at high redshifts ($z \sim 2-3$), and for triggering a global star formation activity during that quasar era. This follows from our inference that much of the relevant volume of the universe (that is, the cosmic web which is home to the denser baryonic clumps, the protogalactic material) was probably impacted and permeated by those RG lobes. The basic reason for this is our estimate that the observed steep cosmic evolution of the RLF still leaves unaccounted a vast population of RGs existing during the quasar era, as their lobe radio fluxes would have rapidly faded to non-detectable levels, via severe IC losses; hence the observed RLF must be corrected for this youth-redshift degeneracy. Another likely consequence of these expanding radio lobes would be a substantial metal pollution of the IGM through much of the cosmic web at high z.

We have argued that the inverse Compton scattering of the CMBR by the electrons in the faded lobes of these RGs can cumulatively contribute just a tiny fraction (of order 1%) of the observed x-ray background, even at 1 keV. Thus, this population of high-z RGs, suspected to be missing from the known RLF, does not violate the XRB constraint.

We have discussed a large body of recent observations, as well as several new simulations of lobe interactions with gas clouds, which provide substantial additional support for this scenario.

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