Radio Galaxies and the Magnetization of the IGM

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Abstract.
Observed radio galaxies had a much higher comoving density during the ‘quasar era’, at \( z \sim 2 \) – 3, but these sources are only detectable for small fractions of their active lifetimes at such high \( z \) due to expansion losses and increased inverse Compton losses against the cosmic microwave background. Using recent models for the evolution of the size and luminosity of powerful double radio sources, as well as ΛCDM simulations of the cosmic web of baryonic material, we argue that during the quasar era a high volume fraction of this web was occupied by the lobes of double radio sources. They could have seeded the IGM with an average magnetic field approaching \( 10^{-8} \)G. Further, these advancing overpressured lobes could compress the denser interstellar gas clouds of the galaxies engulfed by them and thus trigger starbursts. This can probably account for much of the intense star-formation activity witnessed beyond \( z \sim 1.5 \). Also, the sweeping up of the ISM of the gas-rich galaxies by the rapidly advancing radio lobes may well be responsible for the widespread metal pollution of the IGM and proto-galaxies at high redshifts.

1. Introduction

The comoving space density of powerful radio galaxies (RGs) has declined between 100 and 1000 times from redshifts of 2–3 to the present epoch (e.g. Willott et al. 2001). The star formation rate also peaked in roughly the same epoch, and has declined substantially since then (e.g. Archibald et al. 2001; Chary & Elbaz 2001). Severe adiabatic and inverse Compton losses in radio lobes mean that most old and large radio galaxies are very difficult to detect in surveys and only the youngest can be seen at high redshifts (e.g. Blundell et al. 1999, hereafter BRW). Simulations of the growth of structures in cosmological models have indicated that most of the matter that will form galaxies by the current epoch was in the form of filaments that filled only a small portion of the universe at those redshifts (e.g. Cen & Ostriker 1999). Together, these facts lead us to conclude that the formation of many of those galaxies may have been triggered or accelerated by overpressured radio lobes, which probably filled a substantial
portion of the cosmic filaments then. Preliminary discussions of these ideas are in Gopal-Krishna & Wiita (2001, hereafter GKW) and Gopal-Krishna, Wiita & Osterman (2003); more extensive calculations are underway (Osterman et al., in preparation). These extremely extended radio lobes are very likely to be responsible for seeding much of the intergalactic medium (IGM) with magnetic fields (GKW; Kronberg et al. 2001; Furlanetto & Loeb 2001). In addition, they may make significant contributions to the spreading of metals widely through the IGM and into protogalaxies.

2. Radio luminosity function – RLF

In general, RLF studies are plagued by uncertainties resulting from incomplete knowledge of the redshifts of the radio sources; however, results based upon the 3CRR, 6CE and 7CRS surveys of different flux limits have the advantage of having 96% of their redshifts known (Willott et al. 2001). In addition, their selection at low frequencies minimizes the bias due to relativistic beaming.

Powerful (FR II type) radio sources are nearly 3 dex above the local RLF by \(z \approx 2\), and their RLF varies little out to the beginning of the quasar era at \(z \sim 3\), while it appears to decline at higher \(z\) (Willott et al. 2001). Furthermore, 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 correction factor discussed in the following section, we find that at \(z = 2.5\) the actual proper density of powerful radio sources lasting for an interval \(T\) is

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

where \(T_5 \equiv T/(5 \times 10^8\) y). We then integrate 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 \(\sim 2\) Gyr duration of the quasar era. This leads us to the total proper density, \(\Phi\), of intrinsically powerful radio sources:

\[
\Phi = 7.7 \times 10^{-3} \ \text{Mpc}^{-3},
\]

which is independent of the assumed value of \(T\), and nearly independent of cosmological model parameters (see GKW for details).

3. Restricted visibility of radio galaxies

Various recent models of RG evolution (Kaiser et al. 1997; BRW; Manolakou & Kirk 2002) agree that radio flux declines dramatically with increasing source size (adiabatic losses) and with \(z\) (inverse Compton losses off the more intense cosmic background radiation). Theoretical distributions of RG powers, sizes, redshifts and spectral indices can be nicely matched by models that require most RGs to remain active for \(T \simeq 5 \times 10^8\) y (see, also, Wang et al. 2002) and to have a distribution of jet powers \((Q_0)\) that goes as \(\sim Q_0^{-2.6}\) (BRW). X-ray observations indicate that the density of the matter through which the jets propagate declines with distance roughly as \(n(r) = n_0(r/a_0)^{-\beta}\), with \(n_0 = 1.0 \times 10^{-2}\) cm\(^{-3}\), \(a_0 = 10\) kpc, and \(\beta = 1.5\). This leads to the total linear size of the RG being given by

\[
D(t) = 3.6a_0 \left(\frac{t^3 Q_0}{a_0^4 n_0}ight)^{1/(5-\beta)}.
\]
We find that in most RGs, particularly those at $z > 2$, the central engines remain active for much longer times than those galaxies are detected in flux limited surveys, and therefore they should grow to very large linear sizes (typically $D(T) > 1 \text{Mpc}$), although detecting them would require extremely sensitive radio surveys with redshifts. Using the models of BRW we find that the visibility time, $\tau \propto Q_0^{1/2}$, and to properly estimate the actual number of RGs from those detectable in flux-limited surveys, one must multiply by a correction factor $(T/\tau)$ of roughly 50 for powerful RGs during the quasar era (GKW). We are currently investigating how this factor depends on the parameters defining the BRW and Manolakou & Kirk (2002) radio source evolution models.

The likelihood of ‘missing’ faded radio lobes resulting from past activity is underscored by the sophistication needed for detecting even the giant outer lobes of the nearby radio galaxy M87 (Owen et al. 2000). ‘Compact double’ radio sources, several of which are found to have faint, diffuse radio lobes (e.g. Schoenmakers et al. 1999; Baum et al. 1990; Stanghellini et al. 1990), example of this difficulty. Associating these faint structures with their true core, or even with each other, would have been extremely difficult had these sources been imaged only a few hundred years ago when their present central radio components were not yet born. Another indication of the weakening of radio lobes towards higher redshifts is the apparent decrease in the radio-loud fraction of QSOs with redshift, as recently inferred by Impey & Petry (2001).

4. Radio lobes pervade the relevant universe

Recent numerical models of the evolution of ΛCDM universes indicate that at $z \sim 0$, roughly 70% of baryons are in a cosmic web of filaments of warm-hot 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 comprised only about 20% of the baryonic mass, and a quite small fraction, $\eta \simeq 0.03$, of the total volume.

It is certainly to be expected that the massive galaxies that harbor supermassive black holes large enough to form RGs at early times would have typically formed in the densest portions of those filaments, usually at their intersections. The radio lobes ejected from them would mostly remain within the filaments, and since it is in this relatively small, ‘relevant universe’, that new galaxies formed out of denser gas clumps, we really only need to be concerned with what fraction of this relevant universe the lobes permeated. We find that the mean volume of a radio source is $\langle V(T) \rangle \simeq 2.17 T_5^{18/7} \text{Mpc}^3$, and thus, the volume fraction of the relevant universe which radio lobes born during the quasar era cumulatively swept through is (GKW)

$$\zeta = \Phi \langle V(5 \times 10^8 \text{yr}) \rangle (0.03/\eta)(5/R_T)^2 \simeq 0.5,$$

where $R_T \sim 5$ is the typical length to width ratio of an RG; we have conservatively ignored the volume filled by the lobes of the weaker FR I source population, which also evolves rapidly (Snellen & Best 2001). The energy density injected by the lobes into the filaments is $u \simeq 2 \times 10^{-16} \text{Jm}^{-3}$ for those same canonical parameters. Because $\langle V(T) \rangle$ is a sensitive function of $T$, if the typical RG lifetime is $< 10^8 \text{yr}$, then $\zeta < 0.01$ and $u < 9 \times 10^{-18} \text{Jm}^{-3}$ (GKW).
5. Extensive star formation at high-$z$ is triggered by radio lobes

The discovery of the alignment effect between extended optical emission lines and radio lobe directions (e.g. McCarthy et al. 1987; Chambers et al. 1987) quickly led to calculations (e.g. Begelman & Cioffi 1989; Rees 1989) that indicated that star formation could be triggered by these expanding overpressured lobes. This extended optical emission is produced to some degree by direct ionization by the AGN and perhaps by shock heating, but there is often a significant component best explained as due to radiation from young stars. Recent hydrodynamical simulations including cooling (Mellema et al. 2002) confirm that star formation is likely to occur through cloud fragmentation, cooling and compression. HST observations of high-$z$ RGs and associated optical emission (e.g. Best et al. 1996; Bicknell et al. 2000) support this scenario.

To inquire if these lobes are capable of triggering extensive star formation on larger scales we (GKW) used the models of Falle (1991) and BRW to find that: \( p_{\text{lobe}} \propto t^{(-4-\beta)/(5-\beta)} \), but \( D \propto t^{3/(5-\beta)} \), so \( p_{\text{lobe}} \propto D^{(-4-\beta)/3} \). The decline in the external pressure is slower, \( p_{\text{ext}} \propto D^{-\beta} \), so \( p_{\text{lobe}}/p_{\text{ext}} \propto D^{(-4+2\beta)/3} \). For \( \beta = 3/2 \), \( p_{\text{lobe}}/p_{\text{ext}} \propto D^{-1/3} \). The values of \( Q_0 \), \( \rho_0 \) 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.

Thus, these powerful RGs create lobes which typically remain rapidly expanding, with overpressures of factors > 10 (and Mach numbers above 3) out to distances of well over 1 Mpc. Supersonic expansion into a two-phase circumgalactic medium will compress many of the cooler gas clumps, rapidly reducing the Jeans mass by factors of 10–100 and thereby triggering starbursts (Rees 1989; Mellema et al. 2002). The clouds will then remain in substantially overpressured lobes of low density, which can continue to produce extensive starbursts.

Related situations have been considered by Evrard (1991) for the infall of clouds into the hot ICM of clusters of galaxies, and by Jog & Das (1992; 1996) for the infall of a captured galaxy into the ISM of the captor galaxy. The latter authors examined what happens to molecular clouds in a captured galaxy as they enter into the central portions of a larger galaxy where higher pressure gas is awaiting them. Under many reasonable circumstances these clouds undergo radiative shock compression; when the growth time for gravitational instabilities in the shocked outer shell of the cloud becomes smaller than the shock’s crossing time (as it usually will), the fragmenting shell should produce many stars in a rather efficient fashion (Jog & Das 1992; 1996).

It is thus fair to argue that many clumps of gas sitting in localized dark matter potential wells may yield extensive starbursts, or even entire galaxies, after being enveloped by an expanding radio lobe. Hence, we predict an enhanced 2-point correlation function (and an even more enhanced 3-point correlation function) between radio galaxies and newly formed galaxies during the quasar era. Unfortunately, these correlations will be extremely difficult to measure, since the relevant radio sources will have typically faded below detectability even while their expanding lobes continue to have a major impact on the surrounding medium at substantial distances from the AGN.
6. Radio lobes magnetize the IGM

One exciting implication of this scenario is that RGs can inject a substantial amount of magnetic energy into the IGM at $z \sim 2 - 3$. Faraday rotation measurements of quasars provide a nominal upper bound on intergalactic magnetic fields of $B_{\text{IGM}} < 10^{-9} \text{G}$ (e.g. Kronberg et al. 1999). However, if the magnetic field is preferentially distributed in the cosmic filaments where the relevant IGM is also concentrated, then fields within those filaments ranging up to $\sim 10^{-6} \text{G}$ are allowed by these observations (Ryu et al. 1998). Kronberg et al. (1999) have argued that a substantial fraction of the IGM may have been permeated by magnetized outflows from stars in galaxies. The tentative detection of magnetic fields in high-$z$ galaxies (e.g. Oren & Wolfe 1995) poses considerable difficulties for standard dynamo models, since amplification in galactic disks requires many dynamical times (e.g. Furlanetto & Loeb 2001).

The possibility of jets in radio galaxies magnetizing the IGM has been examined previously, but those earlier investigations concluded that either only minute magnetization levels or insignificant volume coverage would be attained (e.g. Daly & Loeb 1990; Rees 1994). In GKW we showed that during the quasar era, the permeation of the IGM by the expanded lobes of radio galaxies could have seeded the IGM with an average magnetic fields of $\approx 10^{-8} \text{G}$ (recall that fields of $\approx 1 \mu \text{G}$ exist even inside the lobes of megaparsec RGs, e.g., Kronberg et al. 2001; Ishwara-Chandra & Saikia 1999), which matches the IGM field strengths inferred by Ryu et al. (1998) and by Furlanetto & Loeb (2001). The latter authors, advancing essentially orthogonal arguments to ours (GKW), based on the evolution of isotropized magnetized bubbles fed by quasars, have argued that the quasar population is capable of polluting $\sim 10\%$ of the entire space with magnetic fields. From independent arguments, Kronberg et al. (2001) have concluded that the accretion energy released by radio-loud QSOs at $z \sim 2 - 3$ is adequate to magnetize the IGM to the level of its thermal energy, provided the radio lobes can expand to fill up the IGM.

7. Enriching new galaxies with metals

Several authors have discussed the issue of ‘metal transport’ from their production sites, namely the ISM of galaxies, to the Mpc-scale IGM with a mean density $< 10^{-4}$ as high (e.g. Gnedin 1998; Shchekinov 2002), and even farther into the voids (Theuns et al. 2002). Lyman-break galaxies at $z > 3$ often have metallicities around 0.1 solar and damped Lyman-$\alpha$ clouds have metallicities $\sim 10^{-2.5}$ solar (e.g. Steidel et al. 1999; Pettini et al. 2001). The difficulty is underscored further with the recent detection of OVI absorption at $z \sim 2 - 3$ from under-dense regions ($\rho/\langle \rho \rangle < 1$) representing the true IGM (Schaye et al. 2000). Supernova explosions in star-forming galaxies are found to fail by at least an order-of-magnitude to pollute the whole IGM to the metallicity levels observed within the available time (e.g. Gnedin & Ostriker 1997; Ferrara et al. 2000). A possible alternative could be mergers of protogalaxies in the process of hierarchical clustering (Gnedin & Ostriker 1997; Gnedin 1998).

In accordance with our picture of a radio lobe-filled universe at high-$z$, we propose here a potentially attractive new mechanism for large-scale metal trans-
port: namely, the sweeping of the ISM of star-forming galaxies by the expanding giant radio lobes during the quasar era, or even earlier. The outflowing radio jets will drag along a significant fraction of the gas in their host galaxy out with them, most of it compressed into a shell along the bow shock outside the lobes, as illustrated by numerical simulations of jets leaving a galaxy’s ISM (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. Eventually, substantial portions of this gas can be mixed into the radio lobe, but these Rayleigh-Taylor and Kelvin-Helmholtz types of instabilities grow relatively slowly under these conditions, and so it seems that most of the enriched gas will comprise part of a shell that will also include swept up ICM as the lobe continues to expand. Note that the morphology of the line-emitting gas surrounding the radio bubbles of M87 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 this star-forming region will have incorporated a fraction of this 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. An advantage of this mechanism is that heating of the denser gas is less of a problem than when the metals are conveyed by supernova driven winds.

In addition to the radio lobes contributing to “metalization” by dragging along some of the enriched gas from their host galaxy, it is worth considering their impact on other young galaxies which they may envelop. If these young galaxies have a multi-phase medium and are not too dissimilar from local galaxies in this regard, then ram pressure stripping (Gunn & Gott 1972) produced by these lobes can be important. Even if the average density of the ICM has fallen as low as $10^{-5}$ cm$^{-3}$ at $r = 1$ Mpc, as expected for $\beta = 1.5$, the density of the shell will typically be compressed to several times this value. With the expansion velocity of the lobes remaining roughly $10^4$ km s$^{-1}$, the ram pressure, $P_{\text{ram}} \simeq \rho v^2 > 3 \times 10^{-11}$ dyn cm$^{-2}$. This pressure is adequate to remove most of the gas from a typical spiral galaxy (with $v_{\text{rot}} \simeq 200$ km s$^{-1}$ and $R \simeq 10$ kpc; see Abadi et al. 1999; Fujita 2001), and is likely to be even more effective in stripping the diffuse gas from smaller, recently forming galaxies at $z > 2$, despite our lack of knowledge of the details of the properties of that ISM. However, colder, denser clumps of gas within those galaxies will probably not be pushed out (cf. Mellema et al. 2002); rather, the arriving lobe may trigger yet more star formation in those regions.

Finally, we note that 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 hitting 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, in the fashion discussed in the last paragraph. These metals could, in turn, contribute to the seeding of additional clouds which are triggered to collapse by this second (or subsequent) period of activity.
8. Conclusions

Even though the local universe is very sparsely populated by powerful radio sources, several large factors conspire to make them remarkably important for galaxy formation during the quasar era. First, their comoving density was roughly 1000 times higher at $\sim 2 < z < \sim 3$. Second, only a small fraction (roughly two percent) of the powerful sources present during that period are detected in the surveys used to produce the RLFs, because of severe inverse Compton and adiabatic losses; these unseen, old radio lobes fill very large volumes. Third, the fraction of the volume of the universe occupied by the material during the quasar epoch that would finally condense into clusters of galaxies was only a few percent, so these lobes only had to permeate this ‘relevant universe’ rather than the entire universe. In that the best models of RG evolution indicate that the lobes are overpressured and supersonically expanding into the relevant universe, the scenario that has many massive starbursts, and even many galaxies, formed in this fashion at high redshifts, is quite plausible.

Another key result is that radio galaxies were likely to have been capable of seeding the IGM with magnetic fields of the appropriate strength. It is very encouraging that two other independent and quite different arguments lead to similar conclusions (Furlanetto & Loeb 2001; Kronberg et al. 2001). Also, the sweeping up of the ISM of the galaxies and star-forming clouds by the expanding lobes of RGs suggests a natural way to spread metals produced in the first stellar generations over large volumes. Detailed investigations of many aspects of this scenario are clearly warranted.

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