Radio Lobes, Extensive Star Formation and the Dispersion of Magnetic Fields and Metals

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Introduction

The dramatic rise in both star formation rate and quasar densities back to $z > 1$ motivates investigation of a possible causal connection.

Three factors combine to make it likely that radio lobes affected a large fraction of the cosmic web in which galaxies were forming at redshifts between 1.5 and 3 (the "quasar era").

1. Most powerful radio galaxies (RGs) are only detectable for a short fraction of their total lifetimes, so the volumes filled by old, invisible, lobes are extremely large.
2. The co-moving density of detected RGs was roughly 1000 times higher at $2 < z < 3$ than at $z = 0$.
3. These RG lobes need only fill much of the "relevant universe", the denser portion of the filamentary structures containing material that is forming galaxies, not the entire universe.

Key Results

Long lived radio lobes probably penetrated a substantial fraction of the cosmic web during the quasar era.

These lobes were sufficiently overpressured so as to induce very substantial star formation, and even galaxy formation, over cosmologically interesting volumes (Gopal-Krishna and Wiita 2001 -- GKW01).

The RG lobes could fill much of the IGM with magnetic fields of appropriate strength ($\sim 10^{-8}$ G; GKW01, Gopal-Krishna, Wiita & Osterman 2003). Independent arguments based on different approaches yield very similar conclusions (Kronberg et al. 2001; Furlanetto and Loeb 2001).

The metals swept up by lobes from host galaxies and from earlier generations of triggered star formation could enrich both the IGM and galaxies forming later (Gopal-Krishna and Wiita 2003).

Radio Galaxies Suffer Restricted Visibility

All recent models of RG evolution (Kaiser et al. 1997; Blundell et al. 1999 -- BRW; Manolakou and Kirk 2002) agree that radio flux declines with: increasing source size because of adiabatic losses, and with redshift because of inverse Compton losses off the CMB.

A jet of power Q_0, propagating through a declining power-law density distribution (**Case 1**), $n(r)$; has total linear size D; with a_0 the core radius (10 kpc), n_0 the central density (0.01 cm^{-3}), and $\beta = 1.5$. (Fig. 1, Case 1.)

$$n(r) = n_0 \left(\frac{r}{a_0}\right)^{-\beta} \qquad D(t) = 3.6 a_0 \left(\frac{t^3 Q_0}{a_0^5 \rho_0}\right)^{\frac{1}{(5-\beta)}}$$

Many properties of low frequency radio surveys (3C and 7C) can be fit if typical RG lifetimes are long (up to 500 Myr) and if the jet power distribution goes as $Q_0^{-2.6}$ (BRW).

For RGs at $z > 2$, most observable lifetimes (τ) are only a few Myr, even if the jet lifetimes (T) are 100s of Myr.

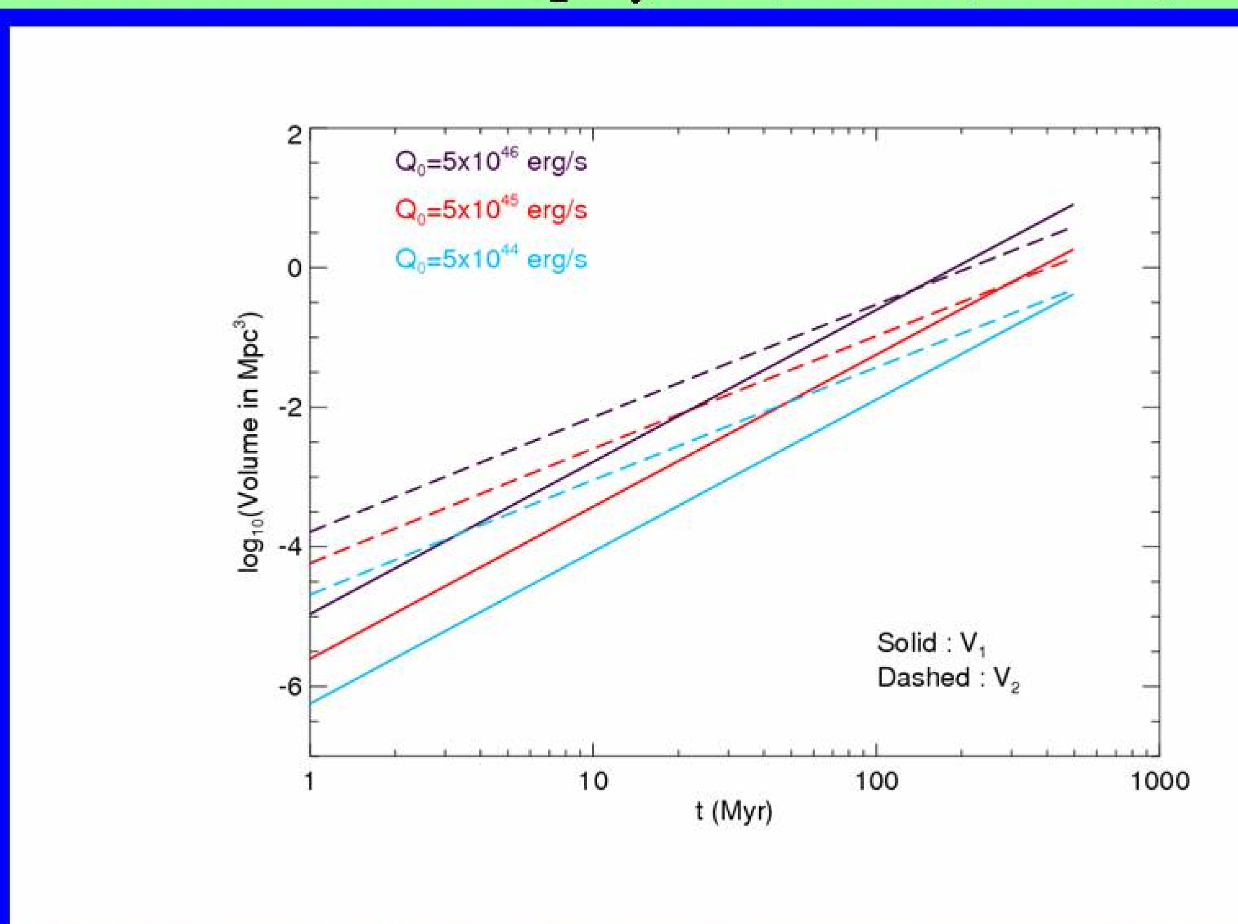

Fig 1. – Volumes filled by Radio Lobes as functions of beam power Q_0, for the powerlaw model (Case 1), and the dense IGM model (Case 2, $\boldsymbol{n}$=30, R=5Mpc).

Radio Luminosity Functions

Powerful (FR II) RGs were nearly 1000 times more common between redshifts of 2 and 3 (Willott et al. 2001).

This RLF is nearly flat for about a decade in radio power above $P_{151} > 10^{25.5}$ W Hz^{-1} sr^{-1}, where FR II sources are most numerous.

With the correction factor ($T/\tau \sim 50$) we find at $z = 2.5$ the proper density of of powerful RGs living for T is

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

with $T_5 = T/(5 \times 10^8$ yr).

One then integrates over the peak of the RLF and must take into account several generations of RGs during the 2 Gyr length of the quasar era.

We find (GKW01) the total proper density of intrinsically powerful RGs is about: $\Phi = 8 \times 10^{-3}$ Mpc^{-3}

Radio Lobes Penetrate Much of the Relevant Universe

During the quasar era, only a small fraction of the baryons had yet settled into the proto-galactic cosmic web: roughly 10% of the mass and **3%** of the volume (Cen & Ostriker 1999).

Thus RG lobes have a big impact if they pervade only this filamentary "relevant universe", with volume fraction

$$\eta \sim 0.03.$$

Assuming BRW parameters and integrating over beam power and z, we find the fraction of the relevant universe filled during the quasar era by radio lobes:

$$\zeta = 2.1 \Phi\ T_5^{18/7}\ \eta^{-1}\ (5/R_T)^2, \text{ is} > 0.1$$

if T > 250 Myr and typical ratios of R_T (RG length to width ~ 5) are assumed (Fig. 2).

Denser Ambient Media at High Redshift

Early work assumed no cosmological evolution in the confining gas density (BRW, GKW01).

This is reasonable as long as the galactic halo or ICM is the predominant confining gas, but at high z, $\rho_{IGM} \sim (1+z)^3$ will dominate for D > 1 Mpc.

A limiting **Case 2**: propagation into a constant density medium where the total mass contained within a sphere of R Mpc is $\boldsymbol{n}$ times larger than that within the standard z = 0 extended halo.

For z = 2.5, $\boldsymbol{n}$ = 30 is reasonable (since η = 0.10 and about 50 % of the mass is in the filaments at z = 0).

At early times the power-law propagation distance (D_1) is roughly 1/3 of the constant density distance (D_2), but for long lived sources $D_1 > D_2$ is still likely (Fig. 1 and Fig. **3**, evaluated for R = 5 Mpc).

So our key conclusion that much of the cosmic web is filled by radio lobes is not likely to be affected by any reasonable cosmological evolution of ambient medium properties.

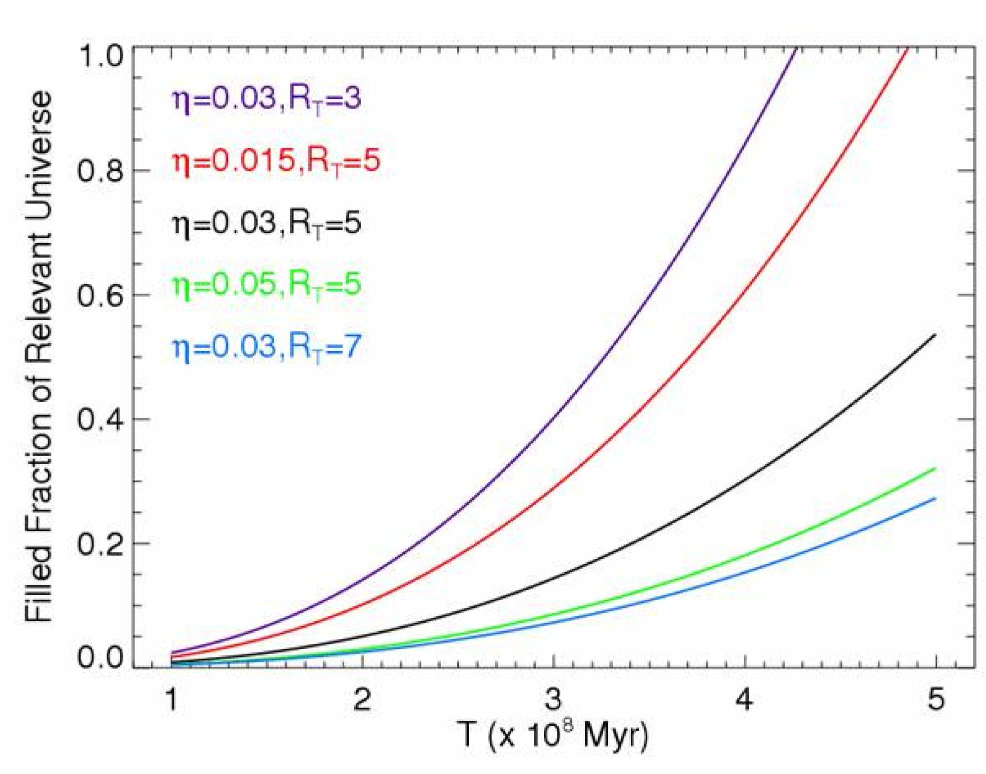

Fig 2. – Fraction of Relevant Universe (ζ) filled by Radio Lobes against lifetimes and volume fractions and axial ratios (Case 1).

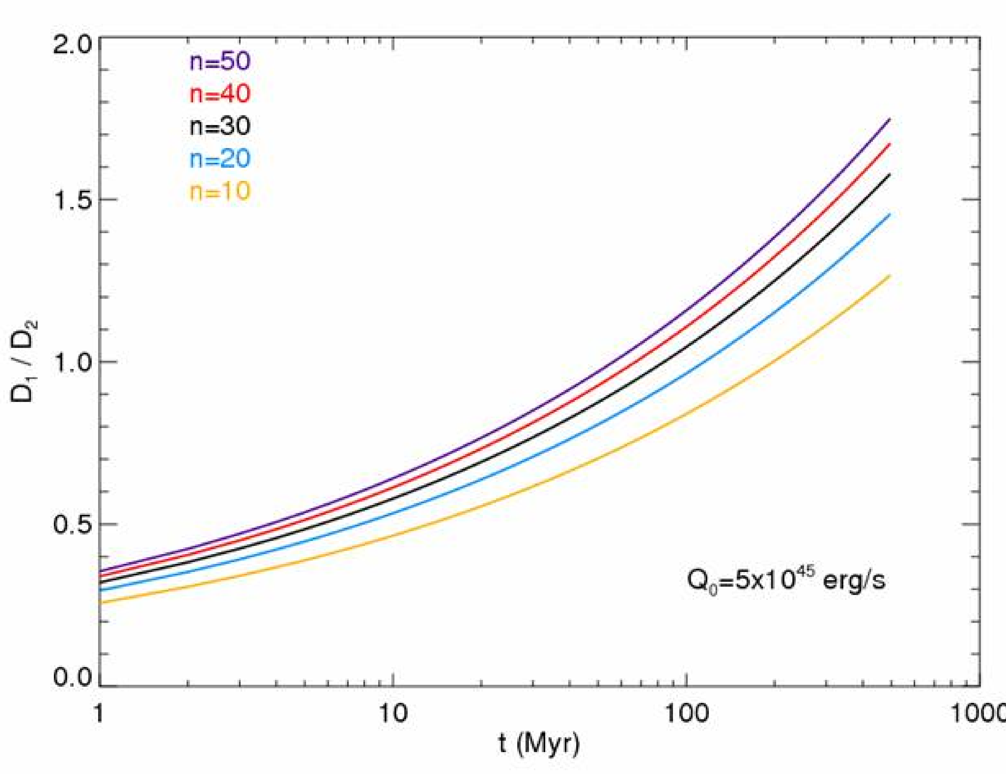

Fig 3. – Ratio of the linear sizes of the RGs for the two models (R = 5 Mpc).

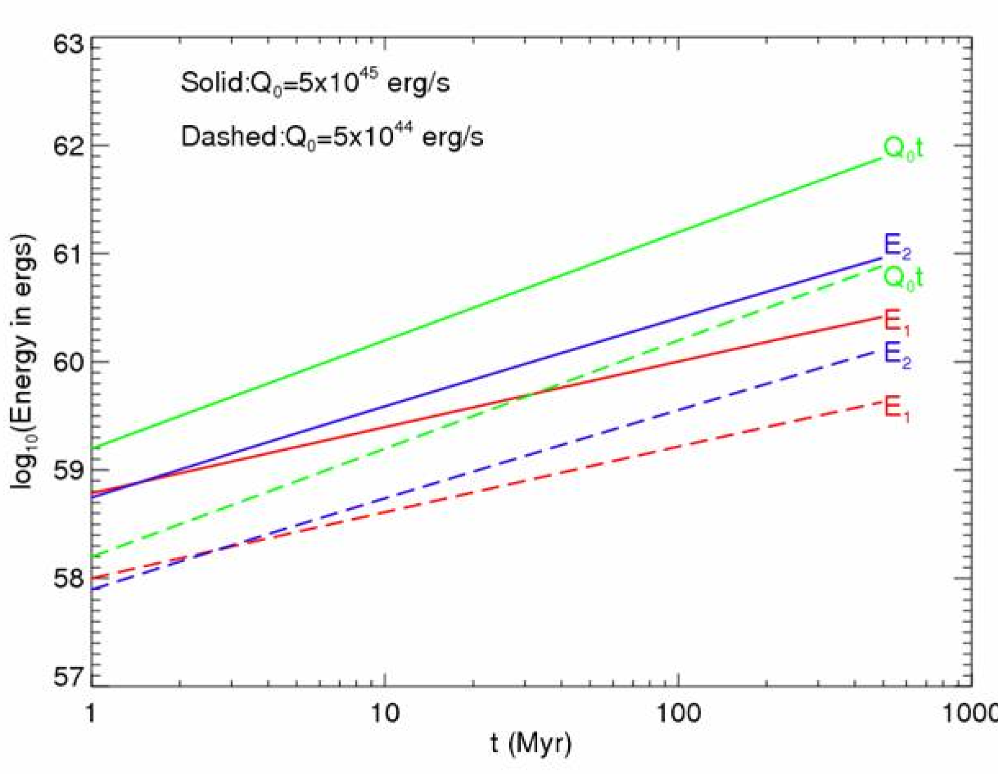

Fig 4. – Energies inputted and stored in one lobe for the two models.

Overpressured Lobes Trigger Extensive Star Formation

RG lobes remain significantly supersonic out to D > 1 Mpc.

Their bow shocks will compress cooler clouds within the IGM (e.g., Rees 1989; GKW01), triggering extensive star formation.

Much of the "alignment effect" (McCarthy et al. 1987) is thus explained.

Recent numerical work that includes cooling (Mellema et al. 2002 -- Fig. 5; Fragile et al. 2003) confirms that RG shocked cloud fragments become dense enough to yield massive star clusters. Fig. 4 shows pressure weighted volumes (E) for Cases 1 and 2: for all plausible assumptions, substantial kinetic energy in the swept up material and overpressure in the lobes is maintained even out to late times.

Hence, RGs may accelerate the formation of new galaxies and in some cases produce them where they wouldn't have formed in the standard picture.

Magnetization and Metalization

We showed (GKW01) that during the quasar era the RGs could inject average magnetic fields of 10^{-8} G into the IGM.

Such field strengths within the filaments are supported by observations (Ryu et al. 1998; Kronberg et al. 2001).

Very different arguments based on total accretion energy extracted via BHs and on the assumptions of isotropized magnetized bubbles also lead to similar conclusions that significant B fields from AGN can fill much of the IGM (Kronberg et al. 2001; Furlanetto & Loeb 2001).

Substantial metal abundances have been found in Lyman-break galaxies at z > 3 and in damped Ly-α clouds.

Gopal-Krishna & Wiita (2003) have shown that the giant RGs can sweep up significant quantities of metals from host galaxies.

These can seed the young galaxies, often triggered by the lobes, with metals.

Subsequent generations of radio activity could further disperse metals produced in early generations of stars in those newly formed galaxies.

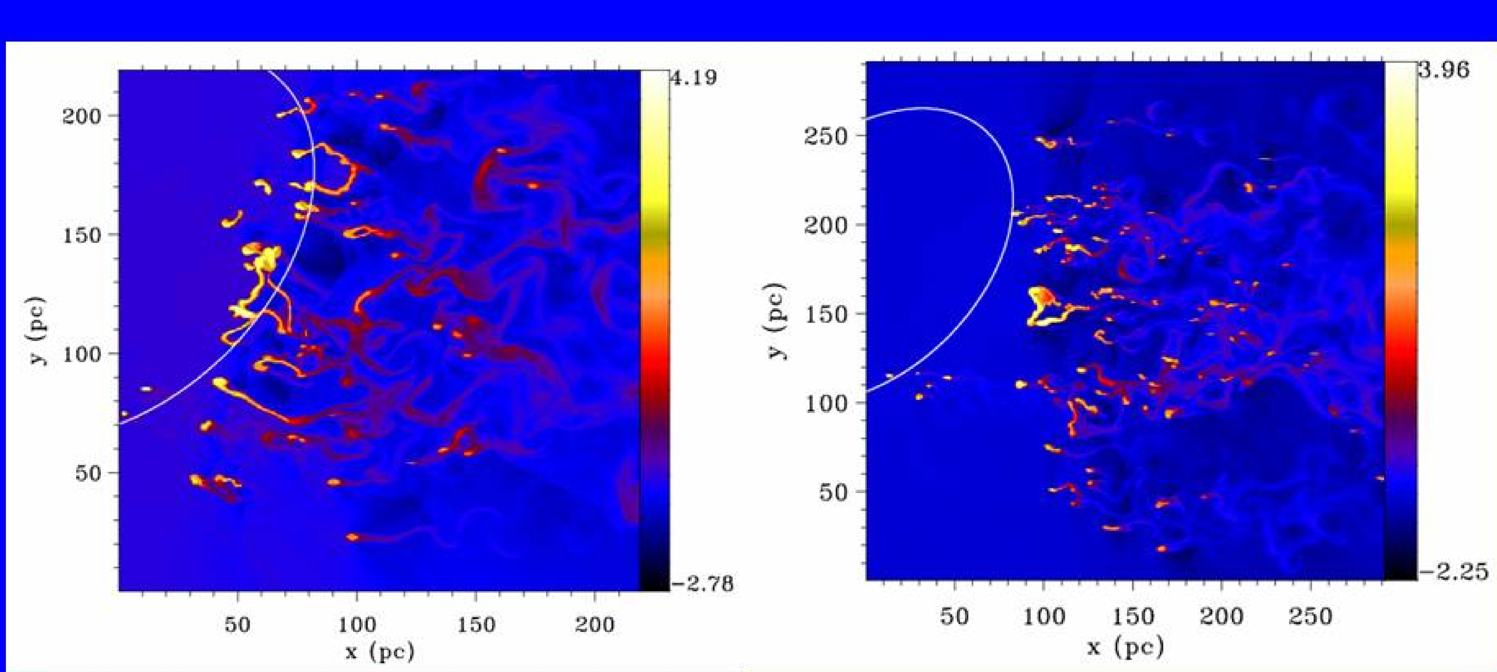

Fig 5. – Density contours at 0.8 Myr (left) and 1.1 Myr (right) after a RG bowshock struck a large elliptical cloud leaving dense cooling fragments Mellema et al. (2002).

References

- Blundell, K.M., Rawlings, S., & Willott, C.J. 1999, AJ, 117, 677 (BRW)
- Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
- Fragile, P.C., Murray, S.D., Anninos, P., & van Breugel, W.2003, ApJ, submitted, astro-ph/0311298
- Furlanetto, S.R. & Loeb, A. 2001, ApJ, 556, 619
- Gopal-Krishna & Wiita, P.J. 2001, ApJ, 560, L115 (GKW01)
- Gopal-Krishna & Wiita, P.J. 2003, in Radio Astronomy at the Fringe, ASP Conf. Ser. Vol. 300, ed. Zenus et al. (San Francisco: ASP), 293
- Gopal-Krishna, Wiita, P.J., & Osterman, M.A. 2003, in ASP Conf. Ser. Vol. 290, Active Galactic Nuclei: from Central Engine to Host Galaxy,ed. Collin et al. (San Francisco: ASP), 319
- Kaiser, C.R., Dennett-Thorpe, J., & Alexander, P. 1997, MNRAS, 292, 723
- Kronberg, P.P., Dufton, Q.W., Li, H., & Colgate, S. 2001, ApJ, 560, 178
- Manolakou, K., & Kirk, J.G. 2002, A&A, 391, 127
- McCarthy, P.J., et al. 1987, ApJ, 321, L29
- Mellema, G., Kurk, J.D., & Röttgering, H.J.A. 2002, A&A, 395, 13
- Rees, M.J. 1989, MNRAS, 239, 1P
- Ryu, D., Kang, H., & Biermann, P.L. 1998, A&A, 335, 19
- Willott, C.J., et al. 2001, MNRAS, 322, 536