Radio galaxies and the star formation history of the universe

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Abstract. Multi-wavelength observations made in the last decade suggest that the universe underwent an intense phase of star formation in the past \((z > 1)\). This intensive activity is commonly attributed to a higher galaxy merger rate when the universe was a fraction of its present age. We examine the role of the powerful radio sources whose comoving density is known to be a few orders of magnitude higher at \(z \sim 2\), the ‘quasar era’. Taking into account recent models for the temporal evolution of the size and luminosity of a powerful double radio source, as well as \(\Lambda\)CDM simulations of the cosmic web of baryonic material at different redshifts, we argue that during the quasar era a high fraction of the volume of the web was occupied by the lobes of double radio sources. Widespread compression of protostellar clouds, triggered by the high pressure of the synchrotron plasma of the radio lobes, can thus be expected to have played a significant role in the global star formation history of the universe. These lobes can also yield a rather high level of magnetization of the intergalactic medium at these early cosmic epochs.

1. Introduction

Flux density-limited samples of radio sources show that the comoving space density of powerful radio galaxies (RGs) 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 (e.g. Archibald et al. 2001). Because of severe adiabatic and inverse Compton losses, 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). Cosmological simulations 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 by overpressured radio lobes, which probably filled a substantial portion of those filaments then. A preliminary discussion of this work is in
Gopal-Krishna & Wiita (2001, hereafter GKW) and more extensive calculations are underway (Osterman, Wiita, Gopal-Krishna & Kulkarni, in preparation).

2. Radio galaxy visibility

All modern 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 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 $T \approx 5 \times 10^8$ yr 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 $n_0 = 1.0 \times 10^4$ m$^{-3}$, $a_0 = 10$ kpc, and $\beta = 1.5$. This leads to the linear size of the RG being given by

$$D(t) = 3.6a_0\left(\frac{T^3}{a_0^5m_pn_0}\right)^{1/(5-\beta)}.$$  

Using these models, 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 $D(T) > 1$ Mpc), although detecting them would require extremely sensitive radio surveys with redshifts. From 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).

3. Radio luminosity function – RLF

Most RLF studies are plagued by uncertainties resulting from incomplete knowledge of the redshifts of the radio sources, but 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.

The powerful FR II sources are nearly 3 dex above the local RLF by $z \sim 2$, and their RLF varies little out to the beginning of the quasar era at $z \sim 3$, 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 §2 we find that at $z = 2.5$ the actual proper density of powerful radio sources born in an interval $T$ is $\rho \approx 4 \times 10^{-5}(1 + z)^3T_5$ Mpc$^{-3}(\Delta \log P_{151})^{-1}$, where $T_5 \equiv T/(5 \times 10^8$ yr). 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 will 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: $\Phi = 7.7 \times 10^{-3}$ Mpc$^{-3}$, which is independent of the assumed value of $T$. 

4. The relevant universe

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.

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. The 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 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 $\langle V(T) \rangle \simeq 2.1 T_5^{18/7} \, \text{Mpc}^3$, and thus, the volume fraction of the relevant universe which radio lobes born during the quasar era cumulatively swept through is:

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

where $R_T \sim 5$ is the typical width to length ratio of an RG. The energy density injected by the lobes into the filaments is $u \simeq 2 \times 10^{-16} \, \text{J m}^{-3}$ for those same canonical parameters. Because $\langle V(T) \rangle$ is a sensitive function of $T$, if the typical RG lifetime is $< 10^8$ yr then $\zeta < 0.01$ and $u < 9 \times 10^{-18} \, \text{J m}^{-3}$ (GKW).

5. Radio lobe triggered star formation

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. Recent hydrodynamical simulations including cooling (Mellema et al. 2002) confirm that this 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) support this scenario.

We further estimate (GKW) that these powerful RGs create lobes which typically remain rapidly expanding, with overpressures of factors exceeding 100 (or Mach numbers above 10) 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).

6. Conclusions

Although the local universe is very sparsely populated by powerful radio sources, several large factors work in the same direction 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 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 many massive starbursts, and even many galaxies, are formed in this fashion, may turn out to be realistic.

An exciting implication of this scenario is that RGs inject a substantial amount of energy in the form of magnetic fields into the cosmic web of filamentary IGM at $z \sim 2$. Equipartition field strengths of $10^{-8}$G can arise (GKW), and are in accord with recent rotation measure based estimates for fields within the denser parts of the IGM (Ryu et al. 1988). It is well worth noting that two very recent independently advanced arguments, starting from essentially orthogonal evidence based on overall energetics (Kronberg et al. 2001; Furlanetto & Loeb 2001) came to very similar conclusions about the importance of RGs for the injection of magnetic energy and for galaxy and structure formation. It is clear that our ongoing investigations of aspects of this scenario will be worthwhile.

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