LARGE-SCALE IMPACT OF THE COSMOLOGICAL POPULATION OF EXPANDING RADIO GALAXIES

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ABSTRACT

We seek to compute the fraction of the volume of the universe filled by expanding cocoons of the cosmological population of radio galaxies over the Hubble time as well as the magnetic field infused by them, in order to assess their importance in the cosmic evolution of the universe. Using N-body ΛCDM simulations, radio galaxies distributed according to the observed radio luminosity function are allowed to evolve in a cosmological volume as using well-defined prescriptions for their expansion. We find that the radio galaxies permeate 10%–30% of the total volume with ∼10^{-8} G magnetic field by the present epoch.

Subject headings: galaxies: active — galaxies: jets — methods: n-body simulations

1. INTRODUCTION

Radio galaxies (RGs) are believed to have significant impact on the evolution of large-scale structures in the universe. The cosmological population of expanding RGs and quasars can permeate large volumes of the intergalactic medium (IGM) and could contribute substantially toward magnetization and metal enrichment of the universe (e.g., Gopal-Krishna & Wiita 2001; Kronberg et al. 2001; Furlanetto & Loeb 2001; Barai et al. 2004; Gopal-Krishna et al. 2004; Barai & Wiita 2007) estimated the cumulative volume filling factor to be ∼0.05. These results were expressed as a fraction

\[ f_{\text{RG}} = \frac{V_{\text{RG}}}{V_{\text{total}}} \]

of the WHIM volume, adopted from the numerical simulations of Cen & Ostriker (1999).

The expansion of shocked and overpressured radio cocoons in a two-phase IGM are argued to compress the cold clouds and trigger star (perhaps even dwarf galaxy) formation (De Young 1989; Rees 1989; Daly 1990; Chokshi 1997; Natarajan et al. 1998; van Breugel et al. 2004; Sikl 2005), as supported by recent observations of jet-induced star formation (e.g., Osterbrock et al. 2001; Furlanetto & Loeb 2001; Barai et al. 2004). The RGs are distributed according to the observed radio luminosity function (RLF), which gives the number of RGs within the simulation box of comoving size \( L \times L \times L \) Mpc on a side, having triply periodic boundary conditions and expanding with the Hubble flow, is evolved from \( z = 25 \) up to \( z = 0 \).

2. THE MODEL

2.1. N-Body Cosmological Simulation

We perform N-body simulations of a ΛCDM universe, where a cubic cosmological box with comoving size \( 256 h^{-1} \) Mpc on a side, having triply periodic boundary conditions and expanding with the Hubble flow, is evolved from \( z = 25 \) up to \( z = 0 \). The P3M (particle-particle/particle-mesh) code (Hockney & Eastwood 1981) is used with 256^3 dark matter particles, and the gravitational softening comoving length is 0.3 of the cell size or 0.15 h^{-1} Mpc. The cosmological parameters are \( \Omega_m = 0.268, \Omega_b = 0.0441, \Omega_{\Lambda} = 0.732, H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}, n_s = 0.947, \text{ and } T_{\text{CMB}} = 2.725 \text{ K} \), consistent with the results of WMAP3 (Spergel et al. 2007).

The baryonic gas distribution is assumed to follow the dark matter in the N-body simulation. The ambient gas density, \( \rho(z, r) \), is obtained from the (matter) density, \( \rho_m(z, r) \), using

\[ \rho(z, r) = \frac{\Omega_m(z, r) \rho_m}{\Omega_m} \]

The external pressure is then \( P_{\text{ext}} = \Omega_m(z, r) \rho_m \). The external temperature is fixed (e.g., Pieri et al. 2007) \( T(z, r) = T_0 \rho(z, r) \). The external temperature is fixed at \( T_0 = 10^4 \text{ K} \) assuming a photoheated ambient medium, and \( \mu = 0.611 \) amu is the mean molecular mass. The RGs are distributed in the cosmological volume as given in § 2.2. They are then allowed to evolve according to the prescription in § 2.3.

2.2. Initial Source Distribution

The cosmological redshift \( z \) and luminosity \( (L = L_{\lambda=1.4} \text{ MHz} W^{-1} \text{ sr}^{-1}) \) distribution of RGs is quantified by the radio luminosity function (RLF), which gives the number of sources per unit comoving volume per unit luminosity. We adopt the RLF \( \rho(L, z) \) computed by Willott et al. (2001) (with \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \)), modeling it as a combination of low-\( L \) and high-\( L \) populations, and using their model C for the redshift evolution.

The RLF is converted to the current consensus cosmology (§ 2.1) using the relation from Peacock (1985) relating the RLF in two cosmologies, \( \rho_1(L_1, z) dV_1/dz = \rho_2(L_2, z) dV_2/dz \). Then

\[ dN(L, z) = \rho(L, z) d[\log_{10} L] \]

(1)

gives the number of RGs within the simulation box of comoving volume \( V_{\text{box}} = (256 h^{-1} \text{ Mpc})^3 \) at epoch \( z \) in the \( L \) interval \( [L, L + dL] \). Sources are generated within radio luminosities \( 24 \leq \log_{10} L \leq 30 \).
The radio luminosity is converted to the constant kinetic power transported by a jet, $Q_{\mathrm{b}}$, using the recent result of Koerding et al. (2008), $\log Q_{\mathrm{b}}[\text{erg s}^{-1}] = 19.1 + \log L_{151}[\text{W/Hz sr}]$.

Using the RLF and an assumed active source lifetime, $\tau_{\mathrm{RG}}$, we obtain the entire cosmological population of RGs starting from $z = 8$, namely the birth redshift ($z_{\mathrm{birth}}$), switch-off redshift ($z_{\mathrm{off}}$), and $L$ of each source. We implement three different values of $\tau_{\mathrm{RG}}$: 10, 100, and 500 Myr. We also consider the possibility that the lifetime is inversely proportional to the jet power, $\tau_{\mathrm{RG}} \propto 1/\xi_0^2$ (Daly & Guerra 2002; Daly et al. 2007), where the constant is found assuming a lifetime of 500 Myr at $Q_{\mathrm{b},\min} = 10^{33.1}$ erg s$^{-1}$.

At each time step of the simulation, we filter the density inside the box such that the new RGs born during that epoch are spatially located in regions which would collapse to form halos of mass $> 10^{10} M_\odot$. We consider the mesh cells that have a filtered density $> 5$ times the mean density of the box, and each new RG is located at the center of one such dense cell, selected randomly.

### 2.3. Radio Galaxy Evolution

After being born, an RG evolves through an active-AGN phase (§ 2.3.1; when $z_{\mathrm{birth}} > z > z_{\mathrm{off}}$), and then through a post-AGN phase (§ 2.3.2; when $z < z_{\mathrm{off}}$). At each time step the total volume occupied is computed by counting the contributions of all the sources born by then.

#### 2.3.1. Active-AGN Phase

In an AGN when the AGN is active, relativistic plasma flows down a pair of jets, each of length $R_\mathrm{a}$, and inflates the huge overpressured radio cocoon. The advance speed $v_\mathrm{a}$ of the jet head is obtained by balancing the jet momentum flux with the ram pressure of the ambient medium,

$$\frac{Q_{\mathrm{b}}}{A_\mathrm{s}(z)c} = \rho_\mathrm{s}(z)v_\mathrm{a}^2(z).$$

Here $A_\mathrm{s}$ is the area of the shocked “working” surface at the end of the cocoon (larger than the instantaneous cross section area of the jet) and $\rho_\mathrm{s}$ is the external density. We use $A_\mathrm{s} = 2\pi R_\mathrm{a}^2\theta_\mathrm{a}^2$ assuming that the shock front has a constant half-opening angle of $\theta_\mathrm{a} = 5^\circ$ relative to the central AGN (Furlanetto & Loeb 2001).

Since $\tau_{\mathrm{RG}}$ is short compared to the Hubble time, energy losses and Hubble expansion are neglected in this phase. All the kinetic energy transported along the jets during an AGN’s age $t_{\mathrm{age}} = (t - t_{\mathrm{birth}})$ is transferred to the cocoon, whose energy is $E_{\mathrm{c}} = 2Q_{\mathrm{b}}^t t_{\mathrm{age}}$, and $p_{\mathrm{V}} = (\Gamma - 1)E_{\mathrm{c}}$. The adiabatic index of the cocoon’s plasma $\Gamma = 4/3$, as it is taken to be relativistic. A shock is driven sideways into the ambient medium at a speed $v_{\mathrm{sh}}$, following $p_{\mathrm{c}} = \rho_\mathrm{s} v_{\mathrm{sh}}^2$.

The RG expands self-similarly during this phase (Falle 1991; Kaiser & Alexander 1997) and we approximate its shape as cylindrical with length $2R_\mathrm{c}$ and radius $R_\mathrm{c}$. The two equations of motion are $dR_\mathrm{c}/dt = v_\mathrm{c}$ for advance along the jet, and $dR_{\mathrm{c}}/dt = v_{\mathrm{c}}$ perpendicular to the jet. We solve for $R_\mathrm{c}$ and $R_{\mathrm{c}}$ using a fourth-order Runge-Kutta integration method. The RG volume during this self-similar expansion is then $V_{\mathrm{RG}}(z) = 4\pi R_{\mathrm{c}}^3/3$.

If $v_\mathrm{a} > v_\mathrm{c}$ or $p_{\mathrm{c}} > \rho_\mathrm{s} v_{\mathrm{c}}^2$, the RG loses its self-similarity and ceases to have a cylindrical expansion (Begelman & Cioffi 1989). It then becomes spherical in shape, and the Sedov-Taylor blast wave model describing the adiabatic expansion of a hot plasma sphere into a cold medium can be used to obtain its radius (Castor et al. 1975; Scannapieco & Oh 2004; Levine & Gnedin 2005),

$$R_{\mathrm{c}}(z) = \xi_0 \frac{E_{\mathrm{c}}}{\rho_\mathrm{s}(z)}^{1/5}. \quad (3)$$

We obtain $\rho_\mathrm{s}(z)$ by averaging the gas density of the mesh cells in the simulation box occurring within the cocoon spherical volume. For a strong explosion in the $\Gamma = 5/3$ ambient gas, $\xi_0 = [(75/16\pi)(\Gamma^2 - 1)(\Gamma + 1)^2/(3\Gamma^2 - 1)]^{1/5}$ is 1.12 (Keitley et al. 2000). Then the RG volume is $V_{\mathrm{RG}}(z) = 4\pi R_{\mathrm{c}}^3/3$.

#### 2.3.2. Post-AGN Phase

When the AGN activity ends, the cocoon self-similarity is lost and we consider that the RG attains a spherical shape, if it had already not done so in the active phase. The pressure inside the cocoon causes the RG to continue expanding as long as it is overpressured (Kronberg et al. 2001; Reynolds et al. 2002). This overpressured cocoon expansion occurs analogous to a spherical adiabatic stellar wind bubble, with the radius evolving as in equation (3). Here the total kinetic energy injected into the cocoon by the AGN throughout the active RG lifetime is $E_c = 2Q_b^t r_{\mathrm{RG}}$.

The RG is considered to undergo adiabatic expansion losses, and the cocoon pressure evolves as $p_{\mathrm{c}} R_{\mathrm{c}}^{5/3}$ constant, with the constant derived from the pressure and size it had at the end of the active phase. The RG follows a spherical expansion as long as its pressure exceeds the external pressure, i.e., $p_{\mathrm{c}}(z) > p_{\mathrm{e}}(z)$, and in this late expansion phase, $V_{\mathrm{RG}}(z) = 4\pi R_{\mathrm{c}}^3/3$.

When $p_{\mathrm{c}}(z) \leq p_{\mathrm{e}}(z)$, or the cocoon has reached pressure equilibrium with the external medium, the RG has no further intrinsic expansion. After this point, the cocoon simply evolves passively with the Hubble flow of the cosmological volume. Thus an RG in pressure equilibrium attains a final volume of $V_{\mathrm{RG}} = 4\pi R_{\mathrm{c}}^3/3$, where $R_{\mathrm{c}}$ is the final comoving radius of the cocoon.

### 3. RESULTS AND DISCUSSION

Figure 1 shows the redshift evolution of two single RGs in the simulation; here we discuss only the one with $\tau_{\mathrm{RG}} = 100$ Myr (solid curves). At the end of the active phase ($z = 5.57$) its cocoon is overpressured by a factor of $\sim 650$. So it continues to expand while its pressure falls faster because of adiabatic losses. Finally when $p_{\mathrm{c}}$ falls to a level to match the external pressure it does not expand anymore. From $z = 1.85$ its comoving radius remains constant at 1.4 h$^{-1}$ Mpc in the passive Hubble phase.

This illustrates that the radio cocoons are persistently overpressured for a substantial period of time even after the AGN has stopped activity, and hence continue to expand into the ambient medium. In Figure 1, after an active life of 100 Myr, the RG remains overpressured for $\sim 3000$ Myr. Such results are in accord with other studies (e.g., Yamada et al. 1999; Kronberg et al. 2001). In our simulations $\sim 20\%$–$50\%$ (depending on the active lifetime) of the sources became spherical in shape during the active-AGN phase.

We count the mesh cells in the simulation box which occur
inside the volume of one or more RG cocoons. The total number of these filled cells, \(N_{\text{RG}}\), give the total volume of the box occupied by RGs. We express the total volume filled as a fraction of volumes of various overdensities in the box, \(N_{\rho} = N(\rho > \bar{\rho})\), where \(\bar{\rho} = (1 + z)^3 \Omega_m H_0^2 / (8\pi G)\) is the mean matter density of a spatially flat universe (the box) at an epoch \(z\). So \(N_{\rho}\) gives the number of cells which are at a density \(\rho\) times the mean density. We find \(N_{\rho}\) for \(C = 0, 1, 2, 3, 5, 7, 10\) gives the total volume of the box.

Figure 2 shows the redshift evolution of the volume filling factors for different active lifetimes. By the present epoch, 0.08 of the entire universe is filled by RGs of active lifetime 10 Myr, the fraction going up to 0.26 for 100 Myr, and 0.32 for 500 Myr. With \(\tau_{\text{RG}} = 100\) or 500 Myr, RGs fill up all of the overdense regions (\(\rho > \bar{\rho}\), or higher) by \(z = 0.3–0.4\). With \(\tau_{\text{RG}} = 500\) Myr, RGs always fill up regions with \(\rho > 5\bar{\rho}\) or higher at all epochs. The case with \(\tau_{\text{RG}} \propto 1/\Omega_m\) fills up 0.24 of the universe by \(z = 0\), and give volume filling fractions similar to the values with a constant lifetime of 100 Myr.

It is the overdense cosmic regions which gravitationally collapse to form stars and galaxies. So evidently the RGs have a profound impact on the protogalactic regions of the universe. The precise effect on star formation is still open to debate (§1), with possible RG influence on both triggering and suppressing star formation in different regions of the universe depending on the exact ambient conditions.

Our volume filling factors of 10%–30% are between the values that Gopal-Krishna & Wiita (2001) (50%) and Barai & Wiita (2007) (≤5%) obtained as a fraction of the volume of the WHIM component of the universe. Our results, based on self-consistent cosmological simulations, give a more reliable estimate of the fractional volume of the universe occupied by RGs. The volumes obtained by Levine & Gnedin (2005) (100% filling by \(z \sim 1\)) are much higher, since they consider the whole AGN population.

We perform preliminary estimates of the energy density and magnetic field in the volumes filled by RGs. The cocoon energy density behaves similarly to the cocoon pressure evolving adiabatically (§ 2.3.2) \(u_e = 3\bar{\rho}_e\). Assuming equipartition of energy between magnetic field of strength \(B\) and relativistic particles, the magnetic energy density is \(u_\mu = u_e / 2 = B^2 / (8\pi)\). The mean thermal energy density of the ambient medium inside the RG volume is \(u_{\text{T,RG}} = 3\bar{\rho}_e kT_e / (2\mu)\). We define the volume-weighted average of a physical quantity \(A\) as \(\langle A \rangle (z) \equiv \sum_i A_i V_i / \sum_i V_i\), where the summation is over all RGs existing in the simulation box at that epoch.

Figure 3 shows the redshift evolution of \(\langle u_{e} \rangle\), \(\langle u_\mu / u_{\text{T,RG}} \rangle\), and \(\langle B \rangle\). The energy densities and magnetic field decrease with redshift as the filled volumes become larger. The ratio \(\langle u_\mu / u_{\text{T,RG}} \rangle\), giving the importance of cocoon magnetic energy over external thermal energy, has a trend similar to that deduced by Furlanetto & Loeb (2001). We find that, by the present, \(u_\mu\) is comparable to \(u_{\text{T,RG}}\) or greater by factors of few, implying that substantial magnetic energies are infused into the IGM by the expanding radio cocoons. At \(z = 0\), a magnetic field of \(\sim 10^{-6}\) Gauss permeates the filled volumes, consistent with the results of Gopal-Krishna & Wiita (2001) and Ryu et al. (1998). At a given redshift, the energy density and magnetic field are larger for higher source lifetimes. The results for \(\tau_{\text{RG}} \propto 1/\Omega_m\) are intermediate between those of 10 and 100 Myr.

We conclude that using our \(N\)-body cosmological simulations, the expanding population of RGs pervade 10%–30% of
the volume of the universe by the present, and occupy 100% of the overdense regions by $z \sim 0.3$. A magnetic field of $\sim 10^{-8} \text{ G}$ is infused in the filled volumes at $z = 0$.

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