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Evidence that powerful radio jets have a profound influence on the evolution of galaxies

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ABSTRACT

The relationships between supermassive black holes and the properties of their associated dark-matter halos imply that outflows from accreting black holes provide a feedback mechanism regulating galaxy formation. Accreting black holes with weak or undetectable radio jets (radio-quiet quasars) outnumber those with powerful jets (radio-loud quasars) by a factor $\sim 10-100$, so powerful-jet outflows are often neglected. However, whenever powerful jets are triggered, there is a dramatic (factor $\gtrsim 100$) step-function increase in the efficiency of feedback. We use a feedback model, together with the measured space density of flat-spectrum radio-loud quasars, to show that a powerful-jet episode probably occurred in every protocluster in the Universe. Before jet triggering, there was time for gravitational collapse to create many ($\sim 10-100$) surrounding protogalaxies massive enough to host radio-quiet quasars. After triggering, the powerful jet pushes back and heats ionized gas so that it cannot fall onto these protogalaxies and cool. Once neutral/molecular gas reservoirs become exhausted, there is a synchronized shut down in both star-formation and black-hole activity throughout the protocluster. These considerations imply that radio-loud quasars have a profound influence on the evolution of all the galaxies seen in clusters today.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – galaxies: jets – galaxies: luminosity function, mass function

1 INTRODUCTION

Powerful-radio-jet activity is regarded as a useful tracer of large-scale structure in the distant Universe (e.g. Miley et al. 2004), but with the exception of a few studies (e.g. Gopal-Krishna & Wiita 2001; Rawlings 2003), its influence on galaxy formation is typically ignored. This is because, even in the young Universe where supermassive black holes have high accretion rates and are visible as quasars, only a few per cent of accreting black holes develop powerful radio jets (e.g. Goldschmidt et al. 1999). It is now accepted, however, that quasars do play a key rôle in galaxy formation because of the existence of remarkably tight correlations between the masses of black holes and the properties of their associated dark-matter halos such as velocity dispersion (e.g. Ferrarese 2002).

Such correlations are most easily understood in terms of ‘feedback models’ (Silk & Rees 1998; Fabian 1999) in which the mechanical power emerging from radio-quiet accreting black holes injects energy into the gaseous component of the young galaxy over and above that which it has acquired by gravitational collapse. In Sec. 2 we adopt a feedback model for radio-loud accreting black holes and in Sec. 3 we use this model, together with hierarchical clustering theory, to compare the predicted cosmic evolution in the comoving space density of radio sources with the evolution observed. We reach some new conclusions concerning the cosmological importance of radio sources in Sec. 4.

The convention for spectral index α is that flux density $S_\nu \propto \nu^{-\alpha}$, where ν is the observing frequency, and the radio luminosity function (RLF), the comoving space density of sources per (base 10) logarithmic interval of 1.4-GHz radio luminosity $L_{1.4}$, is assumed proportional to $L_{1.4}^{-\beta}$. We assume throughout a low-density, Λ-dominated Universe in which $h = H_0/(100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}) = 0.7$; $\Omega_\mathrm{m} = 0.3$; $\Omega_\Lambda = 0.7$; $\Omega_b = 0.04$, $\sigma_{8\ h^{-1}} = 0.9$, and $n_\mathrm{scalar} = 1$.

2 FEEDBACK DUE TO POWERFUL RADIO JETS

Here, we adopt a form of feedback model in which powerful (radio-loud quasar) jets deliver some fraction f_effic of their mechanical power Q to ionized gas which, prior to the powerful-jet episode, is bound to a number N_halo of dark-matter-dominated halos (one hosting the radio-jet-

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producing central engine, the others in the surrounding protocluster), each of mass $M_{\rm halo}$ and velocity dispersion σ. We assume this injection of energy occurs over a timescale $t_{\rm life}$, and that the energy is deposited as thermal energy in the gas (with negligible radiative losses; see Rawlings 2003), and that each halo has just virialized at redshift z, so that $\sigma \propto M_{\rm halo}^{\frac{1}{3}} (1+z)^{\frac{1}{2}}$ (Somerville & Primack 1999). We consider the critical point at which sufficient mechanical energy is delivered to the gas so that it just becomes unbound from each of the $N_{\rm halo}$ surrounding halos. This yields a scaling relation

$$\left(\frac{f_{\rm effic}}{0.5}\right)\left(\frac{Q}{1.25\times10^{40}\ {\rm W}}\right)\left(\frac{t_{\rm life}}{4\times10^{7}\ {\rm yr}}\right)$$
$$\sim \left(\frac{N_{\rm halo}}{100}\right)\left(\frac{f_{\rm gas}}{0.13}\right)\left(\frac{M_{\rm halo}}{5\times10^{12}\ {\rm M_\odot}}\right)\left(\frac{\sigma}{290\ {\rm km\ s^{-1}}}\right)^{2}$$
$$\sim k_1\left(\frac{N_{\rm halo}}{100}\right)\left(\frac{\sigma}{290\ {\rm km\ s^{-1}}}\right)^{5} \qquad (1)$$

where $f_{\rm gas}$ is the fraction of the total (dark-matter-dominated) mass in gas, and k_1 is a constant of order unity. The choices of normalizing constants for each variable will be explained in Sec. 3.

It is clear from Equation 1 that powerful-jet activity can remove gas not only from a single host galaxy, but also from a large number ($N_{\rm halo} \sim 100$) of surrounding galaxy-sized dark-matter halos. In the local Universe, powerful-jet activity is confined to black holes triggered in rich clusters of galaxies (e.g. Cygnus A and 3C 295), and although X-ray observations provide ample evidence of ionized gas being pushed back and heated by such radio sources (e.g. Smith et al. 2002), the cluster potential wells are sufficiently deep ($\sigma \sim 1000$ km s^{-1}) that the gas remains in a gravitationally-bound intracluster medium. This will not be true in similar systems at much earlier times because hierarchical structure formation (e.g. Press & Schechter 1974; Percival, Miller & Peacock 2000) demands that, in the young Universe, the clusters of galaxies seen today were gravitationally-unbound protoclusters, collections of protogalaxies lacking any deep extended potential well, and hence any intracluster medium.

3 COMPARISON OF PREDICTED AND OBSERVED COSMIC EVOLUTION OF RADIO SOURCES

The hierarchical clustering of dark-matter halos and the background cosmology (Spergel et al. 2003) are now so well understood that it is possible to use the feedback model of Sec. 2 to make a firm prediction for the number of powerful-jet episodes triggered per comoving volume per unit cosmic time, modulo just one key uncertainty, the fraction of newly-created halos that give rise to powerful-jet activity. Powerful-jet activity in the local Universe gives vital clues to the critical features of the halos: such jets emerge only from massive elliptical galaxies, with a relatively narrow spread in black hole mass $M_{\rm BH} \sim 10^{9\pm0.5}$ M$_\odot$, corresponding to halo velocity dispersions $\sigma \sim 290 \pm 60$ km s^{-1} (McLure et al. 2004). We introduce a factor $f_{\rm halo}$ to allow for the fact that a halo within this range of σ is a necessary, but not sufficient, condition for powerful-jet activity.

Some choices of normalizing constants in Equation 1 follow from the assumed close mapping between black hole and dark-matter properties: $Q = 1.25 \times 10^{40}$ W corresponds to the most powerful jets observed (Rawlings & Saunders 1991), and is the Eddington luminosity of an $M_{\rm BH} \sim 10^{9}$ M$_\odot$ black hole; and $M_{\rm halo} \sim 5 \times 10^{12}$ M$_\odot$ is the mass of a dark-matter halo with $\sigma = 290$ km s^{-1}, collapsing at $z \sim 2.5$ (Somerville & Primack 1999). Other choices were motivated as follows: theory demands $f_{\rm effic} \sim 0.5$ (e.g. Bicknell et al. 1997); $f_{\rm gas} = 0.13$ corresponds to the ratio of baryons to dark matter, assuming that baryons in forms other than hot gas can be neglected; and $t_{\rm life} = 4 \times 10^{7}$ yr is (for an assumed quasar accretion efficiency ~ 0.1) the mass-doubling timescale for Eddington-limited growth of a black hole, consistent with lower-limits on radio source lifetimes derived from the observed linear sizes of powerful radio galaxies (e.g. Kaiser, Dennett-Thorpe & Alexander 1997; Blundell & Rawlings 1999).

Powerful jets are liable only to be triggered when two supermassive black holes coalesce (Wilson & Colbert 1995), and since this can only happen as the result of a major merger (a special class of 'halo creation event'), we have used hierarchical structure formation theory (Percival et al. 2000) to predict how the trigger rate of powerful jets depends on cosmic epoch (Fig. 1). Note that episodes of powerful-jet activity are predicted to occur over a wide range of cosmic epochs, persisting at some level throughout the later stages of the 'epoch of reionization' during which a partially ionized Universe at $z \sim 15$ (Spergel et al. 2003) becomes fully ionized by $z \sim 6$ (Becker et al. 2001).

Predicting the radio emission from powerful-jet episodes is, in general, an extremely complicated function of properties like the time after the jet-triggering event and the gaseous environment, as well as observational choices like frequency. We therefore focus on episodes whose observational manifestation will be flat-spectrum ($\alpha \sim 0$) radio emission which arises when the jets happen to be favourably oriented, i.e. within a 'beaming angle' covering a sky fraction $f_{\rm beam} \sim 0.01$ (see Jarvis & Rawlings 2000). Such 'Doppler-boosted' emission arises from synchrotron-self-absorbed knots at the base of the jet, and the ratio of its luminosity to Q should be fairly constant throughout the lifetime $t_{\rm life}$ of the radio source (and relatively insensitive to environment and redshift effects) whereas, in contrast, contributions to $L_{1.4}$ from extended structures will, owing to inverse-Compton cooling and other effects (e.g. Kaiser et al. 1997; Blundell, Rawlings & Willott 1999), typically be a strong function of time since the jets were triggered, environment and redshift. We use the creation rate C_{290} for $\sigma = 290$ km s^{-1} halos (from Fig. 1) to estimate, following Efstathiou & Rees (1988), the comoving space density Φ of triggered flat-spectrum sources using

$$\left(\frac{\Phi}{10^{-10}\ {\rm Mpc^{-3}}}\right) \sim k_2\left(\frac{f_{\rm halo}}{0.01}\right)\left(\frac{f_{\rm beam}}{0.01}\right)\left(\frac{f_{\rm RLF}}{10^{-1.75}}\right)$$
$$\times\left(\frac{C_{290}}{4\ {\rm M_\odot\ yr^{-1}\ Mpc^{-3}}}\right)\left(\frac{t_{\rm life}}{4\times10^{7}\ {\rm yr}}\right)$$
$$\times\left(\frac{M_{\rm halo}}{5\times10^{12}\ {\rm M_\odot}}\right)^{-1}, \qquad (2)$$

where k_2 is a constant of order unity (incorporating an as-

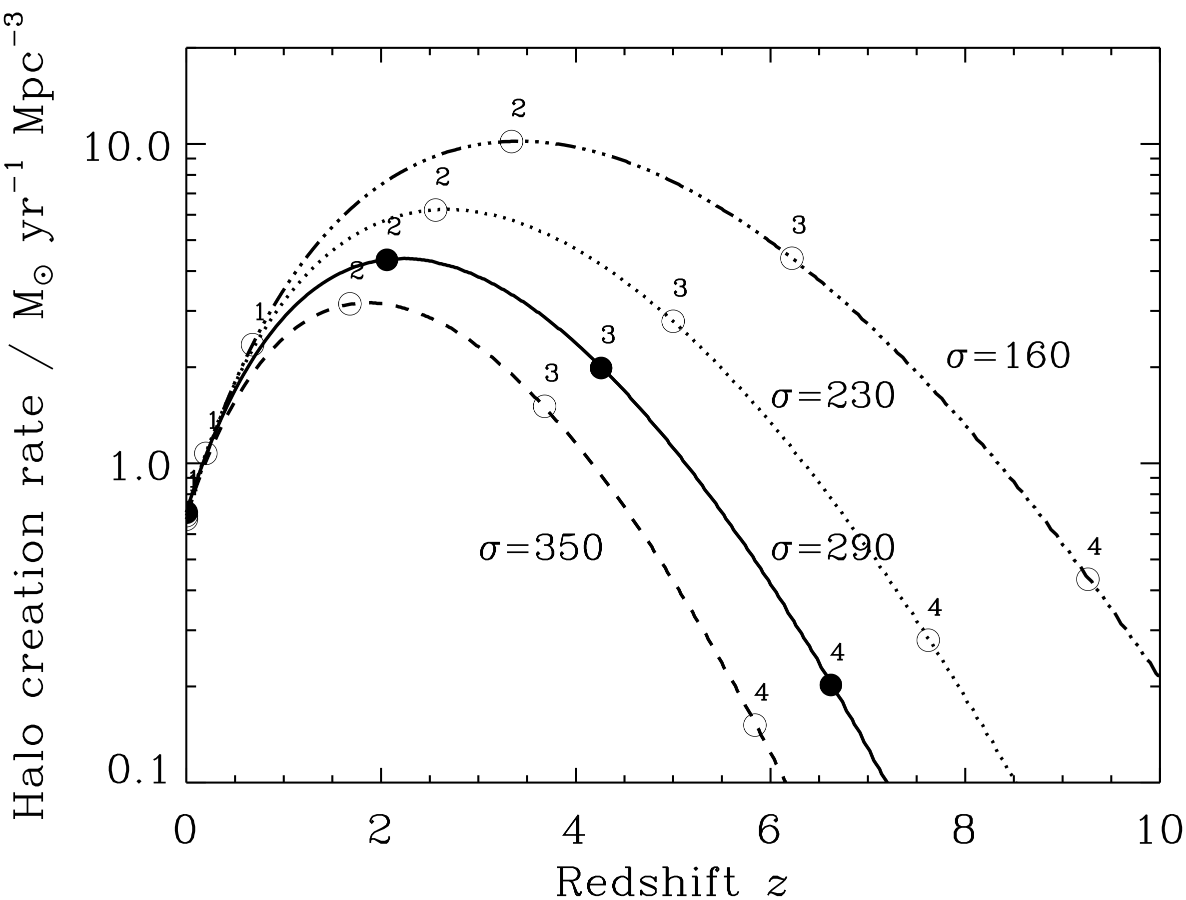

Figure 1. The creation rate of dark-matter halos as a function of redshift z for various halo velocity dispersions σ (in units of km s^{-1}): $\sigma = 160$, dot-dashed line; $\sigma = 230$, dotted line; $\sigma = 290$, solid line; $\sigma = 350$, dashed line. The points corresponding to $\nu = 1, 2, 3$ and 4 for each σ are marked, where ν is the density threshold for collapse in units of the r.m.s. density fluctuation σ_ρ: $\nu = \delta_{\rm crit}/\sigma_\rho(M)$, where $\delta_{\rm crit} \approx 1.7$; mass M is related to a sharp $k-$space filter (used to smooth the density field of mean value ρ_0) by $M = 6\pi^2\rho_0 k_{\rm s}^{-3}$, with $k_{\rm s}$ the cut-off value; and σ and M are related by the spherical-top-hat-collapse model (Somerville & Primack 199) so that $\sigma \propto M_{\rm halo}^{1/3}\ (1+z)^{1/2}$. We have estimated the halo creation rates, following Percival et al. (2000), by: (i) calculating, at each z, the value of M appropriate to the target σ; (ii) using the Press-Schechter (PS; Press & Schechter 1974) formalism (and the $\sigma_{8\ h^{-1}}$-normalized power spectrum) to calculate $g(z) = \nu \exp -\nu^2/2$; (iii) estimating the run of creation rate with z as $g(z) \times h(z)$, where $h(z) = (1+z)^{[2.3+(0.036\times z)/(1+0.203\times z)]}$ is a fitting formula (kindly provided by W. Percival) for $\mathrm{d}\delta_{\rm crit}/\mathrm{d}t$, where t is the cosmic time; (iv) normalizing the curves to the $N-$body simulation data of Percival et al. (2000), and neglecting any variations of this rate with mass, over the small range of interest at $z = 0$. Note that the interpretation of 'halo creation rates' is far more straightforward at high ν (say, $\nu \gtrsim 2$), where very few halos are 'destroyed' by being subsumed in larger halos, than for $\nu \sim 1$ fluctuations (Percival et al. 2000).

sumption that there is $\sim$ 1 triggering event per halo as it evolves through an $\sim$ 1-dex spread in $M_{\rm halo}$), and $f_{\rm RLF}$ (explained fully in the caption to Fig. 2) ensures that Φ is integrated over only the top dex of the flat-spectrum RLF. This is the regime (Fig. 2) in which the high-redshift space density of flat-spectrum quasars is observationally constrained (Jarvis & Rawlings 2000).

The crucial unknown quantity in Equation 2 is $f_{\rm halo}$. We have fixed this at the value ($f_{\rm halo} \sim 0.01$) delivered by requiring roughly equal normalizations for the predicted and measured values of Φ in Fig. 2. With this normalization fixed, and within the considerable current uncertainties, the observational constraints on Φ are in good agreement with the gradual high-redshift decline predicted by hierarchical structure formation theories. However, the more interesting result is that we require $f_{\rm halo} \sim 0.01$, implying that only $\sim$ 1 in 100 triggering events (in the relevant halo velocity dispersion range) generate powerful-jet episodes. The feedback model of Equation 1 implies that each powerful-jet episode influences, in the young Universe, $N_{\rm halo} \sim 100$ halos. By considering the conditions before and after one of these episodes, we will argue in Sec. 4 that the relationship

$$N_{\rm halo} \sim \frac{1}{f_{\rm halo}} \sim 100, \qquad (3)$$

established here using physical arguments based around Equations 1 & 2 and a measurement of the flat-spectrum quasar RLF, is telling us something important about the galaxy formation process.

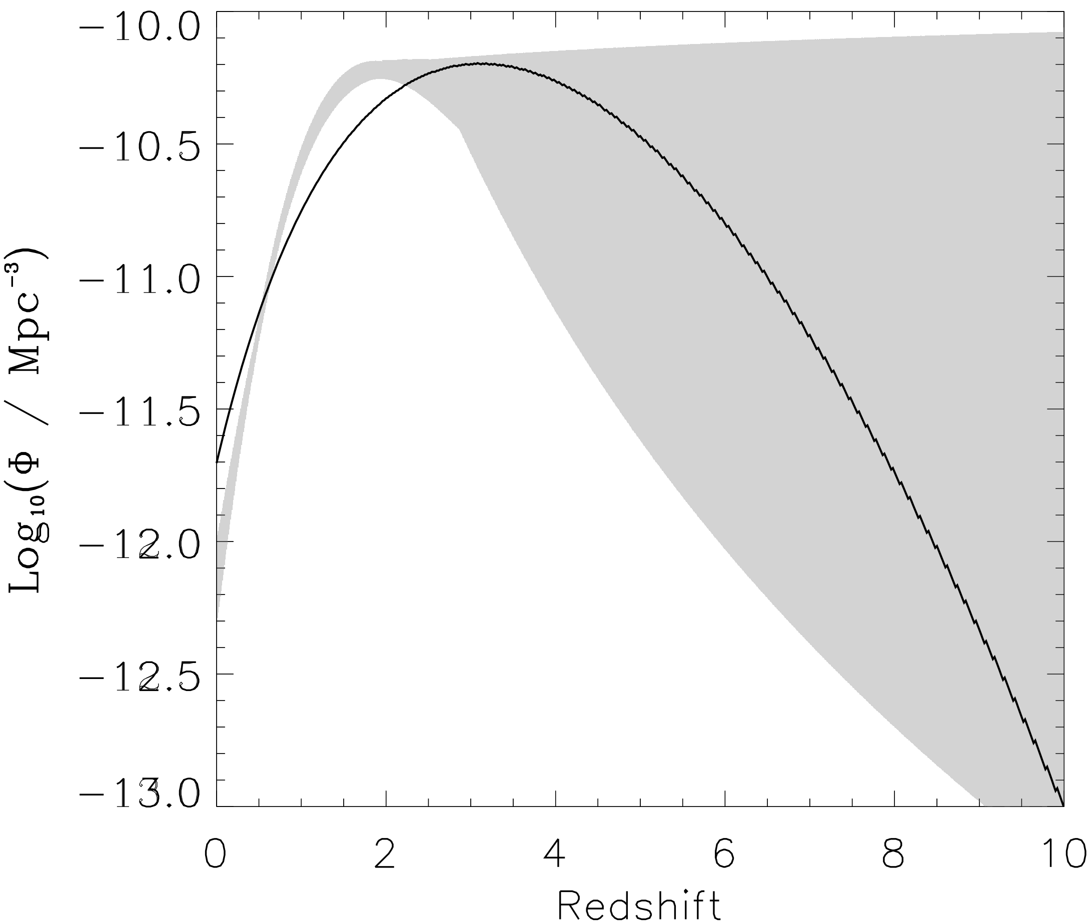

Figure 2. Comparison of the predicted comoving space density Φ of flat-spectrum radio-loud quasars (solid line, calculated using Equation 2) with measured constraints on Φ from existing surveys (shaded regions, 90 per cent confidence regions), from Jarvis & Rawlings (2000) and Dunlop & Peacock (1990). The value of $f_{\rm halo} = 0.01$ was set to obtain rough agreement in the relative normalizations. The value of Φ is integrated only over the top dex of the RLF (as in Jarvis & Rawlings 2000), requiring the introduction of a factor $f_{\rm RLF}$ to account for the lower-$L_{1.4}$ population. We adopt a scaling $L_{1.4} \propto M_{\rm BH}^2$ (Lacy et al. 2001), so that the one-dex spread in black hole masses (McLure et al. 2004) maps onto a two dex spread in $L_{1.4}$. Adopting $\beta = 1.75$ (Jarvis & Rawlings 2000), and going one dex further down the RLF, implies $f_{\rm RLF} \sim 10^{-1.75}$. Note that the model and data diverge significantly at low redshift ($z \lesssim 2$). This is expected because it is well known that any simple Press-Schechter-based formalism fails to fully explain the dramatic drop in quasar activity at low redshifts. There are several reasons for this (e.g. Haehnelt & Rees, 1993) but all linked to two key facts (i) that Press-Schechter theory does not properly account for sub-halos that become part of larger collapsed systems, e.g. galaxies in virialized clusters at low redshift; and (ii) that mergers of baryonic systems like galaxies get strongly suppressed once they begin to inhabit larger collapsed systems in which the velocity dispersion σ greatly exceeds the internal velocity dispersions of the 'sub-halo' galaxies (Carlberg 1990).

4 CONCLUDING REMARKS

In the young Universe, 'high-peak bias' (Kaiser 1984) will have established the regions of space destined, by present epochs, to become clusters of galaxies. Each of these protoclusters will contain ~ 100 protogalaxies which, from Fig, 1, will form over a wide range of epochs and which, because of 'high-peak bias', will be strongly clustered. Such protoclusters have been observed in the form of emission-line-emitting objects and 'Lyman-break' galaxies around high-redshift radio galaxies (e.g. Miley et al. 2004). Central black holes will form in all the high-velocity-dispersion ($\sigma > 160$ km s^{-1}, e.g. Ridgway et al. 2001) halos, presumably with masses set by the feedback processes common in radio-quiet quasars (Silk & Rees 1998); we see from Fig. 1 that these halos tend to be created at much earlier epochs than the higher-velocity-dispersion ones. Eventually, hierarchical processes will cause one pair of halos, each containing a supermassive black hole, to merge, creating a single $\sigma \sim 290$ km s^{-1} halo with a single coalesced black hole, and triggering a powerful-jet episode. This will be a much more dramatic type of feedback event because the radio source injects enough energy into its surroundings that it gravitationally unbinds ionized gas associated not only with the host galaxy, but more widely throughout the protocluster (see also Nath & Roychowdhury 2002, and refs. therein). There has been insufficient cosmic time for a larger dark-matter halo to form, so this process yields a reservoir of protocluster gas which is not yet gravitationally bound, and is now so hot that it cannot accrete back onto the protogalaxies. There will then be a synchronized, protocluster-wide shut down of activity, be it circumnuclear star-formation or black-hole accretion.

For a protogalaxy ~ 1 Mpc from the radio galaxy, fresh supplies of neutral/molecular gas from accretion and cooling will be shut off after $\sim 3 \times 10^7$ yr ($\sim 10-$times the light-travel time; e.g. Blundell & Rawlings 1999), and star-formation and AGN activity will cease once the reserves of neutral gas have been exhausted (taking $\lesssim 10^8$ yr if star-formation rates of $\sim 1000\ M_{\odot}\ yr^{-1}$ use up neutral/molecular gas reservoirs of mass $\lesssim 10^{11}\ M_{\odot}$, e.g. Greve et al. 2003). Accounting for these time lags, and the 'high-peak bias', it is not surprising that there seem to be significant over-densities of both intense starbursting systems (Stevens et al. 2003) and X-ray-selected AGN (Pentericci et al. 2002) around high-redshift radio galaxies. There is also mounting evidence that the amount of gas and dust in the host galaxy of a powerful radio source decreases as the source expands from various anti-correlations between different tracers of this material and source sizes (Baker et al. 2002; Willott et al. 2002; Jarvis et al. 2003).

We conclude that powerful-jet activity represents a dramatic (factor $\gtrsim 100$) step-function increase in the efficiency of feedback mechanisms believed to be an essential part of galaxy formation. Its influence is, however, far more widespread as sufficient energy is delivered to the protocluster environment that gas can no longer cool onto the ~ 100 surrounding protogalaxies. Star-formation and black hole activity throughout the protocluster is shut down, but, accounting both for time before the jet-triggering event (see Fig. 1) and time lags after the event, there was ample opportunity for $\sim 10-100$ of the protogalaxies to shine as radio-quiet quasars, and to build up their supermassive black holes and stellar bulges. In crude terms, this provides a natural explanation for the relative number of radio-quiet and radio-loud quasars at high redshift (e.g. Goldschmidt et al. 1999). The observed space density of flat-spectrum radio quasars (Fig. 2) predicts that a powerful-jet episode occurs in ~ 1 in 100 protogalaxies, which is as expected if each protocluster experiences ~ 1 such event.

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