Quasars and galaxy formation

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ABSTRACT

Quasars are widely believed to be powered by accretion onto supermassive black holes and there is now considerable evidence for a link between mergers, the activity of quasars and the formation of spheroids. Cattaneo, Haehnelt & Rees (1999) have demonstrated that a very simple model in which supermassive black holes form and accrete most of their mass in mergers of galaxies of comparable masses can reproduce the observed relation of black hole mass to bulge luminosity. Here we show that this simple model can account for the luminosity function of quasars and for the redshift evolution of the quasar population provided a few additional assumptions are made. We use the extended Press-Schechter formalism to simulate the formation of galaxies in hierarchical models of the formation of structures and we assume that, when two galaxies of comparable masses merge, their central black holes coalesce and a fraction of the gas in the merger remnant is accreted by the supermassive black hole over a time-scale of $\sim 10^7$ yr. We find that the decrease in the merging rate with cosmic time and the depletion in the amount of cold gas available due to the formation of stars are not sufficient to explain the strong decline in the space density of bright quasars between $z = 2$ and $z = 0$, since larger and larger structures form, which can potentially host brighter and brighter quasars. To explain the redshift evolution of the space density of bright quasars in the interval $0 < z < 2$ we need to assume that there is a dependence on redshift either in the fraction of available gas accreted or in the time-scale for accretion.

1 INTRODUCTION

Considerable evidence points toward a connection between the activity of quasars and the formation of spheroids.

High resolution imaging has revealed the presence of host galaxies around a number of quasars (see e.g. McLure et al. 1999). McLeod (1996) finds a correlation between the luminosities of quasars and those of the host galaxies.

Both the space density of bright quasars and the total star formation rate rise by more than a factor of ten in the interval $0 < z < 2$ (see e.g. Richstone et al. 1998; and Madau 1999), suggesting a common pattern for quasars and galaxies. However, the space density of bright quasars drops down earlier than the total star formation rate and is closer to the star formation history of elliptical galaxies, the stellar population of which is known to be old (see e.g. Renzini 1999).

Hierarchical models of the formation of structures can explain the decline in the density of bright quasars at $z \gtrsim 3$ if it is assumed that quasars are linked to the collapse of the first dark matter [DM] haloes of galactic mass (see e.g. Efstathiou & Rees 1988; and Haehnelt & Rees 1993). When the mass function of DM haloes (given by the Press-Schechter formula) is combined with a prescription to associate a galactic luminosity and a quasar light curve to a DM halo, these models can reproduce both the luminosity functions of high redshift galaxies and high redshift quasars (see e.g. Haehnelt, Natarajan & Rees 1998). The main reason for restricting this approach to high redshifts is that at low redshift there is probably a transition from a phase in which quasars form in gas-rich nuclei to a phase in which quasars are refuelled by interactions of increasingly gas-poor galaxies (see e.g. Cavaliere, Perri & Vittorini 1997).

As it is widely believed that the activity of quasars is powered by accretion onto a supermassive black hole [BH] (see Rees 1984 and references therein), the detections of supermassive BHs in a number of nearby galaxies and the discovery of a correlation between the mass of the central BH and the luminosity of the host bulge provide substantial support for the hypothesis that most galaxies contain a supermassive BH (see e.g. Ford et al. 1998; Ho 1998; Magorrian et al. 1998; Richstone et al. 1998; and van der Marel 1998). A recent study by Salucci et al. (1999a) shows that the mass function of supermassive BHs inferred from the relation of BH mass to bulge luminosity is consistent with the luminosity function of quasars. In a subsequent work, Salucci et al. (1999b) find that supermassive BHs harboured by spiral galaxies are less massive than those detected in ellipticals and conclude that the population of bright quasars is dominated by objects that form in spheroids.

A possible explanation of the link between quasars and spheroids is that there is a unifying mechanism fuelling supermassive BHs while forming spheroids. A mechanism with
this characteristics is known to exist and is provided by mergers. N-body simulations have shown that mergers of galaxies of comparable masses (major mergers) result in the formation of elliptical galaxies (see e.g. Barnes 1988; Hernquist 1992, 1993; Hernquist, Spergel & Heyl 1993; and Heyl, Hernquist & Spergel 1994). Kauffmann & Charlot (1988) have proven that the merger scenario for the formation of elliptical galaxies is consistent with the colour-magnitude relation and its redshift evolution. Hydrodynamic simulations have found that shocks due to mergers can cause a fraction of the gas in the interacting galaxies to fall at the centre of the merged system and to fuel a burst of central activity (Negroponte & White 1983; Barnes & Hernquist 1991, 1996; and Mihos & Hernquist 1994). These computational results have their observational counterparts, since a significant fraction of the imaged quasar populations is known to reside in interacting systems (see e.g. Bahcall et al. 1997; and McLure et al. 1999).

Cattaneo, Haehnelt & Rees (1999) have shown that a very simple model in which after each major merger the central BHs in the progenitors coalesce and a fraction of the cold gas in the merger remnant is accreted by the merged BH can reproduce the observed relation of BH mass to bulge luminosity. Here we investigate whether this model can account for the redshift evolution of the quasar population, particularly at low redshift, where the emission is likely to be dominated by reactivation of supermassive BHs which have accreted most of their mass at the peak of the quasar epoch. Our results derive from Monte Carlo simulations of the merging histories of DM haloes in the extended Press-Schechter formalism combined with a simple scheme for galaxy formation, which has been tested against the total luminosity function of galaxies, the luminosity function of early type galaxies, the redshift dependence of the total star formation rate and the redshift dependence of the abundance of neutral hydrogen in damped Lyman-α clouds. The structure of the paper is as follows. In Section 2 we describe the computational algorithm used to simulate the formation of galaxies and the accretion history of supermassive BHs. In Section 3 we present the results of our calculations. Section 4 contains the conclusions of the article.

2 MONTE CARLO SIMULATIONS OF THE FORMATION AND EVOLUTION OF GALAXIES AND QUASARS

2.1 Merging histories of dark matter haloes

The standard paradigm for the formation of structure in the Universe is the gravitational instability of density fluctuations in a primordial Gaussian random field. In this picture, the number density of collapsed DM haloes is accurately described by the Press-Schechter formula

\[ N(M, z) \, dM = \frac{1}{\sqrt{2\pi} \sigma(M)} \left( \frac{\rho(z)}{\sigma(M)} \right)^2 \exp \left( -\frac{\rho(z)^2}{2 \sigma(M)} \right) \, dM \]  

(Press & Schechter 1974). Here \( \rho(z) \) is the cosmological density at redshift \( z \), \( \sigma(M) \) is the variance of the linearly extrapolated density field on the scale \( M \), \( \omega \) is defined as \( \omega(z) \equiv \delta_c D(0)/D(z) \), where \( \delta_c \) is the over-density threshold at which density fluctuations collapse, and \( D(z) \) is the linear growth factor of density fluctuations. The variance of the density field is related to the power spectrum of the density fluctuations. Here we assume a standard cold dark matter power spectrum as given by Bond & Efstathiou (1984), with a normalisation that reproduces the present-day space density of clusters of galaxies (Eke, Cole & Frenk 1996). The dependence of the linear growth factor on redshift is given by Heath (1977). Here we restrict our attention to the case of a flat ΛCDM universe with \( \Omega_M = 0.2, \Omega_\Lambda = 0.8 \) and a Hubble constant of 75 km s\(^{-1}\) Mpc\(^{-1}\).

Techniques for generating Monte Carlo realizations of the merging histories of DM haloes based on extensions of the Press-Schechter formula have been described for instance by Cole & Kaiser (1988), Cole (1991), Lacey & Cole (1993), Kauffmann & White (1993) and Somerville & Kolatt (1999). The basic equation is the conditional probability that a halo of mass \( M \) at redshift \( z \) has a progenitor of mass \( M - \Delta M \) at redshift \( z + \Delta z \),

\[ P(M \rightarrow M - \Delta M, z \rightarrow z + \Delta z) = \frac{1}{\sqrt{2\pi} \sigma(M)} \exp \left( -\frac{(\omega(z) - \omega(M))^2}{2 \sigma^2(M)} \right) \]  

(Lacey & Cole 1993). We follow the description of Somerville & Kolatt (1999) to construct Monte Carlo realizations of the merging histories of DM haloes from equation (2). The probability distribution (2) is used to assign a mass \( M \) to a progenitor at redshift \( \Delta z \) of a DM halo of mass \( M_0 \) at \( z = 0 \). The procedure is iterated and further progenitors are drawn from the distribution (2), but the merging history is followed only for haloes with circular velocities \( v_c = (GM/v^2)^{1/2} \) above a certain threshold \( v^2 \). Haloes with \( v_c < v^2 \) are treated as accreted mass. Progenitors with a mass larger than the not yet allocated mass are discarded. We construct progenitors of progenitors until all haloes have \( v_c < v^2 \). The procedure is repeated for a representative sample of haloes at \( z = 0 \). We adopt a step of \( \Delta z = 0.01 \) and a resolution of \( v^2 = 70 \) km s\(^{-1}\).

2.2 The galaxy formation scheme

The modelling of galaxies within hierarchal cosmogonies has reached a considerable level of complexity. Here we concentrate on the effects of mergers on the growth of supermassive BHs. Therefore we adopt a rather simple scheme for galaxy formation similar to that proposed by White and Rees (1978), which should nevertheless catch the essential features of the hierarchical merging of galaxies (White 1996).

Important conditions for the formation of a galaxy in a collapsed DM halo are the ability of the gas to cool and the ability of the halo to retain its gas in spite of the input of energy and momentum due to star formation and supernova explosions. The ability of the gas to cool depends on the temperature and the density of the gas. For cooling by Bremsstrahlung these dependencies conspire to give an upper limit for the mass of the gas that is able to cool efficiently (Silk 1977; Rees & Ostriker 1977). Feedback from star formation is more important in haloes with shallower potential wells and therefore smaller circular velocities (see i.e. Kauffmann, White & Guiderdoni 1993). Here we do not treat the cooling and feedback explicitly. Instead, we intro-
produce an effective efficiency for galaxy formation, which depends on the halo circular velocity in such a way that the mass of the galaxy associated with a DM halo of mass \( M_{\text{halo}} \) at redshift \( z \) scales as

\[
M_{\text{gal}}(M_{\text{halo}}) = \epsilon_{\text{gal}}(1 + z)^{\alpha} M_{\text{halo}} v_{c}^{2} \exp \left[ -(v_{c}/v_{\text{max}})^{4} \right].
\]

The parameters \( \epsilon_{\text{gal}} \) and \( v_{\text{max}} \) are chosen in such a way that the luminosity function of our simulated galaxies reproduces the observed luminosity function of galaxies at \( z = 0 \) whereas \( \alpha \) models the redshift dependence of the efficiency of cooling and is set by the cosmological evolution of the mean comoving density of neutral hydrogen in damped Lyman-\( \alpha \) absorbers. The exponential cut-off at high virial velocities mimics the inability of the gas to cool and form stars in the very deep potential wells which form at late times.

When DM haloes merge, it will take some time before the corresponding galaxies sink to the centre of the merged halo due to dynamical friction. To model this, we follow Kauffmann, White & Guiderdoni (1993) and assume that initially a single galaxy forms at the centre of each halo. When haloes merge, the central galaxy of the largest progenitor halo becomes the central galaxy of the new halo. The “satellite” galaxies are assumed to merge with the central galaxy on the dynamical friction time-scale

\[
t_{\text{df}} = \frac{1.17 \epsilon_{\text{df}} r_{\text{vir}}^{2} v_{c}}{\ln (M/M_{\text{sat}}) G M_{\text{sat}}}.
\]

\( \epsilon_{\text{df}} \) is a factor that keeps into account the increase in the mass in cold gas forms visible stars and \( M_{\text{halo}} \) is the total mass of the satellite including its DM halo and \( t_{\text{df}} \) is the time-scale of dynamical friction. Recent numerical work by Colpi, Mayer & Governato (1999) has shown that \( \epsilon_{\text{df}} \geq 2 \) for cosmologically relevant situations. The mass of the merged galaxy is assumed to be the maximum of the sum of the masses of the merging galaxies and of the mass given by equation (3). If the latter is larger, we interpret the difference \( \Delta M_{\text{gal}} \) as accretion due to inflow from the intergalactic medium and we add this mass to the total amount of cold gas in the galactic disk.

As in Kauffmann, White & Guiderdoni (1993), we introduce a critical mass ratio \( f_{e} \) above which a merger produces an elliptical galaxy. For mass ratios below the threshold smaller galaxy is assumed to be tidally disrupted and its mass is added to the disk of the larger one. The value of \( f_{e} \) is determined by requiring the Monte Carlo simulations to reproduce the observed bulge luminosity function, once the other free parameters have been fixed.

We model star formation by assuming that only a fraction \( f_{e} \) of the mass in cold gas forms visible stars and that the conversion of cold gas into stars is described by a purely exponential law with a time-scale of 1 Gyr for el-

\( \epsilon_{\text{gal}} \) and \( v_{\text{max}} = 70 \text{ km s}^{-1} \) for a star formation time-scale in disks of : i) 10 Gyr (solid line); ii) 5 Gyr (dashed line); and iii) \( 10(1+z)^{-0.5} \) Gyr (dotted line). The data points have been inferred from the UV-continuum measurements by Lilly et al. (1996; filled dots), Connolly et al. (1997; filled squares), Madau, Pozzetti & Dickinson (1998; filled pentagons), Treyer et al. (1998; empty circle) and Steidel et al. (1998; empty square). The filled triangles show the fits to the data on damped Lyman-\( \alpha \) absorbers by Storrie-Lombardi, McMahon & Irwin (1996) corrected for possible dust obscuration (filled triangles) and are shown for comparison. Assuming that most of the cold gas at \( z \leq 4 \) is in clouds of very high column density because dissipation is very effective in concentrating baryons at the centre of DM haloes, we find the best fit to the data on damped Lyman-\( \alpha \) absorbers for \( \epsilon_{\text{gal}} = 0.014 \).

\[ \text{Figure 1.} \text{ Mean comoving density of star formation as a function of redshift. The lines show the results of our simulations for a star formation time-scale in disks of : i) 10 Gyr (solid line); ii) 5 Gyr (dashed line); and iii) 10(1+z)^{-0.5} \text{ Gyr (dotted line). The data points have been inferred from the UV-continuum measurements by Lilly et al. (1996; filled dots), Connolly et al. (1997; filled squares), Madau, Pozzetti & Dickinson (1998; filled pentagons), Treyer et al. (1998; empty circle) and Steidel et al. (1998; empty square). The filled triangles show the fits to the data on damped Lyman-\( \alpha \) absorbers by Storrie-Lombardi, McMahon & Irwin (1996) corrected for possible dust obscuration (filled triangles) and are shown for comparison. Assuming that most of the cold gas at } z \leq 4 \text{ is in clouds of very high column density because dissipation is very effective in concentrating baryons at the centre of DM haloes, we find the best fit to the data on damped Lyman-\( \alpha \) absorbers for } \epsilon_{\text{gal}} = 0.014. \]

\[ \text{Figure 2.} \text{ Mean cosmological density of neutral hydrogen in potential wells of } v_{c} > 70 \text{ km s}^{-1} \text{ for a star formation time-scale in disks of : i) 10 Gyr (solid line); ii) 5 Gyr (dashed line); and iii) 10(1+z)^{-0.5} \text{ Gyr (dotted line). The parameter } \alpha \text{ in equation (3) sets the peak in the mean cosmological density of neutral hydrogen. A peak at } z \sim 2.5 \text{ is obtained for } \alpha = 1. \text{ The data points (filled squares) give the determinations of the cosmological density of neutral hydrogen in damped Lyman-\( \alpha \) absorbers by Storrie-Lombardi, McMahon & Irwin (1996) corrected for possible dust obscuration (filled triangles) and are shown for comparison. Assuming that most of the cold gas at } z \leq 4 \text{ is in clouds of very high column density because dissipation is very effective in concentrating baryons at the centre of DM haloes, we find the best fit to the data on damped Lyman-\( \alpha \) absorbers for } \epsilon_{\text{gal}} = 0.014. \]
Monte Carlo simulations. The total mean star formation density is dominated by star formation in disks even if about half of the galactic mass ends up in spheroids because mergers convert disk stars into bulge stars. We fit the dust-corrected mean cosmological density of neutral hydrogen in damped Lyman-α absorbers for a cooling efficiency of $\epsilon_{\text{gal}} \gtrsim 0.014$. The equality holds if dissipation is very effective in concentrating baryons at the centre of DM haloes and most of the mass in neutral hydrogen at $z \lesssim 4$ is in clouds of very high column density. For the mass-to-light ratio inferred from the Tully-Fisher relation, this high value of $\epsilon_{\text{gal}}$ can be reconciled with the bright end of the luminosity function of galaxies if the fraction of cold gas that goes into star formation is not much more than a half. The remainder must be either reheated and ejected or end up in a population of sub-stellar objects, which can account for the dark matter in disks and baryonic haloes. Since it is quite improbable that a galaxy with a stellar mass of $\sim 10^{11} M_\odot$ has lost half of its baryonic mass through ejection by supernovae, it is a likely conclusion of our model that at least in massive DM haloes a significant fraction of the mass in cold gas has to go into a population of sub-stellar objects. Figure 3 compares the luminosity functions resulting from our simulations to those observed. If we assume a cooling efficiency of $\epsilon_{\text{gal}} = 0.014$, we find the best fit to the observations for $f_s = 0.53$.

2.3 The growth of black holes through mergers and accretion

Supermassive BHs grow through merging with other supermassive BHs and through accretion of gas. They may also grow through tidal disruption and accretion of stars, but we do not want to discuss this possibility here.

After a galactic merger has taken place, the supermassive BHs contained in the merging galaxies sink at the centre of the new galaxy, form a binary system and eventually coalesce. The time-scale for this process in uncertain and its final outcome can also be quite different, if another galactic merger intervenes before the supermassive BHs have time to merge (Begelman, Blandford & Rees 1980), but here we assume that this time-scale is much shorter than the Hubble time, so that the supermassive BHs contained in the merging galaxies always merge.

The amount of cold gas accreted by the supermassive BH will have a complicated dependence on halo and galactic properties (dynamical and kinematical structure, abundance of cold gas, past merging history, angular momentum), and will ultimately depend on the physics of the mechanism responsible for driving the gas to the centre, but here we concentrate on a very simple model where after each major merger a fraction of the gas in the merger remnant falls to the centre and fuels the BH on a time-scale of $10^7$ yr. The mass accretion rate is the minimum between the rate of fuel supply and the Eddington limit:

$$\dot{M}_* = \min\left(\frac{\dot{M}_\text{res}}{10^7 \text{ yr} \cdot \epsilon_{\text{rad}} t_S}, \frac{M_*}{\epsilon_{\text{rad}} t_S}\right),$$

where $\dot{M}_*$ is the rest mass accretion rate, $M_{\text{res}}$ is the mass in the gas reservoir of the supermassive BH, $M_*$ is the mass of the central BH, $\epsilon_{\text{rad}}$ is the efficiency at which the accreted rest mass is converted into radiation and $t_S$ is the Salpeter
time. The evolution of $M_*$ is computed from $M_*$ assuming that gas is accreted from the innermost stable circular orbit (see e.g. Bardeen 1970).

Equation (5) implies that a BH cannot power a bright quasar if it has not reached a certain mass, even if the fuel supply is potentially available. Meanwhile, star formation is competing with the BH in depleting its gas reservoir. The time over which a BH reaches the mass required to power a bright quasar depends on the initial mass of the BH and on the efficiency for converting accreted mass into radiation. Figure 4 shows the initial BH mass required for a bright quasar to form on a time-scale shorter than the star formation time-scale as a function of the radiative efficiency. From this figure we see that, for interesting values of the radiative efficiency and a star formation time-scale $> 10^8$ yr, the central BH forms and evolves into a bright quasar independently of the initial mass and therefore of whether the BHs in the merging galaxies have coalesced or not. If, instead, the star formation time-scale in the central region of the merger remnant is $\lesssim 10^8$ yr, then it becomes relevant to know what the seed mass is and how frequently supermassive BHs merge. In this article we restrict ourselves to the first possibility to avoid the introduction of further free parameters which might be difficult to constrain.

3 THE REDSHIFT EVOLUTION OF THE QUASAR POPULATION

Carlberg (1990) speculated that the decline in the density of bright quasars after the peak of the quasar epoch might be explained purely in terms of a decrease in the frequency of mergers. For a ratio of BH mass to bulge mass of 0.006 (Magorrian et al. 1998) and a $B$-band bolometric correction for quasars of 0.087 (Pei 1995), bright quasars of $M_B < -26$ and $M_\bullet \gtrsim 6 \times 10^8 M_\odot$ are associated with large ellipticals of $M_{gal} \gtrsim 10^{11} M_\odot$ and the quasar epoch should be marked by the epoch at which large ellipticals are assembled. However, the frequency of major mergers forming ellipticals of $M_{gal} > 10^{11} M_\odot$ (Figure 5, solid line) does not trace the redshift evolution of the comoving density of bright quasars (Figure 6) because the decrease in the frequency of mergers is compensated by an increase in the number of bright galaxies at low redshift. The conclusion is that the decline in the merging rate is not sufficient to explain the fall in the comoving density of bright quasars at $z \lesssim 2$.

The key element which is missing in this analysis is the consumption of cold gas by star formation resulting in increasingly gas-poor mergers. In our simulations we reproduce a ratio of BH mass to bulge mass of 0.006 if we assume that after each major merger the central BH accretes $\sim 2\%$ of the cold gas in the merging remnant. We can therefore refine our analysis considering the merging rate for galaxies with a total mass in cold gas larger than $3 \times 10^{10} M_\odot$ (Figure 5, dotted line). The frequency of gas-rich mergers shows a stronger evolution than the frequency of mergers involving a large total mass, but the extent of this evolution is still insufficient to explain the decline of two orders of magnitude in the density of bright quasars between the peak of the quasar epoch and $z \sim 1$.

To explain the redshift evolution of the density of bright quasars in the interval $0 < z < 2$ we need to assume a dependence on redshift either in the fraction of available gas accreted or in the time-scale for accretion. The results of our simulations are consistent with counts of bright quasars and observations of the quasar luminosity function for an accreted mass after each major merger of $M_{acc} = \min(3 \times 10^{-4}(1 + z)^3, 0.0125) M_{gas}$, an accretion time-scale of $2 \times 10^7$ yr and an efficiency for converting accreted mass into blue light of $\epsilon_{rad} \sim 3.8 \times 10^{-3}$ (Figures 6 and 7). Here $M_{gas}$ is the mass of cold gas in the merging remnant. The scaling as $(1 + z)^3$ has been introduced to mimic a proportionality of the fraction of accreted gas to the density of the host galaxy. The upper limit to the fraction of cold gas that can be accreted has been set to prevent unphysical situations where most of the gas in the merging remnant ends up in the central BH. The introduction of this upper limit affects the relation of BH mass to bulge luminosity, since it prunes most of the point above a certain ratio of BH mass to bulge luminosity (Figure 8). There is no evidence for such a sharp upper limit in the data (see e.g. Ho 1998; Magorrian et al. 1998; and Cattaneo, Haehnelt & Rees 1999), but this could simply mean that there is an intrinsic scatter in the maximum fraction of gas that can be accreted by the supermassive BH. The origin of this scatter could be found.
Figure 5. The redshift evolution of the merging rate for mergers of galaxies of comparable masses (mass ratio $f_e > 0.3$) containing a total baryonic mass larger than $10^{11} M_\odot$ (solid line) and a mass in cold gas larger than $3 \times 10^{10} M_\odot$ (dotted line). The merging rates are computed for a dynamical friction parameter of $\epsilon_{df} = 2.25$ (see Section 2.2 and the caption to Figure 3).

Figure 6. Redshift evolution of the comoving number density of bright quasars ($M_B < -26$). The filled squares are the results of the simulations for an accreted mass after each major merger of $M_{accr} = \min(3 \times 10^{-4}(1 + z)^3, 0.0125)M_{gas}$, an accretion time-scale of $2 \times 10^7$ yr and an efficiency for converting accreted mass into blue light of $\sim 3.8 \times 10^{-3}$. The solid lines show the evolution inferred from the luminosity function in La Franca & Cristiani (1996) and a fit to the counts of bright high redshift quasars in Schmidt et al. (1995).

Figure 7. Evolution of the quasar luminosity function between $z \sim 2$ and $z \sim 1$. The points show the results of the simulations for the model described in the caption of Figure 6. The solid lines give fits to the data for $z = 0.75, 1.25, 1.75, 2.25$ derived by La Franca & Cristiani (1996) assuming a double power law and a pure luminosity evolution.

We have investigated a very simple unified model in which both spheroids and supermassive BHs powering quasars form through mergers of galaxies of comparable masses. We have assumed that cooling only forms disk galaxies and that, whenever two galaxies of comparable masses merge, the merging remnant is an elliptical galaxy, a burst of star formation takes place and a fraction of the gas in the merging remnant is accreted by a central supermassive BH formed by the coalescence of the central BHs in the merging galaxies. We have found that this simple model is consistent with the shape of the quasar luminosity function, but we have also e.g. in a dependence on the angular momentum of the DM halo, in the dynamics of the merger (impact parameter, eccentricity, morphologies of the merging galaxies, etc.) or in the complicated hydrodynamics responsible for driving gas into the centre. If the upper limit is removed, the comoving density of bright quasars continues rising up to $z \sim 3$ and does not start declining until $z \gtrsim 4$. Kauffmann & Haehnelt (1999) have recently incorporated into semi-analytic models of galaxy formation a scheme for the growth of supermassive BHs similar to the one presented in this article, but containing a redshift dependence in the accretion time-scale ($t_{accr} \propto t_{dyn} \propto (1 + z)^{-1.5}$) rather than in the fraction of accreted mass. They find that the steep decline in the comoving density of bright quasars begins at $z \gtrsim 1$ rather than at $z \leq 2$, most likely because a scaling as $(1 + z)^{1.5}$ is insufficient to explain the striking evolution of the quasar population.

4 CONCLUSION
masses of supermassive BHs in nearby galaxies as compiled by Ho (1998) and Magorrian et al. (1998). See also Cattaneo, Haehnelt & Rees (1999).

found that its redshift evolution cannot be explained purely in terms of a decrease in the merging rate and of a decline in the amount of fuel available.

To explain the striking evolution of the space density of bright quasars in the interval $0 < z < 2$, we need to make additional assumptions, such as a dependence on redshift either in the fraction of available gas accreted or in the time-scale for accretion. With these additional assumptions it is possible to obtain results consistent with the redshift evolution of the quasar luminosity function and with the amount of scatter in the relation of BH mass to bulge luminosity (on this point see also Cattaneo, Haehnelt & Rees 1999).

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Figure 8. BH masses and bulge luminosities for an accreted mass after each major merger of $3 \times 10^{-4}(1+z)^3$ the mass of the cold gas in the merger remnant. This fraction increases with redshift up to a maximum of 1.25%. The introduction of this maximum value prunes points above the linear regression (some scatter survives due to spheroids which have suffered tidal disruption). The model shown in this figure gives a present mean mass density in supermassive BHs of $\sim 10^5 M_\odot Mpc^{-3}$. The solid lines enclose the region within $\pm 1\sigma$ in the linear least square fit to the data on the masses of supermassive BHs in nearby galaxies as compiled by Ho (1998) and Magorrian et al. (1998). See also Cattaneo, Haehnelt & Rees (1999).
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