The Astrophysical Journal, 587:L63–L66, 2003 April 20

QUASAR EVOLUTION DRIVEN BY GALAXY ENCOUNTERS IN HIERARCHICAL STRUCTURES

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Received 2003 January 28; accepted 2003 March 17; published 2003 April 1

ABSTRACT

We link the evolution of the galaxies in the hierarchical clustering scenario with the changing accretion rates of cold gas onto the central massive black holes that power the quasars. We focus on galaxy interactions as main triggers of accretion; the related scaling laws are taken from Cavaliere & Vittorini and grafted to a semianalytic code for galaxy formation. As a result, at high z the protogalaxies grow rapidly by hierarchical merging; meanwhile, much fresh gas is imported and also destabilized, so the holes are fueled at their full Eddington rates. At lower z the galactic dynamical events are mostly encounters in hierarchically growing groups; now the refueling peters out, as the residual gas is exhausted while the destabilizing encounters dwindle. So, with no parameter tuning other than that needed for stellar observables, our model uniquely produces a rise from $z \approx 6$ to 2.5, and for $z < 2.5$ a decline of the bright quasar population as steep as observed. In addition, our results closely fit the observed luminosity functions of quasars, their space density at different magnitudes from $z \approx 5$ to 0, and the local m_{BH}-σ relation.

Subject headings: galaxies: active — galaxies: evolution — galaxies: formation — galaxies: interactions — quasars: general

1. INTRODUCTION

Observations pinpoint massive dark objects, conceivably supermassive black holes (BHs) with masses $m_{BH} \sim 10^6$–$5 \times 10^9\ M_\odot$, at the center of most nearby bright galaxies (see Richstone et al. 1998). On the other hand, the space density of bright optical quasars (QSOs) is found to be lower by some 10^{-2} relative to the bright galaxies (see, e.g., Boyle et al. 2000).

These observations support the view of the QSOs as a short active phase (lasting $\Delta t \sim 10^8$ yr) of supermassive BHs that accrete surrounding gas at rates $\dot{m}_{acc} \sim 1$–$10^2\ M_\odot\ yr^{-1}$ (see Rees 1984). If the accretion history starts from small primordial seeds (Madau & Rees 2001), the accretion rate sets not only the QSO bolometric luminosities $L = \eta c^2 \dot{m}_{acc} \lesssim 10^{48}$ ergs s^{-1} (with standard mass-to-energy conversion efficiency $\eta \approx 0.1$; see, e.g., Yu & Tremaine 2002) but also the relic BH masses.

Additional observations relate the history of $\dot{m}_{acc}(z)$, and so the QSO evolution, with the galaxy structure and formation. These include the very magnitude of $\dot{m}_{acc}$ that needs to be drawn from the whole bulge of the hosts, and the correlation of m_{BH} with the bulge luminosities (see Richstone et al. 1998) or better with the velocity dispersion σ (Ferrarese & Merritt 2000; Gebhardt et al. 2000).

Relations of the sort have been explored in the hierarchical clustering scenario; here the galaxies condense from overdense regions in the primordial density field of the dark matter (DM), then are assembled into poor groups and eventually into rich clusters. Such attempts are based either on analytic approaches (see Cavaliere & Szalay 1986; Efstathiou & Rees 1988; Carlberg 1990; Haehnelt & Rees 1993; Haiman & Loeb 1998; Burkert & Silk 2001; Hatzminaoglou et al. 2002) or on semianalytic models (SAMs) of galaxy formation (see Kauffmann & Haehnelt 2000; Monaco, Salucci, & Danese 2000; Volonteri, Haardt, & Madau 2002). But the fraction $f \equiv \Delta m_{acc}/m_c$ actually accreted out of the galactic gas remained as a phenomenological quantity, described only in terms of scaling recipes, either containing tunable parameters or adjusted from the outset to the form of the observed correlations. Yet, all such models hardly accounted for the observed dramatic drop of the QSO population between $z \approx 2.5$ and the present.

On the other hand, a physical law for the accretion has been proposed by Cavaliere & Vittorini (2000, hereafter CV00); they suggested the amount of the cool galactic baryons accreted onto BHs to be given by the fraction f destabilized and sent toward the nucleus by the gravitational torques arising either in major merging events (at $z \gtrsim 3$) or in encounters of the host with other galaxies inside a common DM halo (at $z \lesssim 2.5$). They use two analytic evaluations for the two regimes; in the latter they derive declining encounter rates and fast gas exhaustion concurring to produce an interestingly steep evolution of bright QSOs.

Here we self-consistently compute halo and galactic quantities using a hierarchical SAM of the kind proposed by Kauffmann, White, & Guiderdoni (1993), Somerville & Primack (1999), and Cole et al. (2000). Specifically, we insert the CV00 model in the SAM developed by Menci et al. (2002); this includes galaxy interactions and accounts for several statistical properties of the galaxy population, such as counts, z-resolved luminosity functions (LFs), and sizes. This will allow us to continuously link the accretion history $\dot{m}_{acc}(z)$ and the QSO evolution with a fiducial model of galaxy formation consistent with the stellar observables.

2. MODELING THE GALAXY EVOLUTION

The independent variables of our SAM (Menci et al. 2002) are the circular velocity V of the host DM halos (groups and clusters of galaxies with mass M and virial radius R) containing the galaxies and the circular velocity v of the DM clumps associated with the individual member galaxies. The former grow hierarchically to larger sizes through repeated merging events (at the rate given in Lacey & Cole 1996), while the latter may coalesce either with the central galaxy in the common halo due to dynamical friction or with other satellite galaxies through binary aggregations. The timescale for such galactic processes generally exceeds the timescale for the merging of the host halos, so member galaxies accumulate in growing host halos.

At the cosmic time t, the SAM yields the following dynamical quantities:

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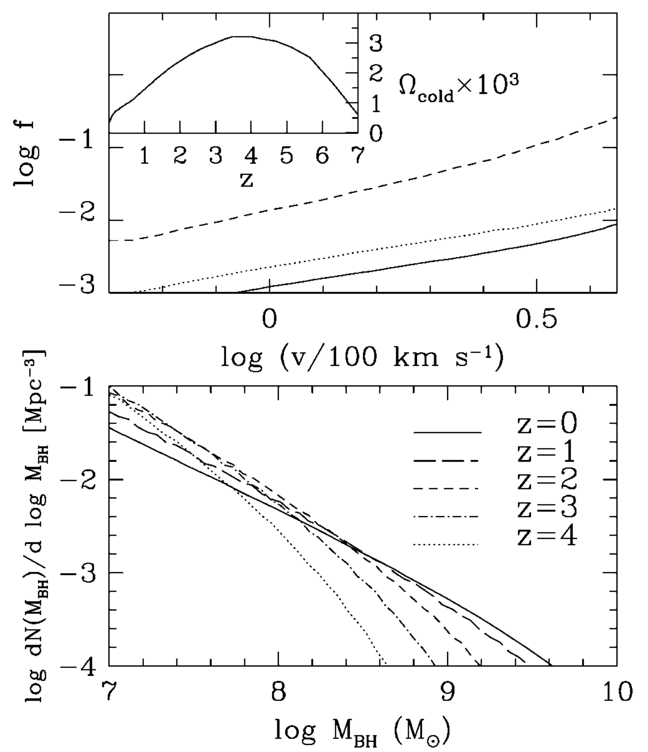

FIG. 1.—*Top*: Fraction of cold gas accreted onto BHs as a function of the circular velocity of the host galaxy at $z = 0.4$ (*solid line*), $z = 1$ (*dotted line*), and $z = 3$ (*dashed line*). The inset shows the cosmological density of all the available cold gas in galaxies as a function of the redshift z. *Bottom*: Mass function of BHs for various values of the redshift z.

1. The distribution $N(v, V, t)$ (in units of Mpc^{-3}) of galaxies with circular velocity in the range $v - v + dv$ in host halos with circular velocity in the range $V - V + dV$. This is derived by computing iteratively the probability for a host halo to be formed from its progenitors, together with the probability that the member galaxies coalesce because of either dynamical friction or binary aggregations. As initial condition we assume a Press & Schechter distribution, and we assign one galaxy to each host halo. From $N(v, V, t)$, we derive the number $N_T(V, t)$ of galaxies in a host halo (membership) and the overall distribution of galaxy circular velocity $N(v, t)$ irrespective of the host halo.

2. The tidal radius $r_t(v)$ and the disk radius $r_d(v)$ and rotation velocity $v_d(v)$ computed after Mo, Mao, & White (1998).

3. The average relative velocity $V_{\rm rel}(V)$ of the galaxies in a common DM halo.

These dynamical quantities are associated with the baryons contained in the galactic DM halos in the way standard for SAMs. Initially the baryons contained in a galactic halo are in the amount $m\Omega_b/\Omega$ (with $m \propto v^3$ the DM mass of the galaxies) and at the virial temperature; the mass m_c of cold baryons is that residing in regions interior to the "cooling radius." Stars are allowed to form with rate $\dot{m}_* = (m_c/t_{\rm dyn})(v/200\ \mathrm{km\ s^{-1}})^{-\alpha_*}$, with the disk dynamical time evaluated as $t_d = r_d/v_d$. Finally, a mass $\Delta m_h = \beta m_*$ is returned from the cool to the hot gas phase because of the energy fed back by canonical Type II supernovae associated with m_*. The feedback efficiency is taken to be $\beta = (v/v_h)^{\alpha_h}$. The values adopted for the parameters $\alpha_* = -1.5$, $\alpha_h = 2$, and $v_h = 150\ \mathrm{km\ s^{-1}}$ fit both the local *B*-band galaxy luminosity function and the Tully-Fisher relation, as illustrated by Menci et al. (2002). At each merging event, the masses of the different baryonic phases are refueled by those in the merging partner; the further increments Δm_c, Δm_*, and Δm_h from cooling, star formation, and feedback are recomputed iterating the procedure described above.

All computations are made in a Λ cold dark matter cosmology with $\Omega_0 = 0.3$, $\Omega_\lambda = 0.7$, a baryon fraction $\Omega_b = 0.03$, and Hubble constant $h = 0.7$ in units of $100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$.

3. BH ACCRETION TRIGGERED BY GALAXY ENCOUNTERS

Here we recall the key points of CV00 and recast their main equations in a form suitable for implementation in our SAM. For a galaxy with given v, the accretion of a fraction f of the cold gas onto the central BH is intermittently triggered by interactions occurring at a rate

$$\tau_r^{-1} = n_T(V)\Sigma(v, V)V_{\rm rel}(V). \quad (1)$$

Here $n_T = N_T/(4\pi R^3/3)$, and the cross section $\Sigma(v, V) \approx \pi\langle(r_t^2 + r_t'^2)\rangle$ is averaged over all partners with tidal radius r_t' in the same halo V. To this effect, the sizes, the relative velocities of the galaxies, and the distribution of galaxy circular velocities in a common halo are previously computed from the SAM sector described in § 2.

The fraction of cold gas accreted by the BH in each interaction event is computed in equation (A3) of CV00 in terms of the variation Δj of the specific angular momentum $j \approx Gm/v_d$ of the gas, to read

$$f(v, V) \approx \frac{1}{8}\left|\frac{\Delta j}{j}\right| = \frac{1}{8}\left\langle\frac{m'}{m}\frac{r_d}{b}\frac{v_d}{V}\right\rangle. \quad (2)$$

Here $b = \max\,[r_d, \bar{d}\,(V)]$ is the impact parameter, evaluated as the maximum between the galaxy r_d and the average distance $\bar{d}(V) = R/N_T^{1/3}(V)$ of the galaxies in the halo. Also, m' is the mass of the partner galaxy in the interaction, and the average runs over the probability of finding a galaxy with mass m' in the same halo V where the galaxy m is located. The prefactor accounts for the probability ($\frac{1}{2}$) of inflow rather than outflow related to the sign of Δj and for the fraction ($\frac{1}{4}$) of the inflow actually reaching the nucleus rather than kindling circumnuclear starbursts (see Sanders & Mirabel 1996).

Note from equations (1) and (2) that both the interaction rate τ_r^{-1} and the accreted fraction f decrease with time, since in the growing host halos the increasing membership $N_T(V)$ is offset by the increasing R, V, and $V_{\rm rel}$. In a group, the values for f range from a few times 10^{-1} to several times 10^{-3}. The above behavior of the accreted fraction f is illustrated in Figure 1 (*top panel*).

The average gas accretion rate triggered by interactions at z is given by (eq. [5], CV00)

$$\dot{m}_{\rm acc}(v, z) = \left\langle\frac{f(v, V)m_c(v)}{\tau_r(v, V)}\right\rangle, \quad (3)$$

where the average is over all host halos with circular velocity V. The bolometric luminosity so produced by the QSO hosted in a given galaxy is then given by

$$L(v, t) = \frac{\eta c^2 \Delta m_{\rm acc}}{\tau}. \quad (4)$$

Here $\tau \approx t_d \sim 5 \times 10^7 (t/t_0)$ yr is the duration of the accretion

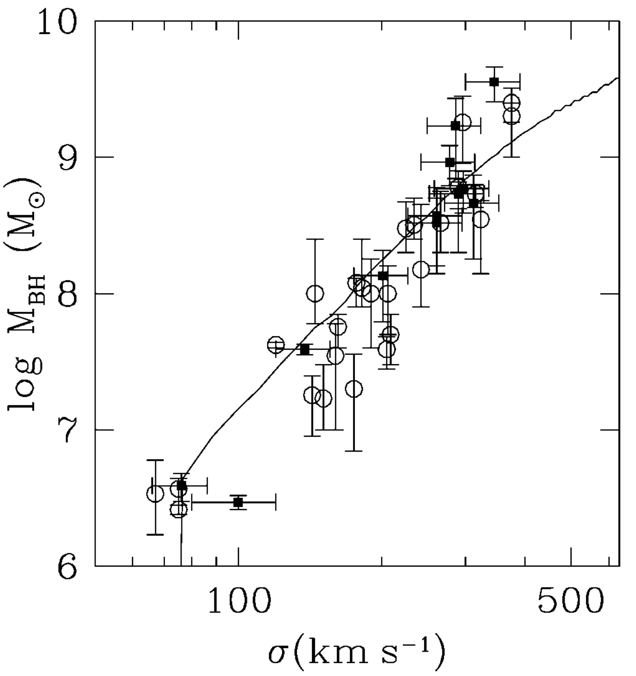

FIG. 2.—Derived relation between the BH mass and the one-dimensional velocity dispersion of the host galaxy (*solid line*) is compared with data from Ferrarese & Merritt (2000, *filled squares*) and Gebhardt et al. (2000, *circles*).

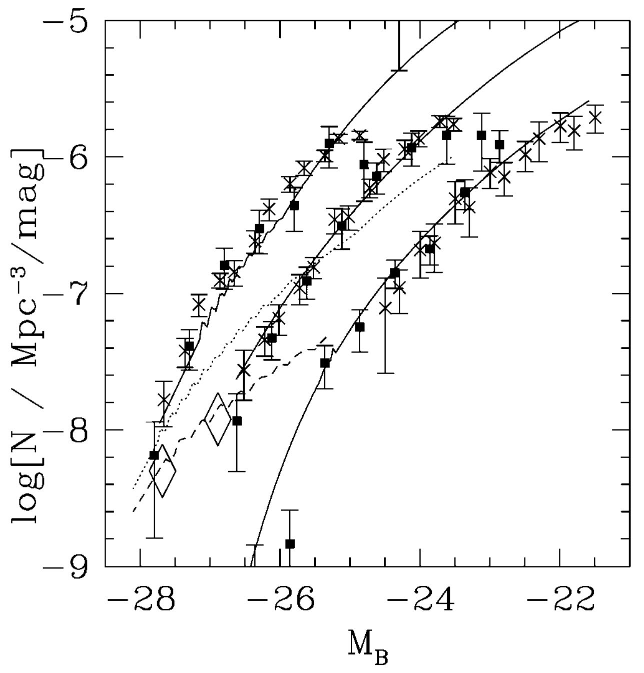

FIG. 3.—LFs from our model (*solid lines*) are shown for $z = 0.55$ (*bottom curve*), $z = 1.2$ (*middle curve*), and $z = 2.2$ (*top curve*) and are compared with the data points. These are taken from Hartwick & Shade (1990, *filled squares*) and Boyle et al. (2000, *crosses*) and rescaled to our cosmology with $\Omega_0 = 0.3$, $\Omega_\lambda = 0.7$, and $h = 0.7$. We also show as a dashed line the model LF for $z = 4.2$ compared to the Sloan data from Fan et al. (2001, *diamonds*). The dotted line is the predicted LF for $z = 3.4$.

episode, i.e., the timescale for the QSO to shine; Δm_{acc} is the gas accreted at the rate given by equation (3). We take $\eta = 0.1$, and we obtain the blue luminosity L_B by applying a bolometric correction of 13 (Elvis et al. 1994).

The mass of the BH hosted in a galaxy with given v at time t is updated after

$$m_{BH}(v, t) = (1 - \eta) \int_0^t \dot{m}_{acc}(v, t')dt', \quad (5)$$

assuming in all galaxies small seed BHs of mass $10^2\ M_\odot$ (Madau & Rees 2001); our results are insensitive to the specific value as long as it is smaller than $10^5\ M_\odot$.

4. RESULTS

In Figure 1 (*bottom*), we plot the mass function of BHs at four different redshifts. Note the mild evolution from $z = 1$ to the present, due to the decrease of the accreted fraction f (see Fig. 1, *top*) and of the related Δm_{acc} due to the declining rate of merging and encounters (see § 3) and to the simultaneous exhaustion of the galactic cold gas $m_c(z)$ available for accretion (see inset in Fig. 1).

The relation that we obtain between the BH mass and the central one-dimensional velocity dispersion σ of the host galaxy is shown in Figure 2. We use the canonical relation $\sigma = v/\sqrt{2}$ approximately holding for an isothermal profile (see Binney & Tremaine 1987).

The steep slope of our relation (close to $M_{BH} \propto \sigma^4$ in the range $10^7\ M_\odot \lesssim M_{BH} \lesssim 10^9\ M_\odot$) is the combined result of two processes: the merging histories of the galactic DM clumps, which by themselves would imply the mass of cold available gas to scale as $\sigma^{2.5}$, and the destabilization of the cold gas by the interactions, which steepens the relation to $\sigma^{3.5}$. The further steepening to σ^4 is provided by the supernovae feedback, which depletes the residual gas content in shallow potential wells. No effort has been made to adjust the latter to match the relation to the data; a slope steeper yet would be provided, especially in the upper range, by adding the feedback from the QSO emission itself onto the host gas (which does not alter the average galactic star formation in a group).

The evolving LF of the QSOs is derived from $N(v, t)$ by applying the appropriate Jacobian; see § 3. The LF will include a factor $\tau/\langle\tau_r(v)\rangle < 1$, since the luminosities in equation (4) last for a time τ and are rekindled after an average time τ_r. The result is

$$N(L, t) = N(v, t)\frac{\tau}{\langle\tau_r\rangle}\left|\frac{dv}{dL}\right| \quad (6)$$

and is shown in Figure 3. Note the strong evolution from $z \approx 0.5$ to 2, due to both the declining $\Delta m_{acc}(z)$ and the timescale τ shortening at higher z.

In Figure 4, we plot the predicted cosmic density $\rho_Q(z)$ of QSOs brighter than $M_B = -24$ and -26. The computed emissions, limited by the Eddington luminosity L_{Edd}, peak at $z \approx 2.5$; such redshifts are those in which our SAM predicts the buildup of bright galaxy to peak (see Menci et al. 2002). Note that if no Eddington limit were imposed, the density would be that represented by the dashed line in the bottom panel, which overshoots the data; this shows that at $z > 2.5$ the QSOs do emit at their full L_{Edd} because of the high merging rate that provides abundant refueling. At later times, the fueling is triggered mostly by the interactions, with encounter rate declining as discussed in § 3, and draws from scarce residual gas approaching exhaustion. These processes cause the dramatic fall of the QSO density that we predict for redshifts $z < 2$.

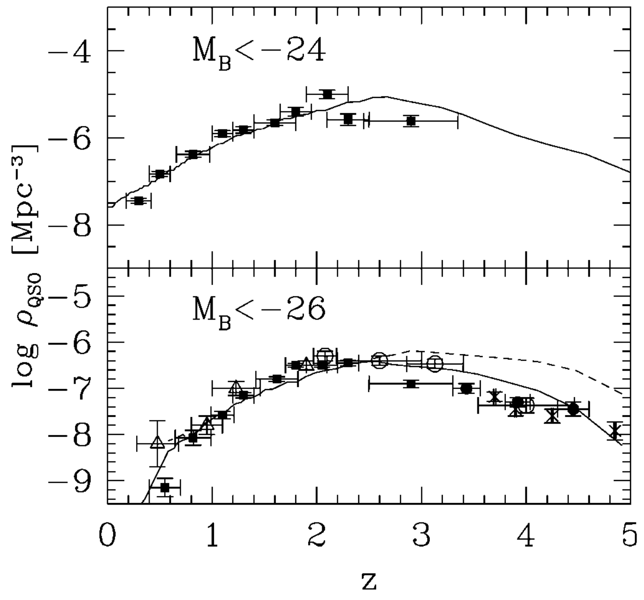

FIG. 4.—Predicted cosmic density of bright (*top*) and very bright (*bottom*) QSOs. The dashed line represents the outcome when no Eddington limit was assumed (see text). The densities have been rescaled as appropriate for the critical cosmology with $h = 0.5$ used by the authors for their (magnitude-limited) data; these are taken from Hartwick & Shade (1990, *filled squares*), Goldschmidt & Miller (1998, *triangles*), Warren, Hewett, & Osmer (1994, *open circles*), Schmidt, Schneider, & Gunn (1995, *filled circles*), and Fan et al. (2001, *crosses*).

5. CONCLUSIONS

Our approach links the evolution of QSOs to that of their host galaxies on using scaling laws for the BH accretion based on triggering galaxy interactions, with no new parameters added to the galaxy formation model. It provides good fits to the observations concerning the m_{BH}-σ correlation, the evolution of the QSO luminosity function, and their space density selected at different optical magnitudes. The agreement holds in the full range $z < 6$ *continuously* covered by our model and supports the underlying picture that follows.

At $z > 2.5$, the QSOs emit at their full Eddington limit, because the high merging rate in this epoch of galaxy assemblage insures both a high baryonic content in their hosts and an abundant BH fueling. As shown in Figure 3, in this range the LFs are *flat* (consistent with recent data; see Fan et al. 2003) and *rise* with time. At $z < 2.5$, the steep drop that we find for the population results from three concurring processes: (1) the declining rate of merging between early galaxies, which halts the acquisition of new gas available for accretion, (2) the progressive exhaustion of the baryon reservoirs in the hosts, consumed by fast conversion into stars and by previous accretion episodes, and (3) the eventual decline of the fraction $f \sim \Delta j/j$ of residual cold gas, which is destabilized and accreted onto the central BHs by the dwindling interactions between galaxies. The latter decline (see Fig. 1) is at variance with the Kauffmann & Haehnel (2000) model and is crucial in matching the observed strong evolution of QSOs at $z < 2$; as a consequence, our model predicts an average Eddington ratio dropping from $L/L_{Edd} \sim 1$ at $z \approx 2.5$ to $L/L_{Edd} \sim 10^{-2}$ at $z \approx 0$, with a weak dependence on m_{BH}, consistent with the available data (see Woo & Urry 2002).

The above picture implies a specific connection of the QSO emission with observable properties of their host galaxies that we will investigate in our next paper. Here we only stress that in our present model, the host galaxies of bright QSOs have dynamic properties conducive to strong interactions, and hence to high luminosities, at early z.

Work supported by Agenzia Spaziale Italiana and the Ministero dell'Istruzione dell'Università e della Ricerca.

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