Mem. S.A.It. Suppl. Vol. 5, 205

Memorie della
Supplementi

Co-evolution of Galaxies and AGNs in Hierarchical Models of Galaxy Formation

N. Menci[1], A. Cavaliere[2], E. Giallongo,[1] and A. Fontana[1]

[1] INAF, Osservatorio Astronomico di Roma, via di Frascati 33, 00040 Monte Porzio e-mail: menci@mporzio.astro.it.it
[2] Dipartimento di Fisica, Universitá di Roma "Tor Vergata", via della Ricerca Scientifica 1, 00133 Roma, Italy

Abstract. We include into a semi-analytical model of galaxy formation a physical description of starbursts and of the feeding of supermassive black holes (BHs), powering the Active Galactic Nuclei (AGNs). Both such processes originate from the destabilization of cold galactic gas in galaxy encounters, occuring mainly at redshifts $z \approx 2-4$, preferentially in massive objects, during the phase of galaxy formation characterized by frequent merging events. At lower z, galaxy interactions become rarer and rarer and the residual gas available for accretion is progressively exhausted; the refueling peters out, the BH accretion is occasionally rekindled by encounters. So, our model uniquely produces at $z > 3$ a rise, and at $z < 2.5$ a decline of the bright quasar (QSO) population as steep as observed, coupled to an almost passive evolution of the galactic stellar populations in massive galaxies. The high-z star formation rate and B-band luminosity functions, and the luminosity and redshift distribution of galaxies in K-band at $z < 2$ are all in good agreement with the existing observations concerning the bright galaxy population. As for the AGNs, our results closely fit the observed luminosity functions of QSOs, their density from $z \approx 5$ to $z \approx 0$, and the local $m_{BH} - \sigma$ relation.

Key words. Galaxies: active –Galaxies: formation – Galaxies: interactions – Cosmology: theory

1. Introduction

The finding of supermassive black holes (BHs) with masses $m_{BH} \sim 10^6 - 5\,10^9\,M_\odot$, at the center of most nearby bright galaxies (Richstone et al. 1998), and the low space density of bright optical quasars (QSOs) compared to galaxies (see Boyle et al. 2000), support the view of QSOs as a short ($\Delta t \sim 10^8$ yrs) active phase of supermassive BHs which accrete surrounding gas at rates $\dot{m}_{acc} \sim 1 - 10^2\,M_\odot$/yr, (see Rees 1984). If the accretion history starts from small primordial seeds (Madau & Rees 2000), the accretion rate sets not only the QSO bolometric luminosities up to $L = \eta\, c^2\, \dot{m}_{acc} \approx 10^{48}$ erg/s (with standard mass-to-energy conversion efficiency $\eta \approx 0.1$ (see Yu & Tremaine 2002), but also the relic BH masses. The correlation of m_{BH} with the velocity dispersion σ of the galactic bulge (Ferrarese & Merrit 2000; Gebhardt et al. 2000) indicate that the history of $\dot{m}_{acc}(z)$ is related to the structure and the formation of the host galaxy.

Send offprint requests to: N. Menci

On the other hand, in the hierarchical scenario of galaxy formation, current semi-analytic models (SAMs, Kauffmann et al. 1993; Somerville & Primack 1999; Cole et al. 2000; Menci et al. 2002) envisage the build up of stars in galaxies as a gradual process driven by the progressive growth of the host dark matter (DM) galactic haloes through repeated merging events. These progressively increase the galactic gas content; its subsequent radiative cooling (providing the gas reservoir for both the star formation and the BH accretion) is partially counteracted by the heating due to the Supernovae winds originated from the previous massive stars. The net result is a gradual increase of the stellar content of the galaxies ("quiescent" star formation) and of the QSO activity at high z, while at lower z the gas consumption inhibits both the star formation and the gas accretion onto BHs.

The quantitative predictions of the above models are challanged by several observational results, which indicate that:
a) the star formation rate at high $z > 3$ is larger than the predicted rate: this is indicated by the excess of bright galaxies in the K-band luminosity functions (LFs) at intermediate redshifts ($z \approx 1-2$, see Pozzetti et al. 2003), and by the corresponding execess of $K < 20$ sources in the counts at $z > 1.5$ (Cimatti et al. 2002), see fig. 1. Since the emission in the K-band is largely contributed by old stellar population, and so is a measure of the amount of stars already formed, the above observations imply that a significant fraction (~ 0.2) of the present star content of massive ($m_* \approx 10^{10} - 10^{11}\ M_\odot$) galaxies is already in place at $z \sim 2$, while the gradual star formation typical of SAMs yields a fraction ~ 0.1.
b) the low-z decline of the QSO population is faster than that resulting from the models: indeed, the number density of QSO with $M_B < -24$ drops by almost three orders of magnitude from $z = 2$ to $z = 0$, a behaviour much steeper than that resulting from the SAMs which predict (at $z = 0$) a population of QSO five times larger.

Here we seek for a unique solution of the two problems above, by including in the SAM a description of the starbursts triggered by galaxy encounters (including the fly-by, i.e., grazing encounters not leading to bound merging). The description we adopt for the latter is based on the physical model for the destabilization of cold galactic gas during galactic merging and fly-by developed by Cavaliere & Vittorini (2000 hereinafter CV00) . The destabilized gas is assumed to feed in part the accretion onto a central supermassive BH (powering the corresponding QSO) and in part a burst of star formation. The amount of destabilized gas, the duration of the bursts, and their rate (set by the galaxy encounters) are determined by the physical properties of the galaxies and of their host halos (groups or clusters) derived from our SAM, see Menci et al. (2002).

2. The SAM Model

The model we adopt is described in detail in Menci et al. (2003, 2004a, 2004b). Here we recall the basic points:

We follow the merging histories of DM clumps, adopting the Extended Press & Schechter description (Lacey & Cole 1993). Initially, one galaxy is associated to each DM halo; when two haloes merge, the contained galaxies merge on a longer timescale, either with the central dominant galaxy (due to the orbital decay produced by dynamical friction) or with other "satellite" galaxies orbiting the same DM halo ("binary aggregations"). Thus, we follow the evolution of the mass distribution of galaxies in the host DM haloes, along the merging tree. We describe the potential depth of the DM halo associated to a single galaxy through its circular velocity v, while the cricular velocity of the halos hosting the galaxies (groups and clusters) is V; the model also computes the tidal radius r_t associated to galaxies with given v.

The properties of the gas and stars contained in the galactic DM clumps are computed following the standard recipes commonly adopted in SAMs. Starting from an initial gas amount $m\,\Omega_b/\Omega$ ($m \propto v^3$ being the DM mass of the galaxies) at the virial temperature of the galactic halos, we compute the mass m_c of cold baryons which are able to radiatively cool in the densest, central regions. This settles in a rotationally supported disk whose radius r_d and rotation velocity v_d is computed after Mo, Mao, & White (1998). Stars form with rate $\dot{m}_* \propto (m_c/t_d)$ with the disk dynamical time evaluated as $t_d = r_d/v_d$. Finally, a mass $\Delta m_h = m_* \, (v/v_h)^{\alpha_h}$ is returned from the cool to the hot gas phase due to the energy fed back by canonical type II Supernovae associated to m_*. The values adopted for the free parameters $\alpha_* = -1.5$, $\alpha_h = 2$ and $v_h = 150$ km/s fit both the local B-band galaxy LF and the Tully-Fisher relation, as illustrated by Menci et al. (2002). The model also matches the bright end of the galaxy B-band LFs up to redshifts $z \approx 3$ (see Poli et al. 2003) and the resulting global star formation history is broadly consistent with that observed up to redshift $z \approx 4$ (Fontana et al. 1999).

At each merging event, the masses of the different baryonic phases are replenished by those in the merging partner; the further increments Δm_c, Δm_*, Δm_h from cooling, star formation and feedback are recomputed on iterating the procedure described above.

The resulting star formation rate (for a given v) is convolved with the spectral energy distribution ϕ_λ obtained from population synthesis models (Bruzual & Charlot 1993) to obtain the integrated galactic stellar emission $S_\lambda(v,t)$ at the wavelength λ.

3. Encounters Triggering Starbursts and BH Accretion

A quantitative model to derive the fraction f of cold gas destabilized by the encounters has been worked out by (CV00) and has been inserted into a SAM by Menci et al. (2003, 2004a)

For a galactic halo with given circular velocity v inside a host halo (group or cluster) with circular velocity V and virial radius R, grazing encounters occur at a rate

$$\tau_r^{-1} = n_T(V)\,\Sigma(v,V)\,V_r(V)\,. \tag{1}$$

Here $n_T = 3\,N_T/4\pi R^3$, 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' and circular velocity v' in the same halo V. The membership $N_T(V)$ (i.e., the number of galaxies contained in a group or cluster with circular velocity V), the distributions of v', r_t', and the relative velocity $V_r = \sqrt{2}\,V$ are computed from the SAM. The duration of each encounter is defined as $\tau_e = \langle (r_t + r_t^{'})/V\rangle$ (with an upper limit given by τ_r).

The fraction of cold gas which is destabilized in each interaction event and feeds the starbursts is derived from eq. A3 of CV00 in terms of the variation Δj of the specific angular momentum $j \approx Gm/v_d$ of the gas;

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

The average runs over the probability of finding a galaxy with mass m' in the same halo V where the galaxy m is located, and the impact parameter b is computed in the SAM. The prefactor accounts for the probability 1/2 of inflow rather than outflow related to the sign of Δj.

We assume that $1/4$ of the destabilized fraction f feeds the central BH, while the remaining fraction is assumed to kindle circumnuclear starbursts, see Sanders & Mirabel (1996). Thus, the star formation rate in the nuclear region due to interaction-driven bursts is given by

$$\dot{m}_* = (3/4)\,f\,m_c/\tau_d. \tag{3}$$

This adds to the continuous, "quiescent" star formation rate $\dot{m}_* = m_c/\tau_d$.

On the other hand, the average gas accretion rate onto the central black hole as

$$\dot{m}_{acc}(v,z) = \left\langle \frac{f(v,V)\;m_c(v)}{4\,\tau_r(v,V)}\right\rangle, \tag{4}$$

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

$$L(v,t) = \frac{\eta\,c^2 \Delta m_{acc}}{\tau_e}\,. \tag{5}$$

Δm_{acc} is the gas accreted at the rate given by eq. (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

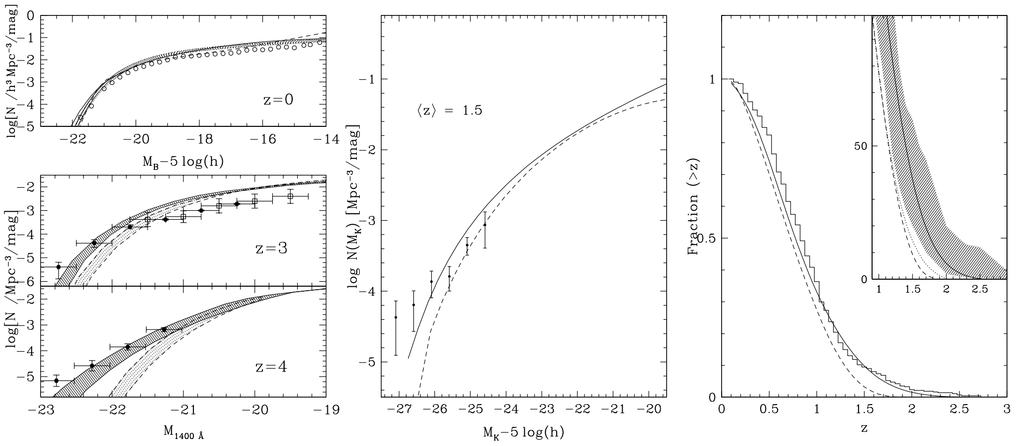

Fig. 1. Left Panels: The predicted LFs of galaxies in the quiescent (dashed lines) and starburst models (solid lines) at $z \approx 0$ (in the B-band, top panel) and at $z = 3-4$ (at 1400 Å, bottom panels). In the top panel, the shaded area is the LF measured by the Sloan Digital Sky Survey (Blanton et al. 2001), and the circles are the data from the 2dFGRS survey (Madgwick et al. 2002). In the bottom panel, the two solid lines refer to the burst model and braket the uncertain due to diferent dust extinction curves; similarly for the dashed curves referring to quiescent model. The spectroscopic data are from Steidel et al. (1999). Middle panel: the K-band galaxy LFs at $z = 1.5$ in the quiescent (dashed line) and in the starburst model (solid line) are compared with the data from the K20 survey (Pozzetti et al. 2003). Right panel: the corresponding cumulative z-distribution of $m_k < 20$ galaxies is compared with observations from the K20 survey (Cimatti et al. 2002). The inset shows the cumulative distribution in the range $1 < z < 3$ with the 3σ Poissonian confidence region (shaded area); the dotted line reproduces from Cimatti et al. (2002) the prediction of the SAM by Somerville, Primack & Faber (2001).

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

$$m_{BH}(v,t) = (1-\eta)\int_0^t \dot{m}_{acc}(v,t')\,dt' \qquad (6)$$

assuming in all galaxies small seeds BHs of mass $10^2\,M_\odot$ (Madau & Rees 2000); our results are insensitive to the specific value as long as it is smaller than $10^5\,M_\odot$.

4. Results

The effect of starbursts on the B, UV, and K-band LFs of galaxies, and on the K-band counts is shown in fig. 1.

The starbursts brighten the B and UV emission (probing mainly the star formation rate) in particular at high $z > 3$, where interactions are more frequent, and leave almost unchanged the faint end of the LFs, since the smaller sizes r_d and the slower rotation velocities v_d of less massive galaxies imply lower values of both the interaction rate and the accreted fraction f. The K-band LF is brightened by ~ 0.5 mag at $z \sim 1.5$, causing it to match the observed shape of the LFs (left top panel). Correspondingly, the burst model *matches* the observed number of luminous ($m_K < 20$) galaxies at $z \approx 1.5$, while the quiescent model underpredicts the number by a factor $\sim 3-4$.

The results of the model for the QSO population are shown in fig. 2. Note that the model is able to match the observed $M_{BH}-\sigma$ relation whose logarithmic slope ≈ 4 is the combined result of different processes: the merging histories of the galactic DM clumps, which by themselves would imply the mass of cold available gas to scale as $\sigma^{2.5}$; the destabilization of

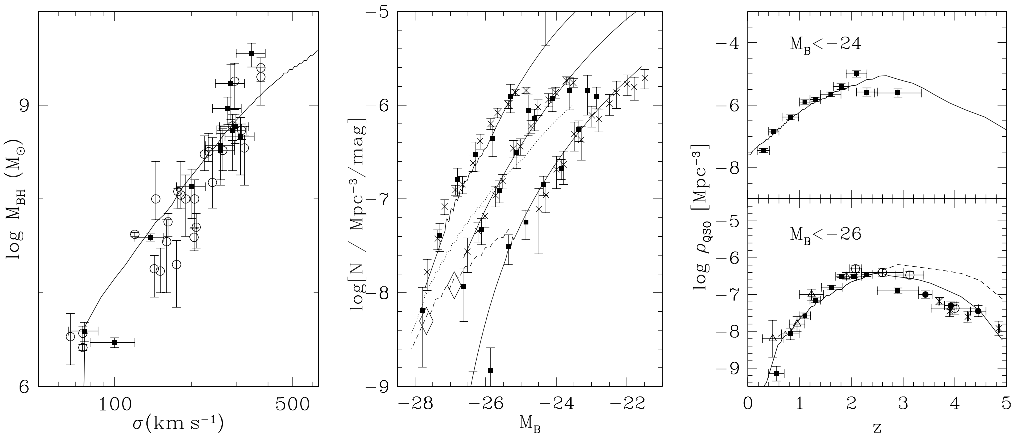

Fig. 2. Left Panel: The predicted $M_{BH} - \sigma$ relation is compared with data from Ferrarese & Merrit (2000 filled squares) and Gebhardt et al. (2000 circles). Middle panel: The LFs from our model (solid lines) are shown for $z = 0.55$ (lower curve), $z = 1.2$ (middle curve) and $z = 2.2$ (uppermost curve), and are compared with the data points. These are taken from Hartwick & Shade (1990, solid squares) and Boyle et al. (2000, crosses), and rescaled to our cosmology. The dashed line is 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 $z = 3.4$. Right Panel: The predicted cosmic density of bright (upper) and very bright (bottom panel) QSOs, rescaled to a critical cosmology ($h = 0.5$), to compare with the data; these are taken from Hartwick & Shade (1990), solid squares; Goldschmidt & Miller (1998), triangles; Warren Hewett & Osmer (1994), open circles; Schmidt, Schneider & Gunn (1995), filled circles; Fan et al. (2001), crosses. The dashed line represents the outcome when no Eddington limit is assumed.

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. Note also that the evolution of the QSO density resulting from the model shows a decline from $z = 2$ to the present as fast as that observed.

5. Conclusions

The global picture emerging from our model is the following. 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 fig. 3, in this range the LFs are *flat* and *rise* with time. In this epoch, interactions also trigger strong starbursts which allow to build up a consistent fraction of the stellar content of massive galaxies, so as to match the observed K-band luminisity functions and counts. At $z < 2.5$ the *steep drop* we find for both the starbursts and for the QSO phase of galactic nuclei 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; 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 Eddington ratio in AGNs drops from $L/L_E \sim 1$ at $z \approx 2.5$ to $L/L_E \sim 10^{-2}$ at $z \approx 0$, with a weak dependence on m_{BH}, consistent the with available data (see Woo & Urry 2002), and the massive galaxies (which underwent a strong starburst phase at higher z and have now almost exhausted the cold gas reservoir) enter a phase of almost passive evolution.

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