A PHYSICAL MODEL FOR THE JOINT EVOLUTION OF HIGH Z QSOS AND SPHEROIDS

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We summarize our physical model for the early co-evolution of spheroidal galaxies and of active nuclei at their centers. Our predictions are in excellent agreement with a number of observables which proved to be extremely challenging for all the current semi-analytic models, including the sub-mm counts and the corresponding redshift distributions, and the epoch-dependent K-band luminosity function of spheroidal galaxies. Also, the black hole mass function and the relationship between the black hole mass and the velocity dispersion in the galaxy are nicely reproduced. The mild AGN activity revealed by X-ray observations of SCUBA sources is in keeping with our scenario, and testify the build up of SMBH triggered by intense star formation.

1. Introduction

The standard Lambda Cold Dark Matter (ΛCDM) cosmology is a well established framework to understand the hierarchical assembly of dark matter (DM) halos. Indeed, it has been remarkably successful in matching the observed large-scale structure. However the complex evolution of the baryonic matter within the potential wells determined by DM halos is still an open issue, both on theoretical and on observational grounds.

Full simulations of galaxy formation in a cosmological setting are far beyond present day computational possibilities. Thus, it is necessary to introduce at some level rough parametric prescriptions to deal with the physics of baryons, based on sometimes debatable assumptions. A class of such models, known as semi-analytic models, has been extensively compared with the available information on galaxy populations at various redshifts (see Granato et al. 2000 and references therein).

The general strategy consists in using a subset of observations to calibrate the many model parameters providing a heuristic description of baryonic processes we don't properly understand. Besides encouraging successes, current semi-analytic models have met critical inconsistencies which seems to be deeply linked to the standard recipes and assumptions. These problems are in general related to the properties of elliptical galaxies, such as the color-magnitude and the [α/Fe]-M relations (Cole et al. 2000; Thomas 1999), and the statistics of sub-mm and deep IR selected (I- and K-band) samples).

These data would be more consistent with the traditional "monolithic" scenario, according to which elliptical galaxies formed most of their stars in a single burst, at relatively high redshifts, and underwent essentially passive evolution thereafter. However the strict "monolithic" scheme cannot be fitted in a consistent model for structure formation from primordial density perturbations.

However, the general agreement of a broad variety of observational data with the hierarchical scenario and the fact that the observed number of luminous high-redshift galaxies, while substantially higher than predicted by semi-analytic models, is nevertheless consistent with the number of sufficiently massive dark matter halos, indicates that we may not need alternative scenarios, but just some new ingredients.

Previous work by our group (Granato et al. 2001; Romano et al. 2002; Granato et al. 2004) suggests that a crucial ingredient is the mutual feedback between spheroidal galaxies and active nuclei at their centers. important clues to understand the formation and evolution of spheroids arise from the now well established correlation between their stellar mass (or velocity dispersion) and the mass of the supermassive black hole (SMBH) hosted in their centers, and responsible for high-z quasar activity.

Granato et al. (2004, henceforth GDS04) presented a detailed physically motivated model for the early co-evolution of the two components, in the framework of the ΛCDM cosmology. The model has been built following suggestions of a scenario previously explored with a partly empirical approach (Granato ϵ

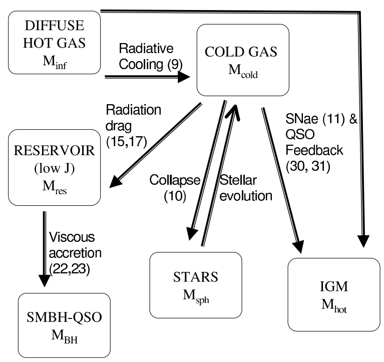

Figure 1. Scheme of the baryonic components included in the model (boxes), and of the corresponding mass transfer processes (arrows). The numbers near the arrows point to the main equations describing those processes in Granato et al. (2004).

2. Model description

The model follows with simple, physically grounded, recipes and a semi-analytic technique the evolution of the baryonic component of proto-spheroidal galaxies within massive dark matter (DM) halos forming at the rate predicted by the standard hierarchical clustering scenario for a ΛCDM cosmology. The main difference with respect to other models is the central role attributed to the mutual feedback between star formation and growth of a super massive black hole (SMBH) in the galaxy center. Indeed, the treatment include plausible prescriptions for the chain of processes leading to SMBH growth trough accretion, and for the effects on the ISM of the ensuing QSO activity. A scheme of the baryonic components included in the model, and of the relevant transfer processes is shown in Fig. 1.

The kinetic energy fed by supernovae is increasingly effective, with decreasing halo mass, in slowing down (and eventually halting) both the star formation and the gas accretion onto the central black hole. On the contrary, star formation and black hole growth proceed very effectively in the more massive halos, until the energy injected by the active nucleus in the surrounding interstellar gas unbinds it, thus halting both the star formation and the black hole growth (and establishing the observed relationship

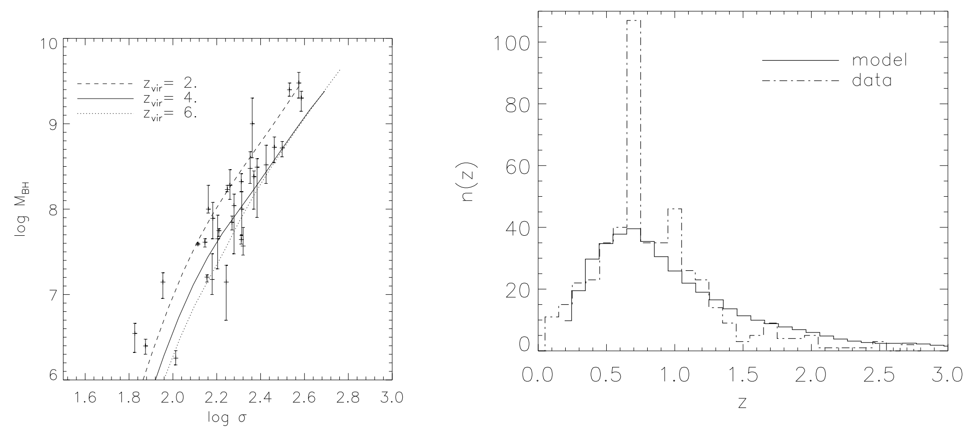

Figure 2. Left: predicted relationship between black-hole mass and line-of-sight velocity dispersion of the host galaxy for different virialization redshifts. Right: Predicted redshift distribution of galax- ies brighter than K = 20 compared with the re- sults of the K20 survey

between black hole mass and stellar velocity dispersion or halo mass, see Fig. 2). As a result, the physical processes acting on baryons reverse the order of the formation of spheroidal galaxies with respect to the hierarchical assembling of DM halos, in keeping with the previous proposition by Granato et al. (2001).

Not only the black hole growth is faster in more massive halos, but also the feedback of the active nucleus on the interstellar medium is stronger, to the effect of sweeping out such medium earlier, thus causing a shorter duration of the active star-formation phase (for more details, see GDS04).

According to GDS04 (as well as Granato et al. 2001), the high redshift QSO activity marks and concur to the end of the major episode of star formation in spheroids. Thus there is a clear evolutionary link between the SCUBA sources and high-z QSOs. Indeed, the proposed scenario is based on a close and circular relationship between star formation activity, BH growth and feedback of the AGN activity on star formation. This relationship manifest itself as a a well defined and distinctive sequence connecting various populations of massive galaxies: (i) virialization of DM halo; (ii) vigorous and rapidly dust-enshrouded star formation activity, during which a central SMBH grows; (iii) QSO phase halting subsequent star formation and (iv) essentially passive evolution of stellar populations, passing through an

Extremely Red Object (ERO) phase. As demonstrated by GDS04, this scenario fits nicely two very important populations at high redshift, which are extremely problematic for standard semi-analytic models (e.g. Somerville, 2004): vigorously star- forming, dust-enshrouded starbursts (in practise SCUBA sources; stage (ii)) and quiescent red spheroids (stage iv). Also, the epoch dependent luminosity function of spheroids and the local mass function of SMBHs is well reproduced. On the other hand, the general consistence of this sequence with high redshift QSO population has been investigated by Granato et al (2001), while a detailed analysis is the subject of papers in preparation. In the next section, we analyze as an example the SMBH growth during stage (ii), as traced by X-ray observations of sub-mm selected sources.

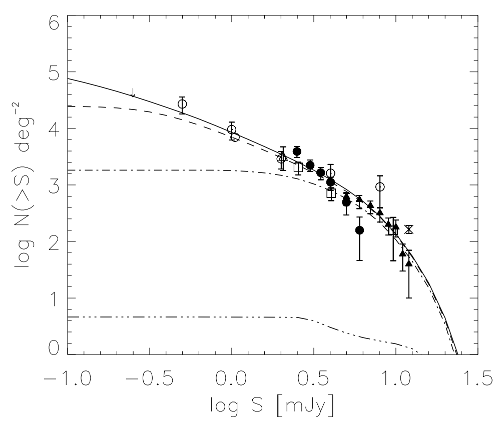

Figure 3. Number counts predicted by GDS04 model for SCUBA sources with accretion rates greater than several thresholds. Solid: all sources; dash: $\dot{M} > 0.02 M_{\odot}\mathrm{yr}^{-1}$; dot-dash: $\dot{M} > 0.2 M_{\odot}\mathrm{yr}^{-1}$; three dot-dash: $\dot{M} > 1 M_{\odot}\mathrm{yr}^{-1}$ ($L_{\rm bol} > 10^{46}\mathrm{erg\ s}^{-1}$). See text for explanations.

3. AGN sctivity in SCUBA sources

The model predicts the overall time development of AGN activity in forming spheroids, though precise predictions in most electromagnetic bands are made uncertain by environmental effects, that can significantly influence the way this activity shows up. This is particularly true in our scenario, since the QSO growth occurs in a rather extreme ambient, with no obvious analog in the local universe. The situation is relatively more favorable with X-ray photons, especially HX ones, which are the less affected by interactions with the ISM, and are less likely to be confused with those produced by processes directly connected with SF, such as X-ray binaries.

Recently Alexander et al. (2003) noticed that a fraction $\gtrsim 30 - 50\%$ of bright (> 5 mJy) SCUBA sources hosts mild AGN activity, with X ray (0.5-8 keV) *intrinsic* luminosity between 10^{43} and 10^{44} erg s^{-1}. Using a plausible bolometric correction of $L_{\rm bol}/L_X[0.5 - 8{\rm keV}] \simeq 20$ (Marconi et al. 2004) and with the accretion efficiency 0.1-0.15 adopted by GDS04 (quite standard), these figures translate into accretion rates onto the central SMBH of 0.02-0.2 $M_\odot$ yr^{-1}. Fig. 3 shows number counts for SCUBA sources with accretion rates greater than several thresholds, and demonstrates that our model is fully consistent with Alexander et al. findings. Indeed, almost all SCUBA sources brighter than $\simeq 5$ mJy are expected to host an AGN with *intrinsic* $L_X[0.5 - 8{\rm keV}] > 10^{43}$ (dashed line in Fig. 3), leaving room for sources with high column density.

According to our interpretation, the moderate AGN activity revealed by X-ray observations in many bright SCUBA sources corresponds to the build up by accretion of the central SMBH, induced by star formation, and well before the bright QSO phase that cause the end of the major epoch of star formation in these objects.

Acknowledgments

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