Observational tests of the galaxy formation process

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Abstract. The mutual feedback between star formation and nuclear activity in large spheroidal galaxies may be a key ingredient to overcome several difficulties plaguing current semi-analytic models for galaxy formation. We discuss some observational implications of the model by Granato et al. (2003) for the co-evolution of galaxies and active nuclei at their centers and stress the potential of the forthcoming surveys of the Sunyaev-Zeldovich effect on arcminute scales, down to $\mu$K levels, to investigate the early galaxy formation phases, difficult to access by other means.

Keywords: Galaxy formation, Active Galactic Nuclei

1. Introduction

As first pointed out by Silva (1999), and confirmed by other groups (e.g., Devriendt & Guiderdoni, 2000; Kaviani et al., 2003), semi-analytic models, built in the framework of the currently standard hierarchical clustering paradigm, under-predict by a large factor the surface density of galaxies detected by (sub)-mm surveys. The available redshift information (Dunlop, 2001; Chapman et al., 2003) albeit limited, indicates a strong excess of high luminosity, presumably very massive, galaxies at high $z$, compared to model predictions. The excess is confirmed by deep IR (I- and K-band) surveys (Daddi et al., 2003; Kashikawa et al., 2003; Poli et al., 2003; Pozzetti et al., 2003; Somerville et al., 2003).

Yet another difficulty for these models comes the observed colour-magnitude and [$\alpha$/Fe]-magnitude relations for elliptical galaxies; in particular, the $\alpha$/Fe ratio increases with luminosity (Thomas et al., 2002). Since Fe is mostly produced by type Ia supernovae, the over-abundance of $\alpha$-elements, compared to Fe, is most simply understood if the star formation is halted before type Ia SNe can enrich the interstellar medium. But this interpretation implies a shorter duration of the star-formation activity for more luminous – i.e. more massive – galaxies (Granato et al. 2001; Romano et al., 2002, and references therein). On the other hand, the depth of the potential well increases.
with the galaxy mass. Therefore, supernova explosions can unbind the interstellar medium (thus halting the star formation) more easily in less massive galaxies. This is why current semi-analytic models (Devriendt & Guiderdoni, 2000; Cole et al., 2000; Somerville et al., 2001; Menci et al., 2002) tend to predict an $[\alpha/Fe]$-magnitude relation quite opposite to the observed one.

However, the data summarized above are not necessarily in contradiction with the hierarchical clustering scenario, since the predicted number of large dark matter halos at the relevant redshifts is consistent with that of observed luminous galaxies. But the observed high-$z$ galaxies are far more luminous, and their chemical abundances are very different, than expected if most of the star formation occurs in small objects that later merged to build the large spheroidal galaxies. It is thus likely that the inconsistencies originate from a poor modelling of the physical processes involved.

The observations apparently require that large halos present at high redshift have essentially all their baryons still in a gaseous form and give origin to a single gigantic burst of star formation, which is halted by an energy injection that, unlike that from supernovae, is increasingly effective with increasing halo mass. As discussed by Granato et al. (2001, 2003), a very important ingredient that has been largely ignored in semi-analytic models is the mutual feedback between star-formation and nuclear activity of spheroidal galaxies. In the following, we will summarize the main aspects of the model by Granato et al. (2003), with emphasis on the possible role of the feedback, and present some observational tests of the ensuing galaxy formation scenario.

2. Co-evolution of galaxies and active nuclei

According to the model by Granato et al. (2003) the evolution of the gas within massive dark matter halos, forming at the rate predicted by the canonical hierarchical clustering scenario, is controlled by gravity, radiative cooling, and heating by feedback from supernovae and from the growing active nucleus. Supernova heating is increasingly effective with decreasing binding energy in slowing down the star formation and in driving gas outflows. Thus, the more massive proto-galaxies virializing at earlier times are the sites of the faster star-formation. The correspondingly higher radiation drag fastens the angular momentum loss by the gas, resulting in a larger accretion rate onto the central black-hole.

This scenario has a clear-cut implication for the relationship among the black-hole mass and the stellar velocity dispersion, which has been
interpreted by many authors in terms of either energy or momentum balance of the quasar-driven outflow (Silk & Rees, 1998; Fabian, 1999; Cavaliere et al., 2002; King, 2003). These approaches yield a power-law relationship, $M_{\text{BH}} \propto \sigma^p$, with $p$ in the range 4 to 5. On the other hand, according to Granato et al. (2003) for lower and lower halo masses an increasing fraction of mechanical energy deposited in the interstellar medium does not come from nuclear outflows but from supernovae. The heating due to the latter is increasingly effective in slowing down the black-hole growth in the less massive halos. Therefore, while the power-law $M_{\text{BH}}-\sigma$ relationship is recovered (with both slope and normalization nicely consistent with observations) for $\log \sigma \gtrsim 2.2$, a steepening is predicted for lower values (see Fig. 6 of Granato et al., 2003).

The observed $M_{\text{BH}}-\sigma$ relation entails an increase of the $M_{\text{BH}}/M_{\text{halo}}$ ratio with increasing $M_{\text{halo}}$. Therefore the gas heating per unit halo mass increases with halo mass, if the quasar radiates at the Eddington limit (as it is likely during its fast growth phase) and releases a constant fraction of its power in mechanical form. However, this is not enough to sweep out the interstellar gas of the most massive galaxies on a timescale $\leq 5 \times 10^8-10^9$ years, i.e. as short as necessary to avoid the Fe enrichment by type Ia supernovae. To this end, it is necessary that the fraction of mechanical energy released by the quasar is either higher or more tightly coupled to the interstellar gas for more massive galaxies. The latter is a likely possibility: if anything, the optical depth is larger for bigger galaxies. However, the physics of such coupling is poorly understood. Granato et al. (2003), based on the model for AGN-driven outflows by Murray et al. (1995), assume that the fraction, $f_h$, of bolometric luminosity going into gas heating increases as $L_{\text{bol}}^{1/2}$. Interestingly, the effective, luminosity weighted, value of $f_h$ is consistent with the value ($\sim 0.1$) that can account for the pre-heating of the intergalactic medium in groups of galaxies (Cavaliere et al., 2002; Platania et al., 2002).

This simple recipe yields a duration, $T_{\text{sb}}$, of the most active star formation phase decreasing with increasing $M_{\text{halo}}$ and virialization redshift $z_{\text{vir}}$. In the redshift range $3 \lesssim z_{\text{vir}} \lesssim 6$, $T_{\text{sb}} \simeq 0.5-1$ Gyr for $M_{\text{halo}} \geq \text{few} \times 10^{12} M_{\odot}$. Thus, the physical processes acting on baryons reverse the order of the formation of spheroidal galaxies with respect to the hierarchical assembly of dark matter halos (Anti-hierarchical Baryon Collapse scenario; Granato et al., 2001).

Coupling the model with GRASIL (Silva et al., 1998), the code computing in a self-consistent way the chemical and spectrophotometric evolution of galaxies over a very wide wavelength interval, Granato et al. (2003) obtained predictions in excellent agreement with observations.
for 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.

3. Sunyaev-Zeldovich effects from the early phases of galaxy formation

The model by Granato et al. (2003) effectively assumes that the gravitational potential wells appear instantaneously. This stems from the analysis by Zhao et al. (2003) of high-resolution N-body simulations, showing that the growth of dark matter halos consists of an early fast accretion phase, which establishes the potential well, followed by a slow accretion phase, when the mass increases by a substantial factor without changing the potential well significantly. On the other hand, according to other analyses (e.g., Lacey & Cole, 1993) the halo (and the associated potential well) is assembled continuously over a long time-scale.

Furthermore, the model makes the usual assumption that the gas is shock-heated to the virial temperature as soon as the potential well develops and is held in quasi-static equilibrium while it cools and contracts (Rees & Ostriker, 1977; White & Rees, 1978). This is also being disputed: according to some recent analyses (Birnboim & Dekel, 2003; Binney, 2003) only a fraction of the gas is heated.

De Zotti et al. (2003) pointed out that galactic scale Sunyaev-Zeldovich (SZ) effects may be a viable tool to investigate these early phases (see also Rosa-Gonzalez et al., 2003). In fact, the forthcoming generation of SZ instruments will be orders of magnitude more efficient, allowing to reach $\mu$K level with arcminute resolution (Carlstrom et al., 2002). The proto-galactic gas in a large galaxy may be expected to have a large thermal energy content, leading to a SZ signal at the several $\mu$K level during two evolutionary phases: i) when the protogalaxy collapses if the gas is shock-heated to the virial temperature; ii) in a later phase, as the result of strong feedback from a flaring active nucleus (Natarajan & Sigurdsson, 1999; Aghanim et al., 2000; Platania et al., 2002; Lapi et al., 2003).

As discussed by De Zotti et al. (2003), these SZ signals may have already shown up as the excess power on arcminute scales detected by the BIMA experiment (Dawson et al., 2002). The forthcoming sensitive high-frequency surveys might produce direct counts of such signals. As shown by Fig. 1, we expect a surface density of $\sim 0.3$ deg$^{-2}$ at $S_{30\text{GHz}} \simeq 1 \text{ mJy}$, and much higher counts at 100 GHz. Of course, the counts at
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Figure 1. Predicted counts of galaxy-scale SZ effects (diamonds) at 30 and 100 GHz, compared with counts of flat-spectrum radio quasars plus BL Lacs (+), flat-spectrum galaxies (+), steep-spectrum radio sources (dashed line), advection-dominated sources (thin solid line), normal plus starburst galaxies (dotted line), GPS sources (De Zotti et al., 2000; three dots - dash), and gamma-ray burst afterglows (Ciardi & Loeb, 2000).

bright fluxes are likely dominated by SZ effects in clusters of galaxies (not shown in Fig. 1), which however should be easily distinguishable because of their much larger angular size and much lower redshift.

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The roots of the work summarized in this paper go back to 1977 when two of us (LD & GDZ), under Alfonso’s guidance, started an investigation of the morphological, dynamical, X-ray and microwave (SZ) properties of clusters of galaxies in the framework of the then standard scenario for large scale structure formation (adiabatic density perturbations in a baryon-dominated universe), with special attention to the observational windows (X-ray and microwave) whose exploration had started only a few years before. One remarkable outcome of this work was the demonstration of the possibility of determining cluster distances directly, by combining X-ray and microwave measurements. Remarkably, the work we are carrying out now, after 26 years, is much on the same line and, once again, we are resorting to the SZ effect.
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