From Interstellar Clouds to Star-Forming Galaxies: Universal Processes?
Proceedings IAU Symposium No. 315, 2015
P. Jablonka, Ph. André & F. van der Tak, eds.

doi:10.1017/S1743921316007535

AGN feedback and star formation in ETGs: negative and positive feedback

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Abstract. AGN feedback from supermassive black holes (SMBHs) at the center of early type galaxies is commonly invoked as the explanation for the quenching of star formation in these systems. The situation is complicated by the significant amount of mass injected in the galaxy by the evolving stellar population over cosmological times. In absence of feedback, this mass would lead to unobserved galactic cooling flows, and to SMBHs two orders of magnitude more massive than observed. By using high-resolution 2D hydrodynamical simulations with radiative transport and star formation in state-of-the-art galaxy models, we show how the intermittent AGN feedback is highly structured on spatial and temporal scales, and how its effects are not only negative (shutting down the recurrent cooling episodes of the ISM), but also positive, inducing star formation in the inner regions of the host galaxy.

Keywords. ISM: kinematics and dynamics, galaxies: active, galaxies: cooling flows, galaxies: elliptical and lenticular, cD, galaxies: starburst, galaxies: evolution

1. Introduction

In a quite widespread view, merging is considered the main cause of QSO activity, because it is believed to be, after the end of the galaxy formation epoch, the only mechanism to add fresh gas to the central SMBHs in early type galaxies (ETGs). However, it has also been shown (e.g., Ciotti & Ostriker 1997) that the stellar mass losses produced during stellar evolution cyclically feed a central gas inflow, and then trigger the QSO activity in isolated ETGs (sometimes considered "red and dead"). Indeed, recent observations indicate that the QSO activity can be independent of galaxy merging. QSO activity is also invoked as the explanation of star formation quenching in ETGs (negative feedback) but, as stressed in Ciotti & Ostriker (2007, hereafter CO07)), AGN feedback can induce star formation (positive feedback) during "cooling flow" episodes fueled by stellar mass losses. In fact, also in isolation, significant amounts of fresh gas ($\simeq 20-30\%$ of the initial stellar mass M_* of the galaxy, depending on the IMF) are injected over the galaxy body by stellar evolution, at a rate approximately given by $\dot{M}_*(t) \propto M_*(0)\, t^{-1.3}$ (Ciotti *et al.* 1991, see also Pellegrini 2012). These losses interact with the pre-existing hot ISM, and mix with it, due to thermalization of the stellar velocity dispersion. In a galaxy of total B-band luminosity $L_{\rm B}$, SNIa's explosions at a rate $R_{\rm SN}(t) \propto L_{\rm B}\, t^{-s}$ provide additional mass and heat to the ISM, with rates $\dot{M}_{\rm SN}(t) = 1.4 M_{\odot}\, R_{\rm SN}(t)$ and $L_{\rm SN}(t) = 10^{51}{\rm erg}\, R_{\rm SN}(t)$. Since recent estimates suggest $s \simeq 1$, then the SNIa's specific heating $L_{\rm SN}/\dot{M}_*$ increases with time. The resulting hot atmosphere however cannot be static. The interstellar mass keeps increasing, its cooling time decreases, until a cooling catastrophe takes place in the central galactic region and the SMBH feedback takes place.

In a series of papers, Ciotti, Ostriker and co-workers, with the aid of high-resolution hydrodynamical simulations, and a physically based feedback implementation, studied in detail the AGN activity cycle induced by accretion of stellar mass losses, also considering star formation. In particular, it was shown that AGN feedback is able to avoid the overgrowth of the SMBH that would be caused by accretion of the mass lost by stars if unimpeded, and also that the same feedback can induce significant star formation at the center of ETGs (CO07). By using state-of-the-art galaxy dynamical models, and an updated version of the 2D code of Novak *et al.* (2011, 2012, hereafter N12, and references therein), we are now investigating in detail the ISM behavior in realistic ETG models with evolving input ingredients from the stellar population (Ciotti *et al.*, in preparation).

2. The models

We consider axisymmetric two-component galaxy models with adjustable flattening embedded in a spherically symmetric NFW dark matter halo and with a central SMBH. The stellar component is described by the ellipsoidal deprojection of the de Vaucouleurs law. The total gravitational field, the solution of the two-integrals Jeans equations, and the projection of the resulting kinematical field on the plane of the sky are computed as described elsewhere (Posacki et al. 2013). The velocity dispersion and rotational fields of the stellar populations, needed to compute energy and momentum injection in the ISM due to stellar evolution, are computed by using a generalized Satoh k-decomposition (Ciotti & Pellegrini 1996). The E4 and E7 galaxy models are obtained by flattening (at fixed stellar mass M_*) spherical "progenitors" with central (aperture) velocity dispersion of 180, 210, 250 and 300 km/s, and reproduce observed scaling laws (Negri *et al.* 2014). The initial mass of the SMBH is taken to be $M_{\rm BH} = 10^{-3} M_*$, near to the Magorrian relation, as expected at the end of the period of galaxy formation.

The hydrodynamical equations and the input physics are given in Ciotti & Ostriker (2012), and integrated by an improved version of the N12 code. Mass, momentum and energy sources and sinks associated with evolution of the passively evolving initial stellar population, and with the new stars added by star formation, are treated as described in Negri *et al.* (2015, hereafter N15). In particular the star formation rate is given by $\dot\rho_{\rm SF} = 0.1\rho/\max(\tau_{\rm cool}, \tau_{\rm dyn})$, where ρ is the local ISM density, and $\tau_{\rm cool}$ and $\tau_{\rm dyn} = \min(\tau_{\rm Jeans}, \tau_{\rm rot})$ are the cooling and dynamical times, respectively. In N15 we showed that this prescription reproduces the observed Kennicutt-Schmidt law remarkably well. Radiative and mechanical feedback from the accreting SMBH (both depending on the hydrodynamically self-consistently determined mass accretion rate on the SMBH, $\dot M_{\rm BH}$), are finally considered. In the energy equation, photoionization and Compton heating and cooling ($T_{\rm C} \simeq 2\times 10^7$ K), bremsstrahlung and line cooling are taken into account, with modifications due to the ionization effects of AGN radiation. In the momentum equation, radiation pressure due to AGN activity is computed by solving the radiative transport (in spherical symmetry) for the accretion luminosity $L_{\rm BH}$, considering photoionization+Compton opacity, and electron scattering. For simplicity at this stage we ignore the detailed treatment of dust formation and destruction, and the associated radiation pressure effects (Hansley *et al.* 2014, N12), as well as the radiation pressure due to star light in different bands (e.g., see Ciotti & Ostriker 2012). For given $\dot M_{\rm BH}$, then,

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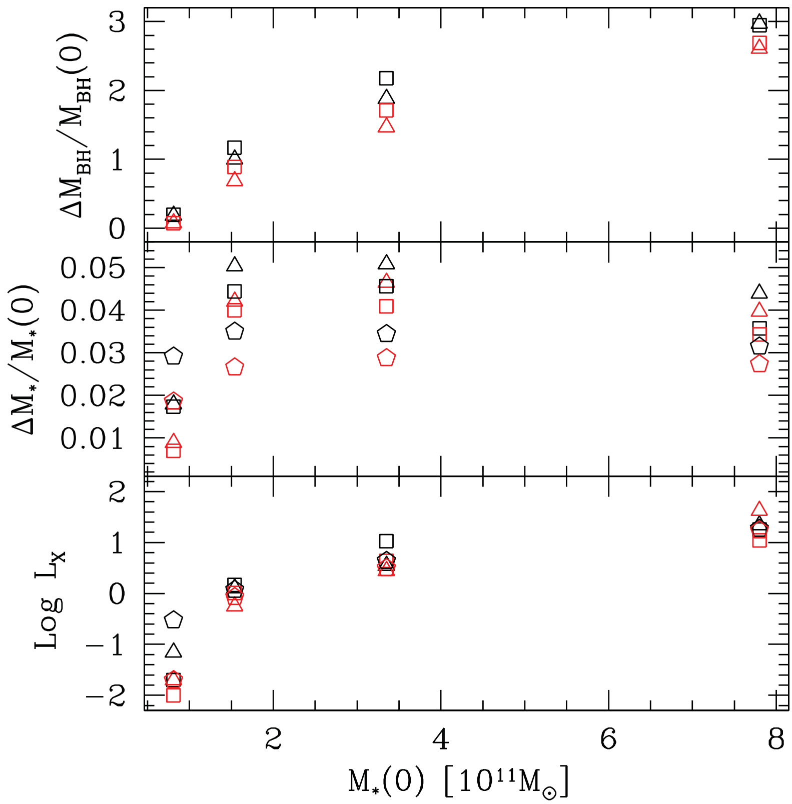

Figure 1. Global properties of the models at the end of the simulations (13 Gyr), as a function of their initial stellar mass, for E4 (black) and E7 (red) models. Triangles, squares, and pentagons refer to models with radiative plus mechanical AGN feedback, mechanical AGN feedback only, and no AGN feedback, respectively. *A color version of this figure is available online.*

one has:

$$L_{\rm BH} = \epsilon_{\rm EM} \dot{M}_{\rm BH} c^2, \qquad \epsilon_{\rm EM} = \frac{\epsilon_0 A \dot{m}}{1 + A\dot{m}}, \qquad \dot{m} \equiv \frac{\dot{M}_{\rm BH}}{\dot{M}_{\rm Edd}} = \frac{\epsilon_0 \dot{M}_{\rm BH} c^2}{L_{\rm Edd}}, \tag{2.1}$$

where $A = 100$, $\epsilon_0 = 0.125$ and $L_{\rm Edd}$ is the Eddington luminosity.

Mechanical feedback is due to mass, momentum, and energy injection of a conical-shaped nuclear wind, with half-opening angle of $\simeq 45°$. In terms of solid angle, this means that the wind is visible from $\sim 1/4$ of the available viewing angles. The relevant relations here are $\dot{M}_{\rm BH} = \dot{M}_{\rm in}/(1+\eta)$, $\dot{M}_{\rm out} = \eta \dot{M}_{\rm BH}$, $\dot{p}_{\rm w} = \dot{M}_{\rm out} v_{\rm w}$, $L_{\rm w} = \epsilon_{\rm w} \dot{M}_{\rm BH} c^2$, where $\eta \equiv 2\epsilon_{\rm w} c^2/v_{\rm w}^2$, $\dot{M}_{\rm in}$ and $\dot{M}_{\rm out}$ are the mass inflow and outflow rates at the first grid point (a few pc from the SMBH). In the current simulations, $\epsilon_{\rm w}$ follows a prescription similar to that adopted for $\epsilon_{\rm EM}$, with maximum value of 10^{-4}, while the wind velocity $v_{\rm w}$ is 10^4 km/s.

3. Results

As illustrated in Fig. 1 (top panel), the central SMBH grows more, in absolute terms ($\Delta M_{\rm BH}$) and also in percentage ($\Delta M_{\rm BH}/M_{\rm BH}(0)$), for increasing stellar mass M_* of the host galaxy; the growth reaches a factor of $\simeq 3$ in the biggest galaxies with AGN feedback (to be compared with a factor $\simeq 30$ in models without AGN feedback). Moreover, at

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any fixed M_*, more mass is accreted by the SMBH in E4 galaxies than in E7 galaxies. This is due to the fact that edge-on flattened galaxies are less bound (see N15) than more spherical systems. As expected, at fixed M_* and galaxy shape, the accreted mass increases from models with full AGN feedback (triangles), to models with mechanical AGN feedback only (squares), and finally to models without AGN feedback (pentagons). Therefore, since we start with a SMBH mass $\sim$ on the Magorrian relation, this relation is quite well preserved thanks to the effect of AGN feedback, which is able, in combination with large-scale SNIa heating, to maintain small the SMBH masses, avoiding the accretion of $\simeq 99\%$ of the mass injected by the stars over the galaxy body.

The stellar mass added to the galaxy due to star formation in the gas supplied by evolving stars (ΔM_*, middle panel), is larger in E4 galaxies than in E7 galaxies of same M_*. The total mass in new stars is of the order of $4 - 5\%$ of the initial M_*, indicating that an important fraction of the injected mass ($\simeq 0.2 - 0.3 M_*$) escapes as a galactic wind, supported by SNIa heating with the additional contributions of the thermalization of stellar winds, of type SNII explosions in the new stellar populations, and of the AGN feedback. In general, as already found in the case of spherical models (CO07), models with AGN feedback tend to form *more* stars than models without (with the exception of very low mass galaxies, where AGN feedback is able to sustain global galactic winds). This positive feedback is explained by considering that the AGN prevents the rapid fall of the cooling material to the center, allowing for more time for star formation. A clear sign of this effect is the characteristic size of the region of star formation, which is confined to the very center of the galaxy in absence of AGN feedback (a small fraction of the optical effective radius), while in models with AGN feedback it reaches a size of the order of a kpc or more. The results of this work (in absence of AGN feedback) agree well with those extensively discussed in N15 including star formation.

An important observational feature of the models is of course the evolution of their luminosity, both of the central accreting SMBH ($L_{\rm BH}$), and of the galaxy hot ISM ($L_{\rm X}$). In Fig. 1 we show $L_{\rm X}$ in the X-ray $0.3 - 8$ keV band at the end of the simulations, with values in nice agreement with observations, and only moderately dependent on AGN feedback. The evolution of $L_{\rm BH}$ (not shown), is confirmed to be highly fluctuating, as already found in our previous works based on simpler galaxy models. The duty-cycle (phenomenologically defined as the fraction of time spent by the SMBH at $L_{\rm BH}$ higher than a few percents of $L_{\rm Edd}$), is of the order of $\simeq 3 - 5\%$.

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