*Perseus in Sicily: From Black Hole to Cluster Outskirts*
*Proceedings IAU Symposium No. 342, 2018*
*K. Asada, E. de Gouveia Dal Pino, M. Giroletti,*
*H. Nagai & R. Nemmen, eds.*

doi:10.1017/S1743921318003745

# AGN feedback and the origin and fate of the hot gas in early-type galaxies

**Silvia Pellegrini**[1], **Luca Ciotti**[1], **Andrea Negri**[2]
**and Jeremiah P. Ostriker**[3]

[1]Department of Physics and Astronomy, University of Bologna, via Gobetti 93/2,
40129 Bologna, Italy
email: `silvia.pellegrini@unibo.it`

[2]Instituto de Astrofísica de Canarias, calle Vía Láctea,
E-38205 La Laguna, Tenerife, Spain

[3]Department of Astronomy, Columbia University, 550 West 120th St,
New York, NY 10027, USA

**Abstract.** We present the results of two-dimensional, grid-type hydrodynamical simulations, with parsec-scale central resolution, for the evolution of the hot gas in isolated early-type galaxies (ETGs). The simulations include a physically self-consistent treatment of the mechanical (from winds) and radiative AGN feedback, and were run for a large set of realistic galaxy models. AGN feedback proves to be very important to maintain massive ETGs in a time-averaged quasi-steady state, keeping the star formation at a low level, and the central black hole mass on observed scaling relations. A comparison with recent determinations of the X-ray properties of ETGs in the local universe shows that, at later epochs, AGN feedback does not dramatically alter the gas content originating in stellar recycled material. Thus, the present-day X-ray luminosity is not a robust diagnostic of the impact of AGN activity, within a scenario where the hot gas mostly originates from the stellar population.

**Keywords.** ISM: evolution, galaxies: elliptical and lenticular, cD, galaxies: evolution, galaxies: ISM, galaxies: nuclei, X-rays: galaxies, X-rays: ISM

## 1. Introduction

A few basic facts relate the supermassive black holes (MBHs), the ISM, and the stellar population of ETGs. The first is that ETGs host central MBHs, whose mass $\mathrm{M_{BH}}$ scales with the stellar mass, and was mostly built by accretion during bright QSO phases (at least for $\mathrm{M_{BH}} \geq 10^8 \mathrm{M_\odot}$; Yu & Tremaine 2002). The second is that star formation (SF) stopped at early times, and local ETGs show very low levels of SF, and little (if any) young stellar population (e.g., Kuntschner *et al.* 2010, Davis *et al.* 2014). The third is that ETGs contain a hot ISM, whose X-ray properties have been accurately determined from *Chandra* observations (Kim & Fabbiano 2015; Goulding *et al.* 2016). This ISM is continuously replenished by the collective mass input provided by the stellar population during its normal ageing; this mass input rate $\dot{M}$ and its evolution [$\dot{M}(\mathrm{t}) \approx 10^{-11} L_B(L_{B\odot})\, \mathrm{t}(12\ \mathrm{Gyrs})^{-1.3} \mathrm{M_\odot/yr}$, with $L_B$ the galaxy luminosity, for a passively evolving stellar population, after $\sim 2$ Gyr of age] is accurately known from theory and observations; it corresponds to a significant fraction of the initial stellar mass of the ETG, when integrated over its lifetime. The fourth, final fact is that this continuous mass input develops a flow directed towards the galactic center (e.g., Ciotti *et al.* 1991) that feeds the MBH and causes the "AGN feedback" phenomenon.

Basic questions are then raised: can the MBH accretion energy prevent MBH masses from growing too much, and remain comparable to those built by the end of the quasar phase? How does the accretion energy interact with the galactic ISM? How much of it is absorbed, and with what effects on the ISM? Is the gas displaced from the galactic central regions, and even removed from the galaxy? Does the gas content originating in the stellar population have an X-ray luminosity $L_X$ that agrees with observations? Does SF remain low? To address these questions, we ran high-resolution 2D hydrodynamical simulations with an adapted grid-type code (ZEUS-MP) to study the evolution of the ISM in presence of stellar and AGN feedback. The main results are briefly presented below (see Ciotti *et al.* 2017, hereafter C17, and Pellegrini *et al.* 2018, for more details).

## 2. The models

The main features of the simulations and of the numerical implementation of the various inputs of mass and energy to the ISM are found in our recent works (Negri *et al.* 2014, 2015, C17; see Ciotti & Ostriker 2012 for a detailed description of the realization of all input sources to the hydrodynamical equations, and of AGN feedback).

The simulations have been run for a large set of axisymmetric two-component (star+dark matter) galaxy models, of shapes ranging from E0 to E7. The Jeans equations provide the internal stellar kinematics, on which the stellar kinematical heating is then based. The stellar density profile follows a deprojected ellipsoidal Sersic law, and the main galactic observables are related in order to lie on the main scaling laws. The spherical, NFW dark matter halo has a dark-to-stellar mass ratio of $M_h/M_\star \simeq 20$, and a dark mass content within the effective radius $R_\mathrm{e}$ lower than that in stars, following the results of dynamical modeling of kinematic observations of ETGs. The hot gas originates from stellar mass losses and SN ejecta, and evolves under the action of gravity, of cooling, and of the various energy sources. SF is also included, via a simple scheme shown to reproduce well the Kennicutt-Schmidt relation (Negri et al. 2015).

The models include an accurate and physically self-consistent implementation of AGN feedback, both radiative and mechanical, the latter due to AGN winds. Thanks to the central resolution (5 pc) the fiducial accretion radius is resolved (e.g., Pellegrini 2010, Ciotti & Pellegrini 2017). The heating by AGN feedback results from the mass accretion rate on the MBH directly computed with the high central resolution, from a self-consistent treatment of the mass, energy and momentum balance of the inflowing and outflowing material at the innermost gridpoint, and from radiative and mechanical efficiencies that vary with the mass accretion rate, in agreement with current observational and theoretical findings (C17). The strength of AGN feedback is then not "adjusted", since the heating of the ISM resulting from the accretion process (that is resolved down to the accretion radius) is self-determined.

In the simulations the galaxies start almost empty of ISM, a situation expected to result from the combined effects of the SNe explosions and of the AGN energy injection, that are believed to clear the galaxies from the ISM and 'quench' star formation (e.g., Pellegrini *et al.* 2018 and references therein). The ISM is then replenished by the collective input provided by the stellar population, and its evolution is followed from an age of $\sim 2$ Gyr (after the main galaxy formation phase), for $\sim 10$ Gyr. The simulations were run for a large set of representative (isolated) galaxy models, varying their $M_\star$, their shape, internal kinematics, presence of AGN feedback and star formation.

## 3. Results

Many simulation outputs are considered by C17: maps of the hydrodynamical properties of the gas, surface brightness maps, maps of the SF rate, of the mass in newly formed

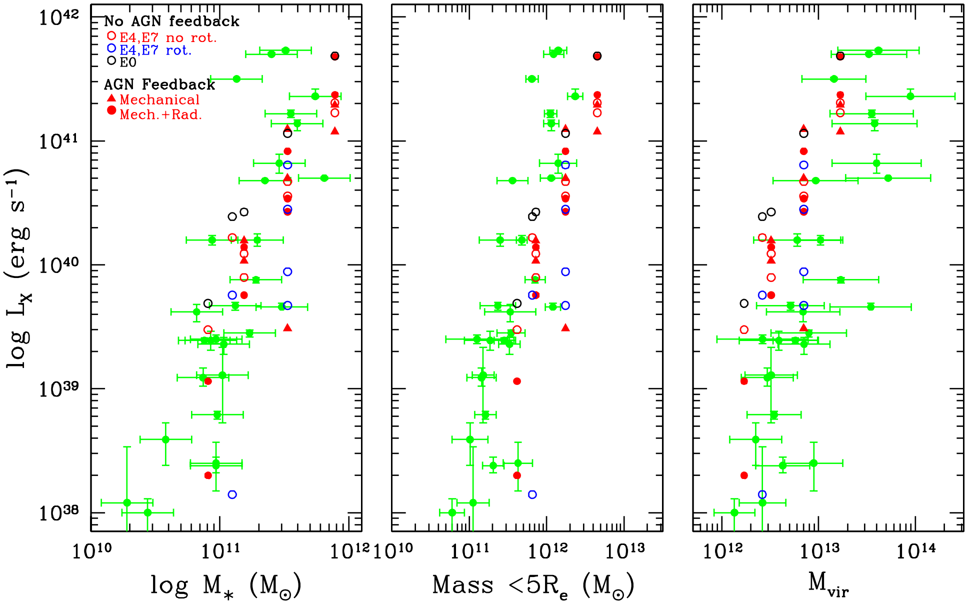

**Figure 1.** Observed (green) and model X-ray luminosities versus the total stellar mass $M_\star$ (left), the total enclosed mass within $5R_e$ (middle), and the total virial mass $M_{vir}$ (right). Observed $L_X$ values for ETGs are taken from Forbes *et al.* (2017). The models have E0, E4 and E7 shapes; full symbols refer to non-rotating galaxies with AGN feedback (mechanical, or mechanical and radiative); open symbols refer to simulations without AGN feedback, and in this case the E4 and E7 galaxies can be rotating (blue open circles) or not (red open circles). See Pellegrini *et al.* 2018 for more details.

stars, the distribution in age of the new stars, the growth of the MBH mass, the nuclear luminosity, the duty cycle of AGN activity and of the gas. At the nucleus, high and low radiative efficiency accretion periods alternate; a negligible time is spent in the (cold mode) phase of high radiative efficiency, and most of the time is spent in a “quiescent” (hot mode) low nuclear luminosity phase; in an average ETG, the Eddington-scaled mass accretion rate keeps below $10^{-3}$ for $\simeq 75\%$ of the time, as observed in the local universe (Pellegrini 2010, Gallo *et al.* 2010). The duty-cycle of AGN activity is a few percent. At the end, $M_{\rm BH}$ has grown by a factor of 2−3, instead of a factor of $\simeq 100$, as found without AGN feedback. During nuclear outbursts, cold, inflowing, and hot, outflowing gas phases coexist in the central galactic region; overall, AGN activity has a positive effect for star formation, as already found previously (Ciotti & Ostriker 2007; Nayakshin & Zubovas 2012). At the end of the simulations, in a representative galaxy, roughly half of the total mass loss is recycled into new stars, and just 3% of it is accreted on the MBH, the remainder being ejected from the galaxy.

At the present epoch, $L_X$, and the emission weighted temperature $T_X$, agree well with those observed (see Fig. 1). In the figure the models successfully reproduce even the largely different $L_X$ values at the same galaxy mass, thanks to the sensitivity of the gas flow to many galaxy properties (C17). Another important finding is that there is not a significant difference in $L_X$ of models with and without AGN feedback, when a large set of galaxy models is considered. The basic explanation for this finding is that recurrent feedback helps to temporarily displace the gas from the center (out to a radius of the order of 10 kpc), thus $L_X$ is temporarily reduced, even considerably; but feedback does not clear the galaxy from all its gas, it just produces an increase (of the order of 20%−40%) in the ejected mass from the galaxy (C17).

## 4. Conclusions

We performed simulations of the ISM behavior in ETGs starting from initial conditions created at the epoch of quenching ($z > 2$), when SNe and AGN-driven powerful outflows are supposed to remove the gas residual of the major star formation process, and stop further intense SF. The mass input to the ISM comes from supernovae and stellar winds, takes into account their secular trend, and the contributions of both the ageing and the newly born stars.

We found that after $z \simeq 2$ AGN feedback is very important to maintain massive ETGs in a time-averaged quasi-steady state, keeping low the SF, and the MBH mass; however, it does not dramatically alter the gas content originating in stellar recycled material, that is able to account for a major part of the observed $L_X$. Thus, the distribution of values for the present-day $L_X$ is not a robust diagnostic of the impact of AGN activity, within a scenario where the hot gas mostly originates from the stellar population.

Evidently, if AGN-driven outflows are to clear the gas out of massive ETGs at early epochs, this requires an efficiency of energy transfer from the AGN to the ISM much larger than found by C17 at low redshift. Similarly, if cosmological infall at later epochs is very important, contributing to a mass within a few $R_{\rm e}$ much larger than that provided by stars, then again the effects of AGN feedback should be stronger than found by C17, to prevent substantial cosmological accretion of material from outside the ETGs, and then an exceedingly large $L_X$. Further work including the confining action exerted by an intragroup/intracluster medium in central-dominant ETGs, or cosmological infall, would be helpful to assess more thoroughly the origin of the hot gas, and the role of AGN feedback in ETGs.

## References

Ciotti L., D'Ercole A., Pellegrini S., & Renzini A., 1991, *ApJ*, 376, 380

Ciotti, L., & Ostriker, J. P. 2007, *ApJ*, 665, 1038

Ciotti, L., & Ostriker, J. P. 2012, in *Hot Interstellar Matter in Elliptical Galaxies*, Kim D.-W., Pellegrini S., eds., Astrophys. and Space Sci. Library, vol. 378. Springer-Verlag, p. 8

Ciotti, L., Pellegrini, S., Negri, A., & Ostriker, J. P. 2017, *ApJ*, 835, 15 (C17)

Ciotti, L., & Pellegrini, S., 2017, *ApJ*, 848, 29

Davis T. A. *et al.*, 2014, *MNRAS*, 444, 3427

Forbes, D. A., Alabi, A., Romanowsky, A. J., *et al.* 2017, *MNRAS*, 464, L26

Gallo, E., Treu, T., Marshall, P. J., *et al.* 2010, *ApJ*, 714, 25

Goulding, A. D., Greene, J. E., Ma, C.-P., *et al.* 2016, *ApJ*, 826, 167

Kim, D.-W., & Fabbiano, G., 2015, *ApJ*, 812, 127

Kuntschner, H., *et al.* 2010, *MNRAS*, 408, 97

Nayakshin, S., & Zubovas, K. 2012, *MNRAS*, 427, 372

Negri, A., Posacki, S., Pellegrini, S., & Ciotti, L. 2014, *MNRAS*, 445, 1351

Negri, A., Pellegrini, S., & Ciotti, L. 2015, *MNRAS*, 451, 1212

Pellegrini, S. 2010, *ApJ*, 717, 640

Pellegrini, S., Ciotti, L., Negri, A., & Ostriker, J. P. 2018, *ApJ*, 856, 115

Yu, Q., & Tremaine, S. 2002, *MNRAS*, 335, 965