AGN feedback in elliptical galaxies: numerical simulations

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Abstract The importance of feedback (radiative and mechanical) from massive black holes at the centers of elliptical galaxies is not in doubt, given the well established relation among black hole mass and galaxy optical luminosity. Here, with the aid of high-resolution hydrodynamical simulations, we discuss how this feedback affects the hot ISM of isolated elliptical galaxies of different mass. The cooling and heating functions include photoionization plus Compton heating, the radiative transport equations are solved, and the mechanical feedback due to the nuclear wind is also described on a physical basis; star formation is considered. In the medium-high mass galaxies the resulting evolution is highly unsteady. At early times major accretion episodes caused by cooling flows in the recycled gas produced by stellar evolution trigger AGN flaring: relaxation instabilities occur so that duty cycles are small enough to account for the very small fraction of massive ellipticals observed to be in the QSO-phase, when the accretion luminosity approaches the Eddington luminosity. At low redshift all models are characterized by smooth, very sub-Eddington mass accretion rates. The mass accumulated by the central black hole is limited to range observed today, even though the mass lost by the evolving stellar population is roughly two order of magnitude larger than the black hole masses observed in elliptical galaxies.

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1 Introduction

Supermassive black holes (SMBHs) at the centers of bulges and elliptical galaxies (e.g., see [97, 45, 58]) have certainly played an important role in the processes of galaxy formation and evolution (e.g., see among others [172, 52, 13, 18, 94, 186, 75, 72, 162, 120, 46, 4, 84, 40, 142, 107]), as indicated by the observed correlations between host galaxy properties and the masses of their SMBHs (e.g., see [109, 59, 66, 188, 116, 71, 112], see also [173, 17, 25]).

Of central interest for modern astrophysics is the fact that when gas is added to the central galactic regions for any reason, the SMBH will accrete and emit energy, both as a radiation flow and in some mechanical form. The complex interaction of such energy with the galactic gas, and the consequent effects on the galaxy and on the SMBH itself, are defined as “AGN feedback”. A quite widespread view is that, after the end of the galaxy formation epoch, the only way to add fresh gas to the central SMBH is through the merging phenomenon; it follows that the quasar phenomenon should be a secure indicator of (gas rich) galaxy merging over the cosmic epochs. However, this picture is only partially true, as well known to stellar evolutionists and to the “cooling flow” community.

In fact, the mass return rate from the passively evolving stars (primarily from red giant winds and planetary nebulae) in elliptical galaxies can be estimated as

$$\dot{M}_\ast(t) \simeq 1.5 \times 10^{-11} L_B t_{15}^{-1.3} \, M_\odot \, \text{yr}^{-1},$$

(1)

where $L_B$ is the present galaxy blue luminosity in blue solar luminosities, and $t_{15}$ is time in 15 Gyr units ([31], see also Sect. 2.2 and Pellegrini, this volume). This metal-rich, recycled gas is the main ingredient of the so-called cooling-flow model (originally developed for clusters, [37, 53]), that provided the preliminary framework to the interpretation of X-ray halos observed in elliptical galaxies (e.g., see [14, 160] and Fabbiano, this volume).

However soon it was realized that at least two major problems were faced by the classical cooling-flow scenario. The first is a luminosity problem, i.e., the X-ray luminosity $L_X$ of local ellipticals is inconsistent with the standard cooling flow model. In fact, low-redshift elliptical galaxies with optical luminosity $L_B \gtrsim 3 \times 10^{10} L_\odot$ show a significant range in the ratio of gas-to-total mass at fixed $L_B$, with values ranging from virtually zero up to few %, and most of that is seen in X-rays with temperatures close to the virial temperatures of the systems (e.g., see [114]). The second, and even more severe problem, is the mass disposal problem. In fact, from eq. (1) it follows that the evolving stellar population will inject in the galaxy, over a cosmological time, a gas mass summing up $\approx 10 - 20\%$ of the total stellar mass $M_\ast$.

In the classical cooling flow scenario, this gas flows and disappears at the galaxy center, but observations ruled out the existence of such large masses at the center of elliptical galaxies. Young stellar populations observed in the body of ellipticals also cannot account for the total mass released, and alternative forms of cold mass disposal (such as distributed mass drop-out) are not viable solutions ([7]). The mass disposal problem has been exacerbated after the discovery of central SMBHs: in-
fact, the total mass of the recycled gas is two orders of magnitude larger than the mass $M_{BH}$ of the central SMBH. In other words, even in absence of merging, the pure passive stellar evolution injects in the galaxy an amount of gas that, if flowing to the center, would produce a SMBH $\simeq 100$ times more massive than what is observed, $M_{BH} \simeq 10^{-3}M_*$ (e.g., [109]).

A (partial) solution to the luminosity and mass problems was proposed in a first series of papers ([106, 42, 43, 31, 138]), by considering the effect of SNIa heating of the galactic gas, and exploring the time evolution of gas flows by using hydrodynamical numerical simulations. It was found that SNIa input sufficed for low and medium-luminosity elliptical galaxies to produce fast galactic winds, so that the scatter in the $L_X$-$L_B$ diagram could be nicely reproduced. However, it was also found that more massive galaxies should be in the high-luminosity, permanent cooling-flow regime, so that for massive systems, putative hosts of luminous cooling flows, the mass problem was still unsolved; in addition, if this gas is accreted on the central SMBH, then a bright QSO should be observed in all X-ray luminous elliptical galaxies. These considerations lead naturally to the study of accretion on SMBHs at the center of elliptical galaxies, to explore the possibility that radiative and mechanical feedback due to accretion is the solution of the mass disposal problem in cooling flow, and it is the explanation of the maintenance of “small” SMBH masses in presence of very large amounts of recycled gas, and of the shut down of QSO activity in massive ellipticals (e.g., see [176, 28, 55]).

In the past years, we dedicated several papers to the AGN feedback in elliptical galaxies ([28, 29, 131, 162, 30, 33, 139, 34, 90, 169, 170, 133, 127]). The current most satisfactory models are combined models, i.e. models in which both radiative and mechanical feedback effects are at work. In general, all the computed solutions are characterized by relaxation oscillations (e.g., see [132, 38, 118]), and we note that nowadays, several observations support the finding that accretion on central SMBHs is in fact a highly unsteady phenomenon (e.g., see [113, 67, 83]); in addition, evidences of AGN feedback have been clearly detected in the hot gas of nearby elliptical galaxies (e.g., see [92, 152, 129, 60, 47], see also Statler, this volume).

From the astrophysical point of view, the emerging picture of the evolution of an isolated, medium-high mass elliptical galaxy consists of four main (repeating) stages.

Stage 1) After the end of the galaxy formation epoch, the galaxy should be in a more or less quiescent phase. Planetary nebulae and other sources of secondary gas, processed through stellar evolution, inject fresh gas in the galaxy at a rate proportional to the stellar density and with an energy due to the stellar motions which guarantees that, when the gas is thermalized, it will be approximately at the local “virial” temperature. Supernovae (Type Ia) are also distributed like the stars and will tend to drive a mild wind from the outer parts of the galaxy, with the inner parts being quite luminous in thermal X-rays. This is a “normal” giant elliptical galaxy. Low mass ellipticals instead can be found permanently in a state of global, low-luminosity galactic wind.

Stage 2) In massive ellipticals, the gas in the dense inner part of the galaxy is radiating far more energy than can be replaced by SNIa and stellar motions, and
thus a “cooling catastrophe” occurs with a collapsing cold shell forming at \( \approx 1 \) kpc from the center. As this falls towards the center, a starburst occurs, and the galaxy seen as an ULIRG. A radio jet may be emitted, but the AGN flare up is at first heavily obscured and the central source will only be seen in hard X-rays.

Stage 3) Gradually, the gas is consumed, as it is transformed to new stars, and some of it is driven out in a strong wind by the combined effects of feedback from the starburst and the central SMBH, which is now exposed as an optical and then UV “quasar”, complete with Broad Line Region (hereafter BLR) wind, optically thick disc of gas, and young stars.

Stage 4) As gas is used up or blown away, a hot cavity is formed at the center of the system and, since a shock has propagated through that volume, it is essentially like a giant supernova remnant and one expects there to be particle acceleration and non-thermal radiation from the central region ([90]). Then, gradually this hot bubble cools and collapses and one returns to the normal elliptical phase at Stage 1.

The paper is organized as follows. In Section 2 we briefly discuss some class of models that have been studied in the past years, focusing on the radiative or mechanical feedback effects, but not both. In Section 3 we describe in detail the input physics of the combined feedback models. In Section 4 we present for the first time a comparison of the effects of combined feedback on three galaxy models of different mass, related to the Reference Model in [34]. Finally, in Section 5 we discuss the main results obtained.

2 Previous works

Due to the importance of the subject, to its implications in different areas of observational and theoretical astrophysics, and to the fact that the specific nature of AGN feedback is still not completely understood, it is not surprising that a very large body of work has been done on the subject. In general, past investigations focused separately on purely radiative or purely mechanical feedback. Here we briefly describe the main properties and limitations of these two classes of models.

2.1 Radiative feedback

In the published book.

2.2 Mechanical feedback

In the published book.
3 Physical modeling

In this Section we summarize the implementation of the input physics in our 1D code, used to compute the evolution of combined feedback models. We now have a more advanced code version, that will be used in future investigations, and we are also working on a 2D code with a multidimensional implementation of the input physics.

3.1 Structure and internal dynamics of the galaxy

In the published book.

3.2 Passive stellar evolution: SNIa rate and stellar mass losses

In the published book.

3.3 Star formation and SNII heating

In the published book.

3.4 The circumnuclear disk and the SMBH accretion luminosity

In the published book.

3.5 The mechanical feedback treatment

In the published book.

3.6 Radiative heating and cooling

In the published book.
3.7 Radiation pressure

In the published book.

3.8 Hydrodynamical equations

In the published book.

4 Results

We now illustrate the main properties of model B3_{02} (discussed in [34]) and two variants obtained by increasing (B3_{h02}) and decreasing (B3_{l02}) its central velocity dispersion, while keeping the remaining input physics identical. The galaxy models are constructed as described in Sect. 3.1, and their structural parameters are given in Table 1. For sake of comparison, we recall that for model B3_{02} the initial stellar mass is $M_* \simeq 2.9 \times 10^{11} M_\odot$, the Fundamental Plane effective radius $R_e \simeq 6.9$ kpc, and the central aperture velocity dispersion $\sigma_a = 260$ km s$^{-1}$. The initial mass of the central SMBH is assumed to follow the present day Magorrian relation ($M_{BH} \simeq 10^{-3} M_*$), as it is believed that the bulk of the SMBH mass is assembled during the process of galaxy formation (e.g., [75, 162, 107]), a process which is not addressed with the present simulations. Note that these models are not appropriate as initial conditions for cosmological simulations, because their parameters are fixed to reproduce nearby early-type galaxies (at $z = 0$), and also because of the outflow boundary conditions imposed at the galaxy outskirts ($\sim 250$ kpc).

Table 1 The structural parameters of model B2_{02} and its low and high mass variants, and the relevant mass budgets (discussed in Sect. 4.2) at the end of the simulations. Velocity dispersions are in km/s, effective radii in kpc, luminosities are in $10^{10} L_\odot$, stellar masses in $10^{11} M_\odot$. In the logarithms, masses are in Solar Masses.

| Model      | $\sigma_0$ | $R_e$ | $L_B$ | $M_*$ | $\log \Delta M_{BH}$ | $\log \Delta M_*$ | $\log \Delta M_{w}$ | $\log M_{ISM}$ |
|------------|------------|-------|-------|-------|----------------------|-------------------|---------------------|----------------|
| B3_{l02}   | 240        | 5.77  | 3.78  | 2.04  | 8.36                 | 9.22              | 10.21               | 9.13            |
| B3_{02}    | 260        | 6.91  | 5.03  | 2.87  | 9.06                 | 10.22             | 10.31               | 9.34            |
| B3_{h02}   | 280        | 8.20  | 6.59  | 3.95  | 9.41                 | 10.58             | 10.40               | 9.75            |

The initial conditions for the ISM are represented by a very low density gas at the local thermalization temperature. The establishment of such high-temperature gas phase at early cosmological times is believed to be due to a “phase-transition” when, as a consequence of star formation, the gas-to-stars mass ratio was of the order of 10% and the combined effect of shocks, SN explosions and AGN feedback
became effective in heating the gas and driving galactic winds (e.g., see [155, 131, 46, 175, 91]).

Important quantities associated with the model evolution are the mass (luminosity) accretion weighted EM and mechanical efficiencies

\[
\langle \varepsilon_{\text{ADAF}} \rangle \equiv \frac{\int \varepsilon_{\text{ADAF}} \dot{M}_{\text{BH}} dt}{\Delta M_{\text{BH}}} ; \quad \langle \varepsilon_{\text{w}} \rangle \equiv \frac{\int \varepsilon_{\text{w}} \dot{M}_{\text{BH}} dt}{\Delta M_{\text{BH}}}
\]

where \(\Delta M_{\text{BH}}\) is the mass accreted by the SMBH over the time interval considered.

In addition to the time-averaged quantities introduced above, we also compute the number of bursts of each model (each burst being counted when \(L_{\text{BH}}\) becomes larger than \(L_{\text{Edd}}/30\)), the total time spent at \(L_{\text{BH}} \geq L_{\text{Edd}}/30\) (bolometric), the total time spent at \(L_{\text{BH \, UV}} \geq 0.2 L_{\text{Edd}}/30\) (UV, after absorption), and at \(L_{\text{BH \, opt}} \geq 0.1 L_{\text{Edd}}/30\) (optical, after absorption). The two numerical coefficients take into account the fraction of the bolometric luminosity used as boundary condition to solve the radiative transfer equation in each of the two bands (Sect. 3).

### 4.1 Luminosities

The central panel of Fig.1 shows the evolution of the accretion luminosity of model B302, fully discussed in [34]. After a first evolutionary phase in which a galactic wind is sustained by the combined heating of SNIa and thermalization of stellar velocity dispersion, the central “cooling catastrophe” commences. In absence of the central SMBH a “mini-inflow” would be then established, with the flow stagnation radius (i.e., the radius at which the flow velocity is zero) of the order of a few hundred pc to a few kpc. These “decoupled” flows are a specific feature of cuspy galaxy models with moderate SNIa heating ([138]). However, after the central cooling catastrophe, the feedback caused by photoionization, Compton heating, and mechanical feedback, strongly affects the subsequent evolution, as can be seen in Fig. 1 where we show the luminosity evolution of the central AGN with time-sampling of \(10^5\) yrs. The corresponding Eddington limit is represented by the almost horizontal solid line. As already discussed in previous papers, the major AGN outbursts are separated by increasing intervals of time (set by the cooling time and by mass return rate from the evolving stellar population), and present a characteristic temporal substructure, whose origin is due to the cooperating effect of direct and reflected shock waves. These outflowing shocks are a likely place to produce emission of synchrotron radiation and cosmic rays ([90, 171]). At \(t \simeq 10\) Gyr the SNIa heating, also sustained by a last strong AGN burst, becomes dominant, a global galactic wind takes place and the nuclear accretion switches to the optically thin regime.

The top and the low panels show instead the accretion luminosity for the galaxy models with higher (top panel) and lower (bottom panel) velocity dispersion. The differences are apparent, and are in line with energetic expectations. In fact, it is well known that big elliptical galaxies are more bound (per unit mass) than low
mass systems (as dictated by the Fundamental Plane and Faber-Jackson relations), while the specific heating provided by SNIa is independent of the galaxy mass. For this reason, in model B3\textsuperscript{0}_{02}, not only the bursting activity begins earlier than in model B3\textsuperscript{0}_{02}, but also lasts longer. The opposite case is represented by model B3\textsuperscript{1}_{02}, where the SMBH accretion is found, over all the evolution, in the highly sub-Eddington (ADAF), hot and optically thin regime, with absence of central bursts. We note that the SMBH accretion luminosities of the three models are far below the Eddington limit at the current epoch, in rough agreement with current observations, but clearly

Fig. 1 Dotted lines are the optical SMBH luminosity corrected for absorption $L_{\text{BH, opt}}^{\text{eff}}$ (i.e., as would be observed from infinity) for the three models. We recall that at the center we fixed $L_{\text{BH, opt}}^{\text{eff}}(R_1) = 0.1 L_{\text{BH}}$. The almost horizontal solid line is $L_{\text{Edd}}$. The structural properties of the galaxy models are given in Table 1. The feedback is of Type B, i.e., with a nuclear wind mechanical efficiency dependent on the (normalized) accretion luminosity $l \equiv L_{\text{BH}}/L_{\text{Edd}}$, and with a peak mechanical efficiency of $\varepsilon_M = 3 \times 10^{-4}$ and a peak radiative efficiency of $\varepsilon_0 = 0.2$. The model in the central panel is discussed in detail in Paper III. (Adapted from [34] by permission of the AAS).
still more luminous than the average low-luminosity objects (e.g., see [135, 80, 81, 137]). The need of an additional form of feedback in the low-luminosity phases will be briefly addressed in the Conclusions.

In the top panels of Fig. 2 we show the coronal X-ray luminosity $L_X$ (emitted by gas at $T \geq 5 \times 10^6$ K), due to the hot galactic atmosphere integrated within $10R_e$ for the three models. Of course, in model B3$^{12}_n$ no bursts are observed, consistently with the smooth nuclear accretion regime. Instead, in the other two models the spikes in the X-ray luminosity are clearly reminiscent of the SMBH accretion history. These peaks are due to sudden increases in the X-ray surface brightness profiles in the cen-
tral regions ($\approx 100$ pc scale), consequence of AGN feedback. This is apparent from inspection of Figs. 6 and 7 (top left panels). If the central regions are excluded from the computation of $L_X$, this quantity would be seen to evolve in a much smoother way, with fluctuations similar to those of the blu lines ($M_{\text{ISM}}$) in the top panels of Fig. 3. During more quiescent phases, $L_X$ attains values comparable to the observed ones, with present times mean values of $L_X$ lower than in the standard “cooling flow” model: it is expected that a central galaxy in a cluster will reach higher values, due to confining effects of the ICM, while stripping effects of the ICM in satellite galaxies will lead to a further reduction ([170]). Curiously, the $L_X$ values at the end of the simulations are comparable. Of course, only a systematic exploration of the parameter space determining the galaxy structure can confirm if this is a robust result or just a fortuitous coincidence. The most natural explanation of the similarity of the $L_X$ values is that $L_X$ of models B302 and B301 has been finally reduced by the series of bursts (absent in model B302): in fact, note how the interburst $L_X$ of the two models is much higher than in the low-mass model. In the middle panels we show instead the estimated IR luminosity $L_{\text{IR}}$ due to the reprocessing of the radiation emitted by the new stars and by the SMBH and absorbed by the ISM inside $10R_e$. Again, in the low mass model only a smooth evolution is visible. Instead, in the other two models the bulk of the reprocessed radiation comes from AGN obscuration, while the lower envelope is determined by radiation reprocessing of the new stars. Note that the values of high luminosity peaks ($L_{\text{IR}} \sim 10^{46} \text{ erg s}^{-1}$, or more) are similar to those reported for ULIRGs (e.g., see [144, 123]). In addition, peaks of nuclear IR emission coupled with nuclear radio/X-ray emission have been recently reported in a sample of elliptical galaxies ([178]). The bottom panels present the temporal evolution of the optical and UV luminosities of the new stars (corrected for absorption). A large fraction of the starburst luminosity output (in the bursting models) occurs during phases when shrouding by dust is significant (e.g., see [157, 12]). At the end of the burst phase, the new stars in the central regions will emit in UV and optical for $\approx 10^7$ yr, in the range seen in bright E+A sources. Nowadays, the different timescales of nuclear accretion and associated star formation can be measured, with very interesting results ([185]).

As anticipated, we compute the duty-cycle as the total time spent by the AGN at high luminosity phases, normalized to the age of the system at the specified time. In practice, we estimate the observable duty-cycle as the fraction of the total time that the AGN is in the “on” state. The resulting values are very similar to the luminosity-weighted values. First, the low-mass model, consistently with the absence of bursts, has a null duty-cycle in the different bands. Cumulative duty-cycles (i.e., spanning the whole simulation time) of model B302 are $\approx (4.8\times10^{-2}, 2.7\times10^{-2}, 1.9\times10^{-2})$, in the bolometric, optical and UV after absorption. As expected (at each time) the larger duty-cycles are in the bolometric, followed by absorbed optical and finally by absorbed UV. Values for the more massive B301 are $\approx (7.9\times10^{-2}, 3.6\times10^{-2}, 2.3\times10^{-2})$. By construction these values cannot take into account the temporal decline of the accretion activity over the Hubble time. For example, by restricting the computation to the temporal baseline of the last 6 Gyr, the resulting duty-cycle values drop by an
order of magnitude. These values compare nicely with observational estimates (e.g., see [77, 73]).

### 4.2 Mass budgets: SMBH, ISM, and starformation

In Fig. 3 we show the time evolution of some of the relevant mass budgets of the models (summarized in Table 1), both as time-integrated properties and instantaneous rates: black lines refer to the SMBH accretion ($\Delta M_{BH}$), green lines to the gas mass ejected as a galactic wind ($\Delta M_w$), red lines to the new stars ($\Delta M_*$), and finally the blue lines to the gas content in the galaxy. Of course, the SMBH accretion rate parallels the luminosity evolution discussed in the previous Section. A few expected trends are apparent. For example, from the top panels it results that the final accumulated SMBH mass is higher in the more massive models. This is due to two reasons: first because the mass return from the evolving stars in a galaxy scales linearly with the stellar mass, and second, because the gas is more bound (per unit mass) in more massive systems. The total mass ejected as a galactic wind increases with the galaxy mass, but the remarkable fact here is the strong dependence of the star formation history from the galaxy mass. This is due, as already found and described in previous papers, by the fact that in our models star formation is actually stimulated by peak AGN activity. Therefore, AGN activity not only quenches star formation (during the low-luminosity accretion phases), but it can also be a trigger, especially during the “passive” evolution of early-type galaxies. In any case, star formation episodes end abruptly after major SMBH outbursts. The coincidence of vigorous star formation episodes with accretion events and AGN activity can be clearly seen from the middle and bottom panels, by comparison of the black and red lines. Note also how the peaks in the green lines (galactic wind mass loss rate, $\Delta M_w$) are temporally displaced with respect to the starburst-AGN episodes, due to the sound crossing time in the galaxy. About the galaxy mass loss, it is also important to note that the bulk of the degassing is not due to AGN feedback events, but to the secular heating provided by SNIa: absent this ingredient, all galaxy models host gas inflows, with the consequent series of accretion events and final SMBH masses well above the observed range.

As already mentioned above, these violent star formation episodes are induced by accretion feedback\(^1\), and are spatially limited to the central 10-100 pc; thus, the bulk of gas flowing to the center is consumed in the starburst. It is then expected that the final surface brightness profile of the galaxy will be modified. In fact, this can be seen in Fig. 4, where we show the final projected stellar density profile of the models, together with Sersic ([165, 27]) best-fit of the initial and final profiles

$$
\Sigma(R) = \Sigma_0 e^{-\frac{b(R/R_e)^{1/m}}{1}}, \quad b = 2m - 1/3 + 4/405m + \mathcal{O}(m^{-2}).
$$

\(^1\) However, bursting star formation is not necessarily associated with AGN feedback ([99]).
The profiles show an increase with time of the best-fit Sersic parameter $m$, from $\simeq 4.5$ up to $m \simeq 6$, within the range of values commonly observed in ellipticals: also, in the final $B3_{02}$ and $B3_{02}^{b}$ models we note the presence of a central nucleus originated by star formation which stays above the best fit profile. Without entering the debated field of the morphological classification of the centers of elliptical galaxies (e.g., see [57, 69, 70, 104, 44, 98, 167], see also [26]), we notice that the “light spikes” in our models are strikingly similar to the light spikes characterizing “nucleated” or “extra-light”, and that usually are attributed to galaxy merging (e.g., see [86]), and references therein). Observational evidence is also accumulating that the
central parts are quite metal rich (e.g., see [22, 103] and, as noticed in [104], where colors and luminosities of the nuclear regions of elliptical galaxies are studied, on average the “nuclear” clusters are bluer than the surrounding galaxy, as would be expected if the origin were from infalling gas recycled from evolving stars. Finally, several observational indications exist that, while the majority of the stellar mass in elliptical galaxies may have formed at high redshifts, small but detectable star formation events (summing up to $\lesssim 5 - 10\%$ of the total stellar mass) have occurred at low redshift (e.g., see [184, 143, 78, 180]).

### 4.3 Hydrodynamics

In the published book.
5 Conclusions

In this review we have summarized the main results of combined (radiative and mechanical, i.e., produced by direct interaction of a nuclear wind/jet with the ISM) AGN feedback in elliptical galaxies, obtained with the aid of high-resolution 1D hydrodynamical simulations with a physically based feedback description. We presented for the first time a comparison of feedback effects on galaxy models of different mass. For completeness, we recall the main secure points on which our framework is based.

First, it is known from stellar evolution theory, and supported by observations, that the recycled gas from dying stars, available independently of external phenomena such as galaxy merging, sums up to 20-30% of the total mass in stars, and it is released over the cosmic epoch. Therefore, recycled gas is an important source of fuel for the central SMBH, with a total mass $\approx 2$ orders of magnitude larger than the mass measured in SMBHs in the local universe.

Second, the metal rich recycled gas, if not removed from the parent galaxy (by SNIa heating, ram-pressure, or tidal stripping), is necessarily a subject of a classical radiative cooling instability, leading to a collapse towards the center. This is the idea behind the well known (and much debated) “cooling flow” scenario.

Third, as the cooling gas cannot disappear, a star-burst must occur and also the central SMBH must be fed. The details of how much is accreted on the central SMBH vs. consumed in stars vs. ejected from the center by energy input from the starburst and the AGN are uncertain. But the observed mass of central SMBHs, and the mass of the X-ray emitting hot gas, force to conclude that the bulk is transformed into stars or blown out as a galactic wind, with less than 1% going into the central SMBH.

Fourth, since at the end of a major outburst a hot bubble remains at the galaxy center, feedback processes shut themselves off, with a recurrence time determined by stellar evolution and ISM cooling time. Steady accretion on SMBHs is only possible at very low Eddington ratios, and no steady flow appears to be possible for Eddington ratios above $\approx 0.01$. Whenever the luminosity is significantly above this limit, both the accretion and the output luminosity is in burst mode.

Fifth, during the bursting phase the galaxy center would be optically thick to dust, so one would observe a largely obscured starburst and a largely obscured AGN, with most radiation in the far IR. As gas and dust are consumed, the central source becomes visible. Much of the AGN output occurs during obscured phases; then there is a brief interval when one sees a “normal” quasar, and finally one would see a low X-ray luminosity and E+A spectrum galaxy, in the central several hundred pc, for $10^{7-8}$ yrs (e.g., [68]).

All the simulations performed so far confirmed these expectations, and the general results can be summarized as follows:

1) Radiative heating and radiation pressure on the ISM by photons emitted by the central AGN and by the starburst, without any mechanical input, greatly reduces the “cooling flow catastrophe” problem, but leads to a central SMBH that would be too
bright and too massive, and the galaxy would be too blue, due to repeated bursts of central star formation.

2a) In absence of radiative feedback, mechanical energy from an AGN wind with fixed efficiency also does not give a solution that in detail satisfies the observations. For large efficiencies a giant burst and an explosive degassing of the galaxy occurs (e.g., [46, 91]). The gas content of the galaxy drops to levels below what is observed in real elliptical galaxies and the systems would have coronal X-ray luminosities orders of magnitude lower than those typically seen in nearby ellipticals. Also, the computed AGN duty cycle is too small. If the fixed efficiency is made low enough to avoid these problems, then one reverts to the classical cooling flow picture.

2b) Models with mechanical energy efficiency proportional to the accretion luminosity, as indicated both by observations and detailed 2D hydrodynamical simulations for radiatively driven winds (e.g., see [100, 101, 102]) perform better, but are still inadequate. We thus conclude that mechanical energy input - by itself - is unable to provide appropriate levels of feedback that would leave ellipticals at the current epoch with the properties that they are observed to have.

3) The combined models, in which both radiative and mechanical feedback are allowed (as supported by observations, e.g., [1]), are the most satisfactorily. This family of models, with mechanical energy efficiency proportional to the luminosity, when combined with a physically based treatment of the radiative effects, does seem to be consistent with all observations for a range of realistic efficiencies $\varepsilon_w$ (e.g., see [171]). Radiative and mechanical feedback affect different regions of the galaxy at different evolutionary stages. During the “quiescent”, optically thin phases, radiative heating is distributed over all the galaxy body, while the mechanical feedback is deposited in a region of a kpc scale radius. During the bursts, the collapsing cold shells are optically thick, and most of the radiation is intercepted and re-radiated in the IR; mechanical feedback plays a major role in controlling accretion.

4) In combined models, radiative feedback from the central SMBH (primarily the X-ray component) and the young star feedback consequent to central star bursts (e.g., see [179]) can balance and consume the cooling flow gas over the $10^2$-$10^3$ pc scale, but they will not sufficiently limit the growth of the central SMBHs. Mechanical feedback from the central SMBH on the 10-$10^2$ pc scale, mediated by the Broad Line Region winds (e.g., see [9, 4, 5, 46]), is efficient in limiting the growth of the SMBH, but, absent the radiative feedback, would leave elliptical galaxies with more central star formation than observed.

From cosmological point of view, one of the main results of our study is that the evolution of an isolated galaxy, subject to internal evolution only, naturally leads to significant AGN and starburst activity, even in absence of external phenomena such as galaxy merging. This conclusion is gaining more and more observational support (e.g., see [141, 105, 93, 177, 36]).
5.1 Open questions and future developments

The investigation conducted so far, and summarized in the previous Sections, suffers from a few weak points, namely: 1) the newly formed stars are placed in the galaxy where they form; 2) the modifications of the galaxy structure, gravitational field and velocity dispersion profile, due to the stellar mass losses, galactic wind, and star formation, are ignored; 3) the simulations are spherically symmetric, so that Rayleigh-Taylor and Kelvin-Helmholz unstable configurations of the ISM (such as the formation of the cold shells, and the nuclear wind and jet propagation), cannot be followed in detail.

The first two points will be addressed in future works. Instead, we already started the exploration of 2D models, with very encouraging and interesting results ([127]). Additional lines that have been or will be studied are, for example, the properties expected for the starburst population (such as spatial distribution, spectral properties, etc.), the X-ray properties of the perturbed ISM as a function of the combined effect of SNIa and central feedback ([139]), and the cosmic rays emission following a central burst ([90]). Other obvious issues are the effects of environment, as for a cD galaxy in a cluster, the stripping effects ([170]), and the impact of combined feedback models on the ICM (extending the preliminary investigation [35], see also [145]). We finally mention another observational riddle that could be solved by the present models (with some additional work in the physical modelization of feedback in the very sub-Eddington accretion regime), i.e., that of the apparent “underluminosity” of SMBHs in the local universe (e.g., see [54, 135]). In fact, the simulations show clear evidence that an additional form of feedback is needed during the quiescent, low-luminosity accretion phases (in particular at late epochs). Of course, standard radiative feedback is not effective during such phases, and presumably the further reduction is provided by nuclear jets and/or thermally driven winds (e.g., see [2, 117]).

Acknowledgements We thank Ena Choi, Janfey Jang, Greg Novak, Silvia Pellegrini, Daniel Proga, Sergei Sazonov, Min-Su Shin, Anatoly Spitkovski, Rashid Sunyaev for their precious collaboration in the research effort described in this paper. We also thank Dong-Woo Kim and Silvia Pellegrini for organizing the Joint Discussion at the IAU General Assembly in Rio, and for editing this volume. L.C. is supported by the MIUR Prin2008.

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