Active Galactic Nuclei Feedback

Fernando Becerra

Harvard-Smithsonian Center for Astrophysics, Harvard University, Cambridge, MA 02138, USA

Astronomy 202b Term Paper

fbecerra@cfa.harvard.edu

1. Introduction

Current cosmological models have proven to give helpful insights about the formation and evolution of galaxies in the Universe. Although theoretical models have been fairly successful in giving an accurate description of them, there are still some issues that need to be solved. For instance, one of the main problems is the over-predicted rate of star formation in baryonic matter. Numerical hydrodynamical simulations of cosmological structure formation predict that $\gtrsim 20\%$ of the baryons should have condensed into galaxies, in contrast to the $\lesssim 10\%$ that has been observed in form of stars (Balogh et al. 2001), even in the case when these simulations include radiative cooling. This problem is also reflected in the over-production of bright massive galaxies in cases where only gravitational heating is included, thus resulting in an inaccurate reproduction of the high-luminosity end of the galaxy luminosity function.

A second example to consider in the discrepancy between theoretical predictions and observations is the standard "cooling flow" problem. In this case, high-resolution X-ray observations of the intracluster medium (ICM) of clusters and groups of galaxies have revealed lower amounts of thermal gas radiatively cooling to low temperatures than predicted by pure cooling models. Theoretical models predict that radiative cooling time at the centers of groups and clusters should be often less than 1 Gyr, while in ellipticals should be less than 0.1 Gyr, which implies that the gas should cool and accrete onto the central galaxy to form stars. Some studies have detected cold molecular clouds and star formation in galaxy clusters and groups, but at levels far below those expected. In order to solve this issue, we need potential mechanisms that prevent the gas to cool. Many have been suggested over the years, being the most plausible explanation that the gas at the center must experience some kind of heating due to a feedback mechanism that prevent the so-called "cool-core" systems of establishing cooling flows at the rates predicted.

In this context, non-gravitational heating supplied by supernovae (SN) and active galactic nuclei (AGN) have been proposed as possible solutions for these problems. Between those processes, the best candidate to provide an explanation to observations is AGN heating, which appears to be the most likely mechanism to provide enough energy to quench cooling in massive galaxies (Borgani et al. 2002). In particular, observations of outbursts and accompanying energy injection from AGNs of the central dominant (cD) galaxies have confirmed this premise (McNamara & Nulsen 2007).

AGNs are powered by accretion of material onto a black hole (BH), which is located at the center of the host galaxy. The order of magnitude of the energy released by matter falling onto a black hole is given by $E_{\rm BH} = \epsilon M_{\rm BH} c^2$, where ϵ is the efficiency which is commonly assumed to be ~ 0.1, $M_{\rm BH}$ the mass of the black hole, and c the speed of light. For the case of supermassive black holes (SMBHs) of masses $\sim 10^9 M_\odot$, the estimation of the energy released during its formation and growth gives us an order of magnitude of $E_{\rm BH} \sim 2 \times 10^{62}$ ergs s^{-1}. On the other hand, the binding energy of a galaxy can be calculated as $E_{\rm gal} \sim M_{\rm gal}\sigma^2$, where $M_{\rm gal}$ is the total mass of the galaxy and σ the stellar velocity dispersion. For a galaxy with $\sigma < 450$ km s^{-1} we estimate the black hole energy to binding energy ratio to be $E_{\rm BH}/E_{\rm gal} > 100$ for typical values of the galaxy mass. Hence, even a fraction of $\lesssim 1\%$ of the energy of a black hole is enough to heat and blow away the entire gas content of the galaxy and prevent cooling, which might explain the lack of star formation in these systems.

However, there is still a lack of understanding about how gas inflows are triggered by large-scale mechanisms in this picture. It is believed that some physical processes deliver the gas from $\approx$ 10 kpc host-galaxy scales down to the BH accretion disk at radius less than 0.1 pc. In this journey, the gas has to overcome substantial barriers such as the loss of $\approx 99\%$ of its angular momentum, and the competition against gas collapsing and forming stars rather than accreting onto the BH. The current consensus in this issue is that gas inflow from kpc scales down to the central $\approx$ 10-100 pc is driven through a series of gravitational instabilities, which helps the gas to lose its angular momentum. The fate of the gas in smaller scales of the order of $\approx$ 1-10 pc is uncertain, but current models predict a complex interplay between AGN activity, star formation, and stellar winds.

The impact of AGN feedback affects a wide range of structures and scales, from galaxy formation to cool-core systems. In the former case, it truncates the galaxy luminosity function by suppressing the over-production of massive elliptical galaxies predicted by dark-matter-only simulations, while in the latter case it regulates the cooling flow problem explaining the reduced rate at which cooling and star formation proceed. Additionally, it also gives helpful insights about the observed relation between the black hole mass and the bulge velocity dispersion (Ferrarese & Merritt 2000, Gebhardt et al. 2000), which is widely accepted as an indicator of a casual connection or a feedback mechanism between the formation of the bulges and their central black holes. Unfortunately, the details governing the operation of the feedback loop are still not clear, and hence a deeper comprehension of the nature of AGN feedback is vital to our knowledge of galaxy formation and evolution.

This paper is organized as follows. We present the characteristics of the two main modes of AGN feedback, the radiative and the kinetic mode, in Section 2. Then, in Section 3, we present the observational evidence in galaxy groups and clusters of the presence of AGN feedback in those systems. We finally conclude and discuss the future perspectives on this topic in Section 4.

2. Modes of AGN feedback

Any feedback process requires a coupling between the energy released by a BH and the surrounding material to heat the gas efficiently. Observations of massive galaxies and AGN suggest that this interplay between BH and host galaxy can take two forms: the radiative and the kinetic mode. Both modes have been referenced with various names in the literature. For instance, the radiative mode is also called wind or quasar mode, while the kinetic mode is also referenced as jet or radio mode. The former one comprises wide-angle, sub-relativistic outflows and tend to be driven by the radiative output of the AGN. This mode of feedback is important when the AGN/quasar is highly luminous and within about two orders of magnitude of the Eddington limit. The latter one are relativistic outflows with narrow opening angles that are launched directly from the accretion flow itself. This case is commonly observed in massive galaxies at the center of clusters and groups, which generally do not host AGN or quasars and the supermassive black holes at their center are often active radio sources. A schematic diagram of the differences between both modes is shown in Figure 1.

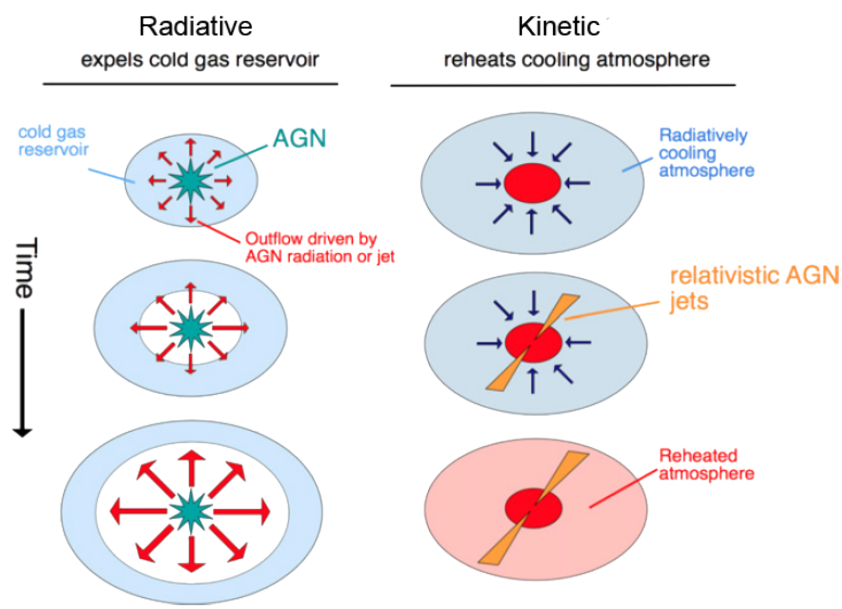


Fig. 1.— Schematic diagram to illustrate the radiative and kinetic mode of AGN feedback. The first one consists on wide-angle outflows driven by radiation from the central quasar. The second one is characterized by small opening angle jets coming from the central radio source, which reheats the radiatively cooling atmosphere. Adapted from Alexander & Hickox (2012).

2.1. The radiative mode

This mode of feedback was probably most efficient at $z \sim$ 2-3, when quasar activity peaked and galaxies were most gas rich. Observational evidence is patchy at that time due to obscuration of the active nucleus, making observations of this mode a very difficult task. The radiative mode has been proposed to be the most likely AGN feedback explanation for the black hole mass-stellar velocity dispersion relation observed in local galaxies.

The first explanation of the $M_{\rm BH} - \sigma$ relation by radiative feedback was proposed by Silk & Rees (1998). They proposed that the maximum collapse rate of an isothermal galaxy with radius r and mass $M_{\rm gal} = 2\sigma^2 r/G$, where σ is the stellar velocity dispersion, can be calculated as its gas content, $M_{\rm gas} = fM_{\rm gal}$, collapsing on a free-fall time, r/σ. The resulting maximum collapse rate is then $\sim M_{\rm gas}\sigma/r \sim 2f\sigma^3/G$. The power required to balance this collapse can be estimated as $\sim f\sigma^5/G$. In the radiative mode this power is supplied by radiation, which is limited by the Eddington luminosity $L_{\rm Edd} = 4\pi G M_{\rm BH} m_{\rm p} c/\sigma_{\rm T}$, where $m_{\rm p}$ is the mass of the proton, and $\sigma_{\rm T}$ the Thomson scattering cross-section for the electron. Hence, the Eddington luminosity is required to be of the same order of the power needed to balance gravitational collapse, $L_{\rm Edd} \sim f\sigma^5/G$, from where we can deduce

$$M_{\rm BH} \sim \frac{f\sigma^5\sigma_{\rm T}}{4\pi G^2 m_{\rm p} c}$$

The relation obtained $M_{\rm BH} \propto \sigma^5$ does not quite fit the value of the slope derived from observations, hence requiring improvements on this model. An alternative is to assume that the radiate pressure from an Eddington-limited quasar, $L_{\rm Edd}/c$, has swept a gas mass $M_{\rm gas} = fM_{\rm gal}$ to the edge of the galaxy. In such a case, the balance between the outward radiation force and the inward one due to gravity gives

$$\frac{L_{\rm Edd}}{c} = \frac{G M_{\rm gal} M_{\rm gas}}{r^2} \Rightarrow \frac{4\pi G M_{\rm BH} m_{\rm p}}{\sigma_{\rm T}} = \frac{f G M_{\rm gal}^2}{r^2}$$

If we consider that the galaxy is isothermal with radius r, its mass can be rewritten as $M_{\rm gal} = 2\sigma^2 r/G$. Hence

$$\frac{4\pi G M_{\rm BH} m_{\rm p}}{\sigma_{\rm T}} = \frac{fG}{r^2}\left(\frac{2\sigma^2 r}{G}\right)^2 = \frac{4f\sigma^4}{G}$$

from where we can finally get

$$M_{\rm BH} = \frac{f\sigma^4\sigma_{\rm T}}{\pi G^2 m_{\rm p}} \tag{1}$$

The remarkably agreement between this simple model and the observed $M_{\rm BH} - \sigma$ relation can be interpreted as (weak) observational evidence for AGN feedback.

If the quasar is locally at its Eddington limit, then it falls below this limit when the mass of the galaxy is included, hence the necessity of a stronger interaction that does not rely on radiation pressure on electrons. Two possibilities arise to improve this scenario: (1) winds generated close to the quasar that flows through the galaxy pushing the gas out, or (2) dust in the gas, which is expected from the interstellar medium of a galaxy. In the latter case, dust grains embedded in the gas will be partly charged in the energetic environment of a quasar, which binds them to the surrounding partially-ionized gas. In such a case $L_{\rm Edd}$ is reduced by a factor $\sigma_{\rm d}/\sigma_{\rm T}$, where $\sigma_{\rm d}$ represents the equivalent dust cross-section per proton wighted for the dust content of the gas and the spectrum of the quasar.

Fabian et al. (2008) found that the ratio $\sigma_{\rm d}/\sigma_{\rm T}$ varies from ~ 1000 for a gas with a Galactic dust-to-gas ratio exposed to a typical quasar, to 500 for low Eddington rate objects. Given that both the active nucleus and the galaxy are at their respective Eddington limits, this implies that a quasar at its Eddington limit for ionized gas is at an effective Eddington limit for dusty gas of a surrounding object 1000 times more massive. In other words, this implies a galaxy mass to black hole mass ratio of $M_{\rm gal}/M_{\rm BH} \sim \sigma_{\rm d}/\sigma_{\rm T} \sim 1000$, which has been previously deduced from observations (Häring & Rix 2004). From this ratio we can solver for $\sigma_{\rm T}$ and replace its value in Equation 1, obtaining

$$M_{\rm gal} = \frac{f\sigma^4\sigma_{\rm d}}{\pi G^2 m_{\rm p}}$$

which corresponds to the Faber-Jackson relation (Faber & Jackson 1976) for a constant mass-to-light ratio. Furthermore, rewriting the mass of the galaxy as $M_{\rm gal} = 2\sigma^2 r/G$ we get

$$\frac{\sigma^2}{r} = \frac{2\pi G m_{\rm p}}{f\sigma_{\rm d}}$$

which recovers some aspects of the fundamental plane (Djorgovski & Davis 1987). Hence, this approach reveals that AGN feedback might play an important role in shaping both the black hole and the galaxy bulge.

If instead the interaction is due to winds rather than radiation pressure, the kinetic luminosity is given by

$$\frac{L_{\rm w}}{L_{\rm Edd}} = \frac{f}{2}\frac{r}{r_{\rm g}}\left(\frac{v}{c}\right)^3\frac{N}{N_{\rm T}}$$

where $r_{\rm g}$ is the gravitational radius GM/c^2 and $N_{\rm T} = \sigma_{\rm T}^{-1} = 1.5 \times 10^{24}$ cm^{-2}. From that formula we can see that for high wind power ($L_{\rm w} \sim L_{\rm Edd}$) the wind needs to have a high column density ($N \sim N_{\rm T}$), high velocity ($v \sim 0.1c$), and high covering fraction f at large radius $r > 10^3 r_{\rm g}$.

In order to reproduce the $M_{\rm BH} - \sigma^4$ scaling, the thrust of the wind needs to be proportional to the Eddington limit, which implies that the wind may need to be dusty. The problem with this picture is that dust might not be able to survive in environments close to the black hole, where the escape velocity is high.

Outflows from X-rays warm absorbers flowing at ~ 1000 km s^{-1} have been observed in Seyfert galaxies (Reynolds 1997), but they are still insufficient by a large factor to fit in this scenario. Faster winds with velocities of the order of tens of thousands of kilometers per second are required, such as those seen in UV observations of broad absorption line (BAL) quasars and in X-ray observations of some AGN, but observational evidence has not been conclusive to support this picture yet.

2.2. The kinetic mode

Due to radiation pressure the radiative mode of AGN feedback can empty a massive galaxy of gas. In such a case, it will try to refill with at least stellar mass loss if isolated or with intracluster plasma if in a cluster or group. The role of the kinetic mode of feedback then appears to be keeping the galaxy empty, or at least keeping the gas hot so it does not cool. This mode is usually observed as bubbles or cavities in the cores of clusters and groups of galaxies in the local Universe. In those cases, the most massive galaxies at the center of groups and clusters are often surrounded by gas with a radiative cooling time short enough that a cooling flow should be taking place (Fabian 1994).

Considering that the X-rays emitted from clusters of galaxies represent a loss of energy of the ICM, then the resultant cooling time, $t_{\rm cool}$, can be expressed as the enthalpy per unit volume H_ν divided by the luminosity per unit volume, which gives us the expression

$$t_{\rm cool} \approx \frac{H_\nu}{n_e n_{\rm H} \Lambda(T)} = \frac{\gamma}{\gamma - 1} \frac{kT}{\mu X n_e \Lambda(T)} \tag{2}$$

where γ is the adiabatic index, μ the molecular weight, X the hydrogen mass fraction, and $\Lambda(T)$ the cooling function.

Another parameter that can be estimated from X-ray observations is the mass inflow rate due to cooling. In this case we define a cooling region delimited by the cooling radius, which is usually defined as the radius at which $t_{\rm cool}$ is equal to the look-back time to $z = 1$. We can use then the luminosity $L_{\rm cool}$ associated with the cooling region. If we assume that $L_{\rm cool}$ is due to radiation of the total thermal energy of the gas plus the pdV work done on the gas as it enters the cooling radius, then we can write an expression for the luminosity as

$$L_{\rm cool} = \frac{dE}{dt} = \frac{dE_{\rm th}}{dt} + \frac{pdV}{dt} = \left(\frac{\gamma}{\gamma - 1}\right) \frac{pdV}{dt}$$

Additionally, pressure can be expressed as a function of density as $p = \rho kT / \mu m_{\rm p}$, then the term pdV can be rewritten as $dMkT/\mu m_{\rm p}$. Using a value of $5/3$ for γ, we obtain:

$$L_{\rm cool} = \frac{5}{2}\frac{\dot{M}}{\mu m_{\rm p}}kT \Rightarrow \dot{M} = \frac{2}{5}\frac{L_{\rm cool}\mu m_{\rm p}}{kT}$$

From X-rays observations we can measure the luminosity of the cooling region, and using the above expression we can get an estimate for the mass cooling rate. The deduced value is of the order of tens, hundreds, or even thousands of solar masses per year. As a consequence of this effect gas should be cooling and forming stars, hence more massive galaxies should be significantly growing their stellar mass now. Observations have detected some star formation going on, but far from the mass cooling rate predicted. One possible explanation for this discrepancy is that the initial mass function (IMF) of the star formation process in these systems favored low-mass stars, but most observations find an universal IMF that does not present this behavior, which makes the role of low-mass stars not very important.

Furthermore, *XMM-Newton* observations indicate that there was much less gas below one-third of the outer cluster gas temperature than would be expected in a steady flow. Either something was heating the gas or the gas was somehow disappearing. The general consensus now is that the massive black hole at the center of the galaxy is feeding energy back into its surroundings at a rate balancing the loss of energy through cooling.

In this context, an apparent balance between heating and cooling processes has been established and maintained. On one hand, lack of high star formation suggests that cooling does not exceed heating by 10% or so. On the other hand, the presence of central abundance gradients and pronounced temperature drops indicate that heating does not generally exceed cooling by much either. This picture implies a relatively close heating/cooling balance that needs to be hold over a fair amount of time.

3. AGN feedback in galaxy groups and cluster

The derivation of a simple luminosity-temperature relation for clusters can be done by using the so-called "self-similar scaling relations" in a cosmological context. We start by considering that galaxy clusters of different masses are scaled versions of each other. Then, the density of each dark matter halo is proportional to the critical density of the Universe at the cluster's redshift through the so-called "overdensity" $\Delta = \rho_{\rm DM}/\rho_{\rm c,z}$, where $\rho_{\rm c,z} = 3H(z)^2/8\pi G$ with $H(z) = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda} \equiv H_0 E(z)$. Now, if we define the mass M as the mass inside the radius R at a given overdensity Δ, we can express $M \propto \rho_{\rm c,z}\Delta R^3 \propto \rho_{\rm c,0}E(z)^2\Delta R^3$. From the last equation, we can get the relation:

$$R \propto M^{1/3}E(z)^{-2/3}$$

Furthermore, if we consider that during cluster formation the gravitational collapse of diffuse gas heats the gas itself at the virial temperature of the potential well of the dark matter halo, we can write $T_{\rm vir} \sim GM\mu m_{\rm p}/kR$. Replacing the expression for R previously obtained in the formula for the virial temperature, we get a relation between the mass and the temperature of the form $T \propto M/R \propto MM^{-1/3}E(z)^{2/3} \propto M^{2/3}E(z)^{2/3}$, hence

$$M \propto T^{3/2}E(z)^{-1}$$

To finally derive the relation between luminosity and temperature, we should consider that hot gas emits through bremsstrahlung radiation. Then the X-ray luminosity can be written as $L_{\rm X} \propto \rho^2 \Lambda V$, where ρ is the average density and Λ the cooling function, which for the bremsstrahlung regime takes the form $\Lambda \propto T^{1/2}$. In addition, assuming that the gas distribution traces the dark matter we can write $\rho \propto \rho_{\rm DM} \propto \rho_{\rm c,z}$, so $L_{\rm X} \propto \rho T^{1/2} M \propto \rho_{\rm c,0}E(z)^2 T^{1/2} M \propto E(z)^2 T^{1/2} T^{3/2} E(z)^{-1}$. From the last proportionality we finally get

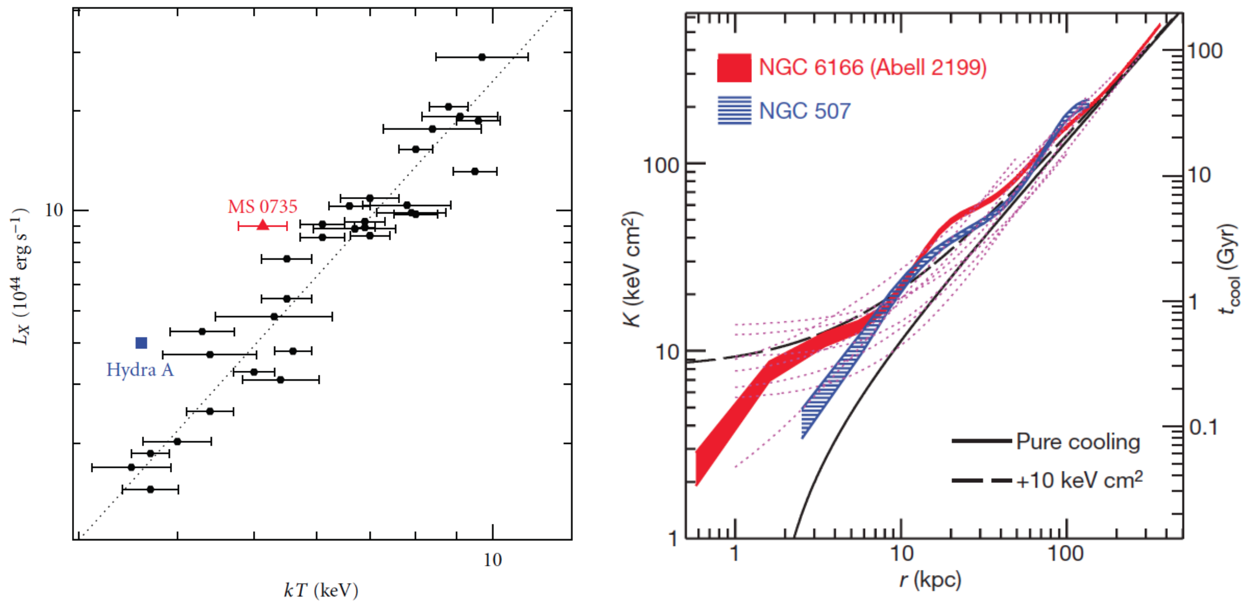
$$L_{\rm X} \propto T^2 E(z)$$

Spectroscopic observations seem to indicate a steeper $L - T$ relation than this prediction, of the form $L_{\rm X} \propto T^{2.5-3}$. Figure 2a shows an example of X-rays observations where the deduced relation is $L_{\rm X} \propto T^{2.64}$. This exponent may become even larger in the range $T_{\rm vir} \lesssim 3$ keV (Ponman et al. 1996) because the number density n decreases at low masses. This drop in n is related to an increase in entropy (Figure 2b), which is postulated as one of the reason for explaining the break of the scaling relation. The only way to increase entropy is through heating, so this turns out to be one of the strongest evidence for non-gravitational processes acting in the intracluster medium.

We can also relate the increase in entropy to an increase in the cooling time as Equation 2 suggests. The disagreement between X-ray observations and theoretical predictions of the cooling time is what is known as the "cooling flow" problem in galaxy clusters. Typical entropy excess of $\Delta K \approx 100$ keV cm^2 at $0.1R$ have been measured in previous studies (Lloyd-Davies et al. 2000, see also Figure 2b). This problem is common to most clusters and affects a large fraction of the ICM. Many explanations have been invoked such as quasar winds that quench star formation in the progenitors of giant ellipticals by preheating the intergalactic gas destined to become the ICM, but quasar winds can not explain the cooling flow problem in the central regions of clusters where the temperature decreases towards the center, also known as "cool-core" clusters.

Observations have revealed the presence of AGNs in the cD galaxies of cool-core clusters in 70% of the cases (Burns 1990, Best et al. 2007). As opposite to quasars, the activity pattern of these objects is closer to a constant string of minor outbursts instead of an erratic behavior. In many low-accretion-rate AGN the released energy is channeled into jets because the gas surrounding the black hole is not dense enough to radiate efficiently. Although their high presence rate at the center of clusters, these objects had been underestimated for a long time partly because of their very poor optical luminosity.

The interaction between the AGN and its surrounding material has been observed as cavities



(a) L-T relation

(b) Entropy profiles

Fig. 2.— *Left*: Bolometric X-ray luminosities versus emission-weighted temperatures. The dashed line represents the best-fit power law to the points, given by the expression $L_X = 6.35 \cdot (kT/6\ \text{keV})^{2.64} \times 10^{44}$ erg s^{-1}. Adapted from Gitti et al. (2012). *Right*: Entropy versus radius. Observations of cool-core clusters are shown in red dotted line, while theoretical prediction of pure cooling model is represented by the black solid line. The black dashed line results from the addition of 10 keV cm^2 to the pure cooling model, which turns out to agree better with observations. Adapted from Cattaneo et al. (2009).

in the X-rays gas, first discovered in the Perseus and Cygnus A clusters. These cavities are regions of enhanced radio-synchrotron emission which are spatially coincident with deficits in the X-ray emission. These observations have played a key role in the importance attributed to radio galaxies at the center of galaxy clusters. The common picture is that jets from the cD elliptical of a cluster extends outward in a bipolar flow, inflating lobes of radio-emitting plasma. These lobes push aside the X-ray emitting gas of the cluster atmosphere, thus forming depressions in the ICM that are detectable as cavities in the X-ray images. This kind of phenomena is present in $\gtrsim 70\%$ of cool-core clusters. Some examples of well-studied cavity systems in clusters and groups are shown in Figure 3, which shows X-ray emission with superimposed radio emission as green contours. In those cases, cavities are observed as bubbles of diminished X-ray emission and intensification of the emission in the radio spectrum.

An estimation of the energy required to create a cavity with pressure p_{cav} and volume V_{cav} can be calculated as the sum of the internal energy of the cavity and the work done by jets to create it $E_{\text{cav}} = E_{\text{int}} + p_{\text{ICM}} V_{\text{cav}}$. The internal energy of the radio-emitting plasma is given by $E_{\text{int}} = p_{\text{cav}} V_{\text{cav}}/(\gamma - 1)$, where γ is the plasma adiabatic index and the cavity pressure $p_{\text{cav}} \geq p_{\text{ICM}}$.

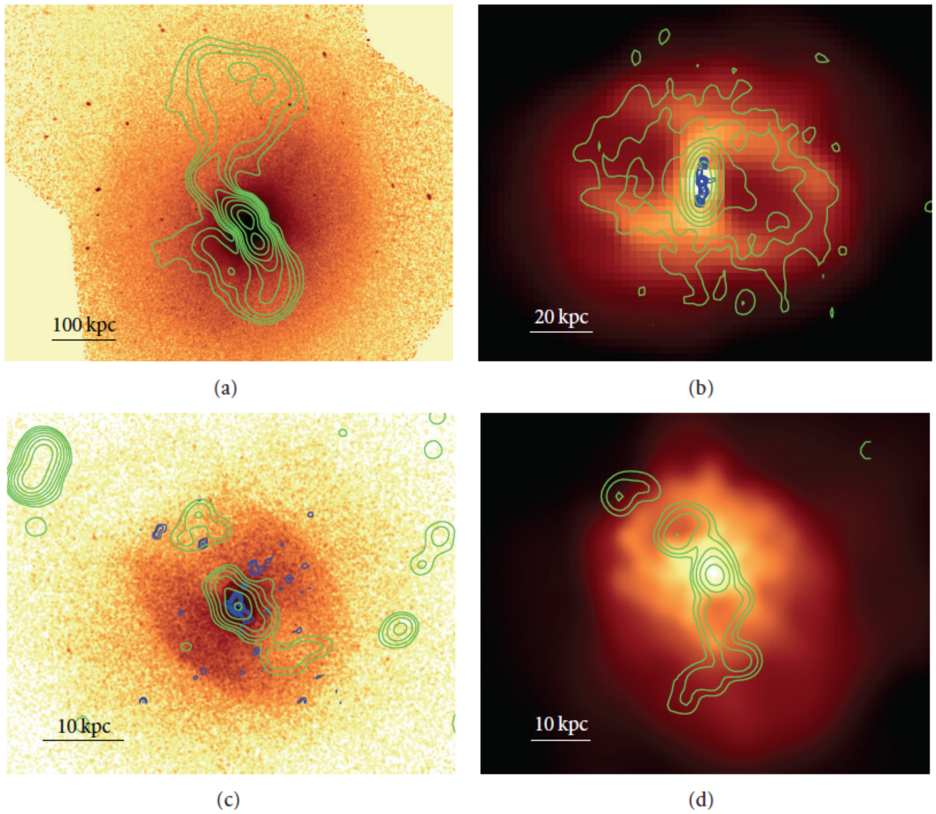


Fig. 3.— X-ray images of the (a) galaxy cluster Hydra A, (b) galaxy cluster RBS 797, (c) galaxy group NGC 5813, and (d) compact group HCG 62. Cavities are observed in all cases as a diminution in X-ray emission and an increment of the radio emission, which is over-plotted as green contours. Adapted from Gitti et al. (2012).

Rewriting the expression for the energy of the cavity we get $E_{\rm cav} \geq \gamma p_{\rm ICM} V_{\rm cav}/(\gamma - 1)$. A typical assumption made is that the internal composition of the cavity is dominated by relativistic plasma, which implies a value of the adiabatic index $\gamma = 4/3$, therefore

$$E_{\rm cav} \geq 4 p_{\rm ICM} V_{\rm cav}$$

Direct X-rays observations of cavities allows us to estimate its size, and hence its volume. Additionally, measurements of the temperature and density of the surrounding ICM permit us to calculate the ICM pressure. With those two values we can easily calculate their product and get an estimation for the energy cavity. One caveat is that simulations indicate that the product $p_{\rm ICM} V_{\rm cav}$ can vary with time during the cavity evolution and may be an inaccurate measure of the total energy released. To overcome this drawback, we define the cavity power $P_{\rm cav}$ as the cavity energy $E_{\rm cav}$ divided by the cavity age $t_{\rm cav}$. The value of $P_{\rm cav} = E_{\rm cav}/t_{\rm cav}$ is easily derivable once we have calculated $t_{\rm cav}$.

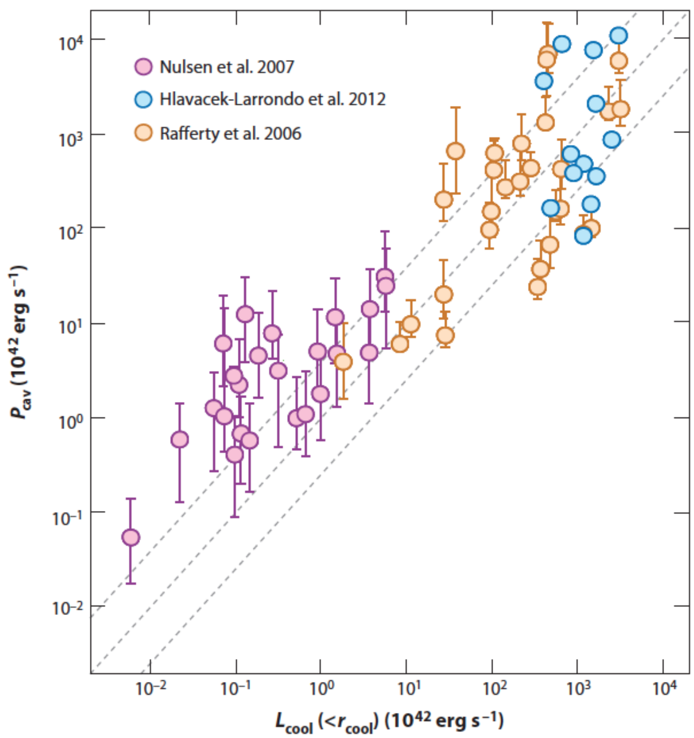


Fig. 4.— Cavity power $P_{\rm cav}$ versus luminosity of the cooling region $L_{\rm cool}$ for a range of objects from clusters, through groups, to elliptical galaxies. Dashed lines represent cavity power calculated based on injected energies of 1, 4, and 16 $p_{\rm ICM}V_{\rm cav}$ from top to bottom. Adapted from Fabian (2012).

There are three ways to estimate the cavity age: (1) by assuming that the cavity rises the hot gas atmosphere at the sound speed $c_{\rm s}$, reaching the projected distance R in the sound crossing time $t_{\rm s} = R/\sqrt{\gamma kT/\mu m_{\rm p}}$, (2) by assuming that the cavity is buoyant and move outwards at the terminal velocity $v_{\rm t}$, reaching R in the buoyancy-time $t_{\rm buoy} = R/v_{\rm t} = R/\sqrt{2gV_{\rm cav}/SC}$ where g is the gravitation acceleration at the position R, S is the cross-section of the cavity, and $C = 0.75$ is the drag coefficient, and (3) by considering the time required for gas to refill the displaced volume of the cavity as it rises $t_{\rm ref} \sim 2\sqrt{R_{\rm cav}/g}$, where $R_{\rm cav}$ is the radius of the cavity. Most studies adopt the buoyancy time, which gives a cavity age of the order of a few 10^7 yr for typical values.

The cavity power $P_{\rm cav}$ can be then estimated directly from observations and represents the energy injected into the hot gas by the AGN outburst. We can compared then $P_{\rm cav}$ to the gas luminosity inside the cooling radius $L_{\rm cool}$, which represents the luminosity that must be compensated by heating to prevent cooling. Figure 4 shows a comparison between $P_{\rm cav} = 4p_{\rm ICM}V_{\rm cav}/t_{\rm buoy}$ and $L_{\rm cool}$ for a range of luminous clusters, groups and elliptical galaxies. Lines of equality between cooling and heating are shown in dashed lines for injected energies of 1, 4 and 16 $p_{\rm ICM}V_{\rm cav}$ per cavity from top to bottom.

From the figure it appears that the systems with high mass and high luminosity need an average of $4p_{\rm ICM}V_{\rm cav}$ per cavity to counter cooling. If instead all points are recalculated as $P_{\rm cav} = p_{\rm ICM}V_{\rm cav}/t_{\rm buoy}$, they only experience a shift down by a factor of 4, and hence only the lower mass systems will still lie around the line $P_{\rm cav} = L_{\rm cool}$. This means that those systems require $1p_{\rm ICM}V_{\rm cav}$ per cavity to offset cooling at the present time. Those few points that still are above the equality line represent systems where the total mechanical power of the AGN far exceeds the radiative losses, and as a result their atmospheres are being heated.

Another interesting result can be deduced by calculating average values for $P_{\rm cav}$ and $L_{\rm cool}$ for different samples. In the case of groups and ellipticals, the ratio of mean cavity power to cooling power seems to be about 5 times larger than in the case of clusters. If the duty cycle of low-mass systems is assumed to be the same as high-mass systems, then the relative heating to cooling ratio appears to be a factor of $\gtrsim 5$ higher in low-mass systems. This implies that groups and ellipticals seem to have five times as much as power available to counter cooling than rich clusters.

The AGN-cooling flow scenario deduced from Figure 4 gives us the basic idea that a self-regulated equilibrium may be achieved, in which mechanical heating from the central AGN balances the radiative losses from the thermal ICM over the system lifetime. Although this scenario is largely accepted, it is still not clear how heating can act preserving at the same time the observed temperature gradient and the cool core.

Giant ellipticals have the same cooling flow problem as galaxy clusters, with even stronger limits on the amount of gas that can cool and form stars. Even neglecting the hot gas in the halo, the final stages of the lives of massive stars return $\sim 30 - 40\%$ of the total stellar mass of the interstellar medium over the lifetime of the Universe. If only a small fraction of the gas from dying massive stars is accreted, then the mass of the black hole would be much larger than the observational estimates.

The same explanation as applied to clusters can not be used for galaxies, because jets drill through the nearby gas and dump most of the energy outside the galaxies in which they are produced. The situation is even worse in galaxies that are not at the centers of clusters. However, there are some counter-examples in which a jet may escape from its host galaxy and still transfer some of its energy to the interstellar medium. Although the existence of a few counter-examples, these observations are not enough to give a full description of the processes heating the atmosphere of massive ellipticals.

4. Conclusions

An active nucleus interacts with the surrounding gas in its host galaxy though mechanisms such as radiation pressure, winds, jets, and outflows. Estimations show that the energy and momentum released by the nucleus is enough to expel the interstellar medium of the host galaxy. This highlights the importance of AGN and the impact that these objects can have in the final mass of the stellar component of the galaxy, as well as in the mass of the black hole. Although many details about these processes are still unclear, it is believed that the AGN-host galaxy interaction is carried on through AGN feedback processes. As a consequence, feedback from the central black holes has turned out to be an essential ingredient that must be taken into account to fully understand the growth and evolution of galaxies and their central black holes, the history of star formation, and the formation of large-scale structures.

AGN feedback presents two main modes: the radiative and the kinetic modes. The radiative mode is characterized by outflows with wide opening angles and power of the order of the Eddington luminosity. This mode was apparently most active when the nucleus was a young quasar, stage at which the nucleus was probably highly obscured making direct observations of these objects a very difficult task. In contrast, the kinetic mode is characterized by relativistic jets with small opening angles. This mode is acting in massive objects in the local Universe, which makes observations of these objects in X-rays and radio wavelengths easier. An attractive possibility to fit both modes in a common picture is that the radiative mode shaped the overall galaxy and black hole mass at early times, while the kinetic mode is in charge of maintaining the situation where needed.

The strongest evidence for AGN feedback has been detected in galaxy clusters and groups. In those systems, the additional heating supplied by AGN arises as the most likely mechanism to explain the steeper relation between X-ray luminosity and gas temperature than predicted in the case that cluster growth were governed by gravity alone. This same process also turns out to be a good candidate to induce the suppression of gas cooling in massive galaxies, and explain the lower cooling rate deduced from observations in comparison to pure cooling flow models.

The discovery of giant cavities in the ICM was a big step towards the understanding of the AGN-host galaxy interacting through AGN feedback. X-ray and radio observations of these cavities have been crucial indicators that powerful AGN outbursts occurring at late times may contribute a significant fraction of the extra non-gravitational energy. In particular, comparisons of the energy injected into the gas by the black hole and the energy required to prevent cooling show a self-regulated scenario where radiative losses from the ICM are equilibrated by mechanical heating from the AGN.

The picture deduced from observations of clusters and groups of galaxies might explain why gas cools and flows onto the central galaxies at a lower rate than predicted by pure cooling flow models. At the same time, due to suppression of star formation, it might explain the exponential turnover of the luminosity function of galaxies in the high-mass range. Hence, AGN feedback arises as the best common solution for the two major heating problems associated with the ICM: those of cooling flow and galaxy formation.

Even though the general picture of the action of AGN feedback and its influence in the host galaxy and the central black hole is generally accepted, we still lack of an understanding of the details. How does it work? When does it act? How is the energy transferred from the AGN to the surrounding gas? Better X-ray and radio observations are crucial in trying to answer these questions. Future X-ray telescopes projects are not clear at the moment, and studies in this wavelength range should rely on the current generation of X-ray observatories. A better scenario stands for the radio part of the spectrum, where the next generation of observatories such as the Atamaca Large Millimeter/submillimeter Array (ALMA) have improved significantly the quality of radio observations. On the other hand, computer simulations should also play a key role in improving our understanding of AGN feedback. Unfortunately, simulations still do not reach the necessary resolution and rely on uncertain models of star formation and the physics of the interstellar medium. A common effort from both the observational and theoretical sides will allow us to widen our knowledge on this fundamental problem.

REFERENCES

Alexander, D. M., & Hickox, R. C. 2012, New A Rev., 56, 93

Balogh, M. L., Pearce, F. R., Bower, R. G., & Kay, S. T. 2001, MNRAS, 326, 1228

Best, P. N., von der Linden, A., Kauffmann, G., Heckman, T. M., & Kaiser, C. R. 2007, MNRAS, 379, 894

Borgani, S., Governato, F., Wadsley, J., et al. 2002, MNRAS, 336, 409

Burns, J. O. 1990, AJ, 99, 14

Cattaneo, A., Faber, S. M., Binney, J., et al. 2009, Nature, 460, 213

Djorgovski, S., & Davis, M. 1987, ApJ, 313, 59

Faber, S. M., & Jackson, R. E. 1976, ApJ, 204, 668

Fabian, A. C. 1994, ARA&A, 32, 277

—. 2012, ARA&A, 50, 455

Fabian, A. C., Vasudevan, R. V., & Gandhi, P. 2008, MNRAS, 385, L43

Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9

Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJ, 539, L13

Gitti, M., Brighenti, F., & McNamara, B. R. 2012, Advances in Astronomy, 2012

Häring, N., & Rix, H.-W. 2004, ApJ, 604, L89

Lloyd-Davies, E. J., Ponman, T. J., & Cannon, D. B. 2000, MNRAS, 315, 689

McNamara, B. R., & Nulsen, P. E. J. 2007, ARA&A, 45, 117

Ponman, T. J., Bourner, P. D. J., Ebeling, H., & Böhringer, H. 1996, MNRAS, 283, 690

Reynolds, C. S. 1997, MNRAS, 286, 513

Silk, J., & Rees, M. J. 1998, A&A, 331, L1

This preprint was prepared with the AAS LaTeX macros v5.2.