Section VI

Outflows and Feedback

Chair: Horacio Dottori

Co-Evolution of Central Black Holes and Galaxies
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Cosmic Feedback from AGN

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Abstract. Accretion onto the massive black hole at the centre of a galaxy can feed energy and momentum into its surroundings via radiation, winds, and jets. Feedback due to radiation pressure can lock the mass of the black hole onto the $M_{\rm BH}$–σ relation, and shape the final stellar bulge of the galaxy. Feedback due to the kinetic power of jets can prevent massive galaxies greatly increasing their stellar mass by heating gas, which would otherwise cool radiatively. The mechanisms involved in cosmic feedback are discussed and illustrated with observations.

Keywords. galaxies: active, black hole physics, X-rays: galaxies: clusters

1. Introduction

It has been realized over the past decade that the black hole at the center of a galaxy bulge is no mere ornament, but plays a major role in determining the final stellar mass of the galaxy. The process by which this occurs is known as cosmic feedback and it takes place through an interaction between the energy and radiation generated by accretion onto the massive black hole and the gas in the host galaxy. The ratio of the size of the black hole to that of the galaxy is huge and similar to a person in comparison to the Earth, so the details of the feedback process are complex.

The overall picture in terms of energetics is fairly straightforward and two major modes have been identified. The first is the *radiative* mode, also known as the quasar or wind mode, which operates, or operated, in a typical bulge when the accreting black hole was close to the Eddington limit. The second mode is the *kinetic* mode, also known as the radio or jet mode. This typically operates when the galaxy has a hot halo (or is at the center of a group or cluster of galaxies) and the accreting black hole has powerful jets. It tends to occur at a lower Eddington fraction and in the more massive galaxies.

It is easy to demonstrate that the growth of the central black hole by accretion can have a profound effect on its host galaxy. If the velocity dispersion of the galaxy is σ, then the binding energy of the galaxy, which is of mass $M_{\rm gal}$, is $E_{\rm gal} \approx M_{\rm gal}\sigma^2$. The mass of the black hole $M_{\rm BH} \approx 2 \times 10^{-3}\, M_{\rm gal}$ (Tremaine *et al.* 2002; Häring & Rix 2004). Assuming a radiative efficiency for the accretion process of 10%, then the energy released by the growth of the black hole $E_{\rm BH} = 0.1 M_{\rm BH} c^2$. Therefore $E_{\rm BH}/E_{\rm gal} \approx 2 \times 10^{-4}(c/\sigma)^2$. For a galaxy $\sigma < 450\,{\rm km\,s^{-1}}$, so $E_{\rm BH}/E_{\rm gal} > 100$.

Fortunately, accretion energy does not significantly affect the stars of the host galaxy, or there would not be any galaxies. The energy and momentum from accretion do couple with the gas. The processes involved in that are reviewed here.

2. The Radiative or Wind Mode

Silk & Rees (1998; see also Haehnelt *et al.* 1998) point out that a quasar at the Eddington limit can prevent accretion into a galaxy at the maximum possible rate (equivalent to its gas content going into free fall at a rate $\sim f\sigma^3/G$, so power needed is $\sim f\sigma^5/G$)

provided that

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

where $\sigma_{\rm T}$ is the Thomson cross section for electron scattering and f is the fraction of the galaxy mass in gas. The galaxy is assumed to be isothermal with radius r, so that its mass is $2\sigma^2 r/G$. The argument is based on energy balance.

Momentum balance gives an expression (Fabian 1999; Fabian *et al.* 2002; King 2003, 2005; Murray *et al.* 2005)

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

which is about c/σ times larger and more in line with the observed $M_{\rm BH}$–σ relation for $f \sim 0.1$.

There are several ways to derive the above formula. A simple one is to assume that the radiation pressure from the Eddington-limited quasar has swept the gas, of mass $fM_{\rm gal}$, to the edge of the galaxy. Balancing forces gives

$$\frac{L_{\rm Edd}}{c} = \frac{GM_{\rm gal}M_{\rm gas}}{r^2}$$

i.e.,

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

from which the result follows.

The interaction cannot rely on radiation pressure on electrons as in the standard Eddington-limit formula, since if the quasar is locally at its Eddington limit, then it must be far below the Eddington limit when the mass of the galaxy is included. (Quasars appear to respect the Eddington limit, see e.g., Kollmeier *et al.* 2006.) The interaction has to be much stronger, either through a wind generated close to the quasar which then flows through the galaxy pushing the gas out, or to dust in the gas, as expected for the interstellar medium of a galaxy (Laor & Draine 1993; Scoville & Norman 1995; Murray *et al.* 2005). Dust grains embedded in the gas will be partially charged in the energetic environment of a quasar, which will link them to the surrounding partially-ionized gas. $L_{\rm Edd}$ is reduced by a factor of $\sigma_{\rm d}/\sigma_{\rm T}$, where $\sigma_{\rm d}$ is the equivalent dust cross section per proton, appropriately weighted for the dust content of the gas and the spectrum of the quasar.

We find that $\sigma_{\rm d}/\sigma_{\rm T}$ is about 500 for a Galactic dust-to-gas ratio (Fabian *et al.* 2008). This means that a quasar at the standard Eddington limit (for ionized gas) is at the effective Eddington limit (for dusty gas), $L'_{\rm Edd}$, of a surrounding object 500 times more massive (Figure 1). Is this just a coincidence or the underlying reason why $M_{\rm gal}/M_{\rm BH} \approx 500$?

We have investigated (Fabian *et al.* 2006, 2008, 2009) whether there are indications of $L'_{\rm Edd}$ in AGN by examining the plane of absorption column density, $N_{\rm H}$ versus Eddington fraction, $\lambda = L_{\rm bol}/L_{\rm Edd}$. Most intrinsic cold absorption seen in X-ray spectra originates fairly close to the nucleus (the required gas mass would otherwise be prohibitive). Therefore an AGN with $\lambda = 1/500$ is highly sub-Eddington for local ionized dust-free gas, but effectively at the Eddington limit for dusty gas clouds which are optically thin to dust absorption. The outer parts of larger optically-thick clouds act as dead weight which increases $L'_{\rm Edd}$ (Figure 1). The net result is that there should be a forbidden zone in the $(\lambda, N_{\rm H})$ plane to the right of the $L'_{\rm Edd}$ curve. This is indeed what we see (Figure 2). At

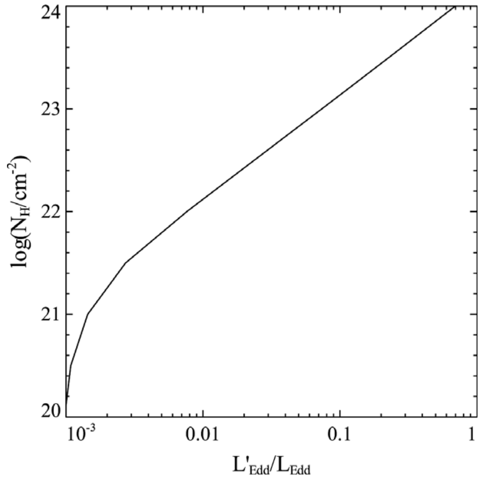

Figure 1. Column density $N_{\rm H}$ of dusty gas required for a given effective Eddington ratio $L'_{\rm Edd}/L_{\rm Edd}$. A quasar spectrum and Galactic dust fraction is assumed, giving $\sigma_{\rm d}/\sigma_{\rm T} \sim 1000$. The result for a typical AGN operating at $L/L_{\rm Edd} < 0.1$ is ~ 300. A value of 500 is adopted in the text.

low column densities, there can be absorption from an outer disk or dust lane, so we ignore the region below about 3×10^{21} cm^{-2} . The observed points show that AGN do indeed influence the amount of gas in a galaxy bulge.

The way that gas can evolve on the $(\lambda, N_{\rm H})$ plane is that gas which strays into the forbidden zone is pushed outward, reducing $N_{\rm H}$ as it does so in a shell, sliding along the curve. Gas which is introduced to a galaxy can stay, fueling both the black hole and star formation, provided both $L'_{\rm Edd}$ and $L_{\rm Edd}$ remain below unity. Repetition of this process

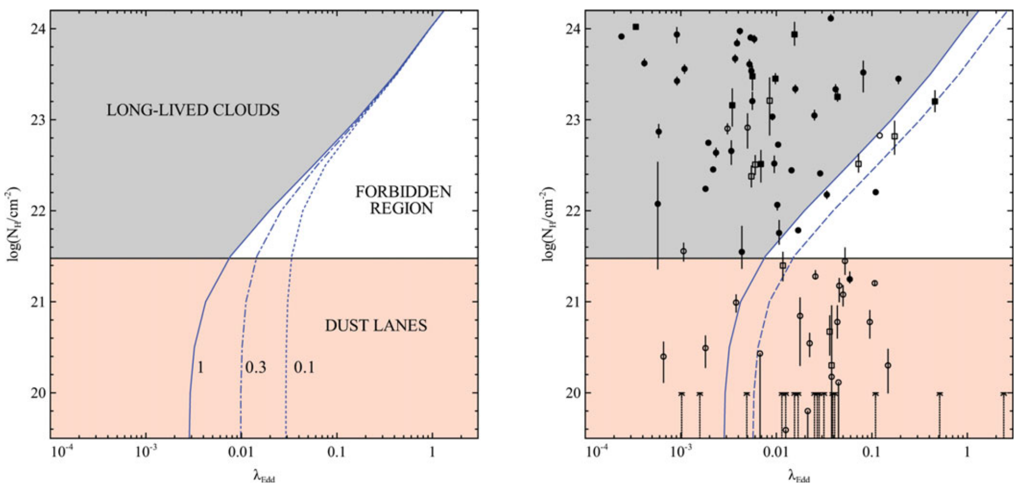

Figure 2. The forbidden region in the $(\lambda, N_{\rm H})$ plane. Dust lanes can occur at large radii at low columns. The three curves indicate different dust to gas ratios relative to the Galactic value. On the right is the plane populated by the *SWIFT*–BAT AGN. The dashed curve is for $L_{\rm Edd}$ appropriate for a region of twice the black hole mass expected at a radius of few pc (Fabian *et al.* 2009). The single point in the forbidden region is a galaxy with an outflowing warm absorber.

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should drive $M_{\rm BH}/M_{\rm gal} \rightarrow 2 \times 10^{-3}$. At higher redshifts, where the metallicity and dust content was less, then this ratio should be proportionately higher. Studies of the $(\lambda, N_{\rm H})$ plane at higher redshifts and with large samples may show us how the gas content of galaxies responds and evolves to the action of quasars.

If the repeated action of radiation pressure on dust is responsible for the $M_{\rm BH}$–σ relation then it must cause the bulge mass

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

or

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

Feedback should shape both the black hole and the galaxy bulge and may even lead to the fundamental plane.

If the main interaction is due to winds, not to radiation pressure, then the wind needs to have a high column density, high velocity v, high covering fraction f, all at large radius r. The kinetic luminosity of a wind is

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

where $r_{\rm g}$ is the gravitational radius GM/c^2 and $N_{\rm T} = \sigma_{\rm T}^{-1}$. To produce $M_{\rm BH} \propto \sigma^4$ scaling, the thrust of the wind needs to correspond to the Eddington limit (the wind may need to be dusty). Warm absorbers flowing at $\sim 1000\,{\rm km\,s^{-1}}$ are insufficient (Blustin *et al.* 2005). BAL quasars flowing at tens of thousands ${\rm km\,s^{-1}}$ may however be important (see Arav, these proceedings).

3. The Kinetic Mode

The more massive galaxies at the centers of groups and clusters are often surrounded by gas with a radiative cooling time short enough that a cooling flow should be taking place. The mass cooling rates would be tens, hundreds, or even thousands of $M_{\odot}\,{\rm yr}^{-1}$. Such objects should be significantly growing their stellar mass now, yet they are not. This is because 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 (for reviews see Peterson & Fabian 2006; McNamara & Nulsen 2007; Cattaneo *et al.* 2009).

Several steps in this feedback process are clearly seen in X-ray and radio observations. The accretion flow onto the black hole generates powerful jets which inflate bubbles of relativistic plasma on either side of the nucleus. The bubbles are buoyant in the intracluster or intragroup medium, separating and rising as a new bubble forms, if the jet operates more or less continuously (Churazov *et al.* 2001). This is seen to be the case, since a study of the brightest 55 clusters (Figure 4; Dunn *et al.* 2006; see also Rafferty *et al.* 2006) shows that over 70% of those clusters where the cooling time is less than 3 Gyr, which need heat, have bubbles, and another 20% have a central radio source.

The kinetic power in the jets can be estimated from the size of the bubbles, the surrounding pressure (obtained from the density and temperature of the thermal gas), and the buoyancy time (which depends on the gravitational potential). The power is high and only weakly correlated with radio power (the radiative efficiency of many jets is very low at between 10^{-2}–10^{-4}). The power is usually in good agreement with the energy loss by X-radiation from the short-cooling-time region. The overall energetics of the feedback process are therefore not an issue.

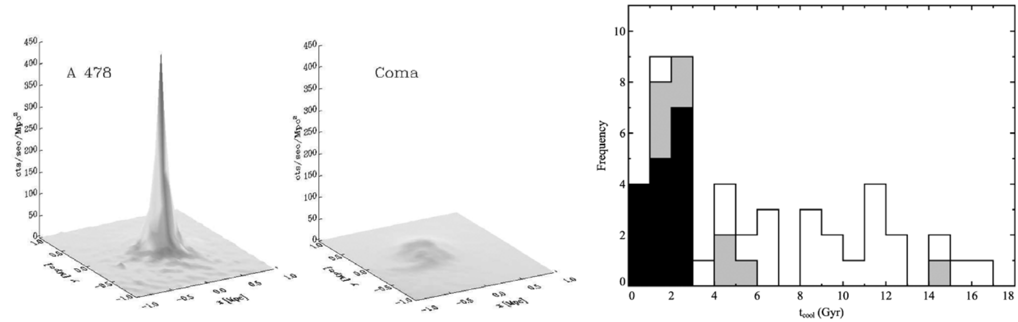

Figure 3. *Left:* The X-ray surface brightness peak at the center of a cool core cluster, A478, which has a short central cooling time, compared with a cluster with a longer cooling time, Coma. *Right:* Histogram of cooling times in the B55 cluster sample (Dunn & Fabian 2006). Black indicates bubbles seen and grey that there is a central radio source.

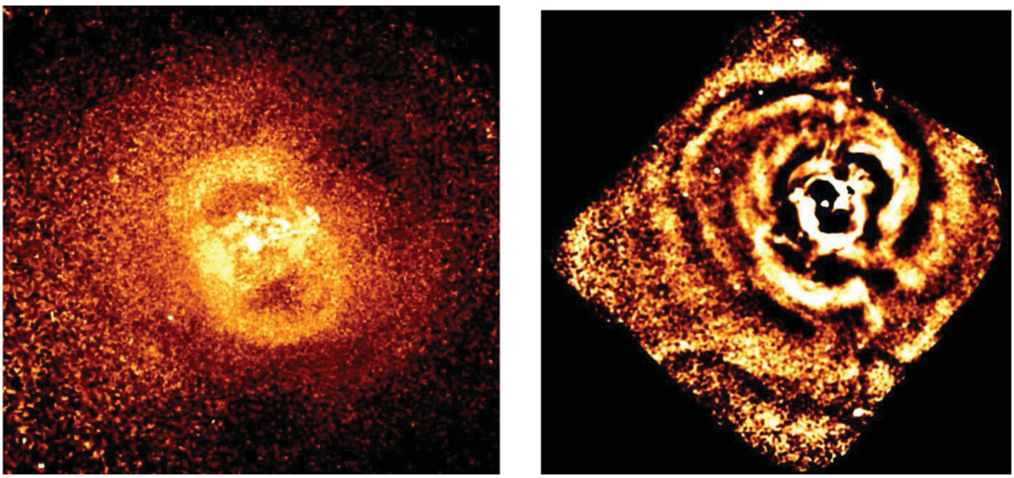

Figure 4. *Left:* Pressure map derived from *Chandra* imaging X-ray spectroscopy of the Perseus cluster. Note the thick high pressure regions containing almost $4PV$ of energy surrounding each inner bubble, where V is the volume of the radio-plasma filled interior (Fabian *et al.* 2006). *Right:* Unsharp masked image showing the pressure ripples or sound waves.

In the case of the Perseus cluster, which is the X-ray brightest in the sky, *Chandra* imaging shows concentric ripples which we interpret as sound waves generated by the expansion of the central pressure peaks associated with the repetitive blowing of bubbles (Fabian *et al.* 2003, 2006). The energy flux in the sound waves is comparable to that required to offset cooling, showing that this is the likely way in which heat is distributed in a quasi-spherical manner. Similar sound waves, or weak shocks, are also seen in the Virgo, Centaurus, and A2052 clusters and in simulations (Ruszkowski et al 2004; Sijacki & Springel 2006).

Let us now consider how the apparent close heating/cooling balance has been established and maintained. The lack of high star-formation rates suggests that cooling does not exceed heating by ten per cent or so. The presence of central abundance gradients and pronounced temperature drops indicates that heating does not general exceed cooling by that much either. This balance needs to continue over tens to hundreds of bubbling cycles (each of a 10–50 Myr or so duration).

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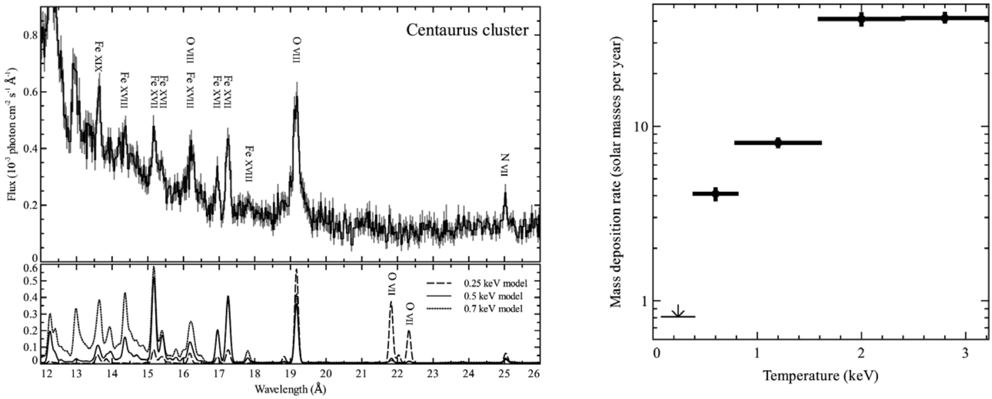

Figure 5. *Left:* RGS spectrum of the center of the nearby Centaurus cluster showing strong Fe XVII and O VIII lines, but no O VII (Sanders *et al.* 2007). *Right:* Mass cooling rate of gas. Note that little gas seems to cool below 0.5 keV.

A simple 1-D feedback cycle seems at first sight possible. If too much gas starts to cool, then the accretion rate should increase, making the heating rate go up and vice versa. However, the time scales involved are long, meaning that feedback would be delayed, and angular momentum could prevent gas reaching anywhere near the black hole.

Studying the details requires the best data on the brightest nearby objects. X-ray images from *Chandra* and moderate resolution spectra from the *XMM–Newton* Reflection Grating Spectrometer (RGS) show X-ray cool gas in the cores of some clusters, with temperatures ranging from 5 to 0.5 keV in the nearby Centaurus cluster (Sanders *et al.* 2007). The coolest gas has a cooling time of only 10 Myr, yet the spectra show no sign of any lower temperature gas (where O VII emission is expected). In this object, the heating/cooling balance looks to hold to a few per cent. How the 0.5 keV gas is prevented from cooling is not obvious. The images show that it is clumpy, so the question arises as to how it is targeted for heating without its immediate surroundings being overheated. A similar picture emerges from several other clusters with excellent data.

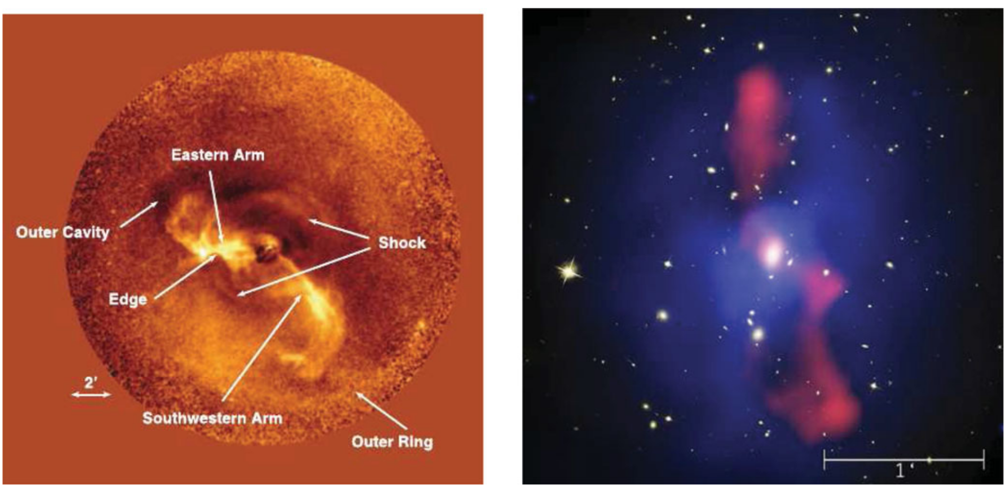

Figure 6. *Left:* The arms and weak shocks produced by the jets of M 87 (Forman *et al.* 2007). *Right:* The gigantic interaction of the radio lobes and intracluster gas of MS 0735.6 (McNamara *et al.* 2009). The figure shows the inner 700 kpc of the cluster, extending well beyond its cool core.

One solution is that the tight balance is only apparent. If the jets become too energetic, then can they push through the whole cooling region (e.g., Cyg A or MS0735.6+7421; McNamara *et al.* 2009) and deposit energy much further out. If cooling dominates, then it can feed the reservoir of cold gas seen in many objects, as well as some star formation. The brightest cluster galaxy (BCG) at the center of A1835 at $z = 0.25$ is an extreme example with over $100\,M_\odot\,\mathrm{yr}^{-1}$ of massive-star formation (O'Dea *et al.* 2008). It is within a factor of two of the highest star formation rate of any galaxy at low redshift (i.e., Arp 220). (Without heating, the central intracluster gas in A1835 would be cooling at over $1000\,M_\odot\,\mathrm{yr}^{-1}$, so a balance remains, but not a very tight one.)

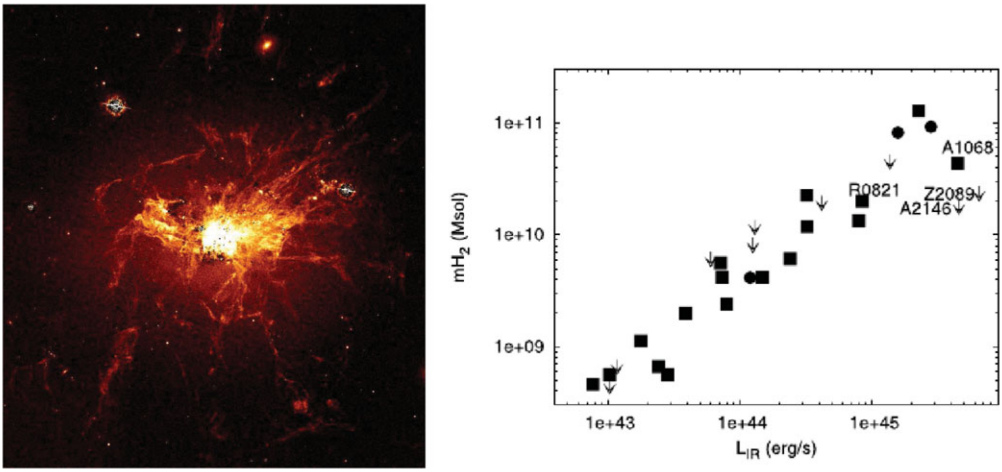

Figure 7. *Left: HST* image of the filaments around NGC 1275 in the Perseus cluster (Fabian *et al.* 2008). *Right:* Mass of H_2 reservoir compared with *Spitzer* IR luminosity (O'Dea *et al.* 2008).

Many BCGs in *cool core* clusters (the ones with the short radiative cooling times) have extensive optical emission-line nebulosities (e.g., Crawford *et al.* 1999). The cold gas is mostly molecular as shown by CO (Edge 2001) and H_2 emission. NGC 1275 at the center of the Perseus cluster is a spectacular example (Figure 6) with its filaments being composed of about $10^{11}\,M_\odot$ of H_2 (Salomé *et al.* 2006). Star formation happens sporadically in that galaxy with $\sim 20\,M_\odot\,\mathrm{yr}^{-1}$ occurring over the past 10^8 yr in the SE blue loop (Canning *et al.* 2009). Dust is seen in the form of dust lanes and infrared emission, with *Spitzer* observations revealing high IR luminosities (Egami *et al.* 2006; O'Dea *et al.* 2008; see also Figure 6). The dust is presumably injected by stars into the central cold gas reservoir, from where the bubbles drag gas out to form filaments.

Much of this IR luminosity is due to vigorous star formation in the BCG, presumably fueled by a residual cooling flow. Some, however, could be due to the coolest X-ray emitting clumps, at 0.5–1 keV, mixing in with the cold gas and thereby cooling non-radiatively (Fabian *et al.* 2002; Soker *et al.* 2004). The outer filaments in NGC 1275 may be powered by the hot gas (Ferland *et al.* 2009).

The conclusion is that gas may be cooling from the hot phase of the intracluster medium at a higher rate than otherwise thought. Some of the cooling occurs non-radiatively by mixing. The gas then hangs around for Gyrs as a reservoir of cold molecular dust clouds, forming stars slowly and sporadically.

Generally the central AGN in BCGs is quite sub-Eddington ($\lambda \sim 10^{-3}$–10^{-2}). The luminous low-redshift quasar H 1821+643 at $z = 0.3$ is a counterexample (Russell *et al.*

2009). The surrounding gas, however, seems to be in the same state as for normal cool core BCGs.

4. Discussion

An active nucleus interacts with the gas in its host galaxy through radiation pressure, winds, and jets. The consequences can be profound for the final mass of the stellar component of the galaxy as well as the black hole.

The radiative or wind mode was most active when the AGN was a young quasar. At that stage the galaxy had a large gaseous component and the nucleus was highly obscured. Direct observational progress is therefore difficult and slow. The kinetic mode, on the other hand, is more easily observed, albeit at X-ray and radio wavelengths, since it is acting now in nearby objects and the surrounding gas is highly ionized. An attractive possibility is that the radiative mode shaped the overall galaxy and black hole mass at early times, and the kinetic mode has since maintained that situation where needed (Churazov *et al.* 2006).

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