

# Observational Evidence of AGN Feedback

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## Summary

## The AGN feedback

- ▶ The interaction process between the black hole at the centre of a galaxy and the galaxy is known as AGN feedback.
- ▶ 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 details of the feedback are complex and the observational evidence is not always clear.

## Kinds of AGN feedback

- ▶ Two major modes have been identified, differentiated by the nature of the energy outflow near the black hole:
  - ▶ **the radiative mode (quasar or wind mode):** when the accreting black hole was close to the Eddington limit.
  - ▶ **the kinectic mode (radio jet or maintenance mode) :** when the galaxy has a hot halo and the accreting black hole has powerful jets.

## Effects

- ▶ The growth of the central black hole by accretion can have a profound effect on its host galaxy.
- ▶ Accretion energy doesn't significantly affect the star already existing, but it can couple strongly with the gas from which new star forms.
- ▶ There is little or no evidence at the present time for AGN feedback operating in low mass galaxies where stellar feedback is important.
- ▶ The clearest observational evidence for AGN feedback is found in the most massive galaxies known, BCG in cool core clusters.
- ▶ AGN feedback is a relatively young topic, and a wide range of argument and opinion has been expressed.

## Accretion in galaxies

- ▶ The equation which can prevent the accretion into a galaxy at the maximum possible rate by a quasar at the Eddington limit is:

$$M_{BH} = \frac{f\sigma^4\sigma_T}{\pi G^2 m_p} \quad (1)$$

where  $\sigma_T$  is the Thomson cross section for electron scattering and  $f$  is the fraction of the galaxy mass in gas.

- ▶ The agreement that this simple formula gives with the observed  $M_{BH} - \sigma$  relation can be interpreted as (weak) observational evidence for AGN feedback.

- ▶ If the main interaction is due to winds, not to radiation pressure, then the wind needs to have a high column density  $N$ , high velocity  $\nu$ , high covergin fraction  $f$  all at large radius  $r$ . The kinetic luminosity of a wind is:

$$\frac{L_w}{L_{EDD}} = \frac{f}{2} \frac{r}{r_g} \left( \frac{\nu}{cc} \right)^3 \frac{N}{N_T} \quad (2)$$

- ▶ To produce  $M_{BH} \propto \sigma^4$  scaling the thrust of the wind needs to be proportional to the Eddington limit.
- ▶ The commonest way in which AGN winds are observed is by line absorption of the quasar continuum by intervening wind material.
- ▶ Generally, good evidence for AGN winds occurs in unobscured AGN, where the UV spectrum can be directly seen.





## The downsizing of AGN

- ▶ It was an important discovery.
- ▶ The most luminous and massive AGN were most numerous at redshifts of 2 - 2.5, the less-luminous peaked at successively lower redshifts with the least luminous peaking around redshift one.
- ▶ Downsizing of AGN was first seen in X-ray surveys.
- ▶ The behaviour is the opposite of what is simply predicted in a hierarchical CDM universe, where the most massive objects form last.
- ▶ It indicates that something is quenching quasar behaviour and the most widely accepted solution is that is due to AGN feedback.

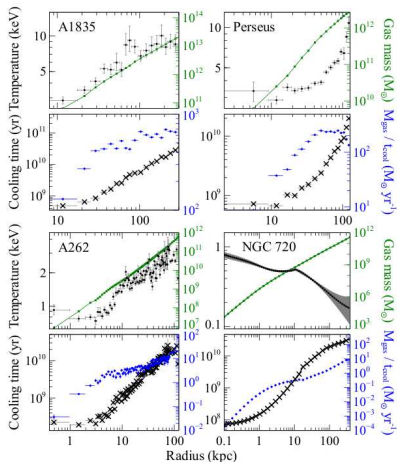
- ▶ Many theoretical models for quasar evolution are based on galaxy-galaxy mergers being the trigger for gas infall onto a black hole.
- ▶ But the evidence for them triggering AGN is weak.
- ▶ The evidence is building that between redshifts of 2 and the current epoch, much of the evolution of AGN is secular.

## The cooling time

- ▶ The more massive galaxies at the centres of groups and clusters are often surrounded by gas with a radiative cooling time short enough that a cooling flow should be taking place.
- ▶ In the small sample shown next, all the clusters show a large central temperature drop within the inner 100 kpc and all objects show a radiative cooling time dropping below  $10^9$  Gyr within the inner 10kpc.

## Some examples

- ▶ A1835 is a high luminosity cluster. It may have the highest star formation rate in a low redshift BCG ( $\sim 125 M_{\odot} \text{yr}^{-1}$ ).
- ▶ A426 is the X-ray brightest clusters
- ▶ A262 is a low-mass cluster
- ▶ NGC 720 is a elliptical galaxy

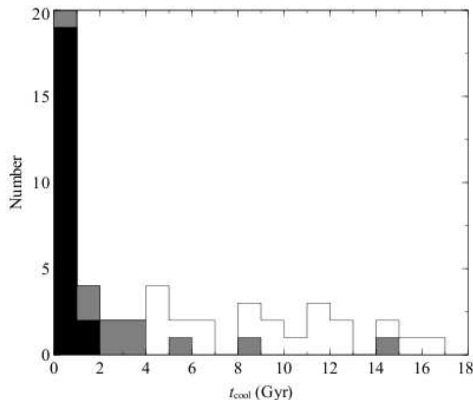


## The cooling time

- ▶ The general consensus now is that the massive black hole at the centre of the galaxy is feeding energy back into its surroundings at a rate balancing the loss of energy through cooling
- ▶ 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 either side of the nucleus.

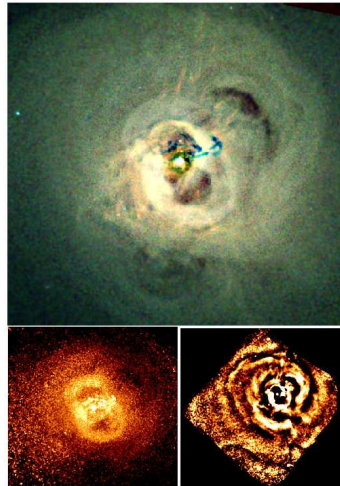
## bubbles

- ▶ A study of the brightest 55 clusters originally showed that over 70% of those clusters where the cooling time is less than 3 Gyr, therefore needing heat, have bubbles.
- ▶ The remaining 30% have a central radio source.
- ▶ The jet bubbling process is not therefore very episodic, but is more or less continuous.



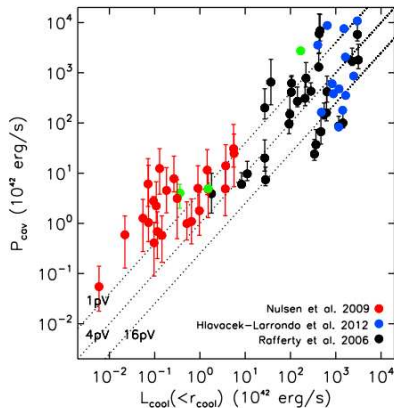
## Bubbles

- ▶ The bubbles or cavities commonly seen in deep Chandra images of cool core clusters are blown and powered by jets from the central black hole.
- ▶ The innermost bubbles are usually fairly spherical and in the best-studied case are surrounded by a thick high-pressure region fronted by a weak shock.
- ▶ Observed bubbles appear to be fairly stable to breakup, contrary to what is seen in many simulations.



## Energy flow and dissipation

- ▶ It's necessary to discuss how the energy flows and is dissipated.
- ▶ In the case of Perseus cluster, 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.
- ▶ Similar sound waves are also seen in several of the very brightest clusters in the Sky.
- ▶ Weak shocks are poor at dissipating energy, so the heating of the gas must depend on the gas viscosity. But this value isn't clear.





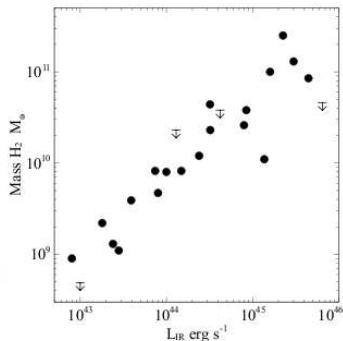
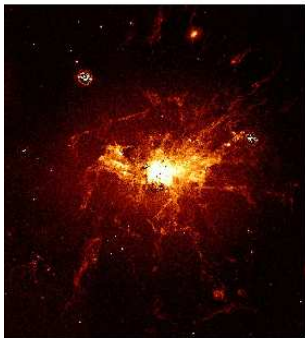
## Bondi accretion

- ▶ Could be relevant here.
- ▶ The whole inner region of radii a few 100 kpc, from beyond the Bondi radius to the innermost regions where the flow becomes supersonic, could resemble a giant Advection Dominated Accretion flow.
- ▶ An ADAF is radiatively inefficient since it transports (advects) the energy released in with the gas.
- ▶ There are not sufficiently observations of this.

## Temperature structure

- ▶ There is less and less gas found at lower temperatures compared with say a steady cooling flow. The gas with the shorter cooling times appears to be missing.
- ▶ In several clusters with excellent data, the heating/cooling balance looks to hold to a few per cent.
- ▶ One solution is that the tight balance is only apparent, but it isn't clear.

- ▶ Many BCGs in cool core clusters have extensive optical emissionline nebulosities.
- ▶ The emission can extend for tens of kpc around the BCG.
- ▶ The bulk of cold gas is molecular. NGC 1275 is a spectacular example, there, the mass of the molecular gas is comparable to the mass of all other gas, hot and cold.



## Heating of cold gas by energetic particles

- ▶ An alternative is that cosmic rays are the source of ionization and excitation.
- ▶ An interesting aspect of this model is that the incident flux of energy onto a filament in the Perseus cluster from the surrounding gas particles is only a few times higher than the total flux emitted by the filament.
- ▶ Molecular filaments, probably due to ram-pressure stripping, are also seen around some galaxies in the Coma and Virgo clusters. Studies of these filaments should help our understanding of the filaments around BCGs and vice versa.

## Turbulence in cool cores

- ▶ Direct measurements of the level of turbulence have been made from X-ray line widths using XMM-Newton.
- ▶ Turbulence energy density is then less than 10 per cent of the thermal energy density, which is consistent with some simulations.
- ▶ Indirect measurements have also been made.
- ▶ The feedback is surprisingly gentle.

- ▶ No evolution in cool core properties is seen in clusters out at  $z \sim 0.5$ .
- ▶ Some works not find strong cool cores other than one  $z \sim 1$ . Can this mean rapid evolution?
- ▶ May be a selection effect and due to enhanced AGN activity in BCG.
- ▶ A counter-exemple is the quasar H1821+643, at  $z = 0.3$ , which indicating that a powerful quasar and a cool core can co-existe.
- ▶ Until such potential selection effects are investigated further it is difficult to speculate from observation about the evolution of cool cores.
- ▶ What may matter most is when the merger history of a cluster, with early mergers being the most destructive of a cool core.

- ▶ The feedback power in these objects exceeds  $10^{45} \text{ ergs}^{-1}$ , so is comparable to the output of a quasar, yet their nuclei are not exceptionally bright.
- ▶ This in turn implies that the central black holes are ultra-massive, well exceeding  $10^{10} M_{\odot}$ .
- ▶ The behaviour of feedback in these luminous clusters appears similar to that in more typical clusters which are one or two orders of magnitude less luminous, meaning that the processes involved are robust.
- ▶ Without any feedback, radiative cooling would lead to mass cooling rates of thousands of  $M_{\odot} \text{ yr}^{-1}$

- ▶ Feedback can be seen operating in many of elliptical-dominated groups of galaxies.
- ▶ More work is needed to explore all that is happening here and to firmly decide whether the activity scales simply with host mass and luminosity, or not.
- ▶ Kinetic AGN may operate in any object with a hot extended corona.



The early predictions of relation between X-ray luminosity and temperature of intraclusters indicated:

$$L \propto T^2 \quad (3)$$

This is the pure gravity prediction. But, the observations show:

$$L \propto T^{2.7} \quad (4)$$

So, some extra energy is required.

The most likely source of the energy to heat groups is AGN.

Contributions to understanding AGN feedback can be expected from all wavebands. The advances which can be anticipated are:

- ▶ JAXA/NASA/ESA X-ray observatory ASTRO-H (2014): high spectral resolution X-ray spectroscopy
- ▶ LOFAR: low frequency radio observations
- ▶ JVL: GH frequencies, will map the interactions of jets with surrounding plasma
- ▶ ALMA: will be a leader in detecting and resolving molecular and dust components and their motions.
- ▶ James Webb Space Telescope: will observe the rich, rest-frame, optical band in distant objects

Both large-area surveys and single objects studies will continue to be essential.

- ▶ An active nucleus interacts with the gas in its host galaxy through radiation pressure, winds and jets.
- ▶ It appears that the radiative or wind mode was most active when the AGN was a young quasar.
- ▶ 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 massive objects.
- ▶ 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.
- ▶ Observational evidence is growing that the baryonic part of the low redshift Universe has been shaped by the energy and momentum output of black holes, through AGN feedback.

