Feedback and Star Formation in Cluster Cores

D. A. Rafferty (Ohio U.), B. R. McNamara (Ohio U.), L. B"irzan (Ohio U.),

Abstract
Using an analysis of sixteen galaxy clusters, one group, and one galaxy drawn from the Chandra X-ray Observatory’s data archive, we evaluate the hypothesis that cooling of the intracluster medium (ICM) can be quenched by energy dissipated by rising bubbles created by radio sources. We find that the instantaneous mechanical luminosities in the bubbles required to offset cooling range between 1-20 $pV$ per bubble. Nearly half of the systems in our sample may have mechanical luminosities large enough to balance cooling. For the remaining systems in our sample, the energy dissipated by the bubbles alone cannot balance cooling unless additional shock heating is occurring. The residual cooling of gas in these systems should lead to star formation in the central galaxy whose rate scales in proportion to the cooling rate. To investigate this scenario, we derive central system properties from the X-ray data and compare these to the central colors.

Buoyant Bubbles
High resolution X-ray images of the centers of clusters and groups show evidence of interactions between the active galactic nucleus (AGN) and the ICM in the form of X-ray cavities. A superposition of radio and X-ray images often shows an anti-correlation:

- These cavities are thought to be low-density bubbles that have been evacuated by the radio jet and are rising buoyantly in the cluster atmosphere. Other cavities, called ghost or radio-empty, do not show this anti-correlation. These cavities are thought to be older versions of the radio-filled ones, in which the synchrotron radio emission has faded.

X-Ray Analysis
Of approximately 80 systems in the Chandra Data Archive that were visually inspected for cavities, 18 systems were found with well-defined cavities.

- Spectra were extracted in circular annuli and deprojected with a single temperature model, giving radial temperatures and pressures.
- To find the bubble volumes, cavities were measured by eye as circles or ellipses and assigned a figure of merit (FOM) from 1 (best) to 3 (worst).
- Work done by the bubble: $W_{\text{bub}} = pV$
- Estimated age of the bubble: $t_{\text{age}} = R_{\text{bub}} / \nu_{\text{esc}}$ or buoyancy rise time.
- $t_{\nu_{\text{esc}}}$ = Sound speed rise time
- $t_{\text{bubble}} = 2R_{\text{bub}} / \nu_{\text{bub}}$ = Bubble refill time.
- Central spectra, used to derive central cooling times, were extracted with 3000 counts.

Central Optical and X-ray Properties
We have used parameters derived from the X-ray spectra to search for correlations between central color or H\textsubscript{a} luminosity of the centrally dominant galaxy (CDG) and other properties of the system:

- The correlation between the mechanical and H\textsubscript{a} luminosities can support feedback cooling models.

Can Cavities Quench Cooling?

High resolution spectra from XMM-Newton do not show the expected signatures of cooling below 2 keV (Peterson et al. 2003). A possible solution is that radiation losses are being balanced by heat supplied by the cavities. If the cavities are to quench cooling, they must supply enough heat to offset the difference between the total and spectral cooling luminosities (ignoring non-X-ray cooling and gravitational heating).

- Roughly half of the objects in our sample have bubbles with enough enthalpy (4-9pV) to balance radiation losses. The remaining objects require more heat input, possibly from thermal conduction from the hot outer atmosphere (see e.g. Voigt & Fabian 2004) or from shocks (e.g. Hydra, McNamara et al. 2004; MS7, Forman et al. 2004). Alternatively, these systems may be in a less active state at present.

Evidence of Feedback?
Some form of feedback between the AGN and the ICM is necessary to maintain the balance of heating and cooling.

- A trend is apparent in our sample: systems with larger X-ray luminosities also have larger mechanical luminosities → this implies feedback between the AGN and the ICM. However, this trend should be treated with caution since our sample is biased towards systems with obvious cavities and does not include systems (such as A1068) that have large cooling rates but show no evidence of possessing bubbles.

Central Properties
There are two trends apparent in the lower plots:
1. (Fig 2) Central blue color excess (which is indicative of star formation) generally increases with $L_{\text{spec}}$, the spectral estimate of the cooling luminosity. This trend is to be expected if the stars are forming from the cooling ICM.
2. (Fig 4) Systems with higher mechanical luminosities tend to have more H\textsubscript{a} emission. The mechanical luminosity in all cases is significantly greater than the H\textsubscript{a} luminosity.

- The central cooling times do not correlate with either U-B color excess or H\textsubscript{a} luminosity; however, all objects with bright central H\textsubscript{a} emission or very blue centers have central cooling times < 0.5x10\textsuperscript{9} yr.

Conclusions

- Of the clusters in the Chandra Data Archive, ~20% have bubbles.
- Bubbles are seen in the atmospheres of clusters, groups and giant ellipticals.
- The correlation between the cooling and heating rates may support feedback cooling models.
- Bubbles alone can quench cooling in some systems, but not all → Need more heat: *Shocks *Conduction
- Star formation indicators (blue excess and $D_{\text{2100}}$ spectral index) correlate with L\textsubscript{bub}, suggesting that star formation is tied to the feedback process.

References: