Probing the Radio Mode AGN Feedback Cycle in the X-ray

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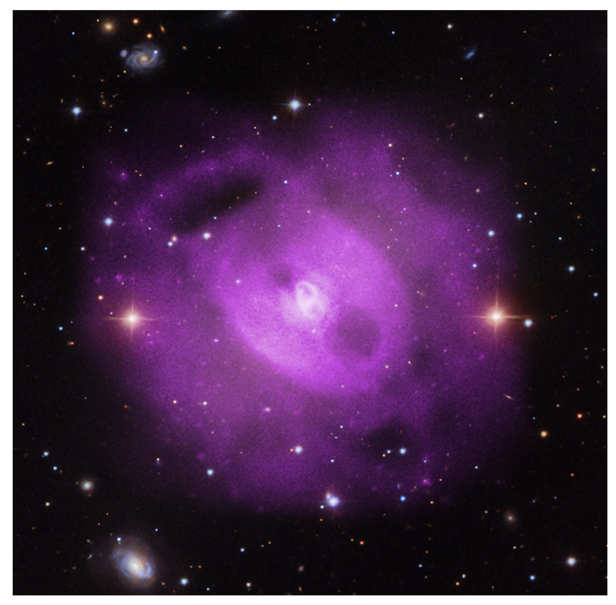
Abstract

Despite the good empirical evidence that radio AGN (active galactic nuclei) limit the growth of the most massive galaxies, we are far from understanding how this process works. Feedback models generally demand that an AGN be fueled by cooled or cooling gas, with accretion of cooled gas increasingly favored by observations and theory. Some observations to probe the radio mode feedback cycle that would be feasible for an X-ray mission with effective area, spatial and spectral resolutions in the ranges of proposed X-ray Surveyor missions are outlined here.

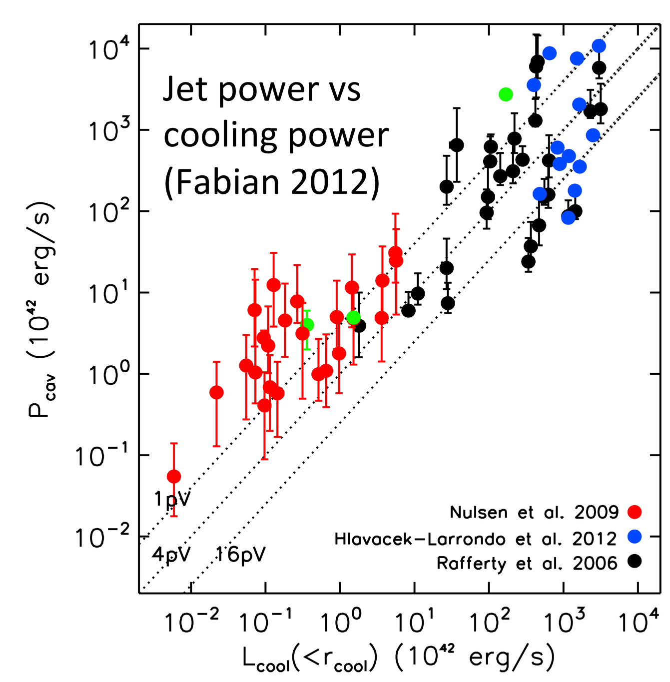
Centaurus A. *Chandra* false color X-ray image. Thermal and nonthermal emission are seen from the shock surrounding the southwest radio lobe



NGC 5813 *Chandra* image (violet) with SDSS optical image (RGB). Multiple cavities have been formed by the radio jets (Randall et al. 2015).

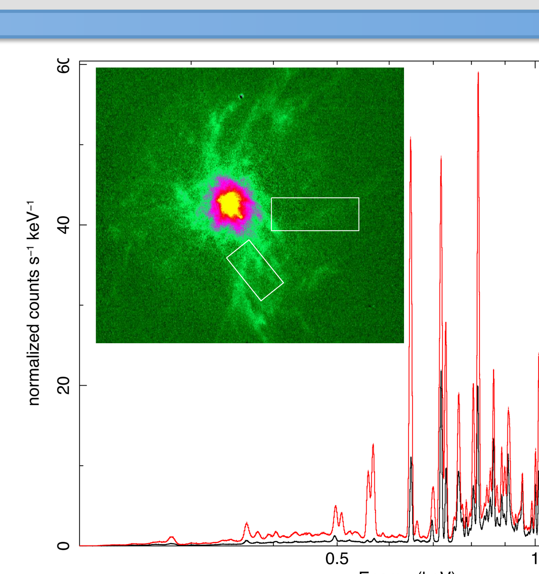
Empirical evidence of radio mode feedback

X-ray cavities commonly associated with radio lobes at the centers of hot atmospheres provide estimates of the jet powers. These typically match or exceed the power radiated by hot gas that could cool within the lifetime of a galaxy group or cluster (Bîrzan et al. 2004; Dunn & Fabian 2006; Rafferty et al. 2006; reviews in McNamara & Nulsen 2007, 2012; Fabian 2012). Where they are seen, alternative power estimates based on the properties of the cocoon shocks are generally consistent with cavity based power estimates.



Thermal instability

If the radio AGN are fueled by cooled hot gas, signatures of cooling should be found in X-ray spectra. Rapidly cooling gas may fall directly out of a hot atmosphere (Sharma et al. 2012). Rotational support or uplift can promote cooling (Li et al. 2015). Such processes can be distinguished by the location, velocity and spectrum of the cooling gas.



David et al. (in prep.) find excess soft X-ray emission over the southern Hα filament in NGC 5044.

Gas cooling at 0.005 $M_\odot$ yr^{-1} is detected at ~4σ in a simulated 400 ksec X-ray Surveyor microcalorimeter spectrum of the southern filament in NGC 5044 (black; cf. 1 $M_\odot$ yr^{-1} red).

Although cooling is suppressed by AGN feedback, there is sufficient cold gas in many systems to expect the cooling gas to be detectable. Low energy X-ray emission lines expected in simple cooling models may be absorbed by adjacent cold gas (Werner et al. 2013). X-ray emission may be further suppressed if cooling is promoted by mixing with cold gas (Begelman & Fabian 1990). Whatever the cooling process, cooler X-ray emitting gas is strongly associated with much colder gas clouds. Physical processes, such as charge exchange (e.g., Walker et al. 2015) and photoelectric absorption, will be evident in spatially well resolved spectra of the cooler X-ray gas and they will provide strong guidance on the cooling mechanisms at work (Fabian et al. 2011).

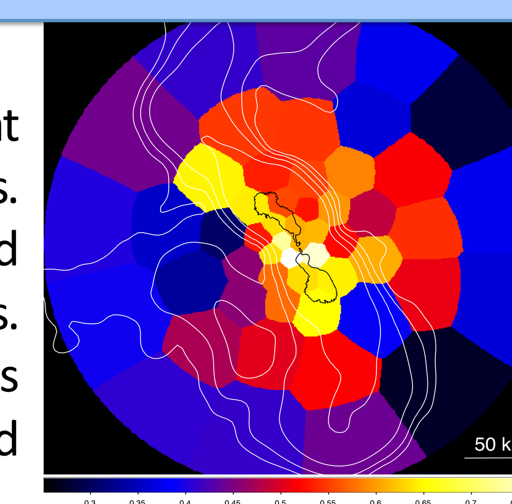
Radio lobe expansion speed

Jet powers have mostly been estimated as the ratio of a cavity's enthalpy to its age. Assuming that the pressure within a cavity is uniform, the thermodynamic energy equation gives the power required to inflate a lobe as $P = \frac{dE}{dt} + p\frac{dV}{dt}$, with $E = \frac{1}{\Gamma - 1} pV$, where p is the pressure in the lobe, V is its volume, E its internal energy and Γ the ratio of specific heats. For a lobe at distance R from the AGN, if $V \propto R^3$ and $p \propto R^{-\eta}$, we then have $P = \frac{3\Gamma - \eta}{\Gamma - 1} pV \frac{1}{R}\frac{dR}{dt}$, which exceeds the enthalpy based power estimate by a factor of (3 – η/Γ). This is roughly a factor of 2 for reasonable parameters. An inflating lobe will detach from its jet when dR/dt < v_{buoy}, the buoyant speed, so that current jet powers need to be roughly twice the mean jet power, unless all the lobes have detached from their jets. This illustrates the large systematic uncertainties in existing estimates of the jet powers.

With arcsec resolution, a large effective area and calorimeter spectrometry, an X-ray Surveyor mission could measure the expansion speeds of many lobes with precision better than 100 km s^{-1}, eliminating the need for most of these assumptions. Such measurements would also be valuable for relating radio source models, notably the stage of radio source evolution, to observations.

Uplift

Observations and simulations (e.g. Churazov et al. 2002) indicate that large quantities of gas are lifted in the wakes of rising radio lobes. Kirkpatrick et al. (2011) found that iron enrichment is anisotropic around radio galaxies in cool cores, being more extended along the radio lobes. The extent of the enriched region is correlated with jet power much as expected from simulations (Morsony et al. 2010). The scale and speed of outflow should be resolved in many nearby systems.

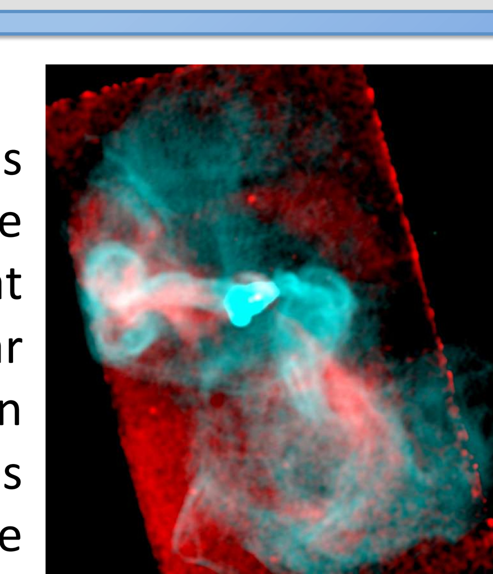


Iron abundance around Hydra A (Kirkpatrick et al. 2009)

By removing gas from its equilibrium position, where heating balances cooling, uplift can promote thermally unstable cooling. This mechanism is a good candidate as the primary source of cooled gas to power the AGN in the radio mode feedback cycle (Li et al. 2015).

Rotation in uplift: "tornadoes"

A rising radio lobe draws surrounding gas into its wake. Gas drawn into the wake will have angular momentum about the radio axis resulting from events, such as minor mergers, that continually perturb the gas. Conservation of angular momentum will cause the gas to spin up and may result in significant rotation speeds about the radio axis. Asymmetries in the initial velocity distribution will generally mean that the rotation axis of the gas is offset from the radio axis. Such a process could account for the spiral appearance of the outer southwestern radio emission of M87 illustrated here. By boosting flow speeds in the wake of a rising lobe, angular momentum can also increase its capacity to lift low entropy gas. Such flows will be evident in high resolution spectra.



X-ray (red) and 1.4 GHz radio (cyan) images of M87 (Forman et al. 2005). Note the spiral appearance of the radio emission to the southwest of the center.

Conclusions

- An X-ray surveyor mission could add greatly to our understanding of the radio mode AGN feedback cycle
- It would enable robust measurements of jet power
- Velocity measurements would determine details of the gas flows associated with advancing radio lobes
- Calorimeter spectra at high spatial resolution would tightly constrain the physical mechanisms that produce cold gas

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