Ghost Cavities in Cluster Cores Viewed with Chandra and the VLA

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Cooling Flow

- Hot ($T=10^7 - 10^8$ K), diffuse ($n_e \sim 10^{-2} - 10^{-3}$ cm^{-3}) gas in galaxy clusters cools as $\tau_{cool} \propto T^{1/2}/n_e$. When $\tau_{cool} < \tau_{Hubble}$ the gas pressure drops sufficiently that gas must flow into the core to maintain pressure support against the outlying cluster atmosphere
- Large quantities of gas (~ 100's – 1000's of $M_\odot$/yr) were predicted to radiatively cool in cluster cores

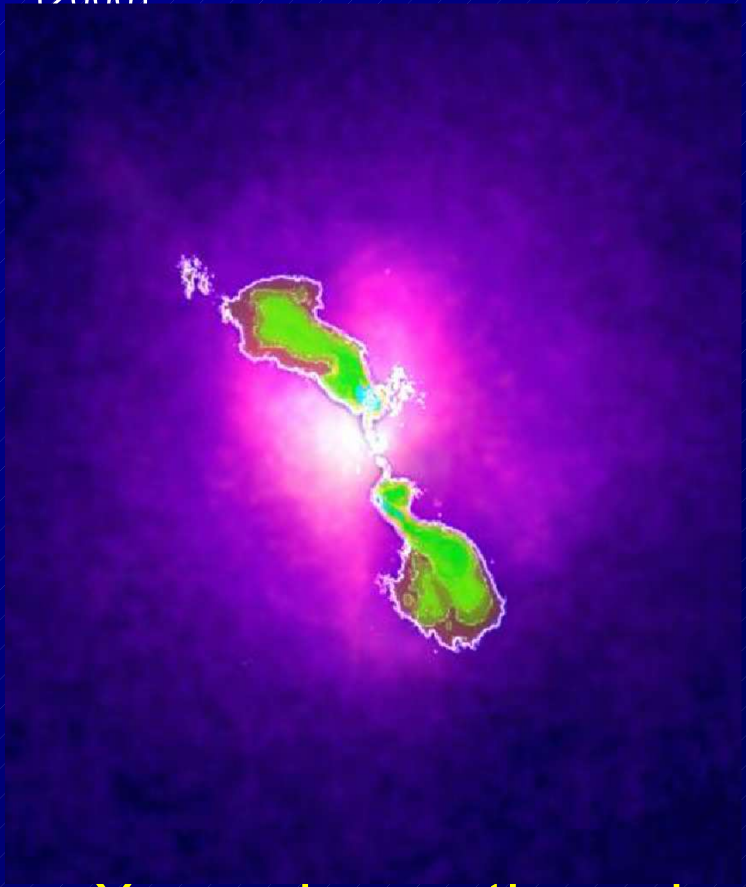
Problem:

Where does all the cooling gas go?

- Optical studies show some star formation in cD but generally only a small fraction (1-10%) of what is predicted to be cooling from X-rays
- X-ray spectroscopic observations show a lack of gas cooler than ½-1/3 of the outer gas temperature -> Need a heating source!
- Several possibilities, but radio galaxies may be the most promising.

Cooling Cores

Hydra A McNamara et al. (2000)



• cooling core cD is nearly always host to a radio galaxy (> 70%)

• often sources have distorted morphology with steep radio spectrum (Hydra A, A2052, Perseus, …)

→ radio galaxy frequency in cooling cores argues in favour of an AGN feedback mechanism

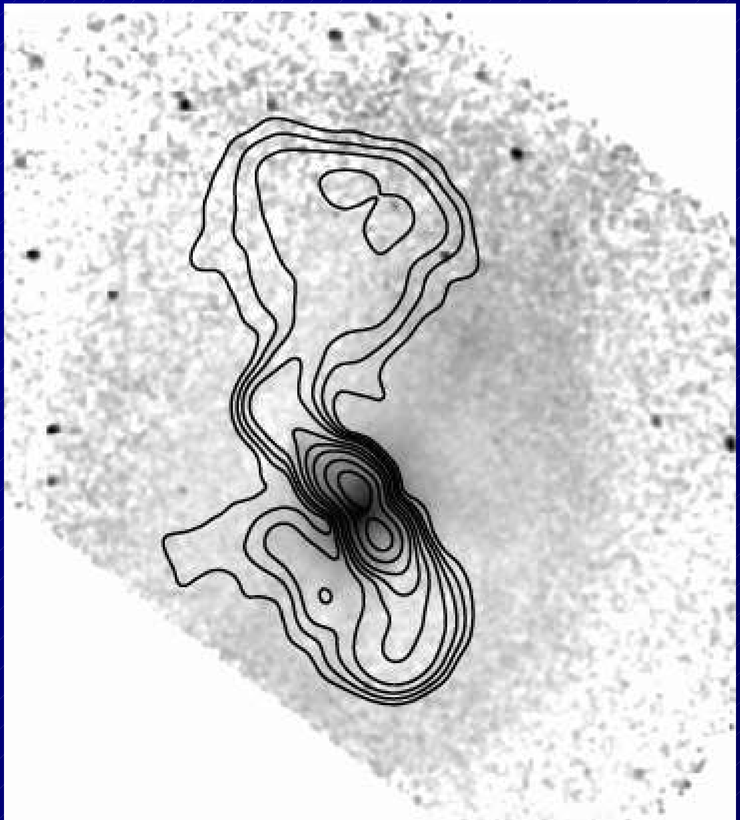
• X-ray observations show clear evidence of interactions

• bright rims are generally due to cool gas → no strong shocks

• feedback cycle possible: needs statistical balancing?

Ghost Bubbles

Hydra A Nulsen et al. (2005)

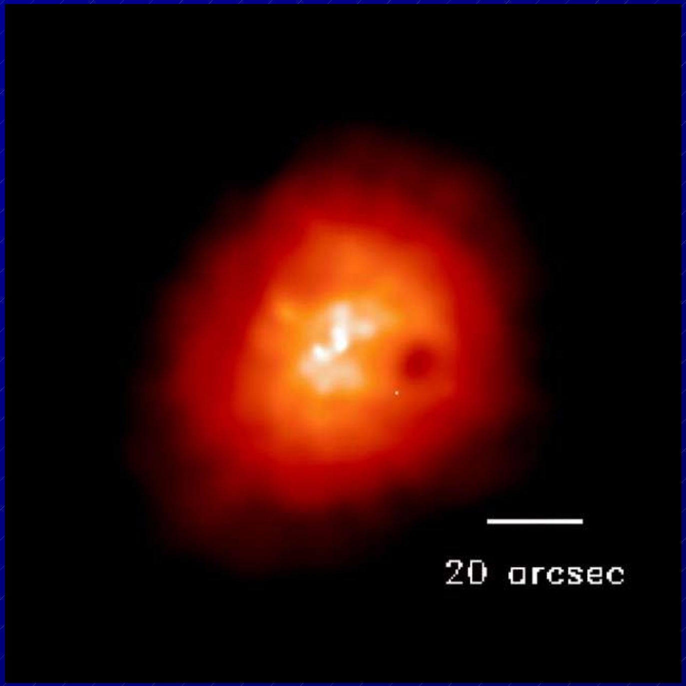


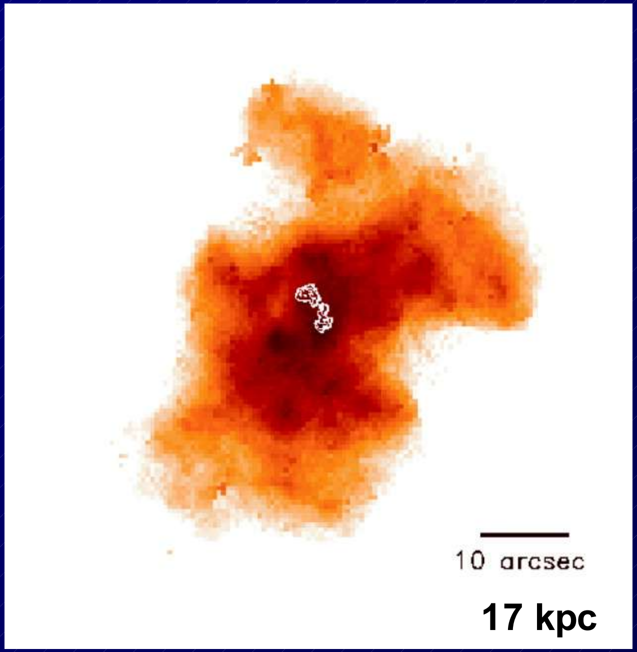
- several cooling core systems show evidence of cavities much larger than the sources seen at GHz frequencies
- low frequency observations of several systems reveal extended emission often filling the ghost holes
- systems provide details of duty-cycle of AGN, evidence of transportation of energy and magnetic fields as well as entrainment of thermal gas

- two systems (Hydra A and MS 0735) show evidence of powerful outbursts and both radio systems have steep spectrum

Gross, poster # 3.12

Ghost Bubbles: Abell 2597



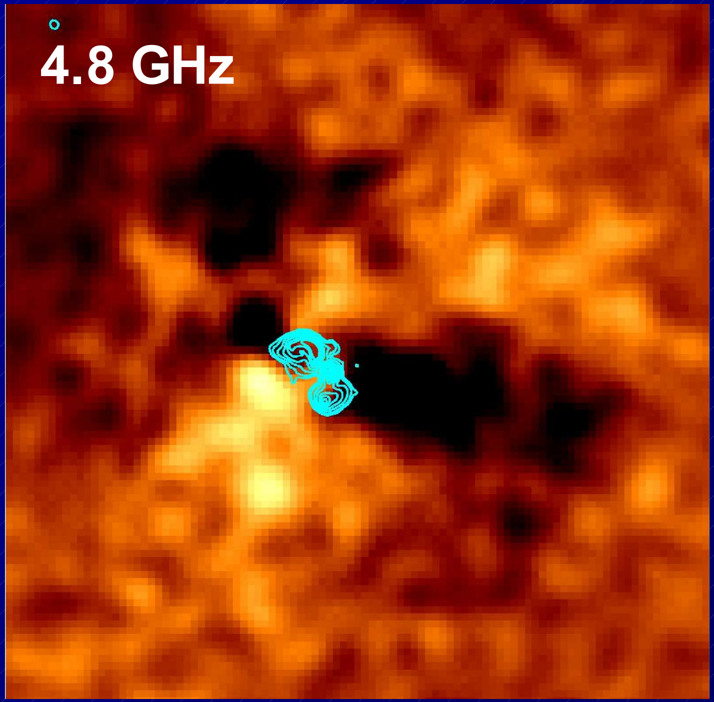


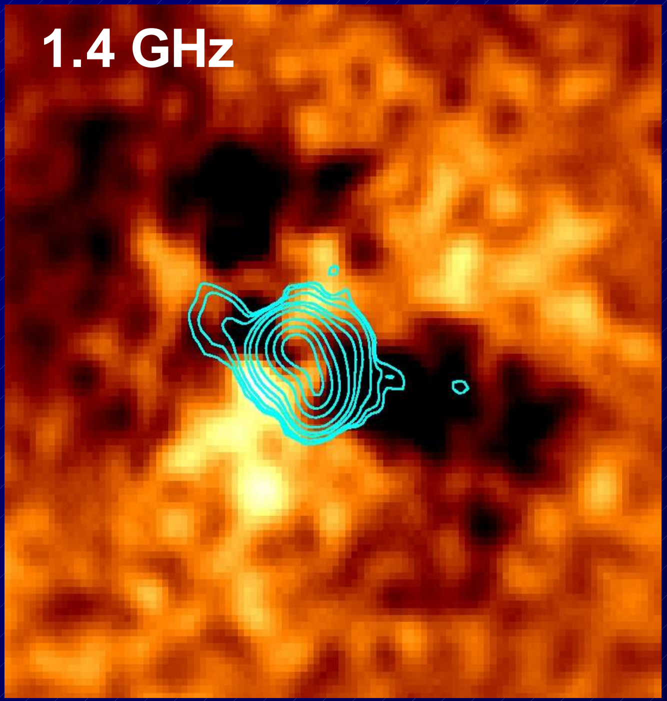
- z = 0.0852
- central radio source PKS 2322-123
- compact, steep radio spectrum
- X-ray data severely impacted by flares

McNamara et al. (2001)

- Chandra observations of the cluster core show significant structure in X-rays, including clumps and cavities
- high frequency (8.4 GHz) radio emission is located well inside the X-ray bubbles

X-ray Structure: Abell 2597 Channel



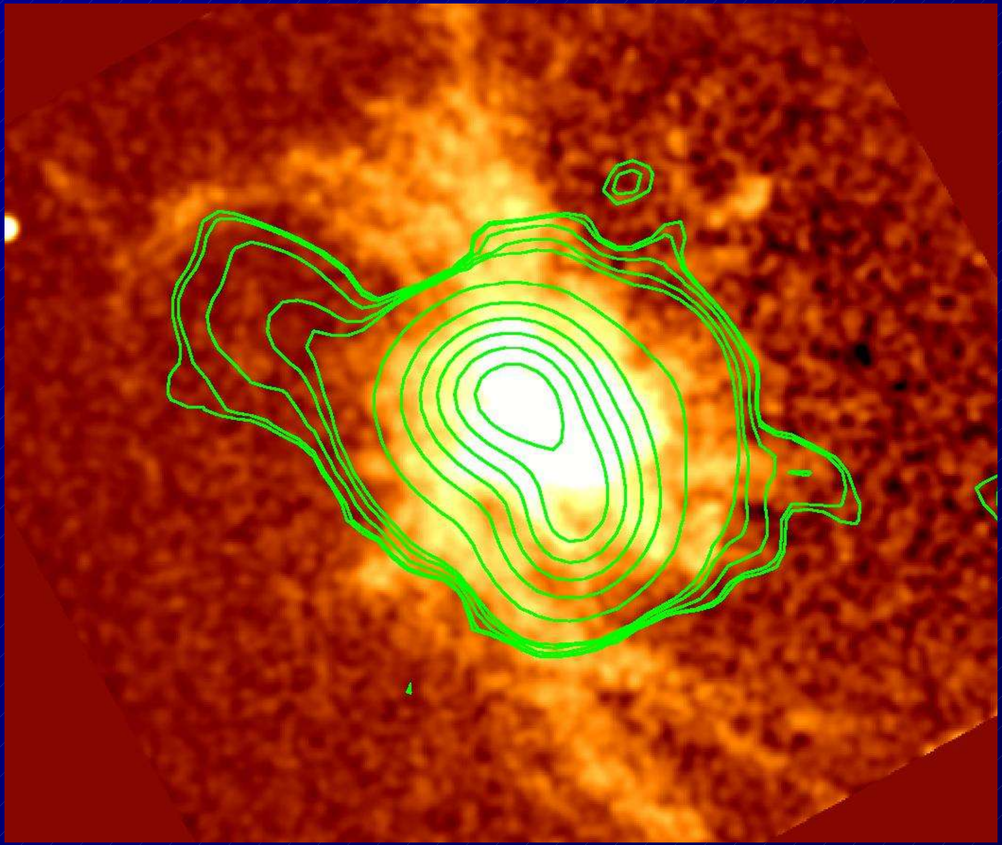


Clarke et al. (2005)

- X-ray residual image shows significant additional structure:
  - inner hole to north east of core (8σ deficit)
  - channel connecting the core to the western ghost bubble (18σ deficit)
- radio observations show evidence of multiple outburst episodes
  - 1.4 GHz extensions to north-east, north-west, and west
  - buoyancy rise time of NE extension is $\tau_{buoy} \sim 5\text{x}10^7$ yr

Abell 2597: Cool Gas

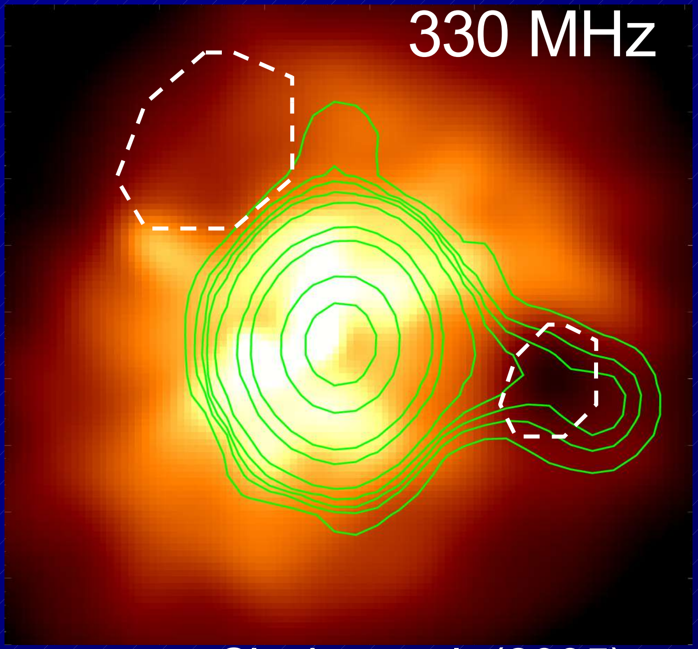
HST STIS Lyα + VLA 1.4 GHz

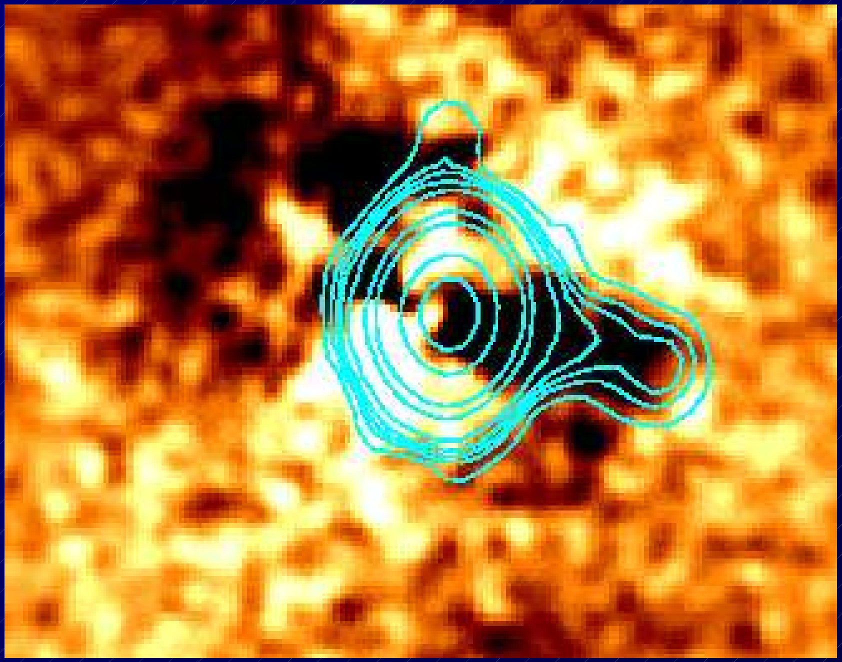


Clarke et al., in preparation

- blue excess around the inner radio lobes (McNamara & O'Connell 1993)
- FUSE observations by Oegerle et al. (2001) found O_{VI} lines: $\rightarrow T_{gas} \sim 3 \times 10^5$ K
- HST STIS observations by O'Dea et al. (2004) Lyα filaments trace edge of radio lobes: $\rightarrow T_{gas} \sim 10^4$ K
- XMM analysis by Morris & Fabian (2005) suggests cooling flow of ~90 $M_\odot$/yr with gas cooling from 4 keV to < .08 keV

Ghost Channel: Abell 2597 at Low Frequencies





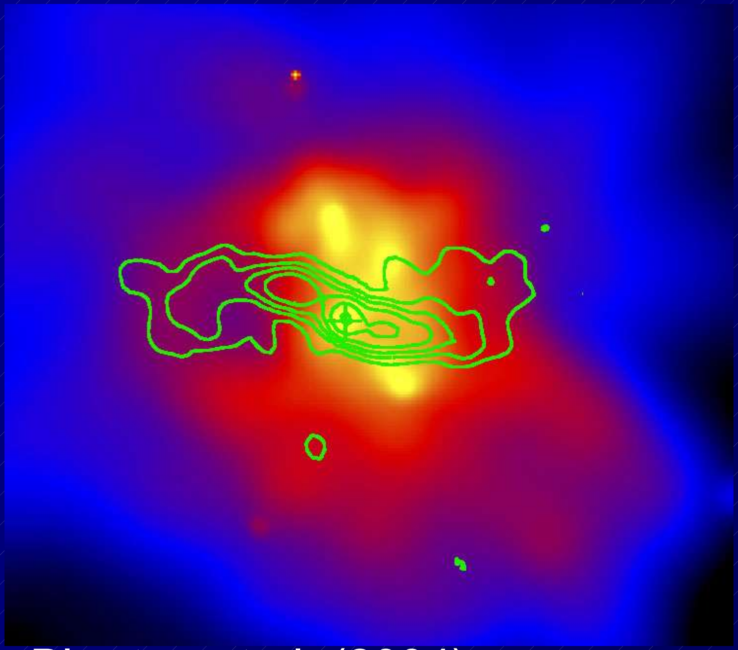
Clarke et al. (2005)

- low frequency data show a western 330 MHz extension running along the channel
- radio source is nearly 7 times larger at 330 MHz
  - – synchrotron lifetime of channel emission is $\tau_{syn} \sim 8 \times 10^6$ yr
  - – buoyancy rise time at $0.6c_s$ is $\tau_{buoy} \sim 2 \times 10^8$ yr

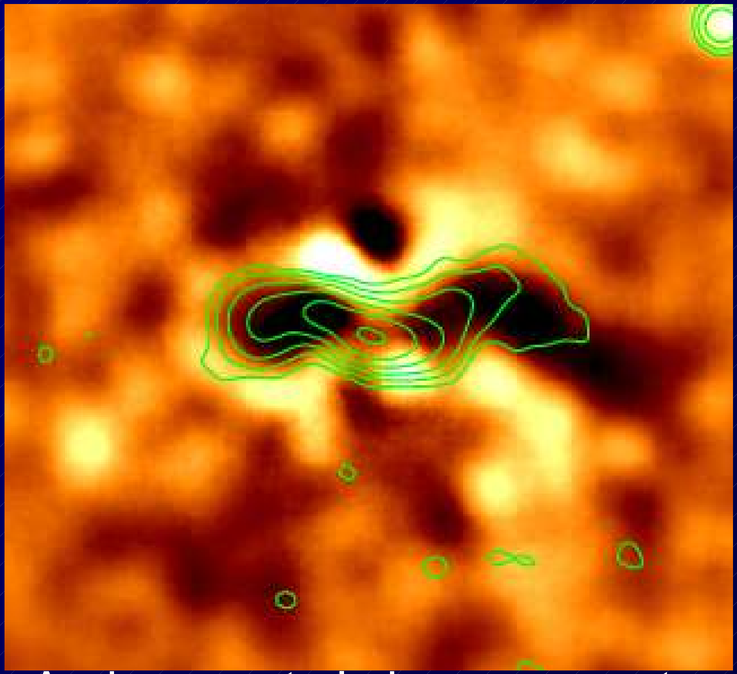
electrons are (re)accelerated in-situ in the channel?

- Is this continuous emission from multiple outbursts along the same channel or a series of discrete bubbles? New radio and X-ray observations are in progress.

Ghost Channel: Abell 262 at Low Frequencies



Blanton et al. (2004)

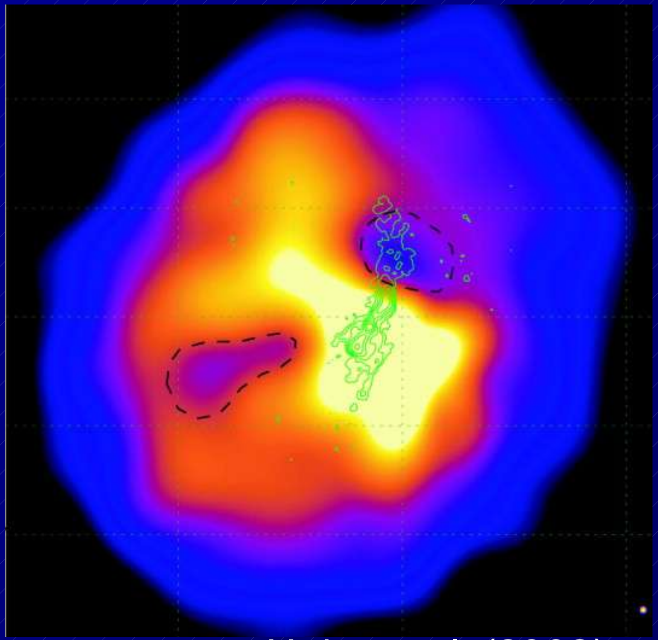


Anderson et al., in prep., poster 3.1

- Chandra image of A262 shows cavity to the east
  - based on eastern hole radio source energy output appears insufficient to offset cooling
- but residual image of A262 shows a channel to the west with 330 MHz radio emission
  - new analysis shows mechanical energy closer to offsetting cooling

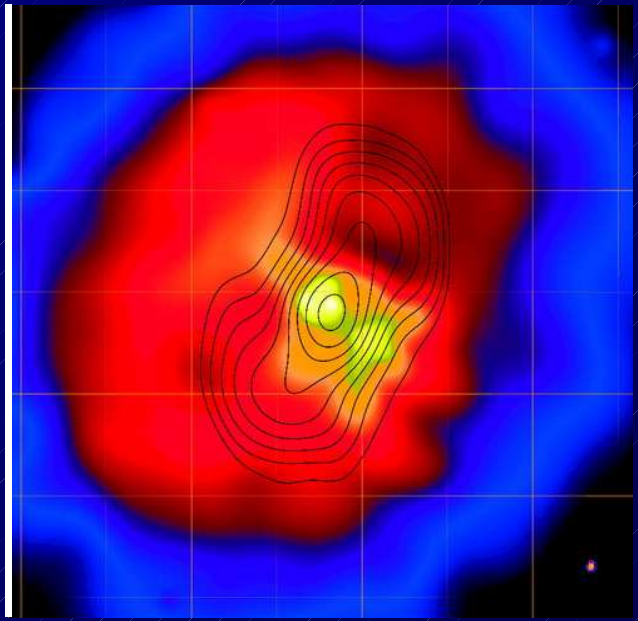
Ghost Bubbles: A4059 at Low Frequencies

8 GHz



Heinz et al. (2002)

1.4 GHz

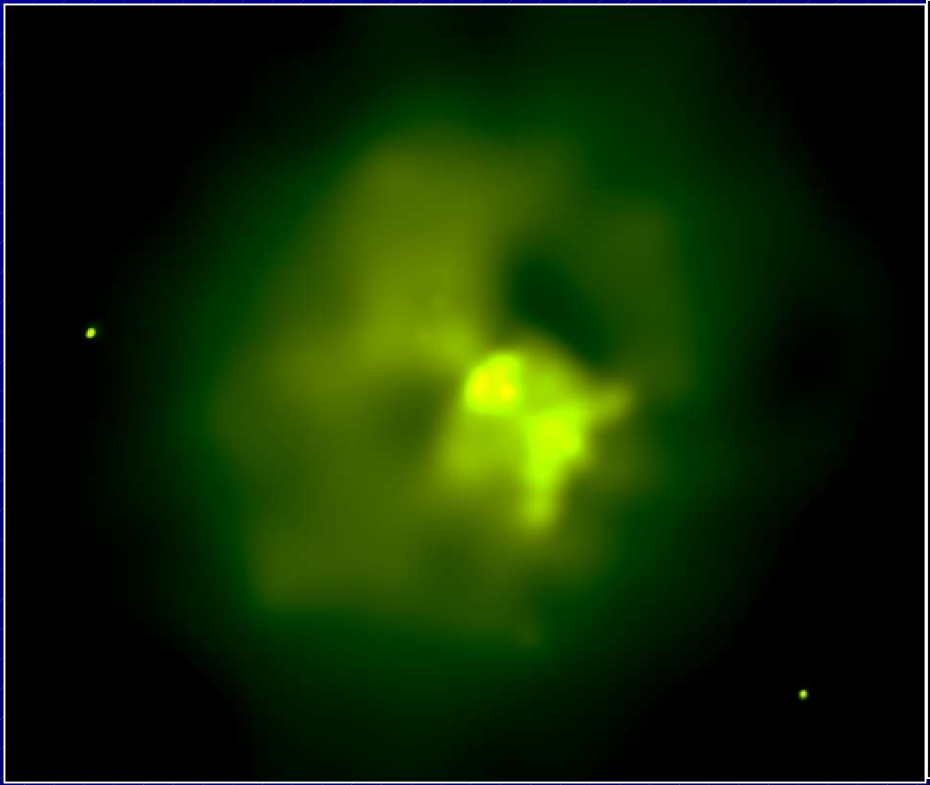


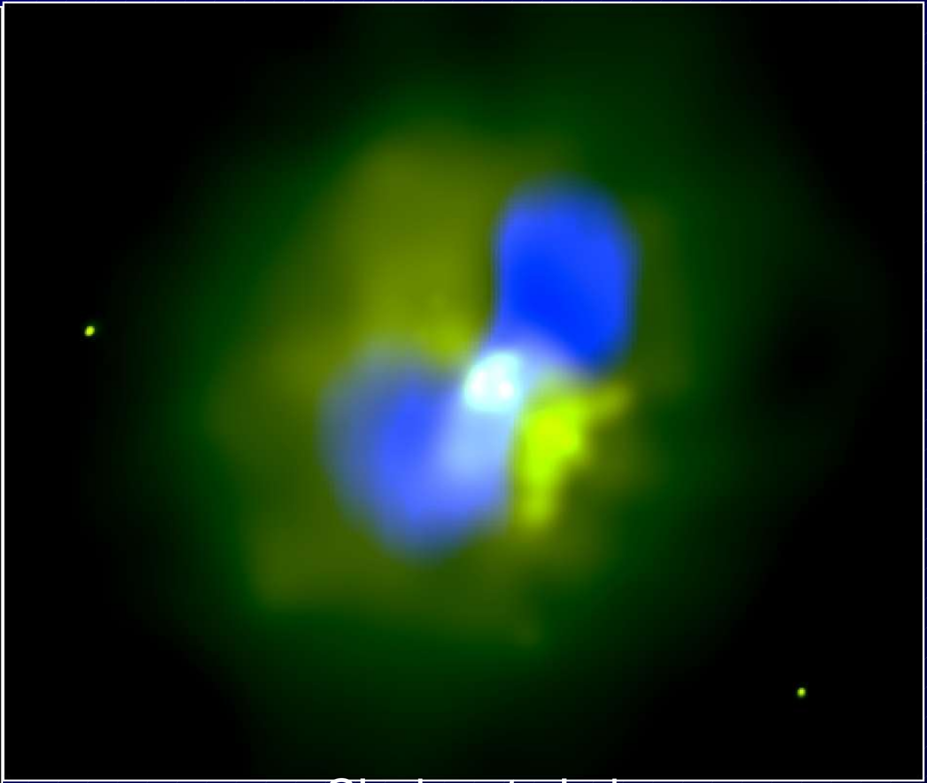
Choi et al. (2004)

- z = 0.049
- central radio source PKS 2354-35
- compact, steep radio spectrum

- X-ray observations show two (ghost) cavities as well as a central bar and sharp southwest ridge
- radio emission shows no direct correlation with cavities
- Choi et al. interpret X-ray bar as bulk motions ~ 500 km s^{-1} together with rotation

Ghost Bubbles: A4059 at Low Frequencies





Clarke et al., in prep.

- new 330 MHz VLA observations show much larger radio source with both lobes filling in the ghost cavities
  - $P_{th} = 1.1\times10^{-10}$ dyne/cm^2 ~ 5 x P_{me},

    k/f=20 for pressure equilibrium at equipartition

Radio Mechanical Power vs Cooling Luminosity

- AGN mechanical power required to create cavities is:

$$\boxed{\frac{1}{(\gamma - 1)}\mathrm{PV} + \mathrm{PdV} = \frac{\gamma}{(\gamma - 1)}\mathrm{PV}}$$

Churazov et al. (2002)

Internal energy of bubble

Work done expanding bubble

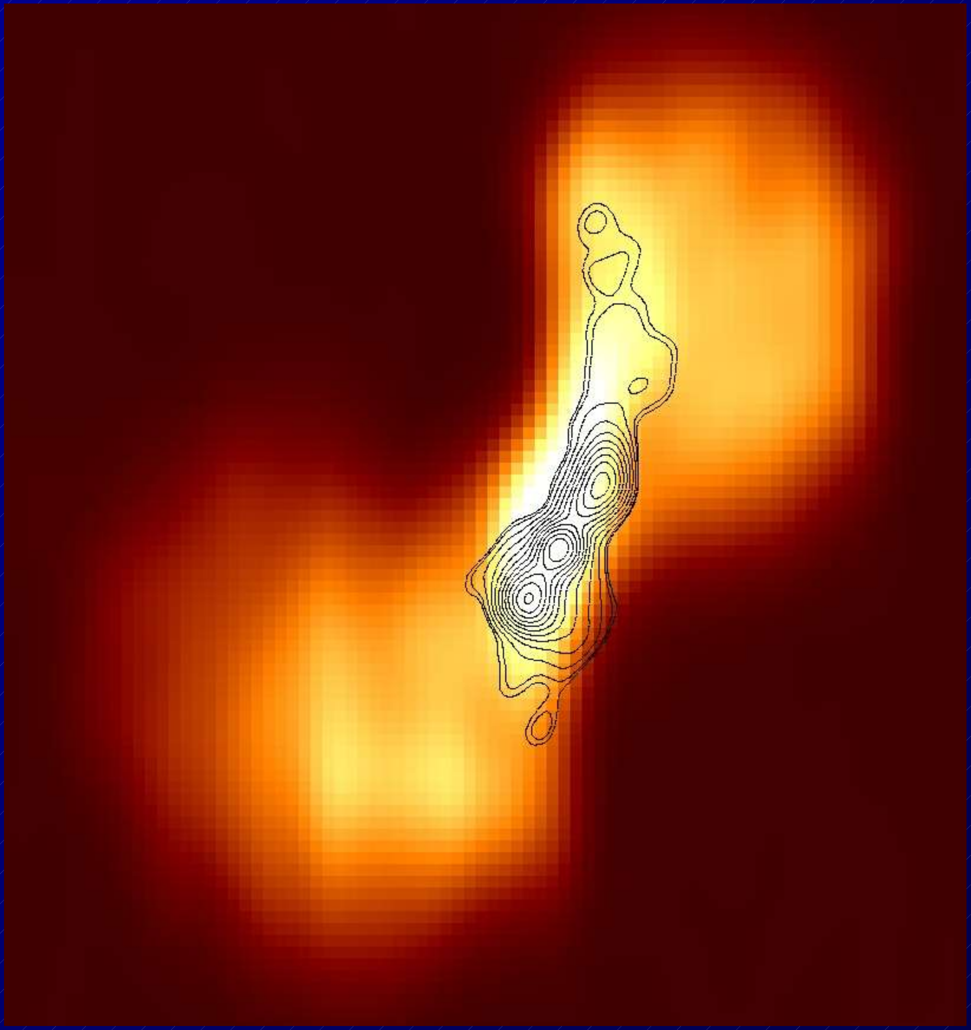
- Cooling luminosity of X-ray gas is: $\boxed{L_{cool} = \frac{5}{2}\frac{kT}{\mu m_p}\dot{M}}$

Sarazin (1988)

	A2597	A262	A4059
4PV (ergs)	4×10^{58}	8×10^{57}	1×10^{58}
τ_{AGN} (yr)	5×10^{7}	1×10^{8}	1×10^{8}
L_{radio} (ergs/s)	4×10^{43}	4×10^{42}	3×10^{42}
L_{cool} (ergs/s)	3×10^{43}	1×10^{43}	1×10^{43}

- AGN mechanical energy input in A2597 ~ balances cooling if τ_{rep}~50 Myr
- A262 and A4059 outbursts appear weaker

A4059: Radio Structure



- 330 MHz data reveal bright inner core and jets leading into diffuse lobes to the northwest and southeast
- may be the result of a change in the AGN jet axis or rotation due to “sloshing” in the cluster core

Summary

- Radio and X-ray observations show that there are dramatic interactions between cluster-center radio galaxies and the thermal ICM
  - thermal gas confines and distorts the radio source
  - the radio lobes displace and compress the thermal gas

- Repeated AGN outbursts may provide the heating necessary to balance radiative cooling in at least some clusters. Outburst history is traced by low frequency radio observations as well as cavities and channels in the X-ray data.

- The detached buoyant lobes distribute relativistic particles and magnetic fields throughout the ICM and may be re-activated by merger shocks to produce the diffuse relic emission in some merging clusters.

Feedback Cycle