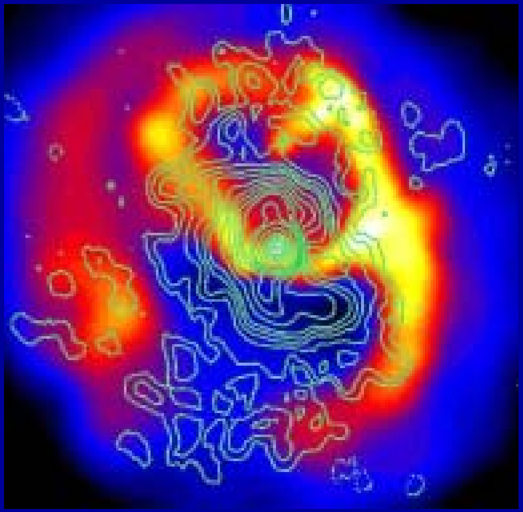
Radio Sources in Cooling Flow Clusters: A Solution to the Missing Cool Gas?



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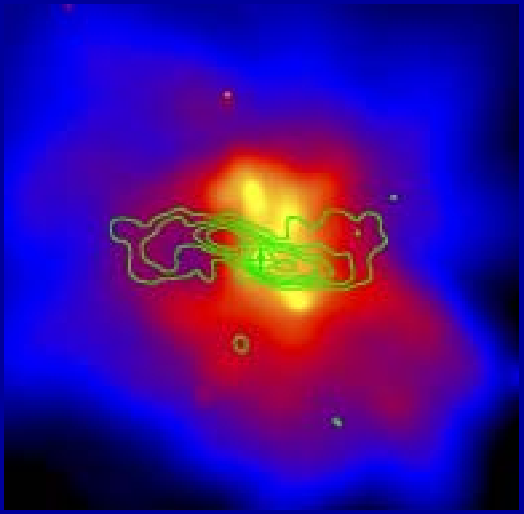


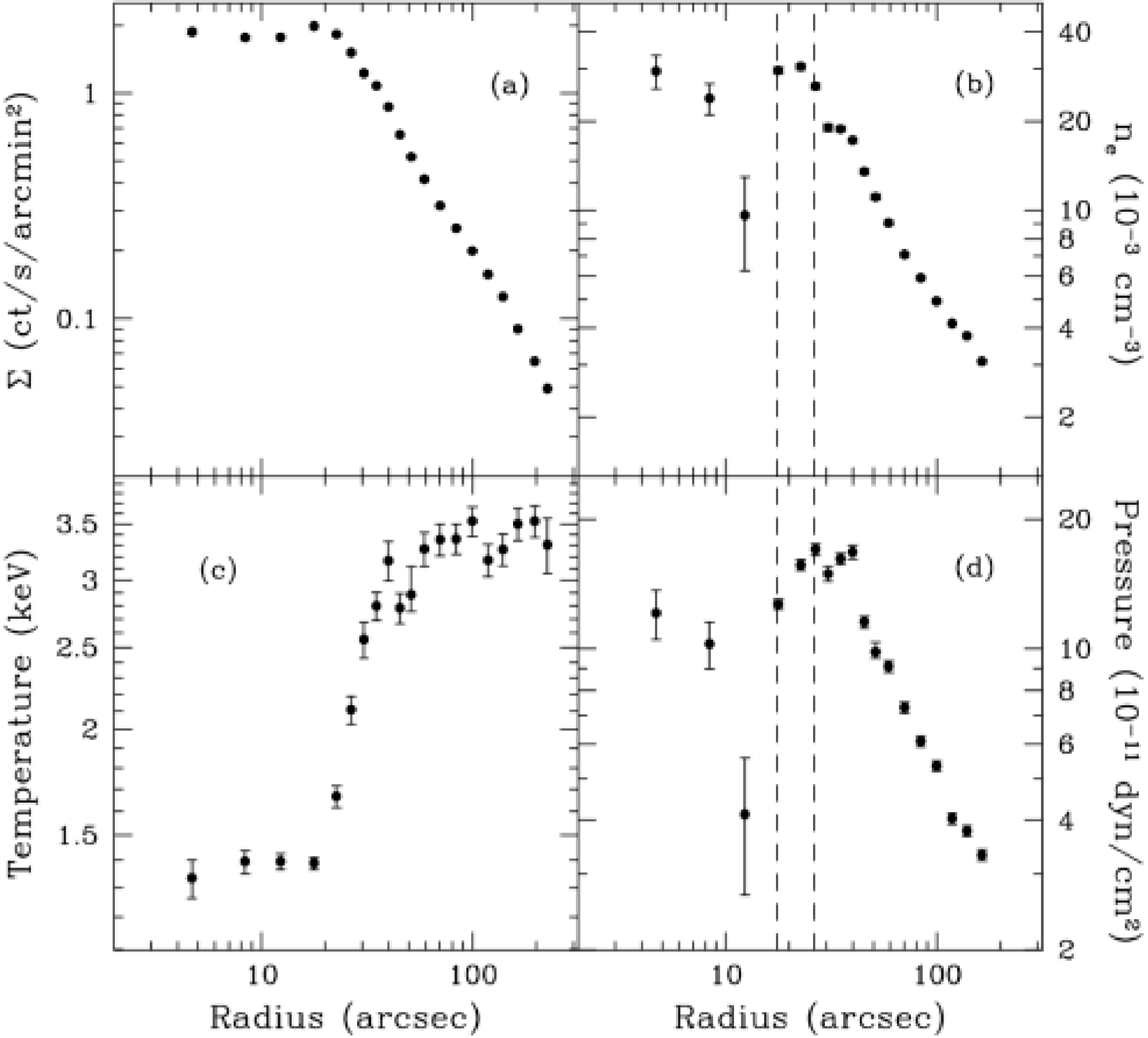
Collaborators: C. Sarazin, B. McNamara, N. Soker, M. Wise, T. Clarke

Cooling Flows

- Occur in both clusters of galaxies and individual galaxies.
- When the cooling time of gas $\boxed{t_{cool} \propto T^{1/2}/n}$ (with T=temp. and n=density) is shorter than the Hubble time, or the time since the last major merger of the system, a cooling flow will be set up.
- In cooling flow clusters, large amounts of gas (~100s Msun/yr) are cooling radiatively – this happens first in the center where the gas is most dense, then outer gas flows in to maintain hydrostatic equilibrium.

The Cooling Flow Problem

- Where does the cooling gas go?
- Central cD galaxies in cooling flows do emit blue light and exhibit massive star formation, however the star formation accounts for only ~ 1-10% of the expected gas derived from the X-ray predictions (as measured from Einstein, ROSAT, and ASCA).
- Both Chandra and XMM-Newton have revealed an apparent lack of the expected quantities of cooler gas below about kT < 1- 2 keV (~10^7 K).
- Radio sources are possible heaters.


(a)
(b)
(c)
(d)
Σ (ct/s/arcmin²)
1
0.1
n_e (10⁻³ cm⁻³)
40
20
10
8
6
4
2
Temperature (keV)
3.5
3
2.5
2
1.5
Pressure (10⁻¹¹ dyn/cm²)
20
10
8
6
4
2
10
100
Radius (arcsec)
10
100
Radius (arcsec)

Radio Sources in Clusters

- Radio sources occur more often in cooling flow clusters than non-cooling flows: 70% of cooling flow clusters contain central cD galaxies with associated radio sources, and 20% of non-cooling flow clusters have radio-bright central galaxies (Burns 1990).
- This is probably no accident: the cooling gas feeds the AGN?

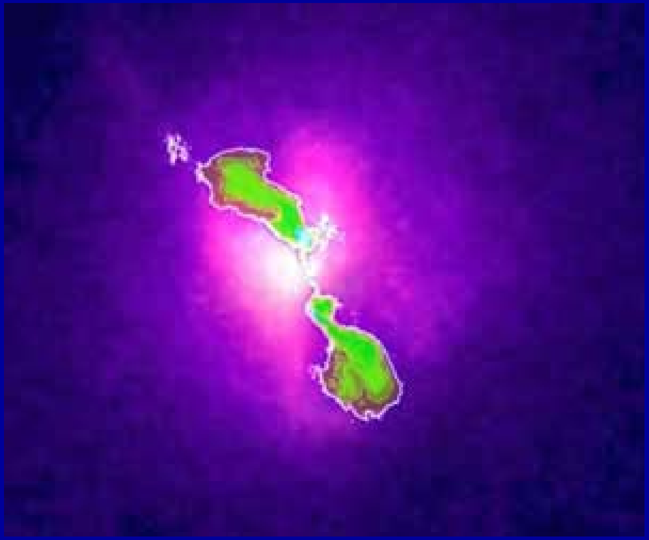
Radio Source / ICM Interactions

- Interactions between radio sources and hot, X-ray gas were seen in a few cases with ROSAT (Perseus, Boehringer et al. 1993; A4059, Huang & Sarazin 1998; A2052, Rizza et al. 2000).
- Numerous more examples have been found with Chandra, and they can now be studied in much more detail.
- In general, the radio sources displace the X-ray gas, which, in turn, confines and distorts the radio lobes. The radio sources create cavities or “bubbles” in the X-ray gas.

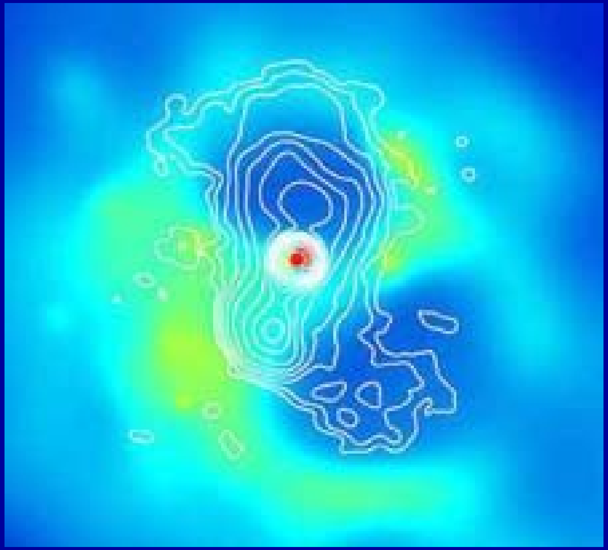
Heating by Radio Sources

- Earlier models (e.g. Heinz, Reynolds, & Begelman 1998) predicted that radio sources would heat the ICM through strong shocks. This heating could help to balance the cooling in cooling flows.
- Shock heating models showed that the gas found around the radio sources should be bright, dense, and hotter than the neighboring gas. This temperature rise has not been observed.
- Newer models (e.g. Reynolds, Heinz, & Begelman 2001) instead invoke weak shocks to do the heating, which can result in X-ray shells that are relatively cool.
- Buoyantly rising bubbles of radio plasma can also transport energy into clusters.

Early Chandra Observations

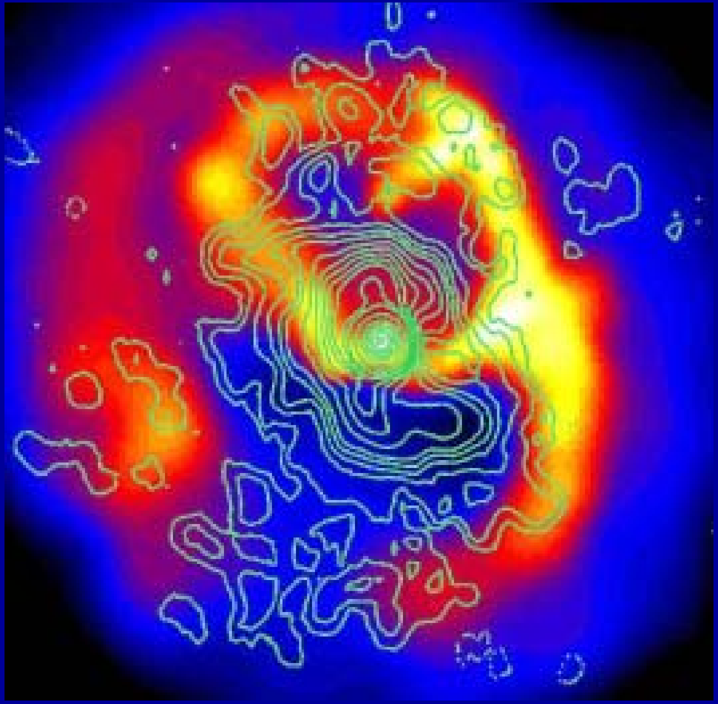


Hydra A, McNamara et al. 2000



Perseus, Fabian et al. 2000

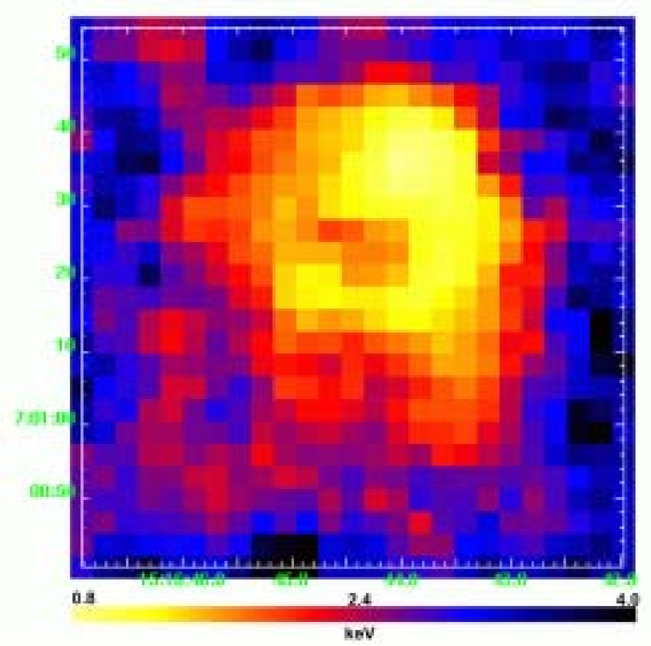
Abell 2052



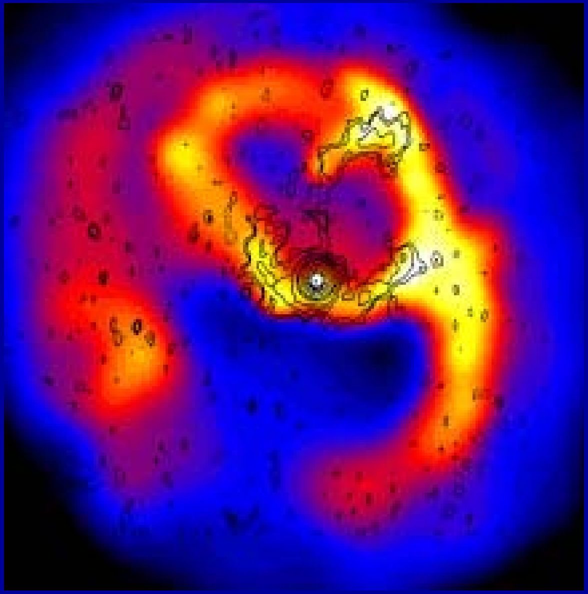
Blanton et al. 2001,2003

- z=0.0348
- Powerful FR I, 3C 317
- Avg. kT ~ 3 keV
- Cool shells, no evidence for shocks with limit M<1.2
- Shell cooling time 2.6 x 10^8 yr

Abell 2052



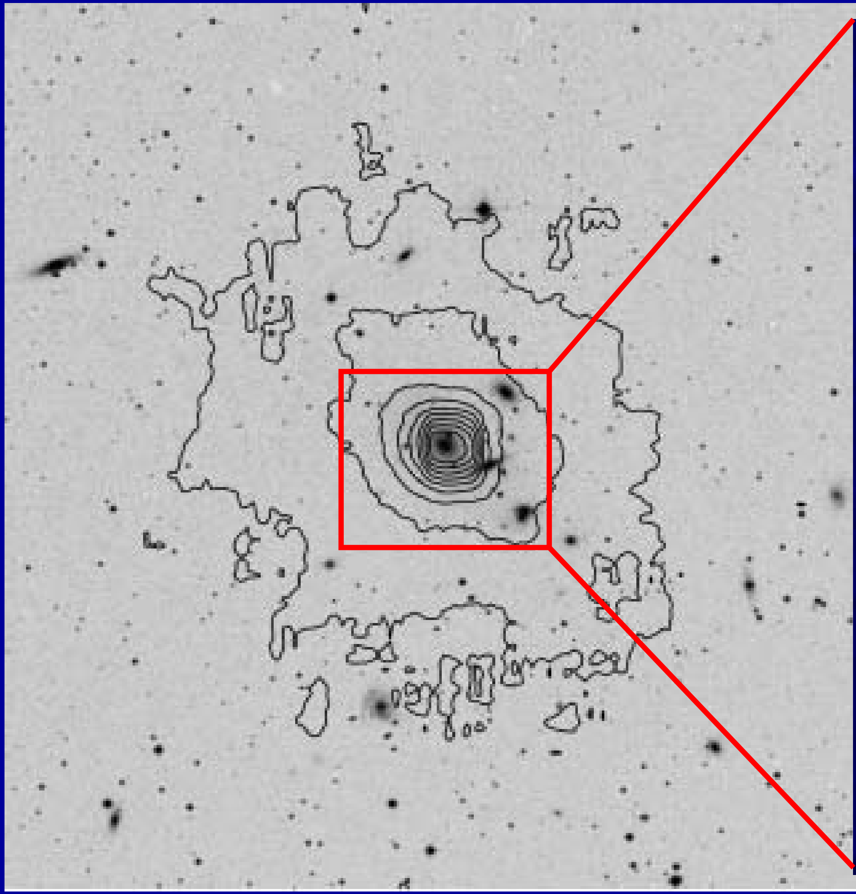
Blanton et al. 2003



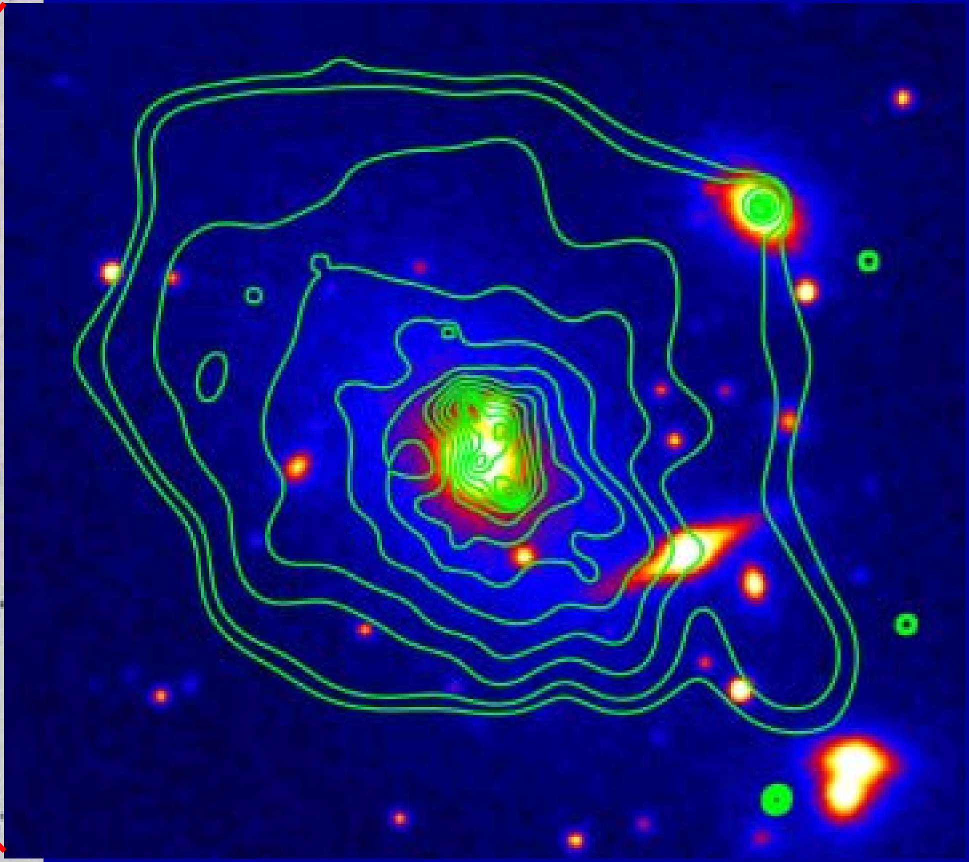
Hα + [NII], Baum et al. 1988;
Blanton et al. 2001

- The coolest X-ray gas in the cluster is in the shells around the radio holes.
- Gas with temperatures of ~ 10^4 K is seen with optical emission lines, coincident with the bright X-ray shells.
- Shell cooling time is longer than radio source age of ~ 10^7 yr, so cool gas in shells pushed out from center.

Abell 262: Old and New

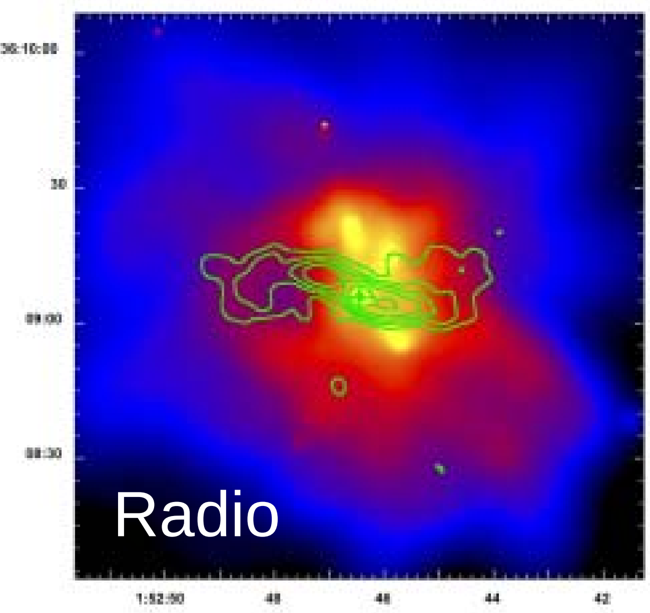


ROSAT HRI
Neill et al. (2001)

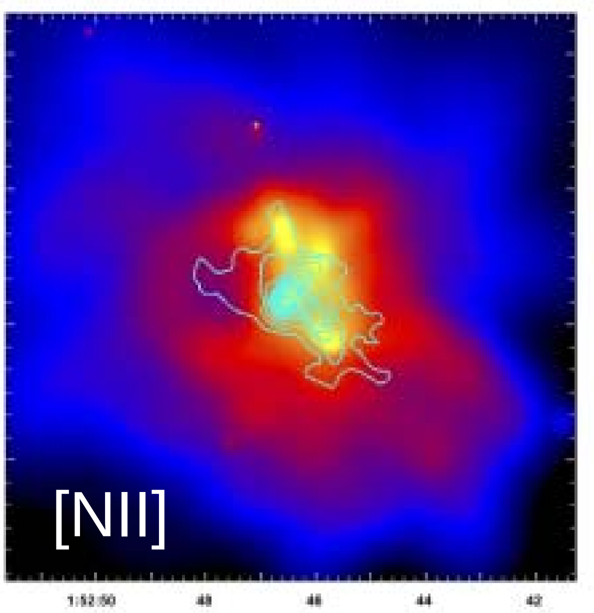


Chandra ACIS-S
Blanton et al. (2003)

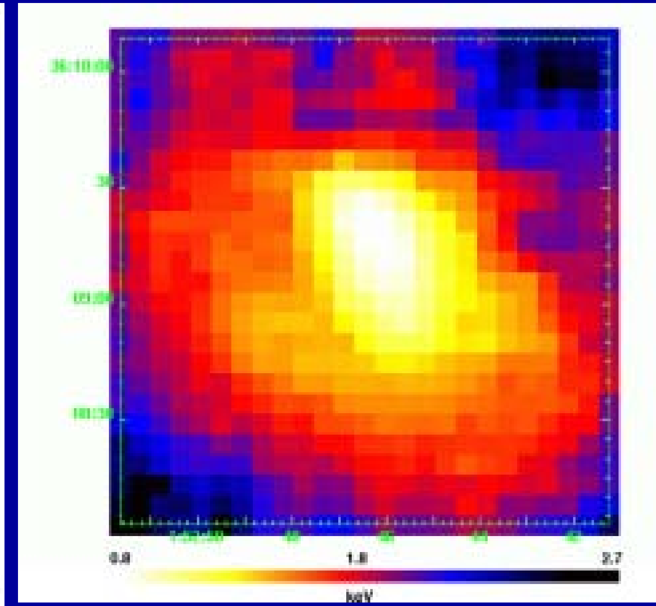
Abell 262



Radio (Parma et al. 1986)



[NII] (Plana et al. 1998)



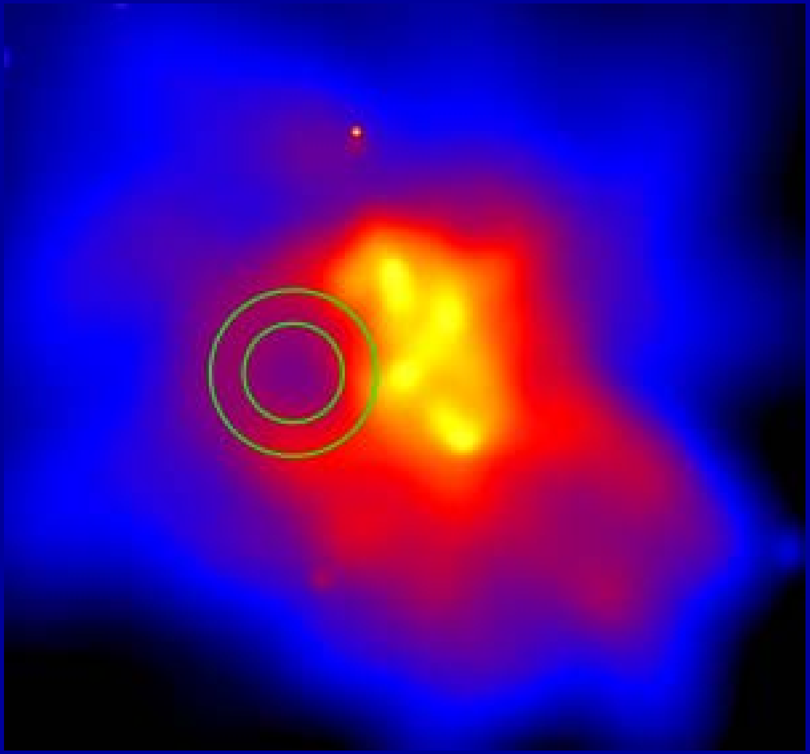
Blanton et al. 2003

- z=0.0163
- Rather weak radio source 0149+35 ($\log P_{1.4}$ = 22.6 W/Hz)
- <kT> = 2.2 keV
- Clear bubble to east of cluster center. Surrounding rims are cool, with cooling time = 4 x 10^8 yr

Pressure in Shells

- In cooling flow clusters, surface brightness deprojected to determine X-ray emissivity and density.
- Common feature of these sources is that the pressure of the bright shells is ~ equal to that just outside of them => no evidence for strong shocks.
- Comparison with the gas pressure in the X-ray shells with the pressures derived in the holes from radio observations, assuming equipartition, shows that the pressures in the shells are about an order of mag. higher than the radio pressures.

Pressure in Shell: Example (A262)

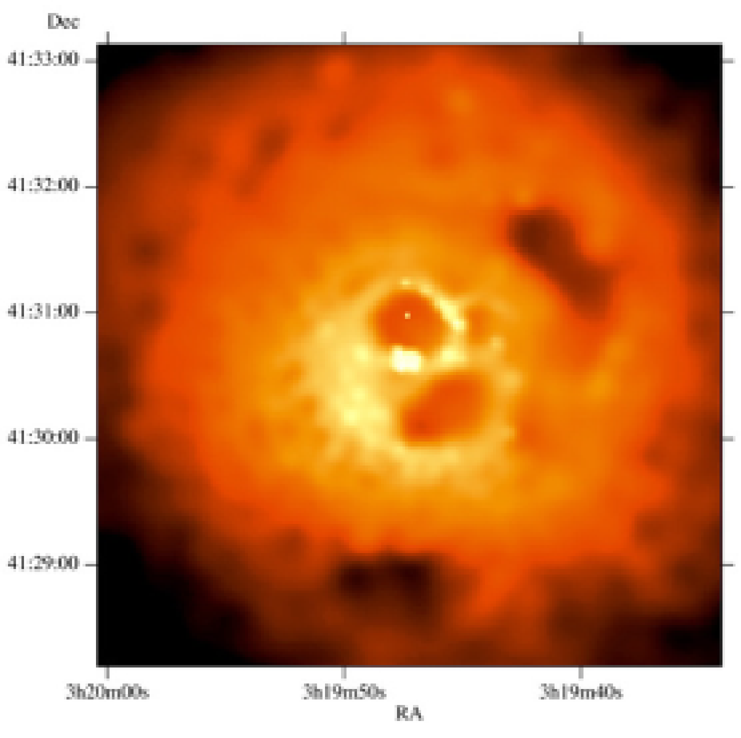


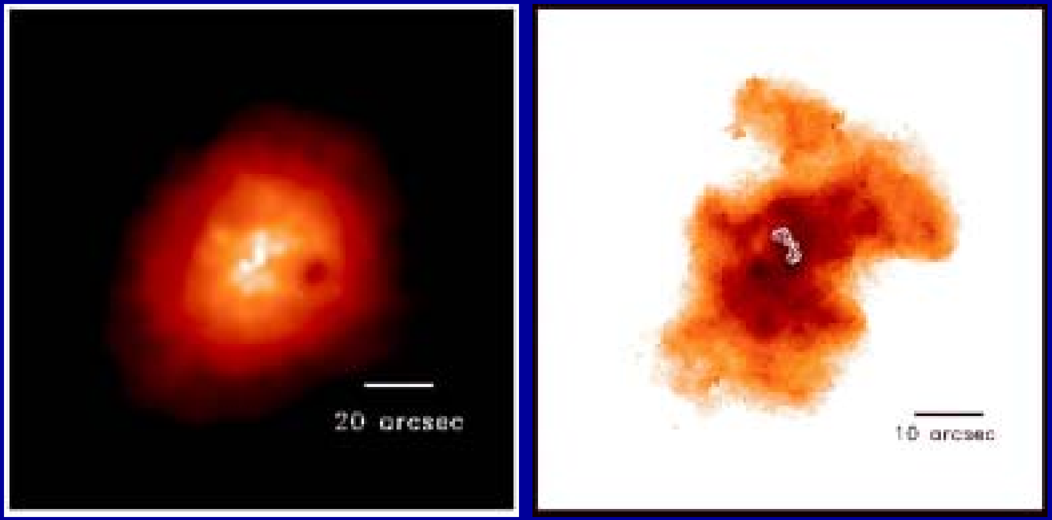
- Pressure in shell around radio source is 1×10^{-10} dyn/cm^2
- X-ray pressure is an order of magnitude higher than radio equipartition pressure of 2×10^{-11} dyn/cm^2 (Heckman et al. 1989)

Pressure Difference: X-ray and Radio

- Problems with equipartition assumptions.
- Possible additional contributions in holes from:
  - Magnetic fields
  - Low energy, relativistic electrons
  - Very hot, diffuse, thermal gas (limited to > 15 keV [Hydra A, Nulsen et al. 2002], 11 keV [Perseus, Schmidt et al. 2002], 20 keV [A2052, Blanton et al. 2003]). Look with XMM-Newton or Constellation-X.

Transportation of Energy to ICM: Buoyant Bubbles





A2597, McNamara et al. 2001

Perseus, Fabian et al. 2000

X-ray Shells as Radio Calorimeters

- Energy deposition into X-ray shells from radio lobes (Churazov et al. 2002):

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

Internal bubble energy

Work to expand bubble

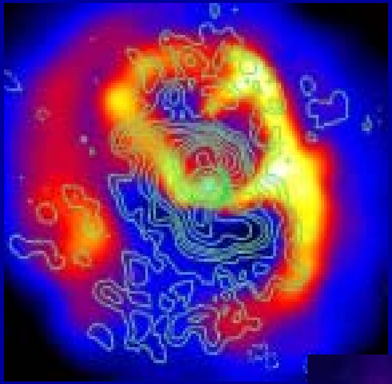
- Repetition rate of radio sources ~ 10^8 yr (from buoyancy rise time of ghost cavities)

Can Radio Sources Offset Cooling?

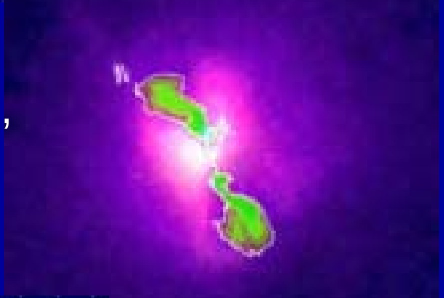
- Assuming X-ray shell and radio bubble are in pressure equilibrium, the total energy output of the radio source, including the work done on compressing the gas is E ~ 5/2 PV (with $\gamma = 5/3$).
- Compare with luminosity of cooling gas

$$\boxed{L_{\mathrm{cool}} = \frac{5}{2}\frac{\dot{M}}{\mu m}kT}$$

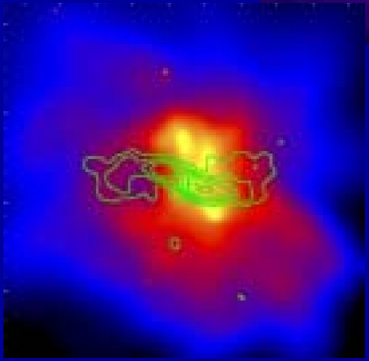
Examples



Blanton et al. 2001,3



McNamara et al. 2000, David et al. 2001, Nulsen et al. 2002



Blanton et al. 2003

- A2052: E = 10^{59} erg
  E/t = 3 x 10^{43} erg/s
  kT = 3 keV, $\dot{M} = 42\ M_\odot$/yr
  L_{cool} = 3 x 10^{43} erg/s
- Hydra A: E = 8 x 10^{59} erg
  E/t = 2.7 x 10^{44} erg/s
  kT = 3.4 keV, $\dot{M} = 300\ M_\odot$/yr
  L_{cool} = 3 x 10^{44} erg/s
- A262: E = 1.3 x 10^{57} erg
  E/t = 4.1 x 10^{41} erg/s
  kT = 2.1 keV, $\dot{M} = 10\ M_\odot$/yr
  L_{cool} = 5.3 x 10^{42} erg/s
  (but, much less powerful radio source)

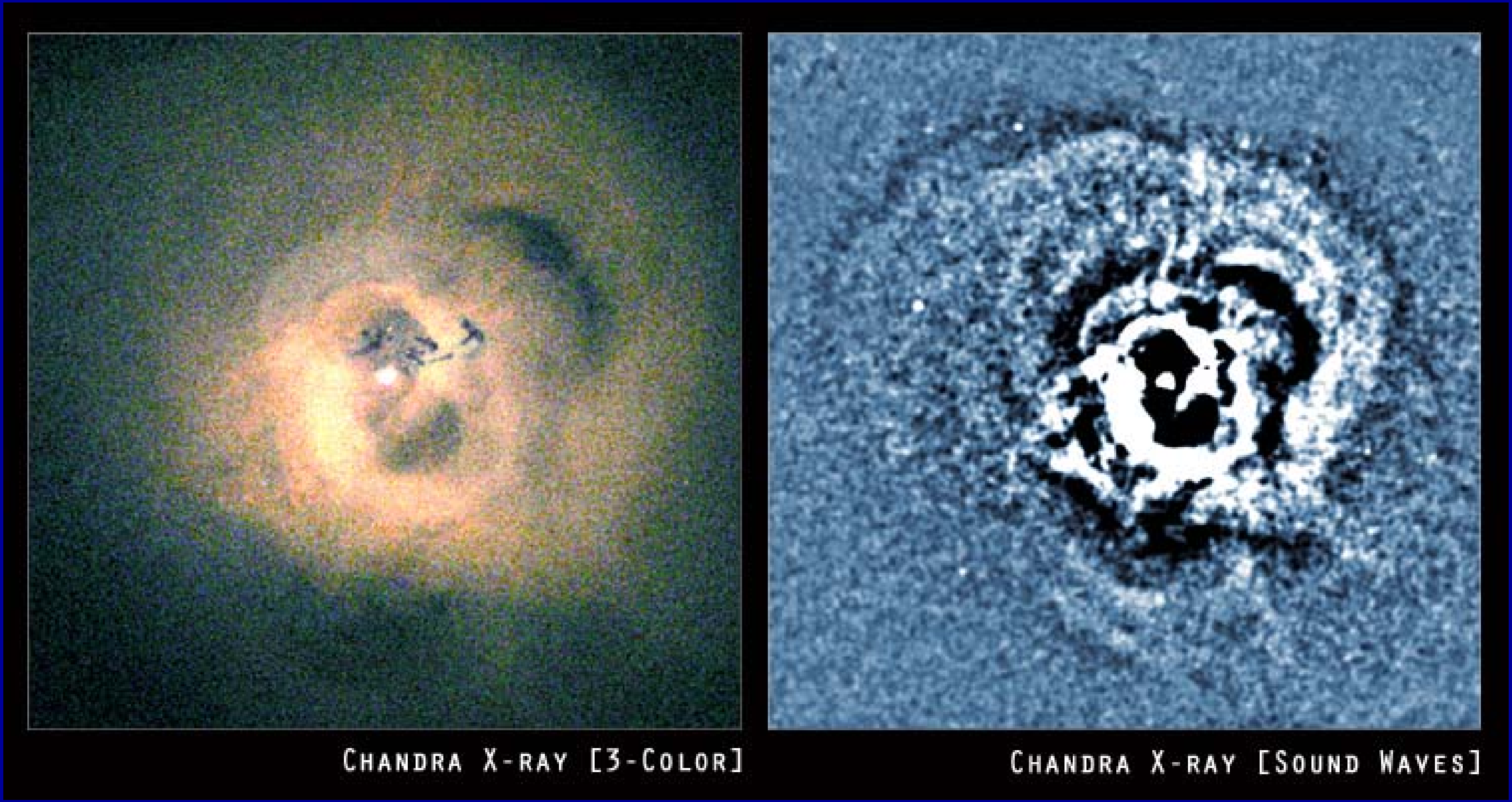
Conclusions

- Radio sources displace the X-ray-emitting gas in the centers of cooling flows, creating cavities or “bubbles.”
- In all clusters observed so far, there is no evidence that the radio sources are strongly shocking the ICM. The bright shells are cool, not hot. Weak shocks may have occurred in the past, creating the dense shells

Conclusions

- The X-ray gas pressures derived from the shells surrounding the bubbles are ~ 10x higher than the radio equipartition pressures. Problems with equipartition assumptions, or additional contributors to pressure in bubbles, such as very hot, diffuse, thermal gas?
- Buoyant bubbles transport energy and magnetic fields into clusters and can entrain cool gas.
- Shell pressures can be used to determine the total energies of the radio sources.
- A rough comparison of the average energy output of radio sources and the luminosity of cooling gas shows that the radio sources can supply enough energy to offset the cooling in cooling flows, at least in some cases.

Sound Waves from Perseus



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