AGN Feedback in Clusters of Galaxies

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AGN Feedback in Clusters

- Simulations (Croton et al. 2006) have shown that feedback is a necessary ingredient to produce the observed luminosity function of galaxies
- Feedback from AGN may set the upper limit to the observed masses of galaxies
- Feedback contributes to cluster preheating and observed ‘entropy floors’
- Feedback plays a role in observed scaling relations (e.g. L-T)
- AGN feedback can potentially affect cluster properties that are used for constraining cosmological models, such as the gas mass fraction.
- Chandra images over the last 10 years show AGN at work in the centers of cool core clusters, inflating bubbles that rise buoyantly through the ICM, and sometimes producing shocks and sound waves.

Cooling Flows

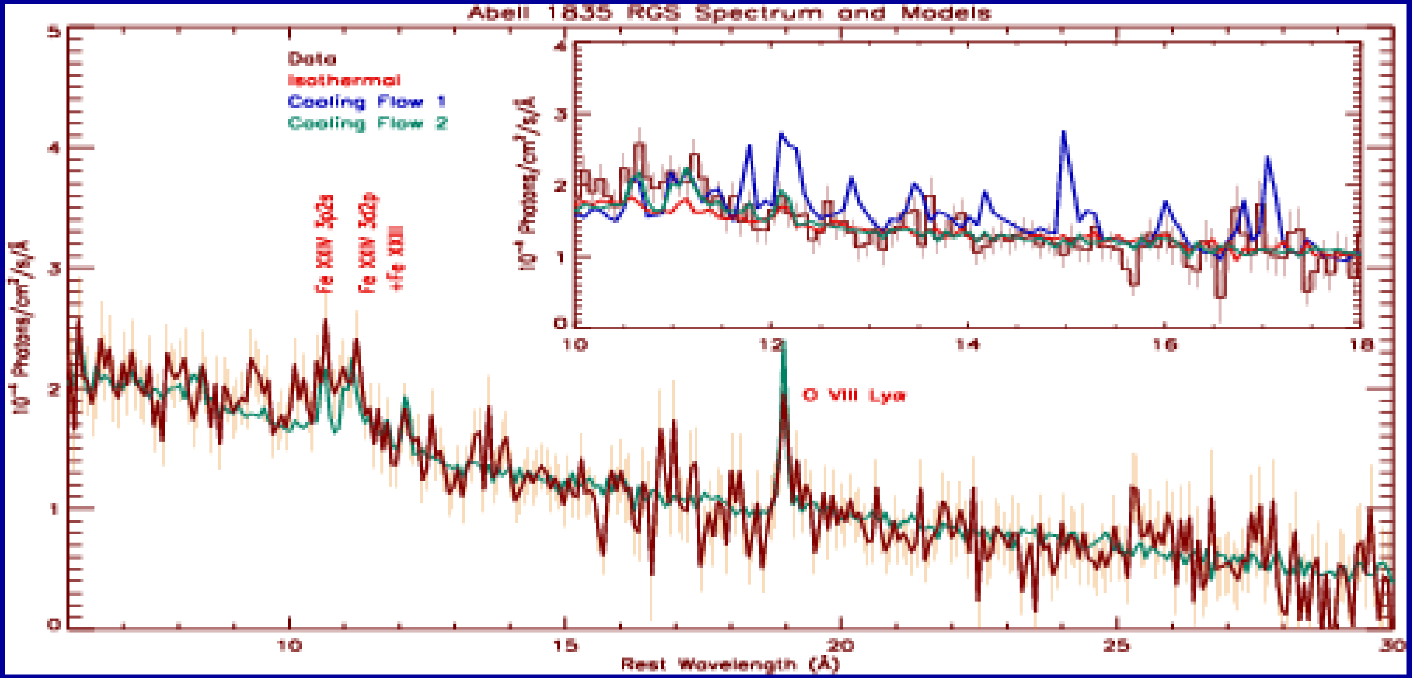
- Occur in both clusters of galaxies and individual galaxies
- When the cooling time of gas t_{cool} $T^{1/2}/n$ (with T=temp. and n=density) is shorter than the Hubble time, or the time since the last major merger of the system, a cooling flow will be set up
- In cooling flow clusters, large amounts 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

NASA/CXO/SAO

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 gas seen in cooling flows in the X-ray at approximately kT < 1- 2 keV (~10^7 K)

High-Res. Spectrum (XMM-Newton)

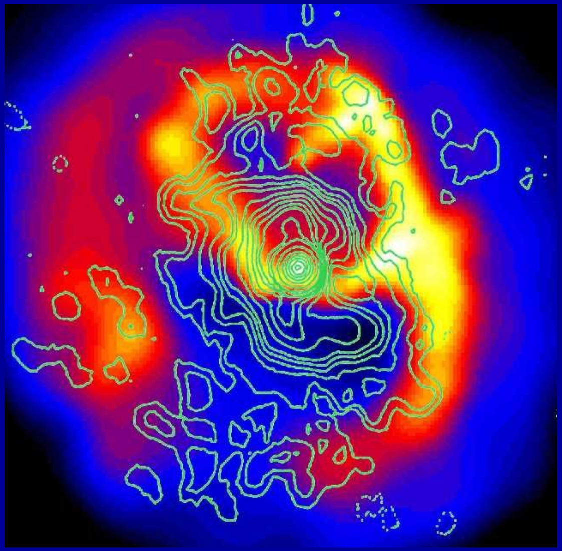


Peterson et al. (2001)

Brown line = data, red line = isothermal 8.2 keV model, blue line = cooling flow model, green line = cooling flow model with a low-T cutoff of 2.7 keV

Radio Sources in Cooling Flows

- >70% of cooling flow clusters contain central cD galaxies with associated radio sources, as compared to 20% of non-cooling flow clusters having radio-bright central galaxies (Burns 1990 / Einstein). Recent studies say up to 100% for cool cores and 45% for non-cool cores (Mittal et al. 2009)
- This is probably no accident: the cooling gas feeds the AGN? Feedback
- Radio sources have a profound effect on the surrounding X-ray emitting gas, as seen with Chandra
- 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.



Abell 2052
Blanton et al. 2001, 2003, 2009

Heating by Radio Sources

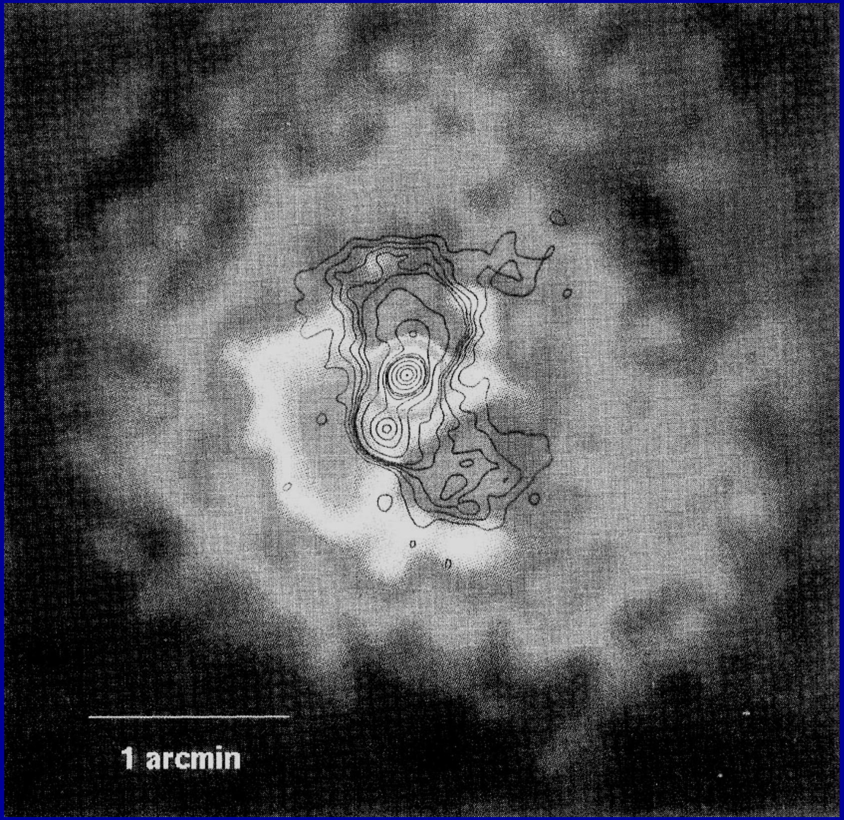
- Earlier models (e.g. Heinz, Reynolds, & Begelman 1998) predicted that radio sources would heat the ICM through strong shocks. This heating could help to balance the cooling in cooling flows.
- Shock heating models showed that the gas found around the radio sources should be bright, dense, and hotter than the neighboring gas.
- Other 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.
- Viscously dissipated sound waves are another possibility.

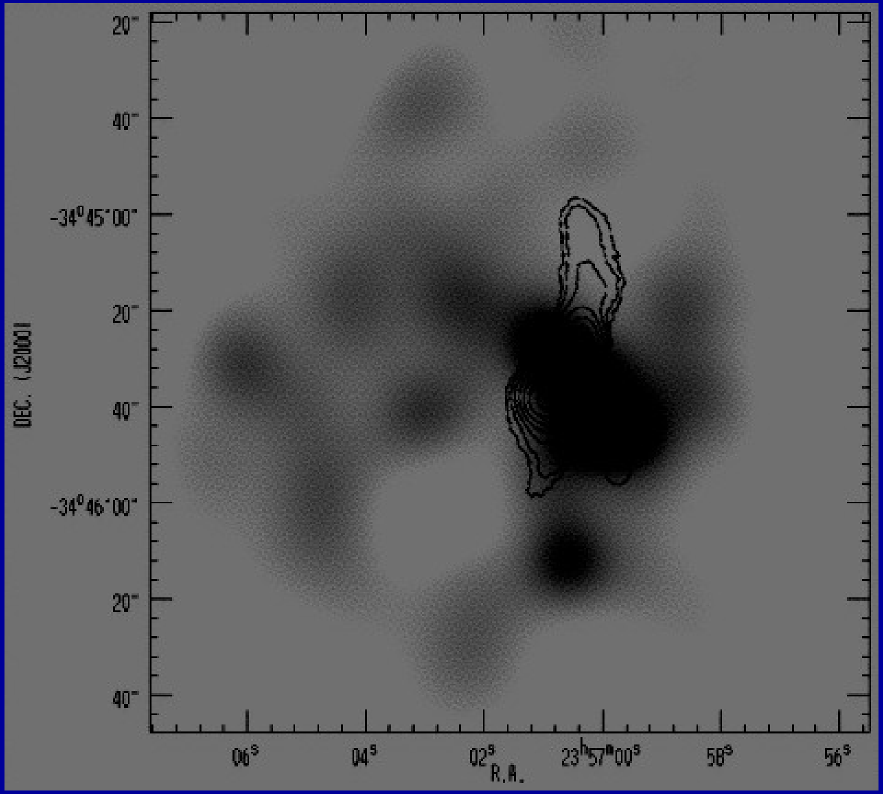
NASA/CXO/SAO

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.

Early (ROSAT) Observations

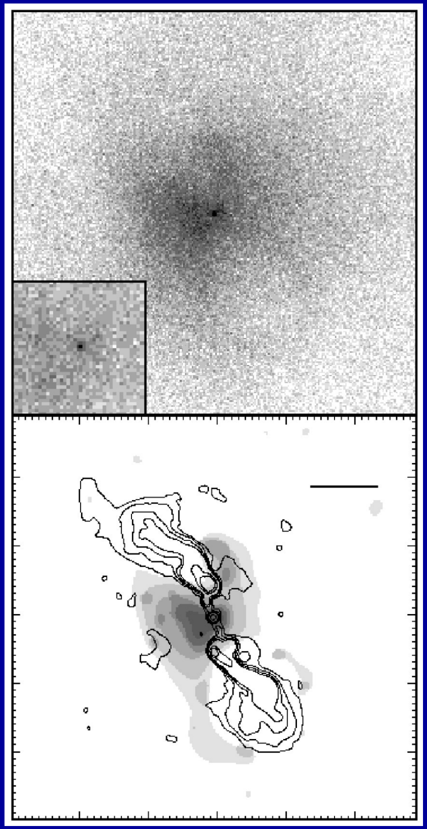


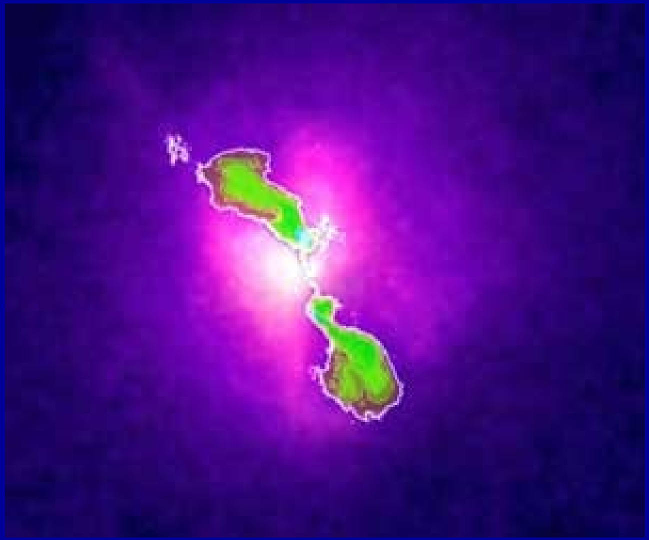


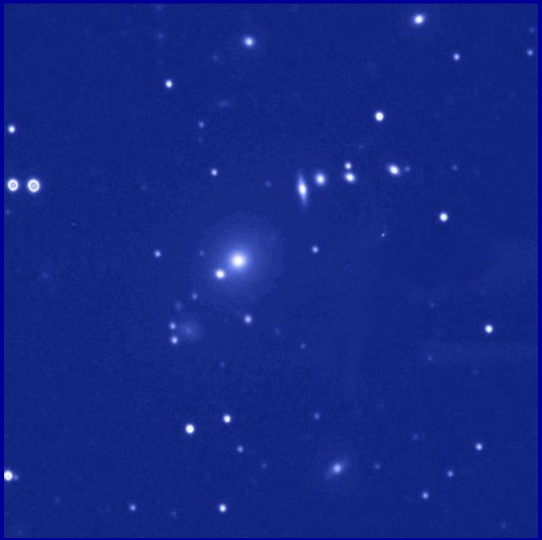
Perseus, Boehringer et al. 1993

A4059, Huang & Sarazin 1998

Early Chandra Observations

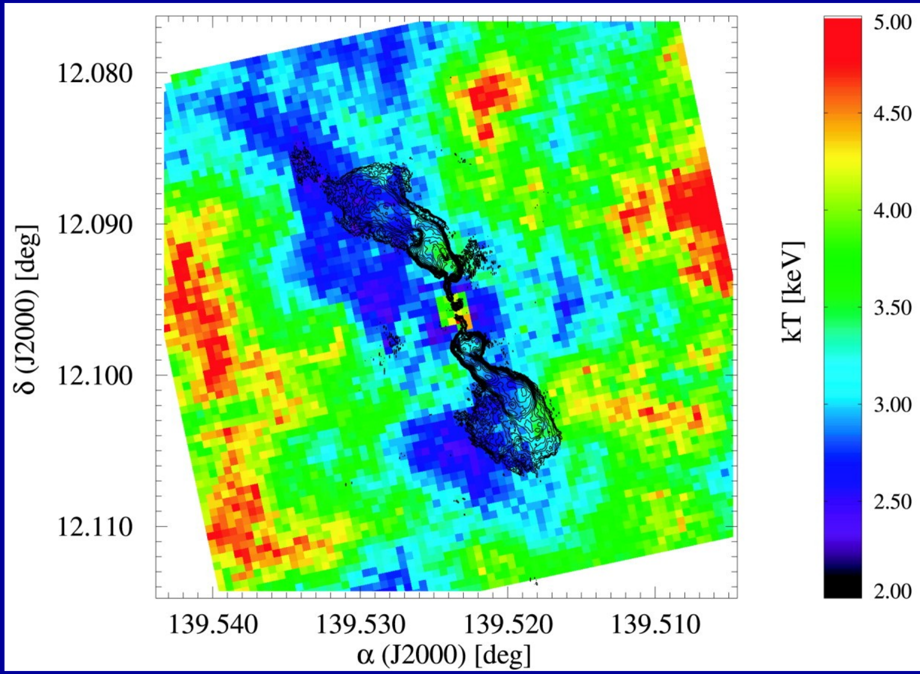






First Chandra observation of radio source/ICM interaction:
Hydra A, McNamara et al. 2000

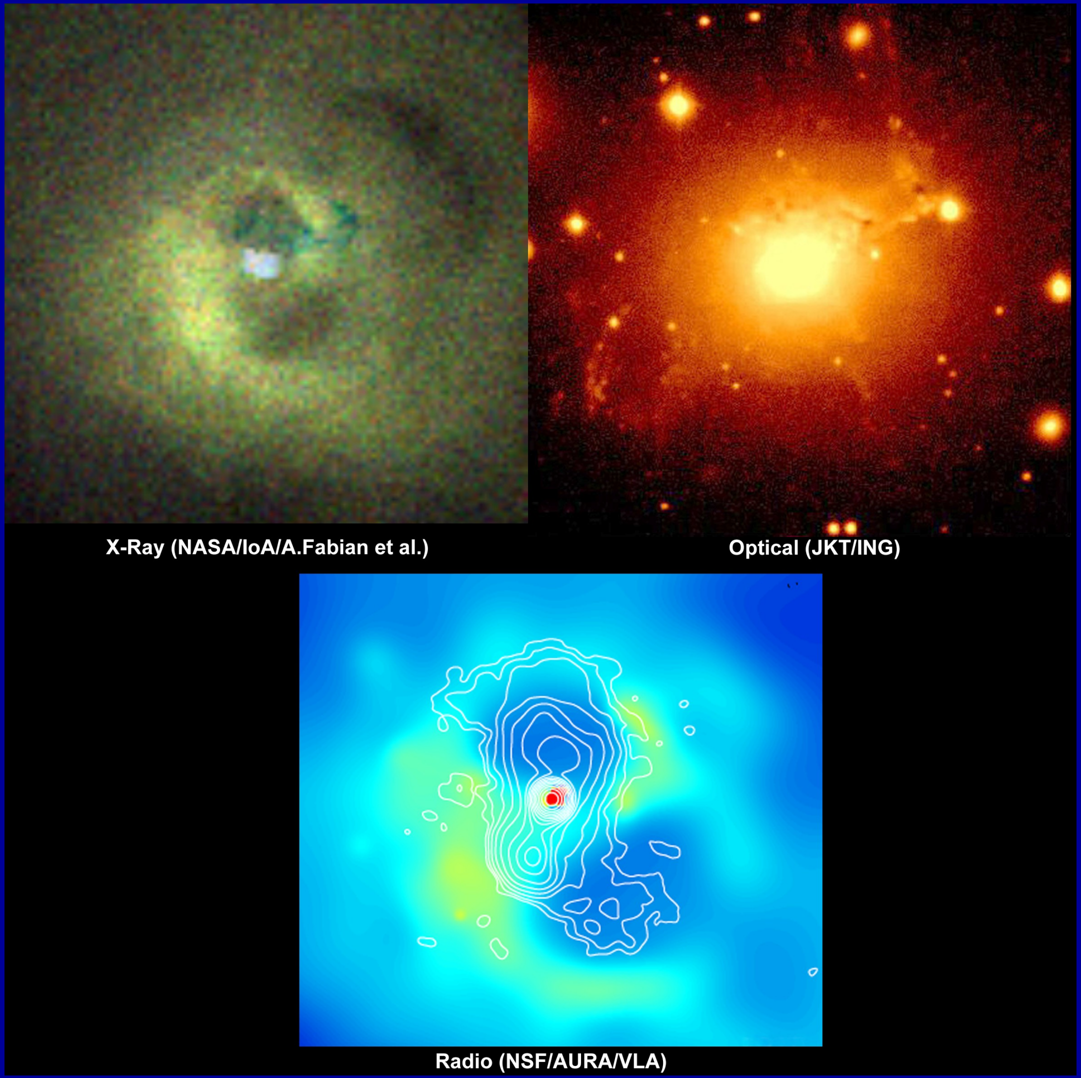
Hydra A



Nulsen et al. 2002

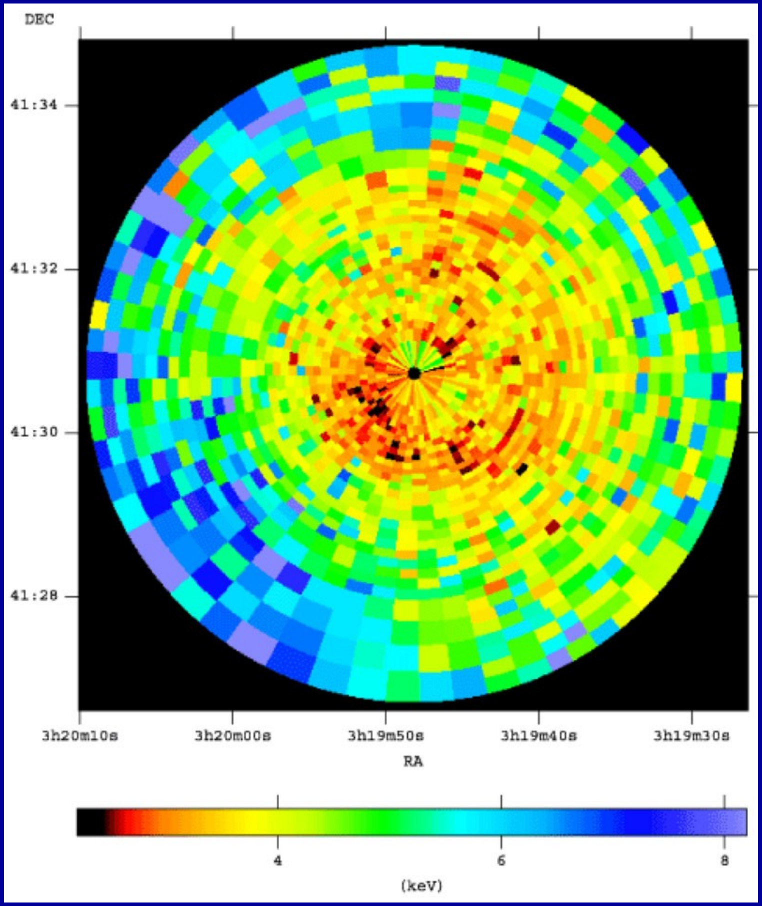
- z=0.052
- Mean kT~4 keV
- Powerful FR I source, 3C 218
- Holes with diameters 25-35 kpc.
- Coolest gas around radio lobes.
- Cooling time in center ~600 Myr.
- No evidence for strong shocks, but weak shocks are not formally ruled out.
- Need repeated outbursts from central source to prevent cooling to even lower temperatures (David et al. 2001).

Perseus



Fabian et al. 2000

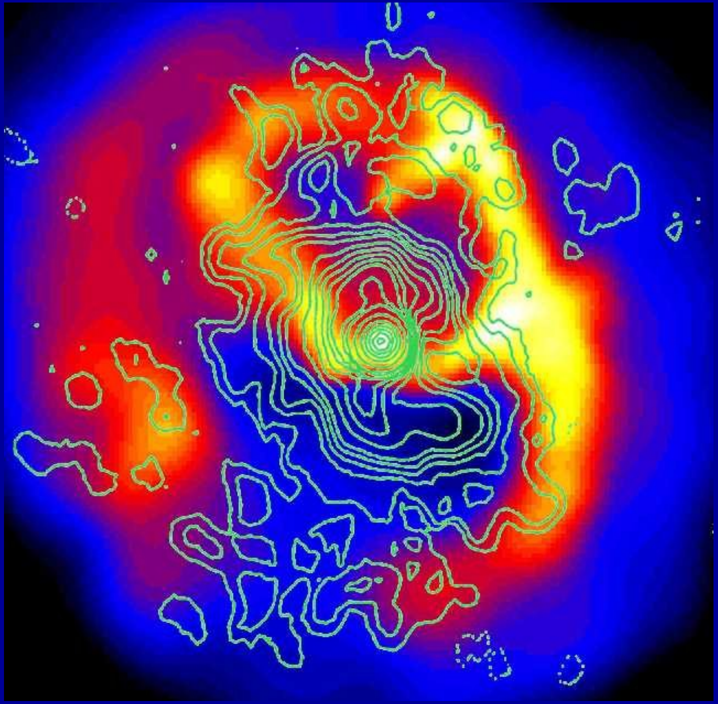
Perseus



Schmidt et al. 2002

- z=0.0183
- Abell 426
- Brightest cluster in X-ray sky
- Powerful radio src 3C 84
- Cooling time ~ 10^8 yr at center.
- Initially, no evidence for shocks - bright rims are cool.

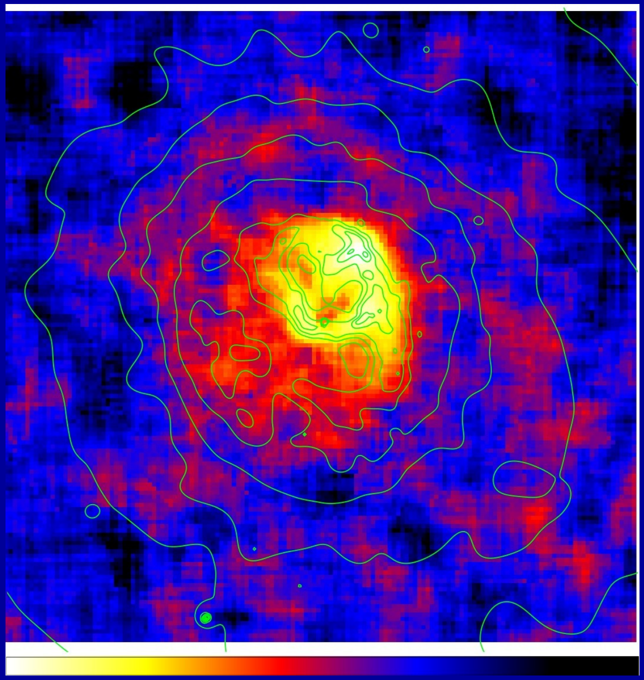
Abell 2052



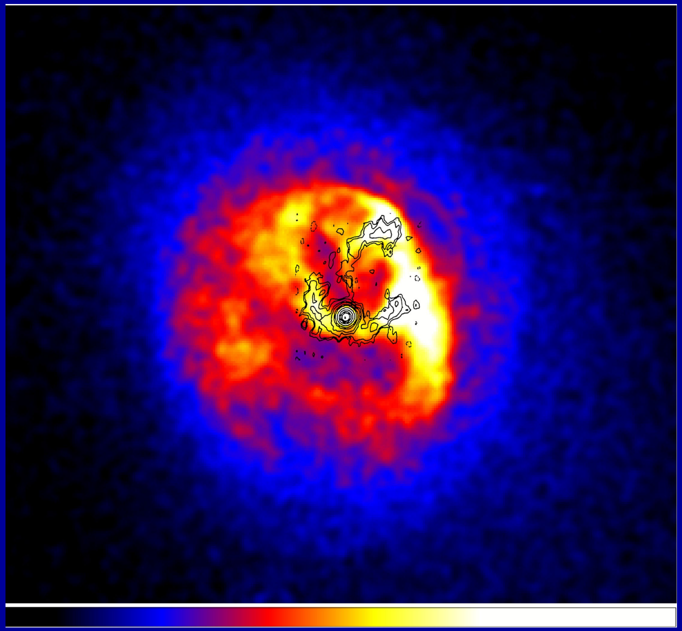
Blanton et al. 2001,2003,2009

- z=0.0348
- Powerful FR I, 3C 317
- Avg. kT ~ 3 keV
- Cool shells, no initial evidence for shocks
- Shell cooling time 2.6 x 10^8 yr - longer than radio source age of ~ 10^7 yr, so cool gas in shells pushed out from center.

Abell 2052



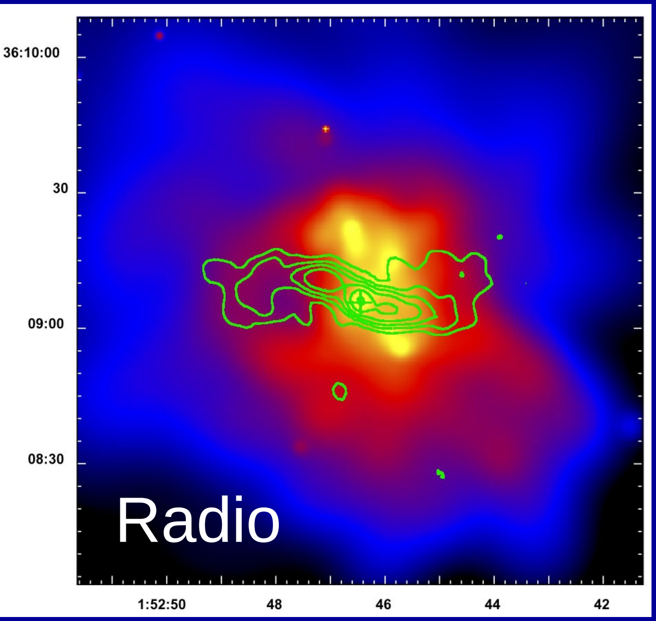
Blanton et al. (2009)

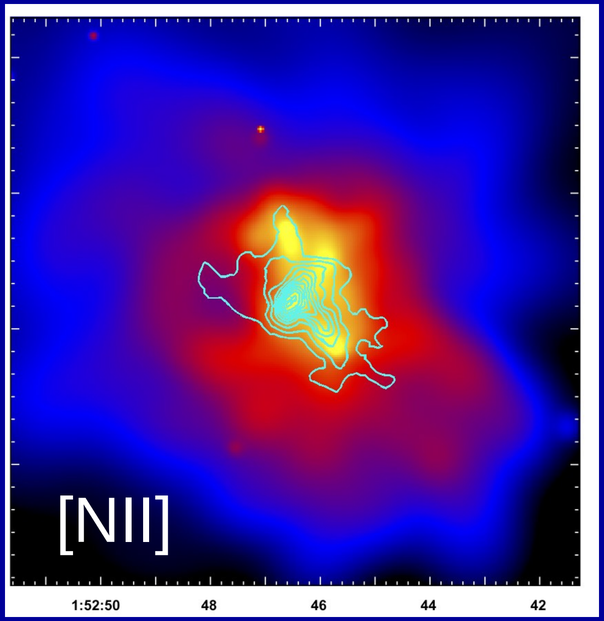


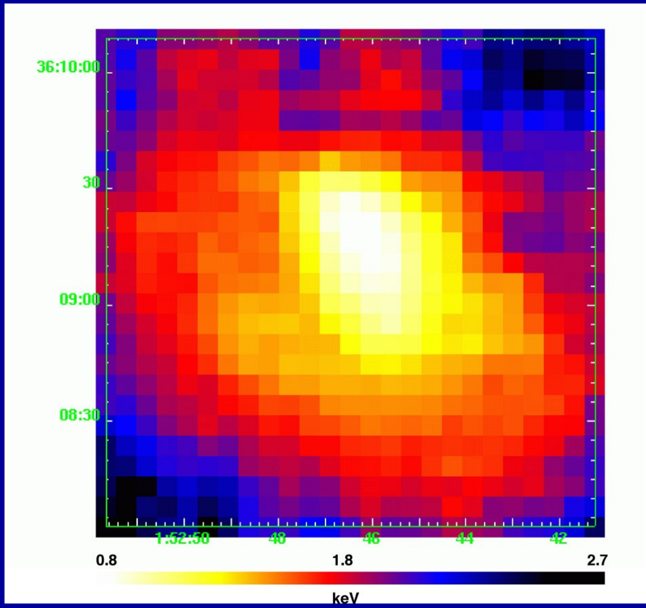
Hα + [NII], Baum et al. 1988; Blanton et al. (2009)

- 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.

Abell 262







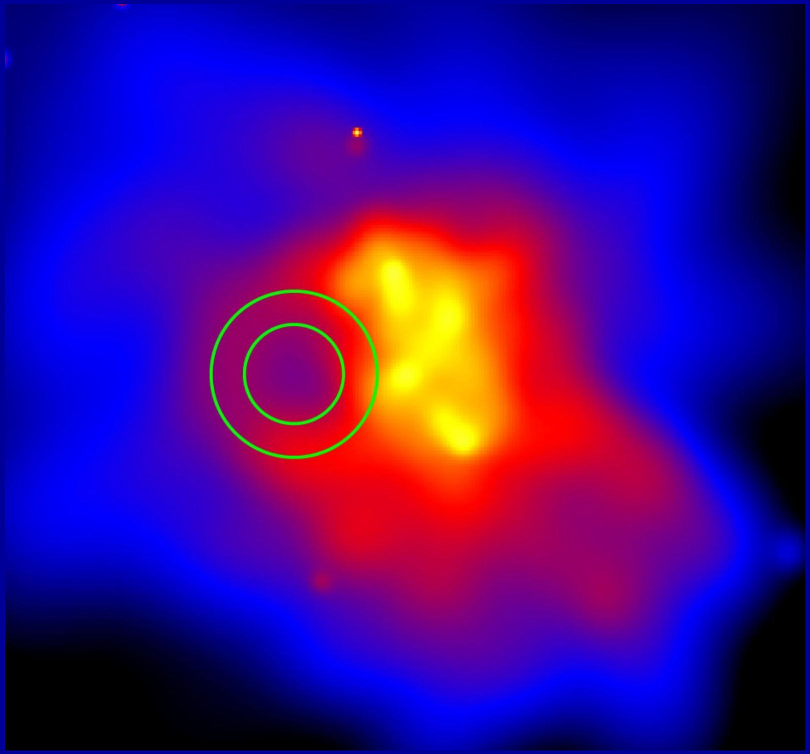
Radio (Parma et al. 1986) [NII] (Plana et al. 1998) Blanton et al. 2004

- 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 = 3 x 10^8 yr

Pressure in Shells

- In cool core 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)

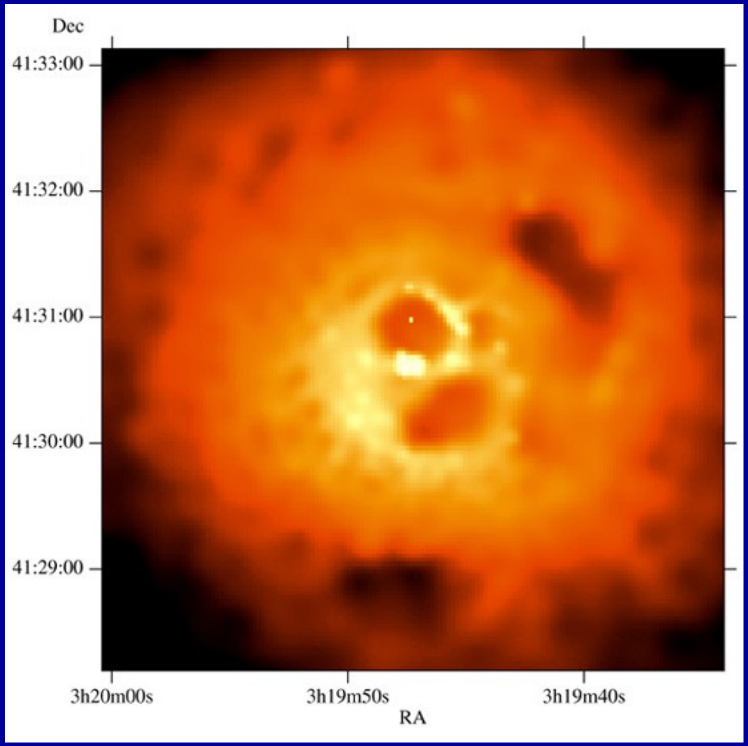


- Pressure in shell around radio source is 1.2 x 10^{-10} dyn/cm^2
- X-ray pressure is an order of magnitude higher than radio equipartition pressure of 2 x 10^{-11} dyn/cm^2 (Heckman et al. 1989)

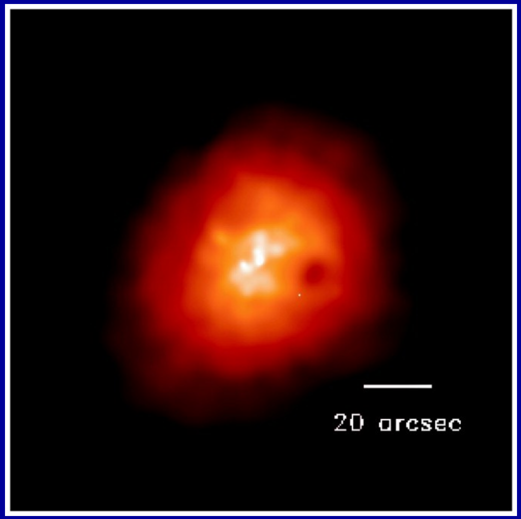
Pressure Difference: X-ray and Radio

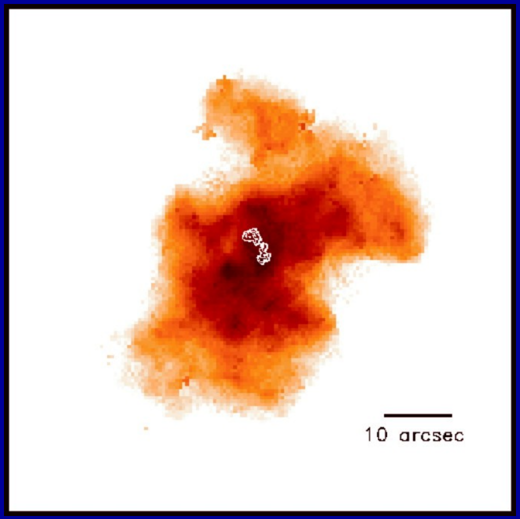
- Problems with equipartition assumptions.
- Possible additional contributions in holes from:
  - Magnetic fields
  - Low energy, relativistic electrons
  - Very hot, diffuse, thermal gas (limited to > 15 keV [Hydra A, Nulsen et al. 2002], 11 keV [Perseus, Schmidt et al. 2002], 20 keV [A2052, Blanton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

Transportation of Energy to ICM: Buoyant Bubbles



Perseus, Fabian et al. 2000

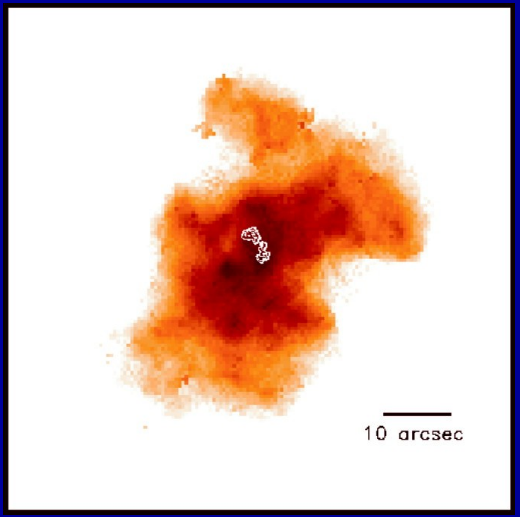




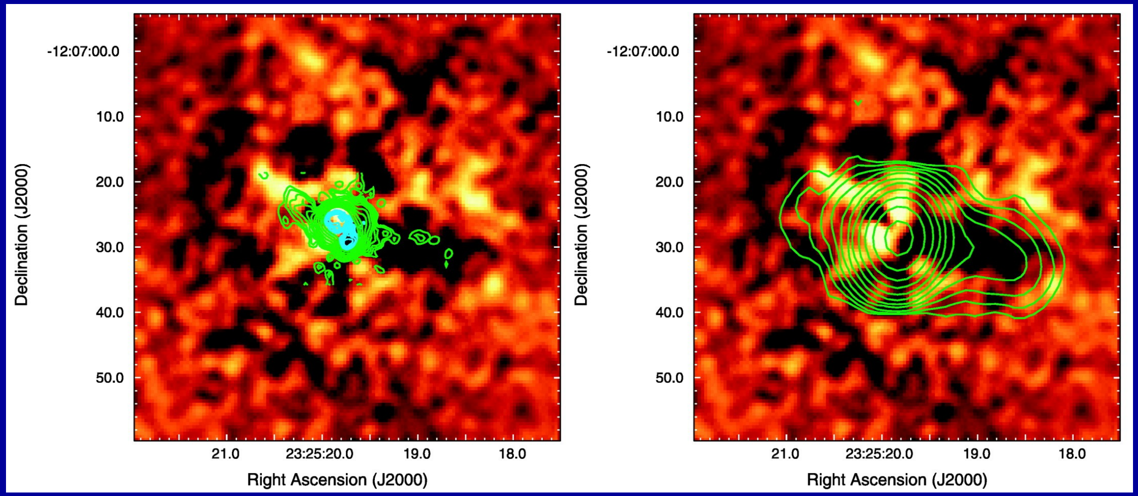
A2597, McNamara et al. 2001

The density inside the radio cavities is much lower than the ambient gas, so the holes should be buoyant, and can create “ghost cavities.” These rising bubbles transport energy and magnetic fields.

Ghost Cavities / Low-freq Radio



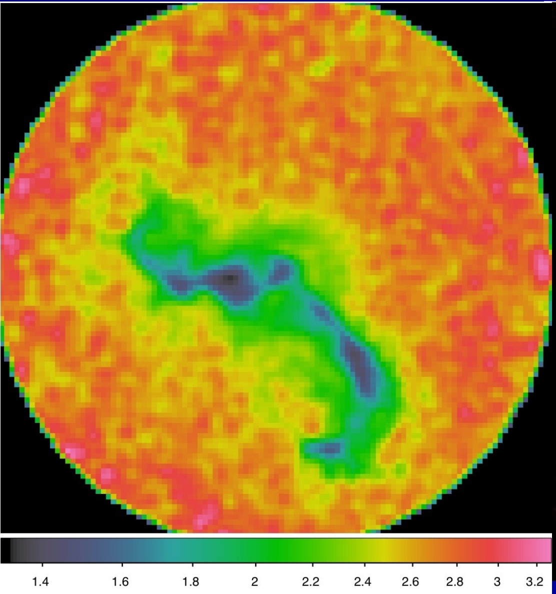
A2597, McNamara et al. 2001



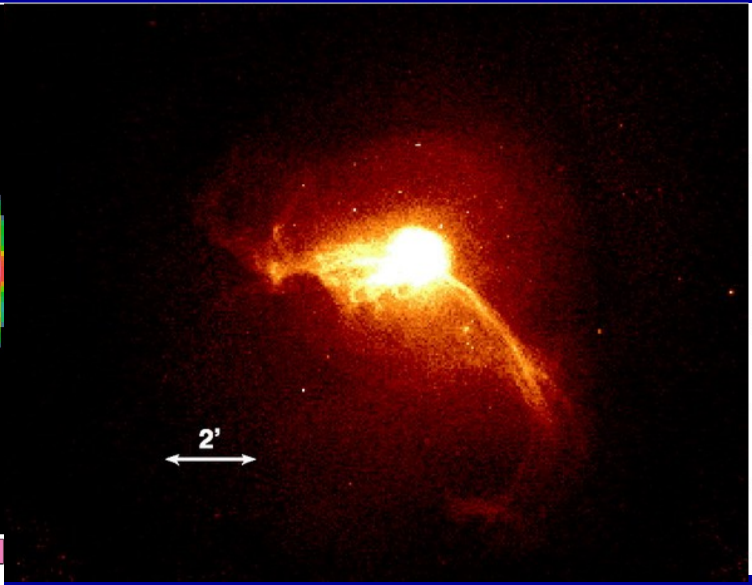
A2597, Clarke et al. 2005
Left: 5 GHz, cyan, 1.3 GHz green Right: 330 MHz

- Low frequency radio emission extends into the ghost cavities. This supports the idea that these cavities were formed earlier in the life of the radio source.

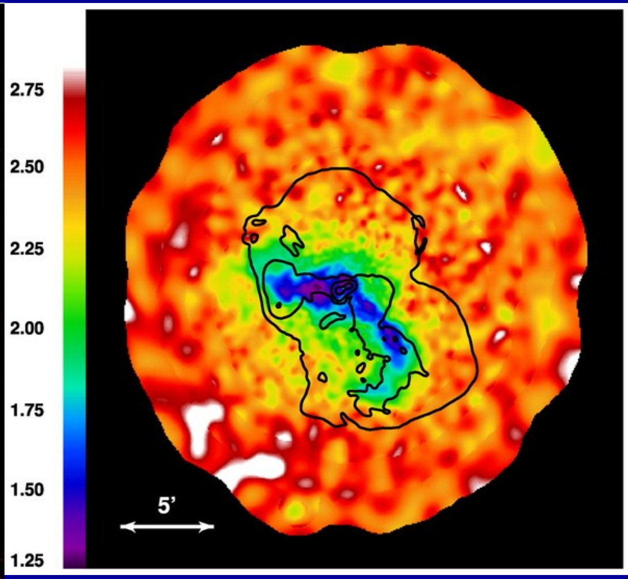
Entrainment of Cool Gas



Chandra Tmap
S. Randall (priv. comm.)



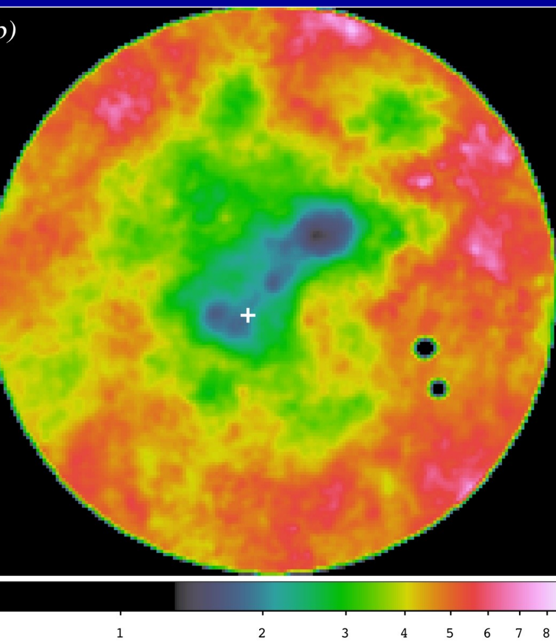
M87/Virgo
Forman et al. 2007

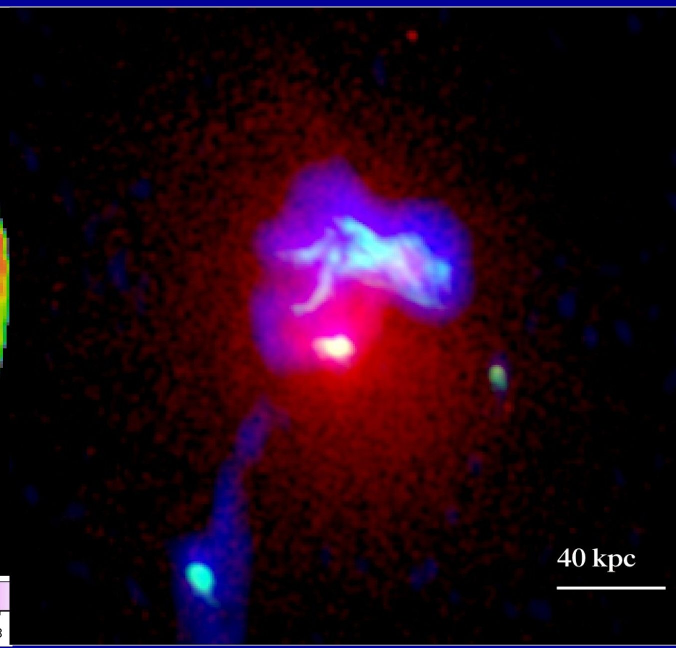


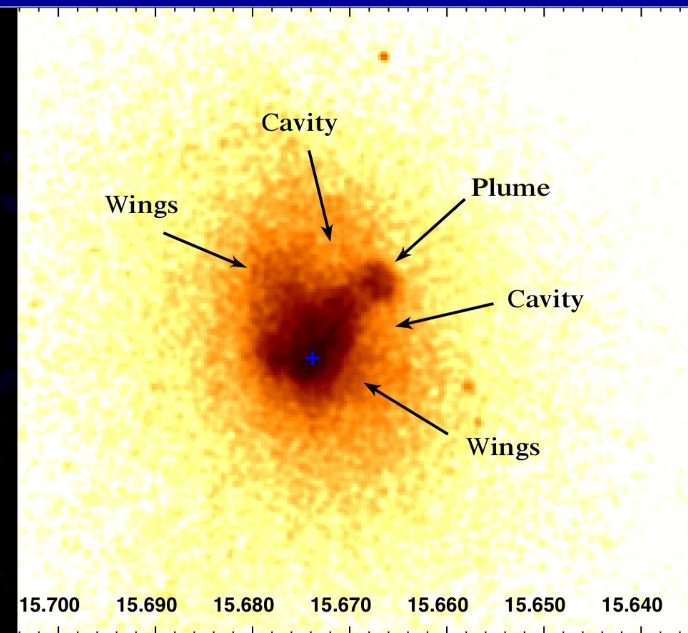
XMM-Newton Tmap
Forman et al. 2005

- Arc of cool gas follows radio lobes - consistent with it originating in cluster center (Young et al. 2002, Belsole et al. 2001, Molendi 2002, Forman et al. 2005).

Entrainment of Cool Gas



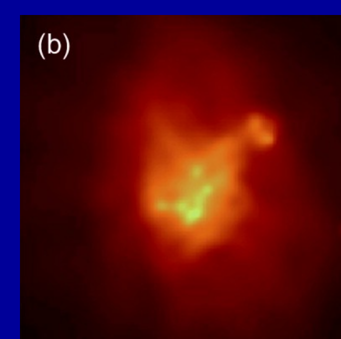




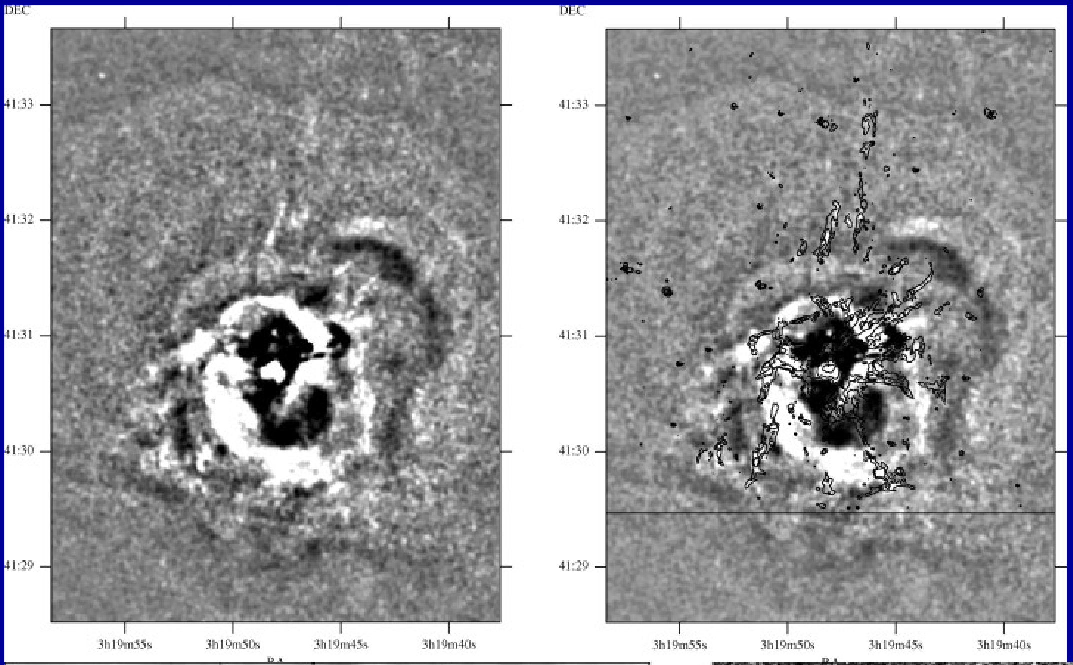
A133

Randall et al. (in prep)

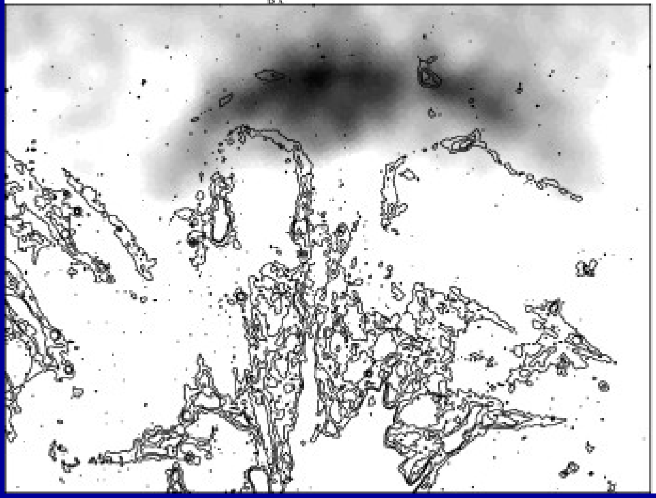
See also Fujita et al. (2002)



Entrainment of Cool Gas



- Perseus cluster, Fabian et al. (2003)
- Unsharp-masked Chandra image and H-alpha contours



X-ray/H-alpha (left)
Air bubble in water (right)
(Fabian et al. 2003)

X-ray Shells as Radio Calorimeters

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

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

Internal bubble energy

Work to expand bubble

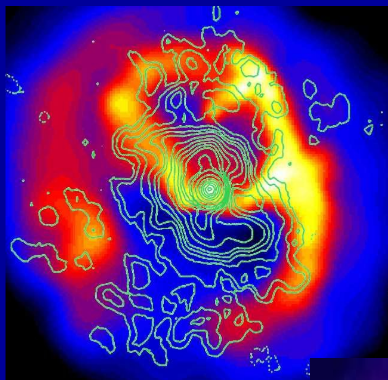
- Repetition rate of radio sources ~ 10^7 - 10^8 yr (from buoyancy rise time of ghost cavities)

Can Radio Sources Offset Cooling?

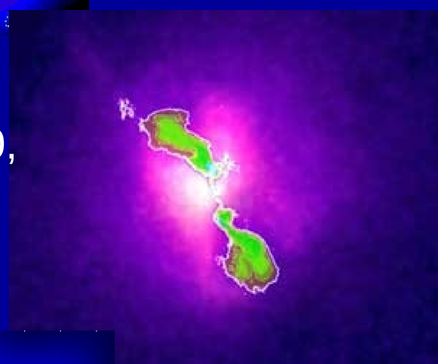
- Assuming X-ray shell and radio bubble are in pressure equilibrium, the total energy output of the radio source, including the work done on compressing the gas is E ~ 5/2 PV (with $\gamma = 5/3$) or 4 PV (with $\gamma = 4/3$) .
- Compare with luminosity of cooling gas

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

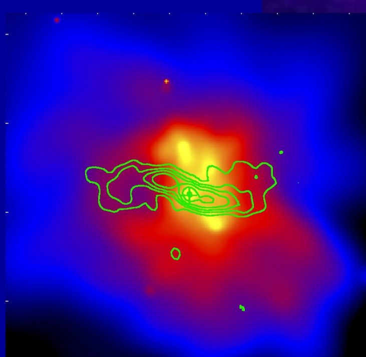
Examples



Blanton et al. 2001,3,9



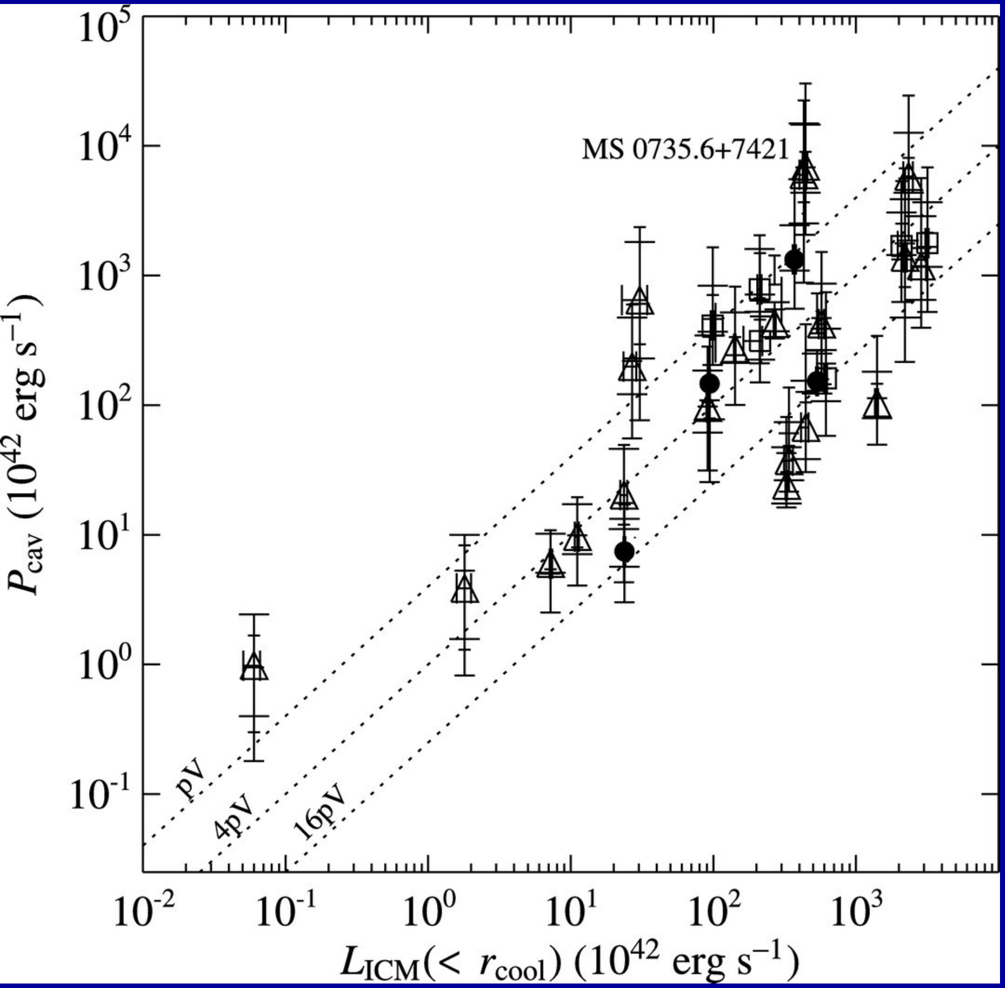
McNamara et al. 2000, David et al. 2001, Nulsen et al. 2002



Blanton et al. 2004

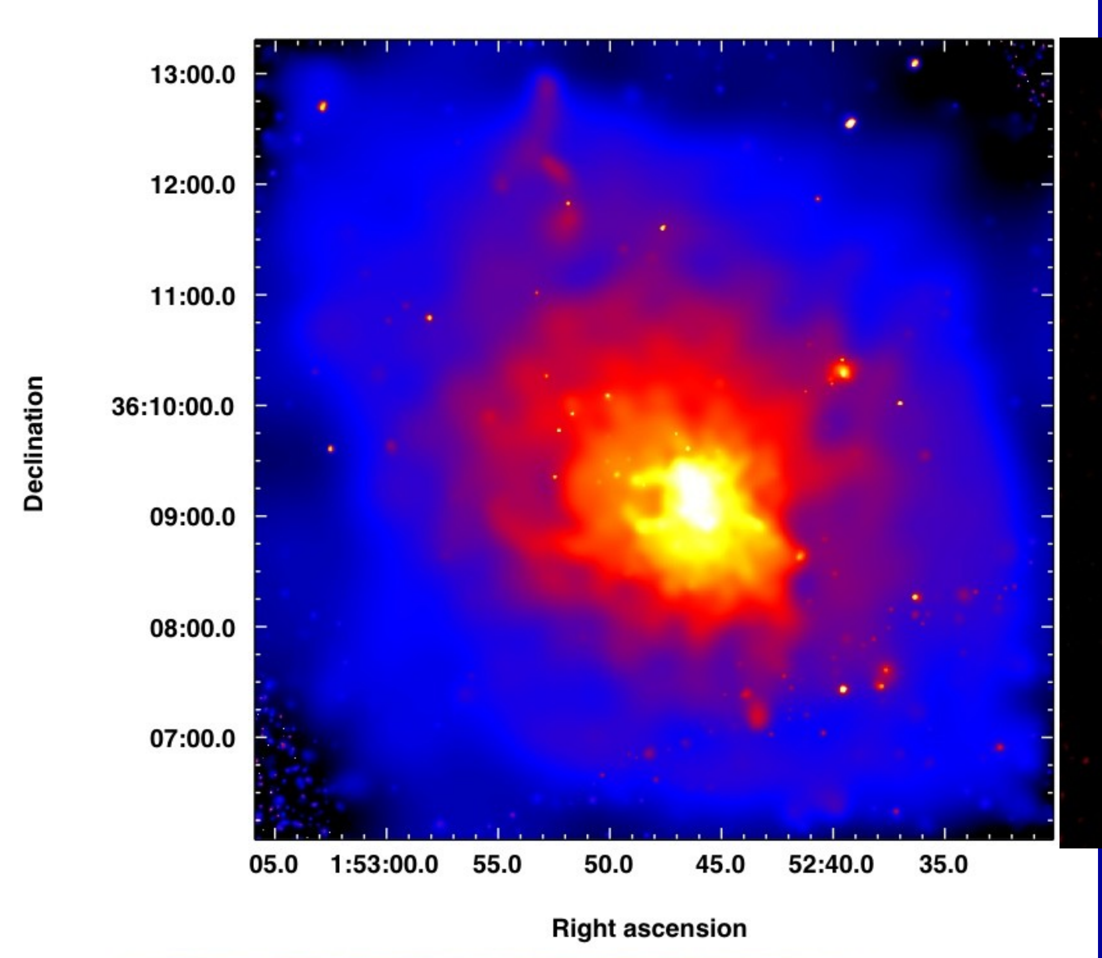
- A2052: $E = 10^{59}$ erg
  $E/t = 3 \times 10^{43}$ erg/s
  kT = 3 keV, Mdot=42 $M_{\odot}$/yr
  $L_{cool} = 3 \times 10^{43}$ erg/s ✔
- Hydra A: $E = 8 \times 10^{59}$ erg
  $E/t = 2.7 \times 10^{44}$ erg/s
  kT = 3.4 keV,Mdot=300 $M_{\odot}$/yr

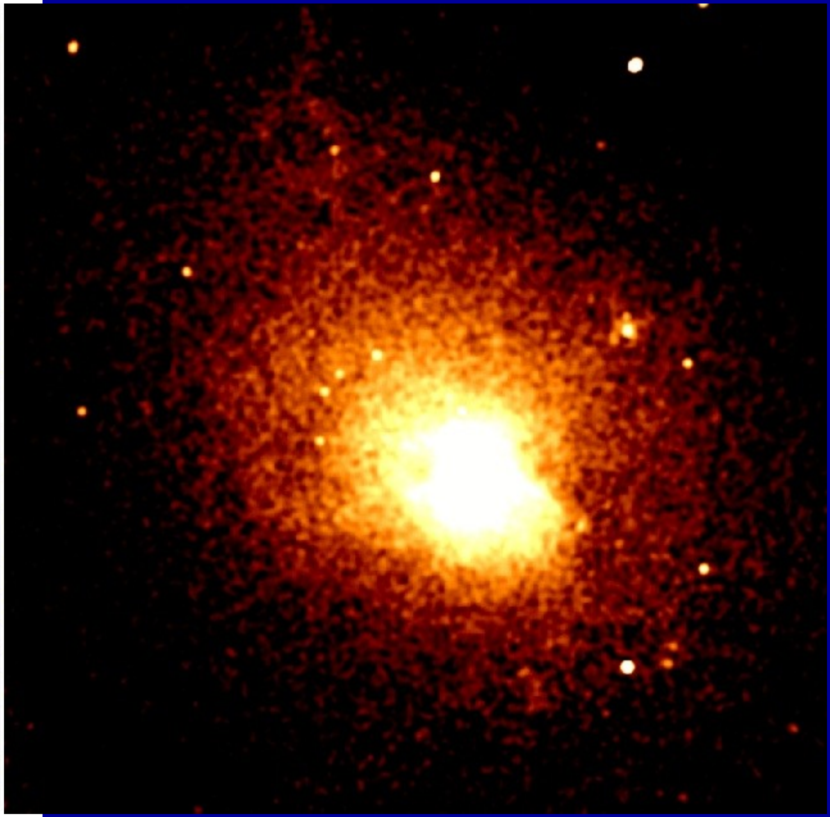
  $L_{cool} = 3 \times 10^{44}$ erg/s ✔
- A262: $E = 1.3 \times 10^{57}$ erg
  $E/t = 4.1 \times 10^{41}$ erg/s
  kT = 2.1 keV, Mdot=10 $M_{\odot}$/yr
  $L_{cool} = 5.3 \times 10^{42}$ erg/s ✘
  (much less powerful radio source)



- Cavity power vs. cooling luminosity for 33 systems (Rafferty et al. 2006)
- Most cooling flows can be balanced by AGN

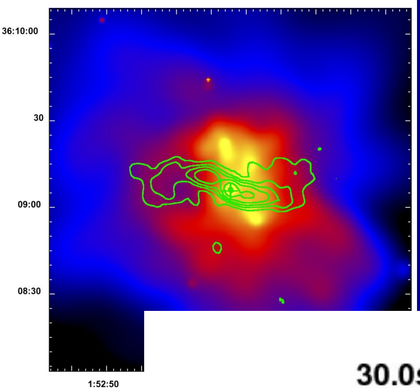
A262 Update

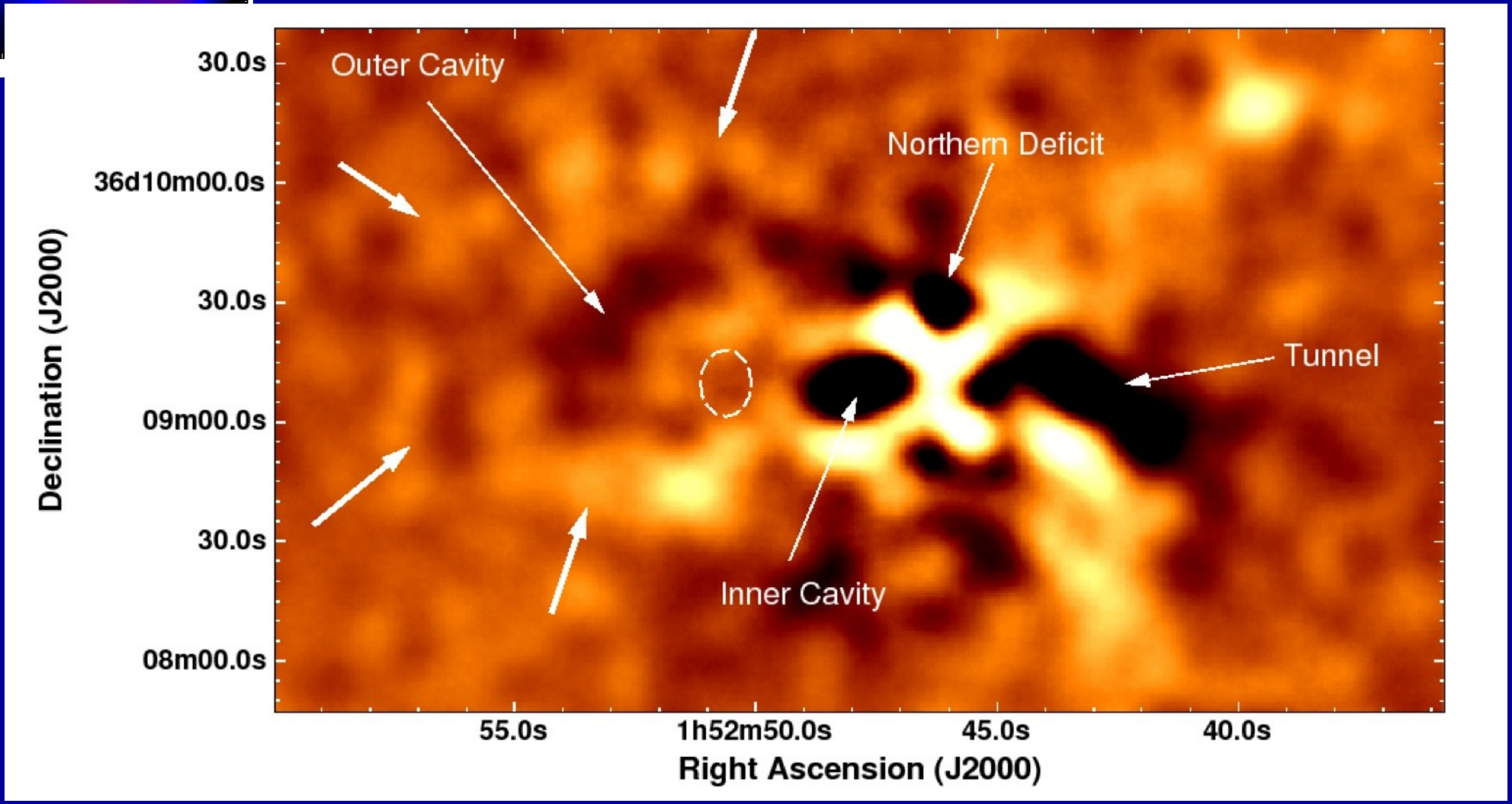




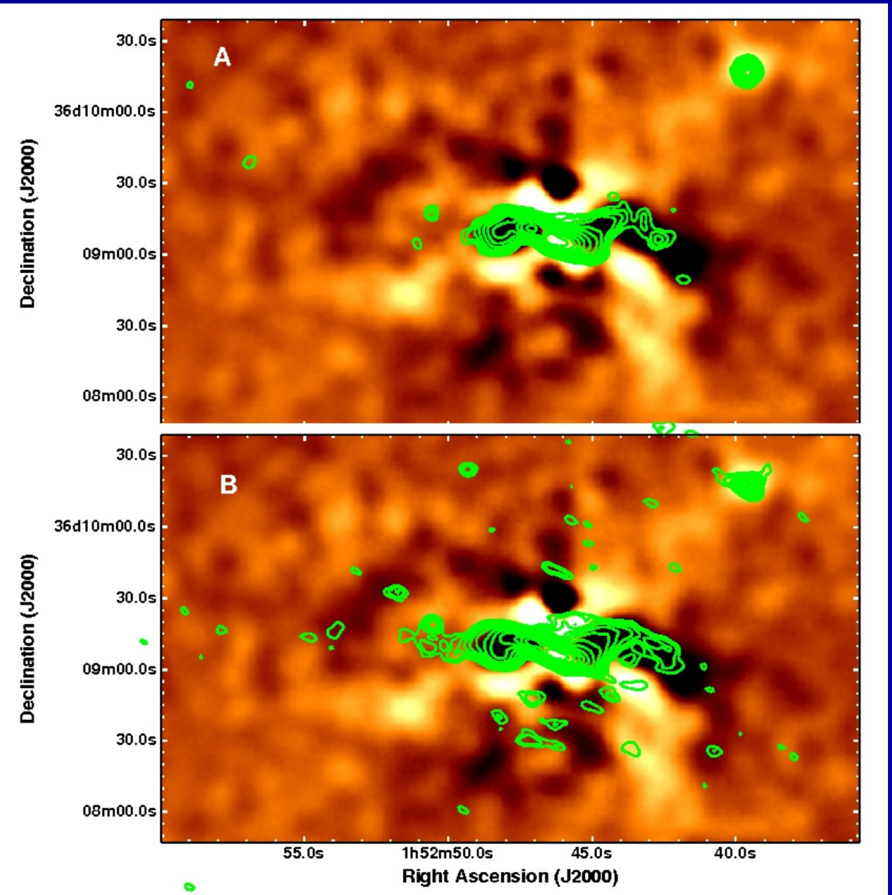
139 ksec new Chandra ACIS-S data
Blanton et al. (in prep)

A262 Update

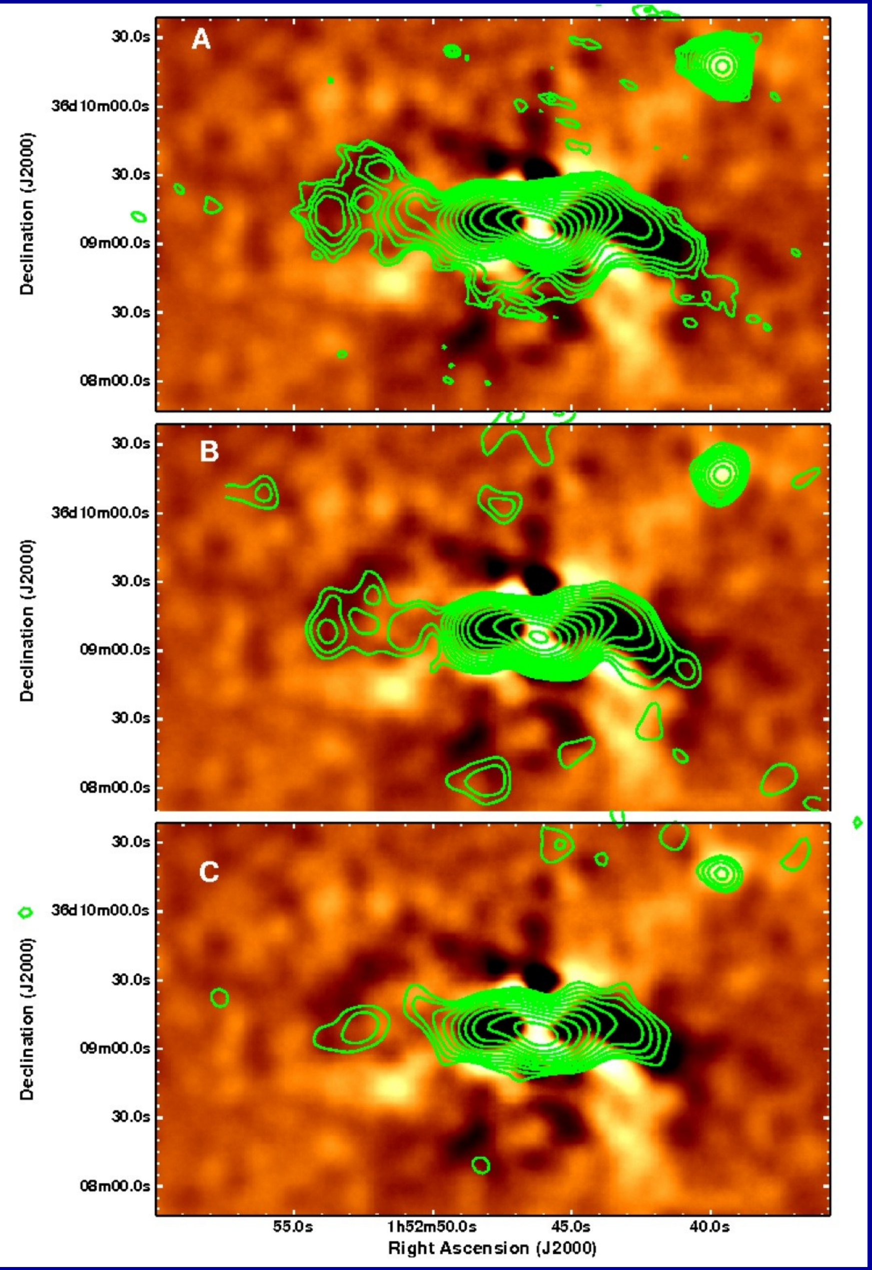




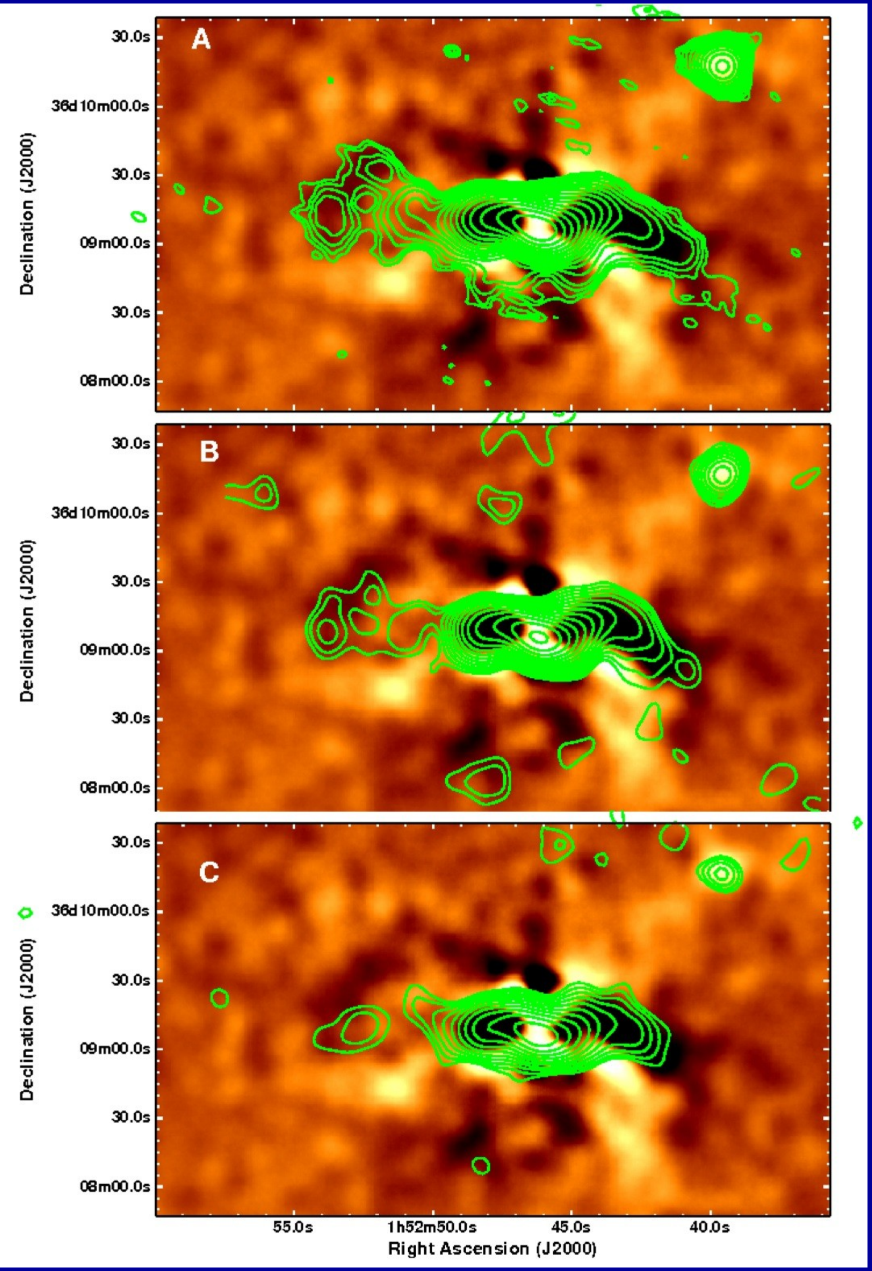
- Subtracting an elliptical model from the X-ray emission from A262 reveals a tunnel to the W and multiple outer cavities to the E (Clarke, Blanton, et al. 2009); Chandra ACIS-S, 139 ksec



- Lower frequency radio emission fills the tunnel and outer cavities.
- Top to bottom:
  1400 MHz (VLA)
  610 MHz (GMRT)

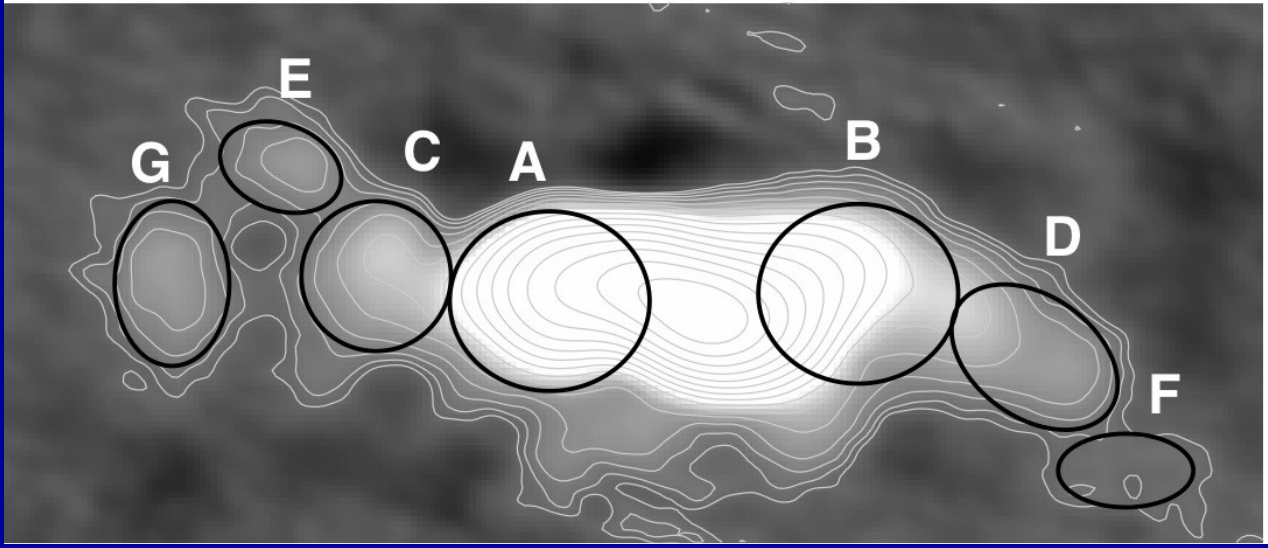


- Lower frequency radio emission fills the tunnel and outer cavities.
- Top to bottom: 610 MHz (GMRT) 330 MHz (VLA) 235 MHz (GMRT)
- Total extent of the radio source is ~60 kpc, more than 3 times larger than previously measured
- Inner E bubble radius ~5 kpc



- Separation of the bubbles gives a cycle time of $t \sim 3 \times 10^7$ yr
- The radio source can offset the cooling, on average, over several outburst episodes

	a kpc	b kpc	E 10^{56} erg
A	5.6	5.0	82
B	5.6	5.0	68
C	4.2	4.2	25
D	5.1	3.4	20
E	3.5	2.4	6
F	3.8	2.0	5
G	4.6	3.2	13



- Separation of the bubbles gives a cycle time of t ~ 3×10^7 yr
- The radio source can approximately offset the cooling, on average, over several outburst episodes (within factor 2)
- Total energy input is 2×10^{58} erg

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CHANDRA OBSERVATION OF THE CENTRAL REGION OF THE COOLING FLOW CLUSTER A262: A RADIO SOURCE THAT IS A SHADOW OF ITS FORMER SELF?

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ABSTRACT

We present a *Chandra* observation of the cooling flow cluster A262. Spectral fits show that the intracluster medium (ICM) in A262 cools by a factor of 3, from 2.7 to 0.9 keV, at the cluster center. A mass deposition rate of $\dot{M} = 19^{+6}_{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ is measured. Complex structure is found in the very inner regions of the cluster, including knots of emission and a clear deficit of emission to the east of the cluster center. The bright X-ray structures are located in the same regions as optical line emission, indicating that cooling to low temperatures has occurred in these regions. The X-ray deficit is spatially coincident with the eastern radio lobe associated with the active galactic nucleus hosted by the central cD galaxy. The region surrounding the X-ray hole is cool and shows no evidence that it has been strongly shocked. This joins the ranks of other cooling flow clusters with *Chandra*-detected bubbles blown by central radio sources. This source is different from the other well-known cases, in that the radio source is orders of magnitude less luminous and has produced a much smaller bubble. Comparing the energy output of the radio source with the luminosity of the cooling gas shows that energy transferred to the ICM from the radio source is insufficient to offset the cooling flow unless the radio source is currently experiencing a less powerful than average outburst and was more powerful in the past.

Subject headings: cooling flows — galaxies: clusters: general — galaxies: clusters: individual (A262) — intergalactic medium — radio continuum: galaxies — X-rays: galaxies: clusters

1. INTRODUCTION

Recent X-ray observations from the *Chandra* and *XMM-Newton* observatories have shed much light on the physical state of the intracluster medium (ICM) in clusters of galaxies. Gas is predicted to cool first in the dense centers of clusters of galaxies, since the cooling time varies as $t_{\mathrm{cool}} \propto T^{1/2}/n_e$, where T is the gas temperature and n_e is the electron number

(McNamara et al. 2000; Johnstone et al. 2002; Blanton et al. 2001, 2003). In addition, the mass deposition rates measured with both *XMM-Newton* and *Chandra* are lower than the rates found with the earlier observatories. Various scenarios have been proposed to explain the new results, including thermal conduction, inhomogeneous abundances, mixing, and heating of the cooling ICM by a central radio source (see Fabian et al.

the center of the cluster, and it was then pushed outward by the radio source.

6.1. *Energy Injection into the ICM*

One of the most promising solutions to the "cooling flow problem" (sufficient quantities of gas are not found at sufficiently low temperatures, as based on expectations from X-ray data) is that energy input from an AGN hosted by a central cluster galaxy can offset the cooling. Even without knowing the details of the mechanism by which this energy is transferred to the ICM, we can test whether the energy output from the radio-emitting AGN is adequate to balance the cooling losses. This has been found to be the case in other objects, such as Hydra A (David et al. 2001) and A2052 (Blanton et al. 2003).

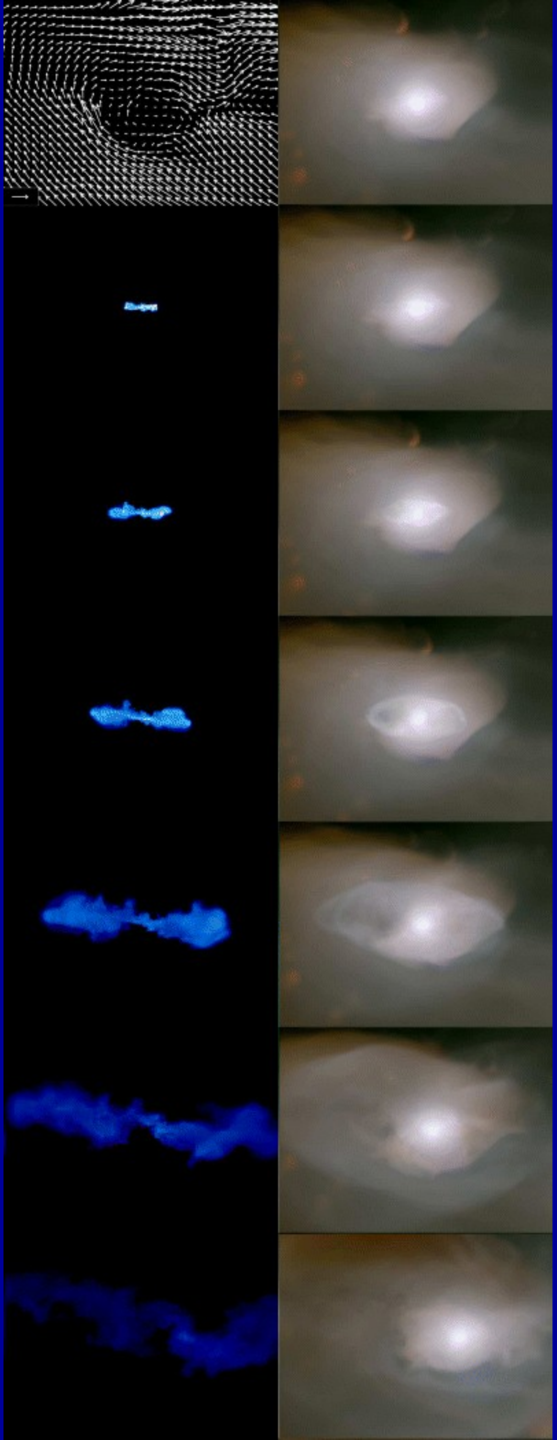
The luminosity of isobaric cooling gas is given by

$$L_{\rm cool} = \frac{5}{2}\frac{kT}{\mu m_p}\dot{M}, \qquad (1)$$

where kT is the temperature of the ICM outside of the cooling region, $\dot{M}$ is the cooling rate, and μ is the mean mass per particle in units of the proton mass. Using $kT = 2.65$ keV and the mass deposition rate of 18.8 $M_\odot$ yr^{-1}, we find $L_{\rm cool} = 1.3 \times 10^{43}$ ergs s^{-1}. We used the mass deposition rate found in the spectral fit in which the low-temperature component was allowed to vary. This represents gas cooling from 2.65 to

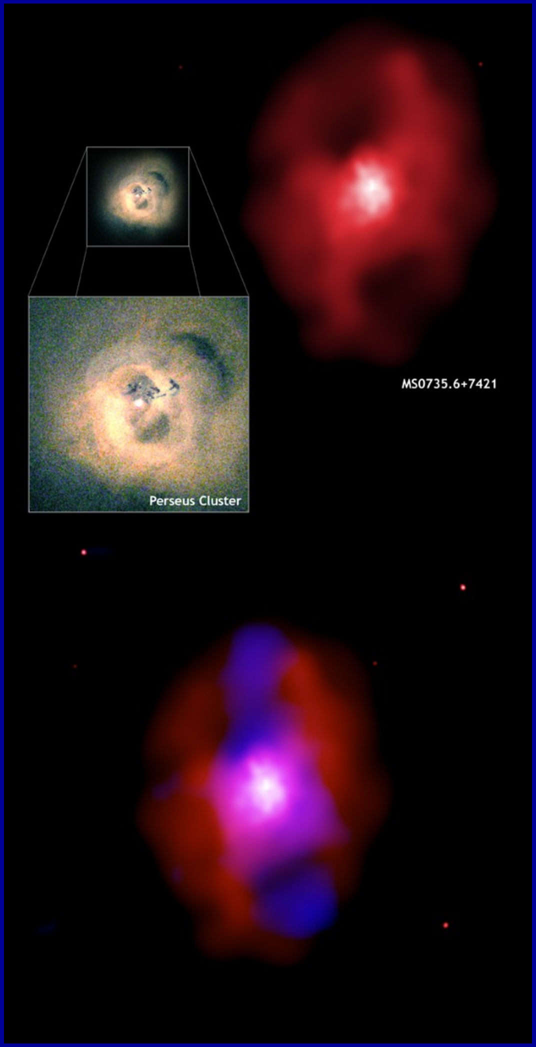
falls more than an order of magnitude short of the necessary average energy output rate required to offset the luminosity of cooling gas in A262. This result is different from that for other well-studied cases, such as Hydra A and A2052, where $E_{\rm rad}$ is sufficient to balance cooling. Although the X-ray gas pressures in the centers of all three clusters are similar, the bubble volumes are much greater in A2052 and Hydra A (bubble diameters of ≈20 kpc) than in A262 (bubble diameter of ≈5 kpc). In addition, the observed radio powers in the other objects are much higher (by orders of magnitude) than in A262. It may be that some mechanism (e.g., thermal conduction) balances radiative cooling in A262 other than heating by the radio source. Alternatively, it is possible that the radio source in A262 is experiencing a less powerful than average outburst and that previous outbursts were more powerful, allowing the radio source to balance the cooling losses on average. Another possibility is that the repetition rate is higher for this radio source than for others—a repetition rate of 6×10^6 yr ($\gamma = 5/3$) or 1×10^7 yr ($\gamma = 4/3$), rather than the assumed 10^8 yr, would be required. The problem with a rapid repetition rate is that, if the axis of the jets remains fixed, this might simply add to the observed energy content of the present radio bubble. The required repetition time is shorter than the synchrotron lifetime of the radio source of 3.5×10^7 yr, so repeated injections into the same bubble would just add to the observed radio emission. If the buoyancy time of the bubbles were small enough, they might move away between outbursts. Taking the sound speed (500 km s^{-1}) as the upper limit of the

And volumes, using radio data, are larger than those estimated previously using the X-ray data alone.



- Simulations show the creation of shocks as well as cavities, Heinz et al. (2006)
- Time series snapshots at 10, 20, 40, 80, and 160 Myr after jet onset. Left panel = radio source, right panel = simulated X-ray image (450 x 335 kpc)

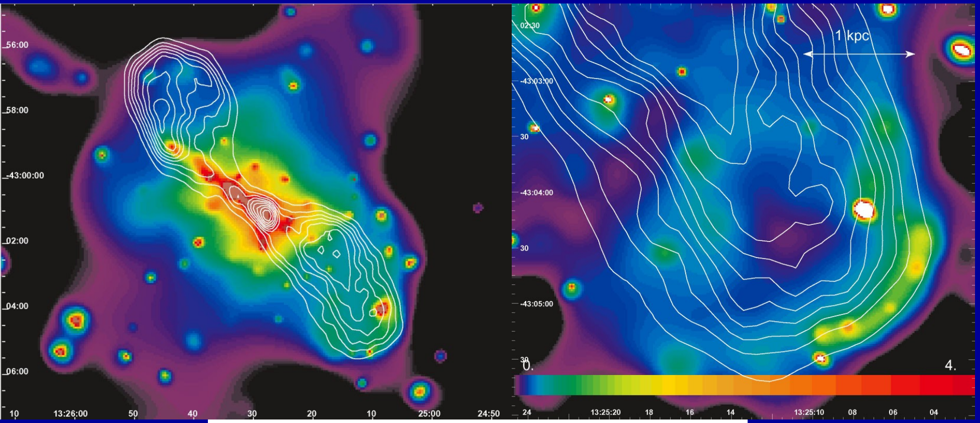
Evidence of Shock Heating

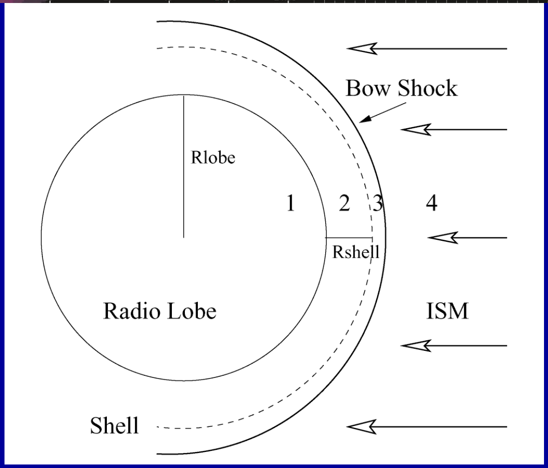


McNamara et al. 2005

- Now seen in a few cases
- MS0735.6+7321 – extremely large cavities (~200 kpc diam)
- Energy injection to inflate cavities and produce shocks ~ 6 x 10^{61} erg (most powerful radio outburst known)

Evidence of Shock Heating

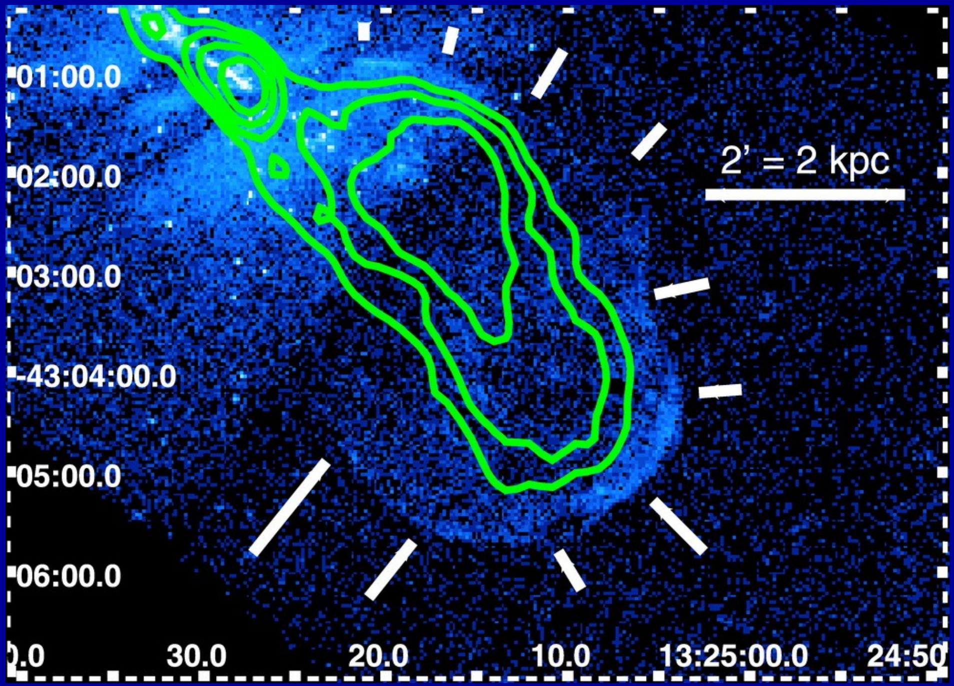




Kraft et al. 2003

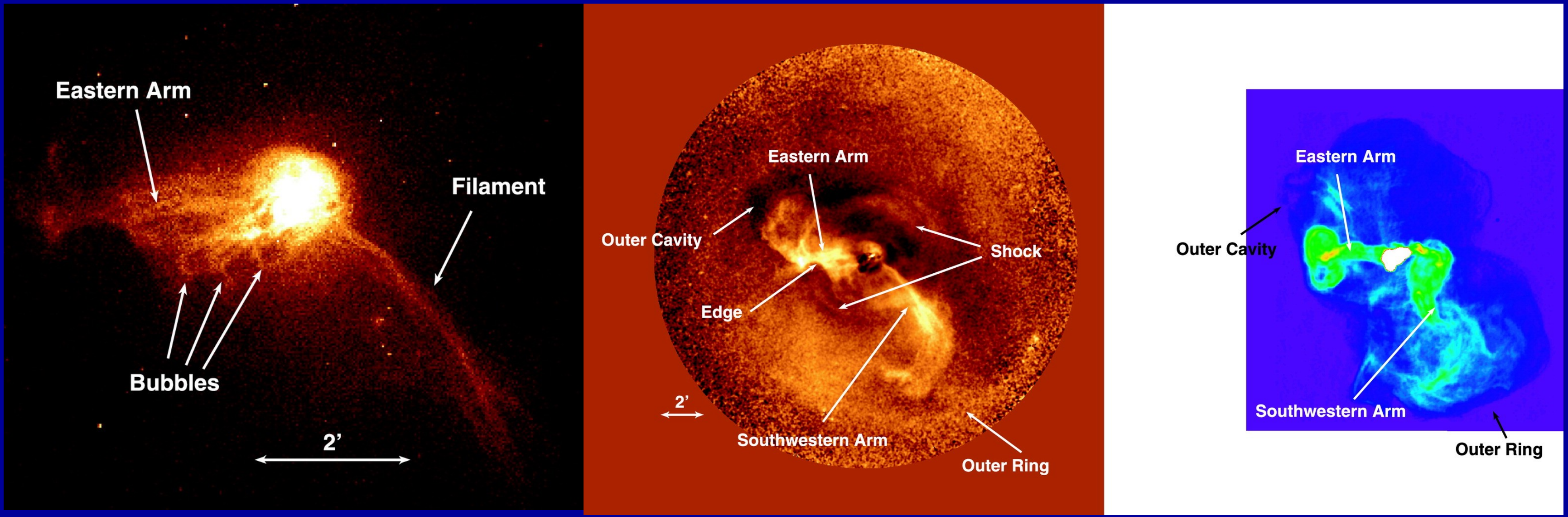
- Cen A galaxy, XMM-Newton
- Nearest active galaxy (3.4 Mpc)
- Double-lobed FR I source ($P=1.9\times10^{24}$ W/Hz)
- Shell/cap on SW lobe - hotter and over-pressured relative to ambient ISM
- Consistent with M = 8.5 shock
- Shock with ISM, not ICM, but clear connection with radio

Shock Heating



- Long Chandra observation reveals shock extending around 75% of the SE radio lobe in Cen A (Kraft et al. 2007)
- See Nulsen talk

Shock in M87

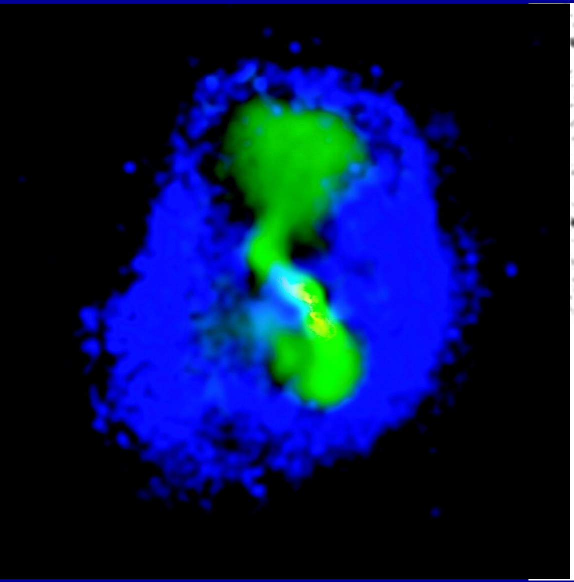


Deep (500 ksec) Chandra image of M87 (Forman et al. 2007). Filaments, bubbles, and a shock are revealed.

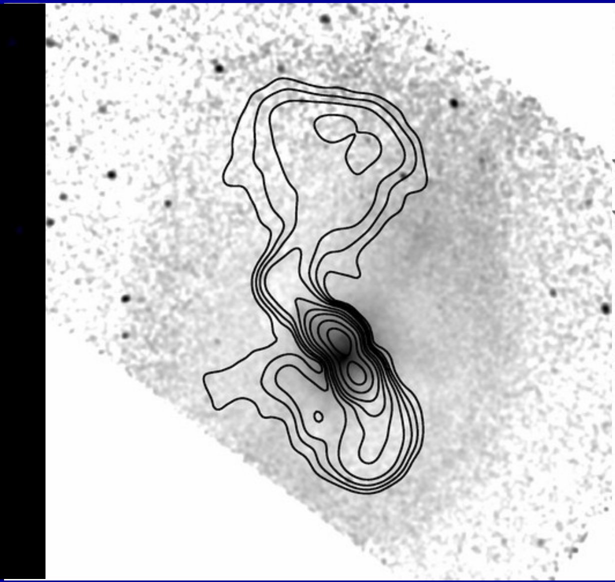
Shock in M87

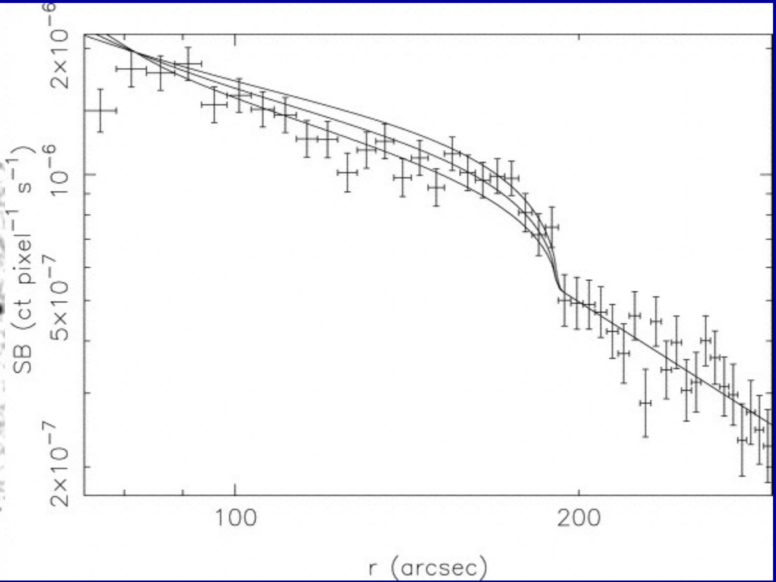
Hard-band (3.5-7.5 keV) image of M87 with point sources removed. The surface-brightness discontinuity is consistent with a weak shock with Mach ~ 1.2.

Shock in Hydra A



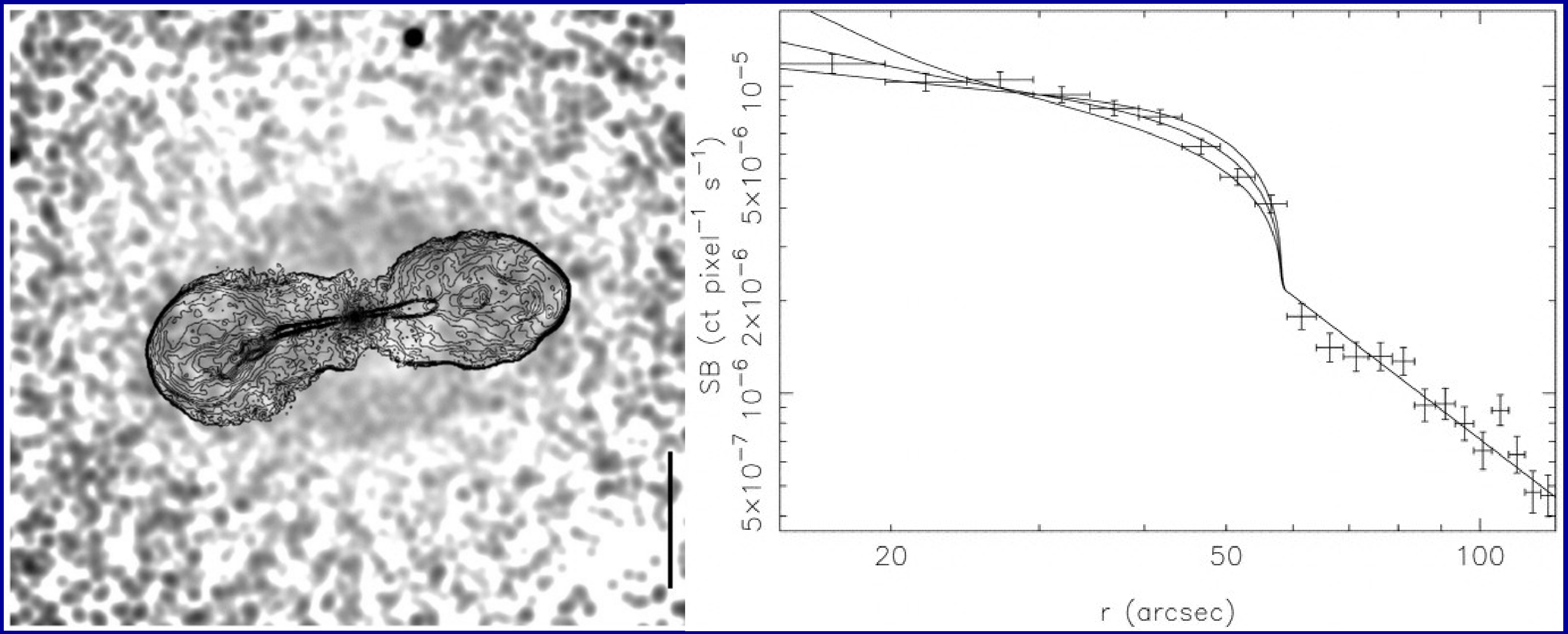
Wise et al. (2007)
Chandra, 227 ksec





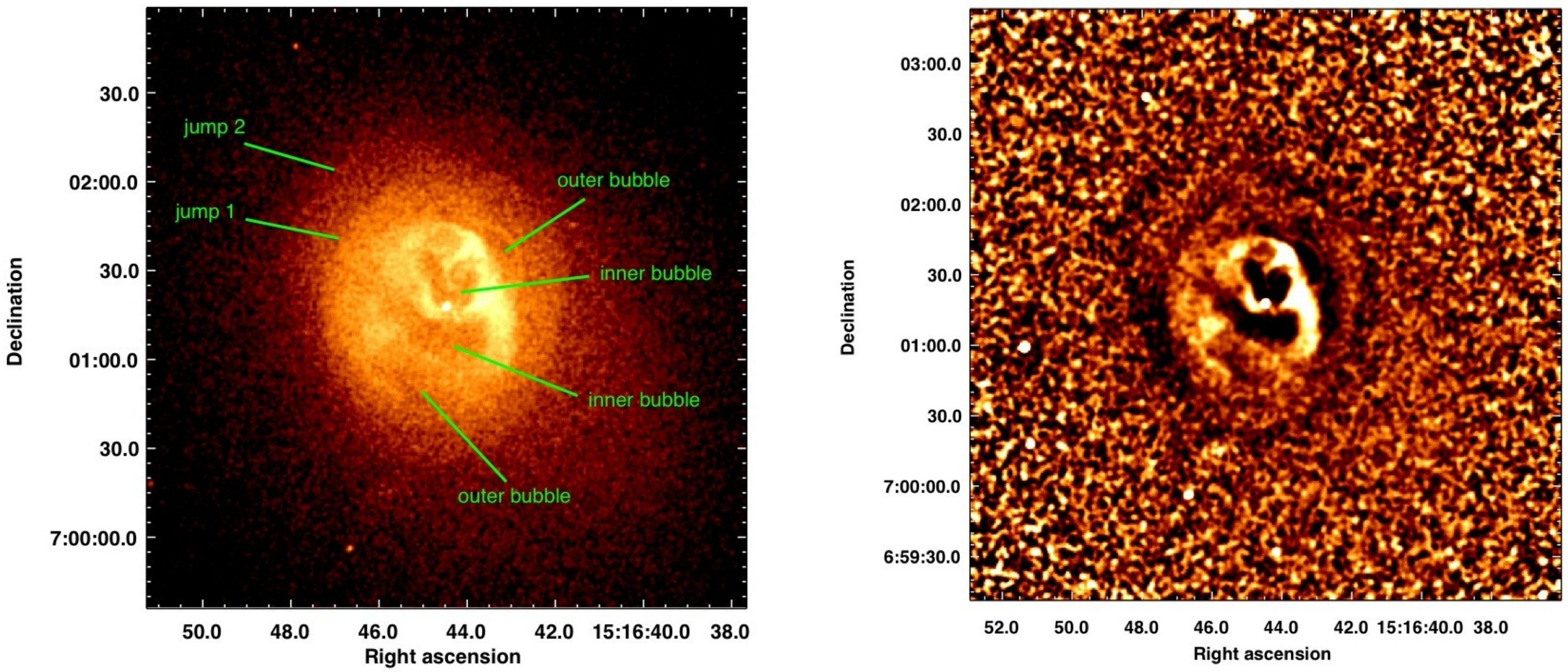
Nulsen et al. (2005). SB discontinuity consistent with weak shock with Mach = 1.34.

Shock in Hercules A



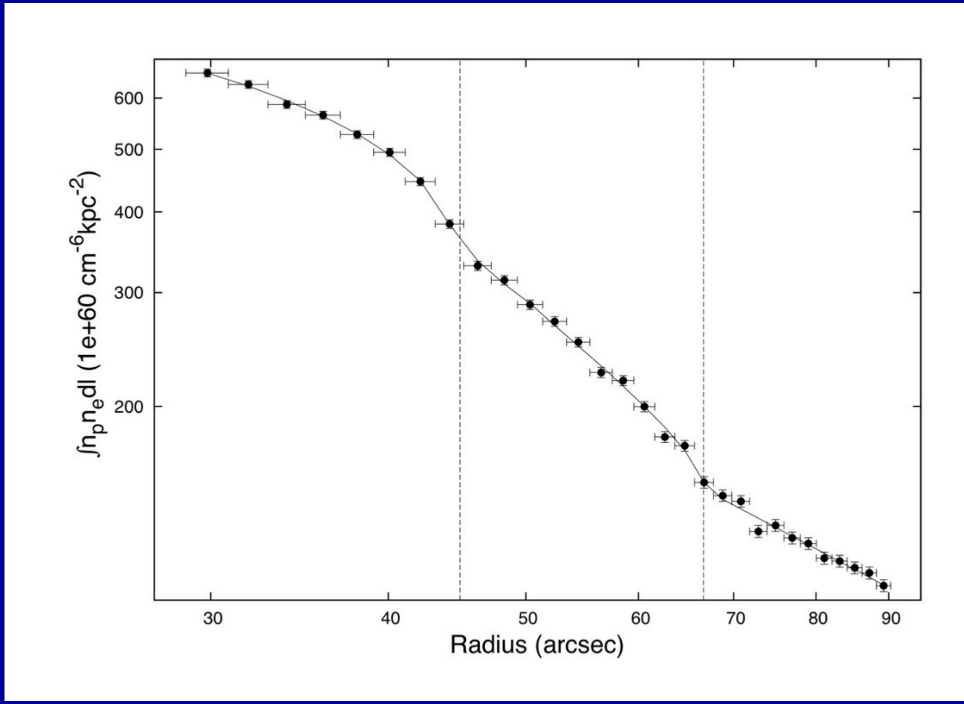
- Mach ~1.65, total energy deposited 3 x 10^{61} erg
- Nulsen et al. (2005)

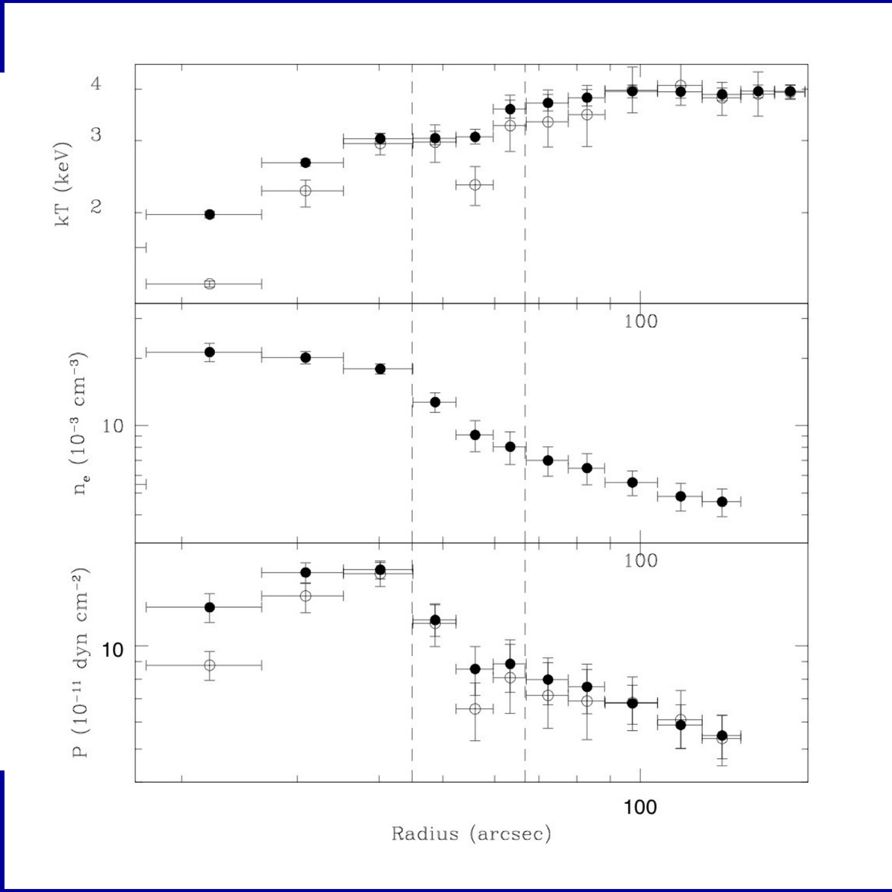
Abell 2052, Shock Heating



Blanton et al. (2009), 163 ksec Chandra ACIS-S

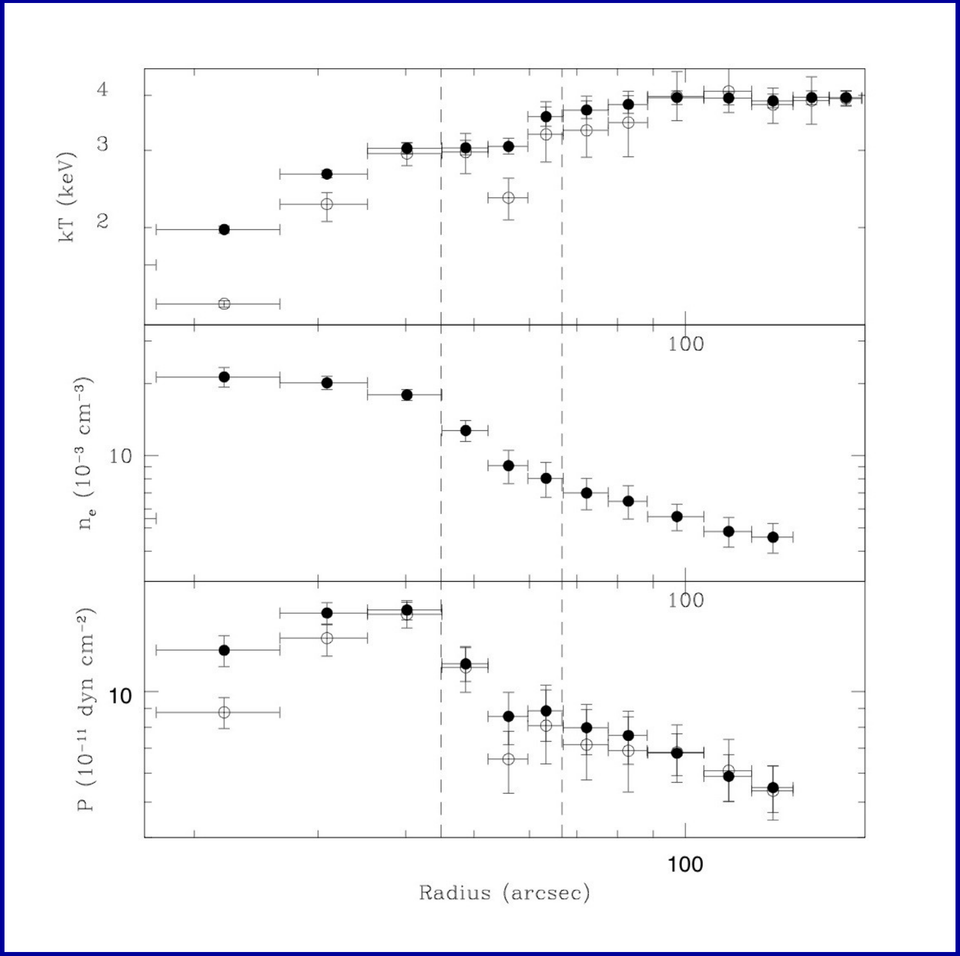
Abell 2052, Shock Heating





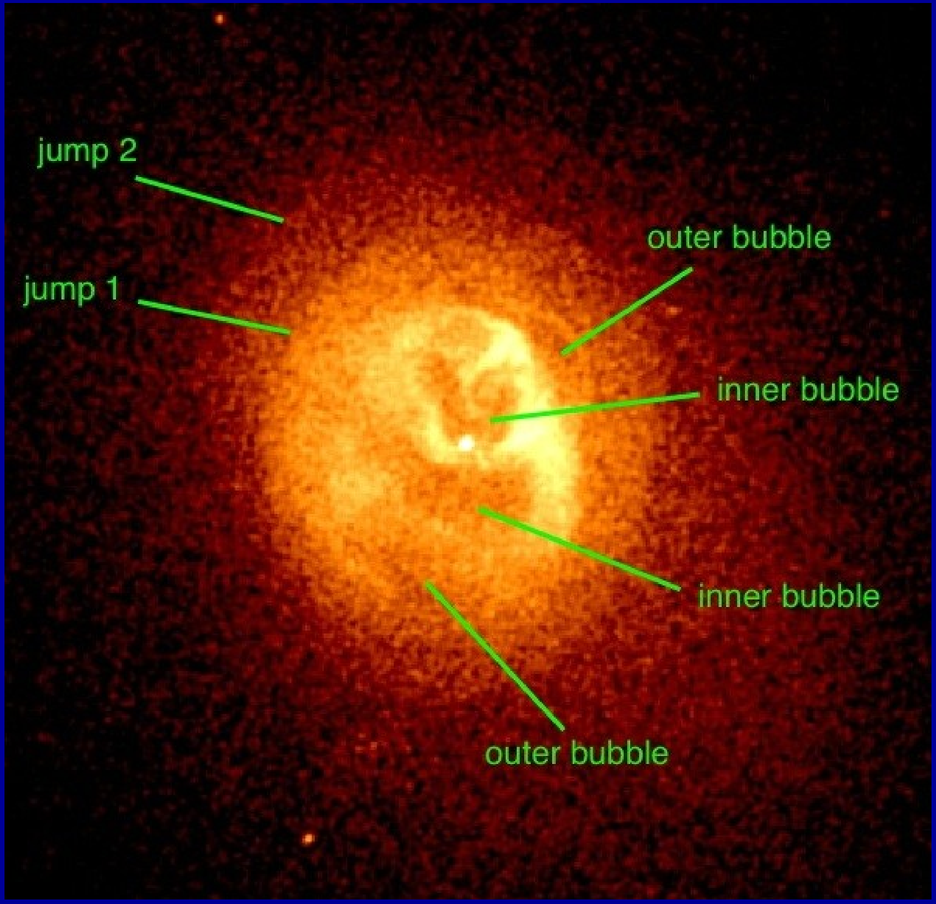
Both shocks (at 31 and 46 kpc from AGN) have Mach ~ 1.2.

Abell 2052, Shock Heating



- Best-fitting temperatures are approximately constant across the shock fronts, however the values are consistent, within the errors, with the T rise expected with shocks
- Other possibilities are isothermal shocks, where conduction is efficient, or cold fronts

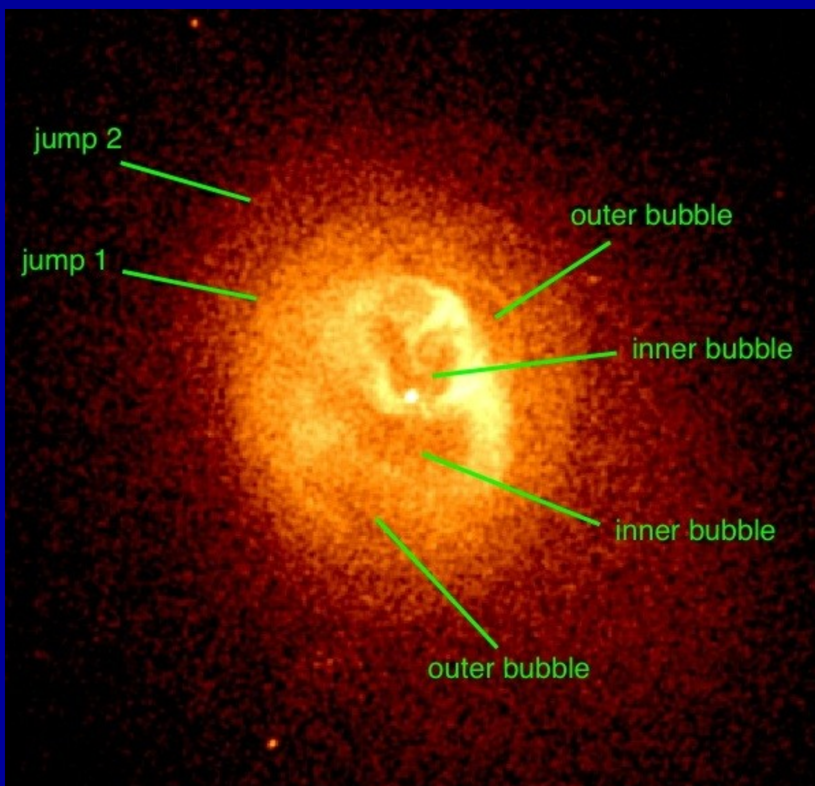
Repetition rate of AGN



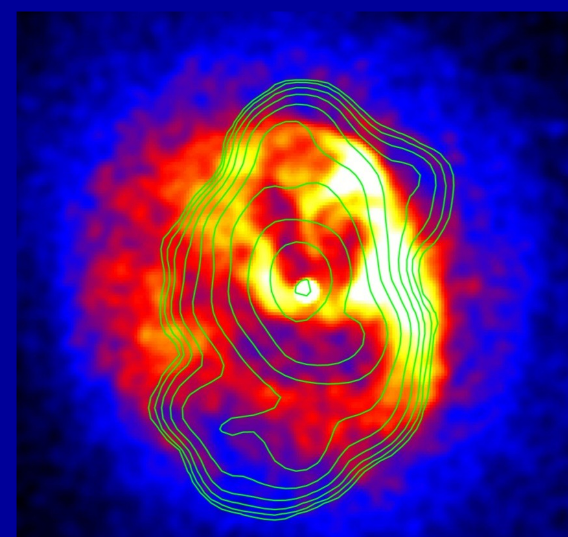
- Estimate cycle time (time between radio source outbursts) using shock velocities and offsets, or buoyantly rising bubbles.
- Both methods give $t \sim 2 \times 10^7$ yr.

Abell 2052: Bubble Energy Input

$$\frac{1}{(g-1)}PV + PdV = \frac{g}{(g-1)}PV$$



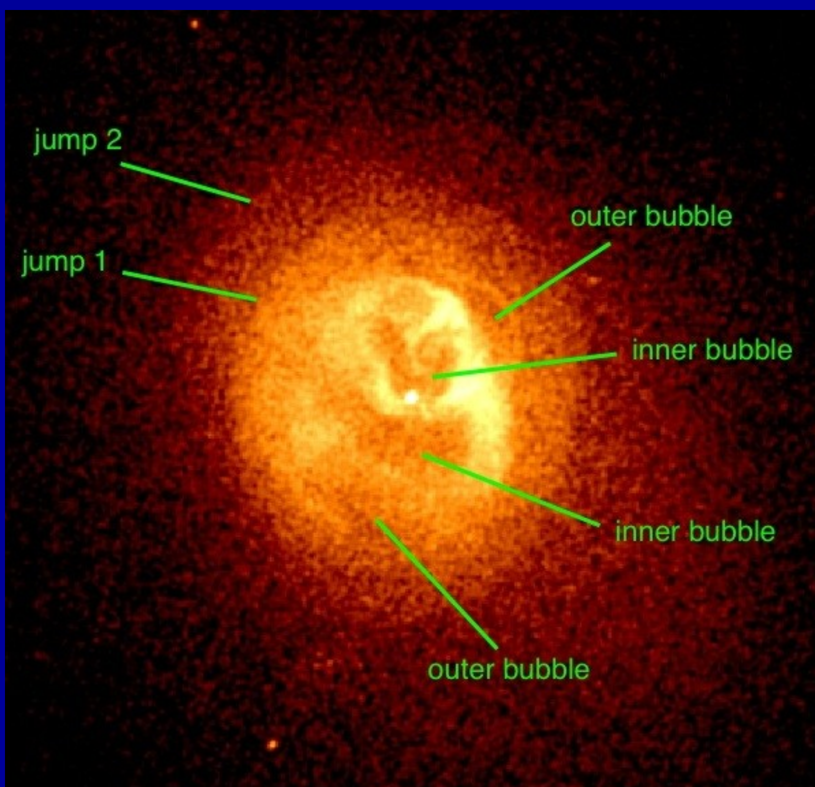
- Using γ=4/3, the energy input rate is 3.2 x 10^{43} erg s^{-1} (6.4 x 10^{43} erg s^{-1}) assuming the bubbles rose at 0.5 (1) times the sound speed



Abell 2052: Shock Energy Input

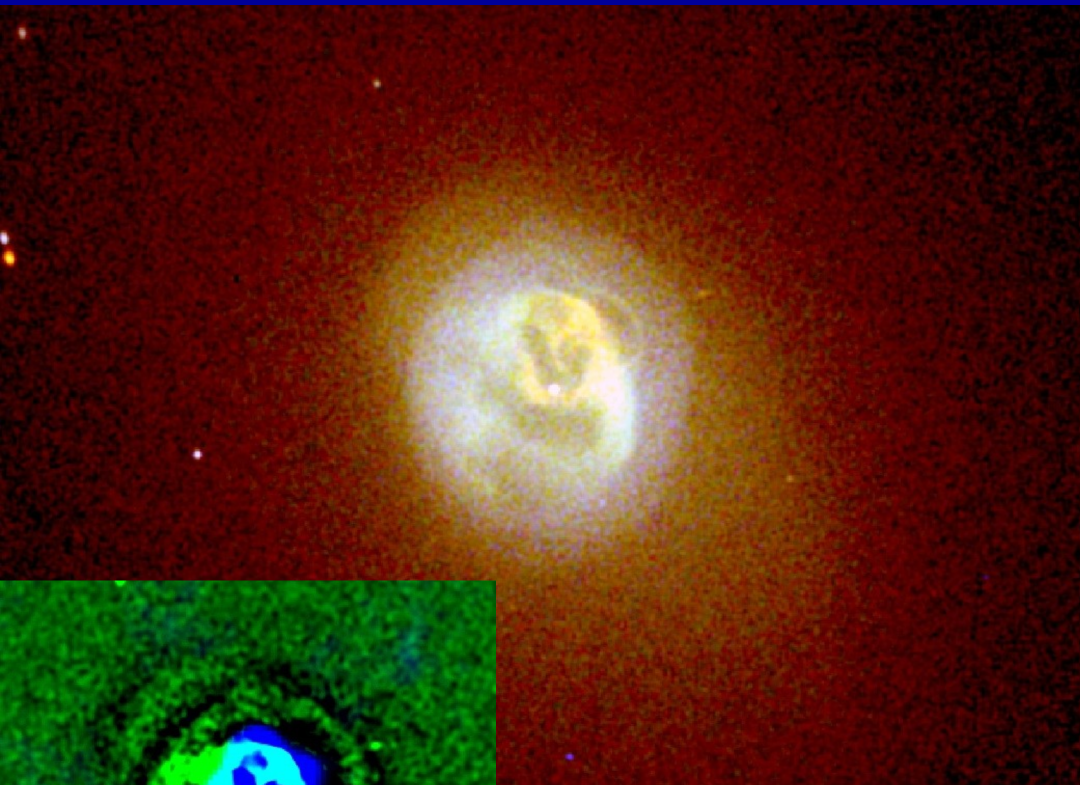
$$\Pi_s = \frac{(g+1)P}{12g^2}\left(\frac{w}{2p}\right)\left(\frac{dP}{P}\right)$$

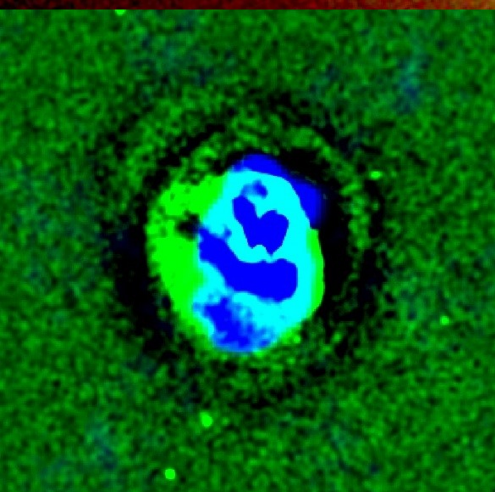
McNamara & Nulsen (2007)



- The shock energy input rate is 1 x 10^{43} erg s^{-1}, a factor of 3-6 lower than the energy input from buoyantly rising bubbles.
- The combination of rising bubble and shock heating offsets the cooling rate of 5.4 x 10^{43} erg s^{-1}

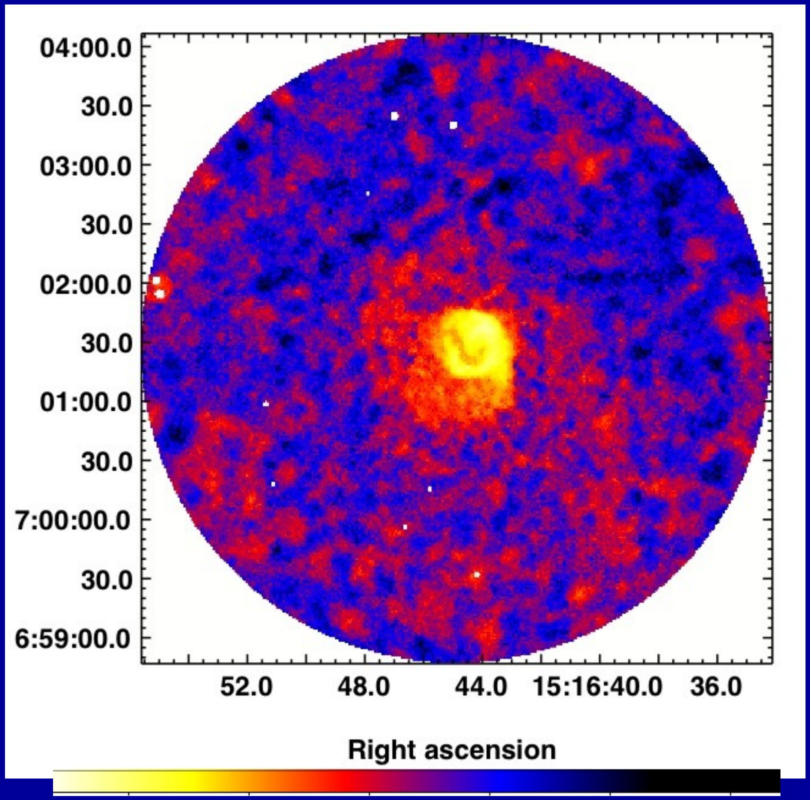
657 ksec, A2052





•Top: red=soft, green=med, blue=hard

•Left: unsharp-mask Chandra, radio overlay

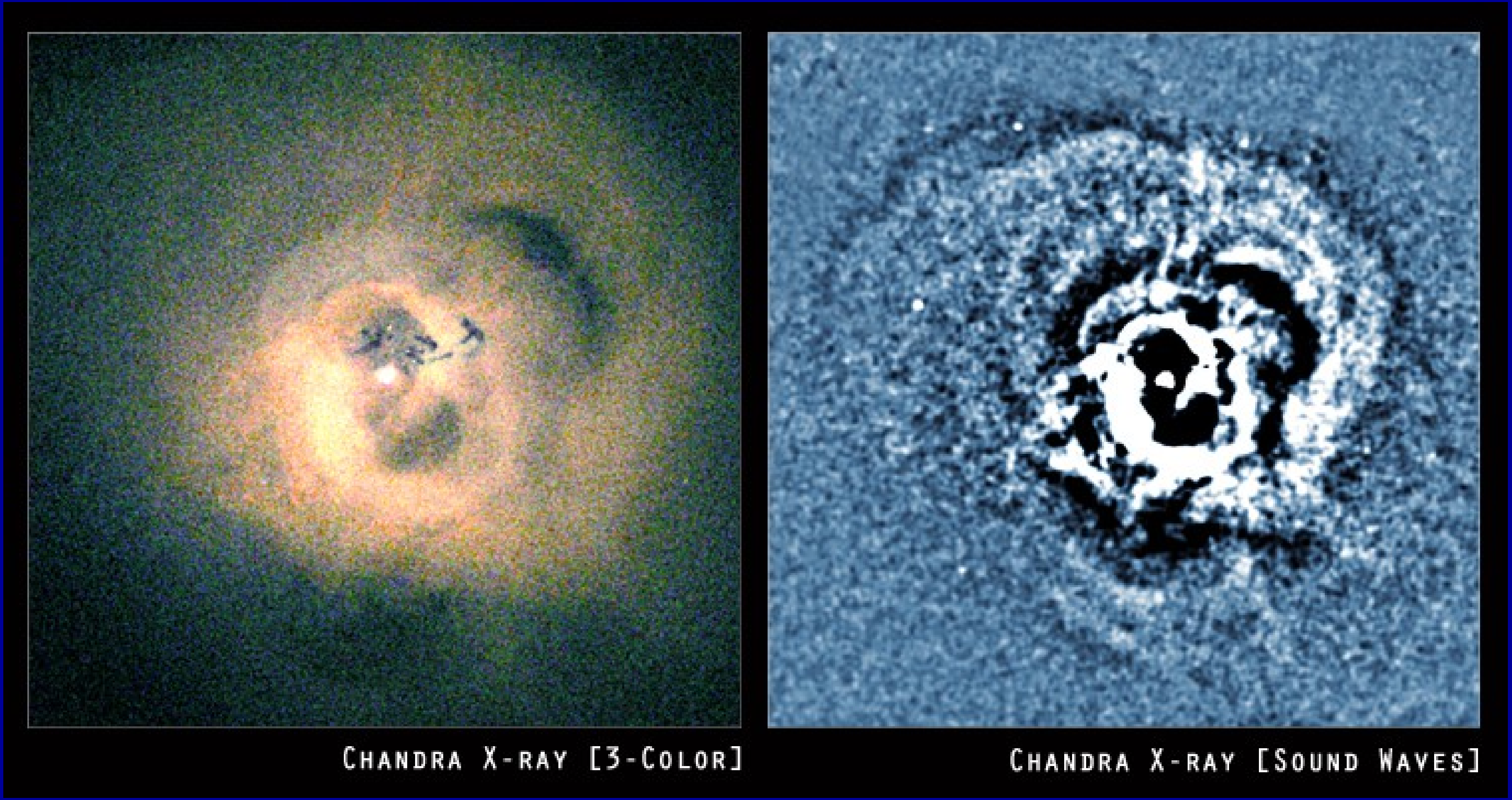


1.0 (keV) 6.0

Temperature map
80,000+ spectra

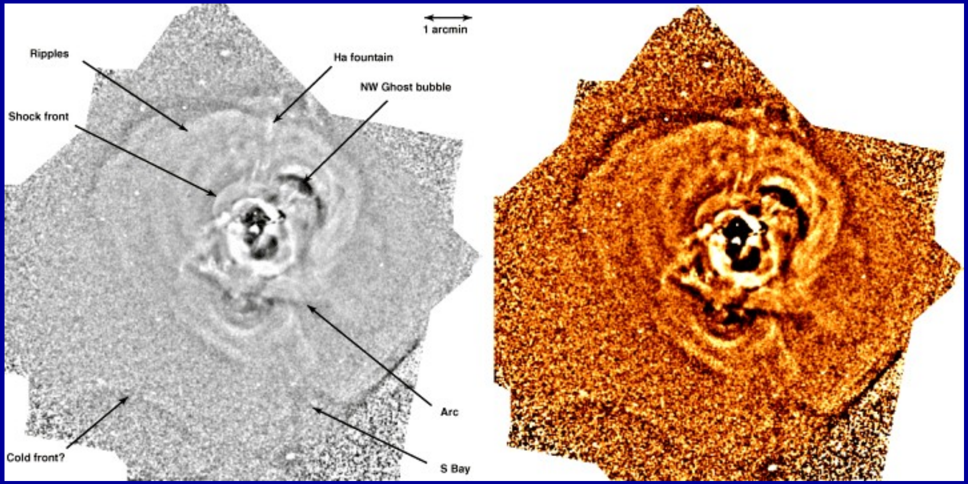
Blanton et al. (in prep), Randall et al. (in prep)

Sound Waves from Perseus



NASA/CXC/IoA/A. Fabian et al.

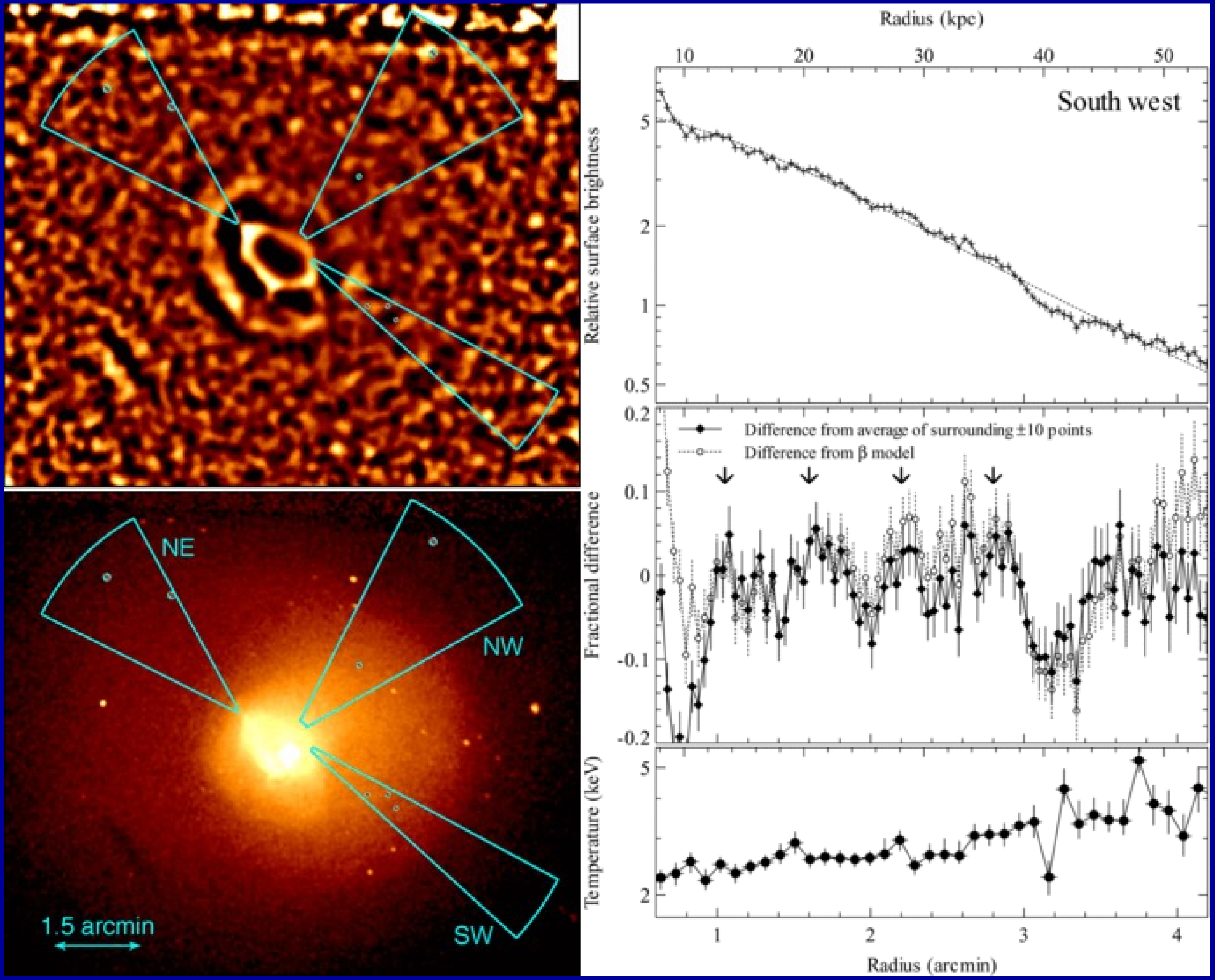
Sound Waves from Perseus



Chandra ~900 ksec, Fabian et al. (2006)

- Ripple separation corresponds to a period of ~10^7 yr
- Temperature jumps have not been observed with the weak shock features – isothermal shocks (suppression from conduction), cool gas entrainment?

Sound Waves from Centaurus



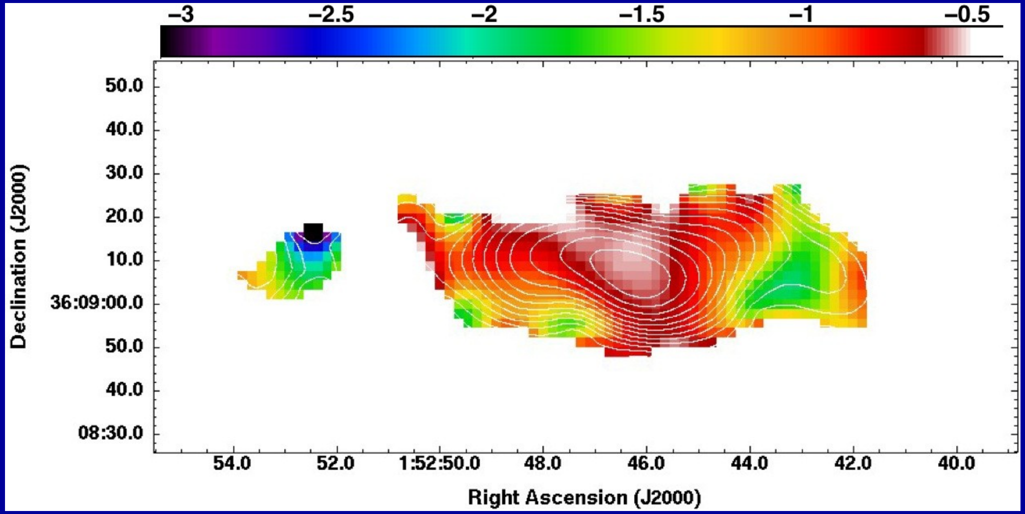
Sanders & Fabian (2008)

Conclusions

- Observations with Chandra over the last decade have shed much light on the balance of heating and cooling in clusters of galaxies.
- AGN heat the gas in the centers of cooling flows, preventing it from cooling to very low temperatures.
- Radio sources displace the X-ray-emitting gas in the centers of cooling flows, creating cavities or “bubbles.”
- Little evidence that radio sources are strongly shocking the ICM. The bright shells are generally cool, not hot. There is evidence for strong shock heating in some galaxies (e.g. Cen A)
- Weak shocks are observed and contribute to heating.
- Sound waves also contribute.

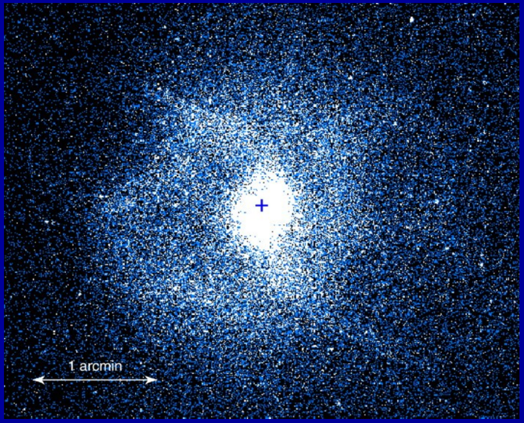
Conclusions

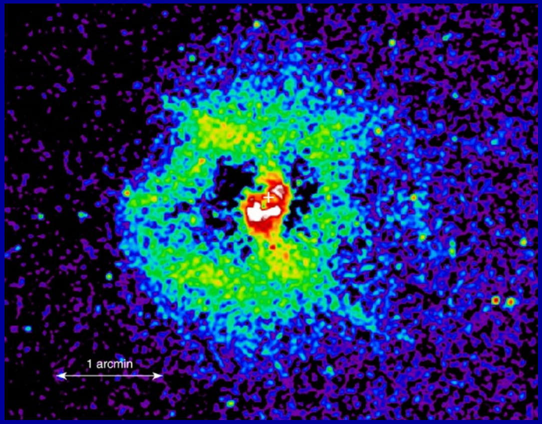
- The X-ray gas pressures derived from the shells surrounding the radio bubbles are ~ 10x higher than the radio equipartition pressures. Problems with equipartition assumptions, or additional contributors to pressure in bubbles, such as very hot, diffuse, thermal gas?
- Buoyant bubbles transport energy and magnetic fields throughout clusters.
- Shell pressures can be used to determine the total energies of the radio sources.
- A 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 in most cases.



- Spectral index map between 235 and 610 MHz
- Spectral index from -0.5 in the core to -1.7 in the W (-0.9 in the E, and -1.8 in E clumps)

Evidence of Shock Heating

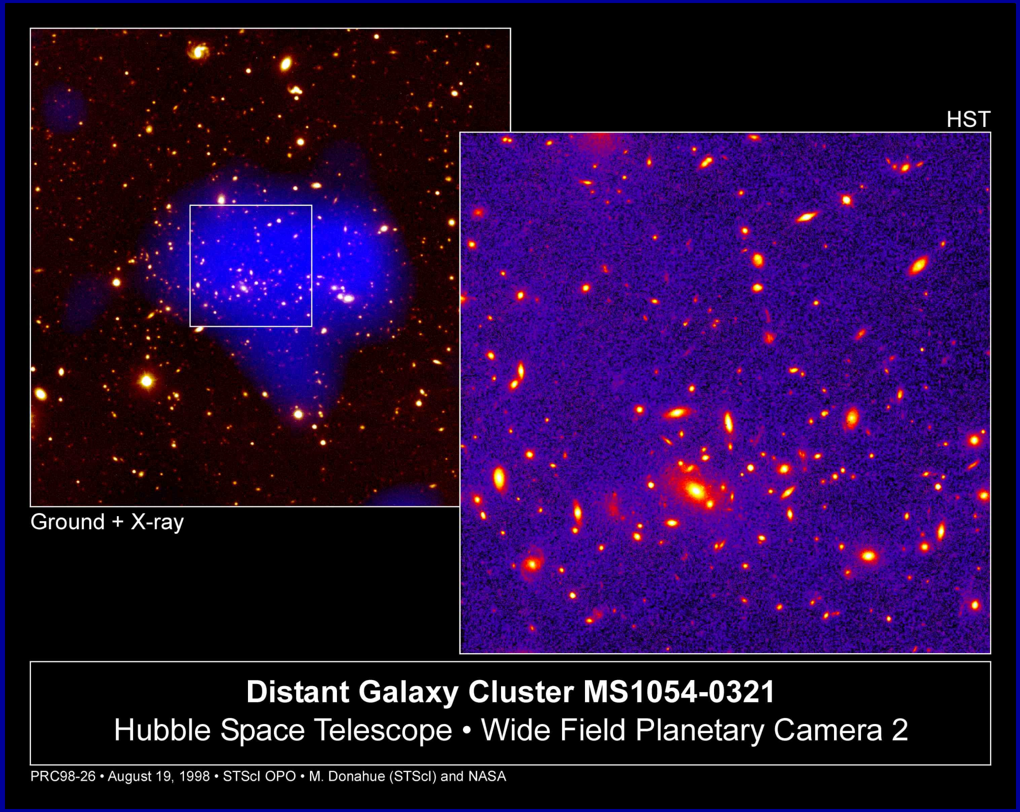




Jones et al. 2002

- NGC 4636, outer part of Virgo cluster
- Bright arm-like features with sharp edges
- No strong radio source
- Arms have higher kT and density than surroundings - consistent with shocked gas with M = 1.73.
- Features are in ISM and may or may not result from a previous radio outburst

Clusters of Galaxies



- Largest gravitationally bound systems in Universe
- 75% of mass is dark matter
- ~20% mass seen in the X-ray (hot gas)
- ~5% mass seen in the optical (galaxies)
- 100's – 1000's galaxies gravitationally bound within a few Mpc