The Jet/ISM Interaction in Three Nearby Radio Galaxies as seen with *Chandra*

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Outline

- Introduction/Motivation
- Centaurus A (NGC 5128,

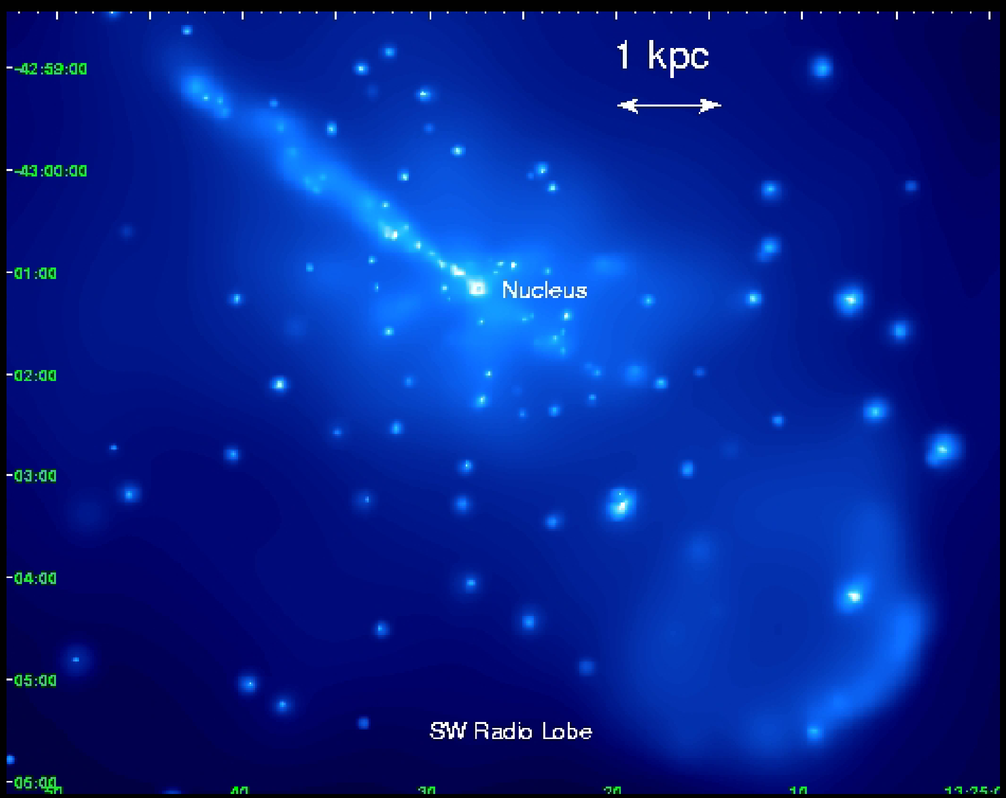
3.4 Mpc, 1’=1 kpc)

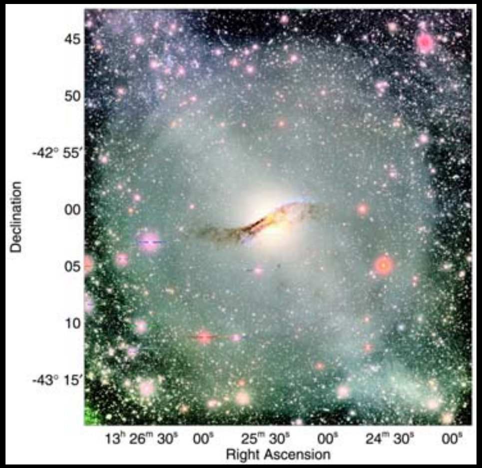
- M87 (16 Mpc, 1’=4.7 kpc)
- NGC 507 (66.7 Mpc, 1’=19.6 kpc)
- Summary and Conclusions

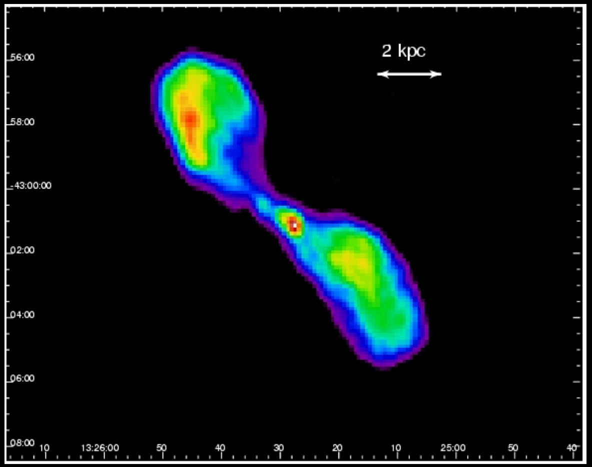
Scientific Motivation

- What is the relationship between ISM/ICM cooling and AGN outbursts?
- Can jet outflows suppress cooling flows?
- How do AGN jets affect gaseous coronae?
- Do AGN outflows affect the mixing/distribution of heavy elements in the ISM/ICM?
- Can periodic radio activity explain the large variance in the observed X-ray luminosity of early galaxies for a given optical luminosity?

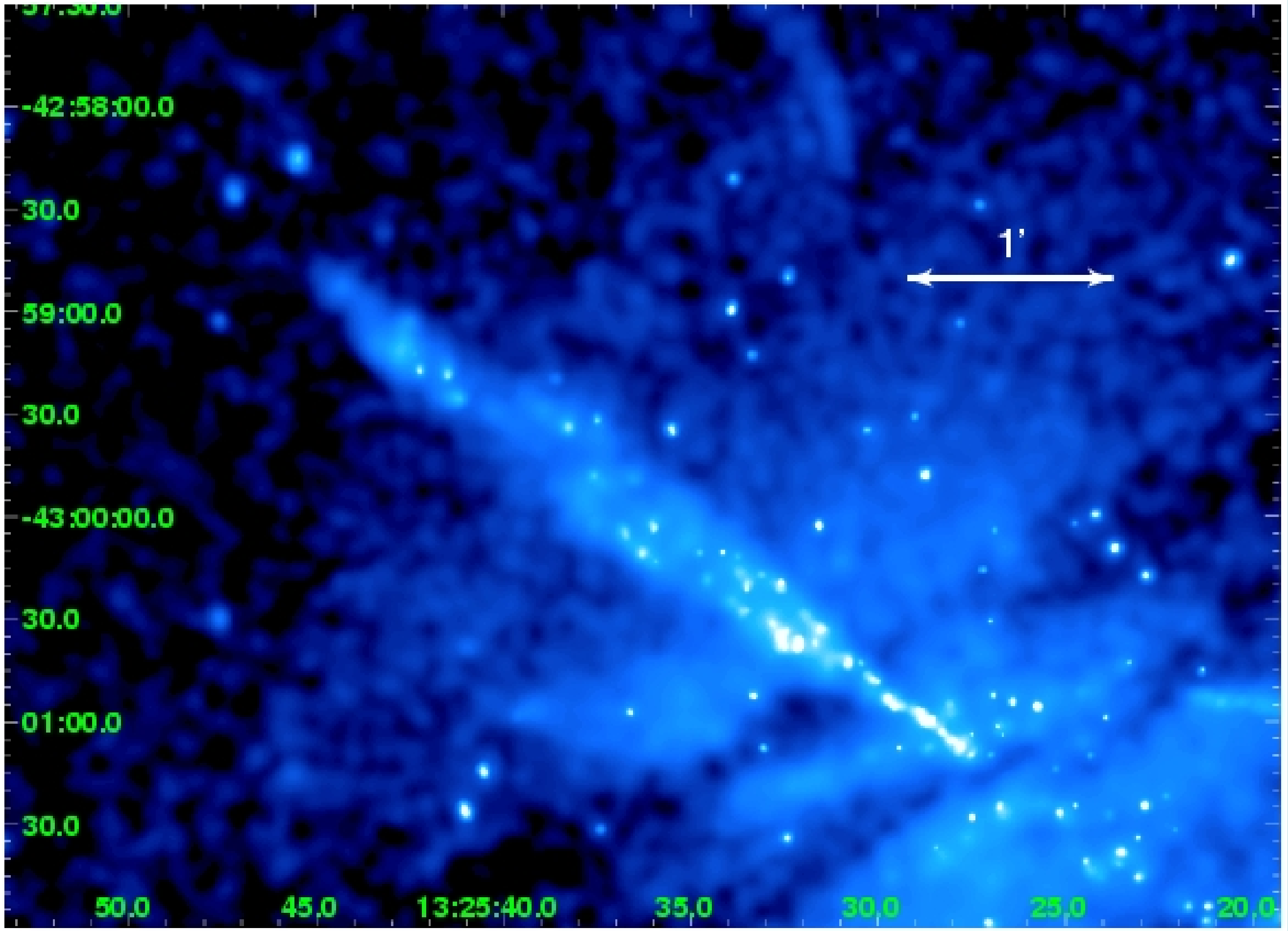
Centaurus A – the Nearest Radio Galaxy





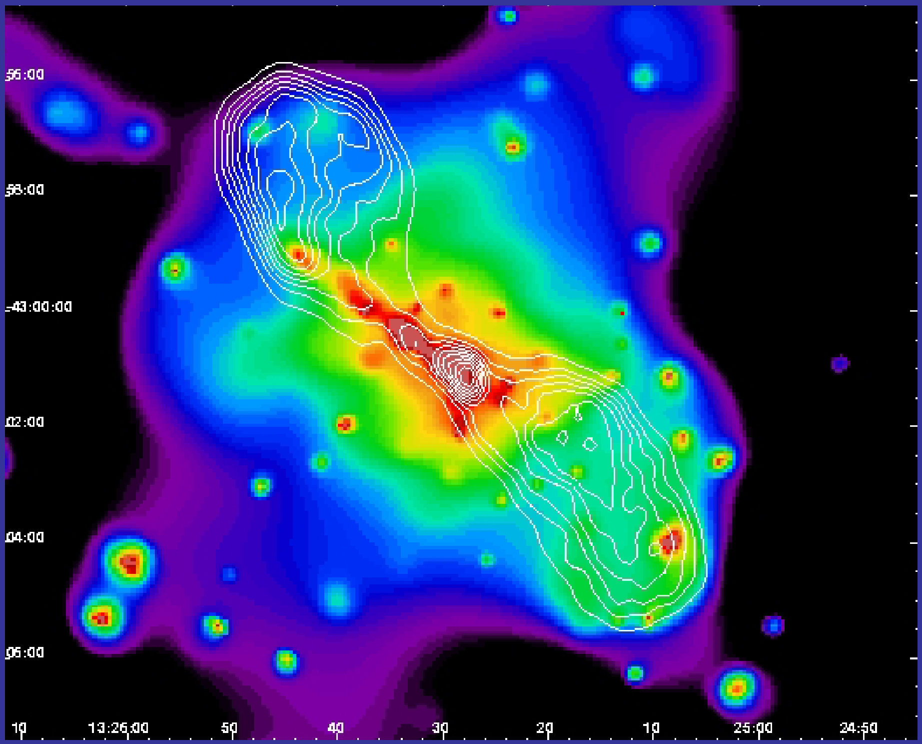


Chandra ACIS-S image of Cen A



Adaptively smoothed Chandra/ACIS-S image of Cen A in the 0.5-2.0 keV bandpass

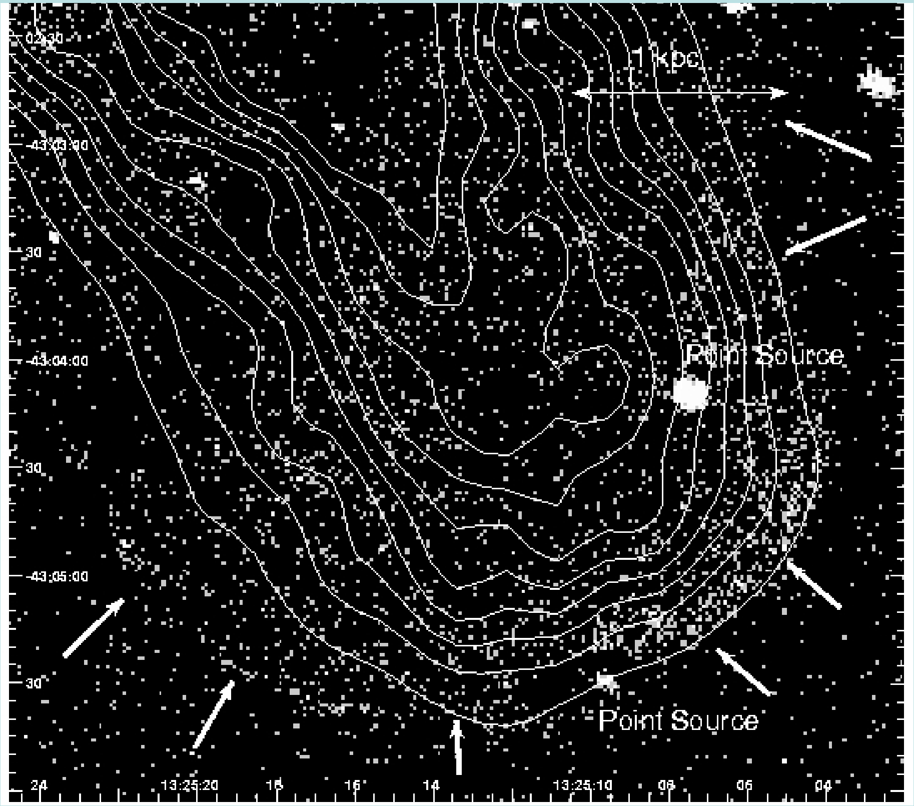
X-ray/Radio Comparison of Cen A



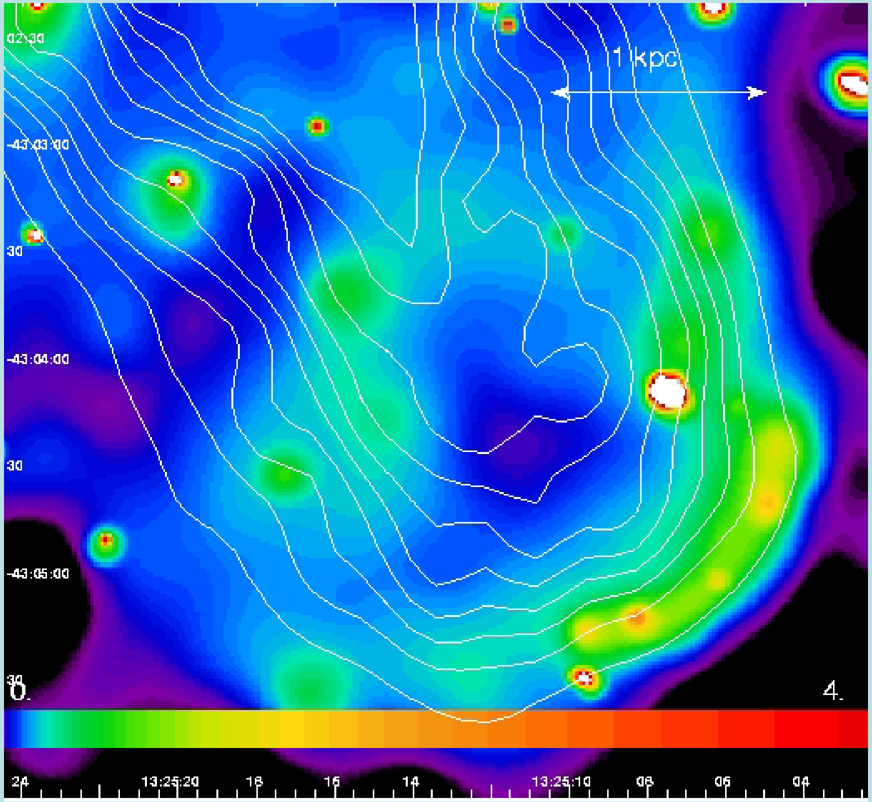
XMM/Newton Image in the 0.5-2.0 keV band with 13 cm radio contours overlaid.

- X-ray enhancement around the SW radio lobe.
- XMM-Newton image of Cen A in 0.5-2.0 keV band with 13 cm radio contours overlaid.

Chandra images of SW lobe with radio contours



Raw Chandra image of SW radio lobe with 13 cm radio contours.



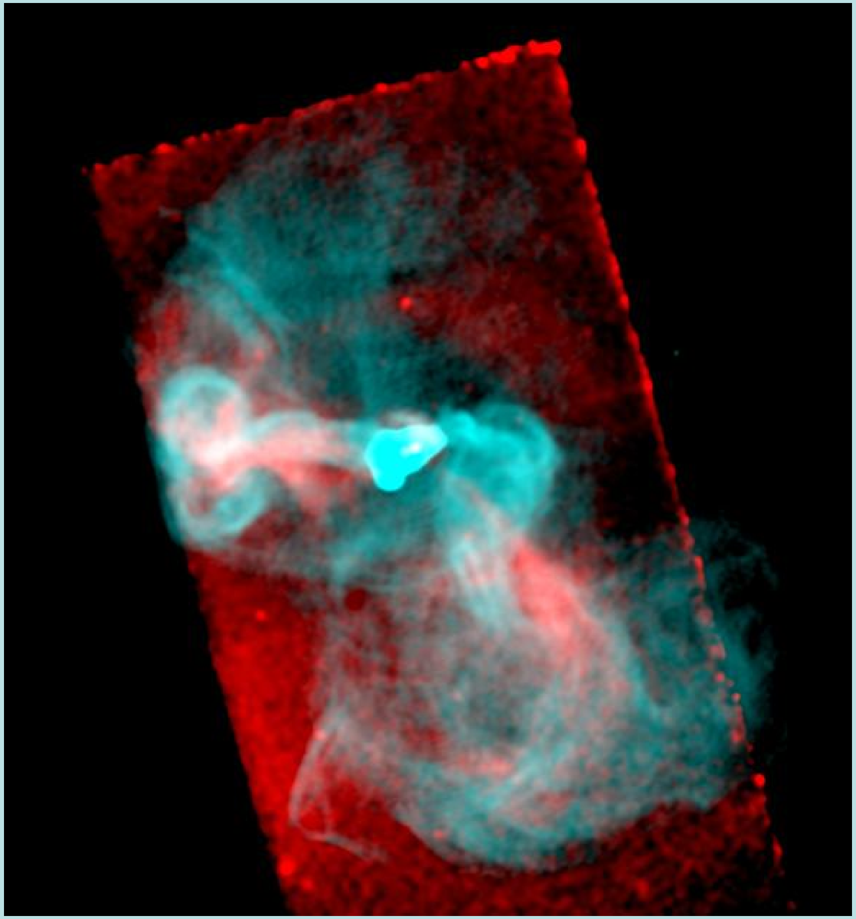
Adaptively smoothed Chandra image of SW radio lobe.

Interpretation

- We model the X-ray emission around the SW radio lobe as a cap of shock heated hot gas swept up by the supersonic expansion/inflation of the radio lobe.
- Based on the temperature/pressure difference between this cap and the ISM, the expansion velocity is 2400 km/s, or roughly Mach 8.
- The thermal energy in the shell (4.2×10^{55} ergs) is a significant fraction of the thermal energy of the hot ISM (2×10^{56} ergs) within 15 kpc of the nucleus. This suggests that the nuclear outflow can (re)heat the ISM, perhaps to a temperature at which it becomes unbound.
- Much weaker `shells' seen around NE lobe.
- Full details shown in poster by Diana Worrall

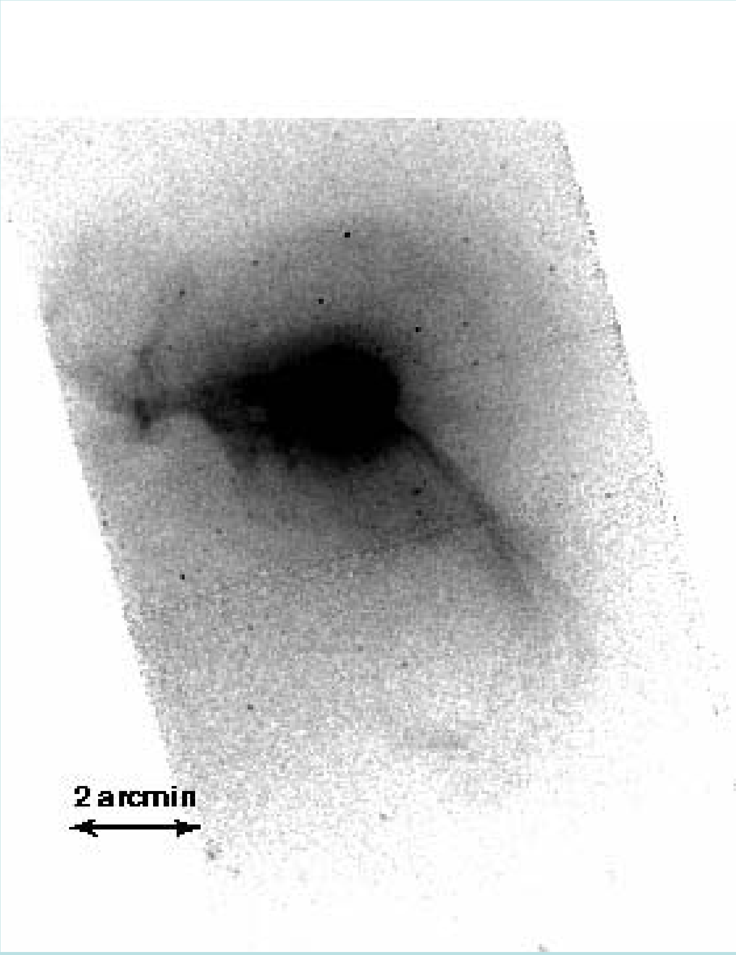
M87 – Previous Observations

- Radio observations show arms, bubbles, and a torus (Owen et al. 2000).
- ROSAT/radio shows interaction of hot gas with radio bubbles/plasma (Churazov et al. 2002).
- Chandra shows a variety of features in the hot gas (Young et al. 2001).
- Initial XMM/Newton observations demonstrated complex abundance gradients and interactions with radio plasma (Molendi et al. 2002).

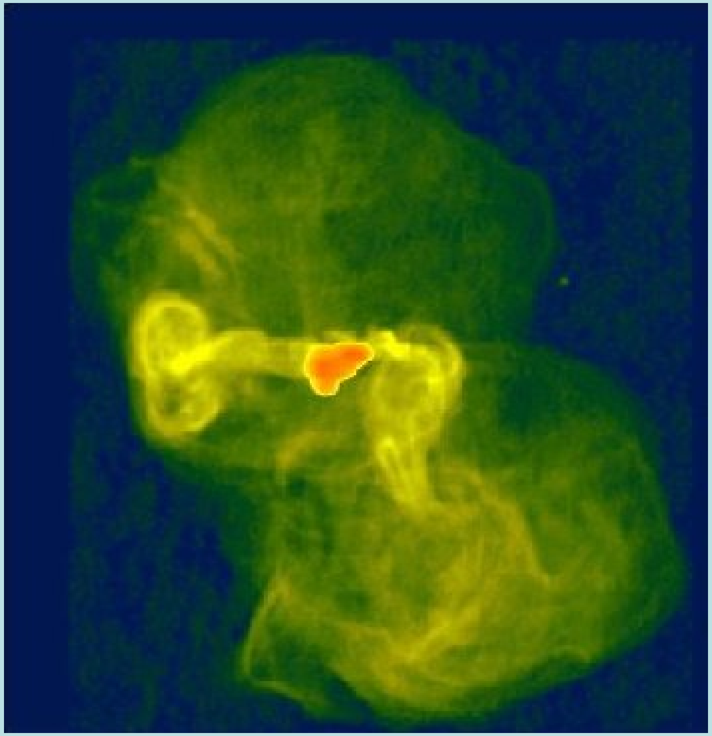


Radio (blue) and Chandra X-ray (red)

M87 –Large scale view

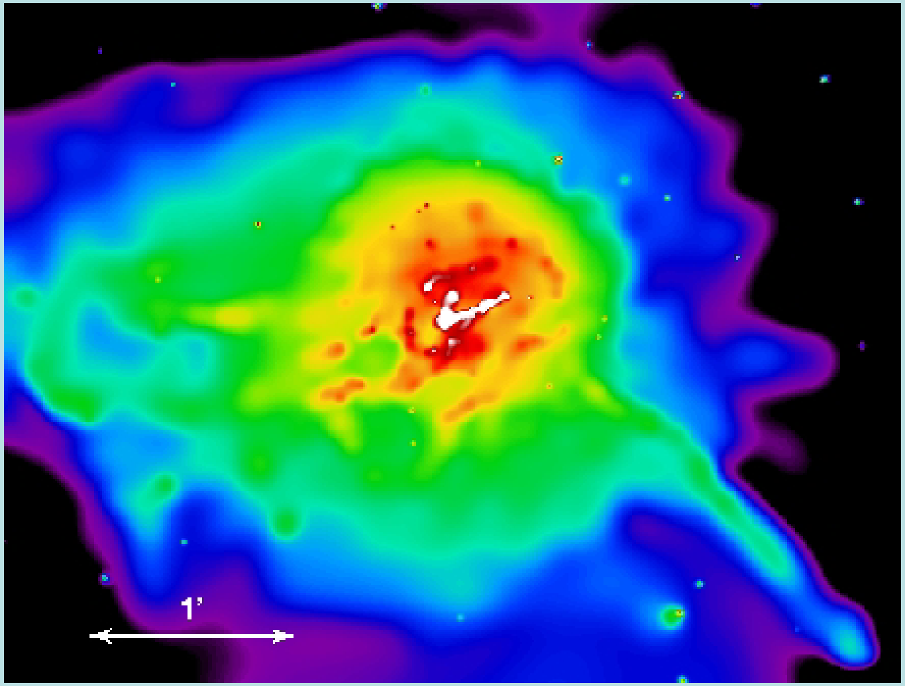


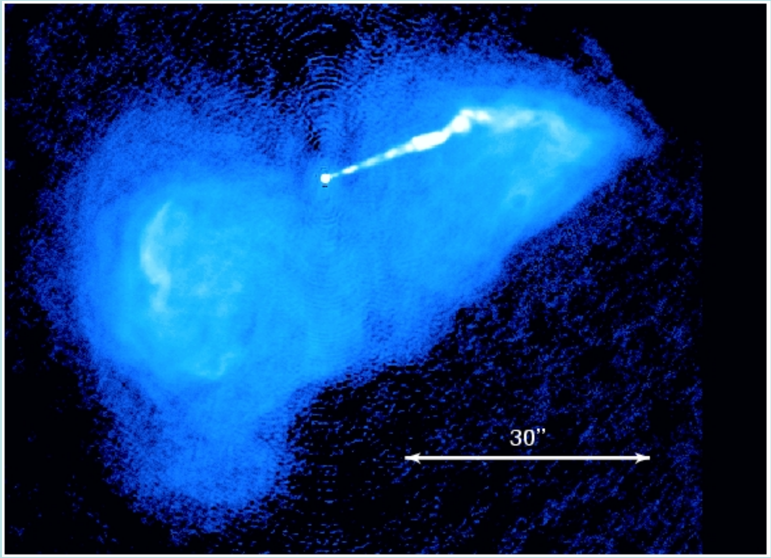
100 ks Chandra image



90 cm radio image (Owen et al. 2000)

Inner region of M87

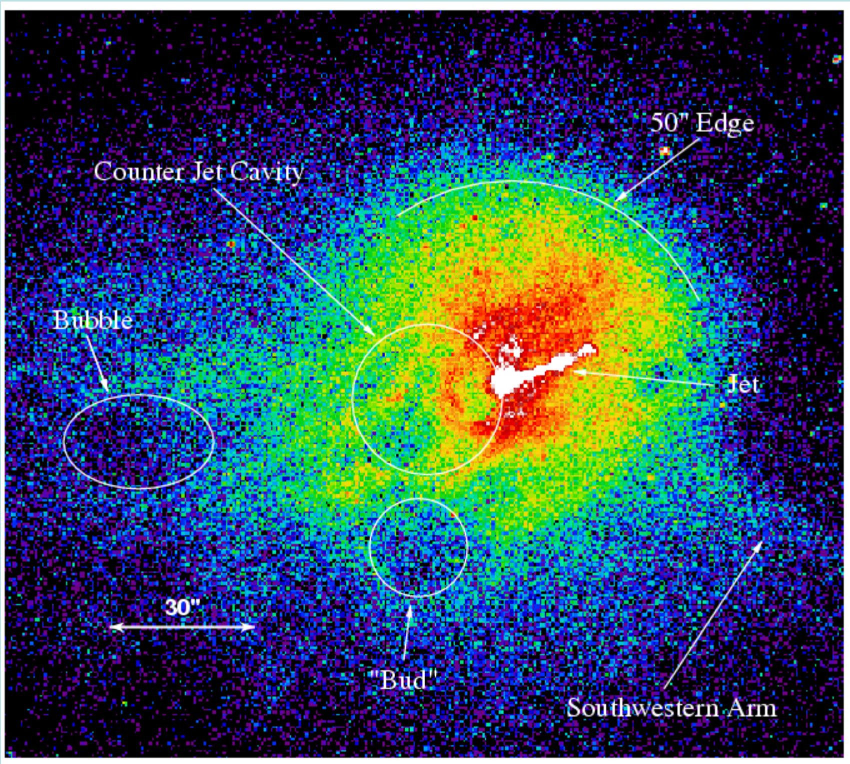




Chandra image, adaptively smoothed, 0.5-2.0 keV band.

Radio image (Owen et al. 2000)

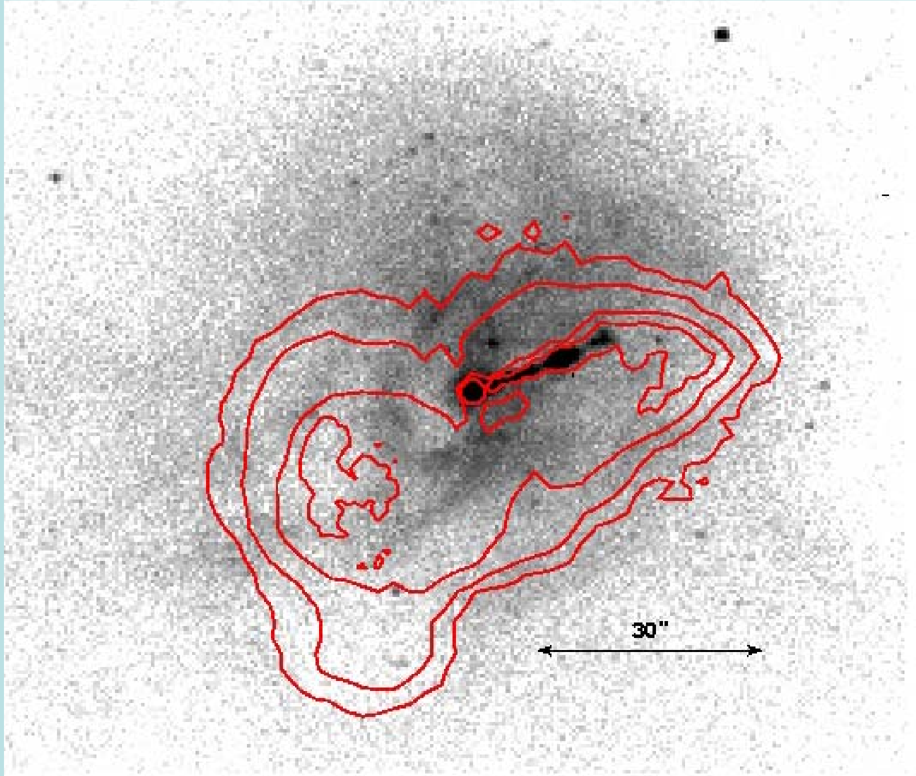
X-ray Features of Central Region of M87



- The X-ray jet.
- X-ray cavities surrounding the jet and the (unseen) counterjet.
- X-ray cavity associated with the ‘budding’ bubble to the S/SW.
- X-ray bright core region.
- At least four cavities to the E.

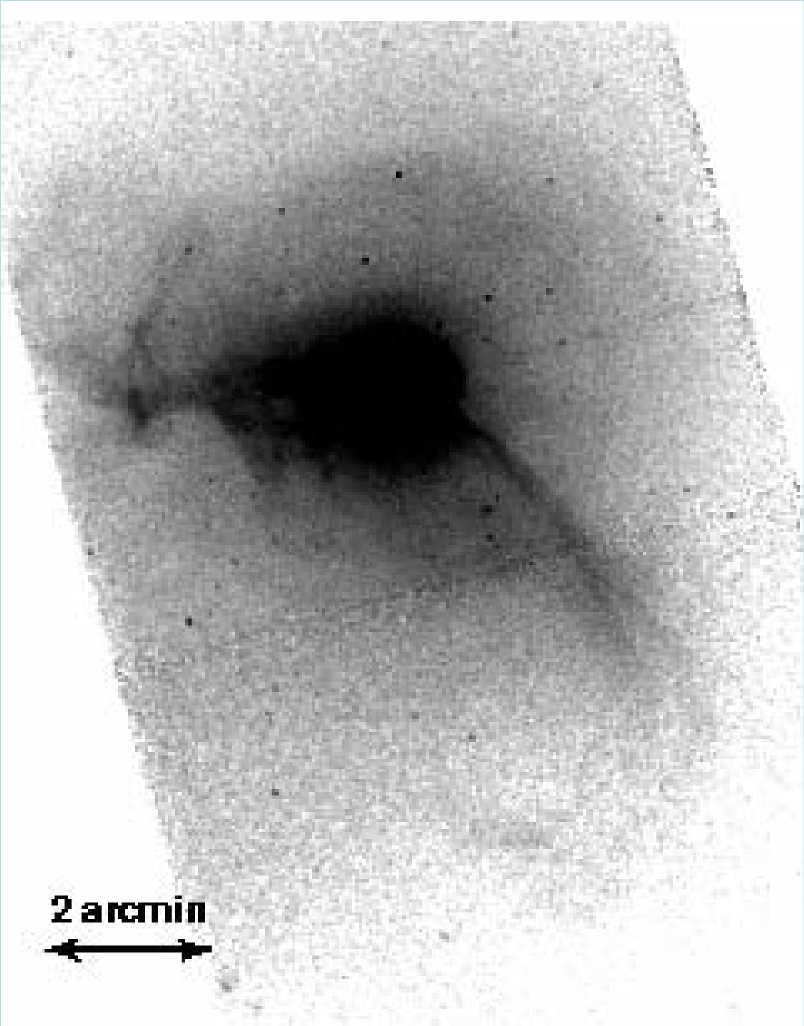
‘Budding’ Bubble

- Many structures aligned with the E/W jet.
- The ‘cavity’ to the S/SE corresponds with a radio feature and is not aligned with the other features.
- Perhaps a buoyant bubble emanating from the central radio cocoon. The velocity of this bubble is 300-400 km/s, so the rise time is about 4×10^6 yrs. It is reasonable to associate this feature with the current outburst.



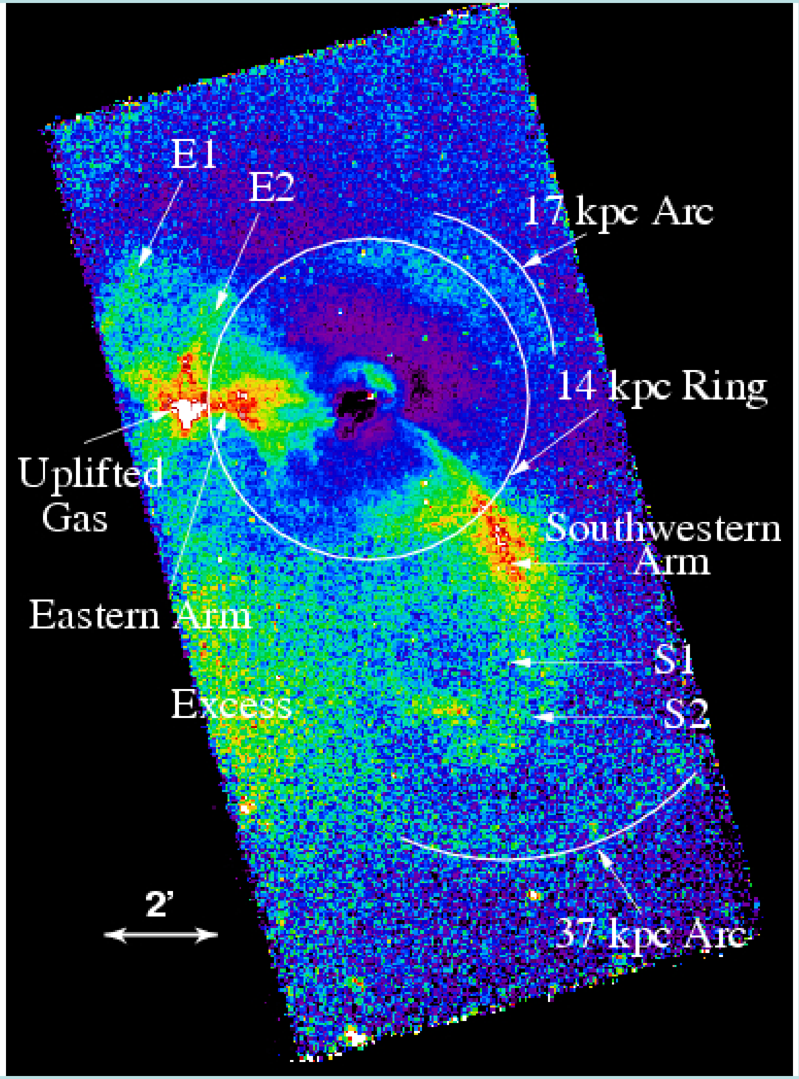
Raw X-ray image with radio contours.

Reflections of multiple nuclear outbursts



Symmetric ring 14 kpc from the nucleus most prominent to the N/NW.
A second ring 17 kpc from the nucleus.
Arms to the E and SW that brighten in the vicinity of the rings.
Beyond 14 kpc, both arms separate into two filaments.
An X-ray arc 37 kpc to the S of the nucleus.

M87 Large Scale structures – azimuthally symmetric emission subtracted.



We model the azimuthal rings as surface brightness discontinuities due to shock waves.

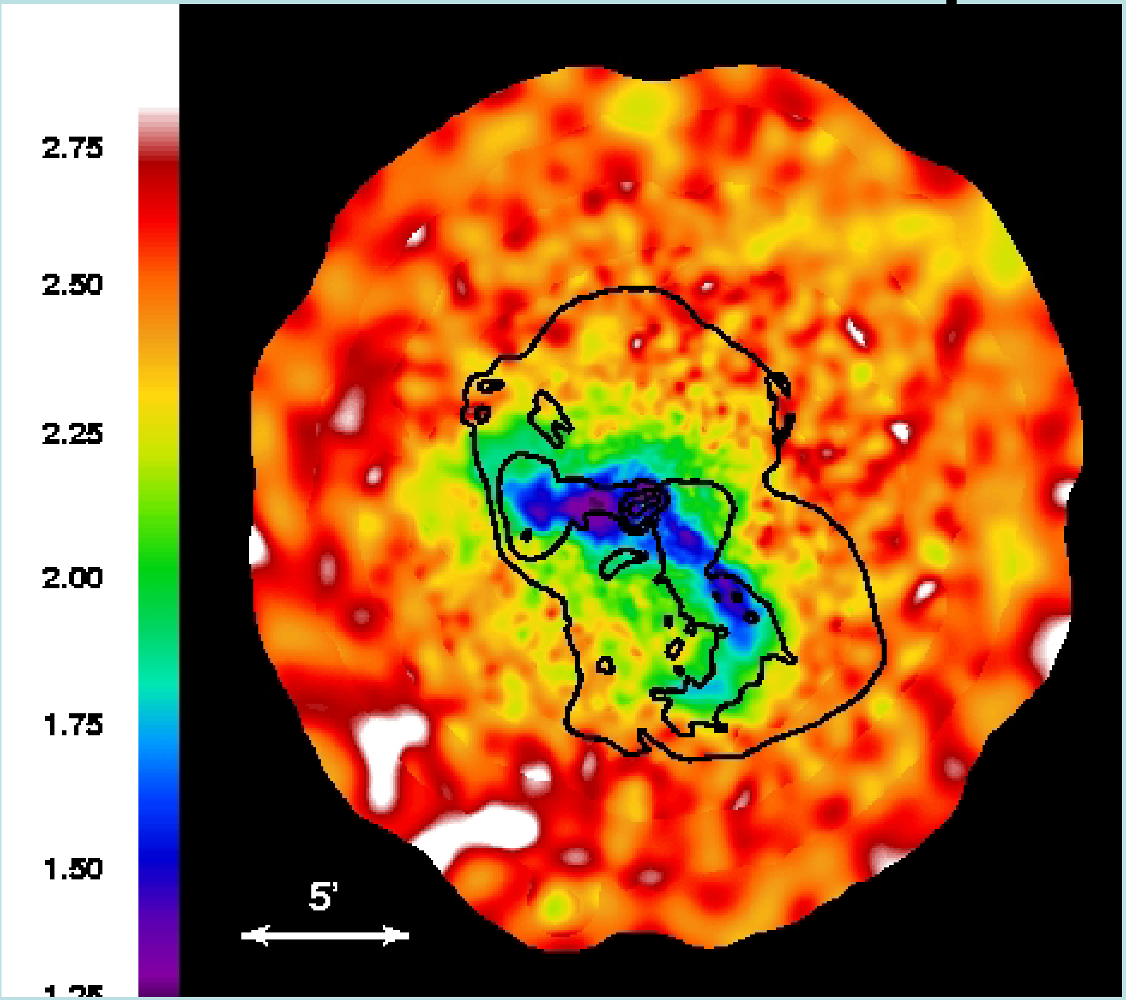
The shock model that matches the observed features is characterized by an explosion of 8×10^{57} ergs about 10^7 years ago.

The shock is mildly supersonic (M=1.2, v=950 km/s).

The 17 kpc ring must have been created by an explosion approximately 4×10^6 yrs before the one that created the 14 kpc ring.

Second example, similar to Perseus (Fabian et al 2004)

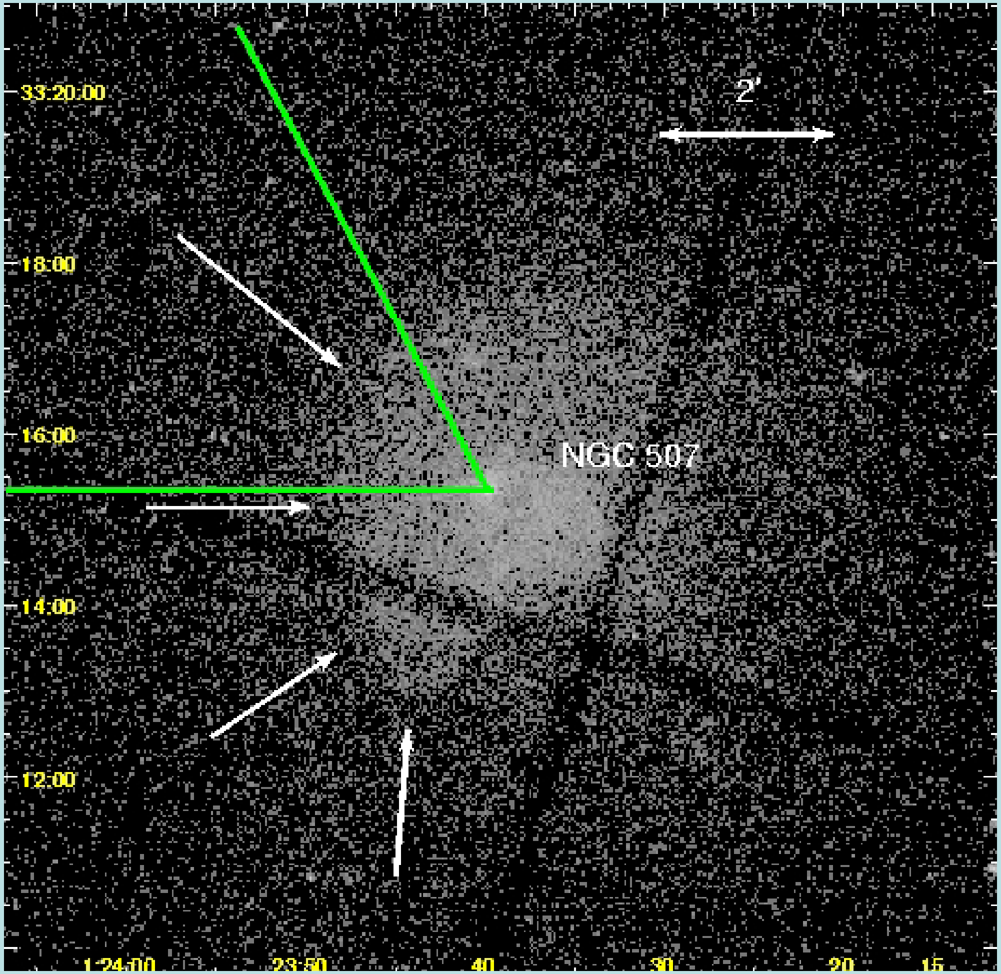
XMM/Newton Temperature Map



Radio contours on XMM/Newton Temperature map.

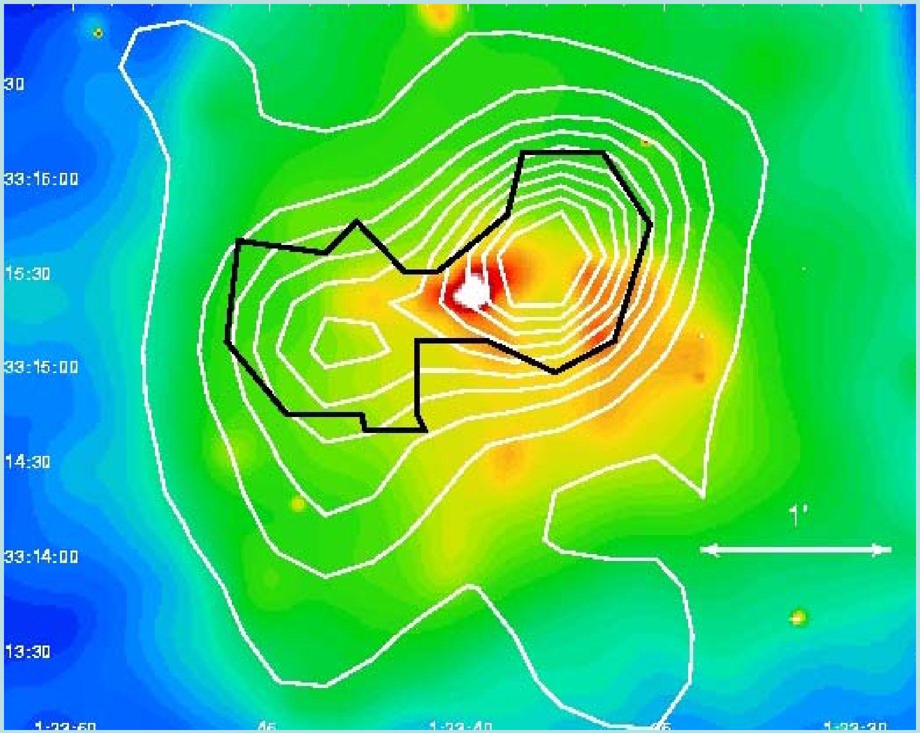
Cooler gas follows radio arms. Buoyantly uplifted from central region. No hint of 37 kpc arc in temperature map.

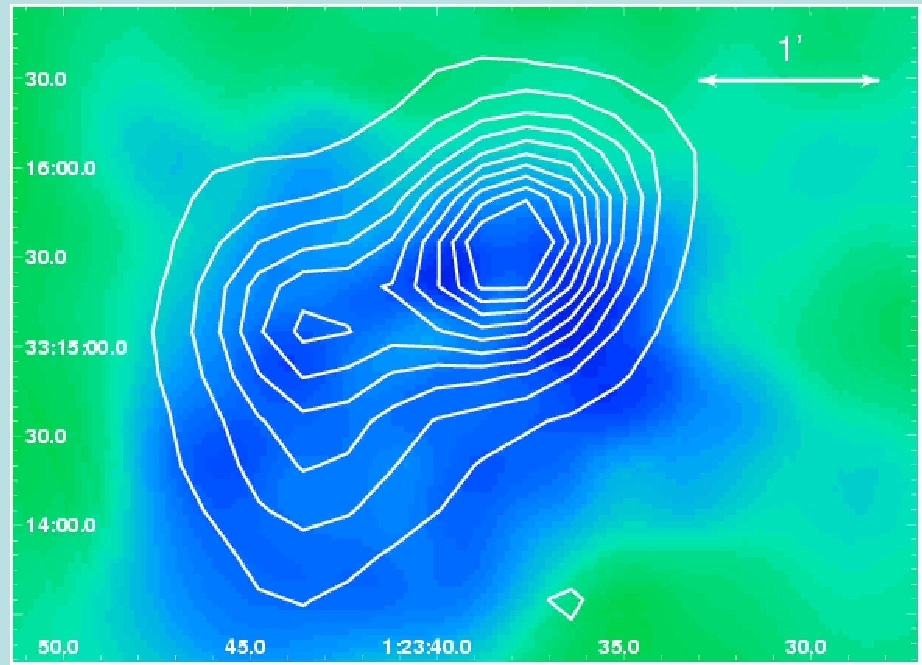
NGC 507 – A cold front without the ‘cold’?



Chandra/ACIS-I image in the 0.5-2.0 keV bandpass. The prominent X feature are the chip gaps.

NGC 507: X-ray radio comparison and temperature map

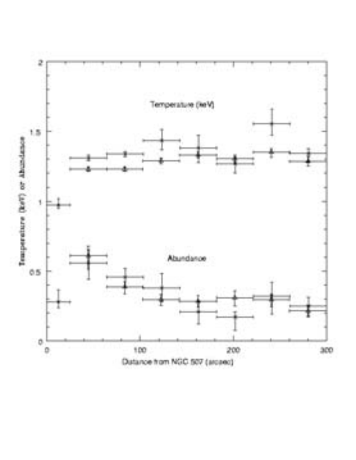


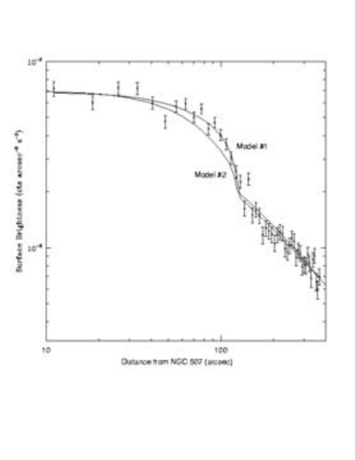


Adaptively smooth Chandra image with NVSS radio contours (white).

XMM/Newton temperature map. The difference between the blue(cooler) and the green is approximately 0.2 keV. The linear scales in the two figures are not the same.

Evidence of an Abundance Front?





- Surface Brightness profile across discontinuity.
- Model 1 – pressure balance at stagnation point – gas parameters can be estimated from large scale halo.
- Model 2 – Temperature (small) and abundance gradient across discontinuity

Observational Highlights

- We have detected a hot shell of X-ray emission around the radio lobe(s) of Cen A demonstrating supersonic expansion at least on scales of kpcs.
- X-ray observations of M87 demonstrate a variety of complex structures indicative of multiple nuclear outbursts.
- Complex interactions between the radio plasma and the hot ISM have been detected in NGC 507 and indicate that the expansion of the lobes can transport low entropy, metal rich material from the center out into the halo.

Conclusions

- Cooling gas can be reheated by:
  - Supersonic outflows, e.g., jets (Cen-A)
  - AGN outbursts generating weak shocks (M87, Perseus)
- Buoyant bubbles
  - Transfer energy and gas (M87, NGC507)
  - Generate abundance gradients (NGC507)