Radio Jet Disruption in Cooling Cores

- **OR, can radio jets solve the cooling core problem?**
- **OR, how do cooling cores disrupt radio jets?**

What is a cooling core?

The old picture: unusually dense, compact X-ray loud cores exist in quiet-looking clusters of galaxies. The high gas density and short cooling time → X-ray gas should be collapsing due to loss of pressure support as it cools: a so-called "cooling flow" or "cooling core".

The new picture: the data do not support the strong cooling or high mass inflow rates which the early models predicted.The cores are cooler than the rest of the cluster gas, but not nearly cold enough.

So, we have new questions:

- → **How is the cooling offset?**
- → **Is there a local heating source in every cooling core?**

Radio galaxies in cooling cores

The central galaxy in essentially every cooling core (CC) hosts an active nucleus with a cluster-center radio source (CCRS).

(This probably due to the massive galaxy itself, not the CC)

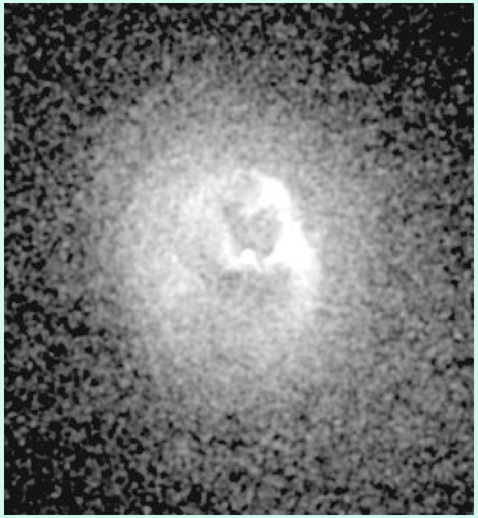
A large fraction of these CCRS are unusual. Unlike the general radio galaxy population, jets in CCRS often disrupt very close to the core, leading to a more diffuse energy flow and "bubble"-like radio halo.

(This must be due to different conditions in the CC)

So the questions are:

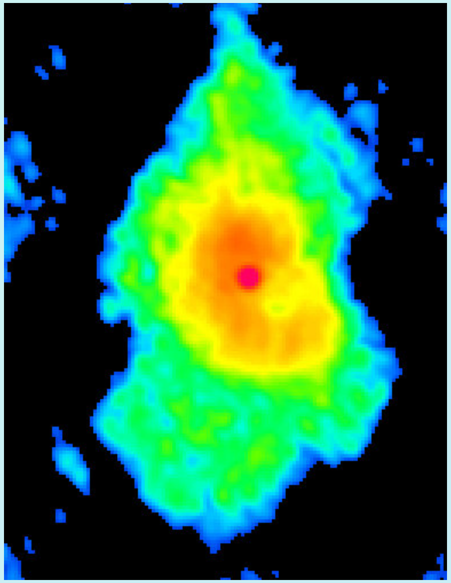
- **→ How do these CCRS interact with the local X-ray loud plasma?**
- **→ Does the interaction heat the plasma enough to be interesting?**

One example: 3C317 in A2052



Left: inner X-ray core of A2052. The cavities or bubbles appear smooth and empty; the rims are cooler than their surroundings.

Right: the radio halo source 3C317, the CCRS in the core of A2052. The radio halo approximately coincides with the X-ray cavities, suggesting they are filled with radio plasma.



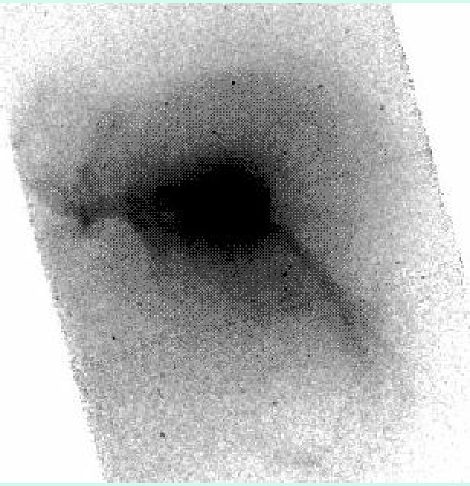
The radio plasma has displaced the X-ray gas, creating and supporting the cavities.

No jet is detected on kpc scales; it must disrupt close to the galactic core, leading to a diffuse mass/energy input to the radio halo.

The radio halo grows due to its internal pressure and buoyancy in the cluster's gravity.

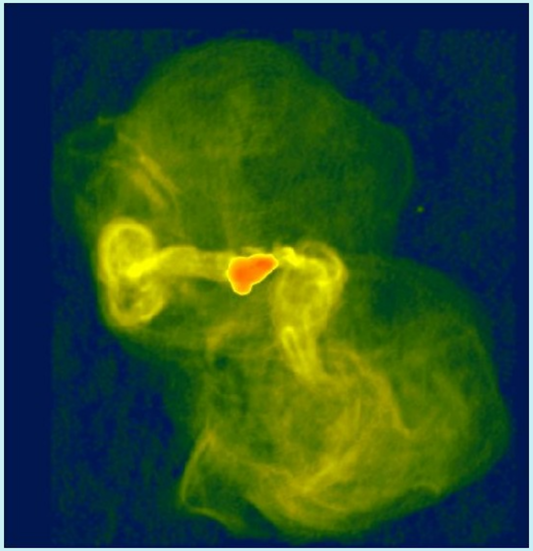
(Image scale ~ 80 kpc, both images. From Owen & Ledlow 1995, Chandra archive.)

Another example: M87 in Virgo, I



Left, the X-ray core of the Virgo cluster. The X-ray plasma is disturbed, and knows about flows in the radio plasma, but doesn’t show simple cavities.

Right, the diffuse radio halo of M87, the central RS in Virgo. The halo is highly inhomogeneous, with suggestions of turbulence and vorticity.



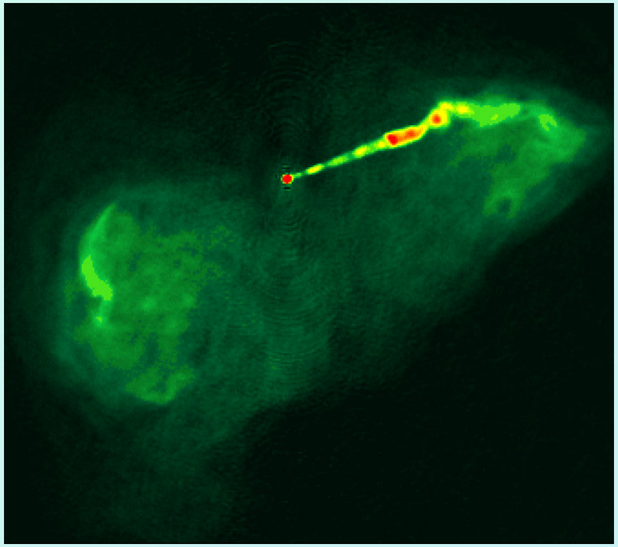
M87 is similar to 3C317, with an amorphous radio halo supported by a diffuse mass/energy input which drives a radio “bubble” into the X-ray gas.

Unlike 3C317, however, the radio and X-ray plasmas are well mixed and turbulent in this source.

Also unlike 3C317, the radio jet in M87 is alive & well on kpc scales (it sits in the orange “inner halo” in the radio image).

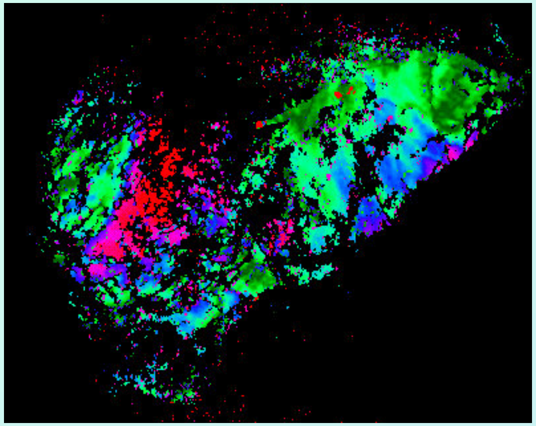
(Image scale ~ 80 kpc, both images. From Forman et al 2004; Owen et al 2000.)

M87 in Virgo, II

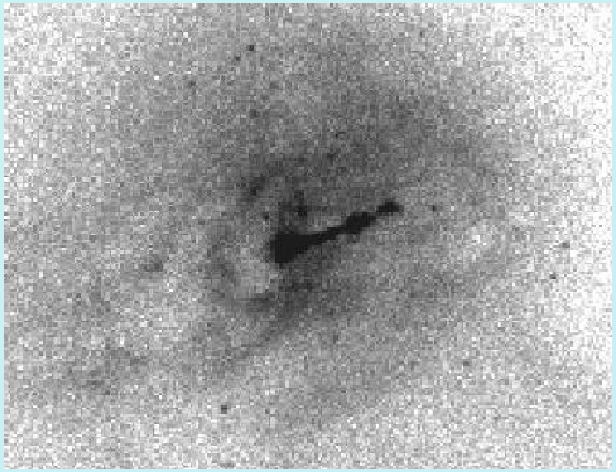


Upper right: radio image of the jet and inner halo. The well-collimated jet propagates 2-3 kpc from the core then bends and disrupts, feeding the inner radio halo.

Lower right: X-ray image of the same region. The jet is seen in X-rays, as are the filaments and cavities where the jet and inner radio halo interact with the local X-ray gas.



Left: radio-derived faraday rotation image, showing magnetized filaments in the X-ray plasma which lies around the inner radio halo.



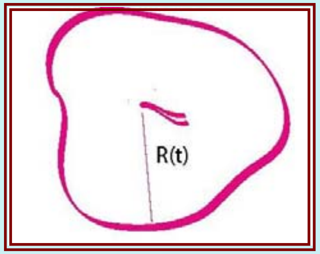
(Image scale ~ 5 kpc, all images. From Forman et al 2004; Hines et al 1989; Zhou 1995)

What is the effect of the jet on the CC?

How important is the radio jet to the X-ray plasma in the cooling core? Can the jet offset radiative cooling? To answer this, we must find the jet power.

Several nearby CCRS have good enough radio and X-ray images to make dynamical models of the CCRS. From these we can estimate the total jet power (in particles and field).

CCRS can be modeled as "bubbles" or as "tails". The models relate their size and expansion rate to jet power and ambient gas conditions.



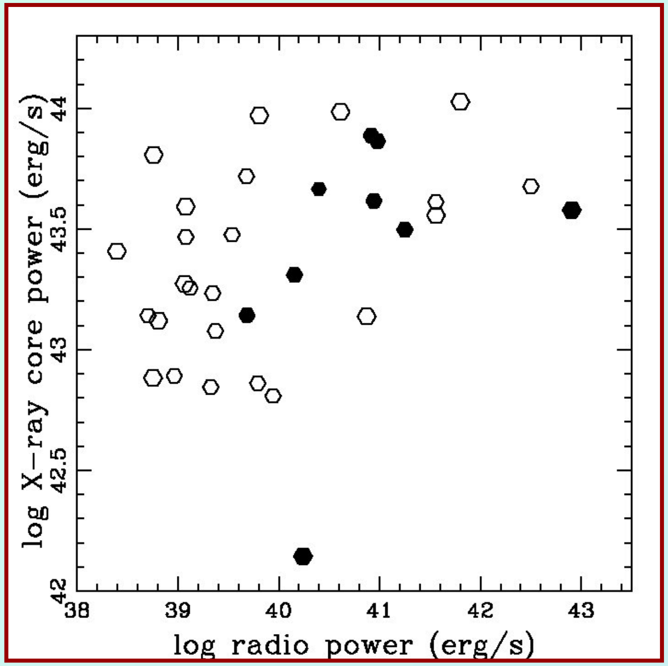
These models suggest the jet power is comparable to the X-ray power. These sources are very likely to be energetically important in the cooling cores.

(Eilek 2004, Markovic & Eilek 2004)

But: are these nice examples typical of all CCRS? Are CCRS always energetically important ?

What about the general CCRS population?

Most CCRS are small and faint. All we can easily measure is their radio power – small compared to the X-ray power of the core. What are these jet powers?



Filled circles: CCRS amenable to dynamical modeling. Open: the small & faint ones.

Remember that a young, jet-fed RS grows and brightens with time; an old one fades even while it keeps growing. Simple models connect the *mean* radio power of a sample to the jet power in *electrons*.

We find the mean electron power << X-ray core power. However, jets also transport ions and B field; the electron jet power may be a small fraction of the total power.

(Eilek 2004)

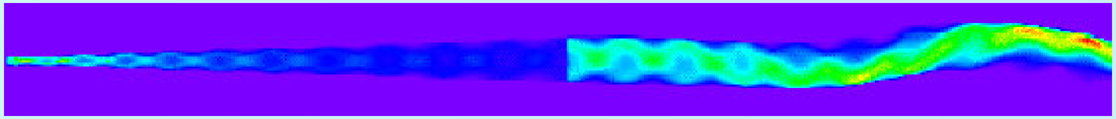
Thus it is possible, but not required, that most or all CCRS are energetically important to the X-ray core in which they sit.

And: how do cooling cores affect jets?

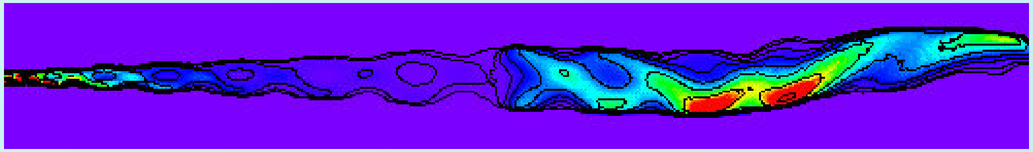
They destabilize them -- often more strongly and dramatically than is the case for jets not in cooling cores.   The jets disrupt, but the energy flow continues, feeding a diffuse CCRS halo.

One possibility for disruption is the Kelvin-Helmoltz instability, as in semi-analytic modeling of the M87 jet, which can constrain physical conditions in the jet.

(Hardee, Lobanov & Eilek 2003)



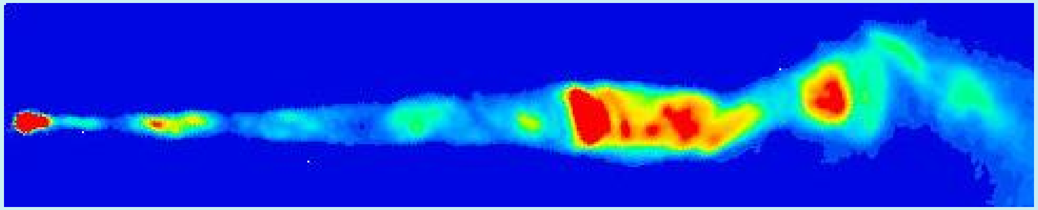
Simulated jet, in the sky plane



Simulated jet, at 20 degrees to line of sight

The disruption and its effects can also be studied with full numerical simulations, which can study jet heating of the X-ray core.

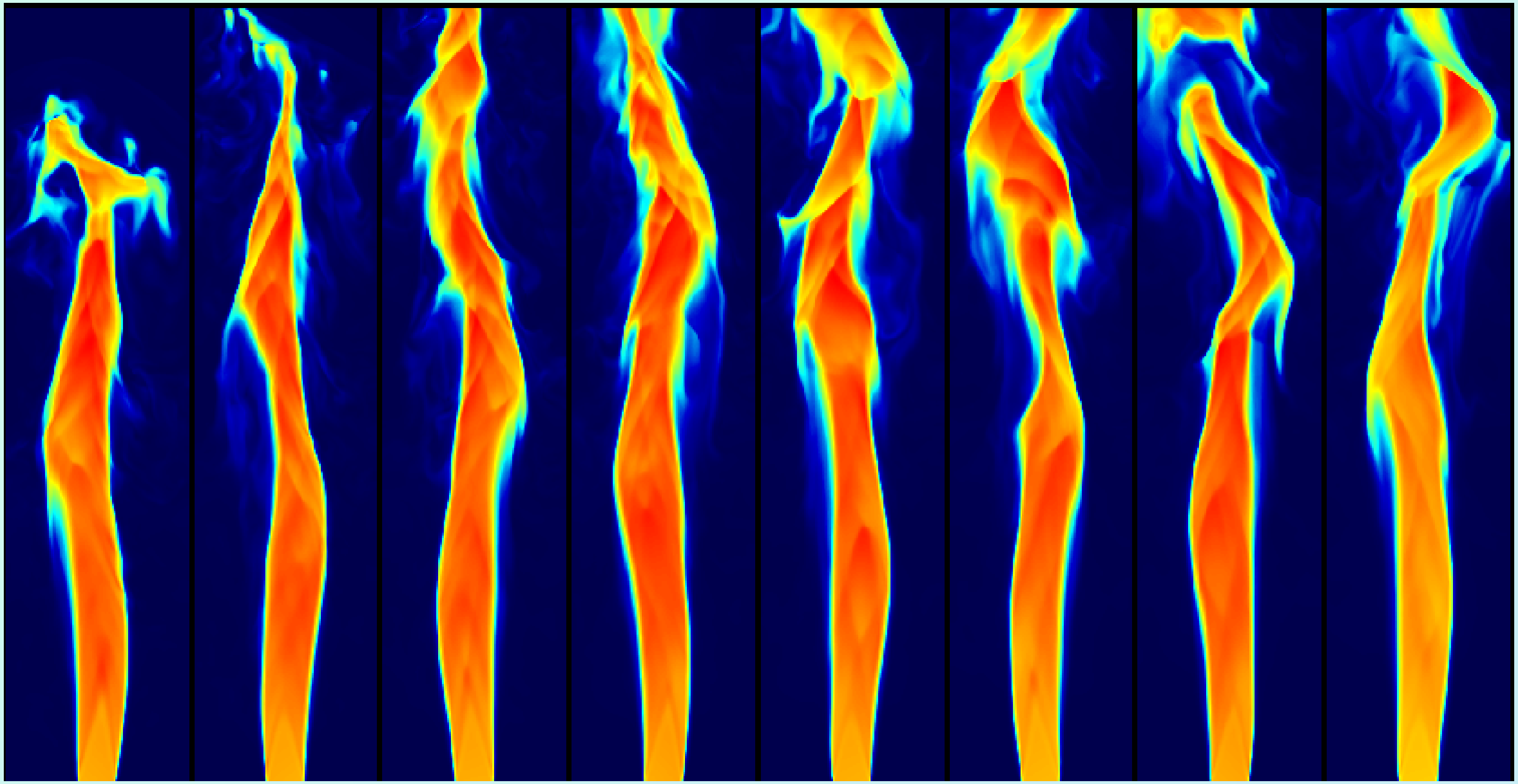
(Hughes, Hardee & Eilek 2004)



The real thing: the jet in M87

Jet development in cooling cores, I.

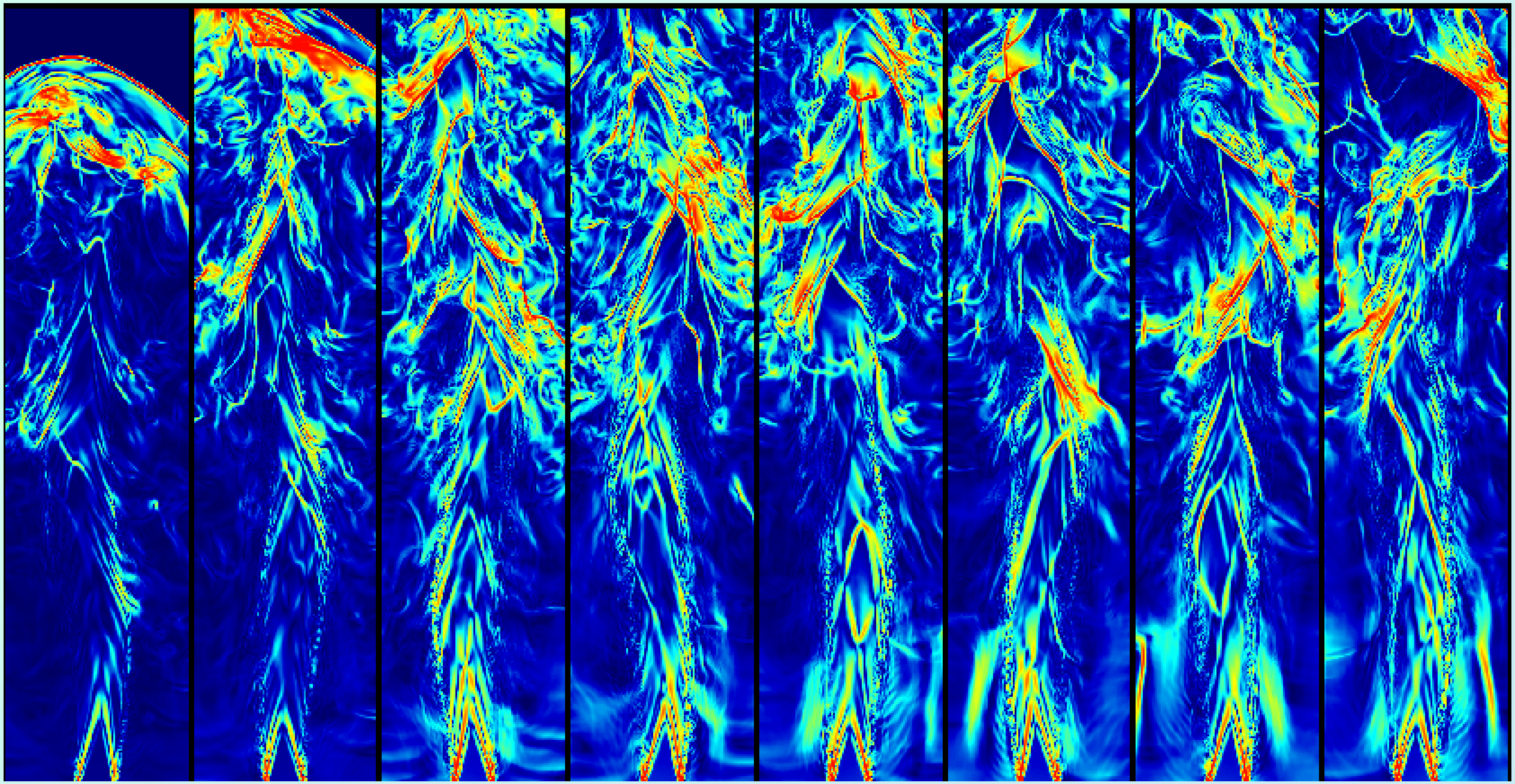
3D relativistic simulations by Hughes etal, in progress, to follow jet propagation, disruption and heating in a CC-like pressure gradient.



Shown: Lorentz factor. Time increases to the right.

Jet development in cooling cores, II.

Simulations such as these can address how effectively an unstable jet heats the ambient plasma in the core (Hughes etal in progress).



Shown: pressure. Time increases to the right.

Conclusion: there are still many questions.

Jets → cooling cores:

How does the jet power couple to the cooling core? Options include

•Doing pdV work on the core;

•Relativistic ions which diffuse through the core plasma;

•Generating turbulence in the core plasma;

•Generating sound waves which escape the core.

Cooling cores → jets:

What rules jet physics in cooling cores?

•Why are jet instabilities more often disruptive in cooling cores?

•Why is it that CCRS are common, but individual objects appear short-lived?

•What is the duty cycle of the central active nucleus?