Radio Galaxies, Jets, & their Environments

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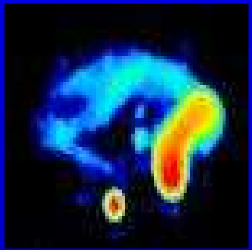
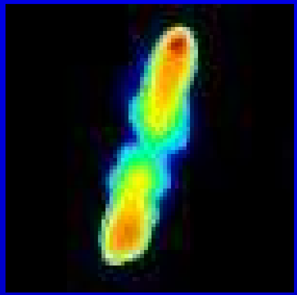




Jet physics again flourishing as a result of Chandra (sensitivity, high- fidelity mirrors)

Broader interest than just radio- source physics

- Signature of a ‘ turned- on’ black hole. Jets intimately related to fueling
- Missing term in our accretion- energy sums
- Signposts to X- ray clusters/groups
- Source of cluster/group heating

In pursuit of the bigger picture, here are some specific questions of jet physics that need to answered:

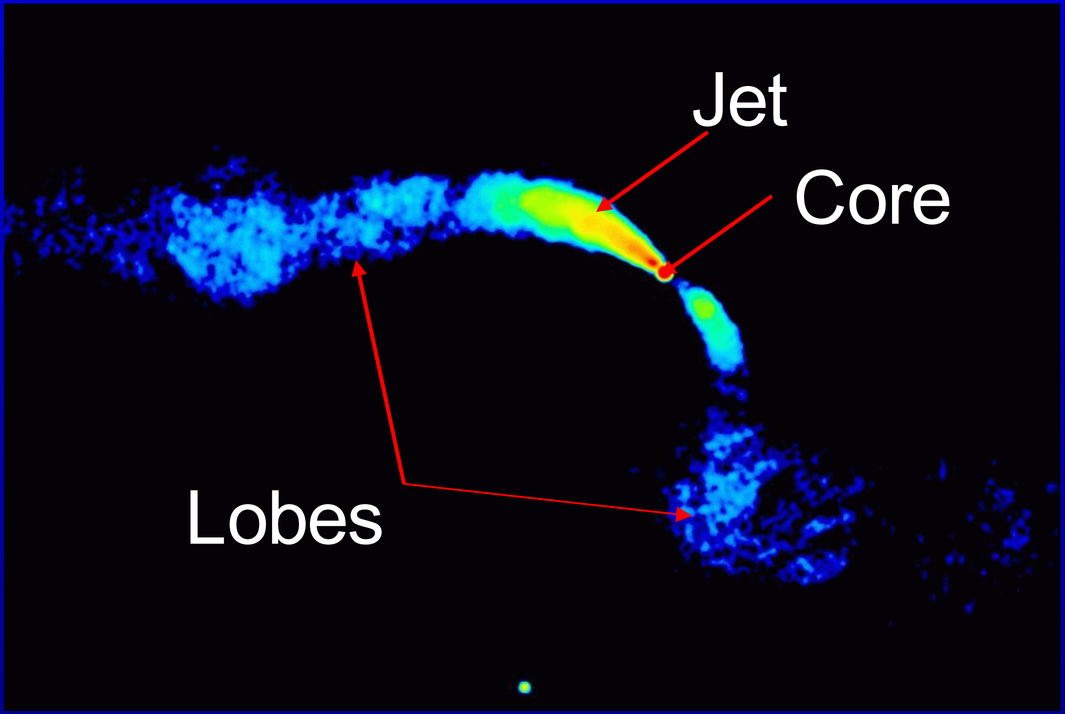
1. *Are the radio structures in a state of minimum energy?*
2. *How fast are jets?*
3. *What keeps jets collimated?*
4. *What is jet plasma – electron/proton or electron/positron?*
5. *Where & how does particle acceleration occur?*
6. *Which radio structures are dynamical & which in equilibrium?*
7. *How is jet energy transferred to the surrounding medium?*

Special thanks to:
Elena Belsole, Mark Birkinshaw, Bill Cotton, Judith Croston, Fred Dulwich, Dan Evans, Jonathan Gelbord, Martin Hardcastle, Dan Harris, Ralph Kraft, Robert Laing, Jim Lovell, Herman Marshall, Steve Murray, Eric Perlman, Dan Schwartz, Aneta Siemiginowska.

Fanaroff & Riley (1974)

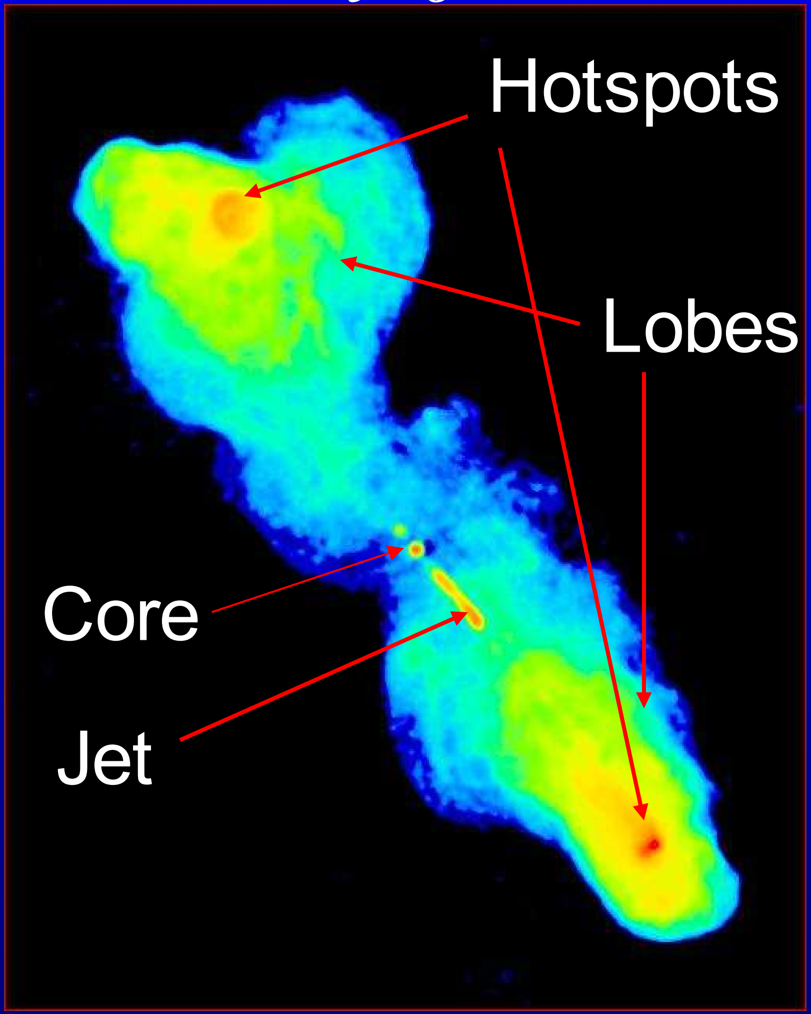
Low- power FRI

BL Lac if jet boosted in line of sight



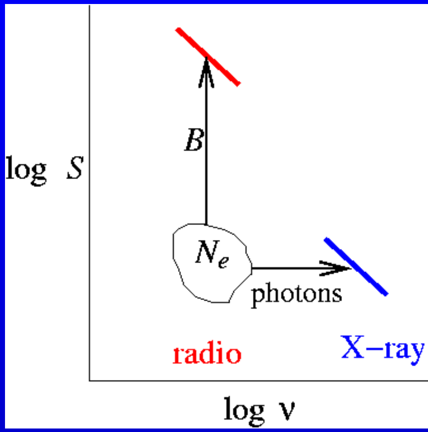
High- power FRII

Quasar if jet boosted in line of sight

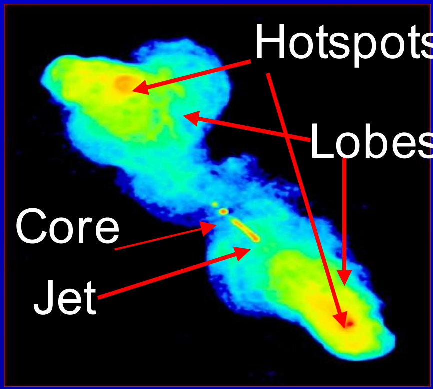


1. *Are the radio structures in a state of minimum energy?*

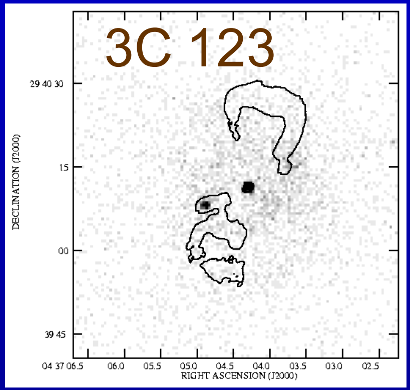
Magnetic field and particles dominate internal pressure.
X- ray crucial. Test minimum energy (B_{me})



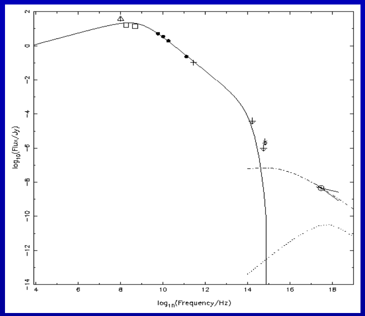
Anticipated science with Chandra from ROSAT, ASCA on hotspots and lobes of a few sources (e.g., Harris et al. 1994, Feigelson et al. 1995, Tashiro et al. 1998*)*



Hardcastle et al. 2001



$B \sim 0.7 B_{me}$



Latest compilations: X- ray detections of ~70% of 65 hotspots (Hardcastle et al. 2004) *and 33 lobes* (Croston et al. 2005). *$0.3\,B_{me} < B < 1.3\,B_{me}$ if all particles radiate (i.e., electrons).*

Low- luminosity hotspots have an X- ray synchrotron compt.

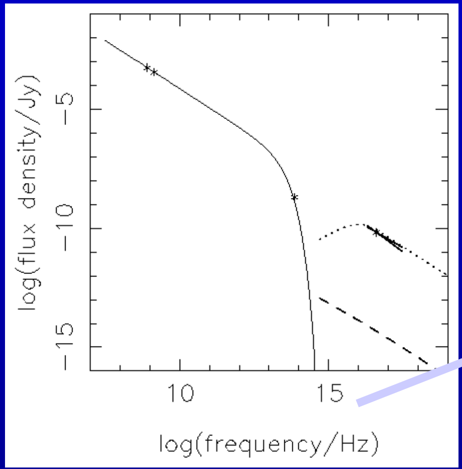
2. How fast are jets?

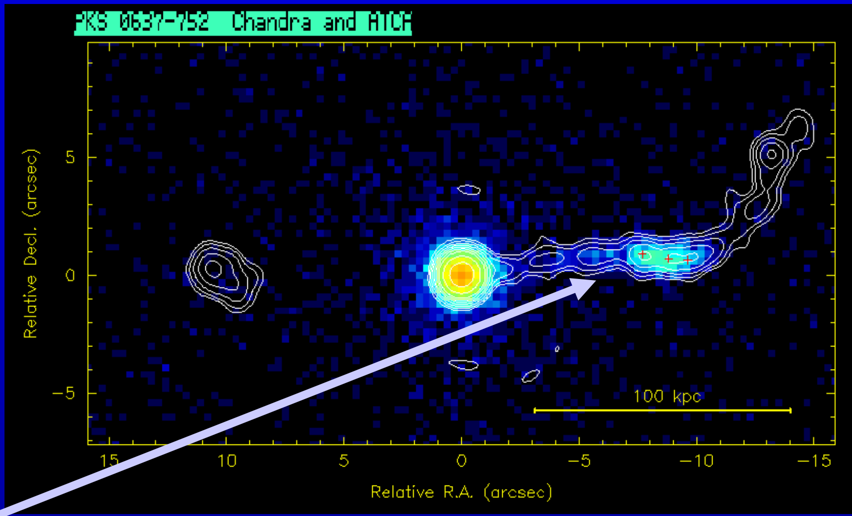
Statistical tests of relativistic beaming based on radio jet- to- counterjet ratios suggested that in even the highest- power sources (quasars) jets slow to ~0.7c on kpc scales.

Chandra made us rethink.

Optical rules out synchrotron from single electron population

Single- zone SSC ~1000x departure from minimum energy





Schwartz et al. 2000

Beamed ic- CMB with B_{me} is favored model

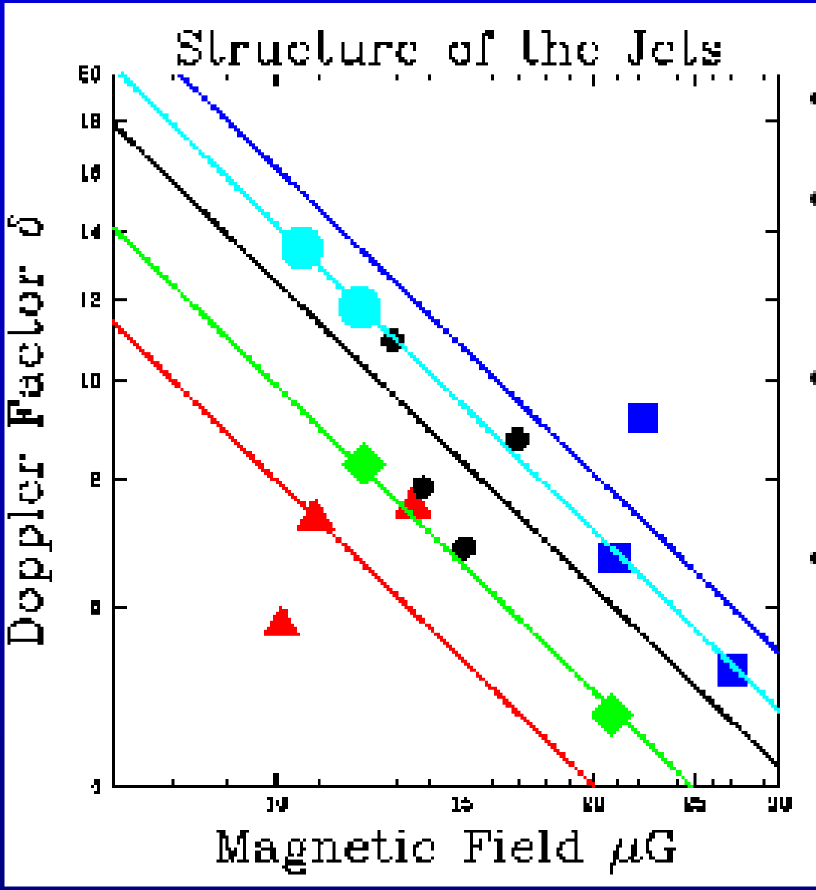
Tavecchio et al. 2000, Celotti et al. 2001

But then θ ~ 5 deg, Γ ~ 20, v ~ 0.999c at ~ 1 Mpc

Two surveys to detect quasar jets selected to be at small angle to the line of sight:
Sambruna et al. 2002, 2003; Marshall et al. 2005

60% detection rate of one or more knots: 10/17 and 22/37
5- 10 ks exposures only.

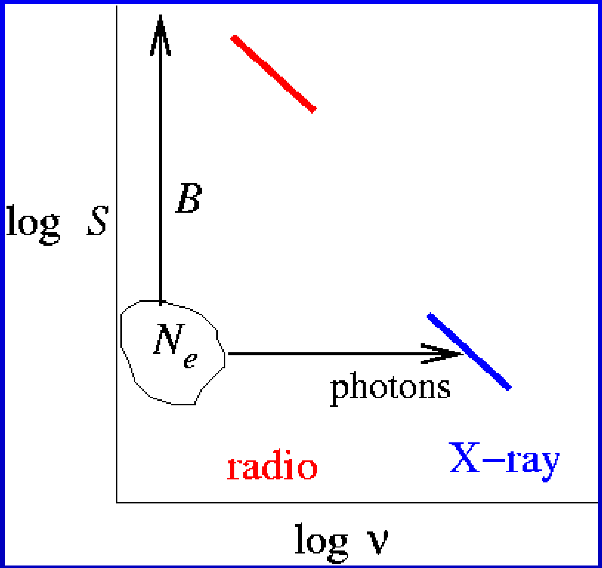
On the assumption of a beamed iC- CMB model and minimum- energy B field, can calculate the bulk relativistic Doppler factor, δ (~Γ), and magnetic field strength. Some other approximations made, but B_{me} is largest uncertainty.



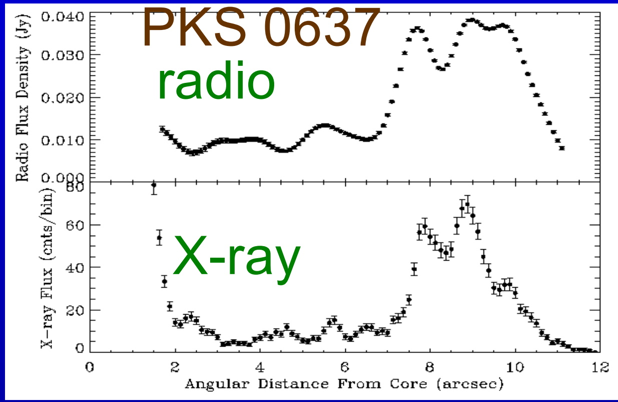
$4 < \delta < 14$ $\quad$ $10\mu G < B < 30\mu G$

Schwartz et al. 2005

Complications for the beamed iC- CMB interpretation for quasars



Sharp gradients in X- ray surface brightness at the edge of the knots unexpected since X- rays are from low- energy electrons with long lifetimes.



Chartas et al. 2000

May suggest jets are clumpy Tavecchio et al. 2003

But, if clumpy SSC can be higher & may not need such fast speeds Schwartz et al. 2000

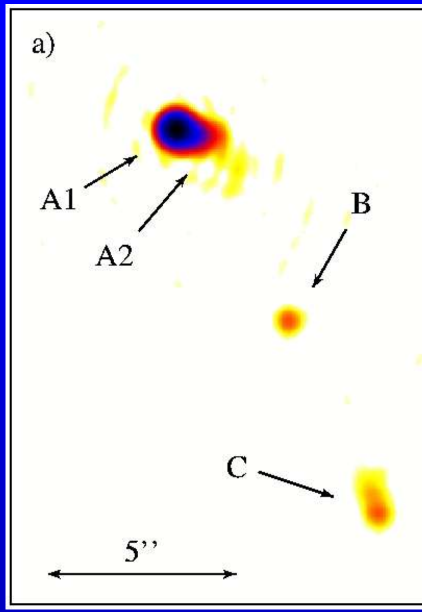
May suggest decelerations Georganopoulos & Kazanas 2004

May suggest bends in jet, since iC- CMB highly beamed

But, X- rays may be dominated by synchrotron emission from high- energy electrons in the Klein- Nishina regime Dermer & Atoyan 2002 *or separate electron population.*

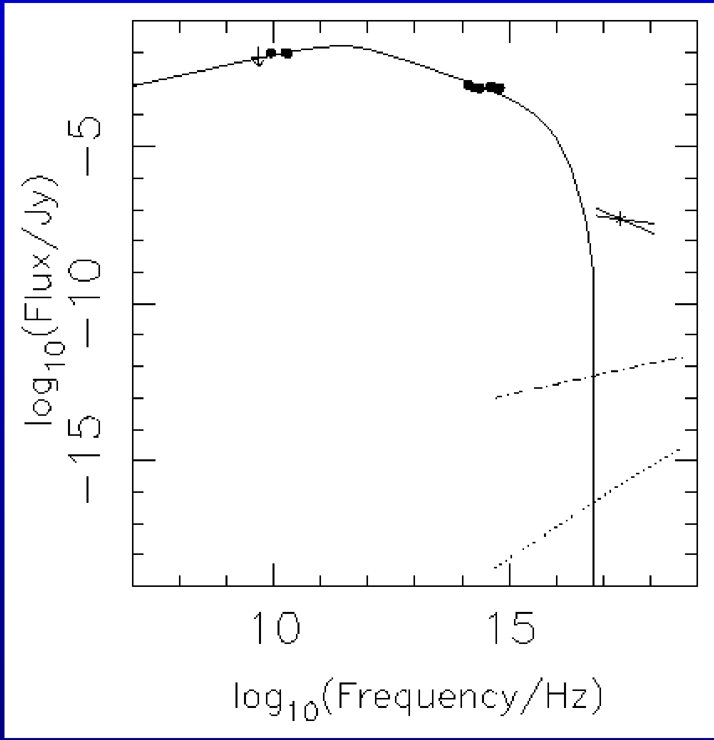
PKS 1421- 490

Gelbord et al. 2005



Quasar jets normally knotty, but here knot B is brightest feature in optical and X- ray

Assuming knot B is not an unusal core, and not a BL Lac interloper, difficult to explain except by synchrotron radiation from a second electron population.



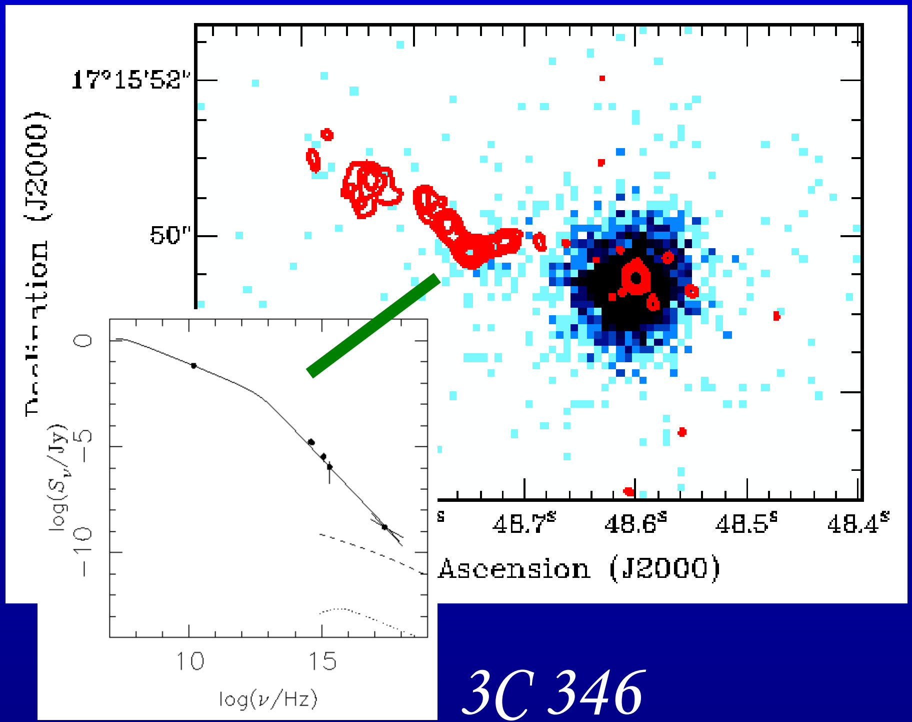
See also QSO 0827+243

Jorstad & Marscher 2004

Unboosted high- power jets

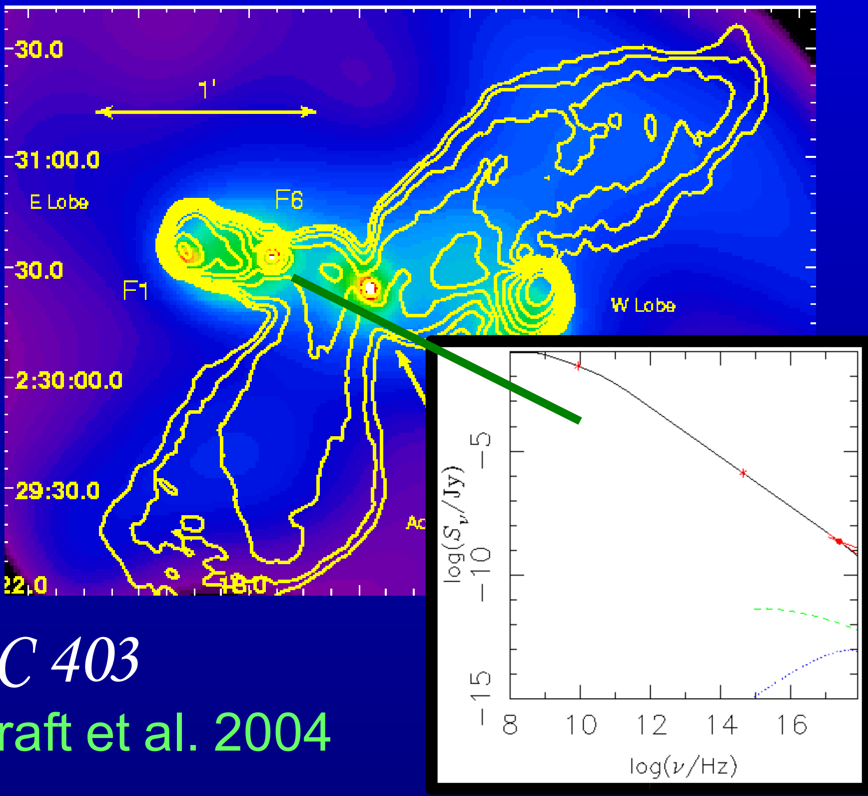
Jets in the unboosted counterparts of quasars (i.e. powerful radio galaxies) have been harder to detect.

X- ray detections tend to be of synchrotron knots. Any iC- CMB would be beamed away from us.



3C 346

Worrall & Birkinshaw 2004



3C 403

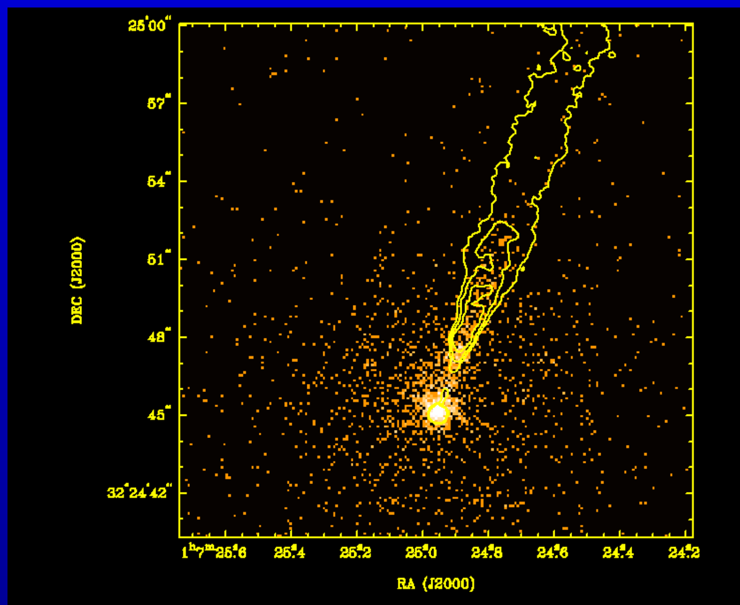
Kraft et al. 2004

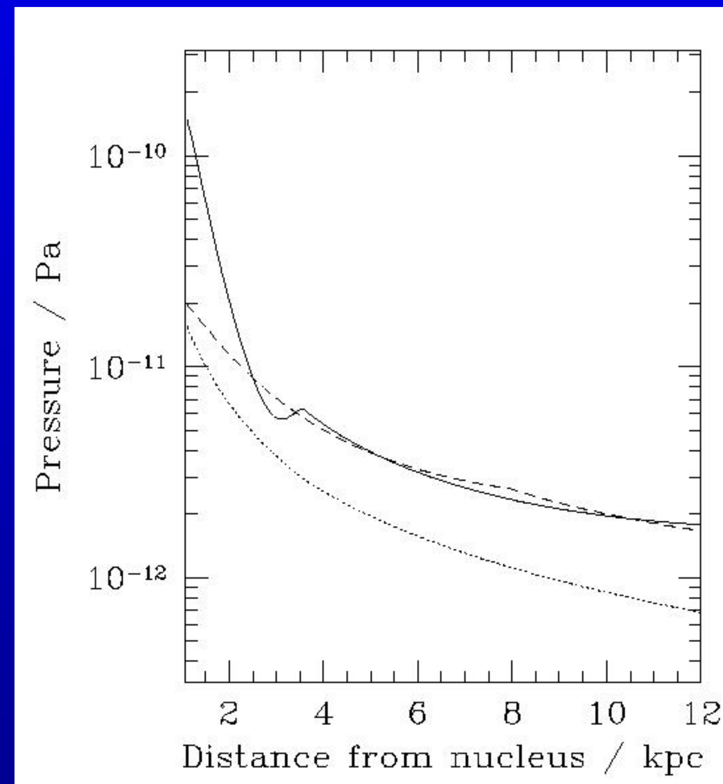
3. *What keeps jets collimated?*

X- ray gas too tenuous support high- power jets (cf lobes). Low power:

3C 31. Radio jet- sidedness velocity mass entrainment density and pressure model (Laing & Bridle 2002) *gives good match to X- ray pressure* (Hardcastle et al. 2002).

Chandra image with radio contours





Solid line: pressure in radio source

Dashed line: pressure of external gas

Dotted line: synchrotron P_{min}

Model being applied to a 2nd low- power source

4. What is jet plasma - electron/proton or electron/positron?

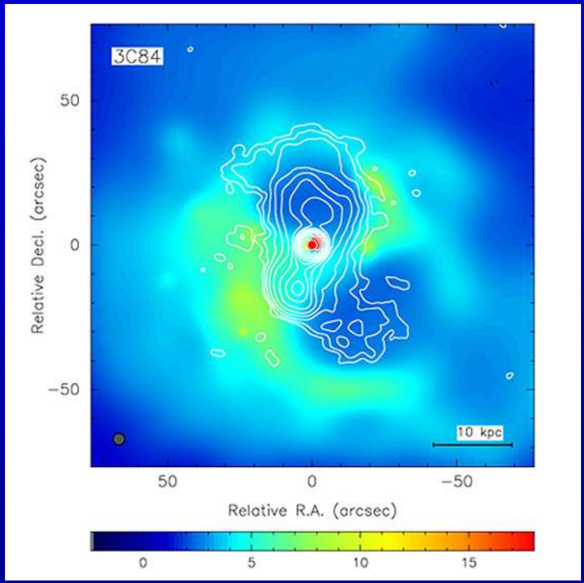
Radiators: electrons (& positrons if present)

Energy carriers: from core to lobe, without losing all energy to radiation heavy particles, i.e., protons to balance charge.

(CR p spectrum has normalization 100x e).

Poynting flux suggested alternative Rees 1971

Low power sources: tend to need protons to support radio structures from pressure collapse, e.g., NGC 1275



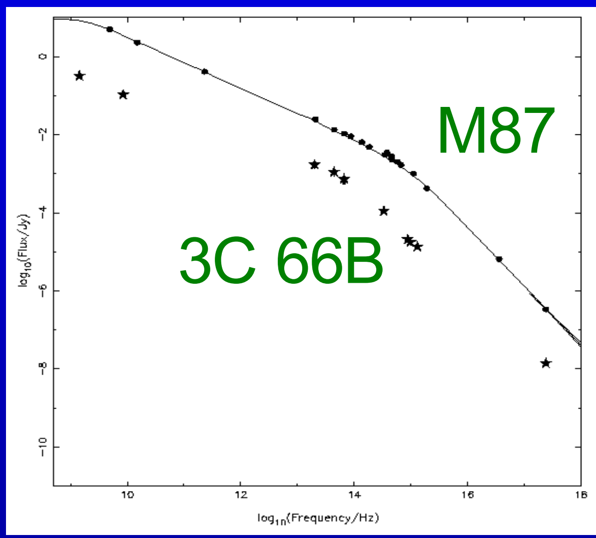
Fabian et al. 2002

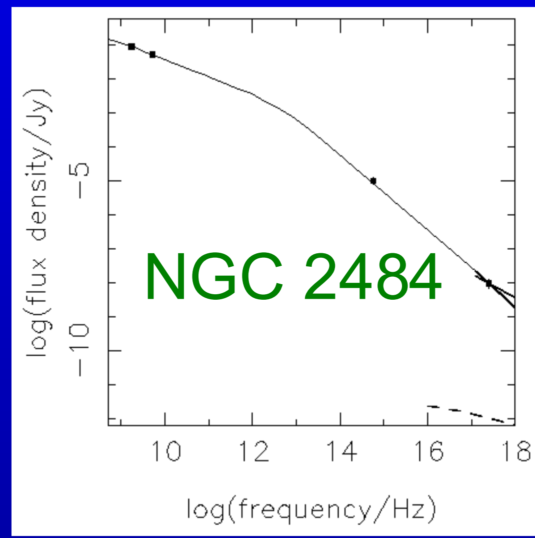
High power sources: minimum energy between electrons only and field seem to apply, and no need to add protons for pressure support.

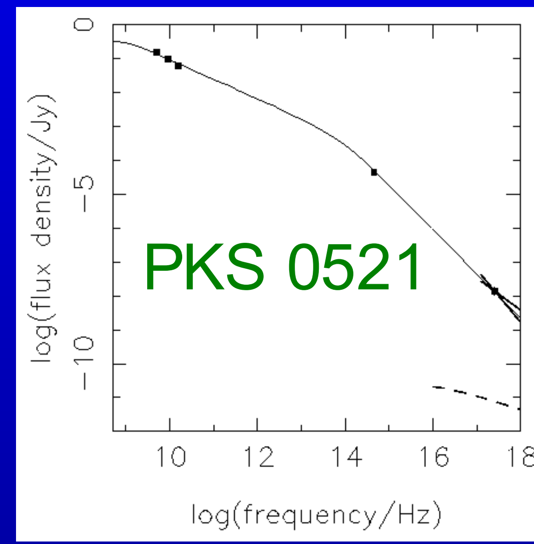
5. Where & how does particle acceleration occur?

low- power jets: uncontroversial that X- rays are synchrotron

X- rays too bright and spectrum wrong for inverse Compton







Böhringer et al., Hardcastle et al., Worrall et al. 2001, Birkinshaw et al. 2002.

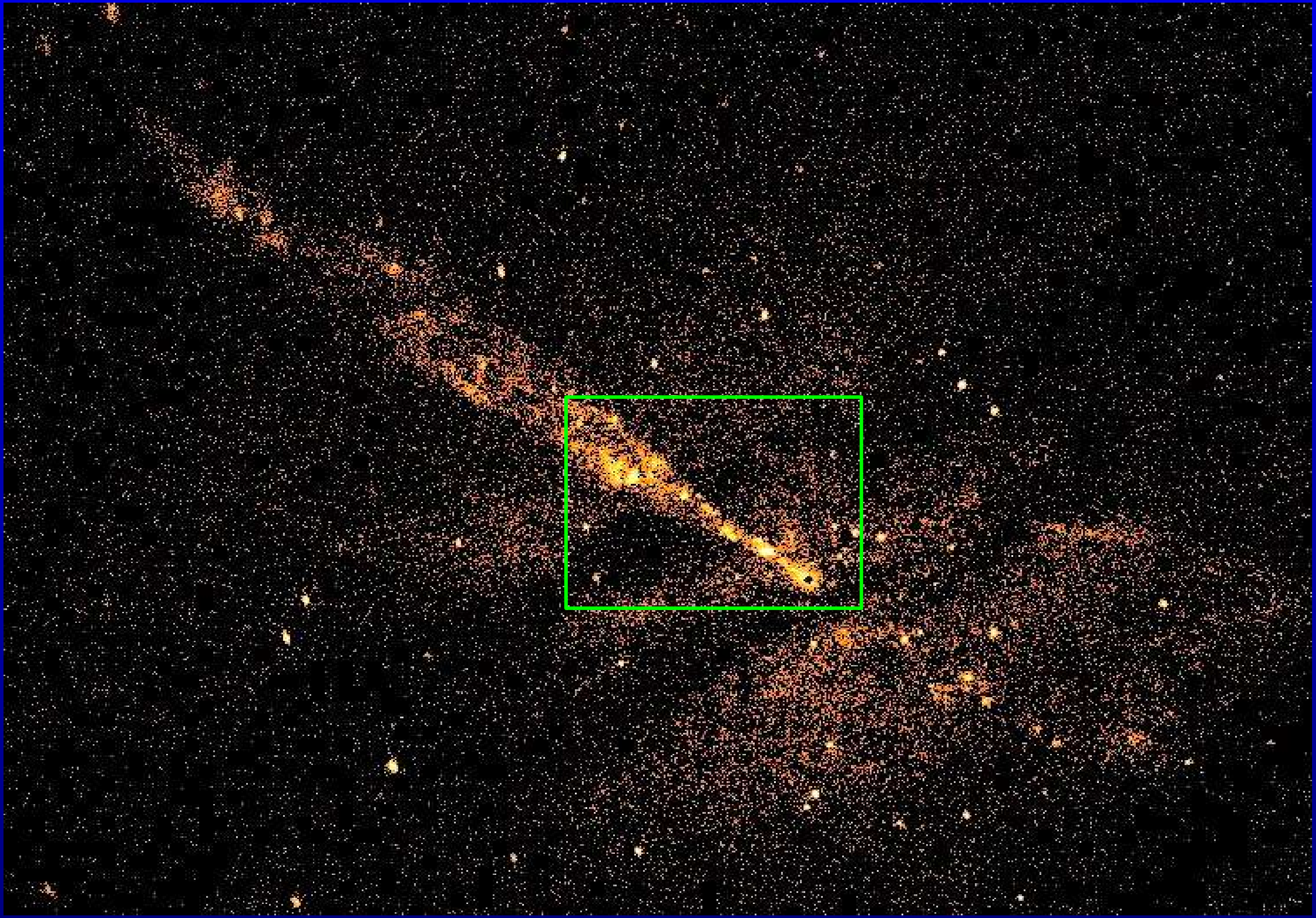
B_{me} ~ 100μG. Electron lifetime tens of years in situ acceleration.

How?

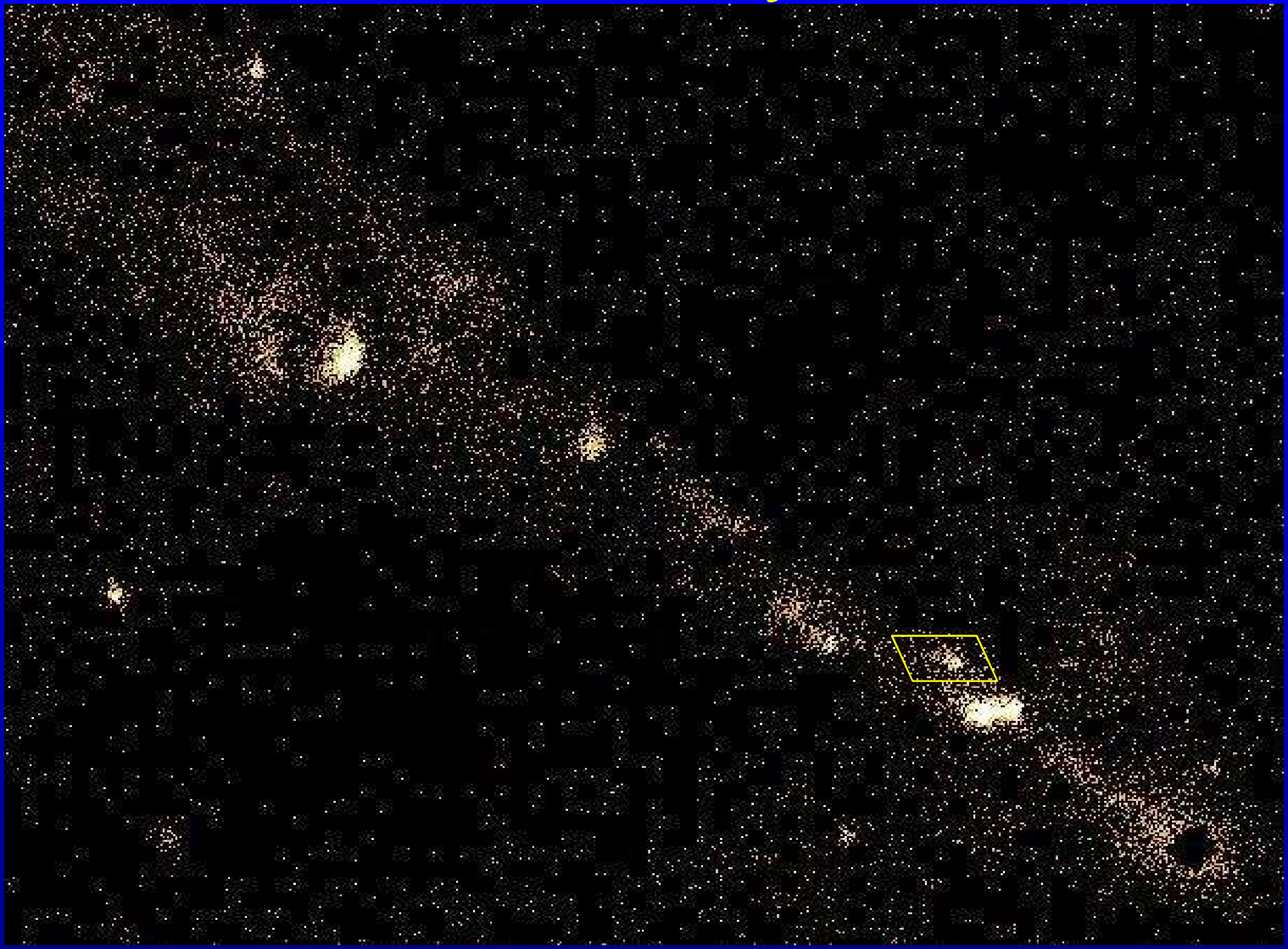
- *Single large- scale shock feature?*
- *Population of shocks in a messy structure (e.g., supersonic MHD turbulence)?*

Chandra observations of Cen A

Jet and weak counter- jet Hardcastle et al. (2003)

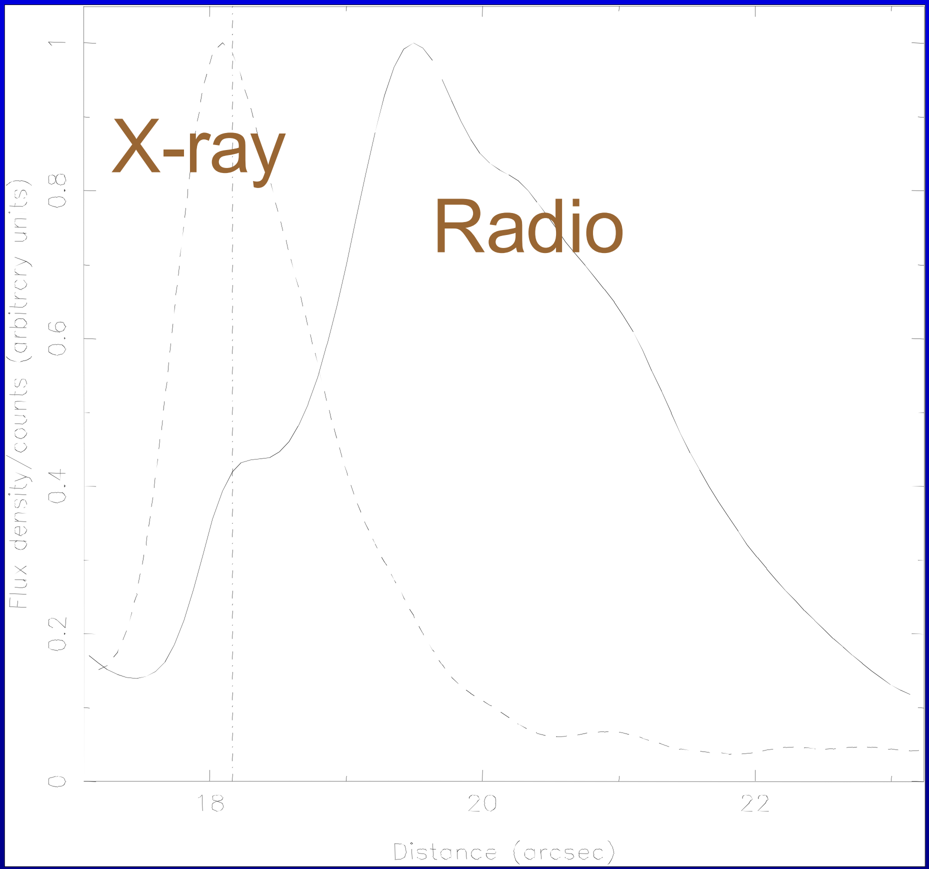


Chandra observations of Cen A

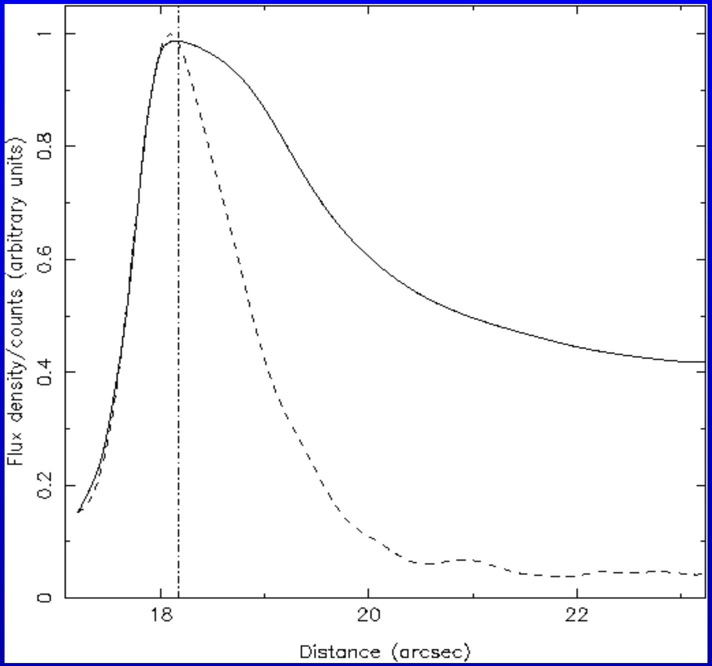


Radio: proper motion (V_{app} ~ 0.5c) in diffuse emission and some of the knots seen over 10 yrs. Others stationary.

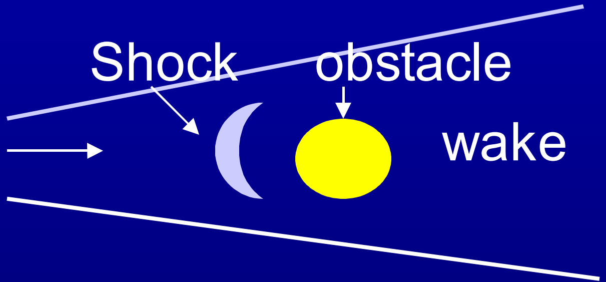
Knot profile



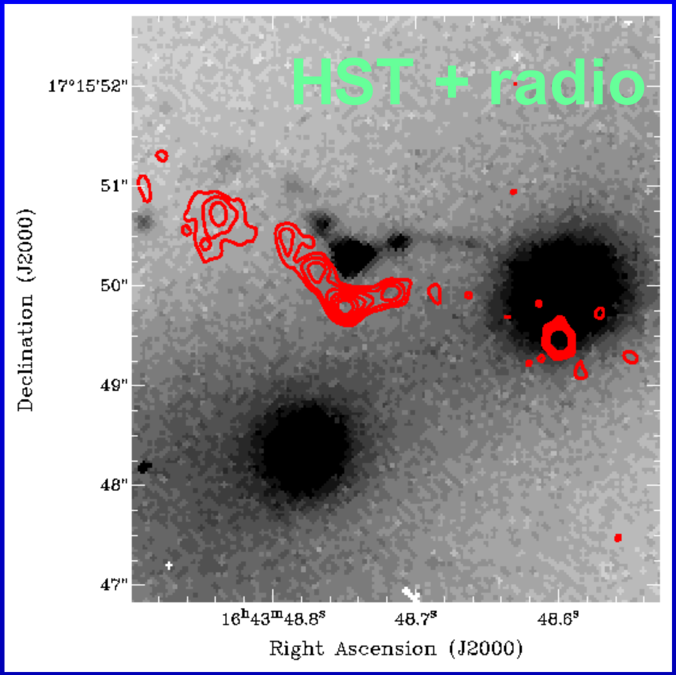
Acceleration and advection (toy profile)

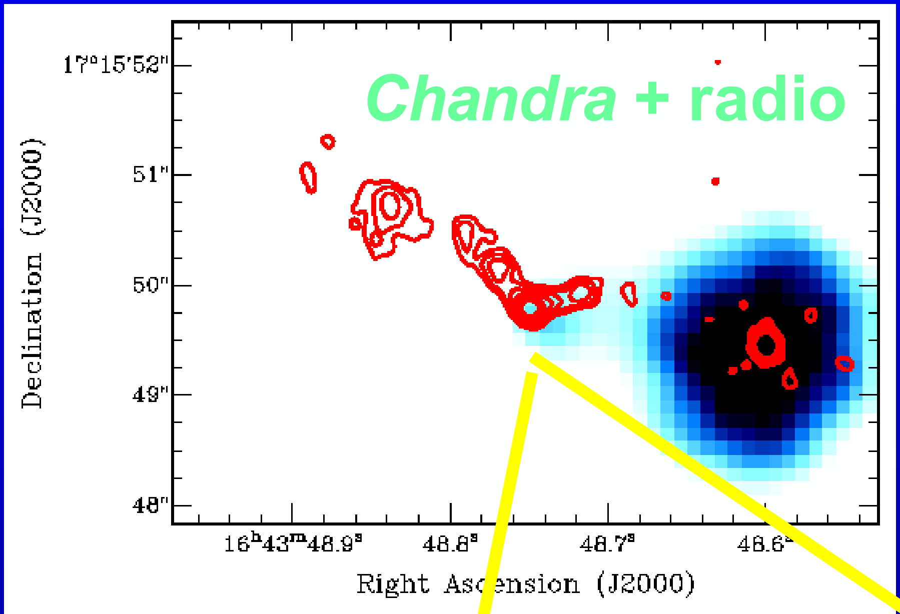


Alternative toy model

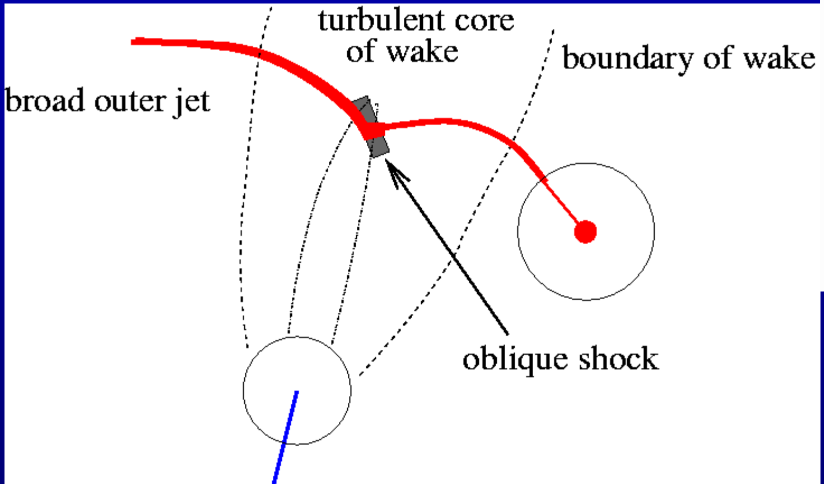


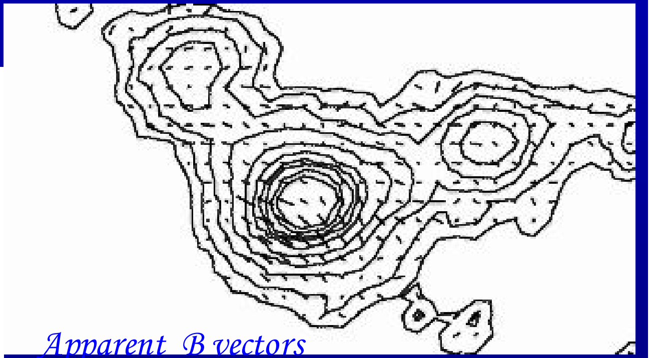
Synchrotron knot in high- power FRII 3C 346



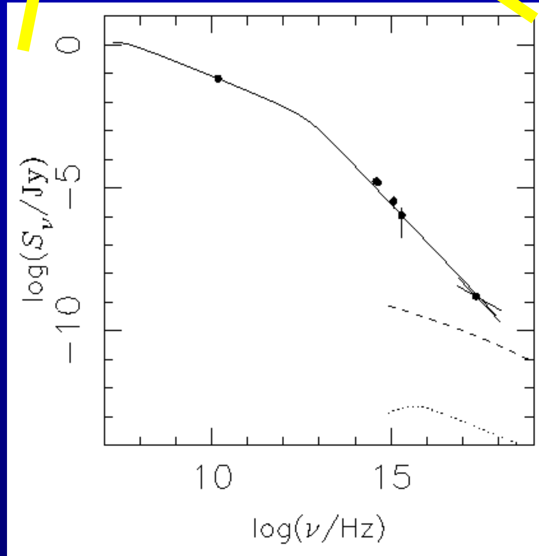


Worrall & Birkinshaw 2005



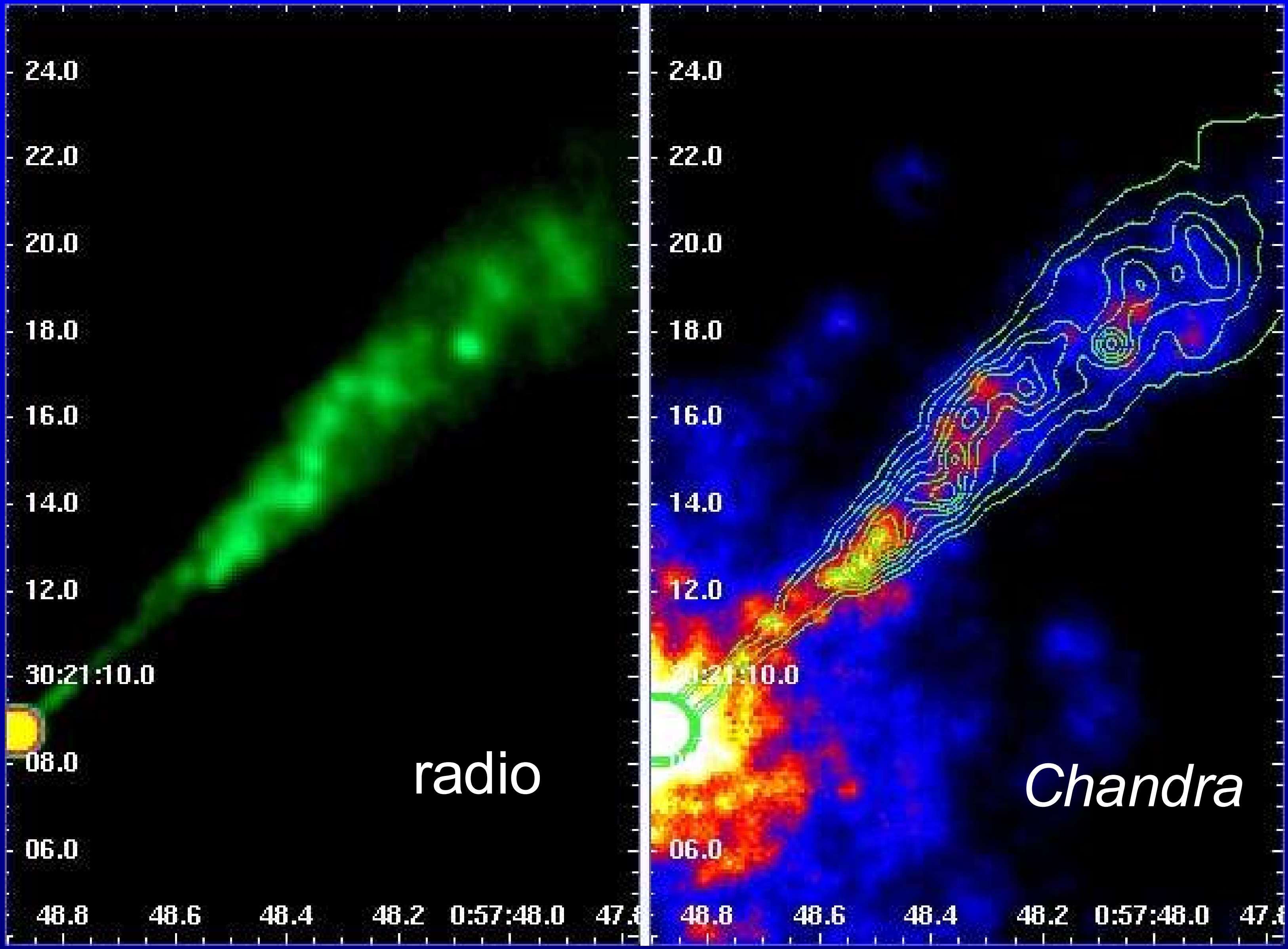


Perlman et al 2005



NGC 315

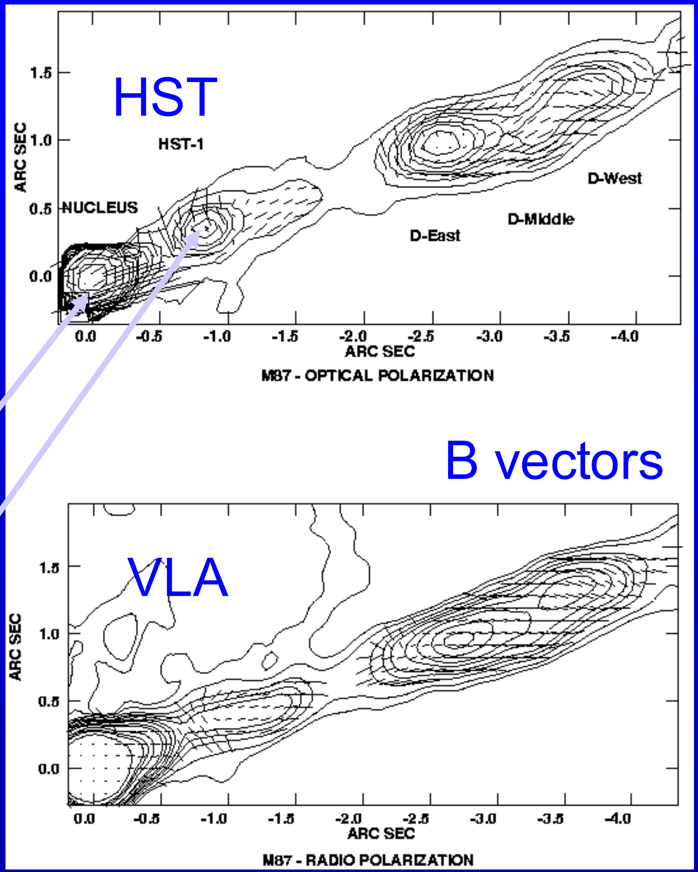
Worrall et al. 2005



Optical Polarization

Polarization fraction & direction changes are signatures of shocks

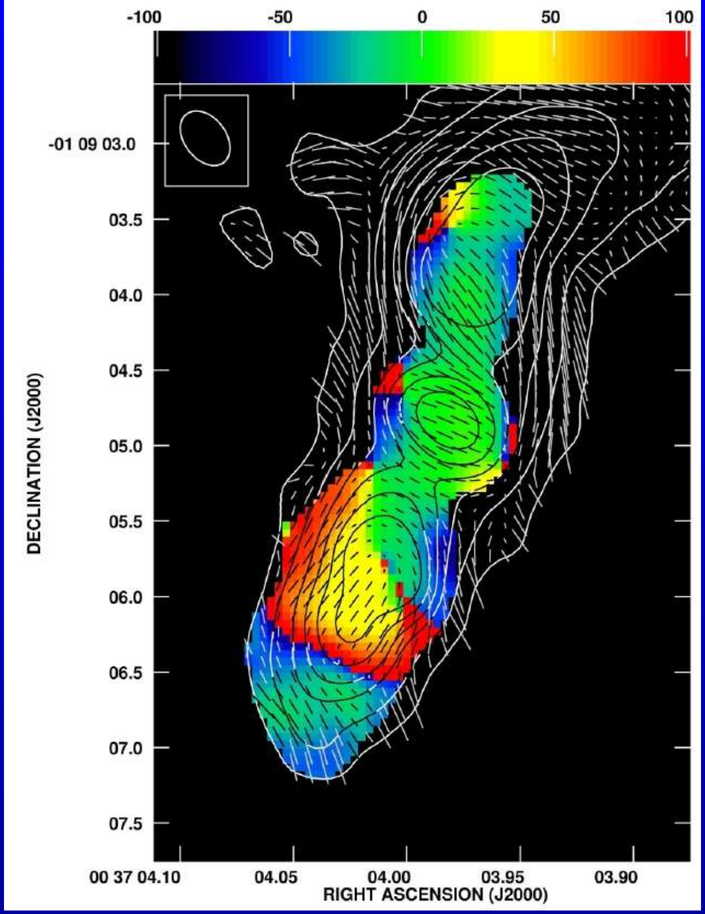
e.g. M 87. Optical narrower than radio. Compressed transverse magnetic fields at the base of bright knots Perlman et al. 1999

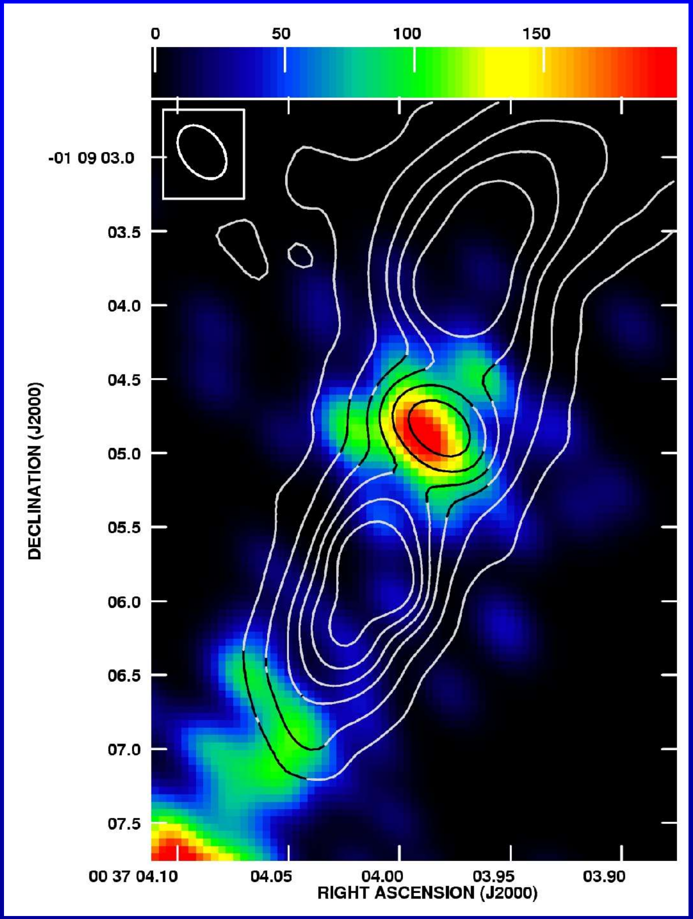


Variability

X- ray and optical variability on timescale of months consistent with shock acceleration, expansion and energy losses Harris et al. 2003; Perlman et al. 2003.

3C 15 Dulwich et al. 2005



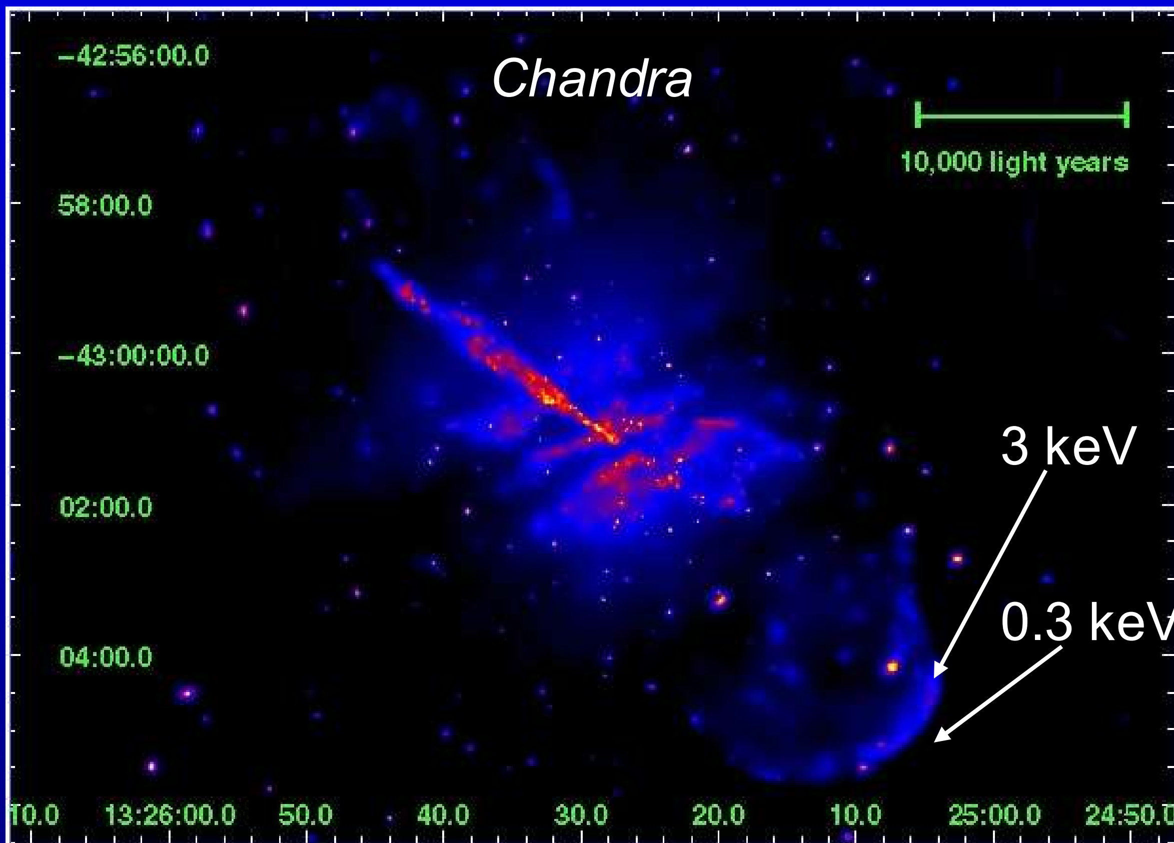


Radio intensity and polarization (apparent B) vectors. Color shows relative alignment of the radio and optical polarization.

Color shows Chandra

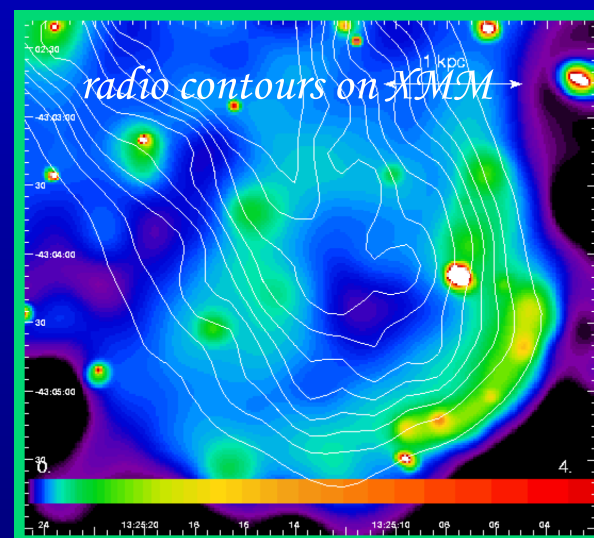
6. *Which radio structures are dynamical & which in equilibrium?*

All are dynamical. Beam- heads of high- power sources should be most dramatic. Shame no good temp/velocity measurements of shocked gas to test jet speed



Cen A

Kraft et al. 2003



Cen A is a bubble waiting to burst!

7. How is jet energy transferred to the surrounding medium?

Increasingly obvious that radio sources provide an important heat source for clusters

Gas in groups containing a bright radio galaxy is systematically hotter than the gas in groups without Croston et al. 2005

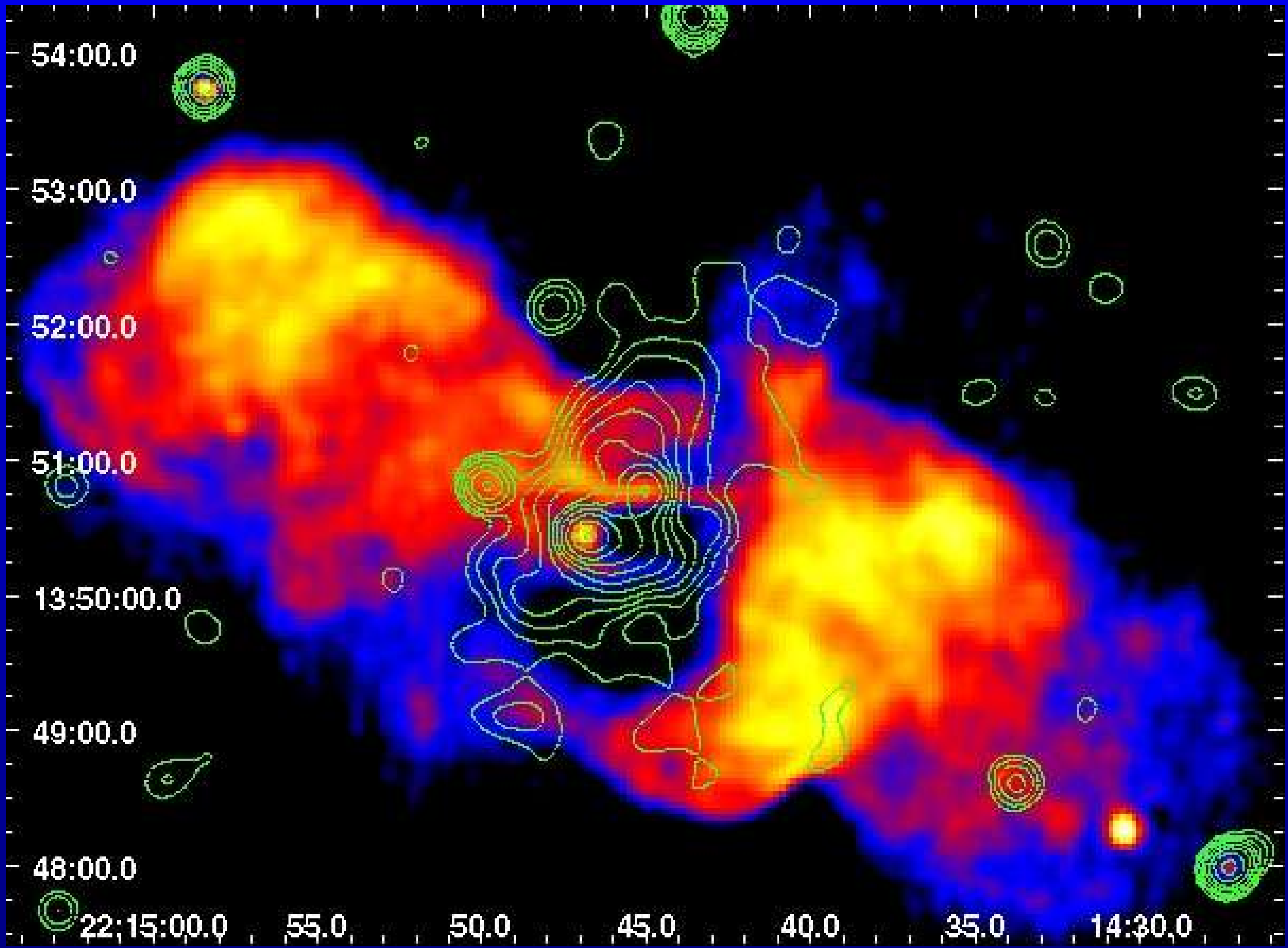
Heating must have set in at least by z=0.5 since cluster properties have not dramatically changed since then Bauer et al. 2005

Low- power rather than high- power radio galaxies are more often in clusters

3C 442A

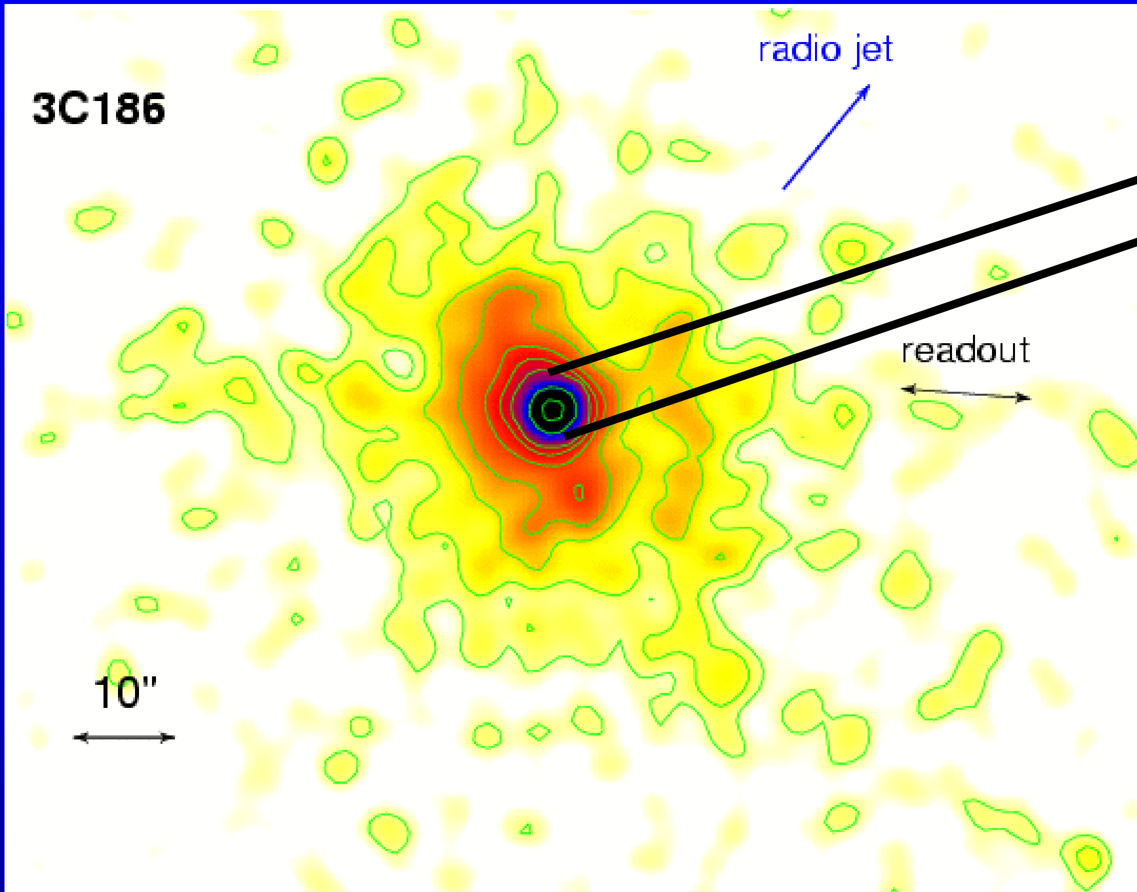
Kraft et al. 2005

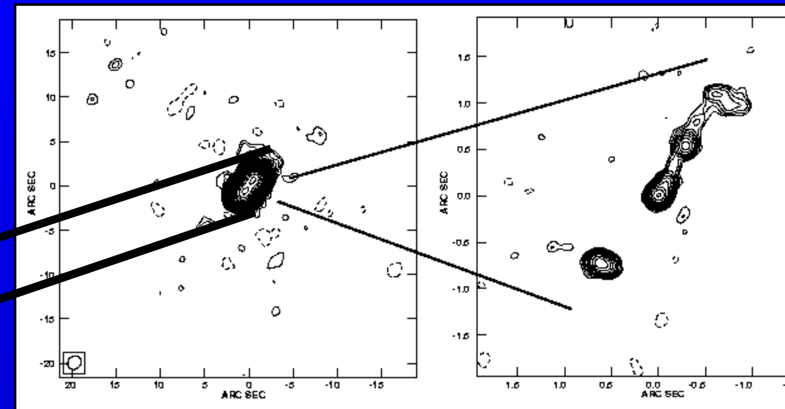
Latest of the z < 0.1 3CRR sample to be observed with Chandra



Chandra contours on radio color

Siemiginowska et al. 2005





z ~ 1

~5 x 10^5 - year old GPS radio galaxy in a kT~5 keV cluster.
Enough power for cluster heating now. Past and future?

Conclusions: best- buy guesses

1. Are the radio structures in a state of minimum energy?

   On average yes between radiating particles (e- /e+) and B field

2. How fast are jets?

   Velocity gradients with spines >>0.7c even in quasar jets at ~1 Mpc

3. What keeps jets collimated?

   Low- power: gas. High- power: ??

4. What is jet plasma – electron/proton or electron/positron?

   Relativistic heavies must be present. More theory needed.

5. Where & how does particle acceleration occur?

   Varies. Better spectra & time- resolved X- ray data needed

6. Which radio structures are dynamical & which in equilibrium?

   All dynamical.

7. How is jet energy transferred to the surrounding medium?

   Varies. Open questions. Need to observe complete samples.