X-ray Observations of Large Scale Jets in AGN

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outline

- Part I: Introduction – Short Review of current situation.
- Part II: Difficulties for application of physics
- Part III: Jet Structure

  hotspots, continuous, and knots

CREDO -1
(a personal perspective)

- Sync. emission is hopelessly mired in the uncertainty of the value of B: total E; pressure; halflife, etc. Very tenuous passage to N(E)
- IC/CMB is not much better because Γ is uncertain. Throughout this talk I use lower case γ for the Lorentz factor of the radiating electrons and upper case Γ for the bulk Lorentz factor of the jet. δ is the Doppler beaming factor.

Electron Halflives

- $\tau = \dfrac{10^{13}}{\gamma \{B'^2 + 40(1+z)^4 \Gamma^2\}}$ years
- for Synchrotron; X-ray frequencies of 10^{18} Hz,

  $\gamma = 0.0005 \sqrt{[\nu(1+z)/B(1)]} \approx 10^7$,

  and τ is of order a year.

IC/CMB with Γ > 5 (often >10)

$\gamma = \{ 2 \times 10^{-6} / \Gamma \} \sqrt{\nu}$ and for $\nu = 10^{18}$, $\gamma \approx 100$
and $\tau \geq 10^5$ years

CREDO -2
The X-ray Emission Process for Quasar Jets

- Whereas there is little debate about radio and optical for both FRI and quasar jets, there is no concensus for the X-rays from quasars and FRII radio galaxies.
- SYNC with $\gamma \approx 10^7$ and halflife ≈ 1 year (like FRI);

  OR
- IC/CMB with $\gamma \approx 100$ and halflife ≥ 100,000 years

X-ray Emission from Jets is a "Win-Win" Game

- Either we get info about the very top end of the relativistic electron spectrum, N(E),
- OR we learn about the very bottom end!
- ***

- **NEITHER END IS ACCESSABLE BY OTHER MEANS**

****

- and now for the bad news…..we don't know which end we are looking at!

CREDO - 3

- essentially all X-ray jets are single sided; hence the Γ,δ [***of the emitting plasmas***] are of order a few or greater.
- The emitting plasmas consist of relativistic ("hot") electrons, but the "fluid" responsible for the energy flow consists of cold pairs, normal plasma (p + e), or Poynting flux.

Part II: Difficulties of applying the physics

- We want to obtain the parameters of the emitting regions….the exponent of the power law describing N(E); break energies; cutoff energies; B field strength; beaming factor, θ, & Γ. Plus all the derived quantities like energy content, pressure, etc.

Synchrotron Assumptions

- <B>is a valid concept; usually B_{eq}
- Emitting volume is same for all wavebands
- SED is concave downwards, with cutoffs.
- filling factor~1 (as opposed to filaments of high B with particles both between and within the filaments)

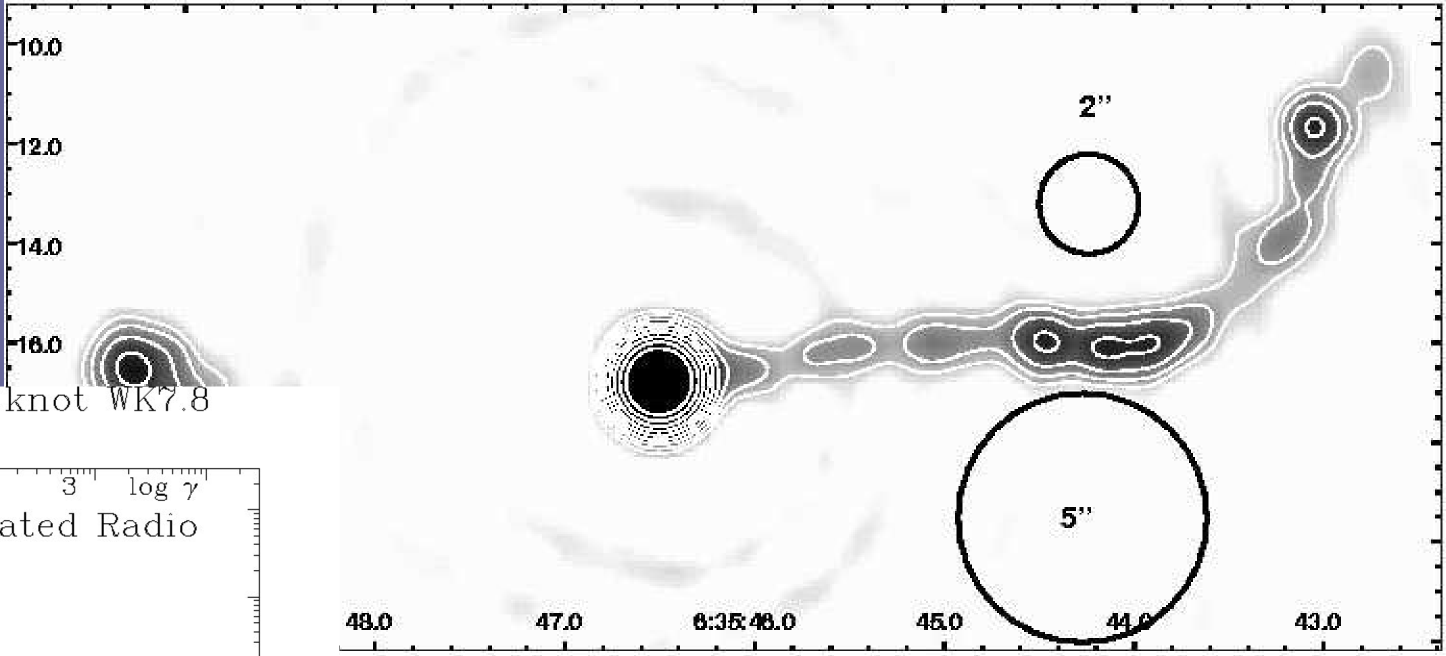
IC/CMB assumptions

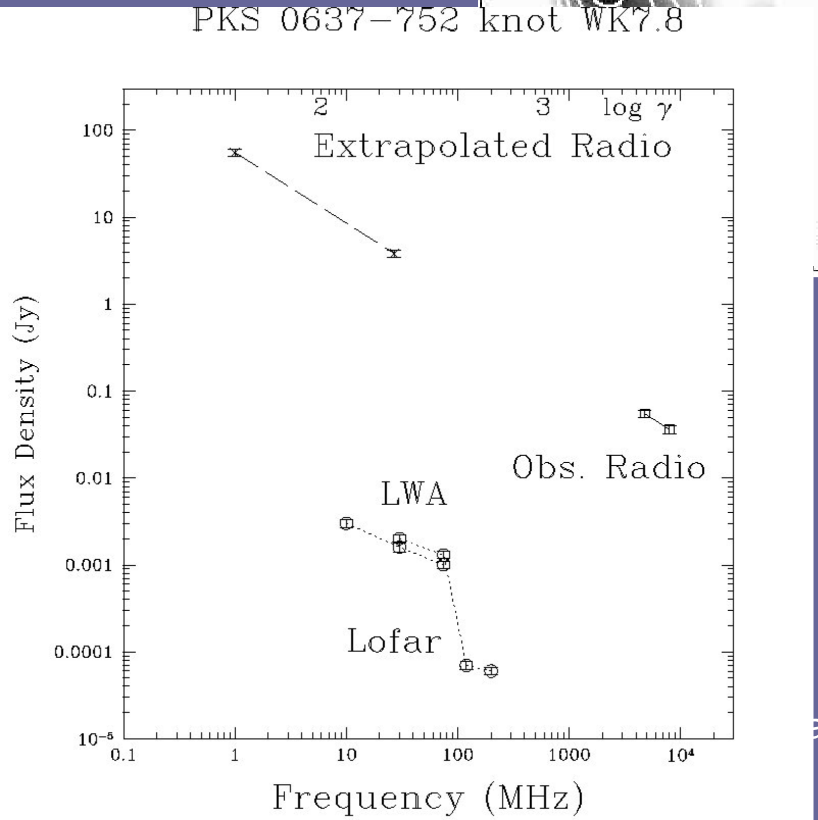
- single emitting volume containing a single PL extending from circa $\gamma=50$ to $\gamma=500000$
- Γ is large enough to produce obs. X-rays
- B_{eq} required to pass from radio to N(E)
- $p=2\alpha_r+1$ is the exponent of lower part of N(E), as well as of the ‘observed’ part.

The next image……

- shows the extent of the extrapolation (in frequency, or, top axis, electron Lorentz factor) between the observed segment of the spectrum of a knot in a jet, and the segment responsible for the X-ray emission for the IC/CMB process.
- It also demonstrates that new radio telescopes under development will help to test this extrapolation.

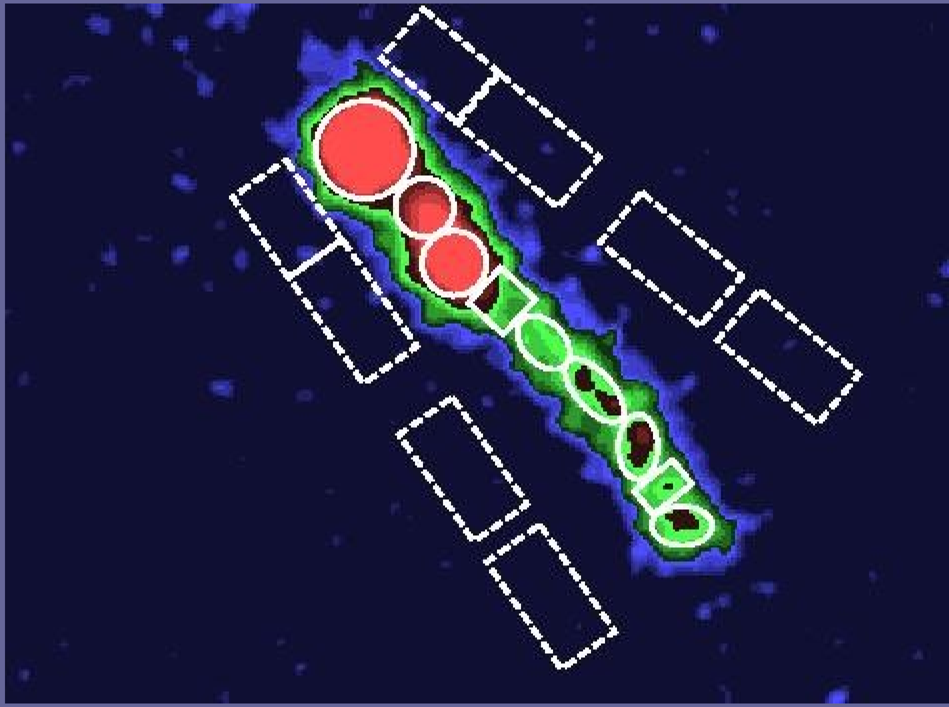
PKS 0637 – Quasar with Jet



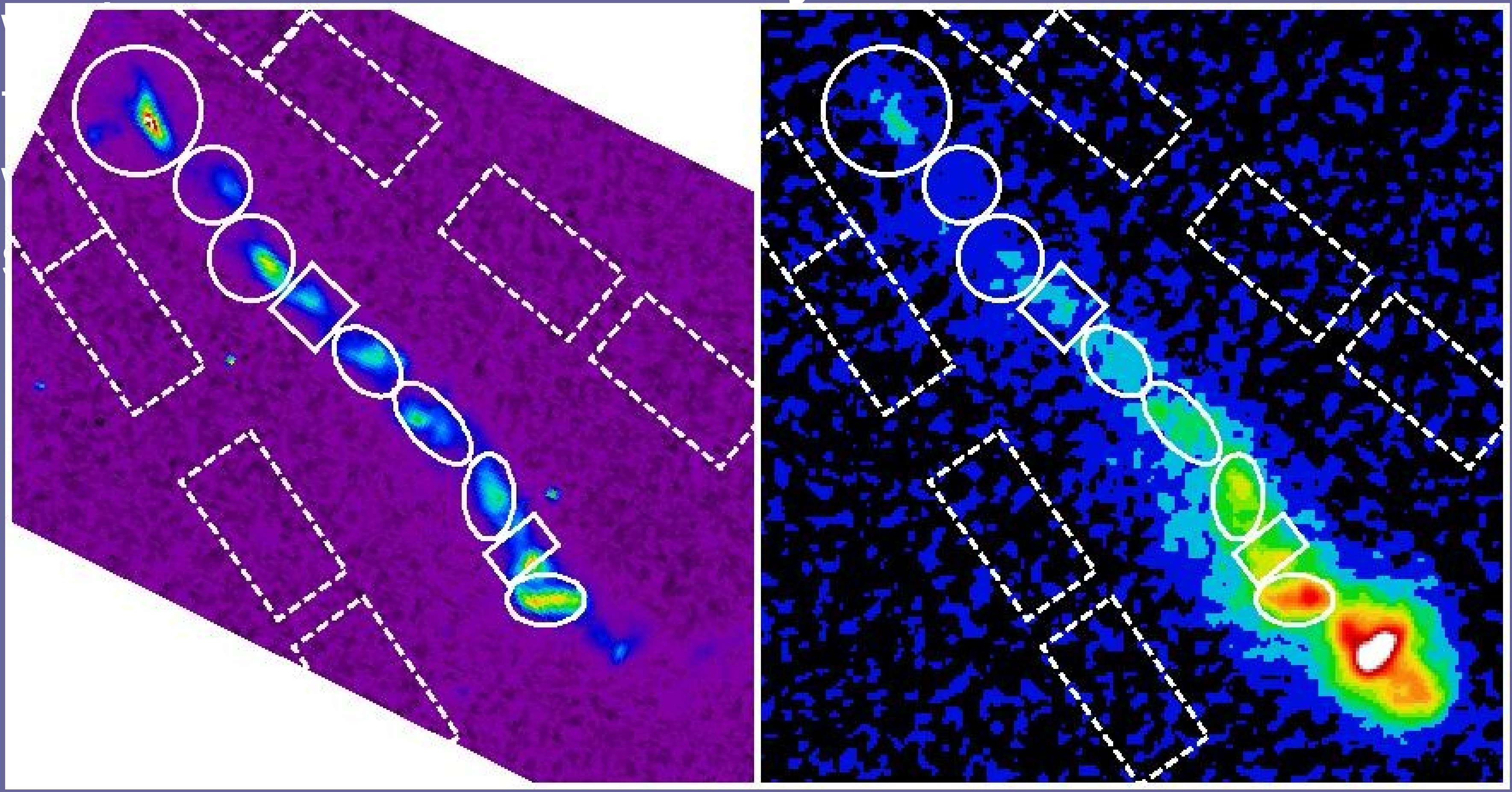


Emitting Volumes: 3C 273

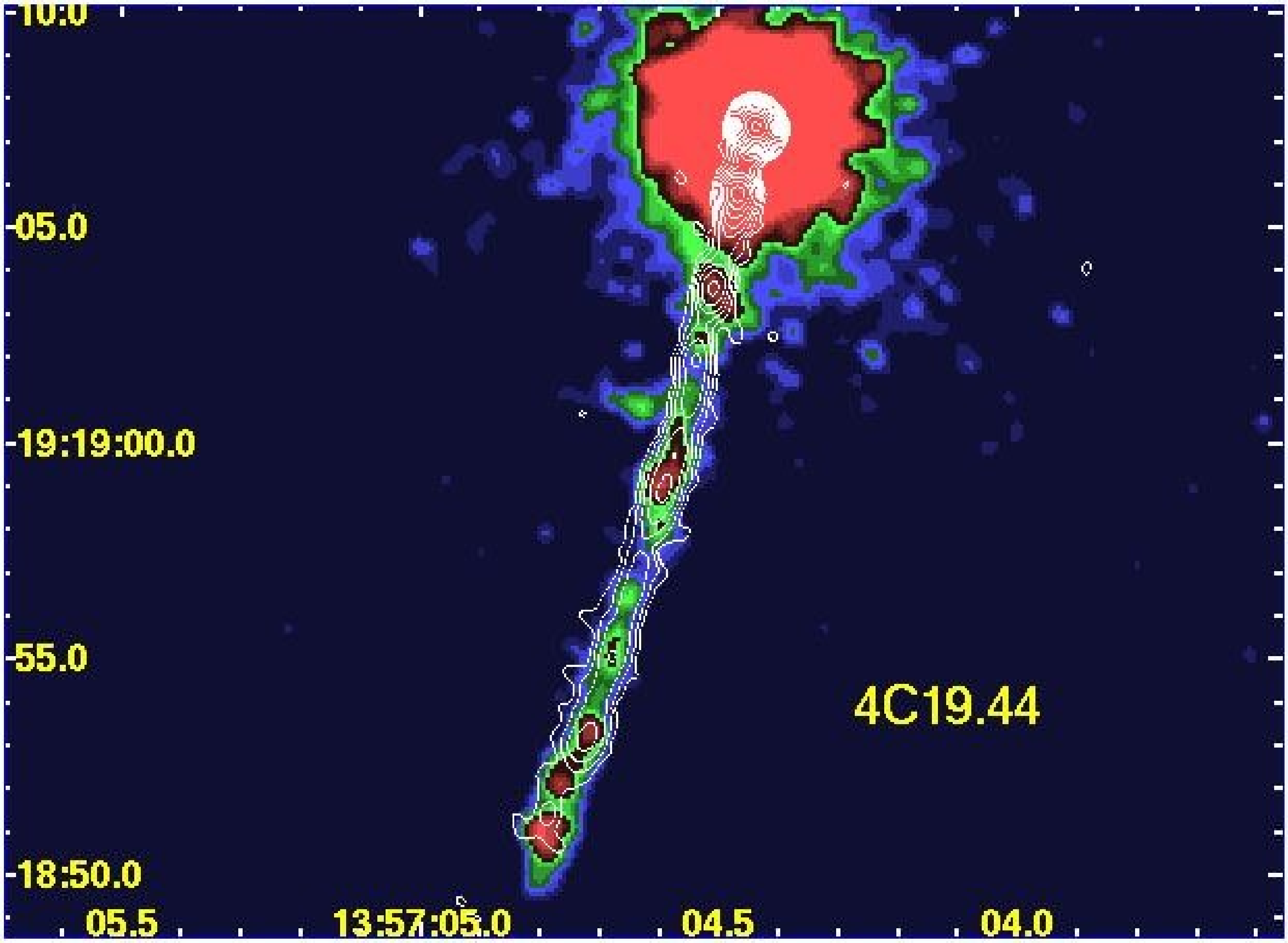
- We want to construct SED's for several bits of a jet. We construct photometric regions based mainly on the X-ray morphology.
- But when we use the same regions for optical and radio…



…the emitting volumes may not actually be the same size as for the X-rays



4C 19.44: global X/radio correspondence is good; however, in detail, this is not the case.



Emitting Volume: Multi zone models:

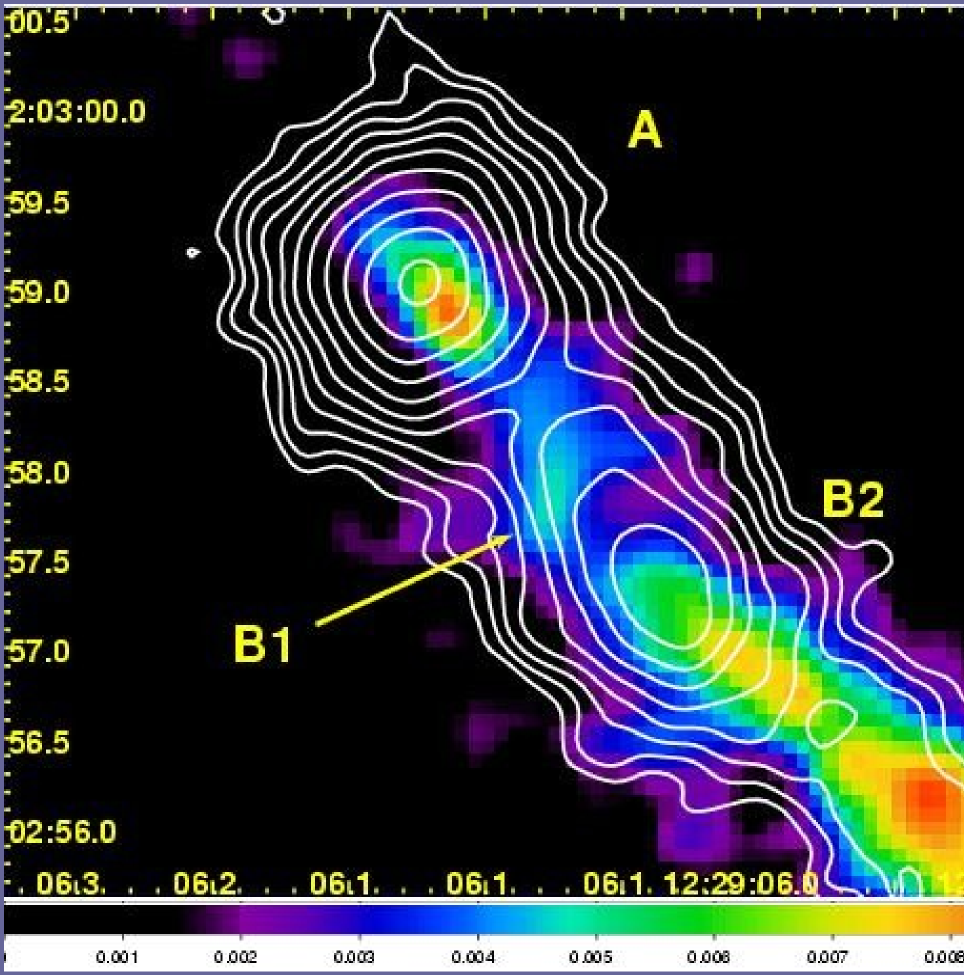
- Laing and Bridle have modeled some FRI jets and argue for the necessity of velocity structure across the jet
- Celotti and others have suggested a fast (Γ>10) spine plus slower sheath on kpc scales.
- Uchiyama (poster #49) and Jester et al. find that a single zone is inadequate for the SED of parts of the 3C273 jet.

Emitting Volumes: Multizone Models

This permits more latitude for adequately fitting SED's, but ***any*** 2 zone model normally precludes the critical tests afforded by comparison of radio, optical, and X-ray data.

Emitting volumes: Mavericks

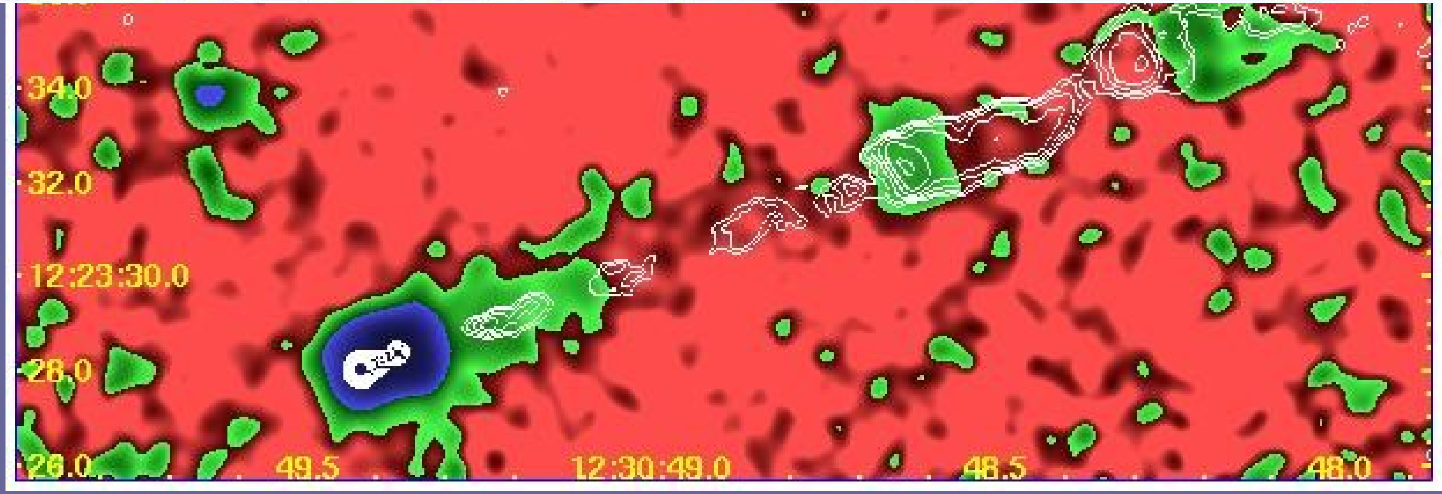
- While there is generally good correspondence between bands, some times we find notable exceptions.
- Here we see the radio (color) deviating from the X-ray (contours).



In the next slide…..

- Note the prominent X-ray emission beyond knot C where the radio contours show a kink to the north. In the bottom panel, we see the hardness ratio for this feature differs from that of knots B and C.


Chandra 98ks image (0.7-2keV); 8 GHz contours

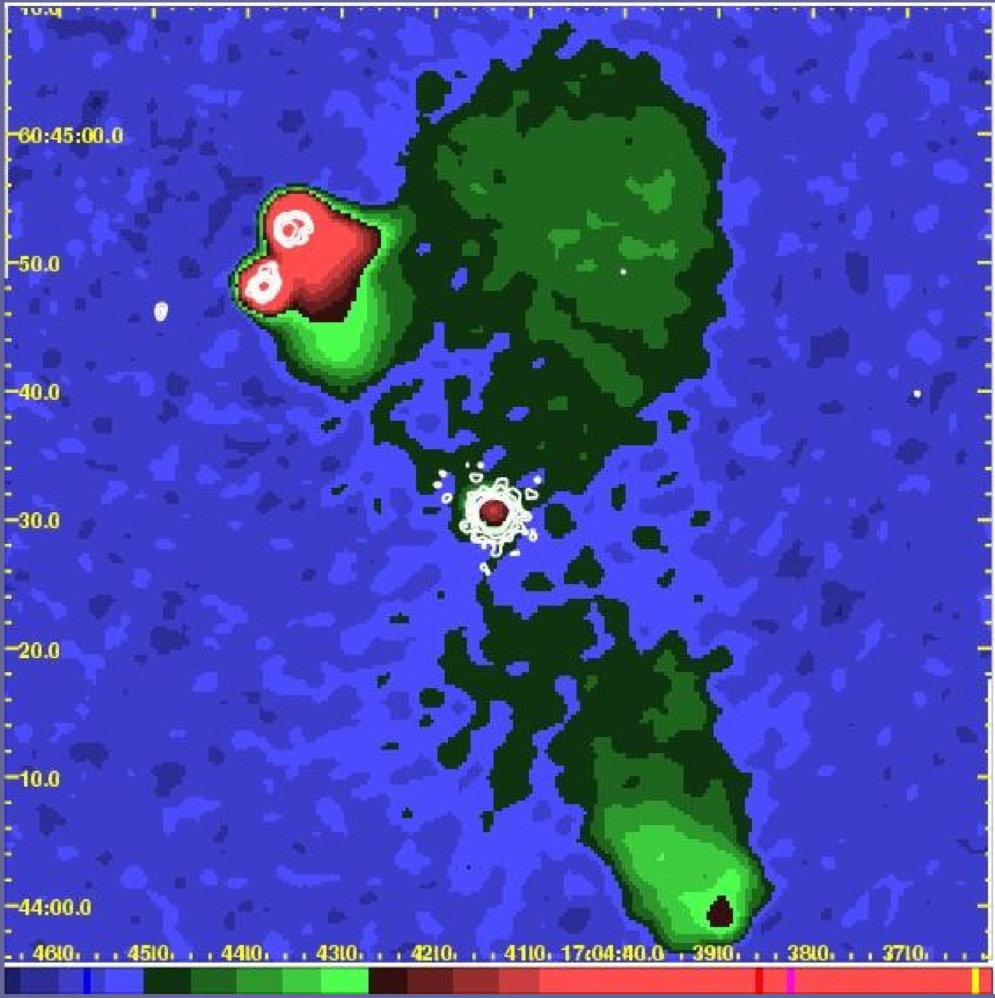

34.0
32.0
12:23:30.0
28.0
26.0
49.5
12:30:49.0
48.5
48.0

PART III: Features

- Hotspots
- Continuous emission between knots
- Knots

Distinguishing Hotspots from Knots

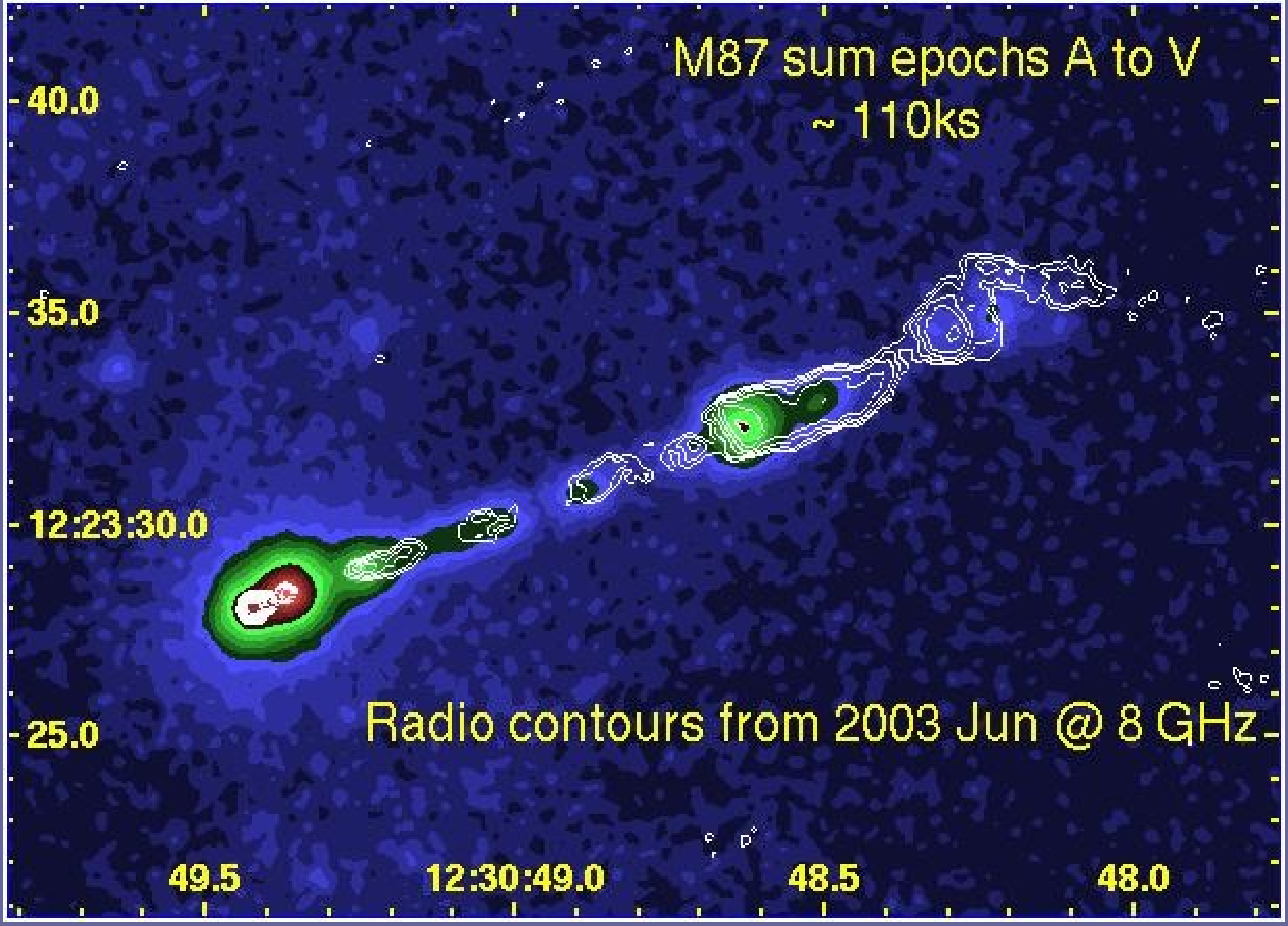
- Terminal HS where jet stops, but is emission always isotropic?
- ‘Classically’ SSC explains the X-rays, but there appears to be additional emission.
- 3C351: at least a factor of 25 between1.4 GHz power of N and S HS’s.
- Hardcastle will discuss on Friday.



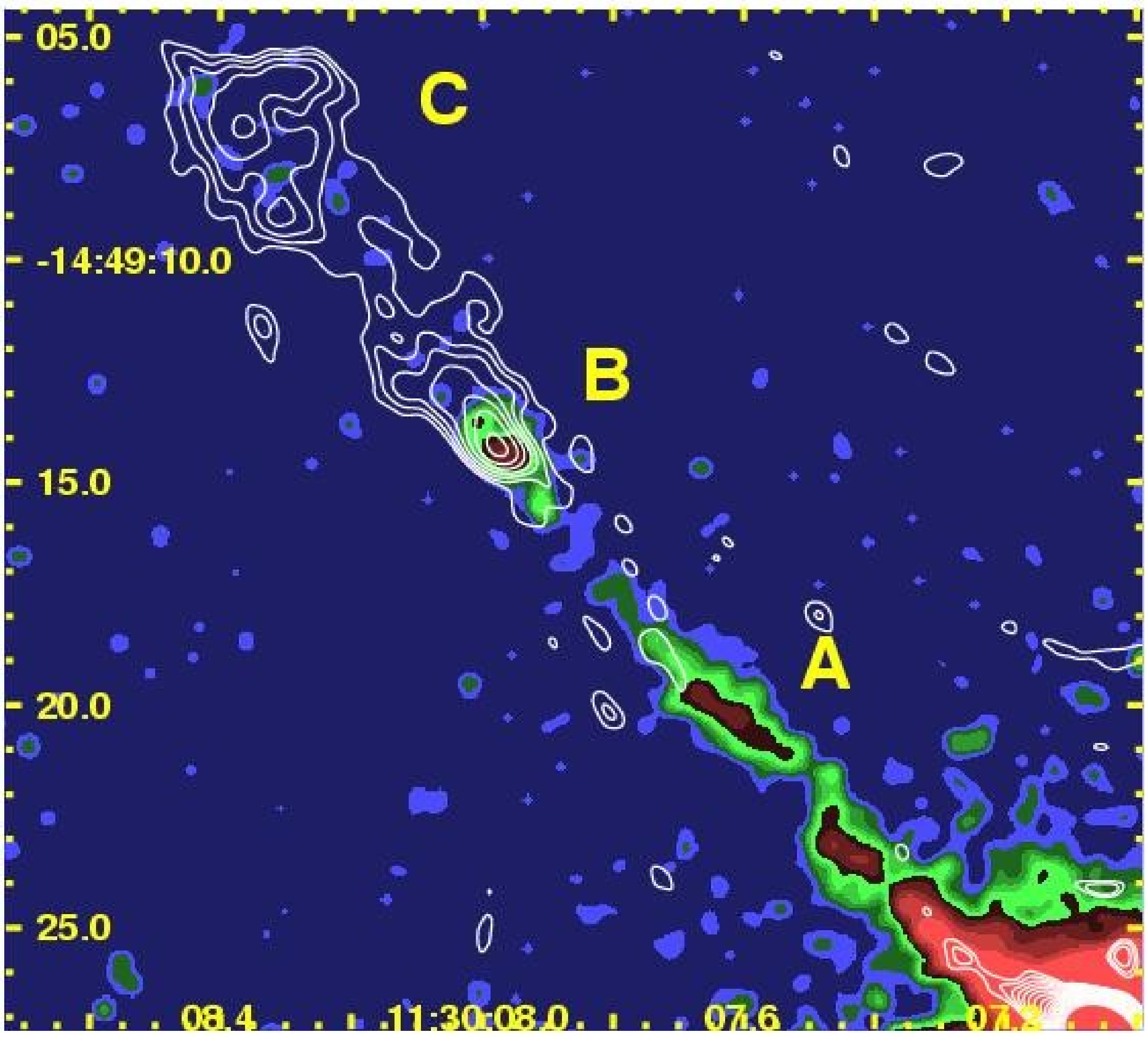
Continuous Emission between the knots

- If synchrotron, requires distributed acceleration (e.g. magnetic acceleration or boundary layer shear acceleration, ref: our hosts at this meeting)
- Could be underlying IC/CMB component.
- In either case we might expect α_x to vary between knots and inter-knot regions. ***Current evidence does not support this***.

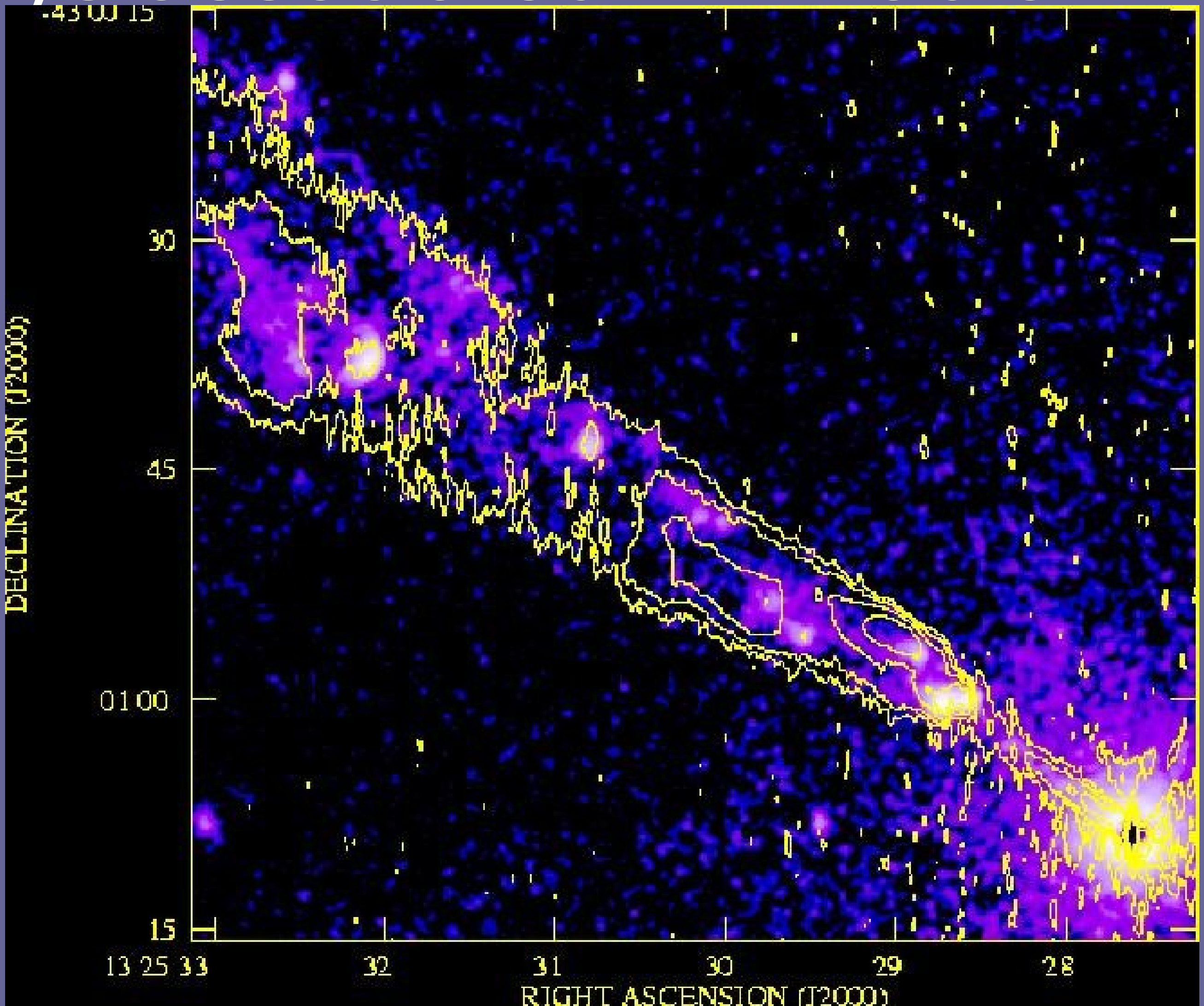
Inter-knot X-ray emission in M87



PKS 1127 @ z=1.1: most of the X-ray emission of the inner jet is not associated with bright radio.



Cen A: another example of distributed X-ray emission, not always associated with radio knots.



Conventional knots: shock acceleration

- Downstream from the shock, we expect to ‘loose’ the highest energy electrons sooner than the lower energies and we assume that we can use distance from the shock as an ‘age’ indicator.
- Sync: X-ray brightness should drop faster than radio.
- IC/CMB: opt. & rad. should drop faster than X-ray

Alternatives to Shocks for Knots

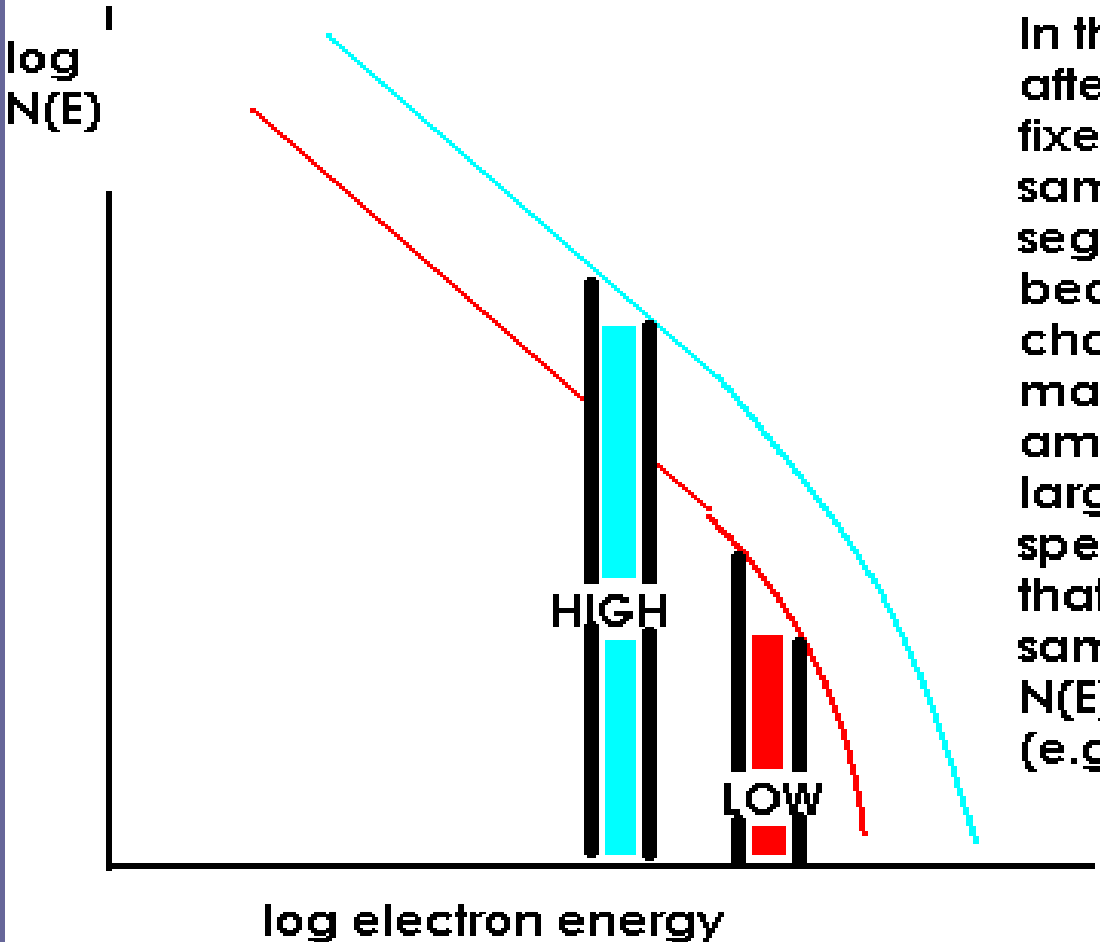
- CHANGE OF DOPPLER FACTOR:
- from change of Γ (unlikely), or
- from change of θ (e.g. helical trajectories)
- ‘BURST’ TYPE EJECTION FROM SMBH.
- CONTRACTION - EXPANSION (i.e. not necessarily in a shock)

EXPANSION LOSSES

- SYNCHROTRON
- all electrons lose same fractional E
- emissivity drops $\propto B^2$
- N(E) is smaller for fixed observing band.
- ***there are 3 effects reducing the emissivity!***

- INVERSE COMPTON
- all electrons lose same fractional E
- [u(v) drops for SSC]
- ***for IC/CMB, there is only one contribution to decay.***

Compression/Expansion for synchrotron emission with a fixed observing band.



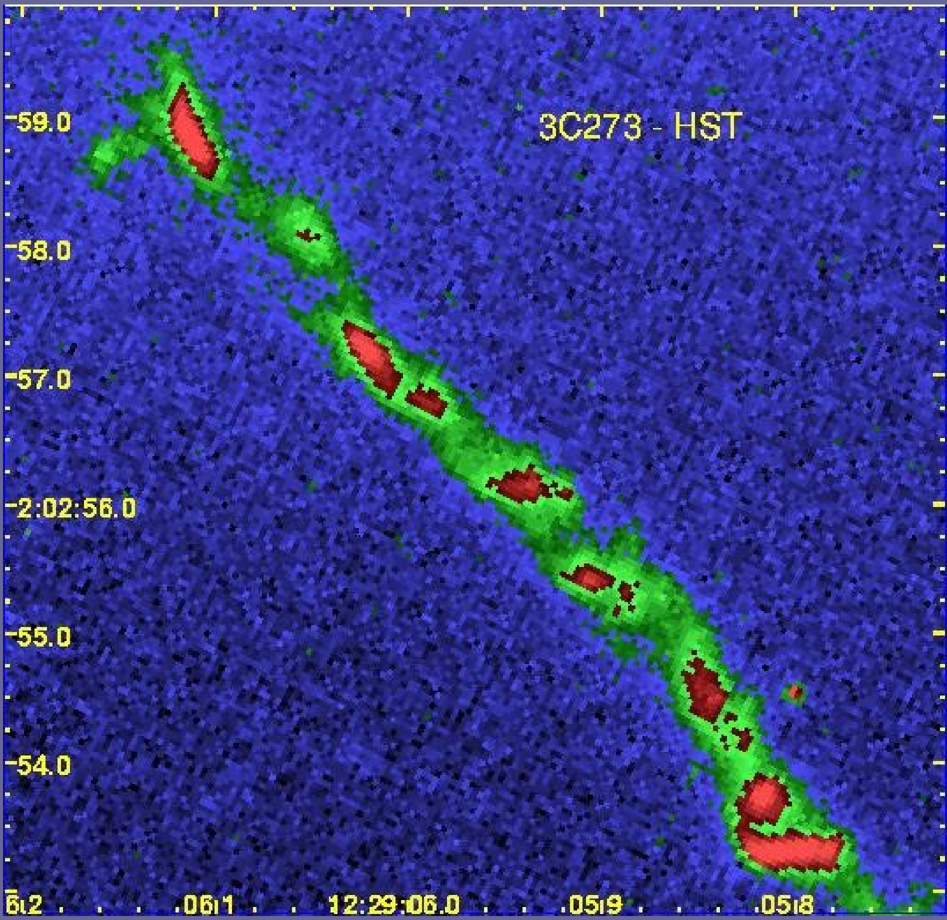
In the high state (e.g. after compression), a fixed observing band samples a lower segment of N(E) because of the change in the magnetic field. The amplitude will be larger and the spectrum harder than that found using the same band when N(E) is in the low state (e.g. after expansion).

Knots from curved trajectory

- Enhanced emissivity could arise from a change in the beaming factor.
- The larger Γ required for IC/CMB models means that Q should have higher contrast knots than FRIs since the emission cone is smaller for larger Γ.

? – What path does the fluid follow

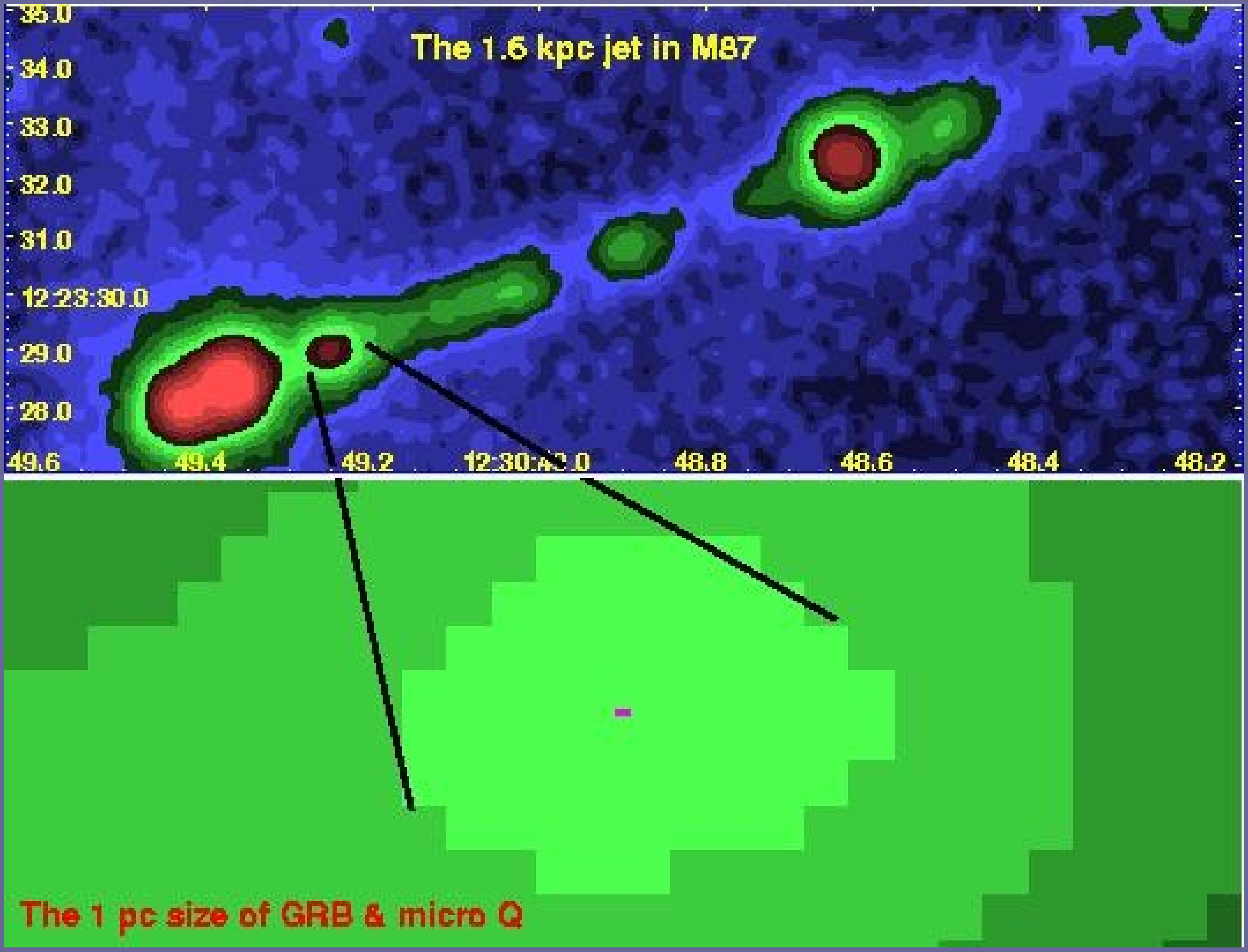
- Straight line ('ballistic') ?
- Helical ?
- NB: a curved trajectory with beaming is a good way to explain the occurrence of knots. ***It also relaxes constraints on the jet angle to the l.o.s.***



Digression: Sizes & Luminosities

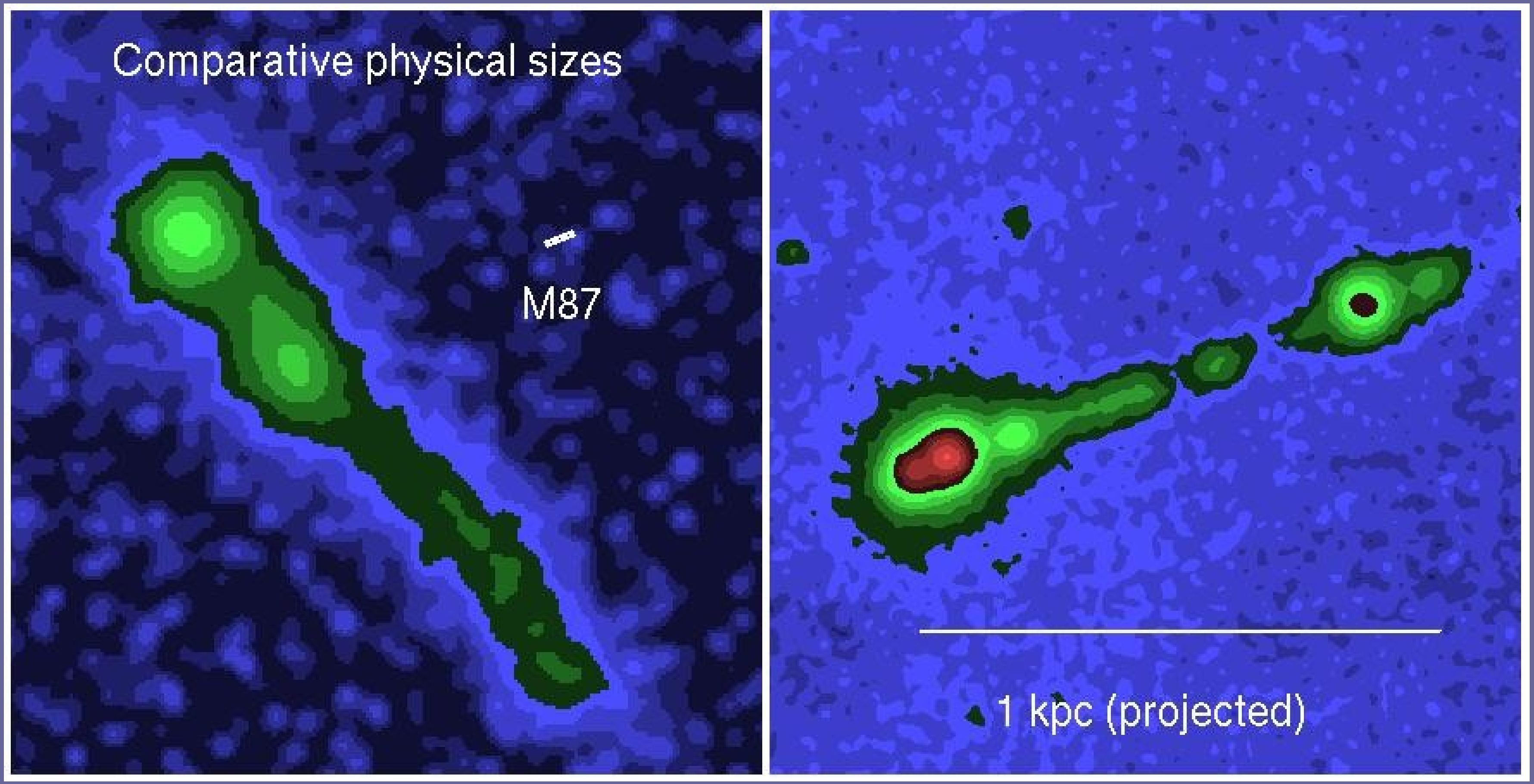
GRB, μQ, FRI, FRII+Q jets are all very pretty; being long and narrow….. but they are of vastly different scales! Don't expect identical physics!

Relative sizes. microQ and M87



3C273 at same brightness scale as M87

jet outside the galaxy   M87 jet within galaxy



Compare 3C 273 with M87: Parameters for a bright knot

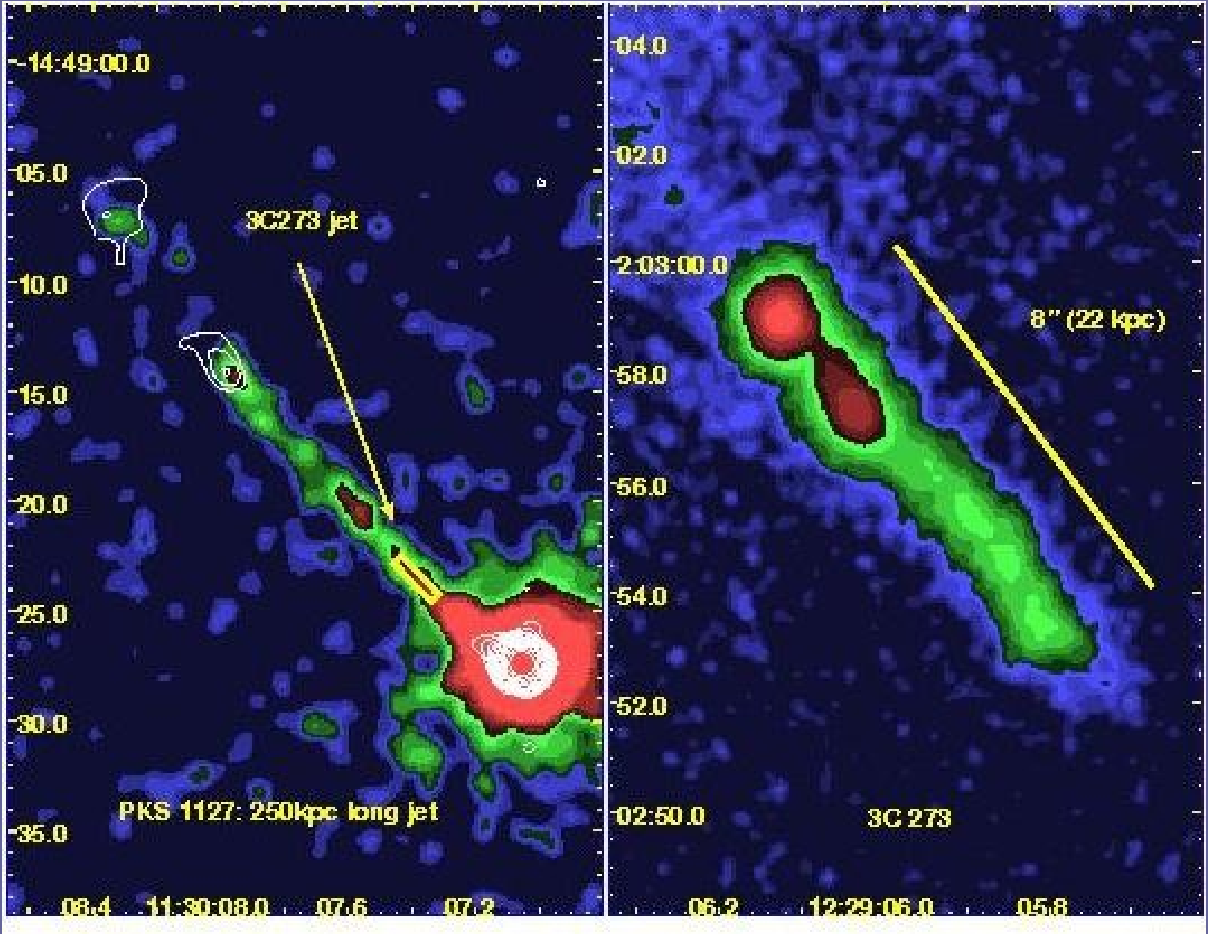
3C 273

- 0.5” ≈ 1300pc
- $L_x \approx 10^{43}$ ergs/s
- $B_x \approx 0.27$ evps/0.05”p
- $\alpha_x \leq 1$

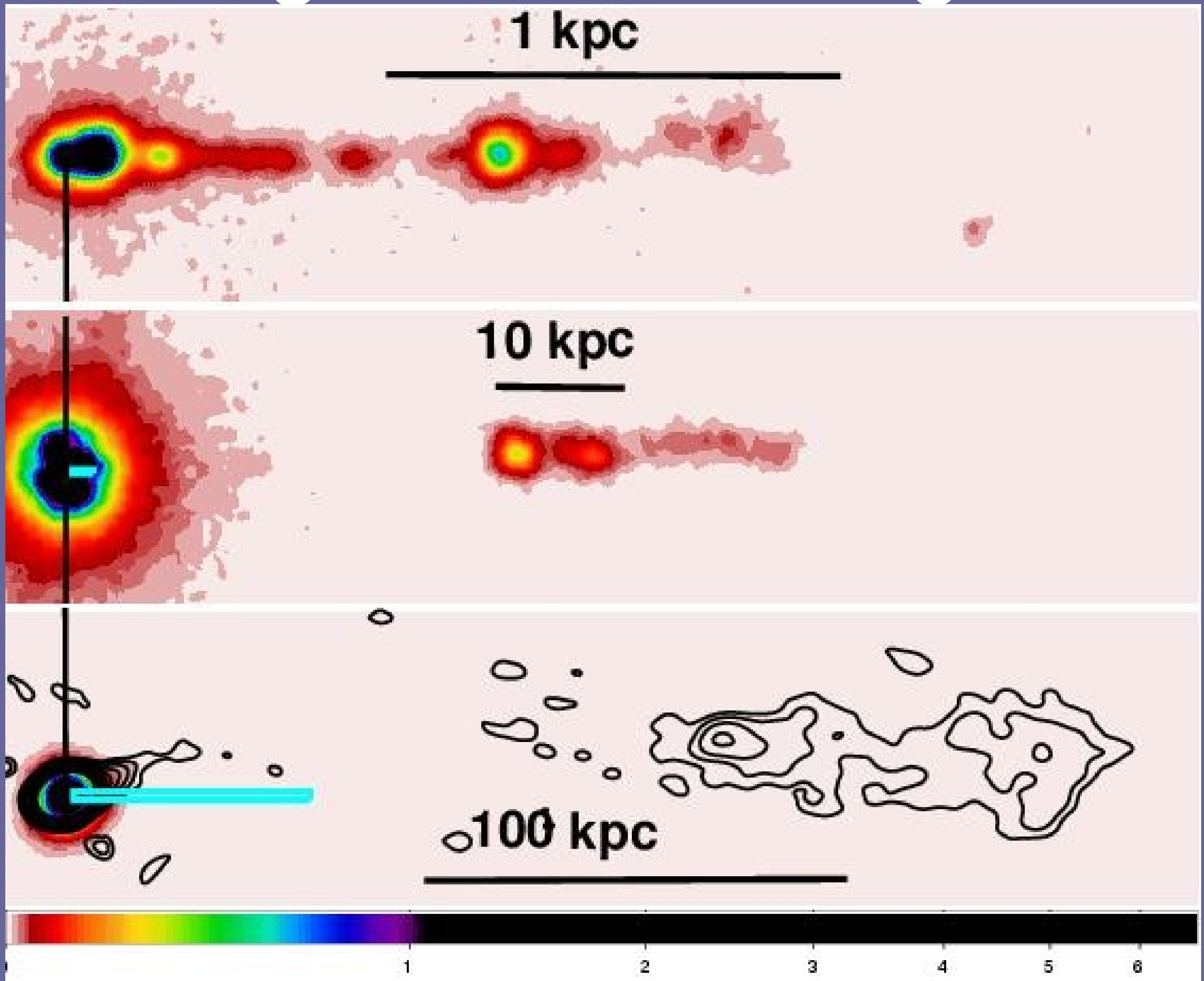
M87

- 0.5” ≈ 38pc
- $L_x \approx 10^{41}$ ergs/s
- $B_x \approx 5.5$ evps/0.05”p
- $\alpha_x \geq 1$

3C 273 compared to PKS1127 @ z=1.1

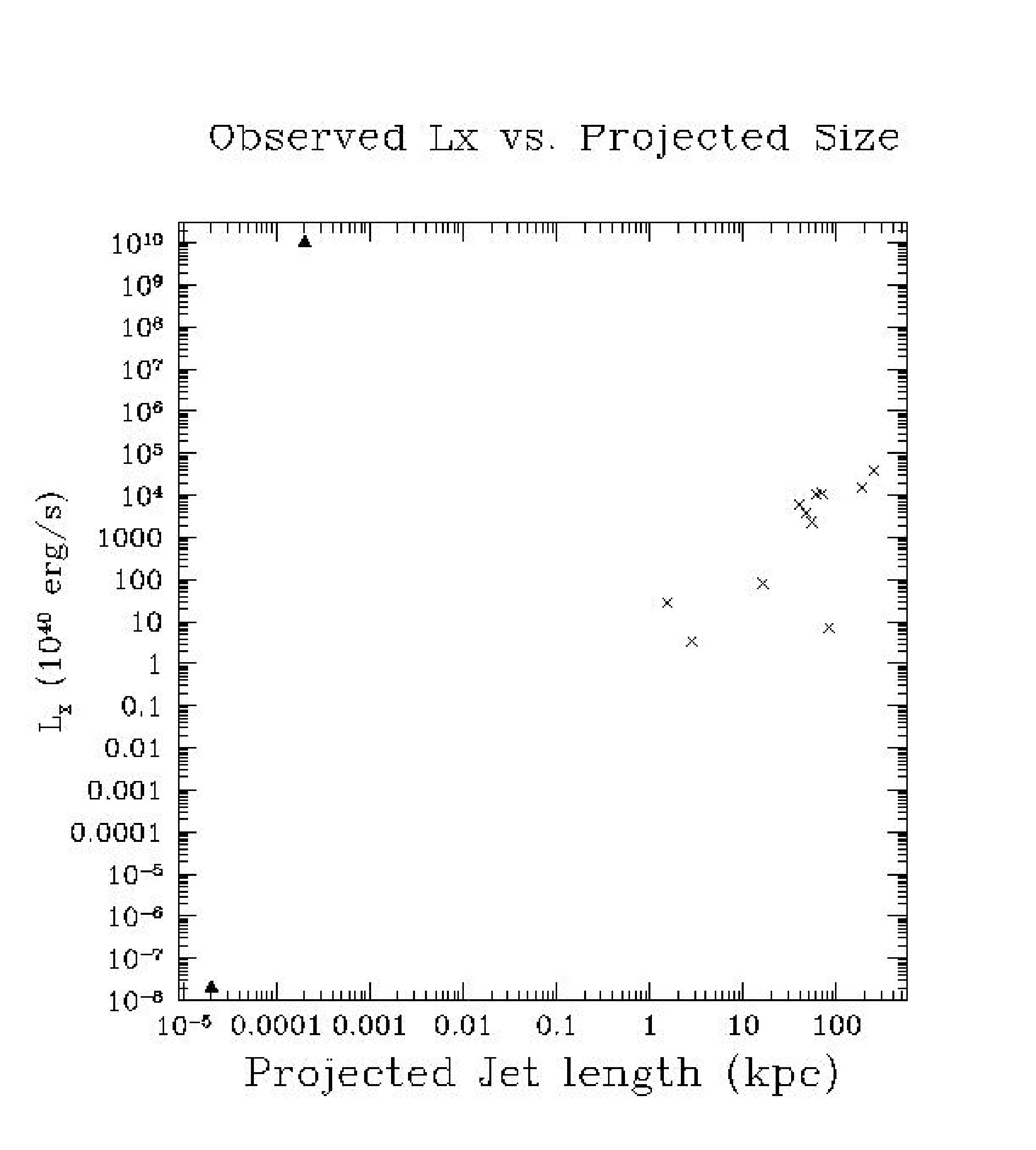


Or all together for a single view:

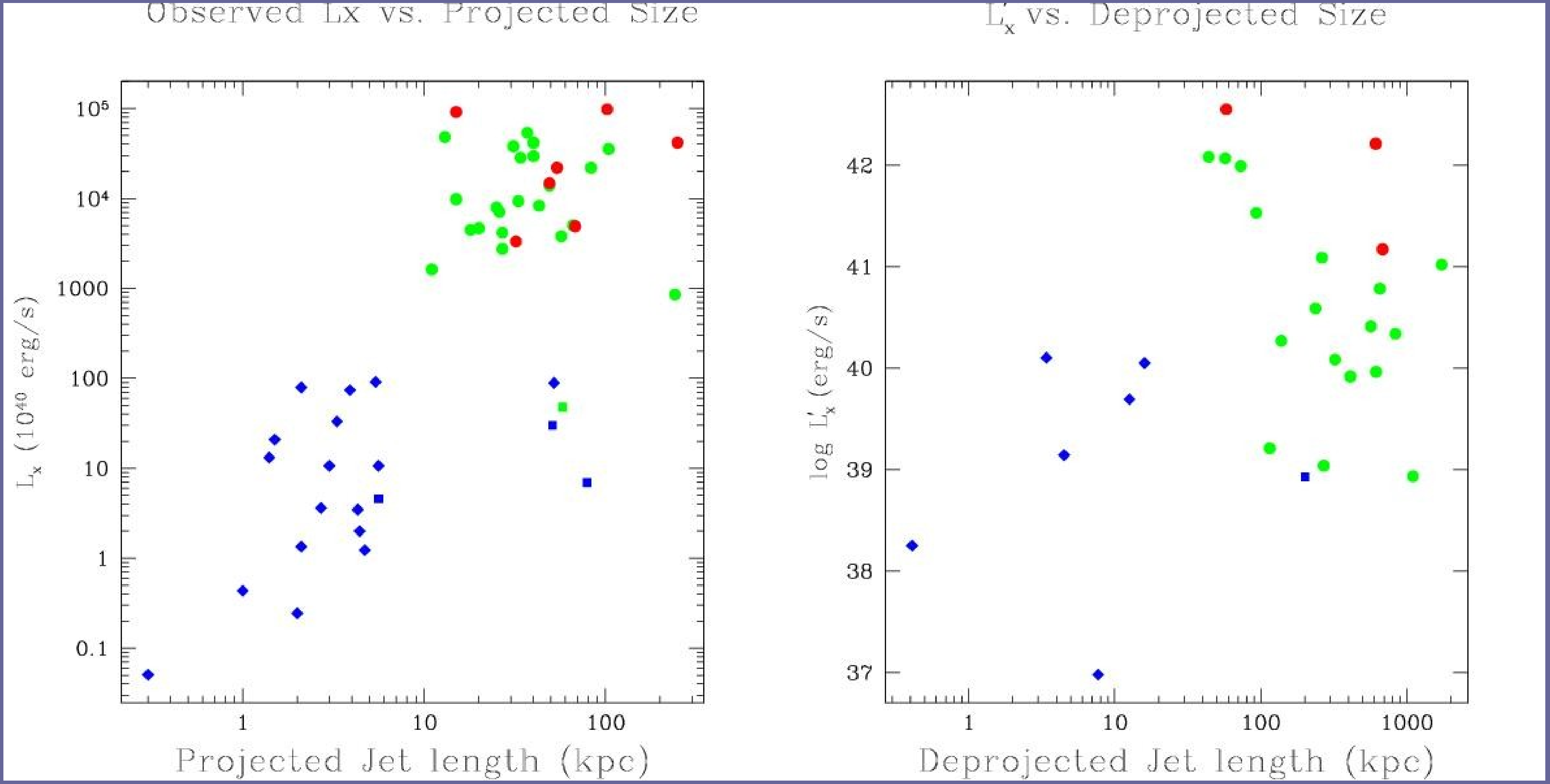


Comparative Sizes: log scale

(missing from this plot are typical VLBI extragalactic jets)

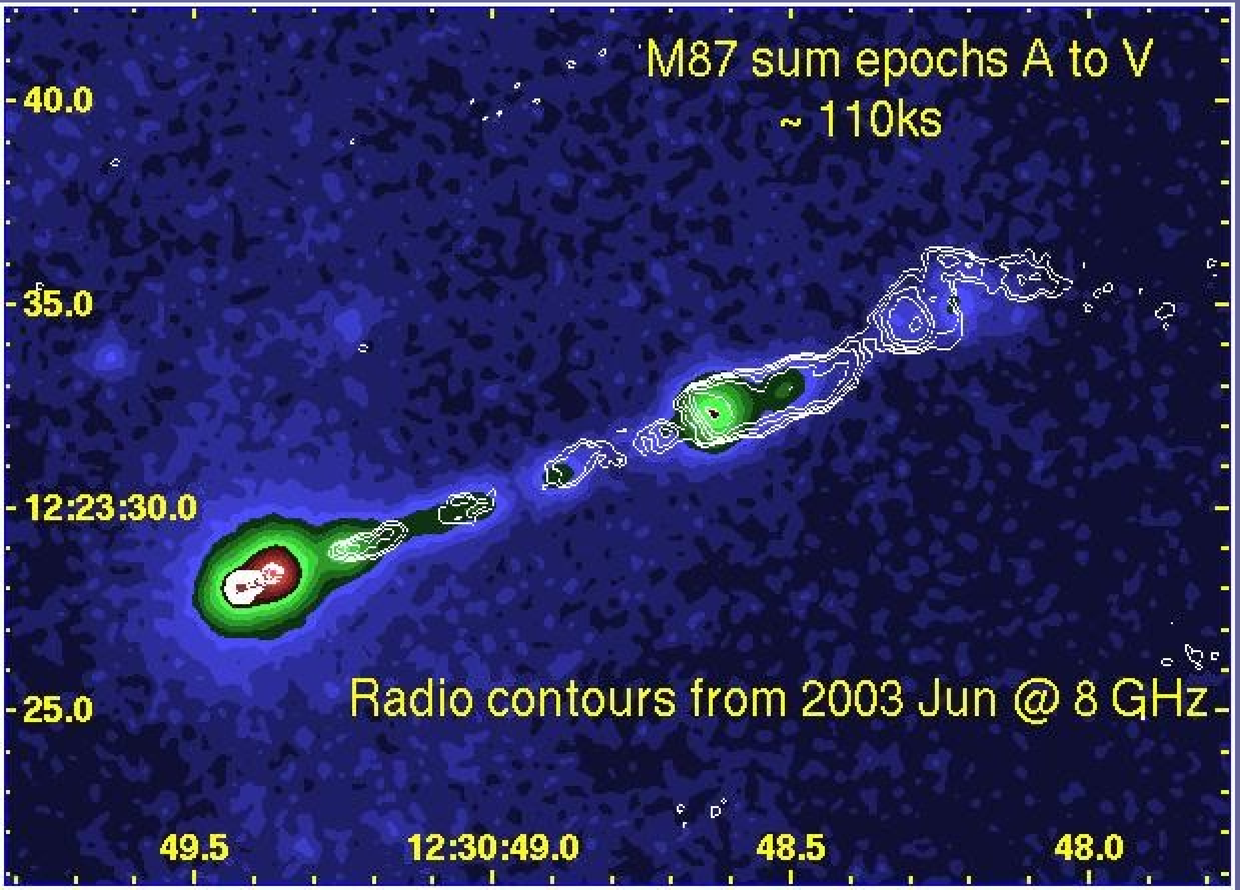


Projected vs. Physical Length via ‘best guess’ θ



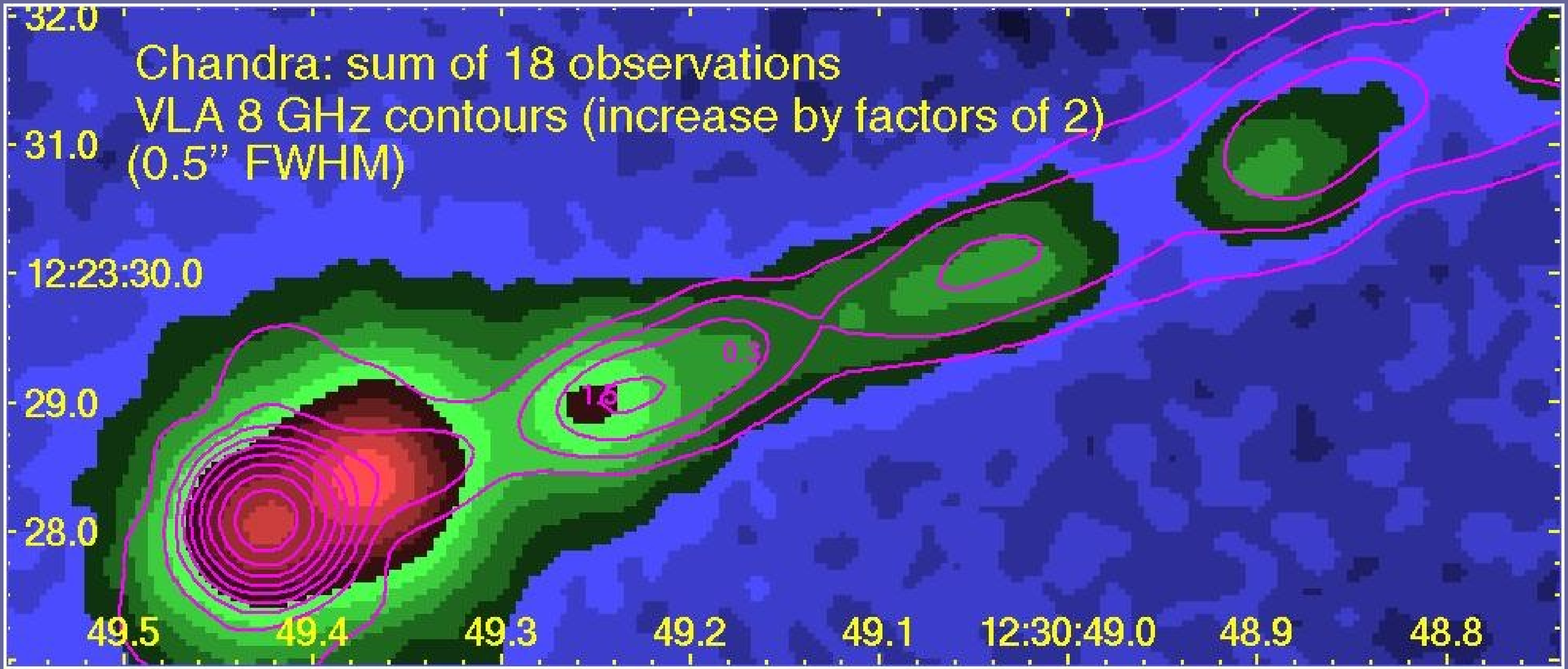
M87 as an example of synchrotron

- Offsets – comparing radio contours on an X-ray image

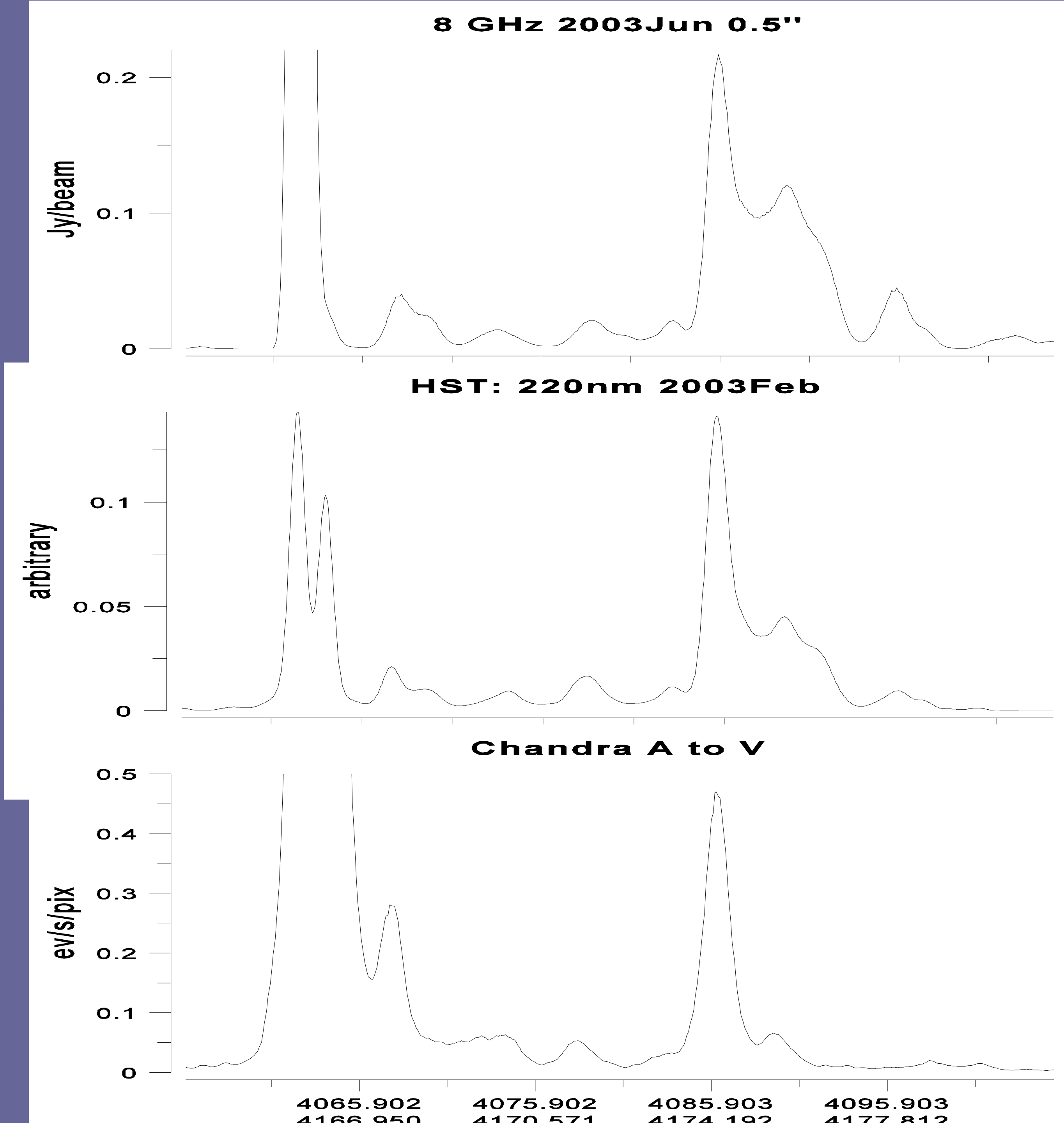


Morphology: X-ray & Radio

- X-ray peaks upstream of radio in knots D & F

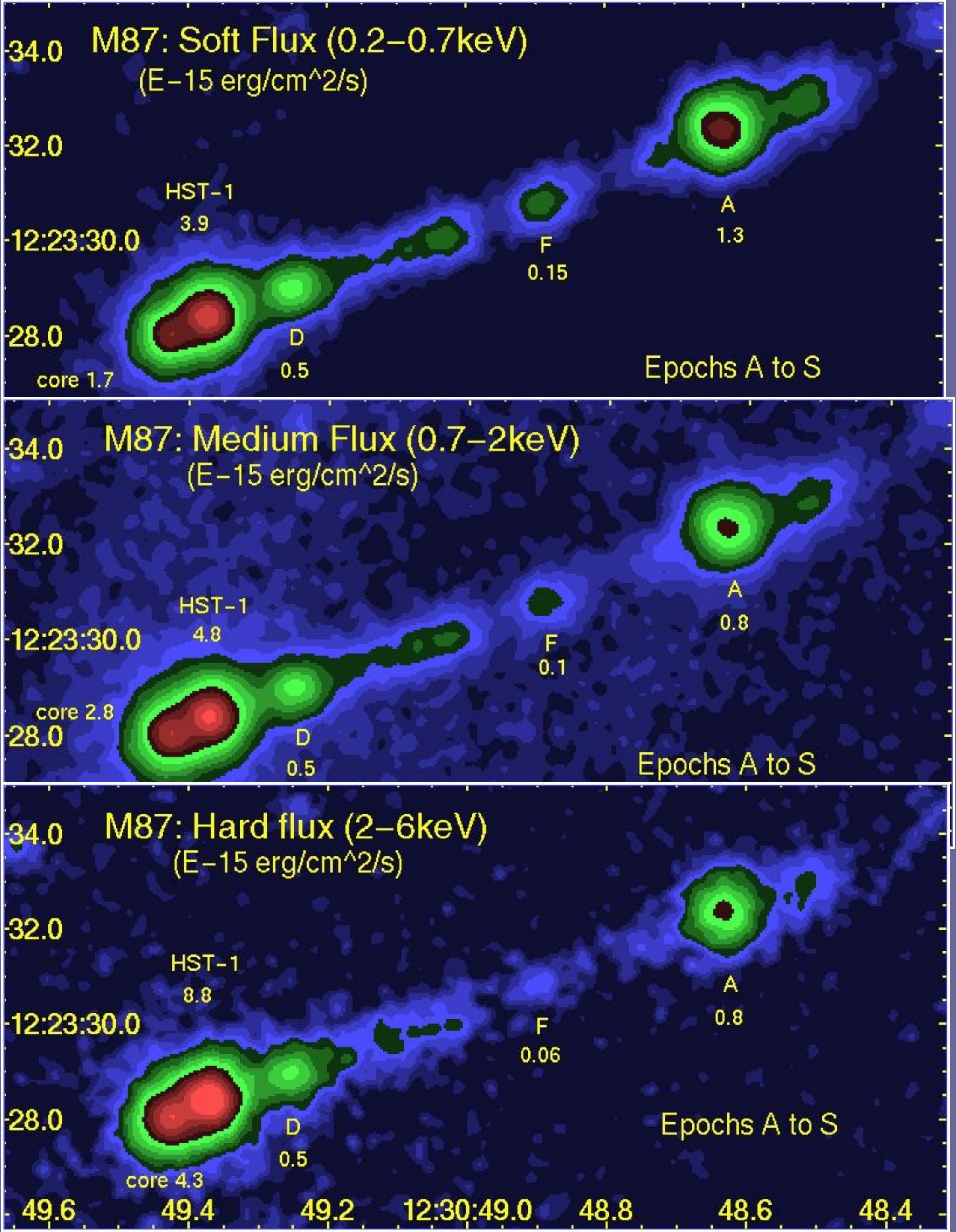


- - radio
- optical
- X-ray



M87 Spectral Changes

- Downstream from the core region, and also from knot A, the X-ray spectrum softens.
- The next slide shows the X-ray jet in 3 X-ray bands, with brightness labels.

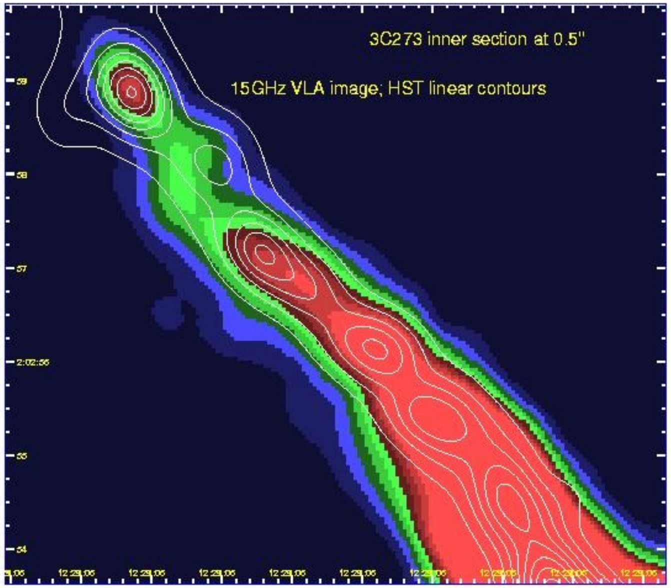


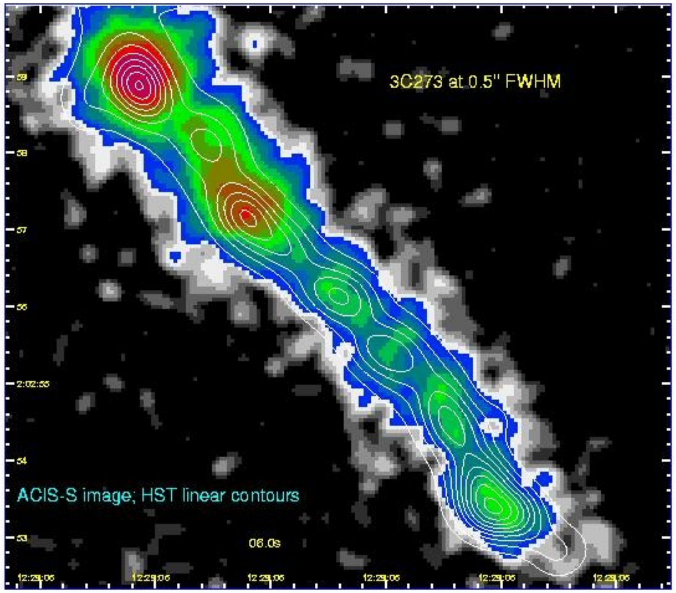
M87: Soft Flux (0.2–0.7keV)
(E–15 erg/cm^2/s)
34.0
32.0
12:23:30.0
28.0
HST-1
3.9
core 1.7
D
0.5
F
0.15
A
1.3
Epochs A to S
M87: Medium Flux (0.7–2keV)
(E–15 erg/cm^2/s)
34.0
32.0
12:23:30.0
28.0
HST-1
4.8
core 2.8
D
0.5
F
0.1
A
0.8
Epochs A to S
M87: Hard flux (2–6keV)
(E–15 erg/cm^2/s)
34.0
32.0
12:23:30.0
28.0
HST-1
8.8
core 4.3
D
0.5
F
0.06
A
0.8
Epochs A to S
49.6
49.4
49.2
12:30:49.0
48.8
48.6
48.4

Offsets in 3C 273 and PKS1127

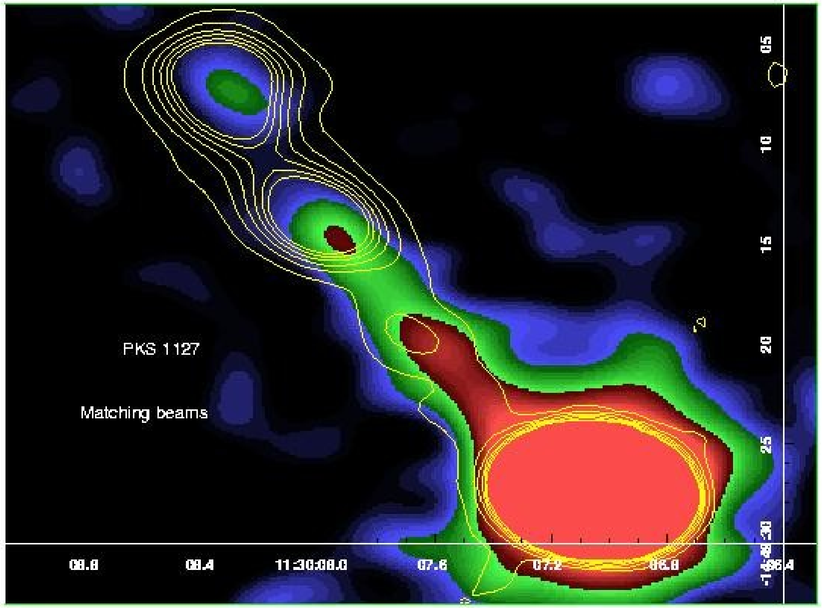
- In a sense, these sort of offsets seem to be scale invariant since we see similar properties for these powerful sources, but on a larger scale.

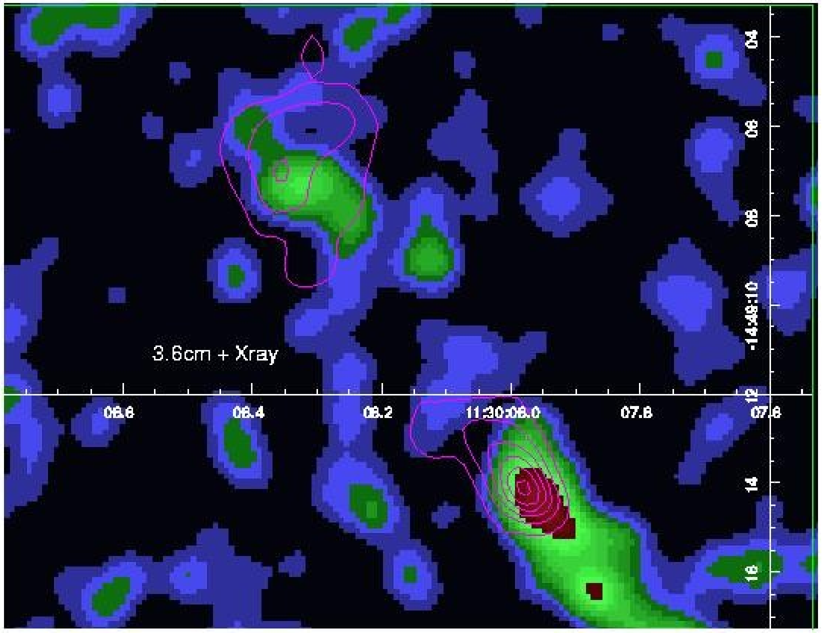
3C273 offsets





PKS 1127 offsets

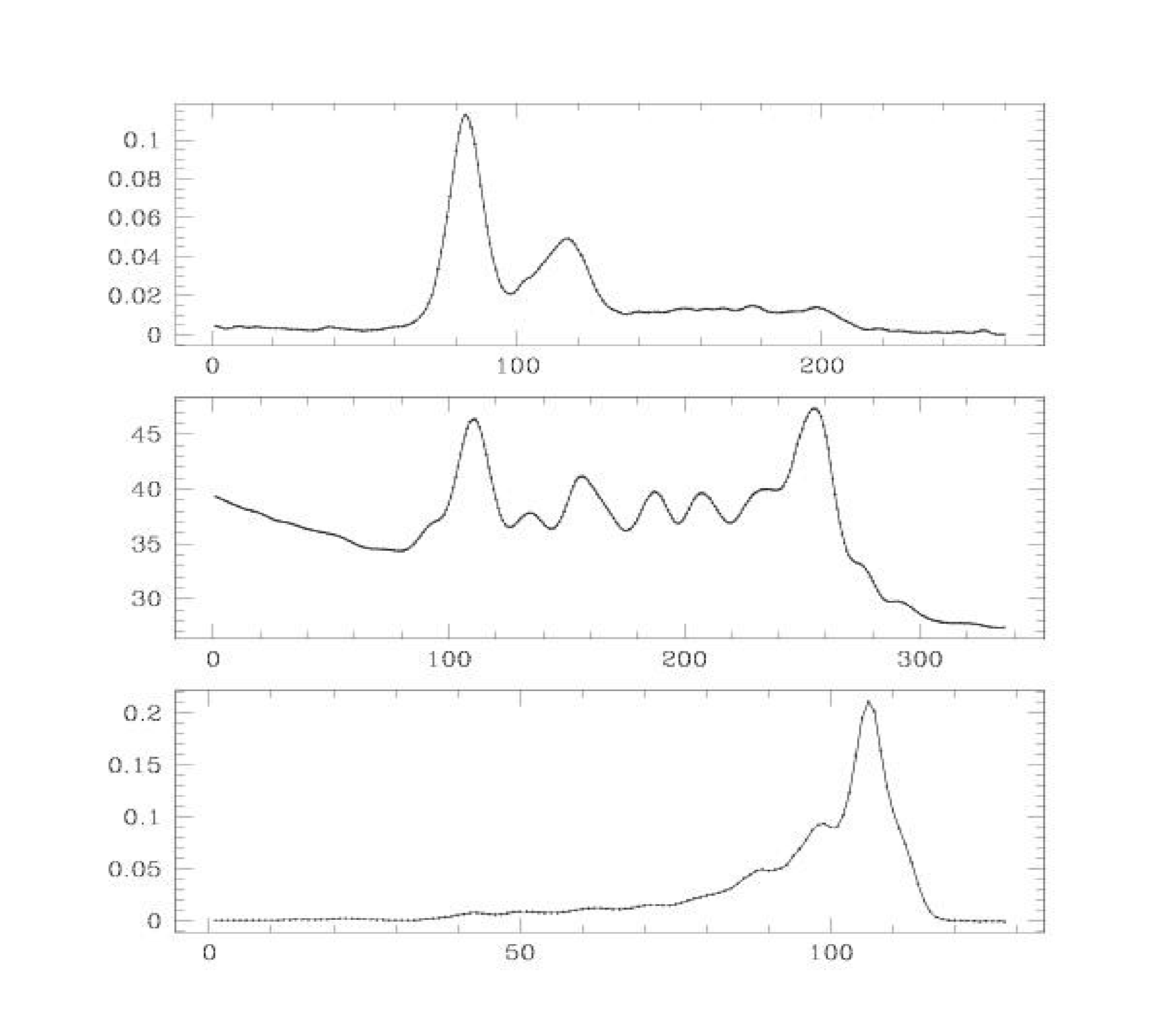




offsets & progressions=2 sides of same coin

- If we were viewing 3C273 at z=1.1, the jet would be unresolved, but there would be a very obvious offset between peak brightnesses: X-ray peaking closer to the quasar; optical and radio progressively further downstream.
- i.e. the internal (unresolved) structure of a knot of PKS1127 could look like this…..

3C273: X, Opt, & Radio

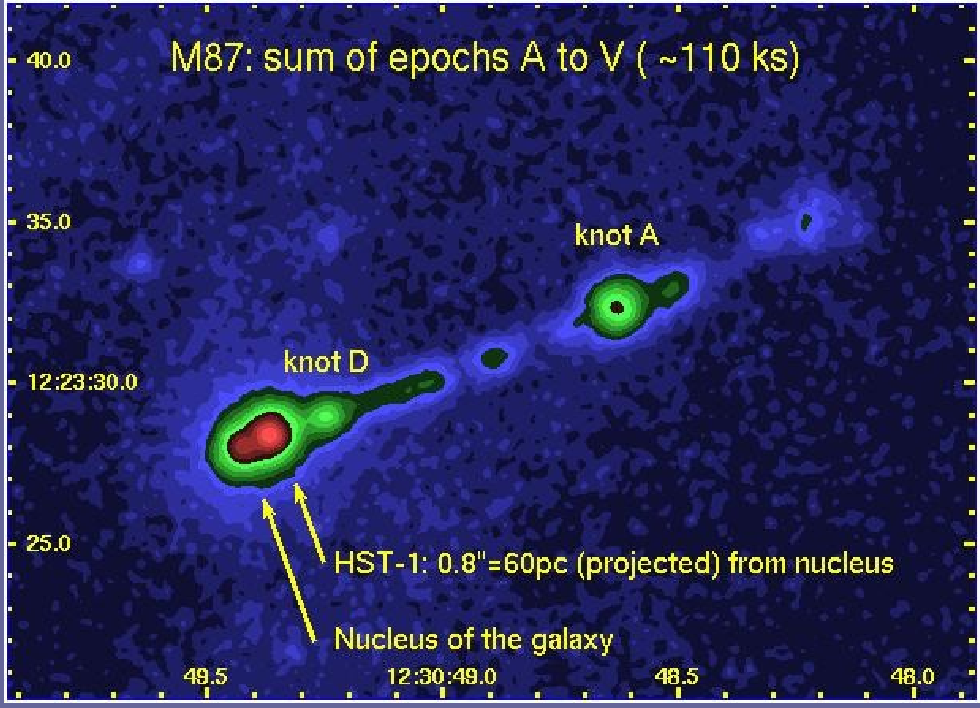


Variability

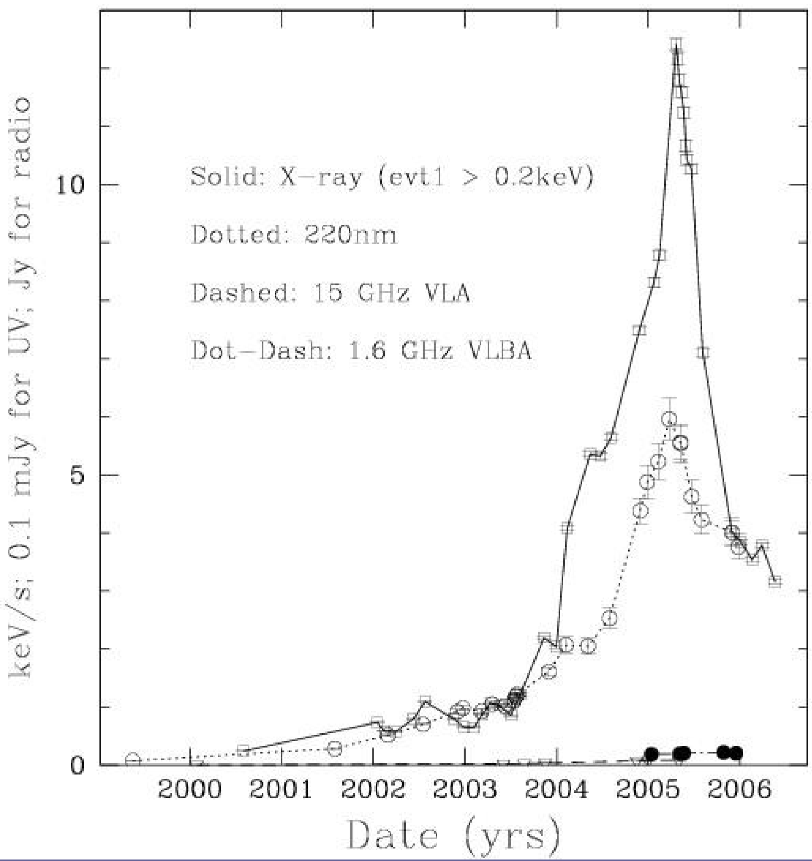
- In addition to M87, variability is also seen in features of Cen A (Kraft et al.)
- The knots of powerful Q are generally too large physically for this test.

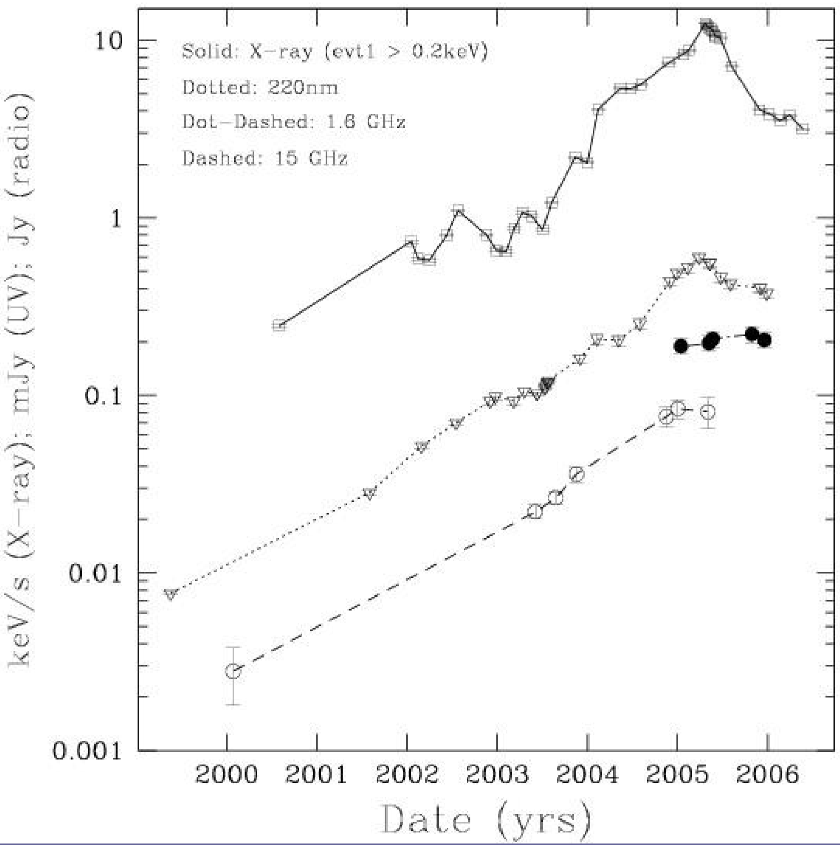
Project: 4 years of monitoring the M87 jet with Chandra

- The Nucleus varies, as expected.
- HST-1 varies and has peaked at 50x the 2000Jul level.
- knot D probably varies.
- knot A shows a mild decay.



HST-1 Lightcurves



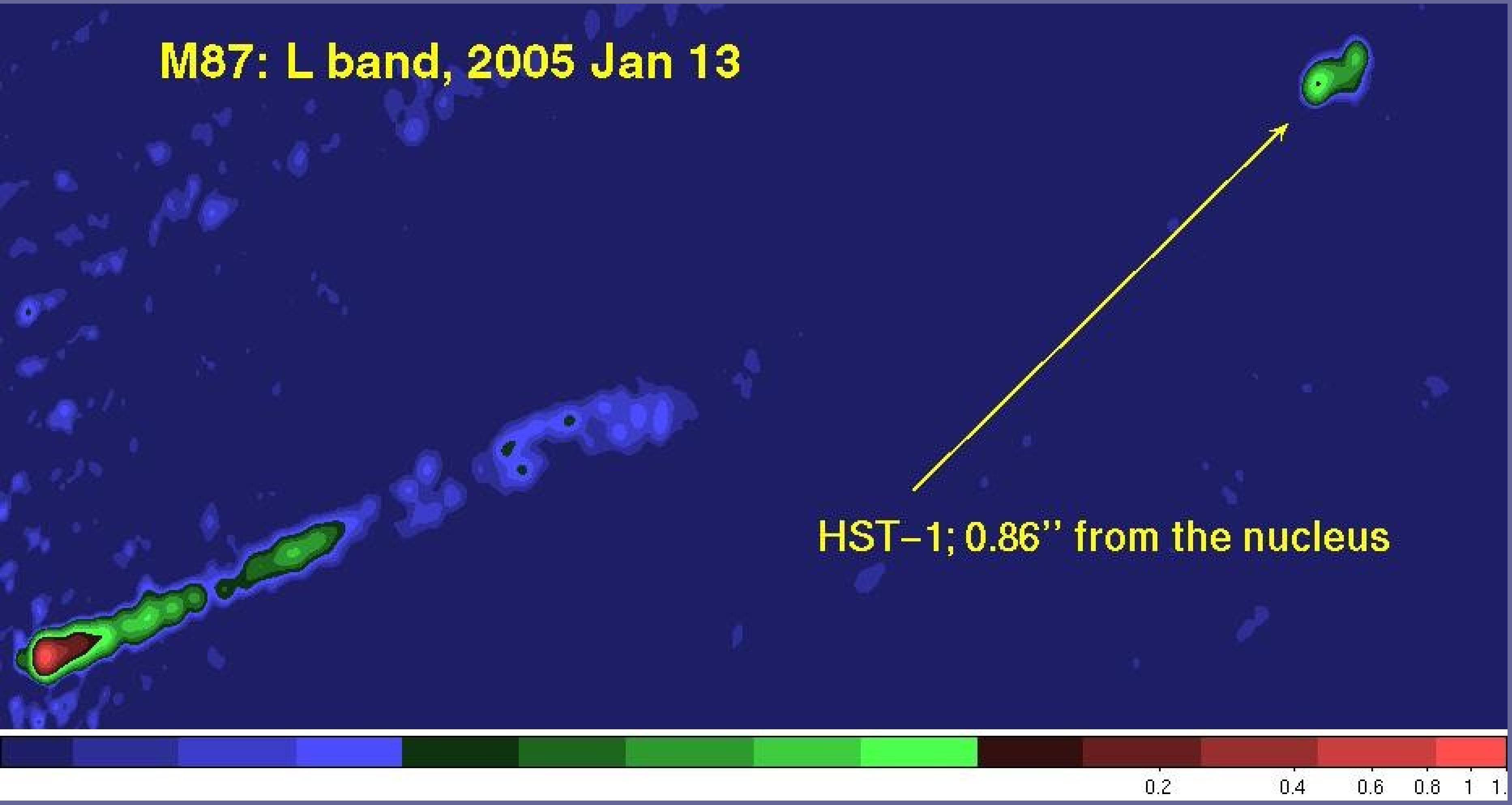


Decay Time

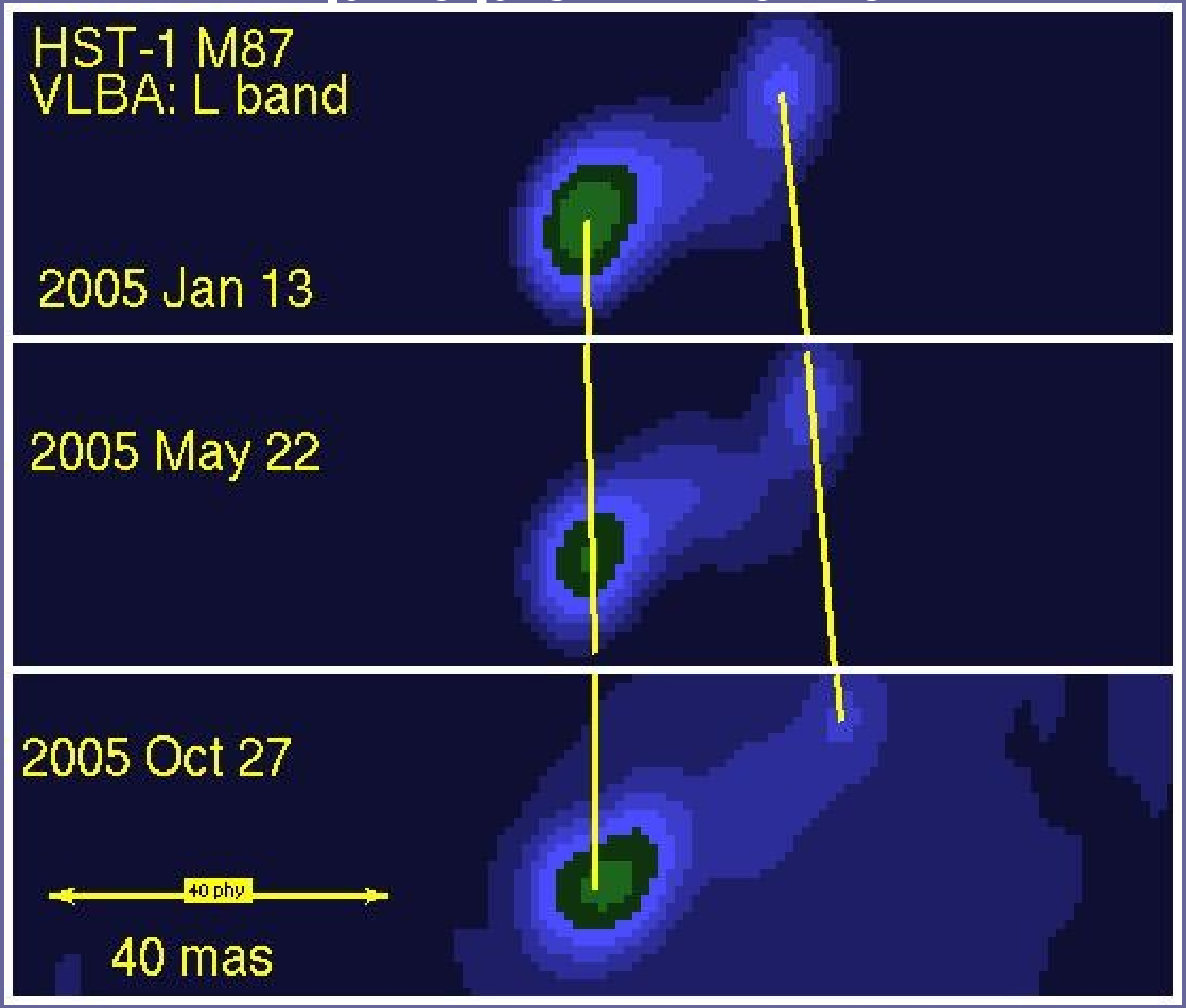
- X-ray: suspect that τ(sync)<light trv.time
- Optical: ? may flatten after initial drop
- Radio: ?

- If all drop together; expansion or change δ
- If optical and radio are slower, should get a new estimate of B field

VLBA data



What we find…2.8c apparent proper motion




M87: L band, 2005 Jan 13
HST-1
2005 May 6
40 mas
2005 May 22
2005 Oct 27
2005 Dec 16
0.2
0.4
0.6
0.8
1

1994-1998; same thing but optical

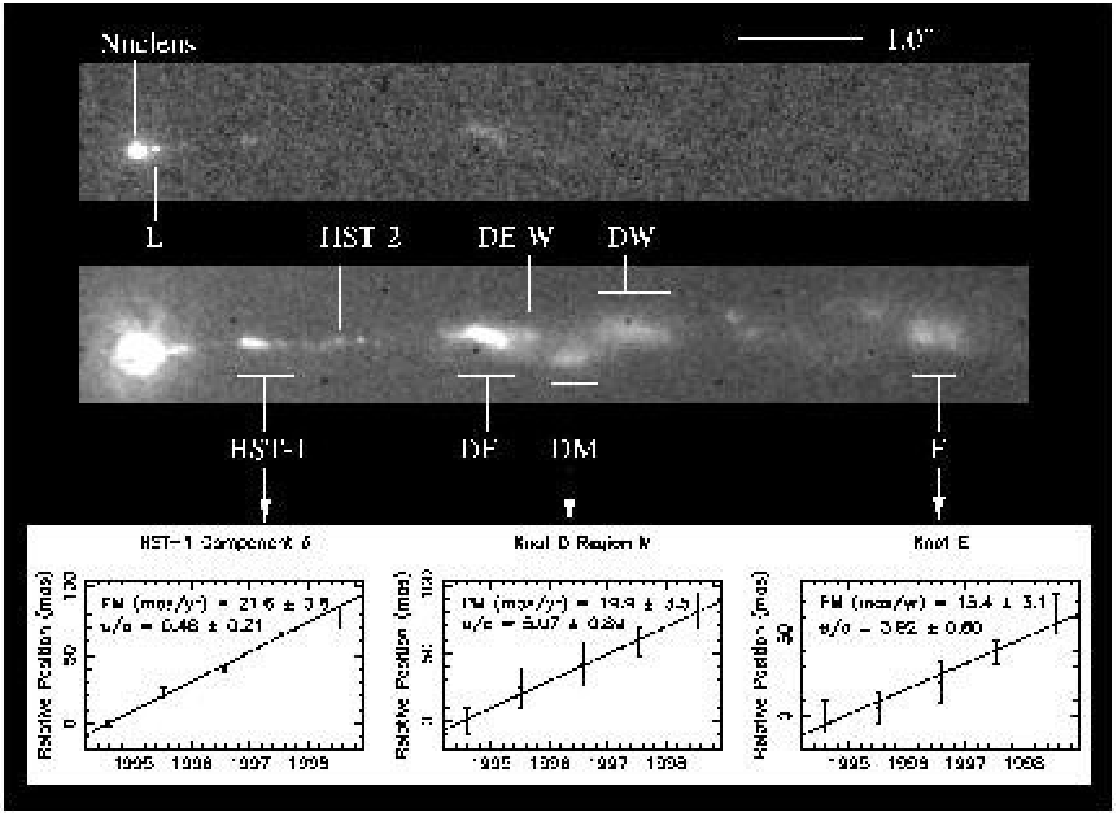


FIG. 1.—Locations of jet features discussed herein. The top panel is the 1994 image in the F342W + F4ND filters, and the bottom panel is F342W alone. Dark spots in the lower panel are Reseau marks on the photocathode. The image has been rotated from its normal appearance on the sky in such a way that the x-axis is along P.A. 290°. Inset plots show relative position vs. epoch for three representative features; fitted proper motions (PMs) and derived speeds in units of c are indicated.

Superluminal optical features

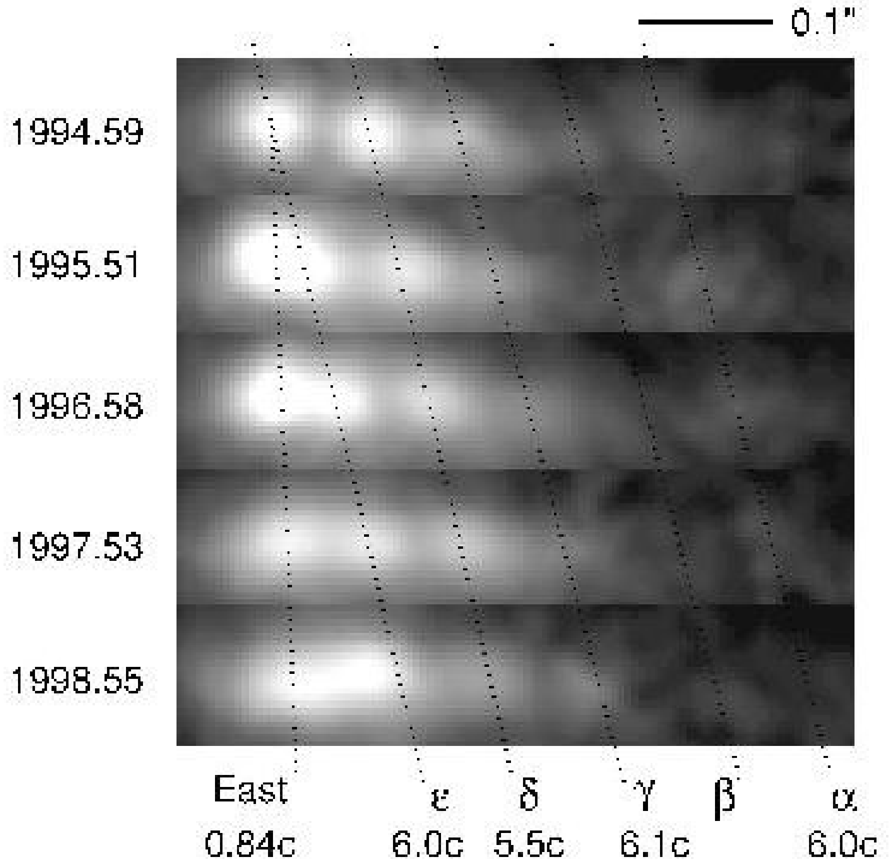


FIG. 2—Sequence of F342W images showing evolution of HST-1 region between 1994 and 1998. The dotted lines attempt to identify and track features between epochs and are labeled with feature names and speeds derived herein.

Parameters for components

- ***1994-1998 optical***
- ***nucleus->hst-1: 0.87''***
- β(leading): 0.84±0.1
- β(following): 4 to 6
- size: ≤ 4pc
- overall size: 24pc

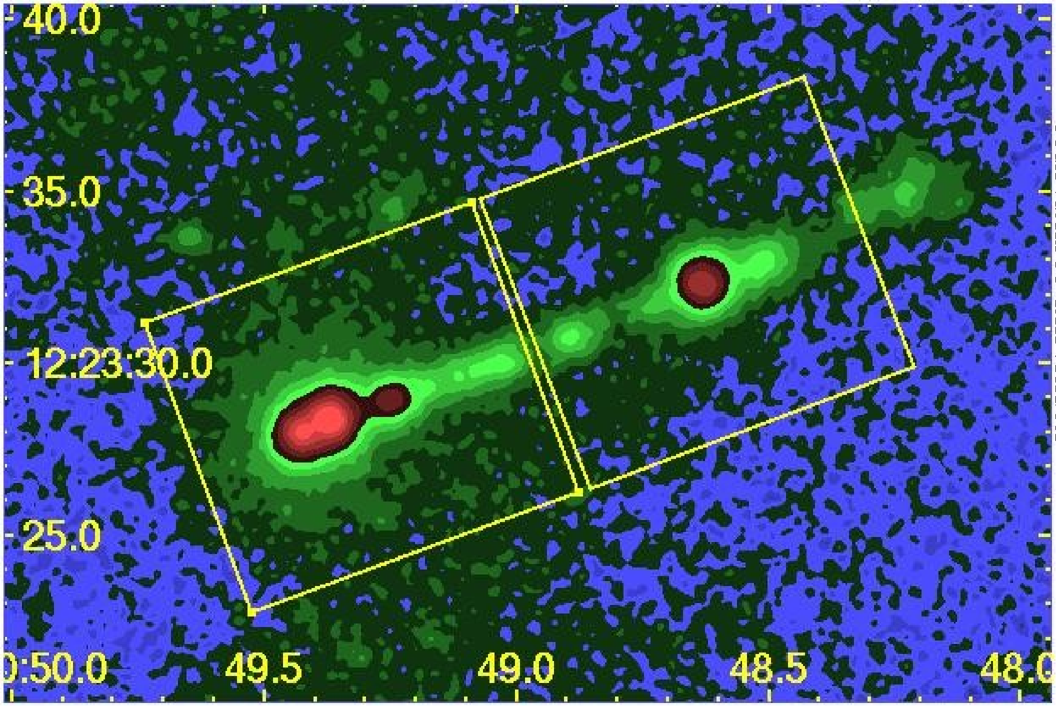
- ***2005 radio***
- ***nucleus->hst-1: 0.86''***
- β(leading): 1.0±0.1
- β(following): 2.8
- size: 10mas or 0.7pc (expected 1mas, 0.1pc)
- overall size: 3pc
- date when following was at leading: 2001 Sep

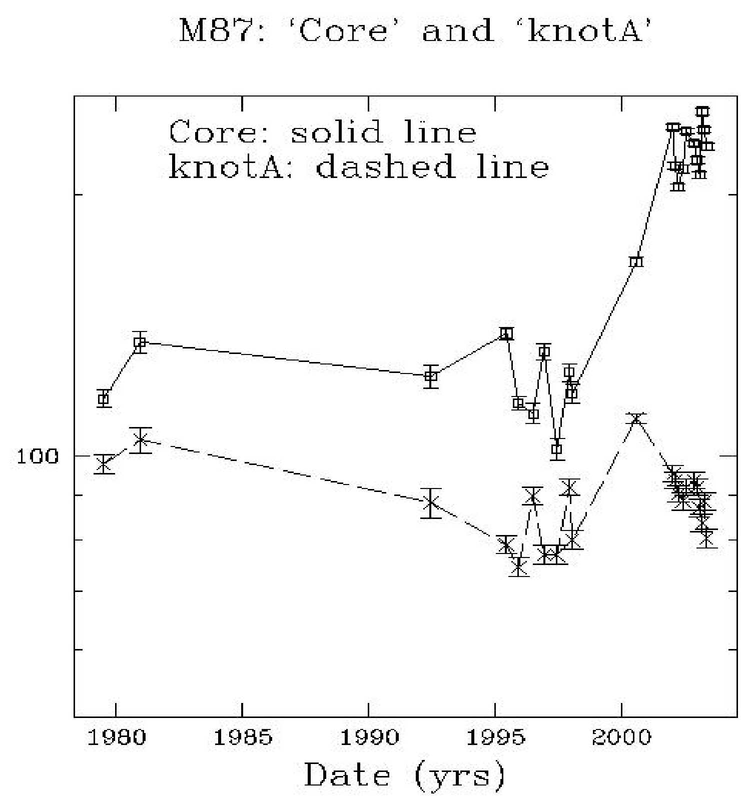
The Red Queen's Race

The upstream edge of HST-1 appears to be moving away from the core with a velocity close to c; yet 10 years later, it has not advanced.

Variability: 1980-2004

- no evidence for a comparable outburst





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