Comparing the Jets in M87 & 3C273

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outline

- Part I: Summary of emission processes.
- Part II: M87 variability
- Part III: Comparison of observables
- Part IV: Comparison of parameters
- Part V: Conclusions

Preamble:

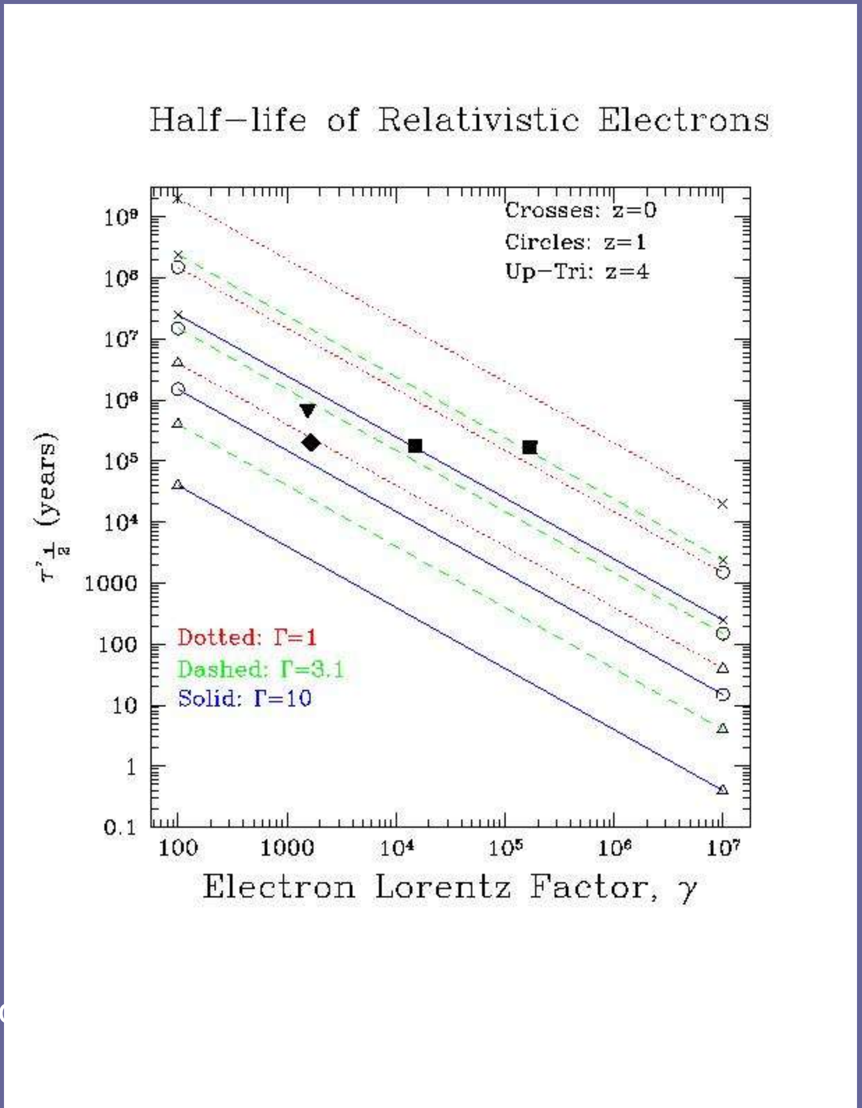
- Throughout this talk I use lower case gamma (γ) for the Lorentz factor of the radiating electrons and upper case (Γ) for the bulk Lorentz factor of the jet.
- The spectral index is defined in the standard way: flux density, $S_\nu = k\,\nu^{-\alpha}$

Premises

- 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.

The fluid does not consist of hot electrons

- The jet fluid (not the emitting plasma) must have existed for at least as long as it takes to get to the end of the jet…..
- Hot electrons suffer inescapable IC losses.



"Conventional Wisdom"

- Most/all X-ray jets appear to be one sided: therefore, δ and Γ are of order a few or greater.
- Low Power Sources: Synchrotron emission is strongly favored for the observed X-rays from FRI radio jets. [spectral index, $\alpha_x \geq 1$; peak brightness offsets between bands; intensity variability]
- High Power Sources: IC/CMB with $\Gamma \geq 5$ is generally invoked for X-rays from these sources; but this interpretation is not universally accepted. Generally, $\alpha_x \leq 1$.

The current X-ray situation

- The question at this juncture is the X-ray emission process for high luminosity quasars and FRII radio galaxies. Is it :
- synchrotron?
- IC/CMB with beaming?
- a combination of these two?
- or something completely different?

X-ray Emission Processes

- **option A: synchrotron - extremely high γ electrons**

for freq of10^{18} $\gamma = 0.0005\sqrt{\nu(1+z)/B(1)} \approx 10^7$

for $\gamma \approx 10^7$; $\tau_o = 10^{13}(1+z)/\gamma\delta\{B'^2+40(1+z)^4\Gamma^2\}$ years (of order a year).

- **option B: IC/CMB with $\Gamma > 5$ (often >10)**

$\gamma=\{ 2x10^{-6} / \Gamma \} \sqrt{\nu}$ and for $\nu=10^{18}$, $\gamma \approx 100$ and $\tau \geq 10^5$ years

Synchrotron Expectations

- α(X-ray) ≥ α(radio) since we expect to see effects of E^2 losses [spectral break or high energy cutoff]. Generally, the SED can be fit with a broken power law (+ a high frequency cutoff).
- Time variability for physically small emitting volumes such that light travel time across the source is not much greater than the half-life of the electrons responsible for the observed radiation.

IC/CMB Expectations

- α(X-ray) $\leq$ α (radio) since the exponent for the X-ray power law reflects the value of the exponent of the electron spectrum at energies which produce synchrotron emission well below the radio frequencies observed from the Earth.
- No time variability since the half-life for these electrons is $\geq 10^5$ years.

Synchrotron Issues

- Acceleration mechanisms must produce $\gamma \approx 10^7$
- The "bow-tie" problem: sometimes the X-ray spectrum is flatter than the SED segment from optical to X-ray. Stawarz, and Dermer & Atoyan have invented methods to produce a 'pileup' of excess electrons close to the high energy cutoff, thereby producing a flatter emission spectrum than would otherwise be the case.

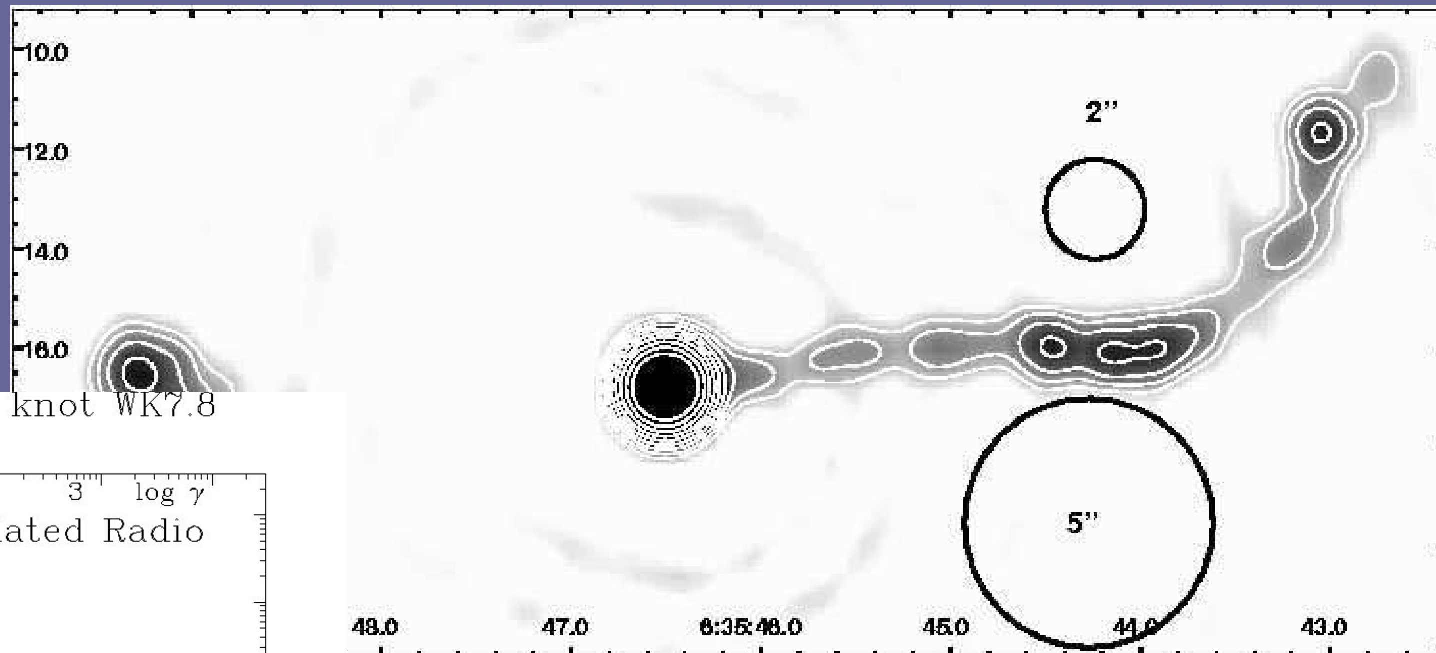
IC/CMB Issues

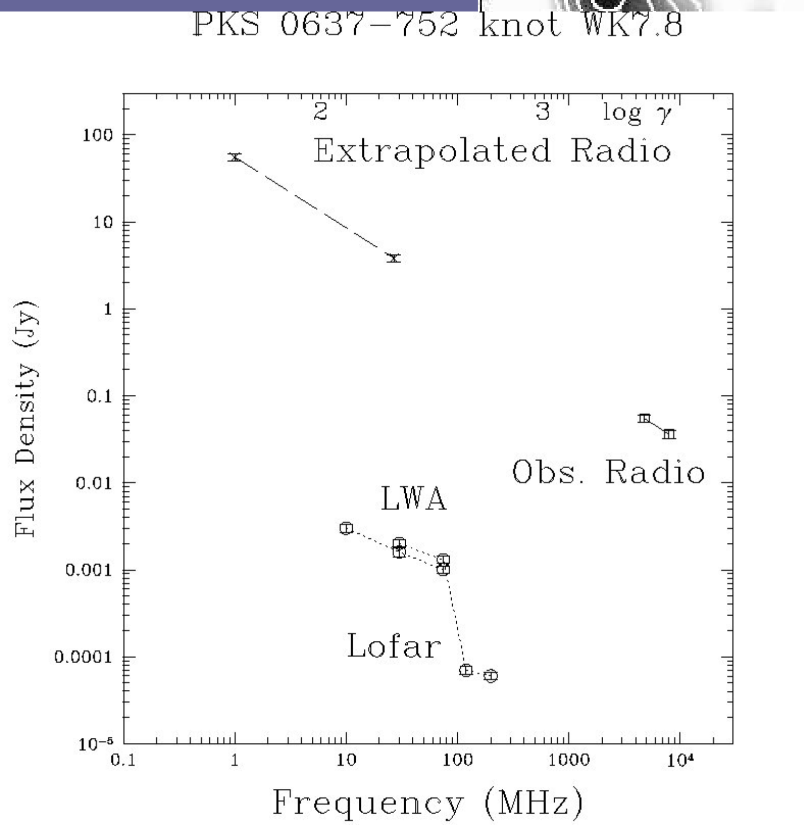
- Once a significant population of low energy electron has been generated at a shock, these longer lived electrons should survive longer than the higher energy electrons responsible for the radio and optical synchrotron emission. This means that X-ray knots should decay more slowly than radio knots downstream from acceleration sites.

IC/CMB Issues

- The uncertainty of extrapolating the electron spectrum from the ‘observed’ segments (ground based radio data) to the low end of the energy spectrum ($10 \leq \gamma \leq 300$); both in amplitude and power law index.

PKS 0637 – Quasar with Jet



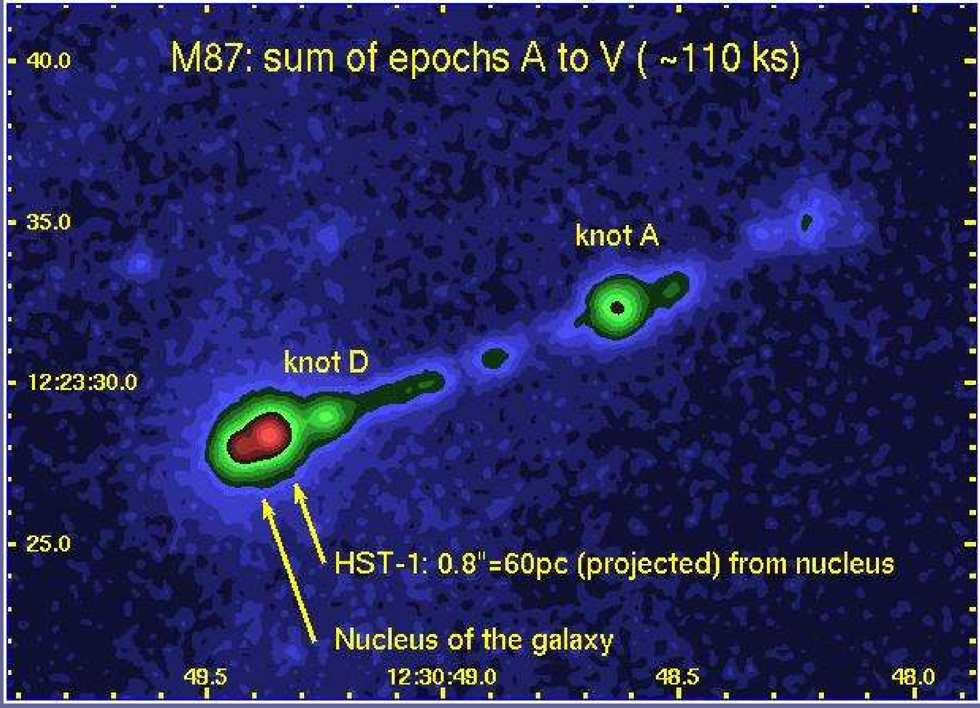


Part II: Variability

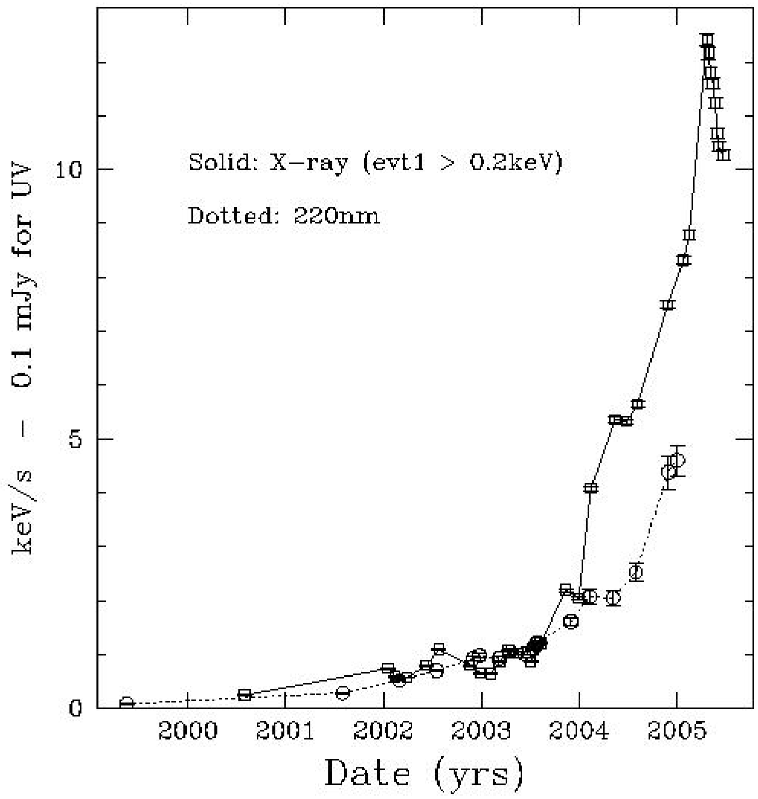
- Intensity variability of physically small regions
- For strong variability, small diameter component needs to dominate….
- i.e. not expected in 3C273 regardless of emission process

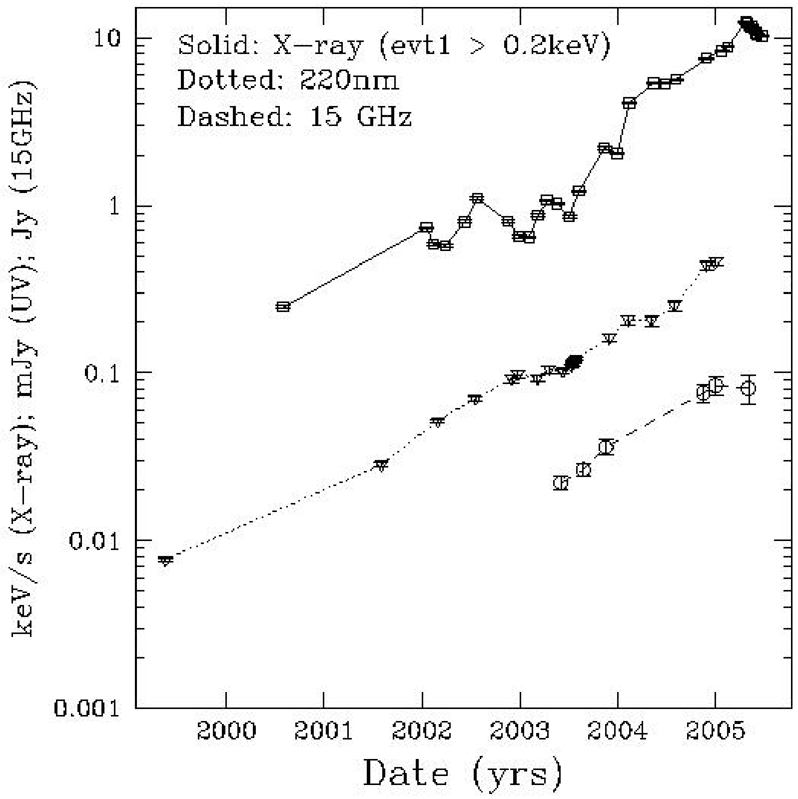
Project: 4 years of monitoring the M87 jet with Chandra

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



X-ray/opt/radio LC for HST-1

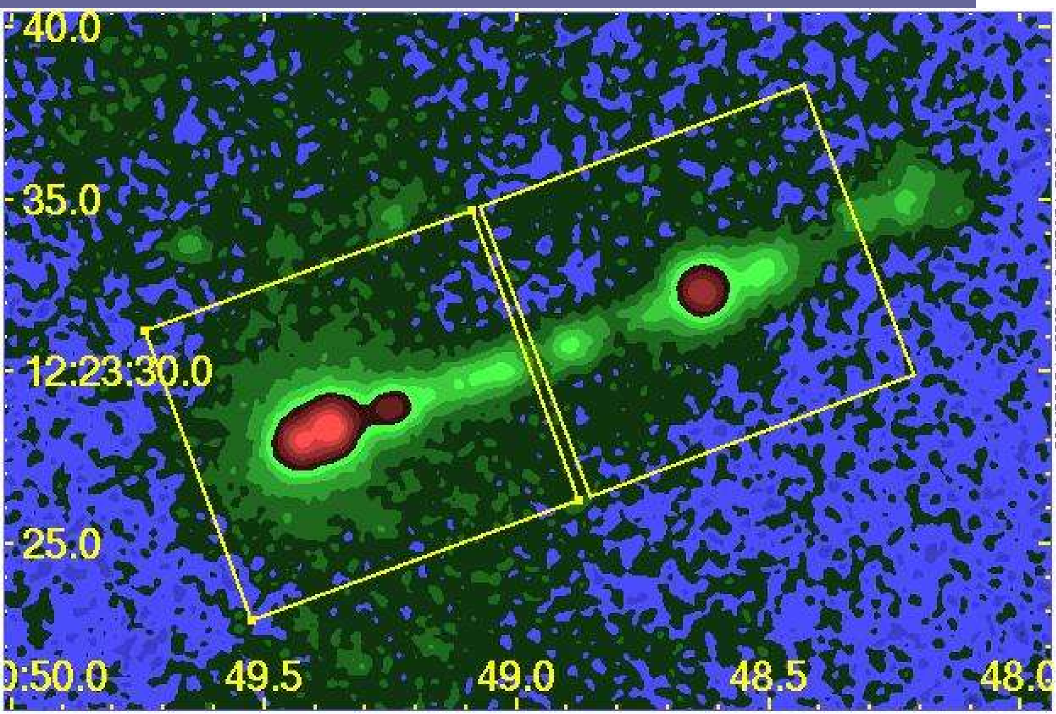


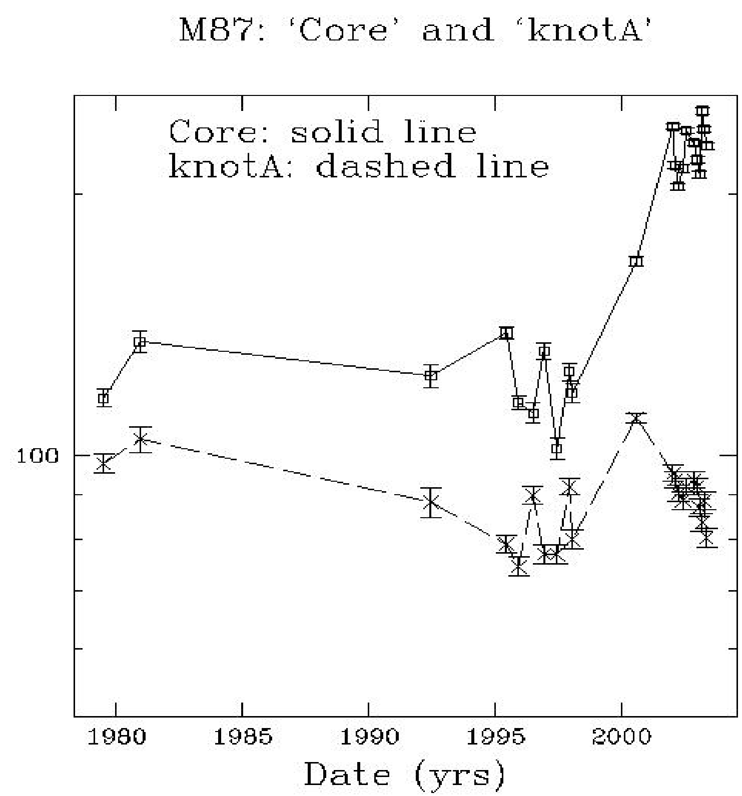


Doubling time for HST-1

- Indications are that the doubling times at X-ray, optical, and radio frequencies are similar. This lends credence to the notion that all emissions come from the same region.

Variability: 1980-2004

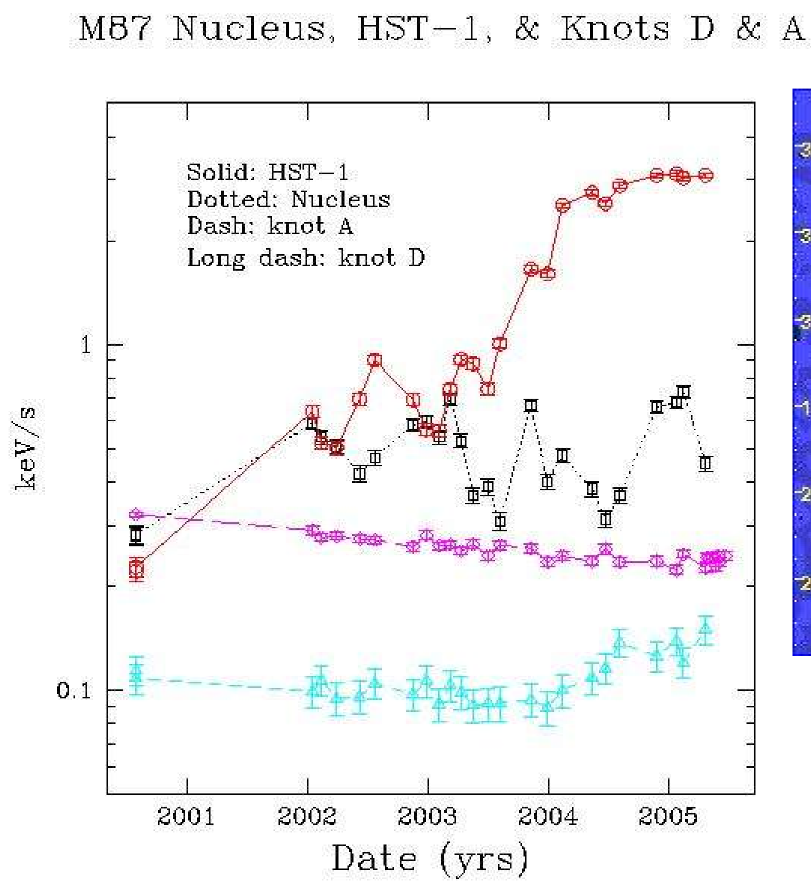


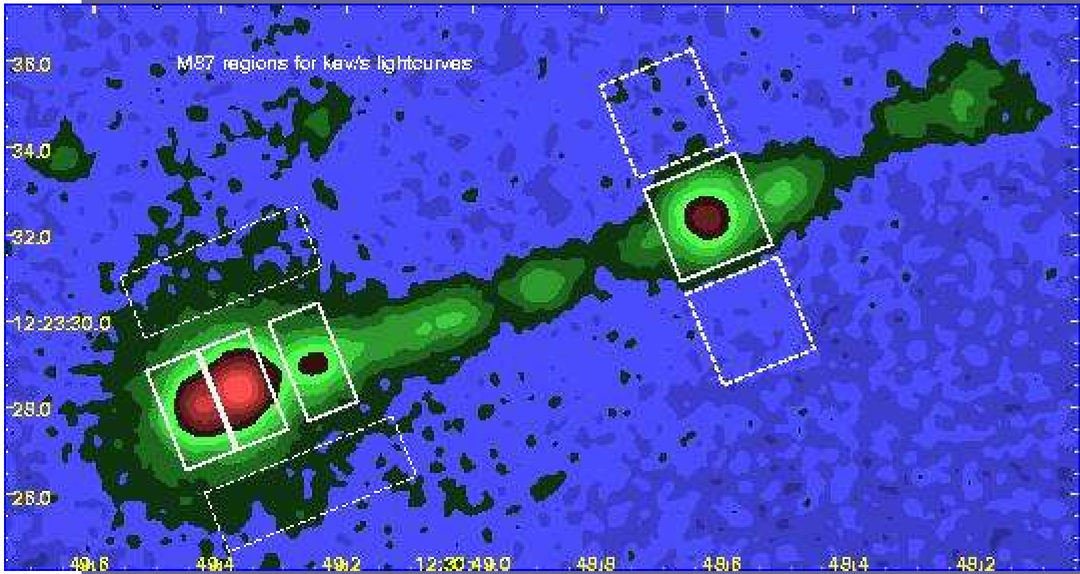


HST-1: Possible Flare Mechanisms

- **Injection of more particles**
- via stronger shock
- via more energy coming down the pipe
- **Compression**
- **Change in beaming factor**
- **Increase in B field**

M87 Variability

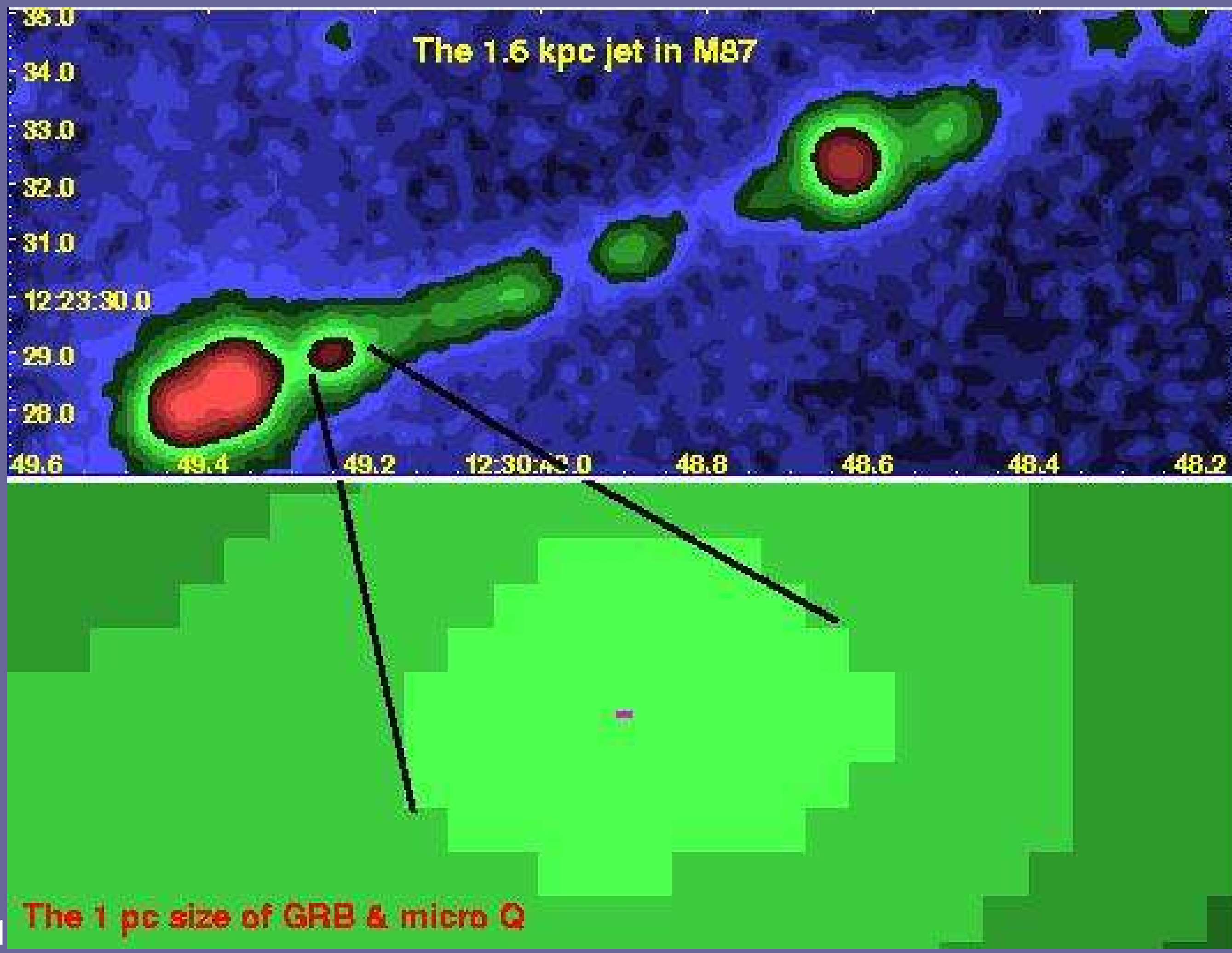




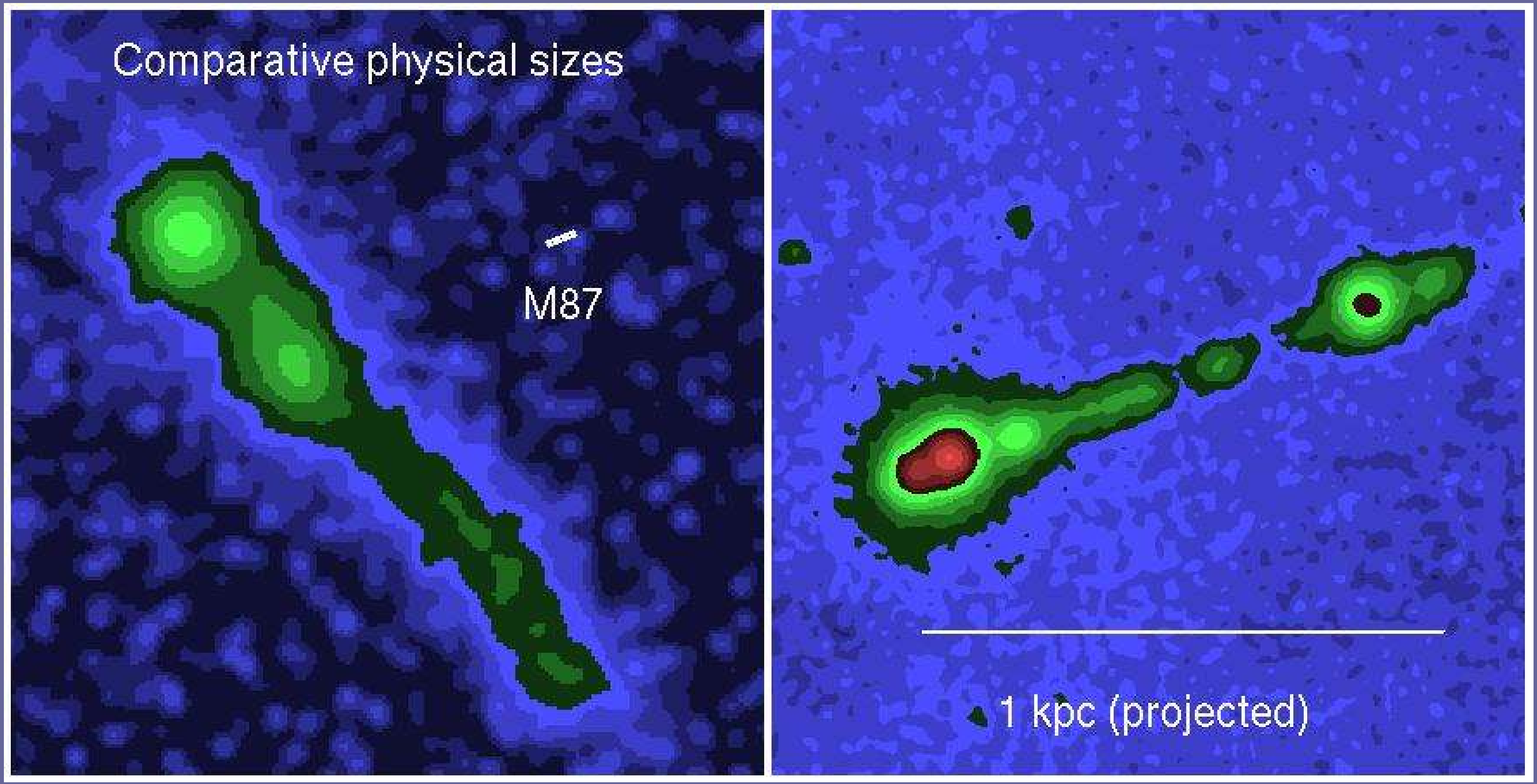
Part III: Comparing Observables

- Sizes
- Morphology – offsets between bands
- Morphology – profiles
- Spectra

Relative sizes.
pc scale and the kpc jets

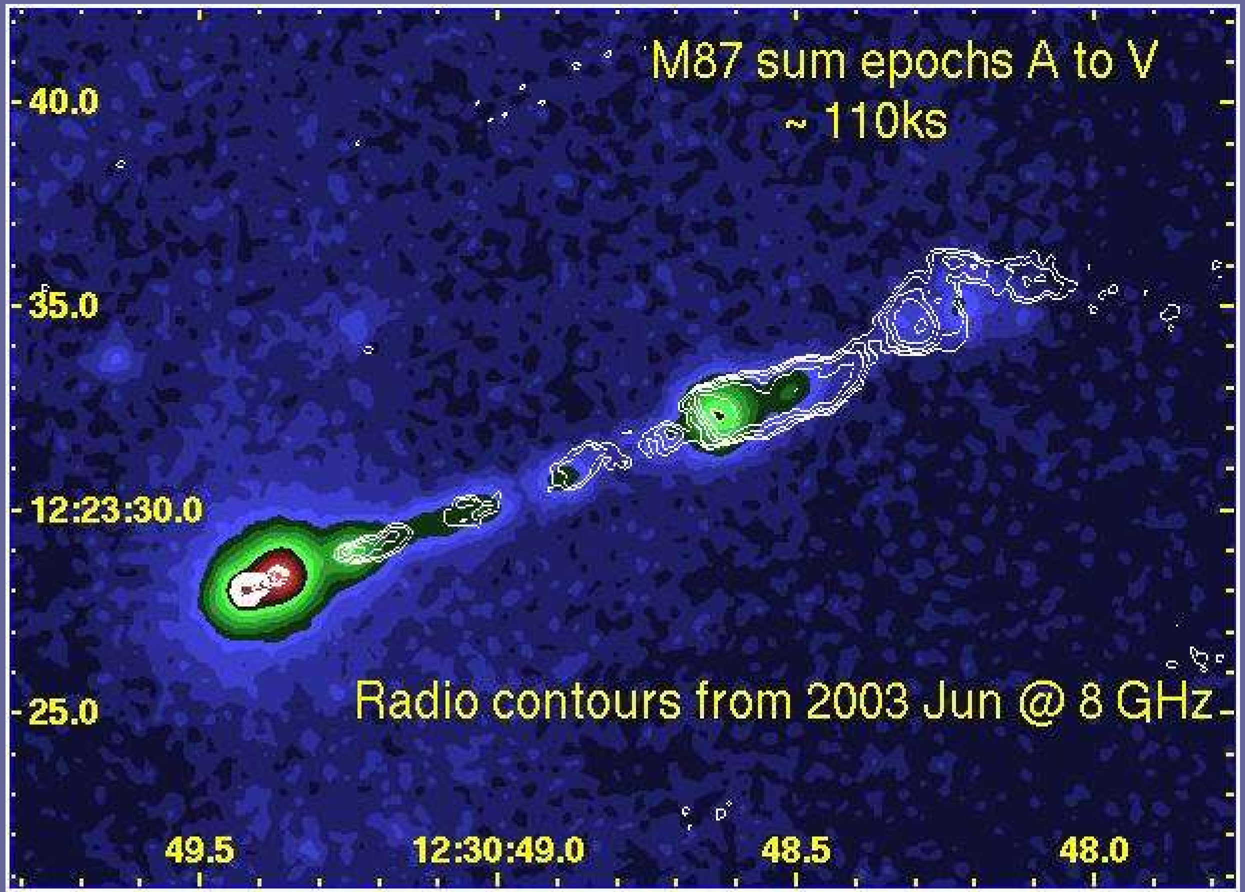


3C273 at same brightness scale as M87



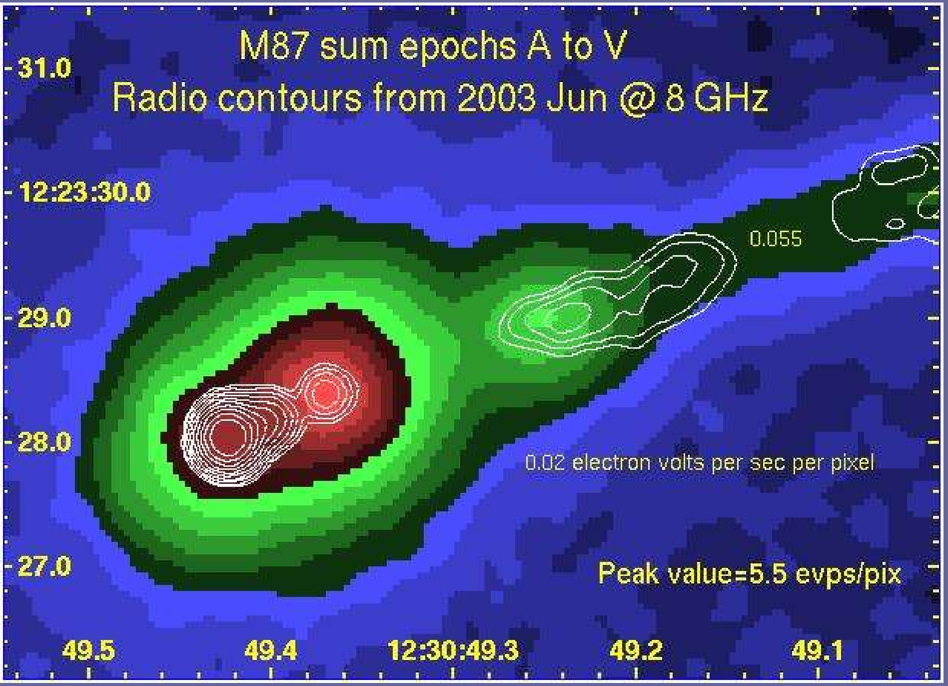
M87 as an example of synchrotron

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

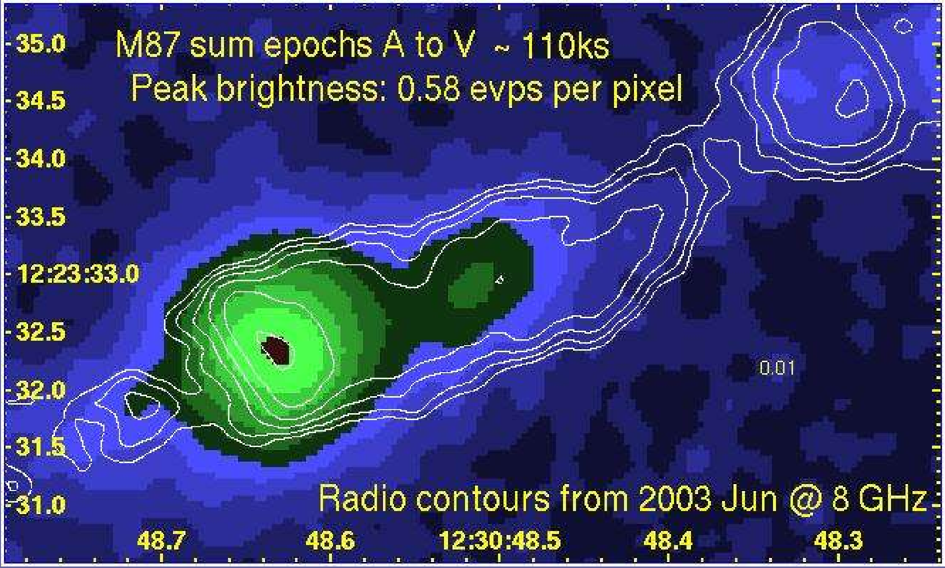


Radio vs. X-ray

Central region

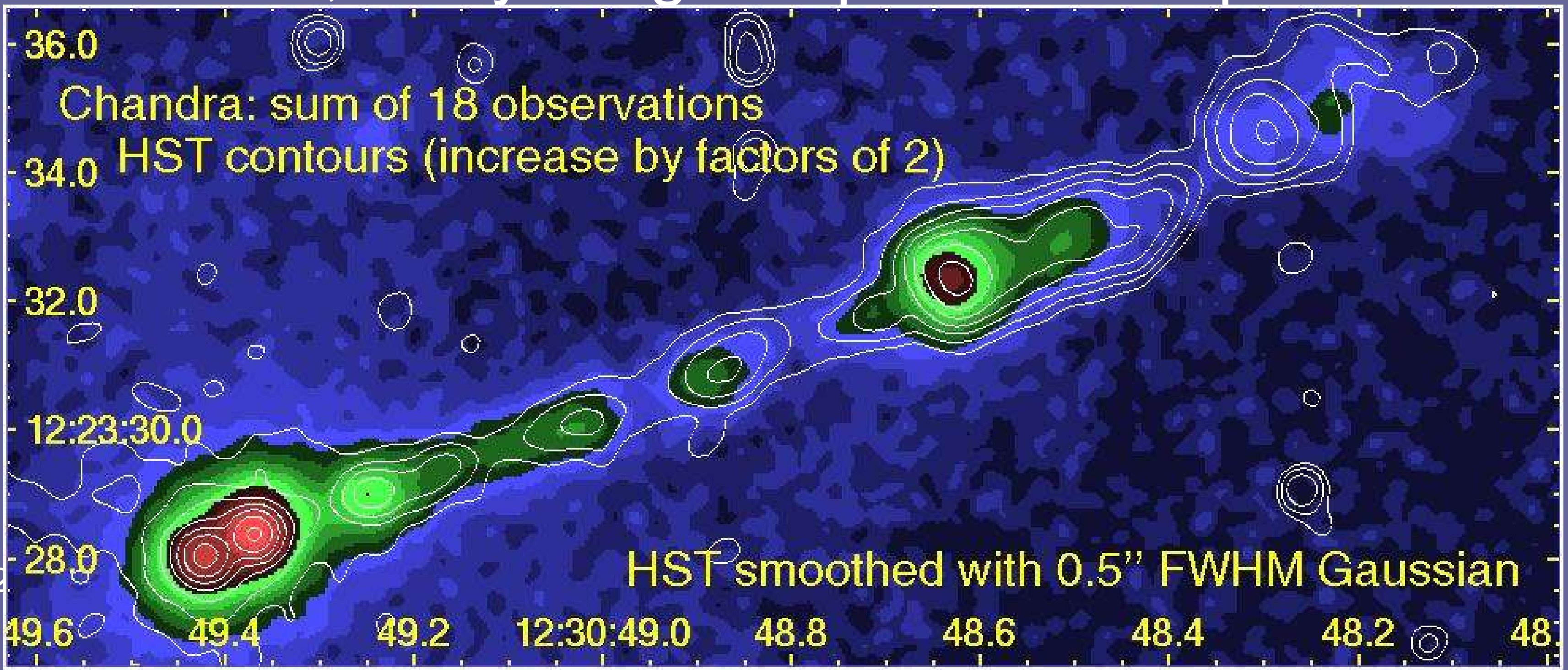


Knot A

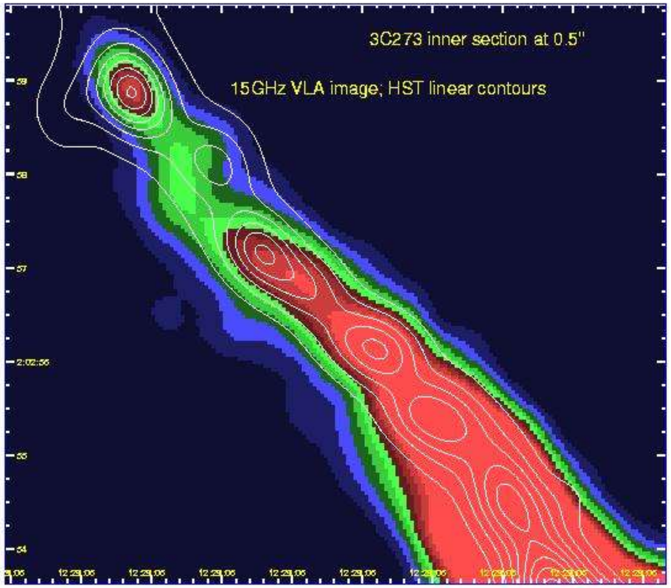


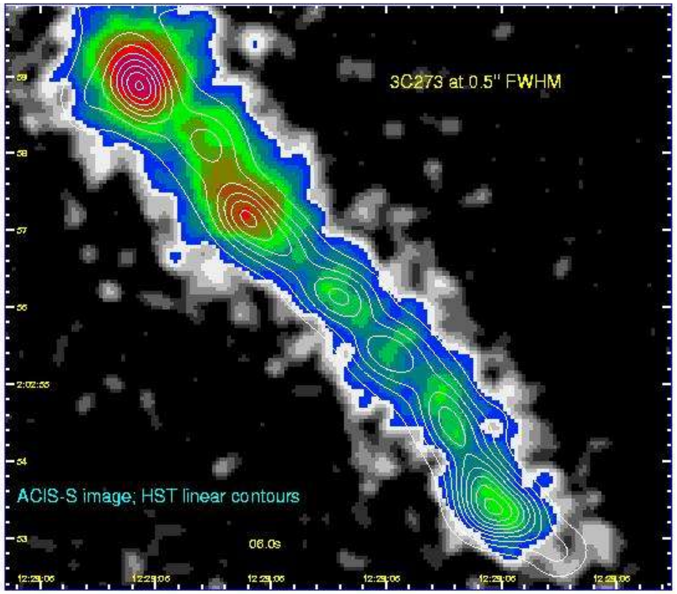
X-ray vs. Optical

- For knot D, note that optical brightness drops a factor of about 2 whereas the X-ray drops a factor of 5
- In knot F, X-ray is again upstream of optical

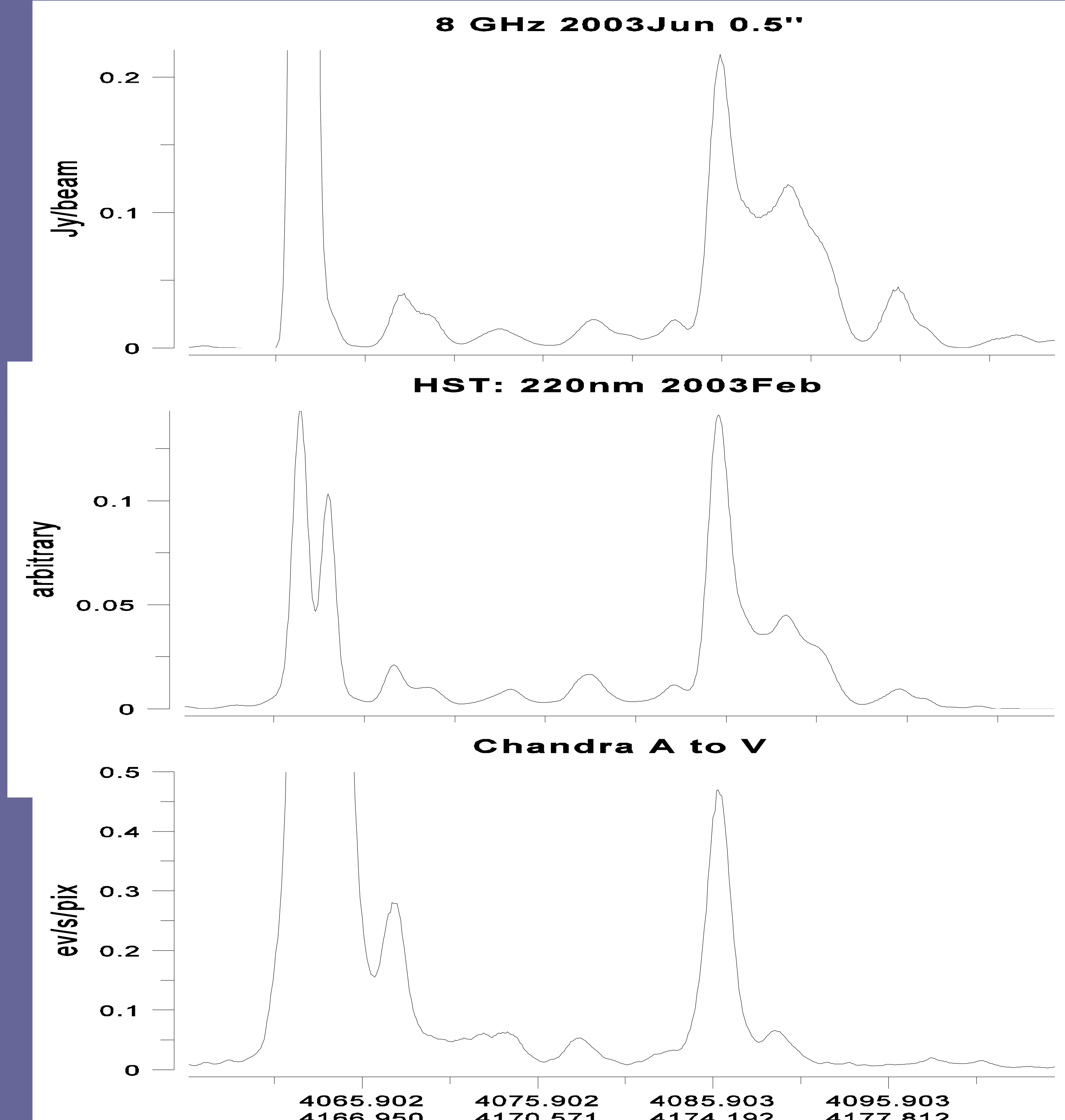


3C273 offsets

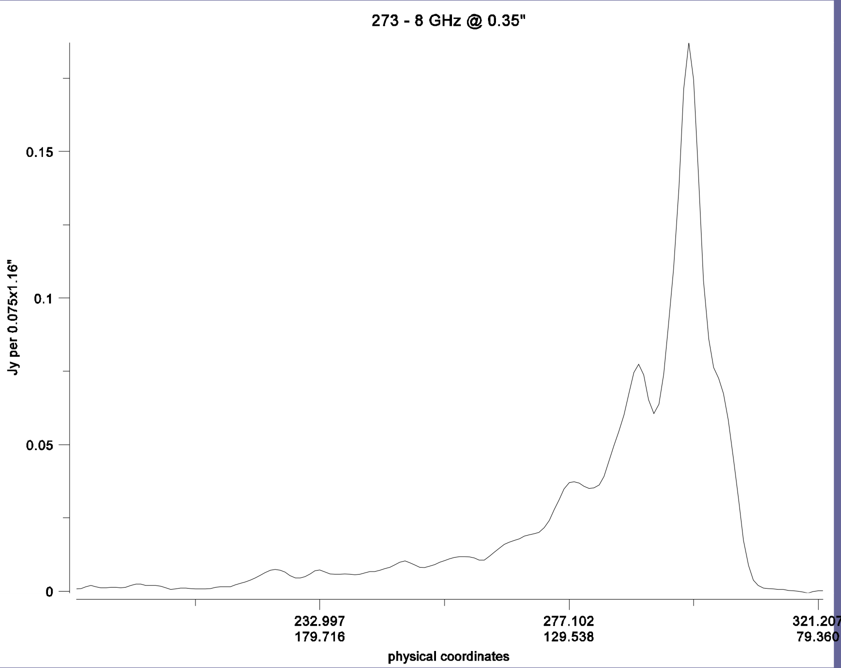


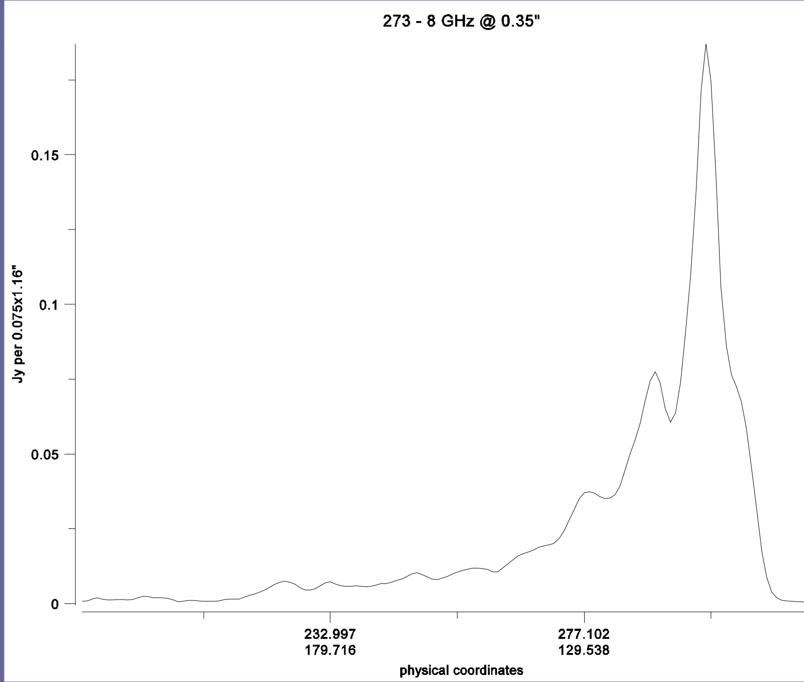


- - radio
- optical
- X-ray

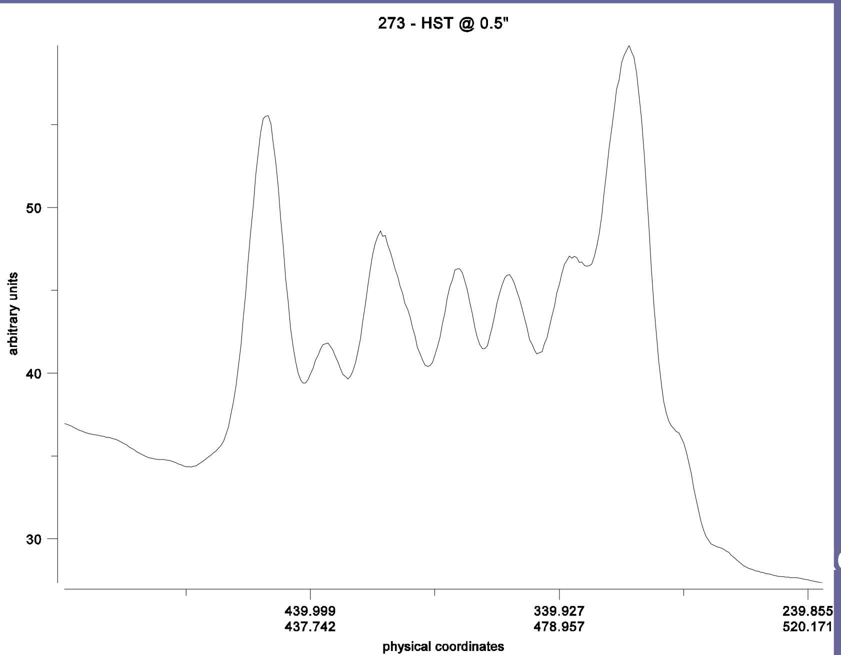


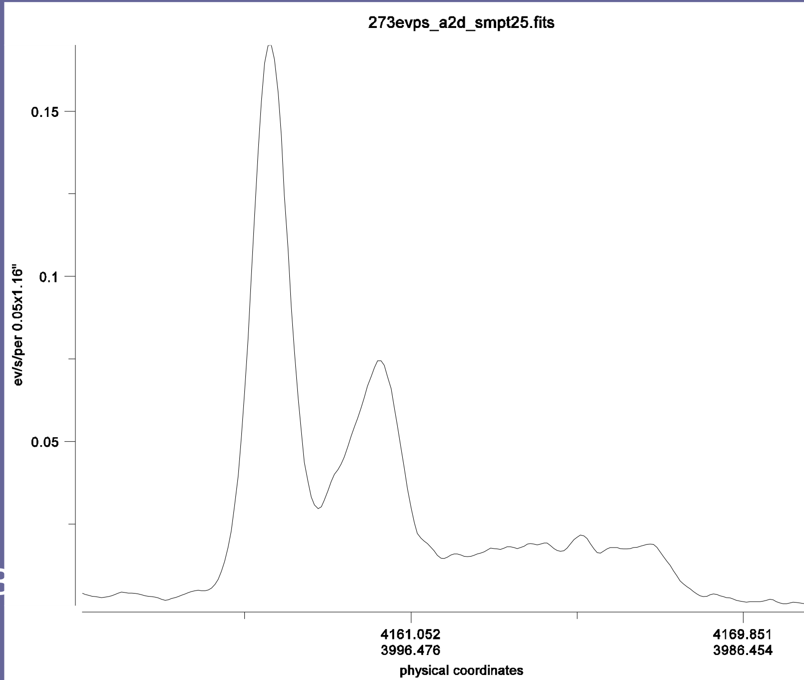
2005 July 11


273 - 8 GHz @ 0.35"
Jy per 0.075x1.16"
0.15
0.1
0.05
0
232.997
179.716
277.102
129.538
321.207
79.360
physical coordinates


273 - 8 GHz @ 0.35"
Jy per 0.075x1.16"
0.15
0.1
0.05
0
232.997
179.716
277.102
129.538
physical coordinates

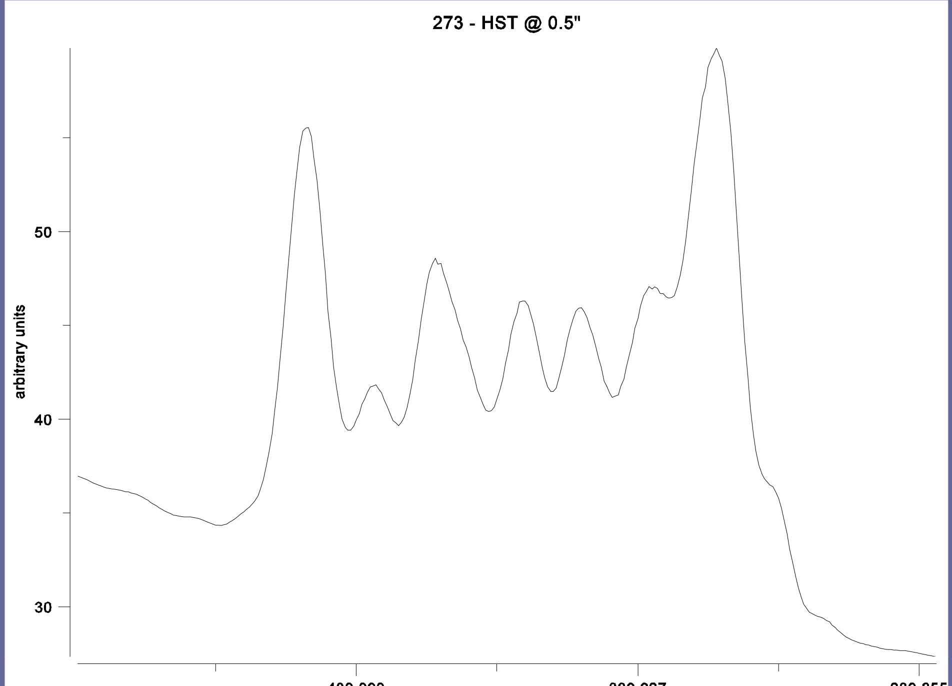
R

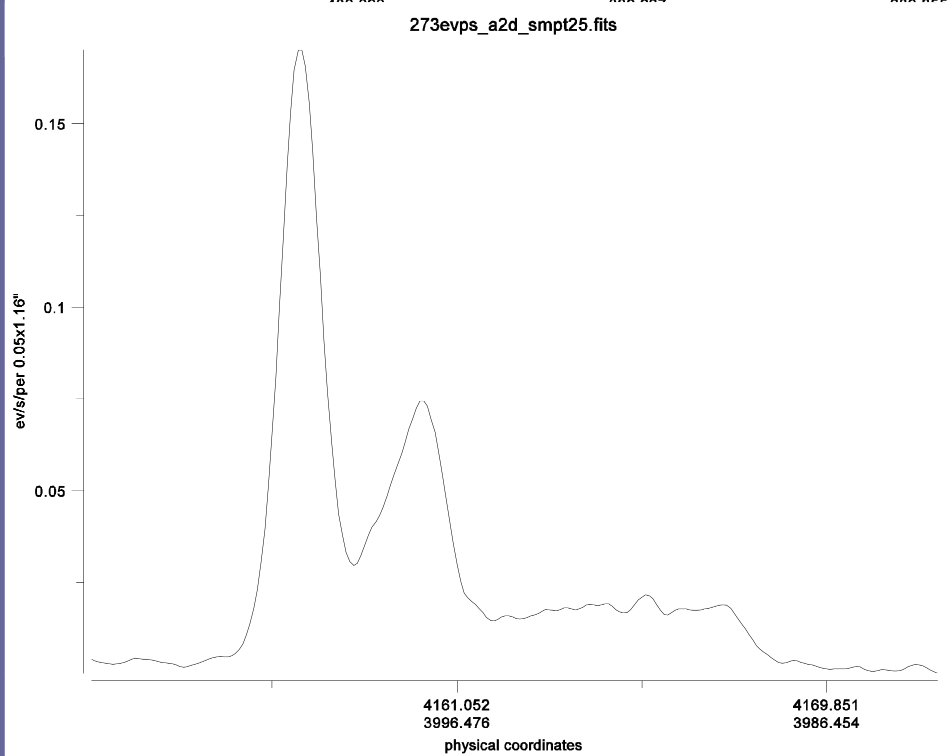

273 - HST @ 0.5"
arbitrary units
50
40
30
439.999
437.742
339.927
478.957
239.855
520.171
physical coordinates

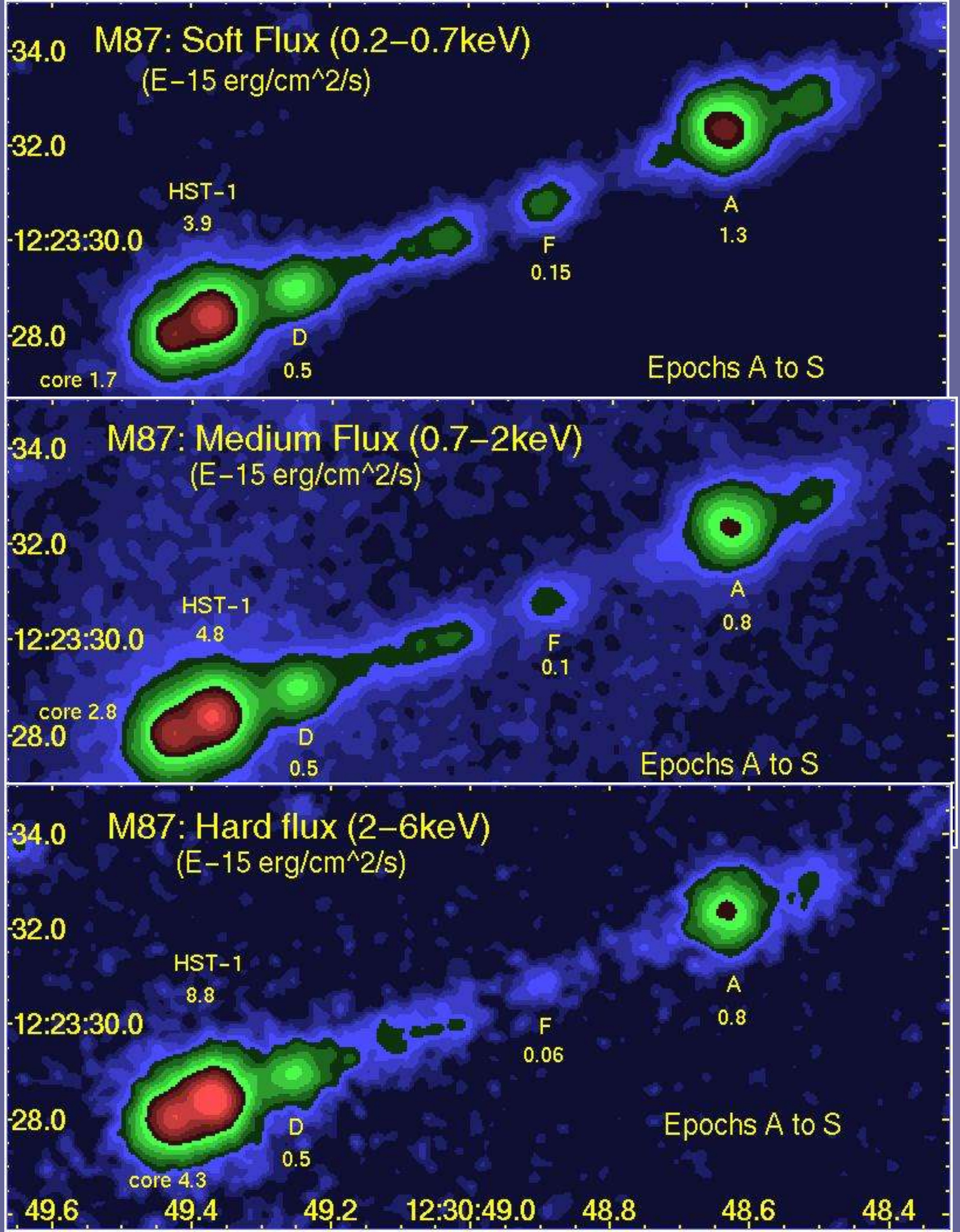

273evps_a2d_smpt25.fits
ev/s/per 0.05x1.16"
0.15
0.1
0.05
4161.052
3996.476
4169.851
3986.454
physical coordinates

<-O

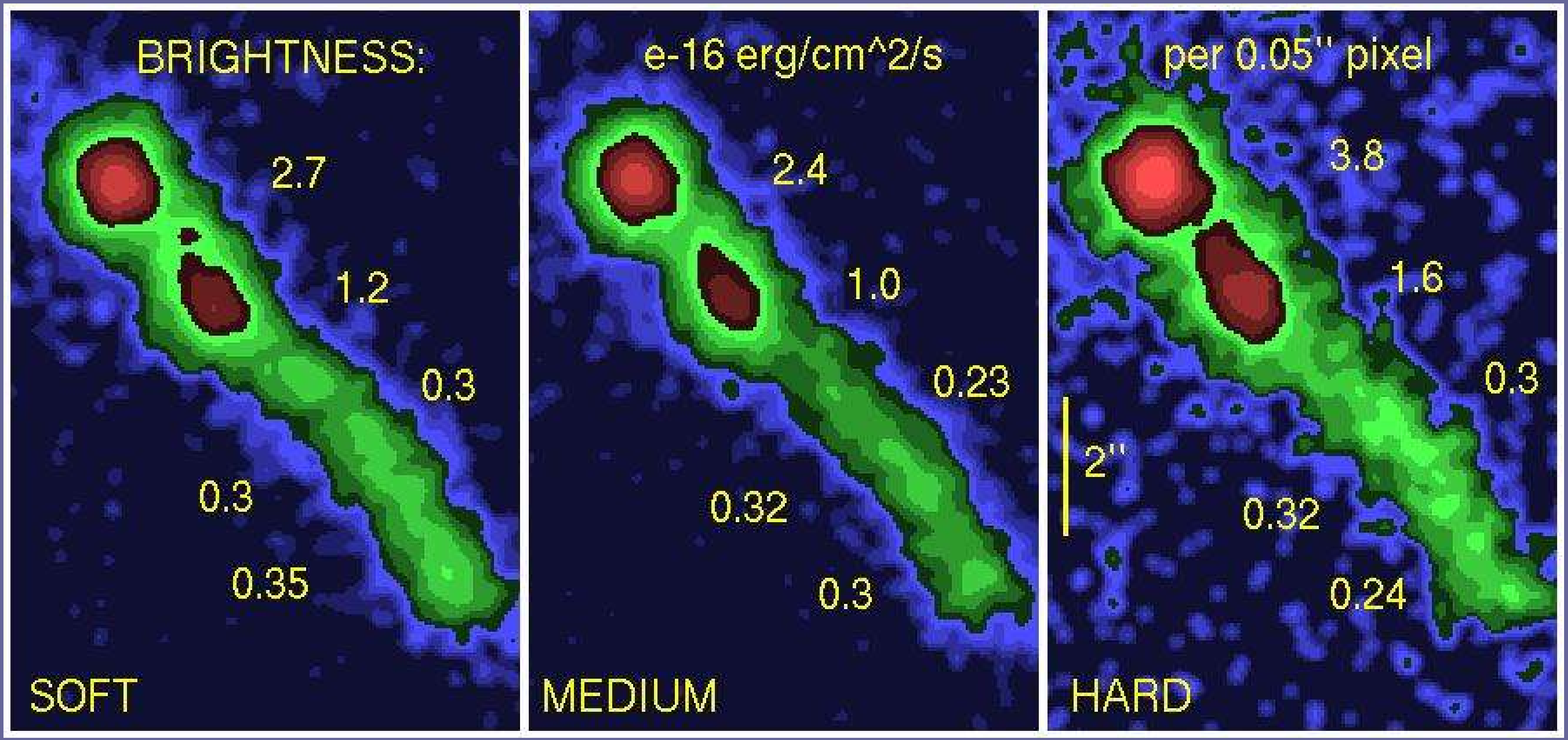
X->


273 - HST @ 0.5"
arbitrary units
50
40
30

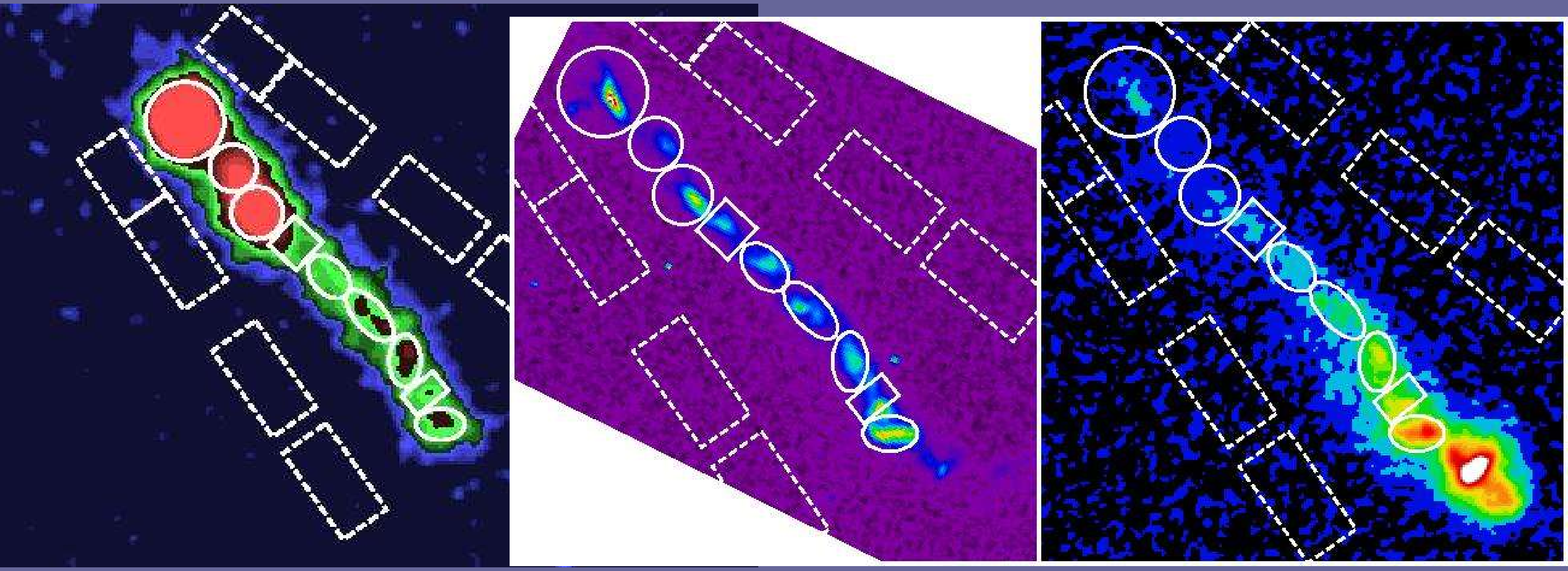

273evps_a2d_smpt25.fits
ev/s/per 0.05x1.16"
0.15
0.1
0.05
4161.052
3996.476
4169.851
3986.454
physical coordinates


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

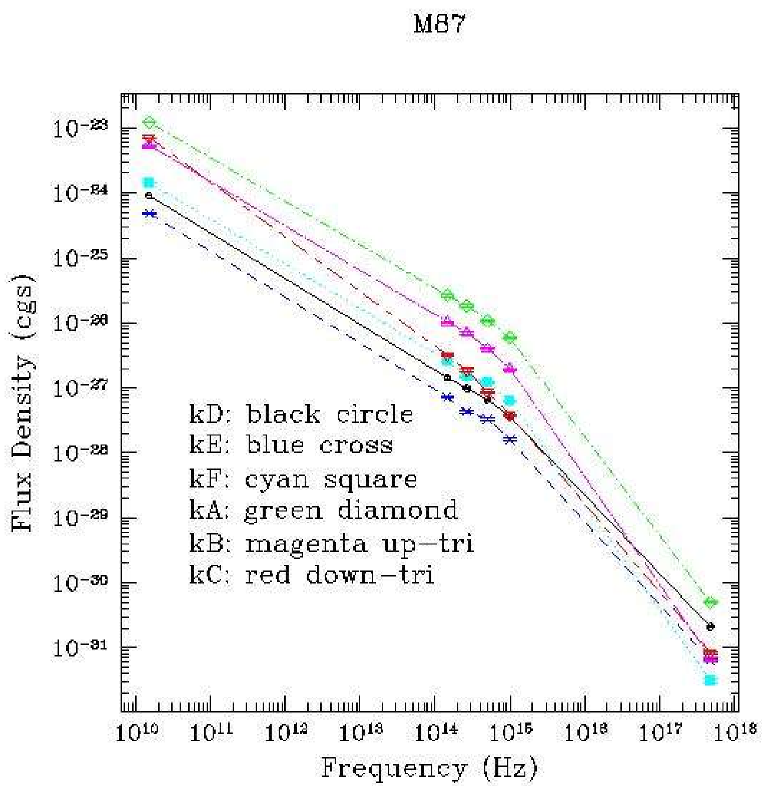
Comparison of soft, medium, & hard bands (Chandra)

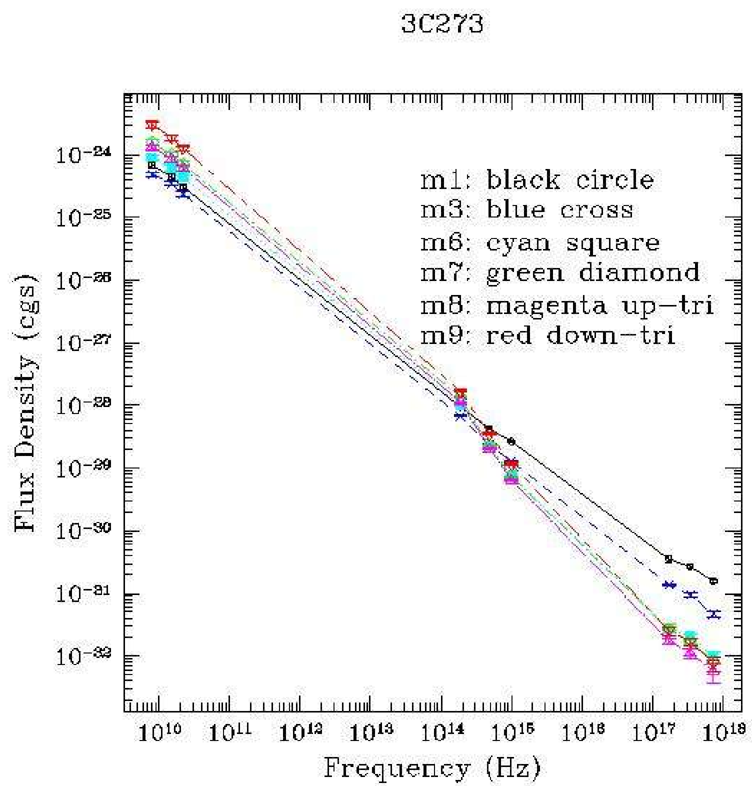


3C 273 - Spectra

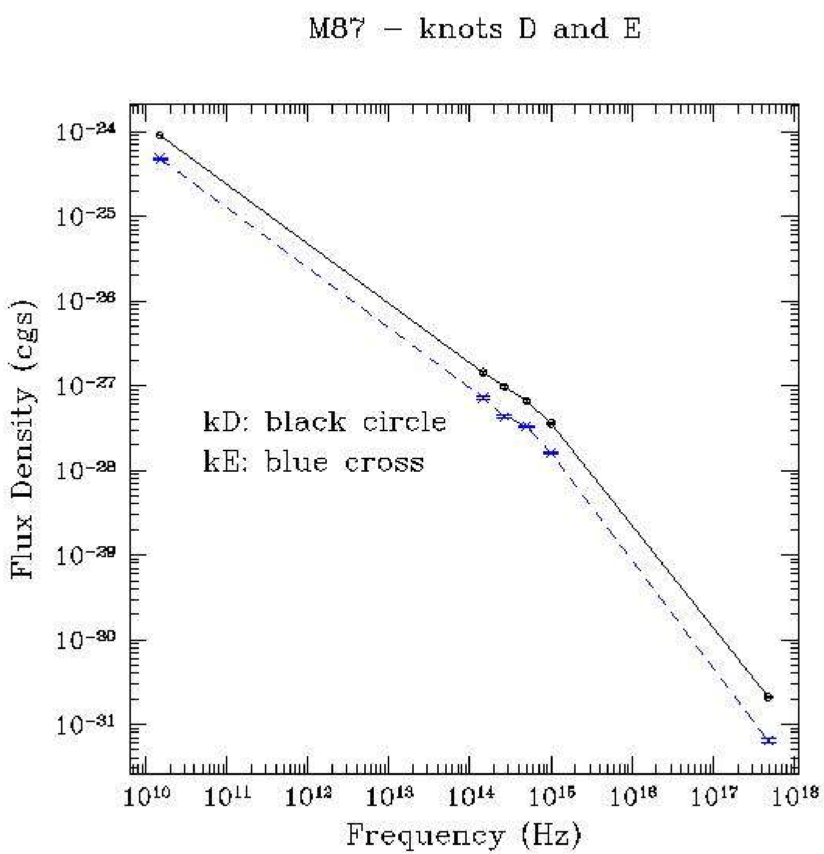


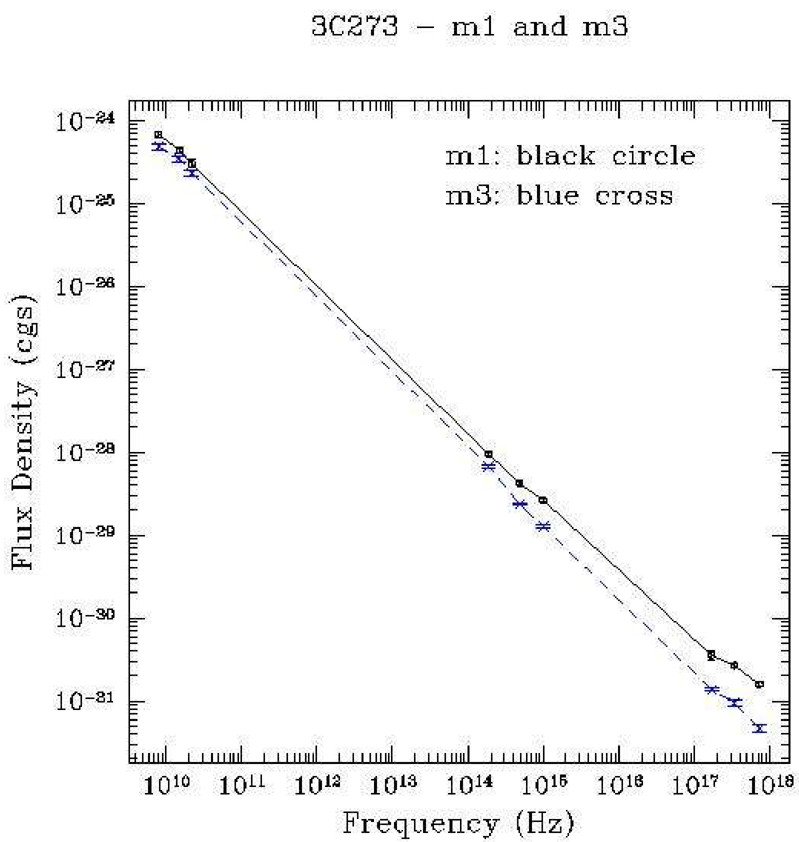
Spectra of knots



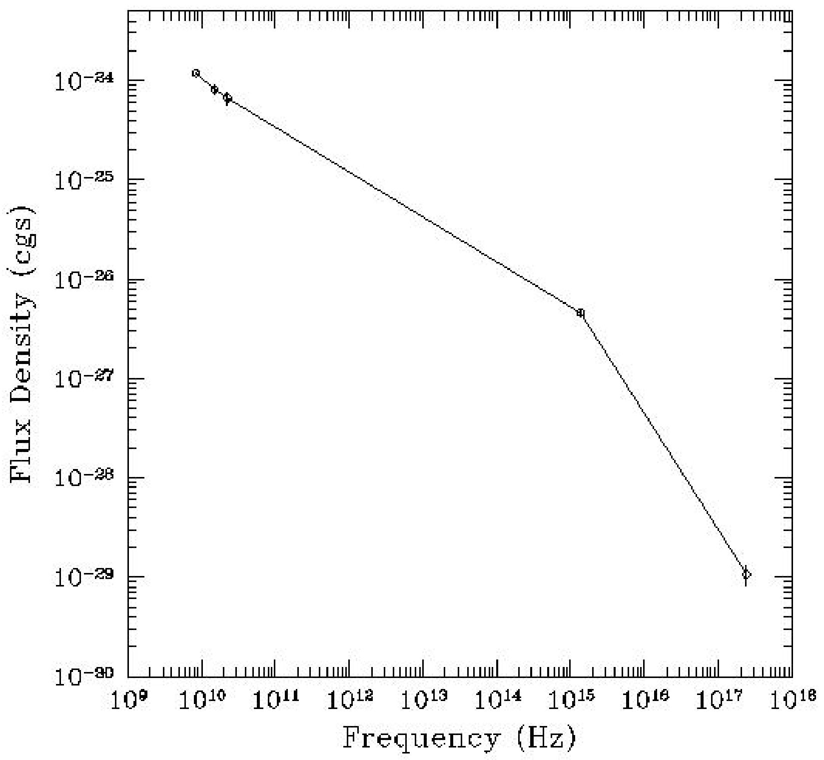


upstream knots

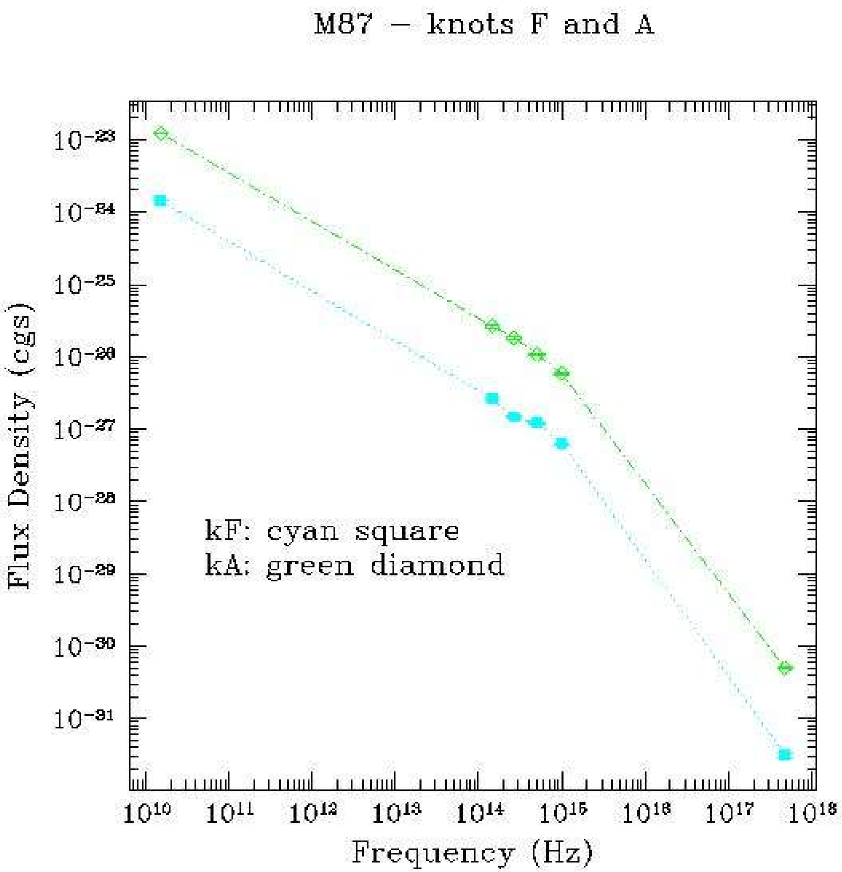


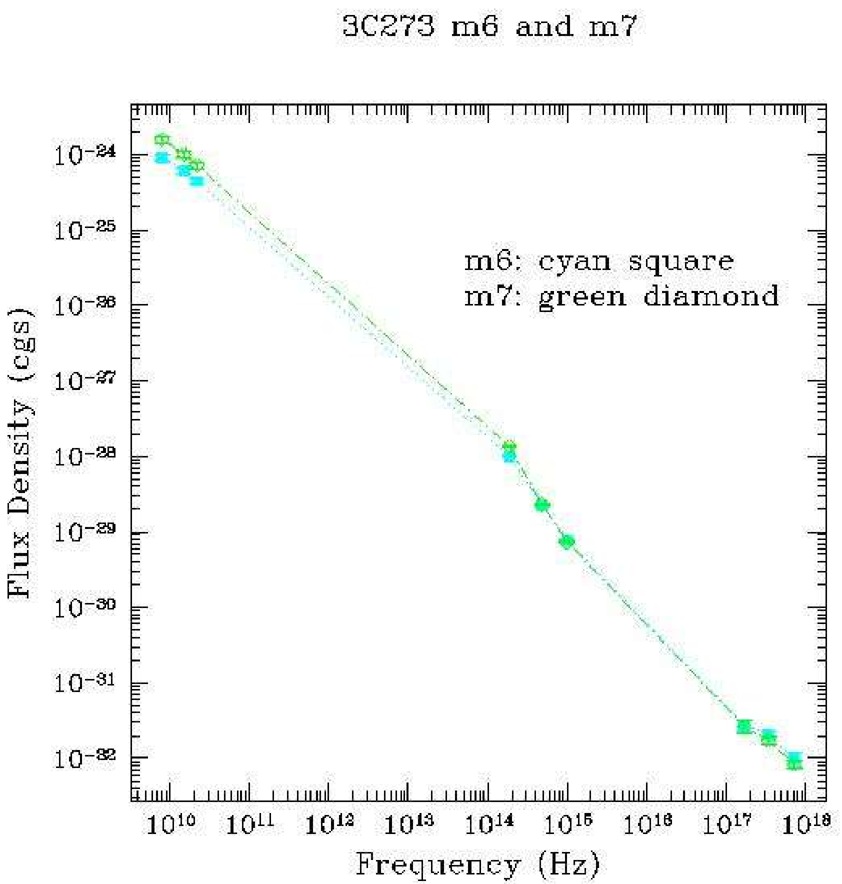


M87: HST-1 spectrum 2005.0

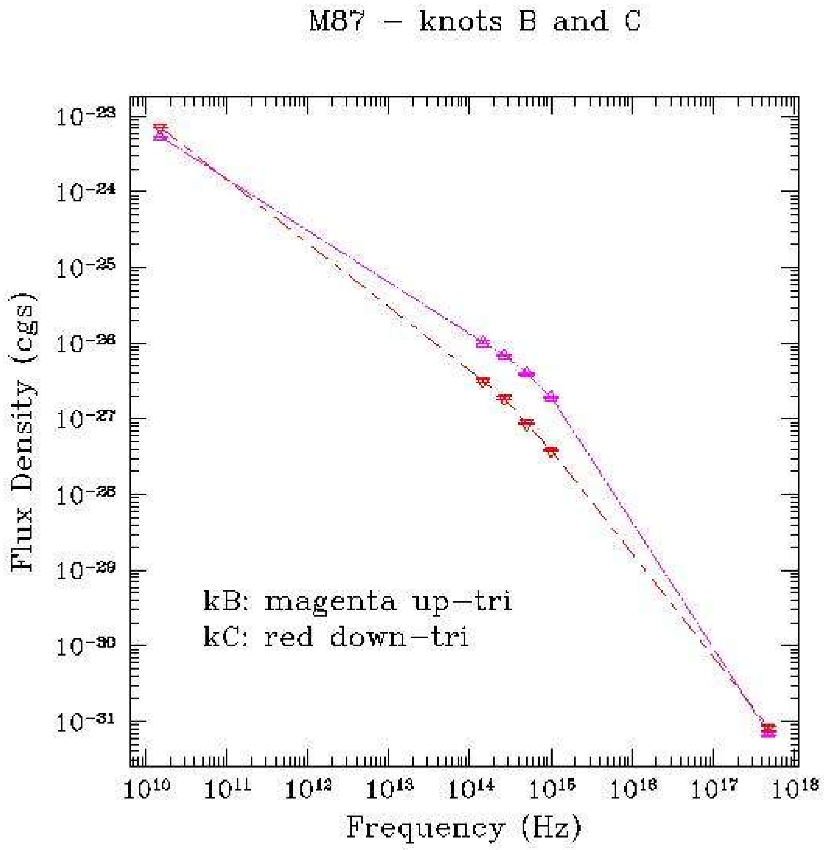


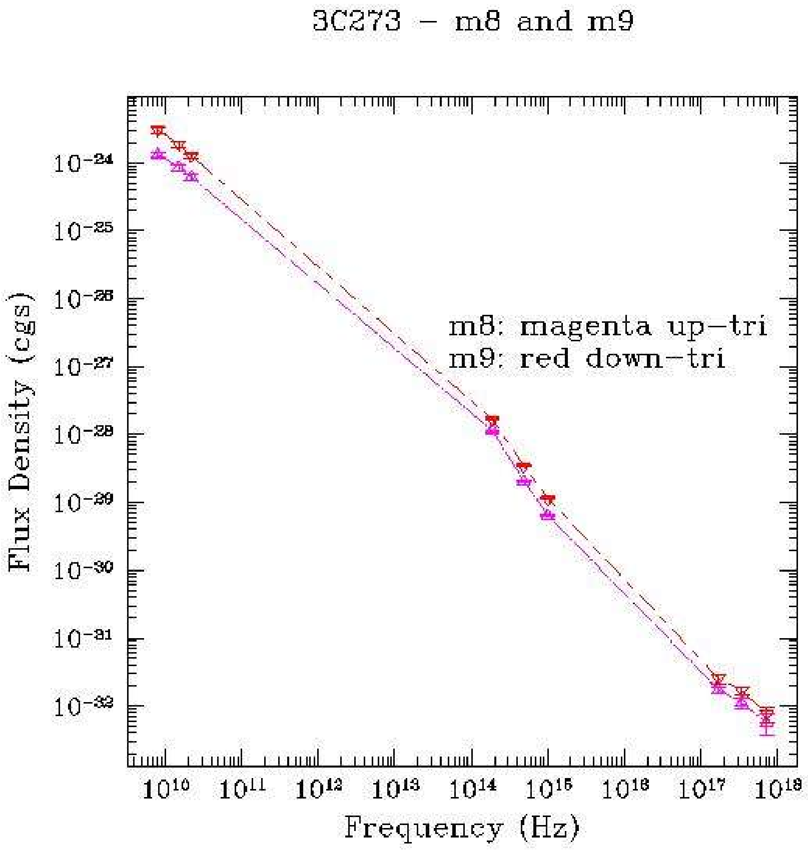
mid-jet knots





knots near the end of the jet





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

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

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

Part IV: Comparing Parameters

– SYNCHROTRON		– IC/CMB with beaming	
Γ	3 to 5	Γ	5 to 20 or more
γ	10^7	γ	100
τ	1 year	τ	100,000 years

Compare bright knots

- Although there is convincing evidence that X-rays from FRI jets (such as that in M87) come from synchrotron emission, this is not the case for powerful jets such as that in 3C273. In the tables below, we compare properties of HST-1 with a few of the knots in the 3C273 jet.

HST-1 (M87) compared to 3C273 knots

- While HST-1 is vastly different from the 3C273 knots in size and distance from the core, the intrinsic luminosities could be quite similar, depending on the beaming factors.
- The δ,θ pairs in the second table were chosen on the basis of the 'mild beaming' synchrotron model for M87; whereas for 3C273, these are the parameters required for producing the X-rays via inverse Compton scattering off the CMB. (Harris & Krawczynski 2002)

M87 & 3C273 – no beaming

	Distance from core (arcsec)	Distance from core (projected) (pc)	Physical size (pc)	Luminosity (sync.) (erg/s)	Luminosity (x-ray) (erg/s)	B(equip.) (μG)
HST-1	0.8	62	1.5	6.5E40	…	13000
273/A	13	48000	370x 1850	2.0E40	1.9E43	172
273/B	17	72000	370x 1850	…	…	134
273/DH	20	75000	…	2.9E43	1.1E41	221

M87 & 3C273 – with beaming

	δ	θ (degrees)	Distance from core (de-proj.) (kpc)	Physical size (pc)	Lumin. (sync.) (erg/s)	Lumin. (x-ray) (erg/s)	B(equip.) (μG)
HST-1	4	15	0.238	0.4	2.5E38	…	1000
273/A	25	2.3	1196	370x 1850	5.1E37	5E37	6.9
273/B	20	2.8	1269	370x 1850	…..	…	6.7
273/DH	10	5.5	783	…..	2.9E39	1E37	22

Summary: Spine/sheath jet structure

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 ($\Gamma>10$) spine plus slower sheath on kpc scales. This permits more latitude for IC models but ***any*** 2 zone model normally precludes the critical tests afforded by comparison of radio, optical, and X-ray data.

Summary: IF Synchrotron

- we are making serious demands on acceleration process to produce $\gamma > 10^7$
- we can study the loss process (because the half-life, τ, is so short),
- we should be able to separate light travel time from loss timescales if we are in E^2 loss regime (sync and IC losses dominate). i.e. since τ goes as $1/\gamma$, at low (i.e. radio) frequencies, the loss time scale should exceed the light travel time across the source.

Summary: Critique of Synchrotron X-ray Emission

- We need to more convincingly demonstrate departures from power laws at high energies.
- Can distributed acceleration account for emission between the knots?

Summary: IF IC/CMB

- if we can estimate Γ from intensity requirements, we will get a rare glimpse of N(E) at low energies.
- Better estimates of P_{nt} B_{eq} E_{tot} etc.

Summary: Critique of IC/CMB

1) We see one sided jets with well defined knots. Since the IC/CMB model requires low γ electrons with long half-lives, why are the knots shorter in the X-rays than in optical and radio? Beaming factor changes rapidly; either because of change of direction or deceleration (and subsequent acceleration at the next knot).

Summary: Critique of IC/CMB

- 2) The validity of the required extrapolation of the electron spectra is unknown and currently untestable. [Both amplitude & spectral shape]
- 3) There is no independent evidence that $\Gamma>10$ instead of a few.
- 4) Failure to find plethora of predicted high z jets and the correlation between z and Γ (L. Stawarz).

Summary: Critique of IC/CMB

- 5) Fine tuning of γ_{min}.
- 6) Coincidence of intensity comparable to synchrotron. Components of intensity are the (unknown) number of low E electrons; Γ of emitting plasma, which enters to a high power both augmenting the CMB and determining δ; and θ (which goes into δ). From an ‘a priori’ viewpoint, all of these factors could vary widely.

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