Observational Studies of Large Scale X-ray Jets

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Outline

- Status of X-ray observations
- Some details of X-ray properties
- Jets from low to high redshift

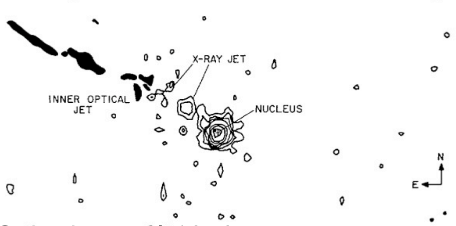
X-ray Jets

- First extragalactic jets were discovered ~50 years ago in early 1960-ties
- 3C 273 - optical jet first and a radio counterpart later
- Before Chandra only a few X-ray jets were known:

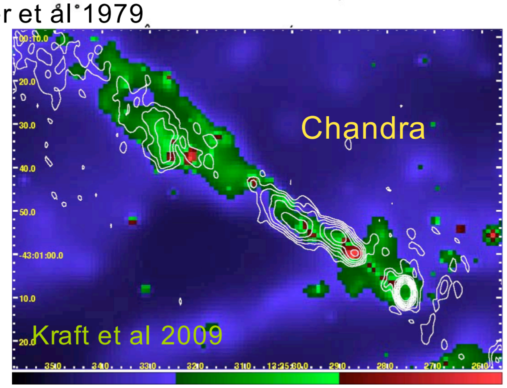
Centaurus A, 3C 273, M87

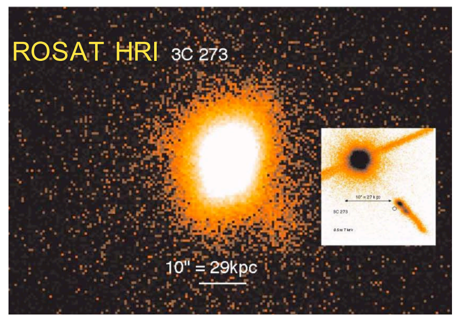
Cen A

Einstein HRI



Schreier et al 1979





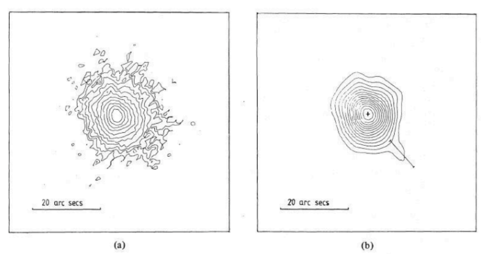


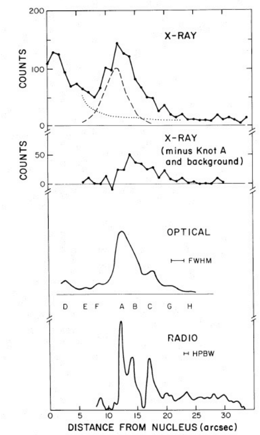
Figure 1. (a) Contour plot of the raw count data from 3C 273 binned in 4 × 4 arcsec pixels. (b) Contour plot of the maximum entropy deconvolution of 3C 273. The optical jet is shown as a bar.

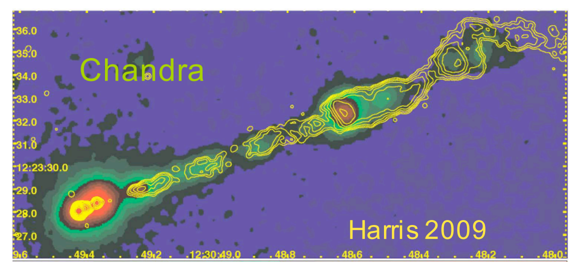
Einstein HRI, Willingale 1981

Schreier et al 1982

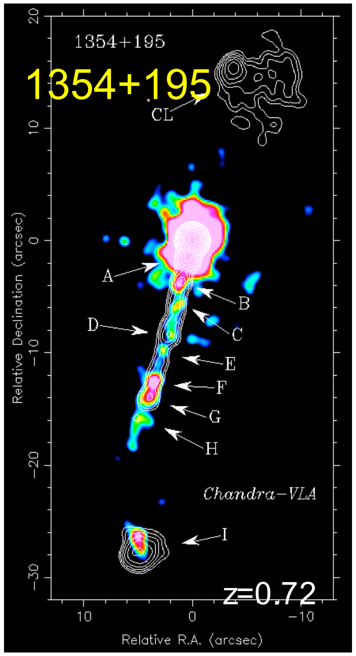
M87

X-ray profiles in Einstein HRI by Schreier et al(1982) observation of M87 indicate X-ray emission from jet knots



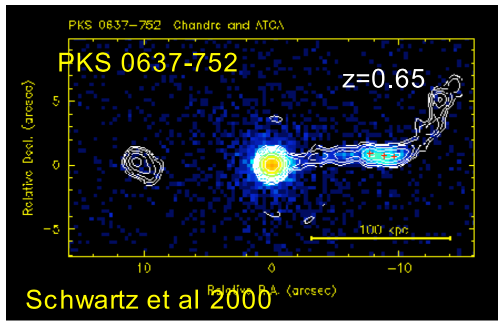


X-ray Jets in Chandra Era

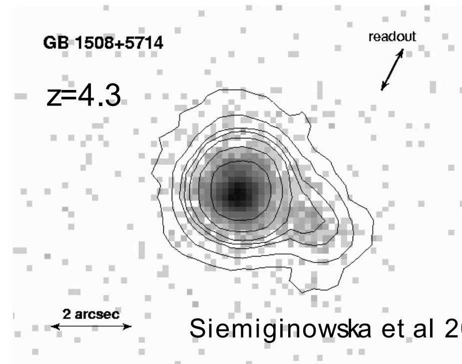


Sambruna et al. 2002

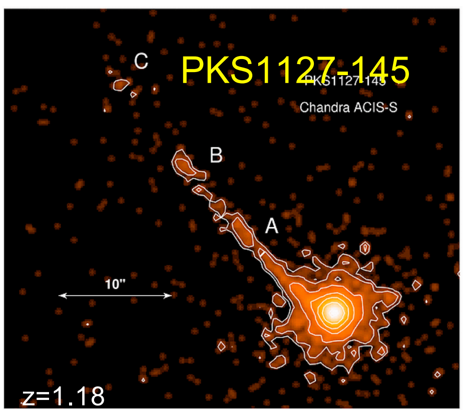
- > 90 X-ray Jets on the XJET Web page (Dan Harris):
  http://hea-www.harvard.edu/XJET/index.cgi
  FRI/FRII, Lobe Dominated and Compact Quasars
- Highest redshift GB1508 +5714 at z=4.3



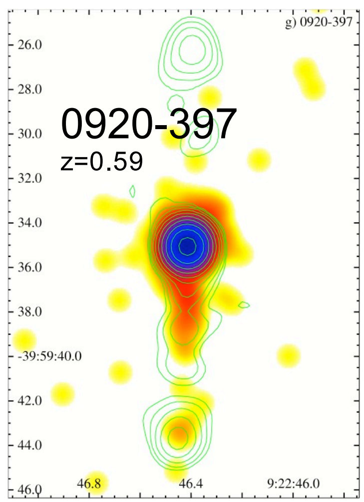
Schwartz et al 2000



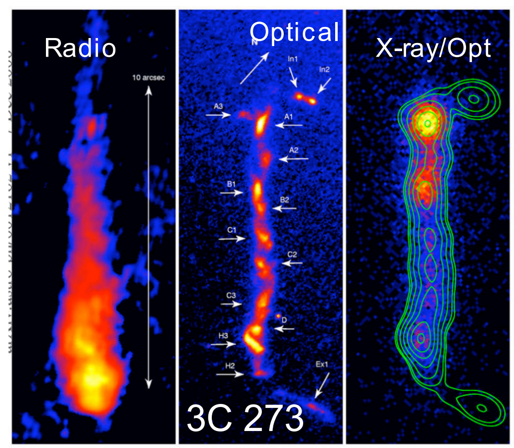
Siemiginowska et al 2003



Siemiginowska et al. 2002, 2007



Marshall et al. 2004



Marshall et al. 2001

Why X-rays?

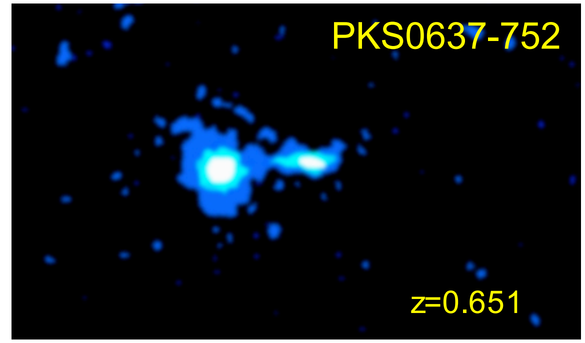
- X-ray emission in jets due to synchrotron or Inverse Compton process.
- Synchrotron emission:
  - $B \sim 10^{-3}$-10^{-5} G and particles with $\gamma_e = E_e/m_e c^2 \sim 10^7$-$10^8$
  - Short life times ~10-1000 years
  - Continuous acceleration at large distances from the origin.
- Inverse Compton process:
  - SSC - Synchrotron photons upscattered to X-rays by the same population of particles in the jet
  - EIC - source of low frequency photons outside the jet
- X-ray observations - important constraints

Why X-rays?

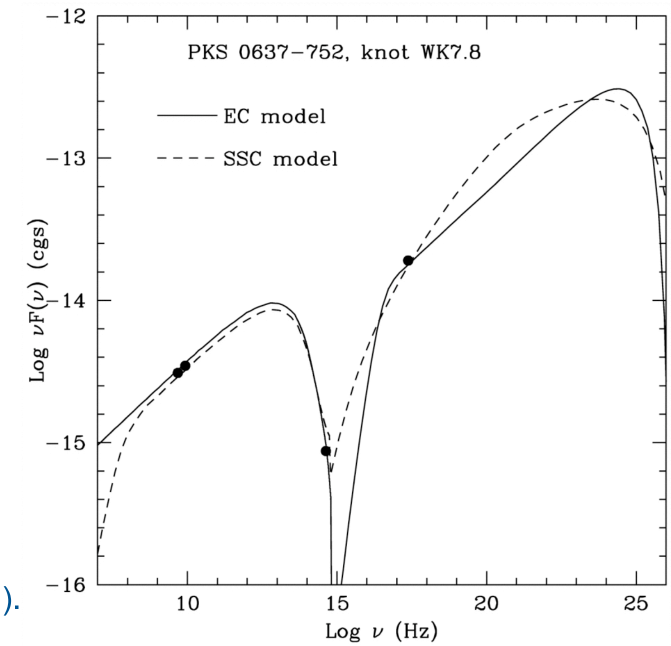
- Spectral shape excludes one population of synchrotron emitting electrons

- SSC emission requires high deviation from equipartition to explain the X-ray intensity

- IC/CMB - high bulk motion of the jet $\Gamma \sim 10$ at large distance from the origin



Schwartz et al 2000



EC: $R = 10^{22}$ cm, $B = 1.5 \times 10^{-5}$ G;
$\delta \sim \Gamma = 10$ ($\theta \sim 6°$).
$\gamma_{min} = 10$ and $\gamma_{max} = 4 \times 10^5$, $K = 6 \times 10^{-5}$ cm^{-3}, p=2.6 ($\alpha = 0.8$).

SSC: $B = 1.25 \times 10^{-6}$ G $\delta = 1$. $\gamma_{min} = 2.5 \times 10^3$, $\gamma max = 4 \times 10^6$, $K = 19$ cm^{-3}, p=2.6
Break at ~100 MHz due to the high value of γ_{min}.

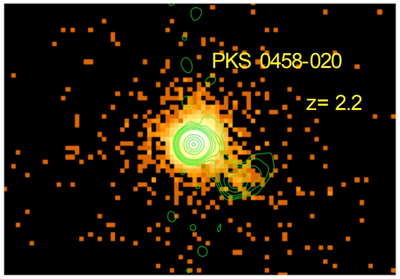
Tavecchio et al 2001

X-ray Observables

- Morphology
    - structures: knots, hot spots
- Total luminosity
- Intensity profile
- Spectra and spectral evolution along the jet
- Variability
- + Multiwavelength studies: radio, IR and optical

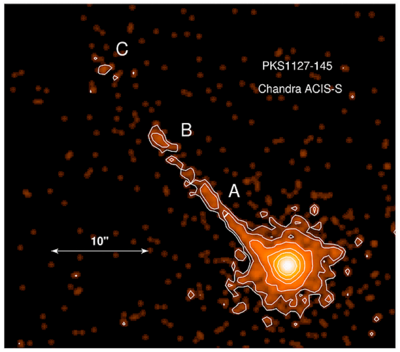
Jets Length

- Nuclear scales < few pc
    - Blazars - core-jet, looking down the jets, direct view of the acceleration site, multi-wavelength variability can probe the jet origin,
    - Associated large scale jets have been detected
- Host galaxy scales < 10-20 kpc
    - Radio Galaxies, Compact Radio Sources
    - Direct interaction with the ISM
    - Feedback
- Large scale, outside the host galaxy, some exceeding >100 kpc distances from the core
    - Continuous jets, straight, curved, many knots
    - One phase or many?



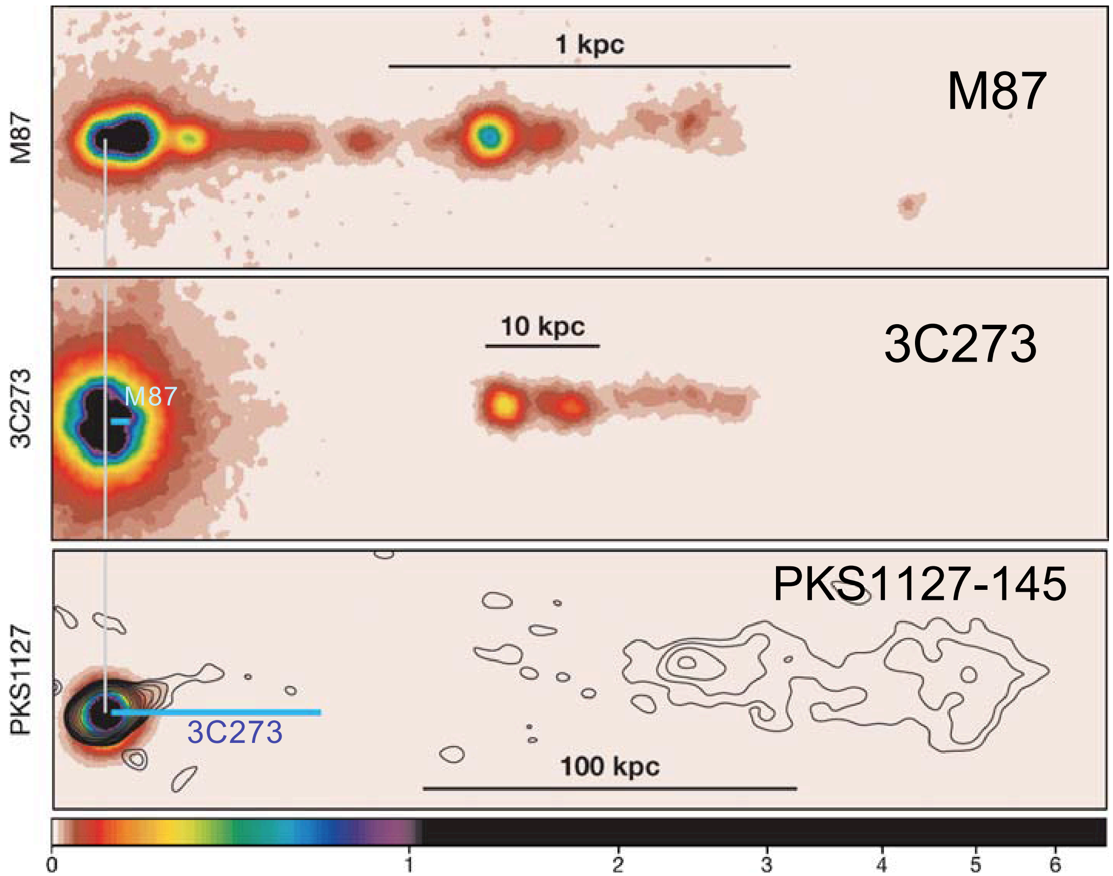
Core-jet and
Large scale
X-ray jet

Cen A
~ 6kpc



~300kpc

X-ray Jets Scale

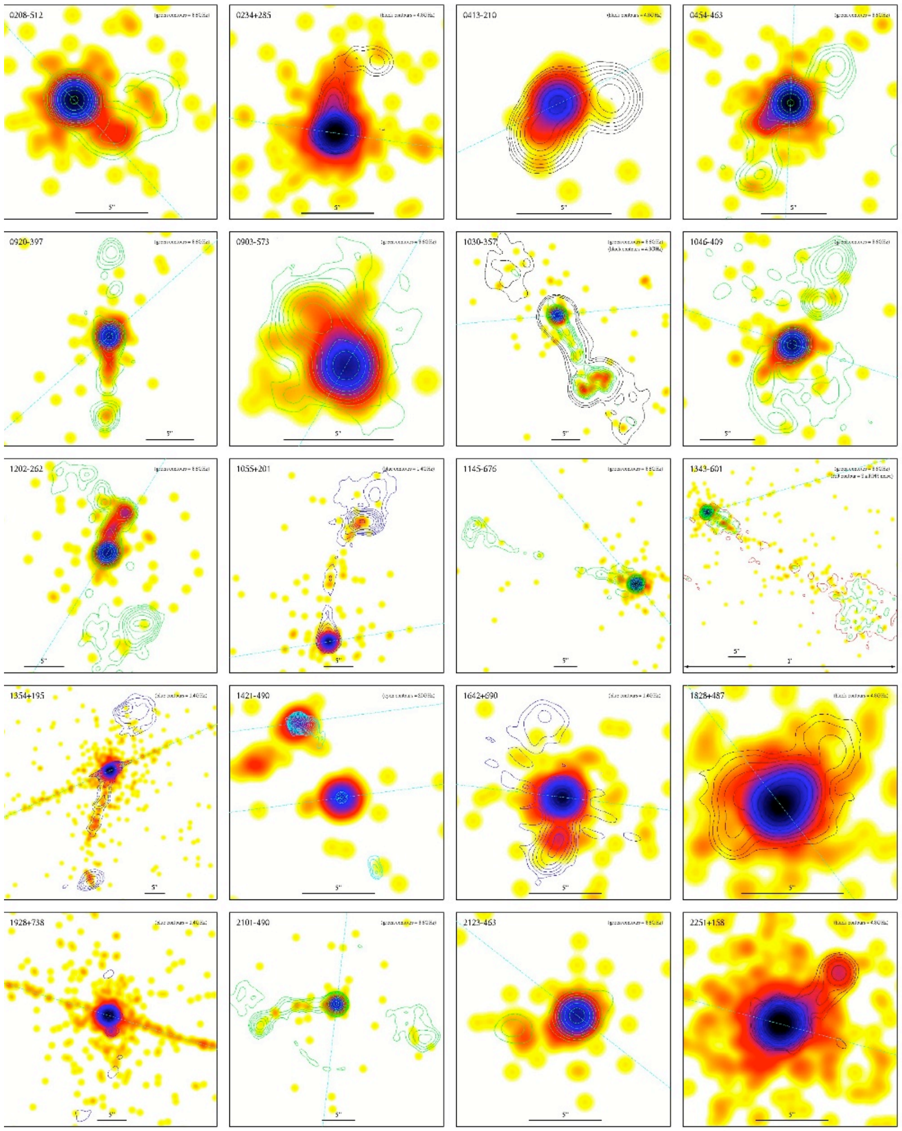


1.6 kpc
21"

56 kpc
21"

238 kpc
29"

Harris & Krawczynski (2006, ARA&A)



Marshall et al, 2005, ApJ

X-rays Morphology

Representative snap shots:

- One sided jets
- Straight
- Curved
- Bent and at the end
- Multiple knots
- Hot spots

Detailed Examples

- PKS1127-145 z=1.18
- 4C19.44 z = 0.72
- 3C273 z = 0.158
- 3C353 z= 0.0304
- M87 z = 0.00436

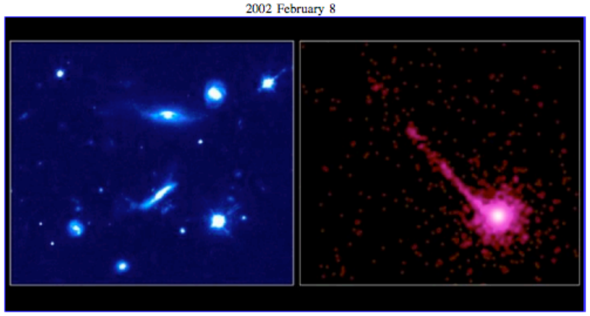
X-ray Jet Discoveries

PKS1127-145
quasar at z=1.18
~300kpc long X-ray jet

Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2002 February 8



PKS 1127-145: Quasar View
Credit: A. Siemiginowska (CfA) & J. Bechtold (U. Arizona), et al., NASA

Explanation: The quasar known as PKS 1127-145 lies ten *billion* light-years from our fair planet. A Hubble Space Telescope view in the left panel shows this quasar along with other galaxies as they appear in optical light. The quasar itself is the brightest object in the lower right corner. In the right panel is a Chandra Observatory x-ray picture, exactly corresponding to the Hubble field. While the more ordinary galaxies are not seen in the Chandra image, a striking jet, nearly a million light-years long, emerges from the quasar to dominate the x-ray view. Bright in both optical and x-ray light, the quasar is thought to harbor a supermassive black hole which powers the jet and makes PKS 1127-145 visible across the spectrum -- a beacon from the distant cosmos.

Tomorrow's picture: Mongolia

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CHANDRA X-RAY OBSERVATORY

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➤ Photo Album

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Images by Category
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Constellations
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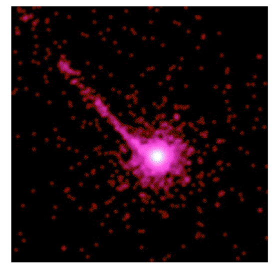
PKS 1127-145:
Chandra Scores A Double Bonus With A Distant Quasar



Credit: NASA/CXC/A.Siemiginowska(CfA)/ J.Bechtold(U.Arizona)
JPEG (52 k) , Tiff (980 k), PS (6 MB)

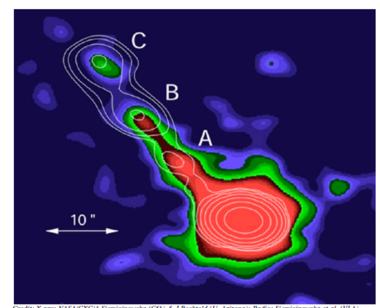
The X-ray image of the quasar PKS 1127-145, a highly luminous source of X-rays and visible light about 10 billion light years from Earth, shows an enormous X-ray jet that extends at least a million light years from the quasar. The jet is likely due to the collision of a beam of high-energy electrons with microwave photons.

The high-energy beam is thought to have been produced by explosive activity related to gas swirling around a supermassive black hole. The length of the jet

On their way to Earth, the X-rays from th pass through a galaxy located 4 billion lig away. Atoms of various elements in this g absorb some of the X-rays, and produce a dimming of the quasar's X-rays, or an X-r shadow. In a similar way, when our body X-rayed, our bones produce an X-ray sha measuring the amount of absorption astro were able to estimate that 4 billion years a gas in the absorbing galaxy contained a m lower concentration of oxygen relative to gas than does our galaxy - about 5 times l astronomers insight into how the oxygen the eons.

High Energy Astrophysics Picture Of the Week   http://heasarc.gsfc.nasa.gov/docs/objects/heapow/archive/active_galax...

HEASARC PICTURE OF THE WEEK



Credit: X-ray: NASA/CXC/A.Siemiginowska (CfA) & J.Bechtold (U. Arizona); Radio: Siemiginowska et al. (VLA)

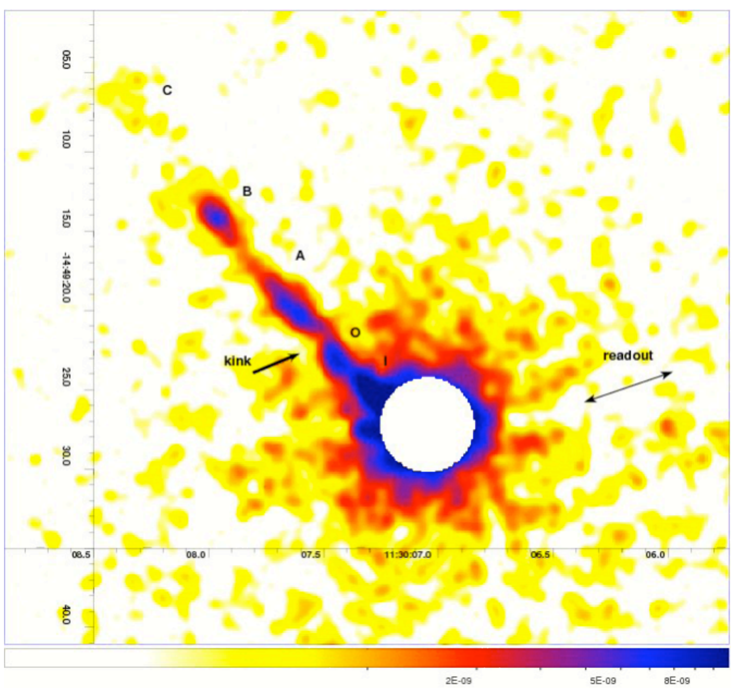
Ins and Outs of Black Holes

Somehow infall of material often produces large collimated outflows. This is exemplified in active galaxies, where large clouds of gas and, possibly stars and planets fall onto a black hole at the center of the galaxy, and producing an enormous jet of material which can be millions of light years long. Such jets are often called radio jets, since most were discovered using extremely high resolution observations with radio telescopes. The radio emission arises from relatively cool material inside the jet. Now high resolution X-ray images obtainable with the Chandra X-ray observatory show astronomers that radio jets are often X-ray bright, too. The image above shows a false-color X-ray image of the active galaxy

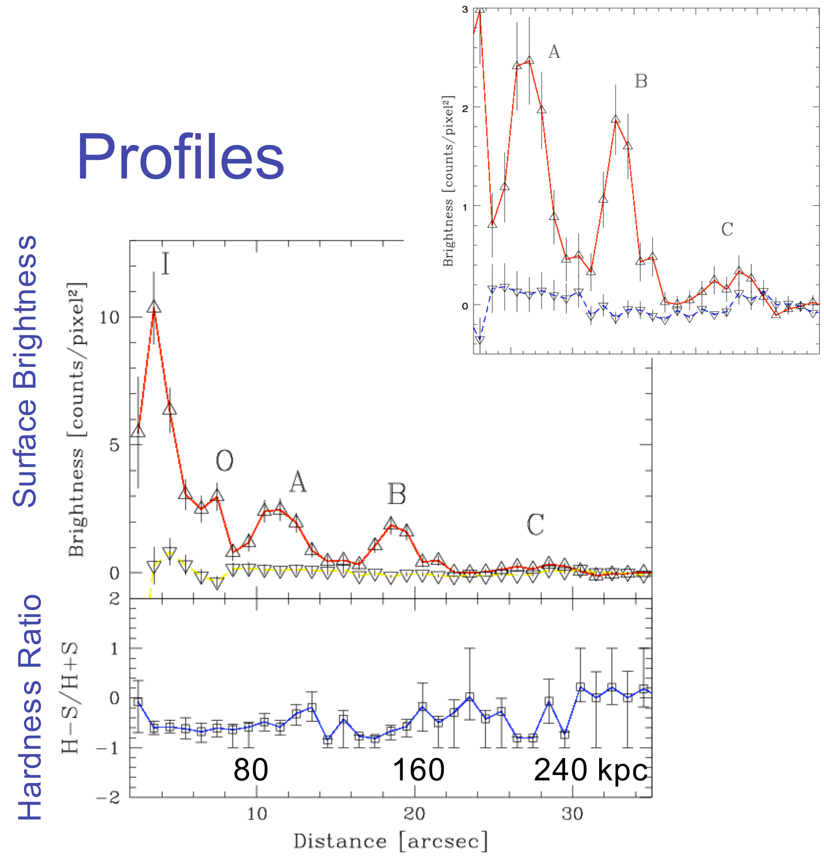
1 of 2   11/2/05 10:39 PM

PKS1127-145: X-ray Jet

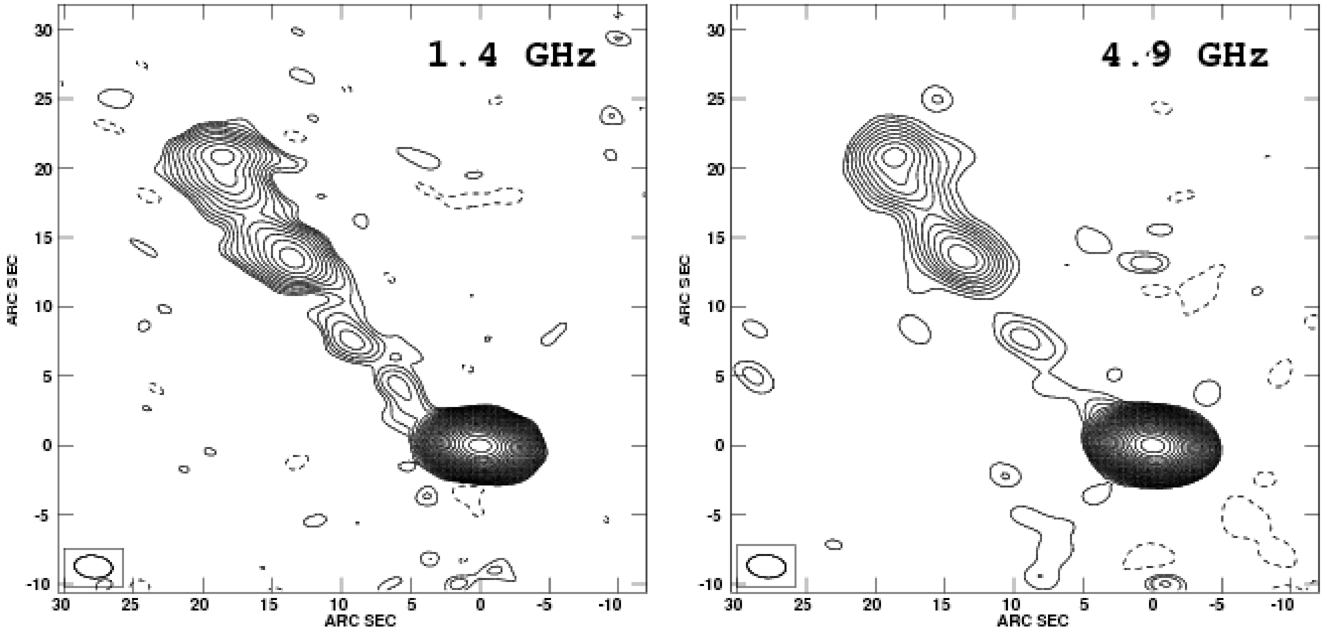
Jet luminosity > 10^{44} erg/s
Core/Jet ~0.01-0.02



Profiles



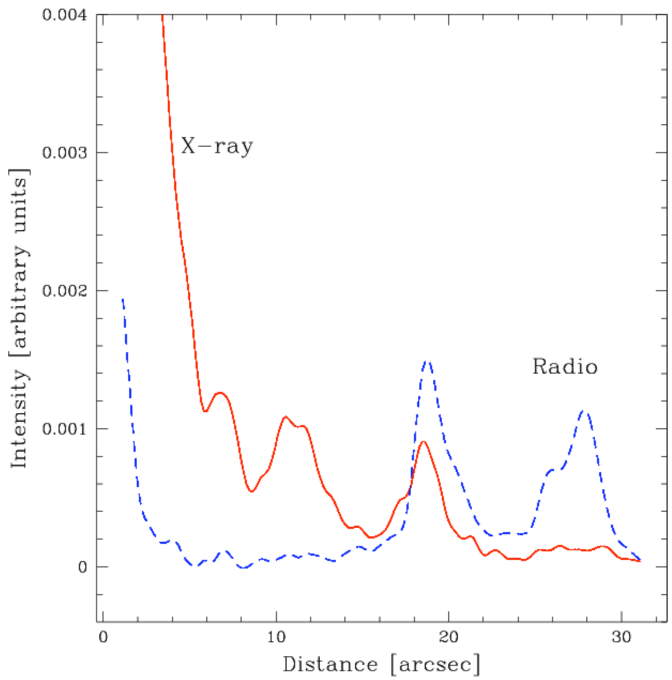
PKS1127-145: Radio Jet

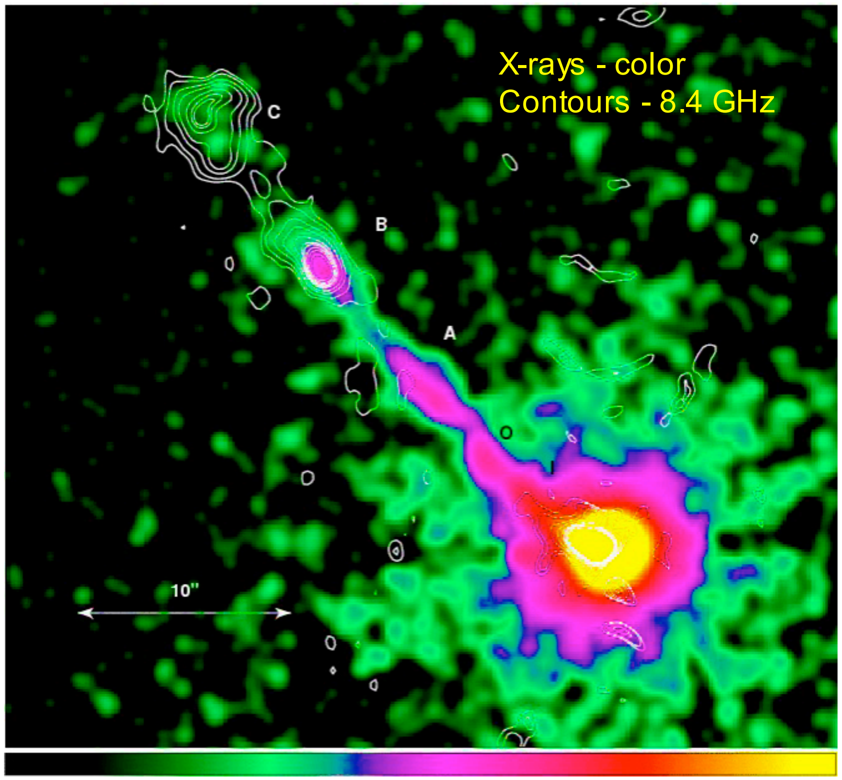


X-ray and Radio Jet

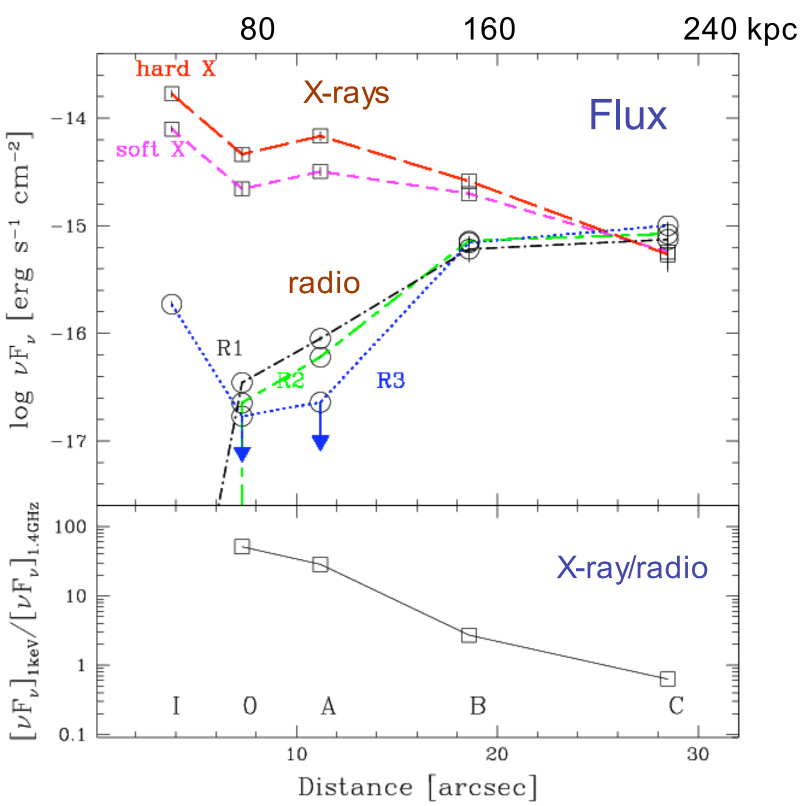
Intensity Profiles:

X-ray decays and radio increases along the jet





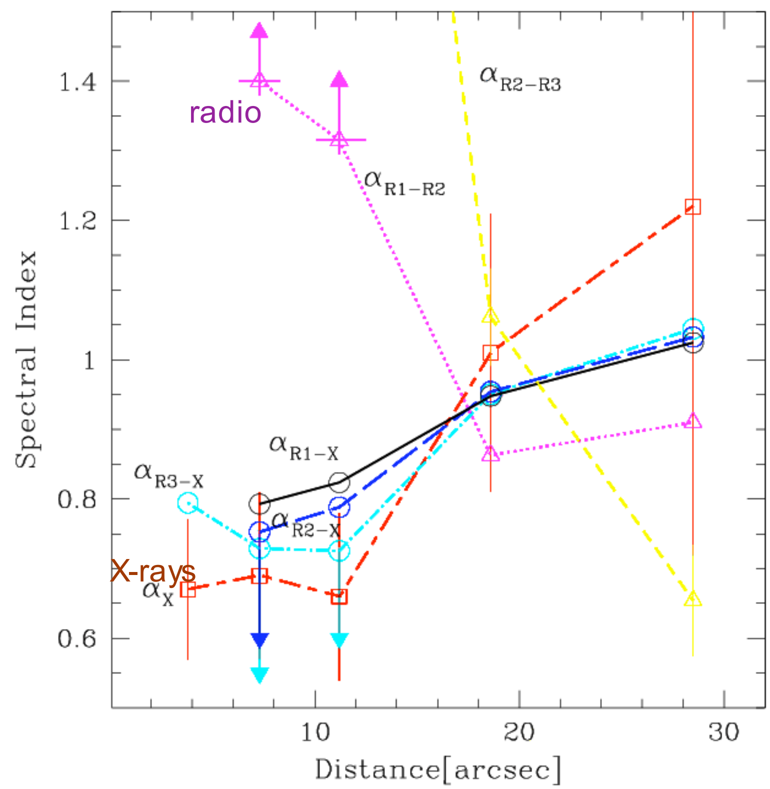
X-ray and Radio Jet - Spectra



Spectral index

X-rays get softer and radio gets harder

Not consistent with one component models



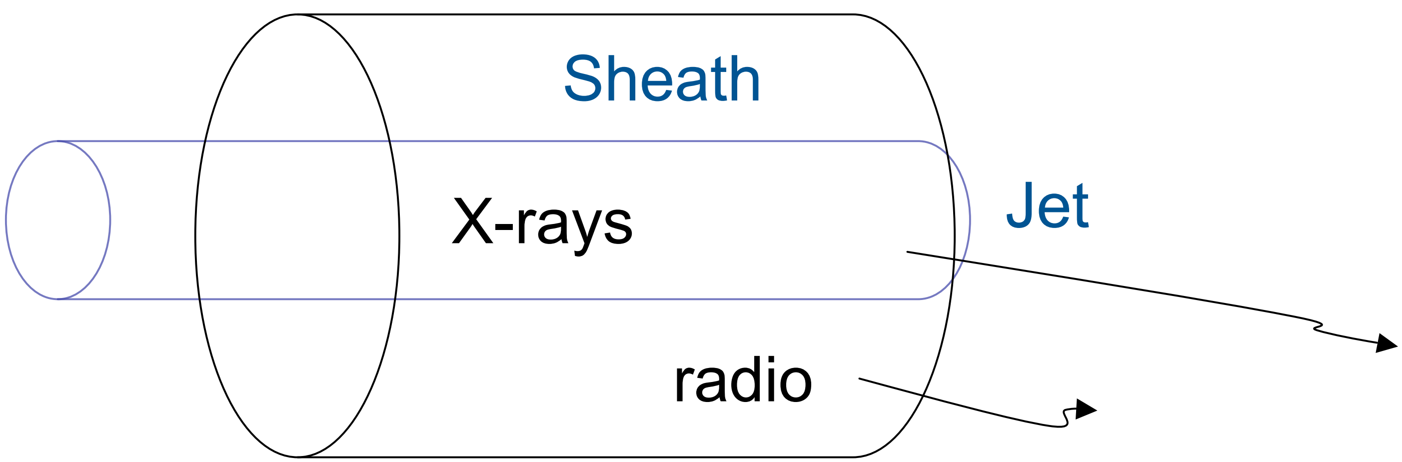
PKS1127-145: Summary

Key Results:

- The jet is long: Radio and X-ray jet is detected up to ~300 kpc away from the core
- The Jet X-ray intensity is decreasing while the radio intensity is increasing with distance from the quasar.
- The one component X-ray/radio emission models fail to explain the observations
- X-ray and radio jet properties suggests two separate components for the emission
- Intermittent quasar activity might be reflected in the observed jet morphology. Each knot represents a continuous jet activity with a duration of 10^5 years

Two-components Model: Jet and Sheath

- Radio and X-ray emissions are produced in separate regions.
- X-ray emission comes from the proper jet and Radio emission from the sheath – a slow moving radial extension of the jet boundary layer.
- X-ray emission due to Synchrotron or IC/CMB



The Proper Jet

- **Synchrotron emission:**

  For $U'_B(r) \sim U'_e(r)$, $B(r) \sim r^{-k}$ and a constant jet opening angle the observed decrease in X-ray luminosity requires k~0.8 and at most a decrease in B-field by a factor of ~0.2

- **IC/CMB emission:**

  $U'_B(r) \sim U'_e(r) \sim r^{-2k}$

  decrease in L_X requires k~1.65 and a decrease in B field by a factor of ~0.03. Any small change in $\delta(r)$ can easily adjust parameters.

- **Transition between two cooling regimes**: $t_{dyn} = t_{rad}$

  Radiative cooling by CMB photons => $r_{tr} \sim 25\ \delta\Gamma^{-1}$ Mpc

  BUT knot B at ~18” ~150 kpc!

  Thus IC/CMB model cannot explain the steepening of X-ray spectrum assuming only the spectral ageing of low energy electrons. Acceleration of electrons is needed.

Sheath

The Sheath dominates Jet's Radio emissions and has two cooling regions:

- Radiative cooling at the inner sheath:

$$t_{rad} < 10\ \mathrm{Myr} < t_{dyn} = 30\ R_{10}\ \mathrm{Myr}$$

frequency dependent looses => steep spectrum

- Adiabatic cooling in the outer sheath:

$$t_{rad} > t_{dyn} < 10 R_{10}\ \mathrm{Myr}$$

frequency independent losses => flat spectrum

Speculation: Modulated Jet Activity

- Can the morphology of the >300 kpc long jet be a result of the intermittent activity of the quasar?
- What is the nature of the knots in PKS 1127-145 jet?
- The knots are potentially too large (> 10 kpc) to be considered as the extended shock waves formed within a continuous jet outflow.
- The knots might form during episodes of separate continuous activity. The size gives a duration for each epoch of ~ 10^5 years.
- Radio core related to blazar phenomena and the core resembles the “classical” GPS object at this time.

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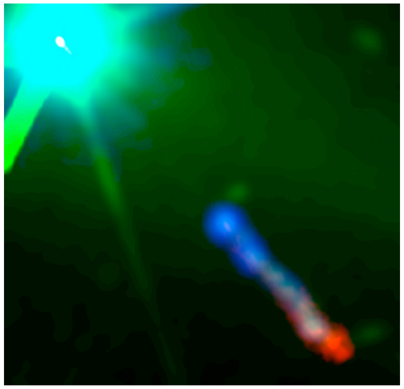
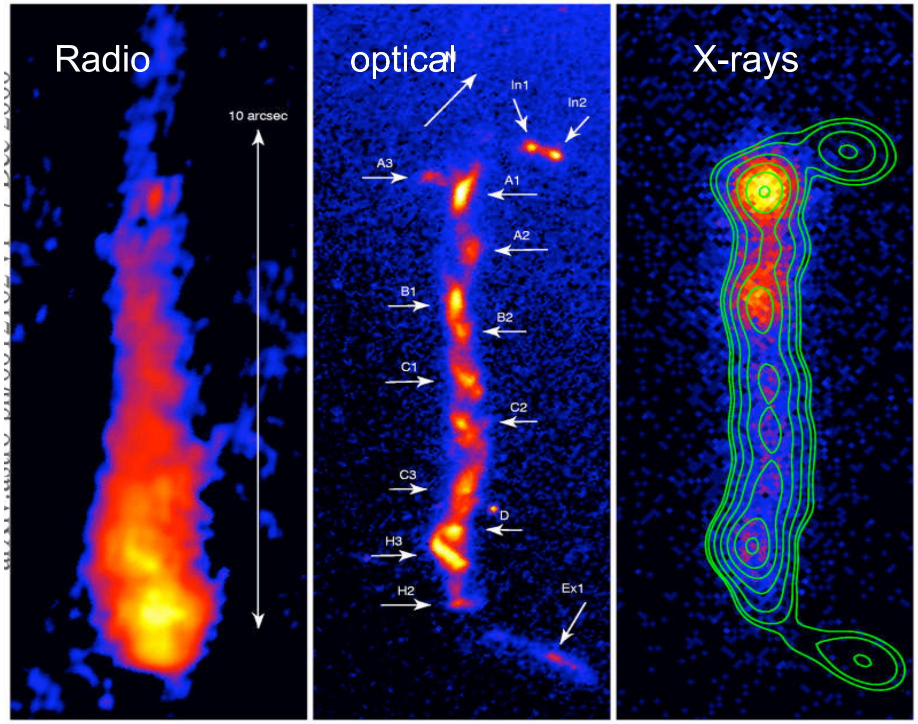
Other X-ray Jets



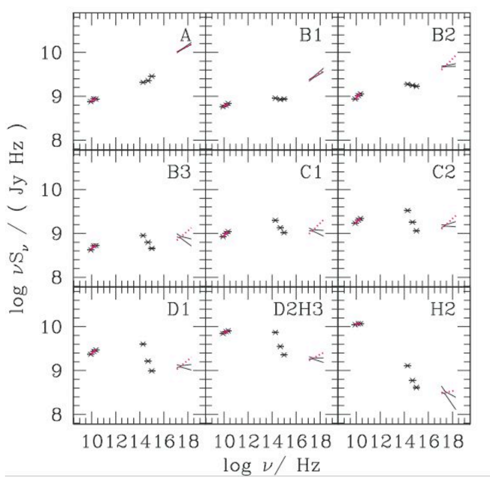
3C273

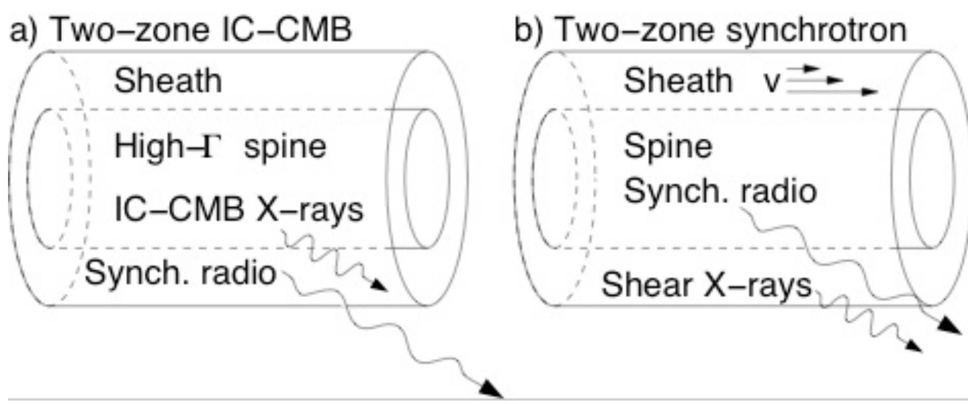
z=0.158



Marshall et al 2001

Similar X-ray/radio intensity profiles
to the ones seen in PKS1127-145
Stronger constraints from SED of knots
Two - component emission model required

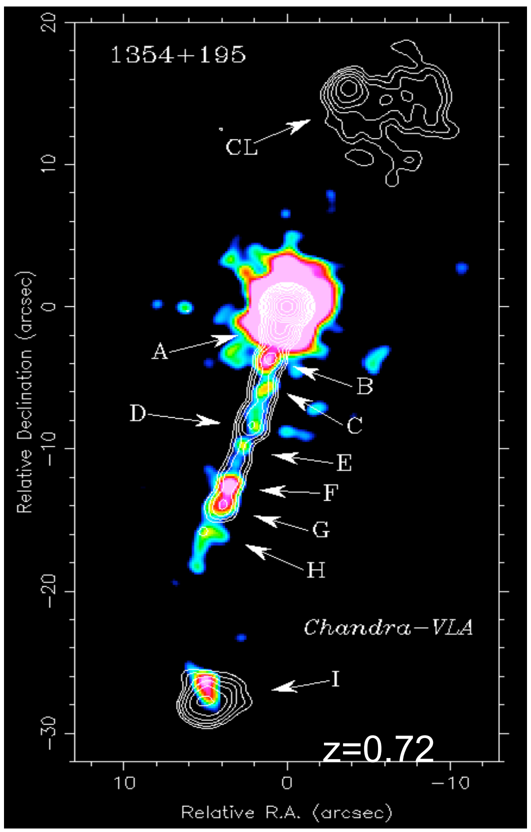


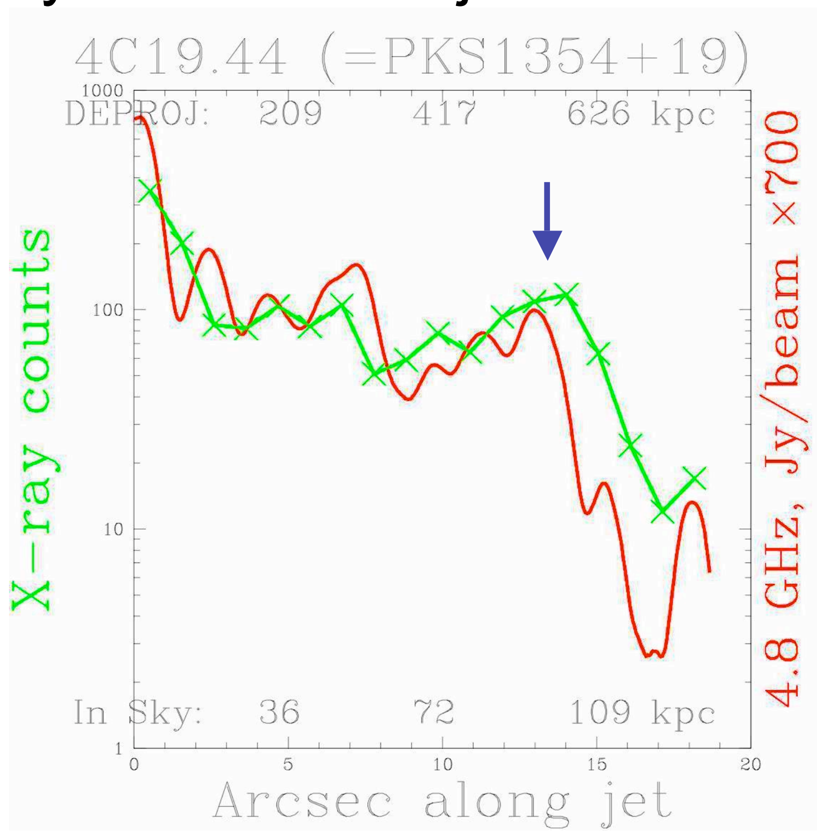


Jester et al 2006

4C19.44

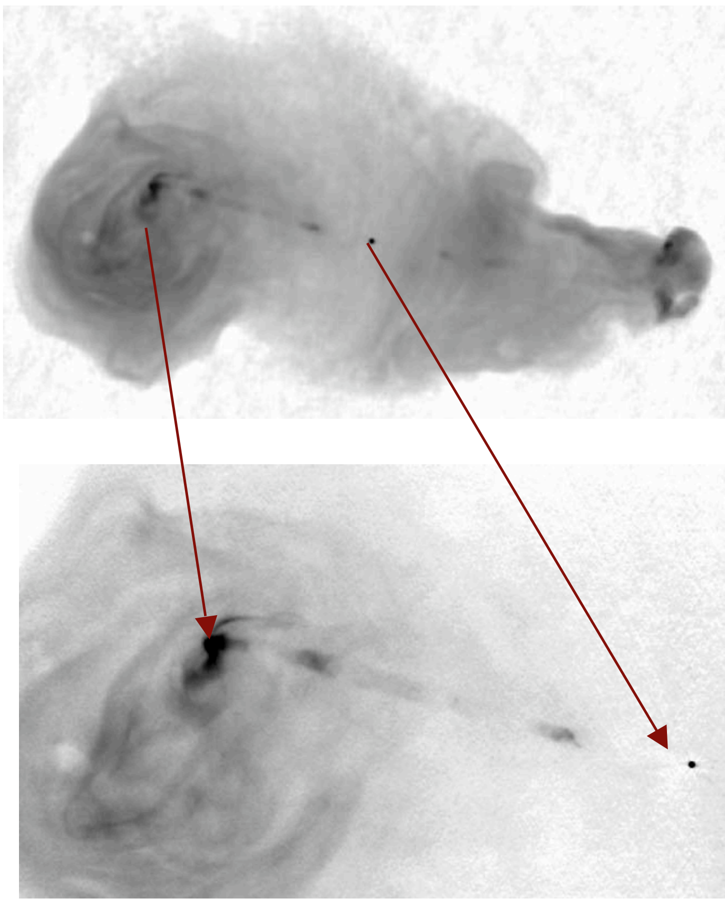
- z=0.72, 100~kpc long and straight jet
- X-ray and radio intensity profiles follow closely each other
- X-ray emission continues beyond the radio jet





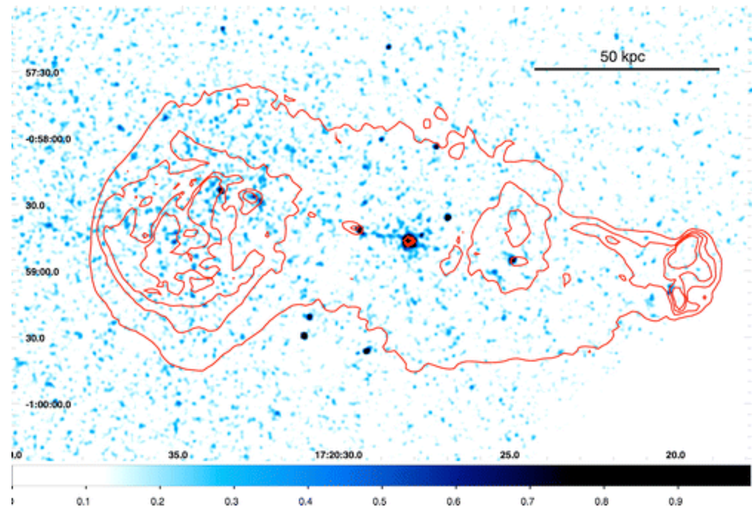
3C 353 - FRII z=0.0304

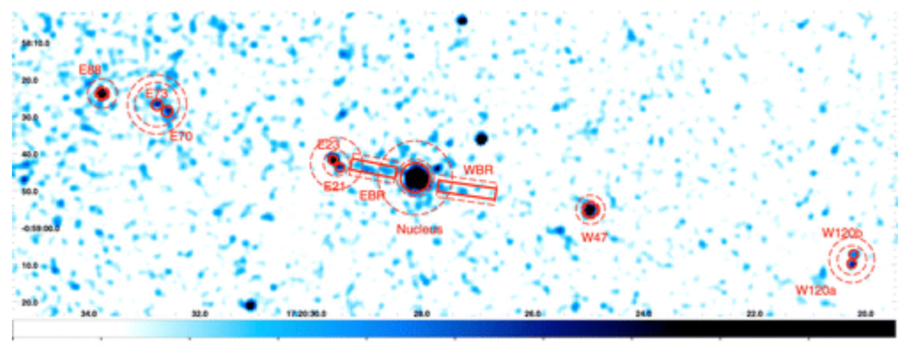
Radio Jet/Lobes



Boundary Layer

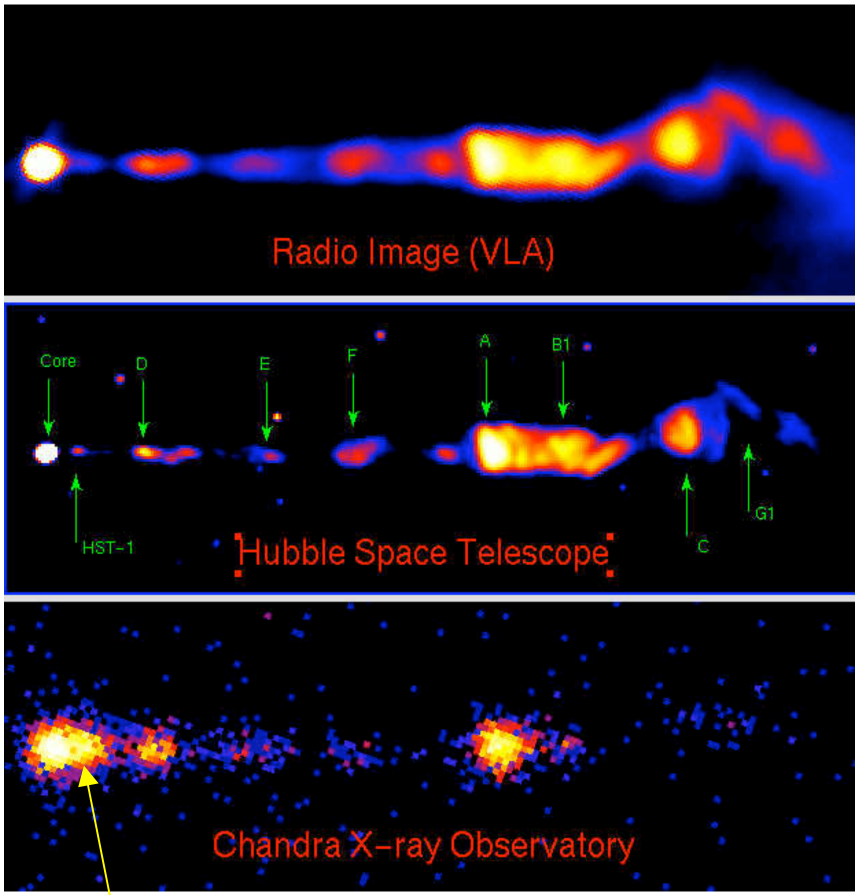
Chandra X-rays



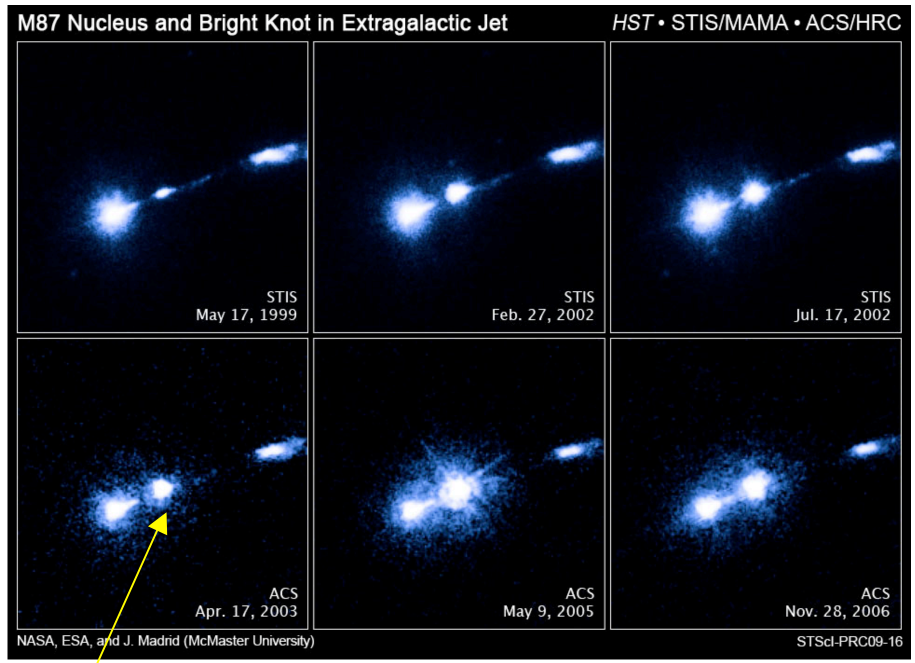


Kataoka et al 2008

M87 Jet: Variability



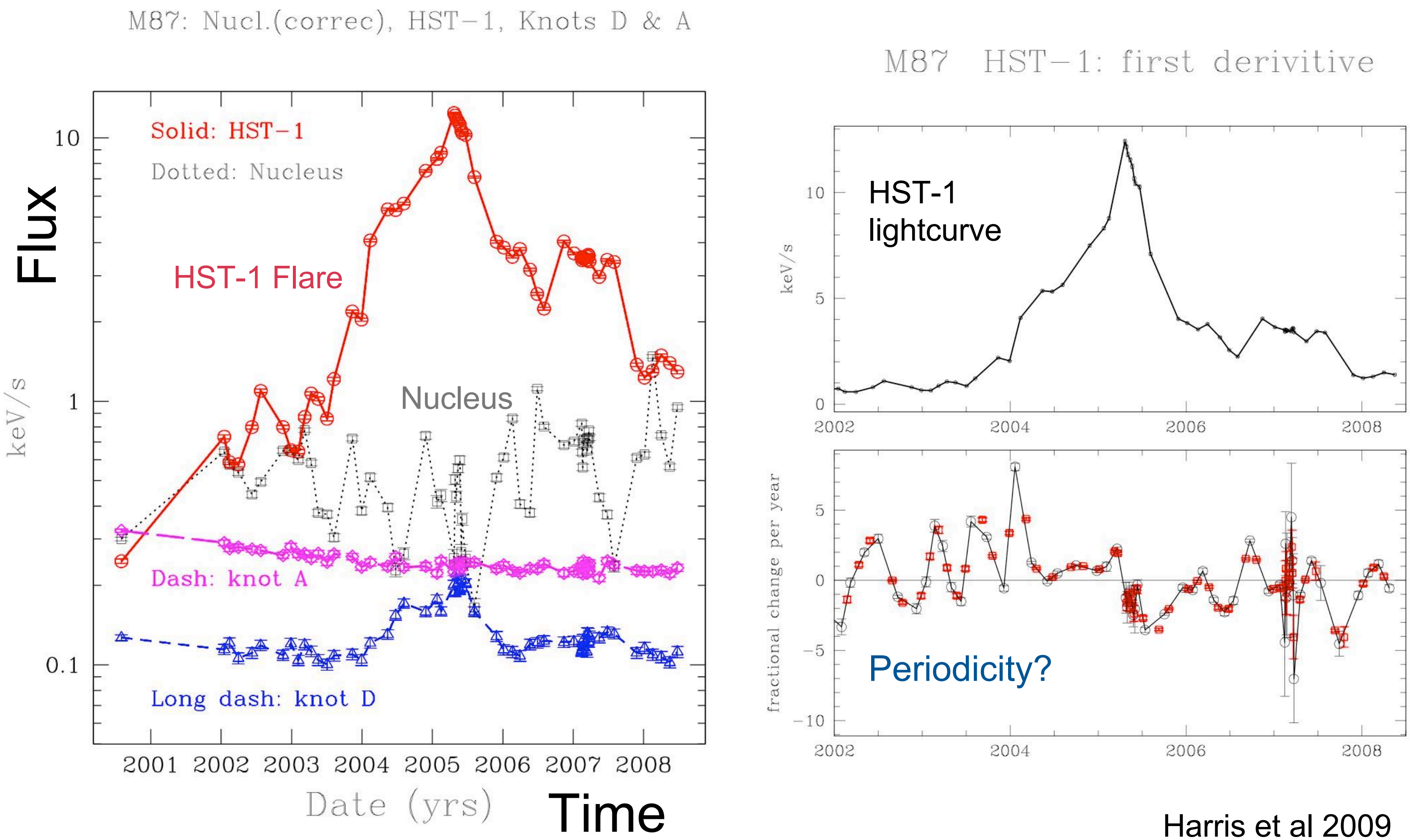
HST images of the HST-1 knot flaring



HST-1 located ~300 pc from the core

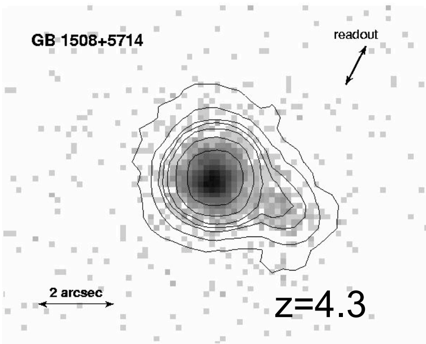
HST-1 knot

M87 Jet: X-ray variability

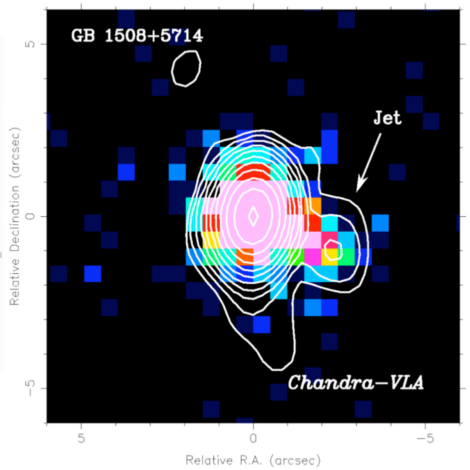


Harris et al 2009

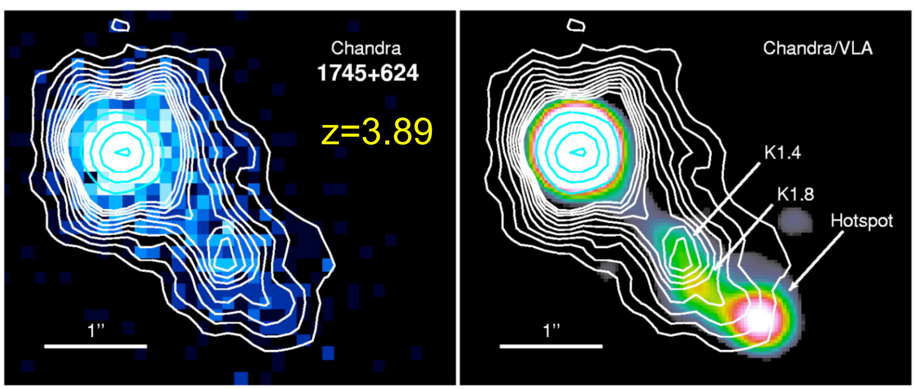
High redshift Jets



Siemiginowska et al 2003



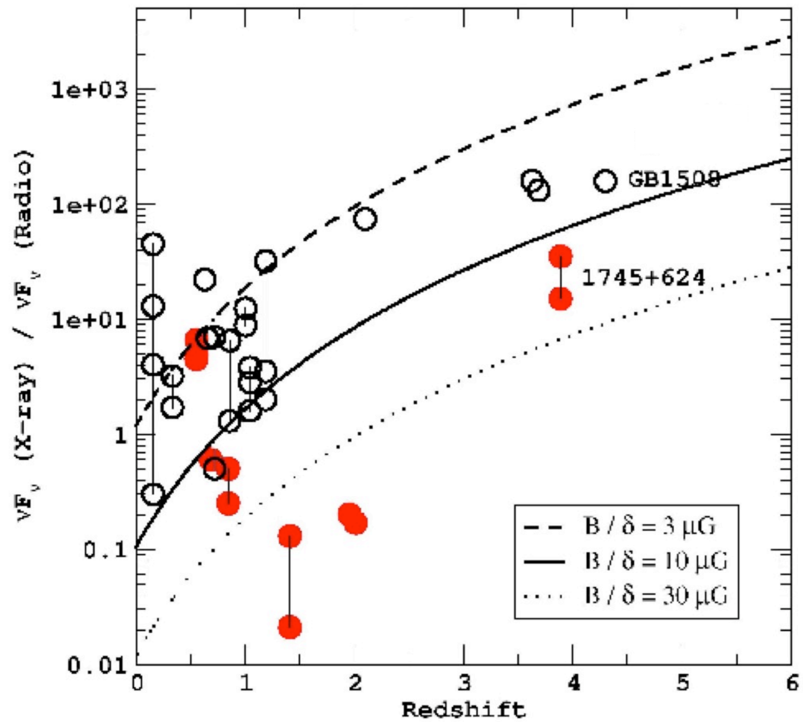
Cheung 2003



Cheung, Stawarz, Siemiginowska 2006

z>2 jets - studies of distant Universe

$U'_{CMB} \sim \Gamma^2(1+z)^4$



Summary

- X-ray emission from jets is common
- Energy dissipated at large distances
- Required:

particle acceleration along the jet

or

high bulk Lorentz factors at high distances from the nucleus

Questions and Future?

- Can we make progress with the future X-ray studies of jets?
- Do we need a sample or a deep image of a few jets?
- No resolution in the planned X-ray missions!
- Only Chandra can make progress in the next few years