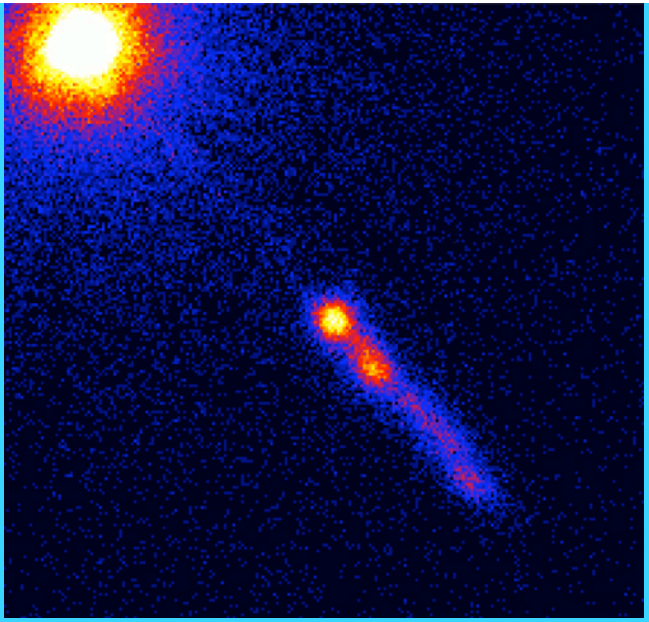

X-Rays & γ-Rays from Relativistic Jets in Quasars

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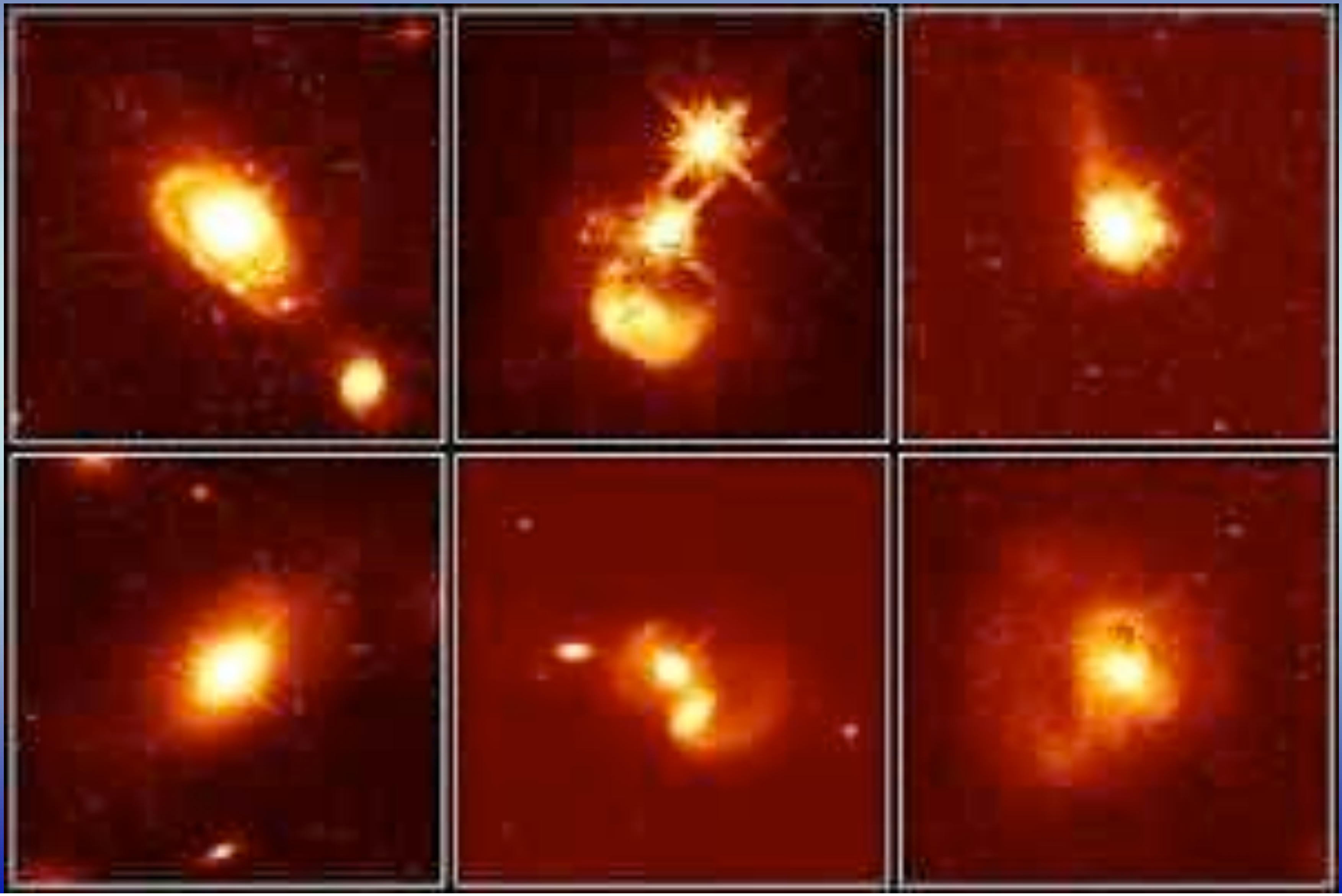
Phenomenology: What Is a Quasar?

- **Ultraluminous (10^{45}-10^{47} ergs/s), active nucleus of a galaxy (most luminous non-transient objects in the universe)**
- **Broad (tens of thousands of km/s) emission lines with high redshifts**
- **Visible/uv continuum has broad "bump" in ν-F_ν spectrum**

Subclass (5-10%): Blazars

- **Emission dominated by relativistic jet (flow Lorentz factors can be at least as high as 40 but usually <10) (jet is 2-sided, but relativistic beaming causes receding side to be too faint to detect)**
- Radio – visible (in some cases even to soft X-rays): incoherent synchrotron radiation (random pitch angles; magnetic field is fairly turbulent – near-zero circular polarization, modest linear polarization)
- **X-ray – *γ*-ray: (inverse) Compton scattering of radio-visible (-X-ray for sources of TeV *γ*-rays) "seed" photons**
- Apparent superluminal motion of bright features on radio images
- **Extremely rapid variations in brightness relative to light-travel time across emission region (Doppler effect for approaching jet)**

Hubble Space Telescope Images of Host Galaxies of Quasars (from NASA's STScI web site, www.stsci.edu)



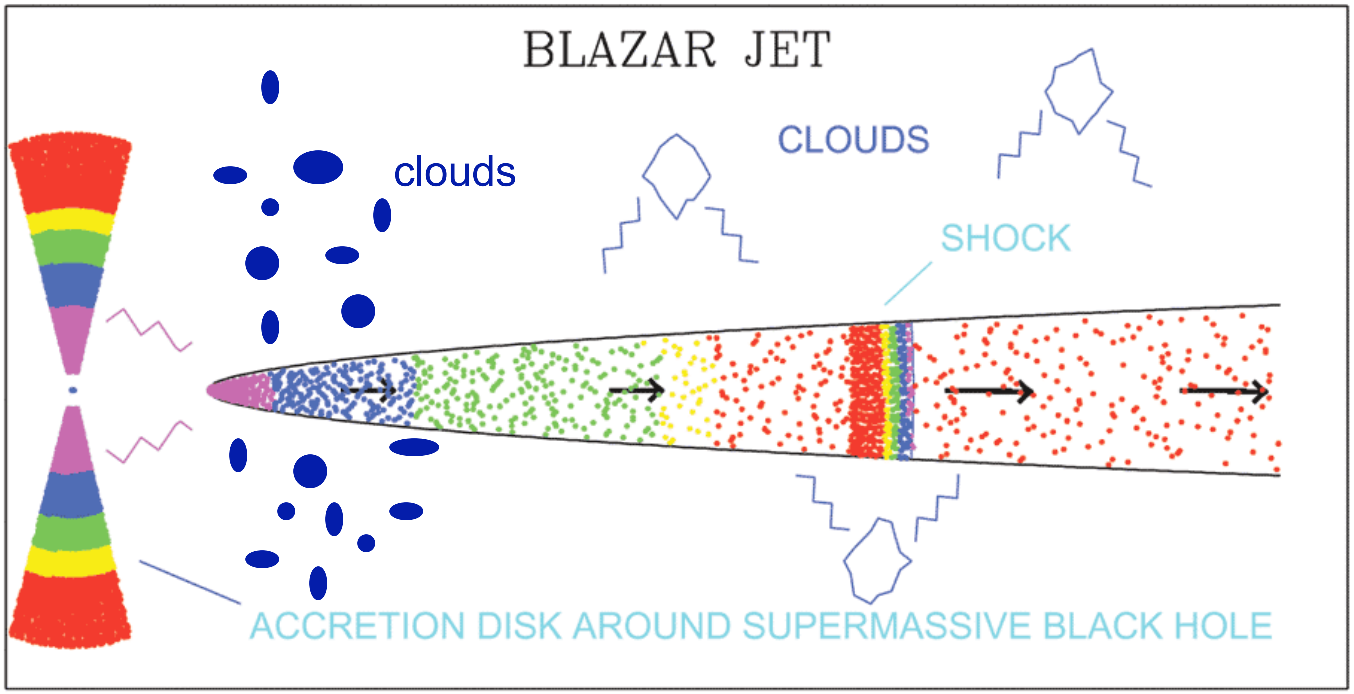
Model of a Quasar

- Supermassive ($3x10^{8±1}$ solar masses) accreting black hole
- Dominant components of observed emission depend on direction of line of sight:

→ Viewed within about 40° of disk equator: non-blazar

→ Viewed within about 20° of jet axis: blazar

→ more extreme for smaller angle, higher Lorentz factor of flow

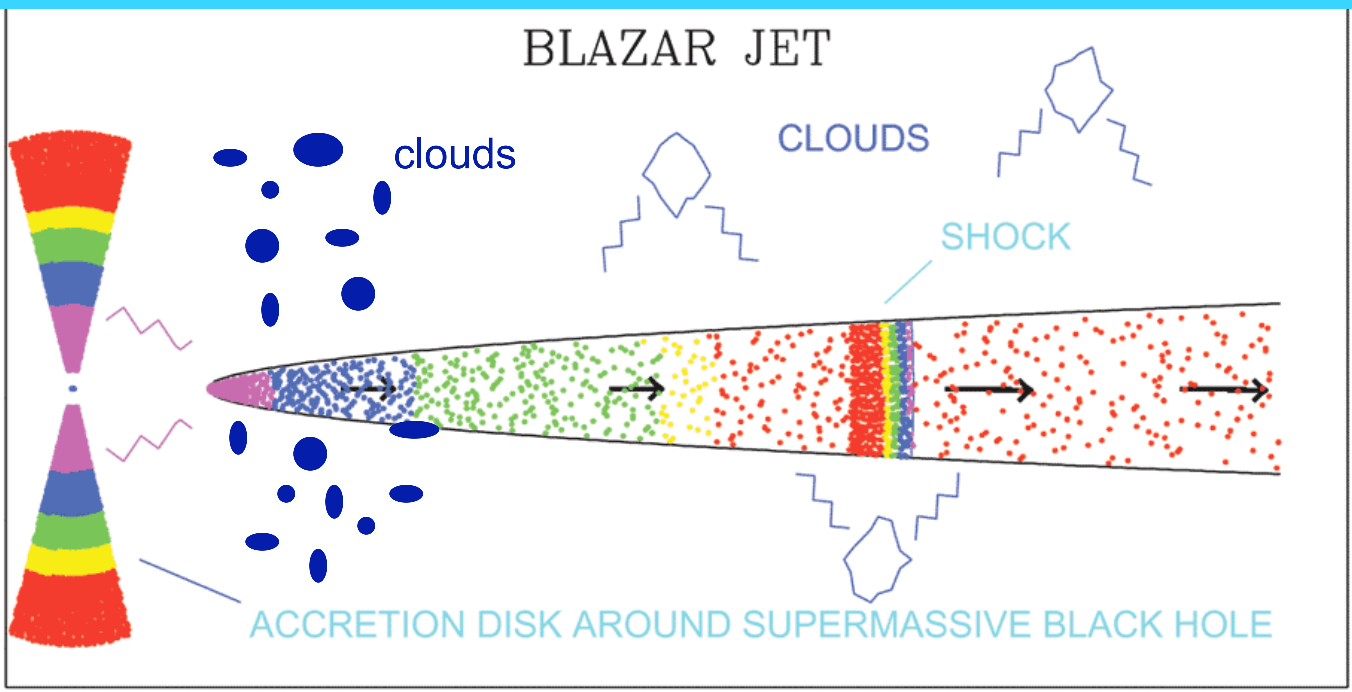


Quasar Emission

- Accretion disk: thermal blackbody emission, temperature depends on distance from black hole ("big blue bump"→ soft X-rays, harder X-rays from electron scattering in "corona" above disk)

- Clouds near base of jet: broadest emission lines (not clear whether motions of clouds are inflow, outflow, rotation, or chaotic); clouds farther out: "narrow" emission lines

→ Jet: synchrotron + inverse Compton (various sources of seed photons: accretion disk, jet, clouds)

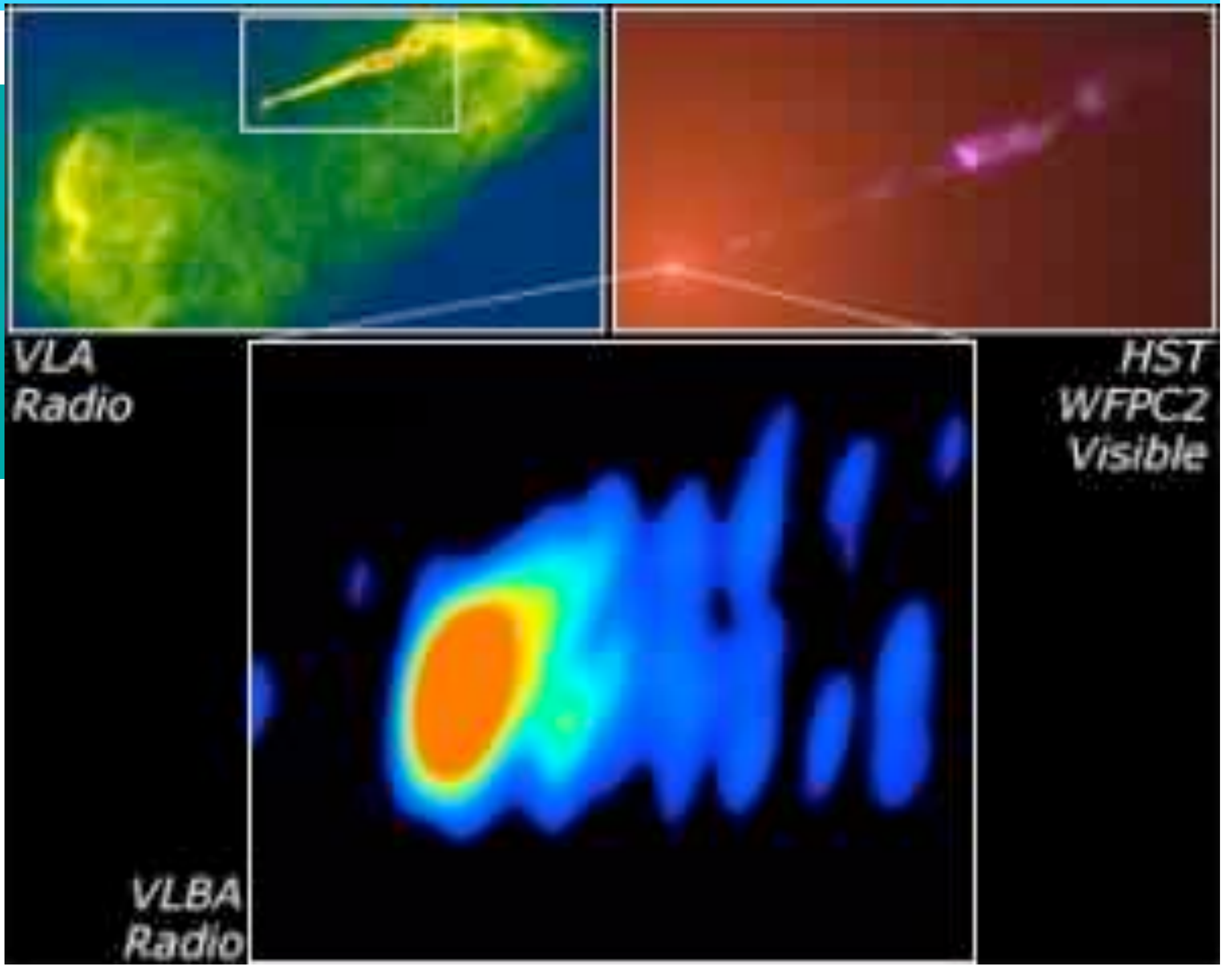


The Jet in the Radio Galaxy M87

- **Hubble Space Telescope observations of motions of stars in nucleus: Central black hole of $3x10^9$ solar masses**
- **Jet appears broad close to black hole (becomes narrowly focused by ~ 1 light-year)**

Observations by Junor, Biretta, & Livio 1999, *Nature*

Images taken from NASA's Space Telescope Science Institute web page, www.stsci.edu



Why Study Quasars?

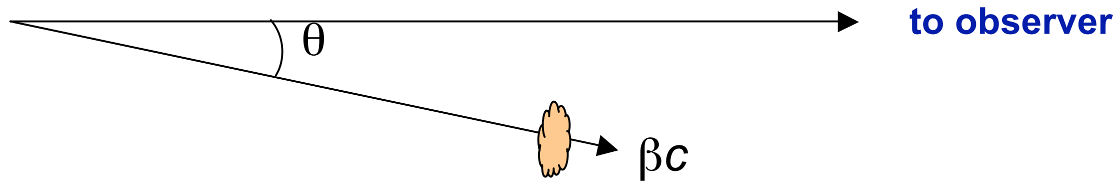
→ Physics under extreme conditions:

- Prolific acceleration of particles
- Prolific production of high-energy photons (up to 10 TeV)
- Exotic forms of matter (perhaps more positrons than protons in jet)
- **Relativistic gas dynamics**
- Relativistic turbulence
- Relativistic plasma processes
- Accretion onto supermassive black holes
- Relativistic effects and illusions
- Probes of the high-redshift universe

Some Issues Addressed by Our Research

- Phenomenology of relativistic jets: Superluminal motion, Lorentz factors, rapid variability in brightness & polarization, changes in direction, magnetic field topology, disturbances in flow, …
- Relativistic shock waves as sites of particle acceleration and magnetic field amplification
- **Similarity between observed features and relativistic gas dynamical simulations**
- Origin of X-rays and γ-rays
- Comparison of bright γ-ray blazars with general population of radio-“loud” quasars
- Evidence for accretion onto black holes

Superluminal Motion (An Illusion)



Velocity transverse to line of sight: $\beta c \sin\theta$; $\Gamma = (1-\beta^2)^{-1/2}$

<u>But</u>, in observer's frame, source keeps getting closer, so arrival times of radio waves are compressed

Time required for source to move distance Δr is $t' = (\Delta r/\Gamma)/(\beta c)$ <u>in source frame</u> (length contraction) → $\Delta r = \Gamma\beta c t'$

Transformation to <u>observer's frame</u>: $t = t'/[\Gamma(1-\beta\cos\theta)]$ (Doppler effect)

So, $\beta_{app} = (\Delta r \sin\theta)/t = \Gamma\beta c(t'/t)\sin\theta = (\beta c t \sin\theta)/(1-\beta\cos\theta)$

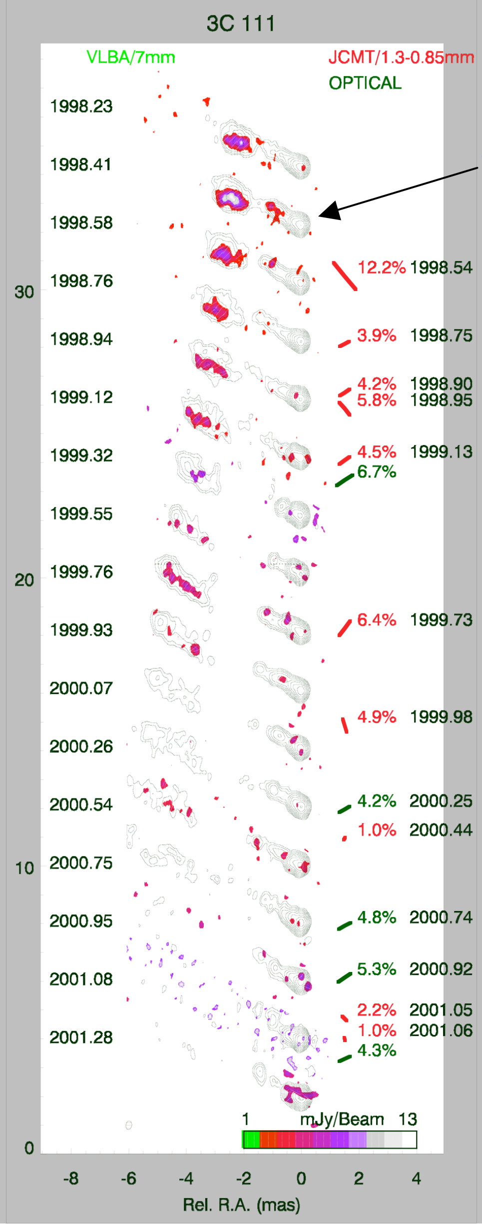
→ <u>Maximum value</u>: $\beta_{app} = \Gamma\beta c$ [occurs at angle $\theta = \sin^{-1}(1/\Gamma)$]

The Radio Galaxy 3C 111 (z=0.0485)

Clear example of one-sided jet structure with superluminal apparent motion at 5c (1.5 milliarcsec/yr)

Jet propagates through galaxy and into intergalactic space, where it feeds giant twin radio "lobes"

Scale: 1 mas = 0.92 pc = 3.0 lt-yr (H_o=70)

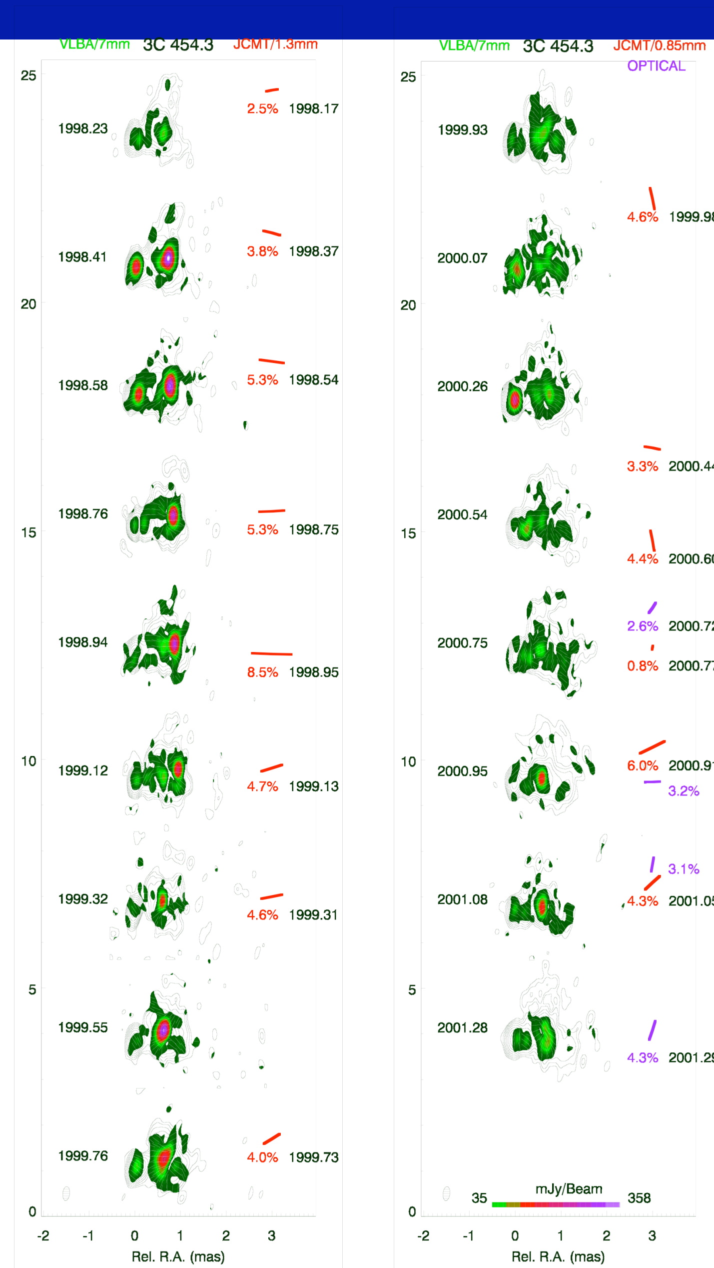


Stationary core

Observations made at 43 GHz with the Very Large Array (VLBA) of the National Radio Astronomy Observatory

The Quasar 3C 454.3 (z=0.859)

Superluminal knot moves through extended stationary feature, then vanishes



Scale: 1 mas = 7.4 pc = 24 lt-yr (H_o=70)

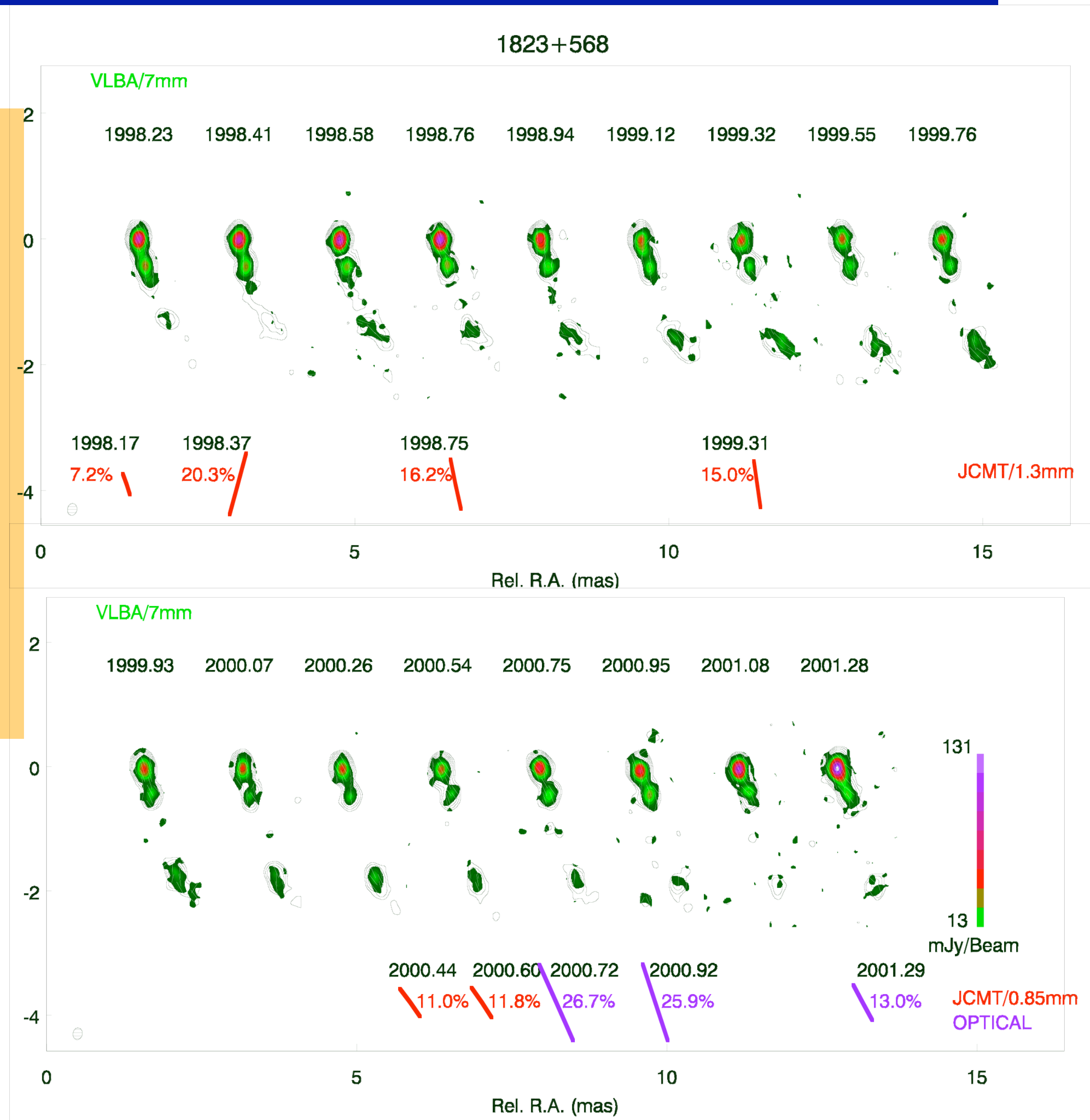
The BL Lac Object 1823+568 (z=0.66 ?)

Superluminal apparent motion at ~12c (0.36 milliarcsec/yr)

Persists for 1.5 yr, then stops! (although weak remnant may continue moving)

→ Disturbance energizes stationary feature (standing shock?)

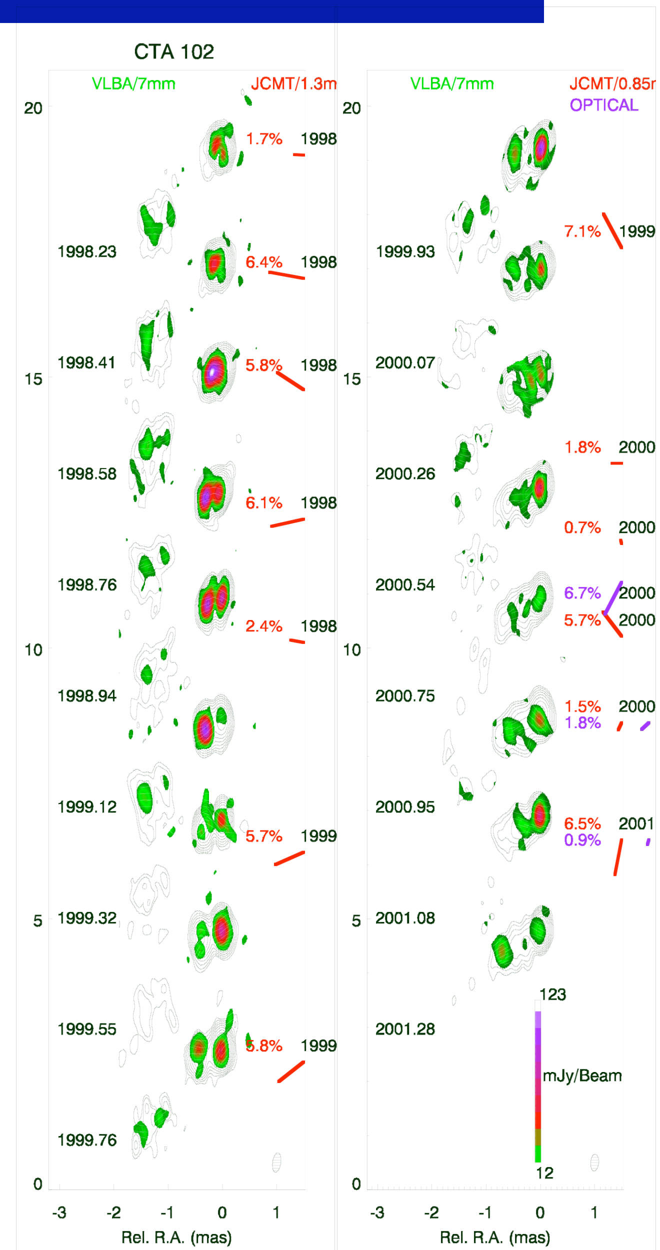
Scale: 1 mas = 6.6 pc = 21 lt-yr (H_o=70)



The Quasar CTA 102 (z=1.037)

Scale: 1 mas = 7.8 pc = 25 lt-yr (H_o=70)

- **"Monster" radio outburst in 1997 produced very bright superluminal (13c) knot, with continued activity as stationary feature 2 mas away from core dissolves**
- **Polarization changes rapidly; similarities with JCMT polarization direction at some epochs, not at others**



BL Lac (z=0.069)

Jet does a hula dance:

- ~ 2-yr cycle of 24° swing in direction of jet near core

→ interpreted as precession

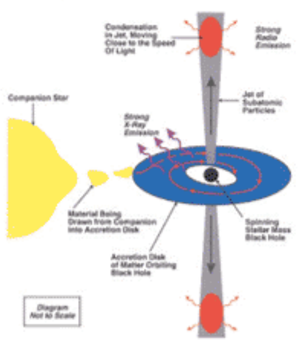
Scale: 1 mas = 1.3 pc = 4.1 lt-yr (H_o=70)

The “Microquasar” GRS 1915+105: A Superluminal Object in Our Galaxy

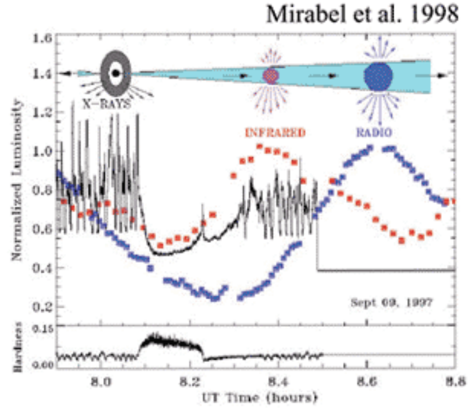
- **Apparent velocity 2-3c, but jet makes a large angle to line of sight; $\Gamma \cong 5$**
- **Binary system, giant star + black hole of 14 solar masses**
- **Ejection of superluminal knots follows drop in X-ray flux, modeled as sudden break off & accretion of inner gaseous disk**

ACCRETION DISK AND JET FORMATION

$\Delta T \propto M_{BH}$

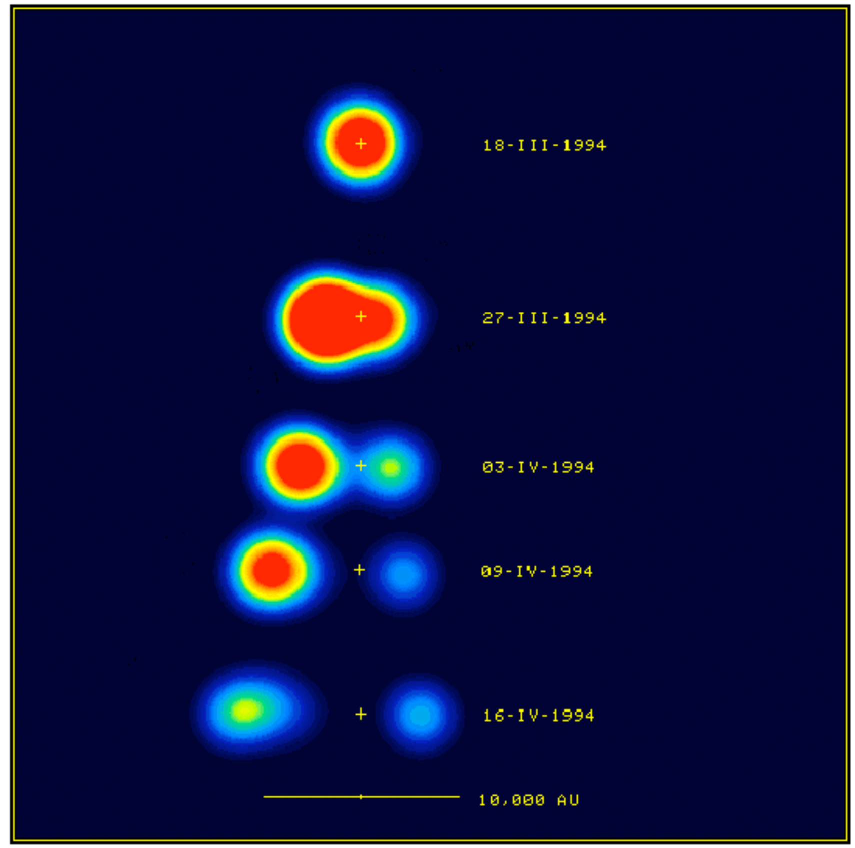


Mirabel et al. 1998



JET FORMATION DURING DISAPPEARANCE OF THE INNER (r ~200 km) ACCRETION DISK

Mirabel & Rodriguez (1994 *Nature*)

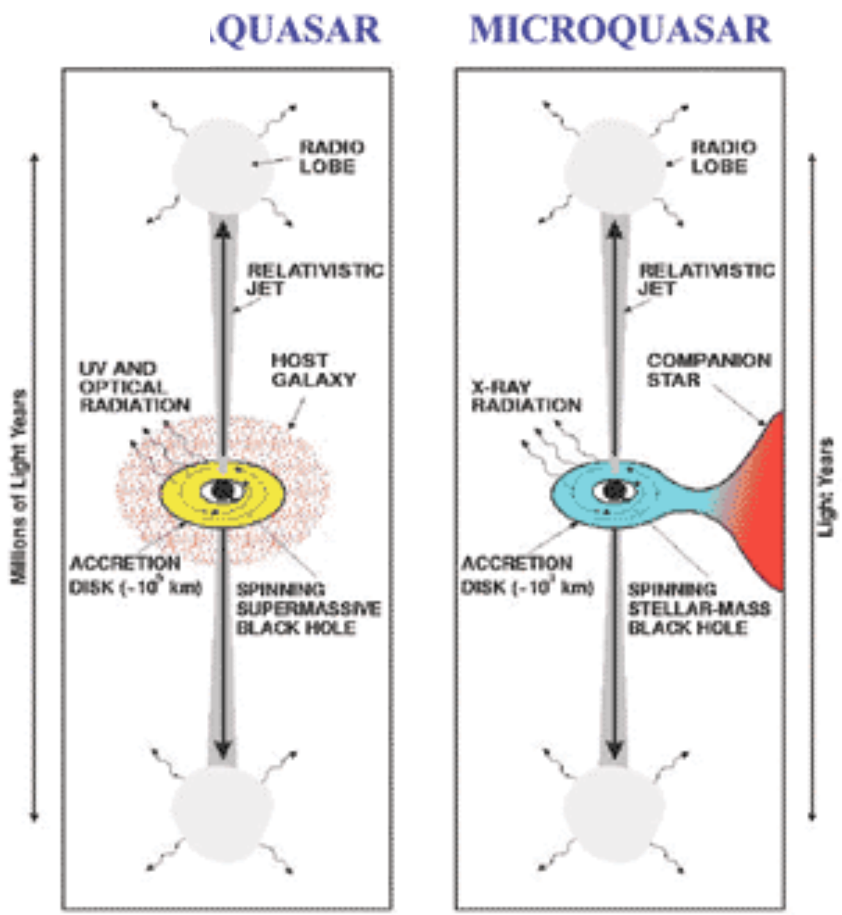


Both figures from Felix Mirabel’s web page:

Moriond.in2p3.fr/J01/transparents/Mirabel/mirabel.pdf

Cartoon of Quasar vs. Microquasar

QUASAR-MICROQUASAR ANALOGY



- Quasi-stellar relativistic object may be a Neutron Star or a black hole (BH)
- In BHs the scales of length and time are proportional to the mass of the BH
- The maximum color temperature of the accretion disk is $T_{col} \propto (M/10M_{\odot})^{-1/4}$

Can this analogy be confirmed by observation of an active galactic nucleus with some features similar to those of microquasars?

Figure from Felix Mirabel's web page

The Radio Galaxy 3C 120 (z=0.033)

Scale: 1 mas = 0.64 pc = 2.1 lt-yr (H_o=70)

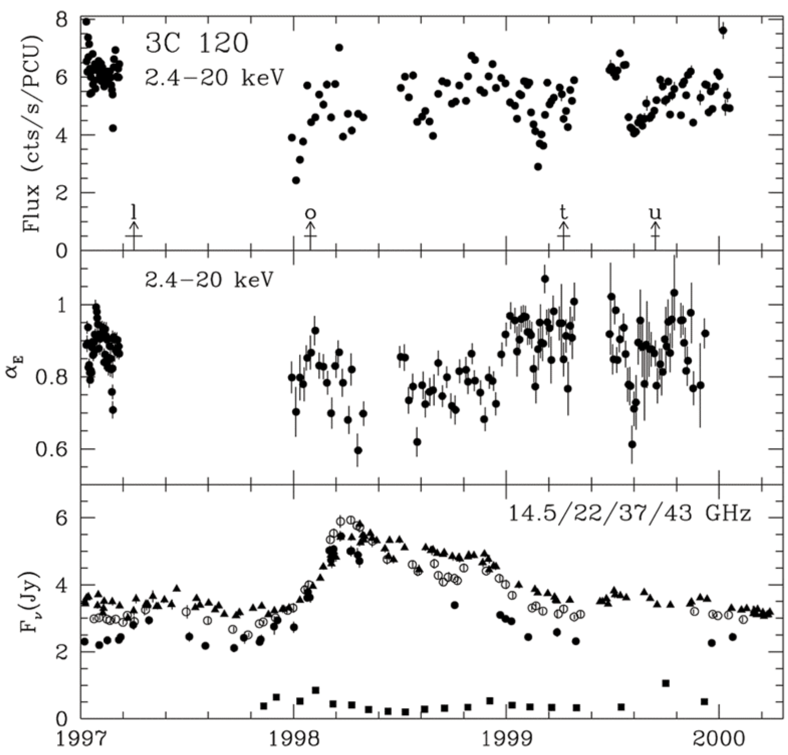
Superluminal apparent motion, 4-6c (1.8-2.8 milliarcsec/yr)

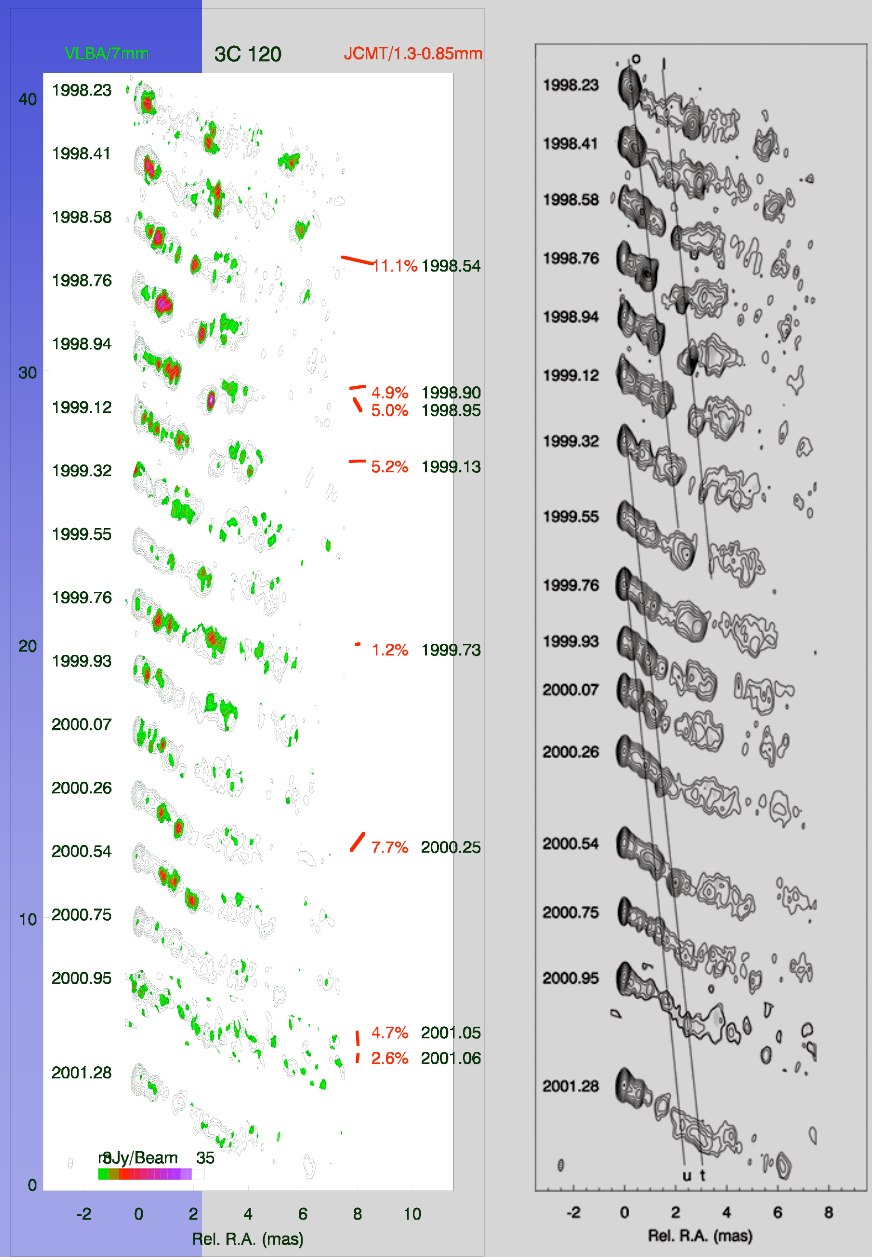
X-ray spectrum similar to BH binaries

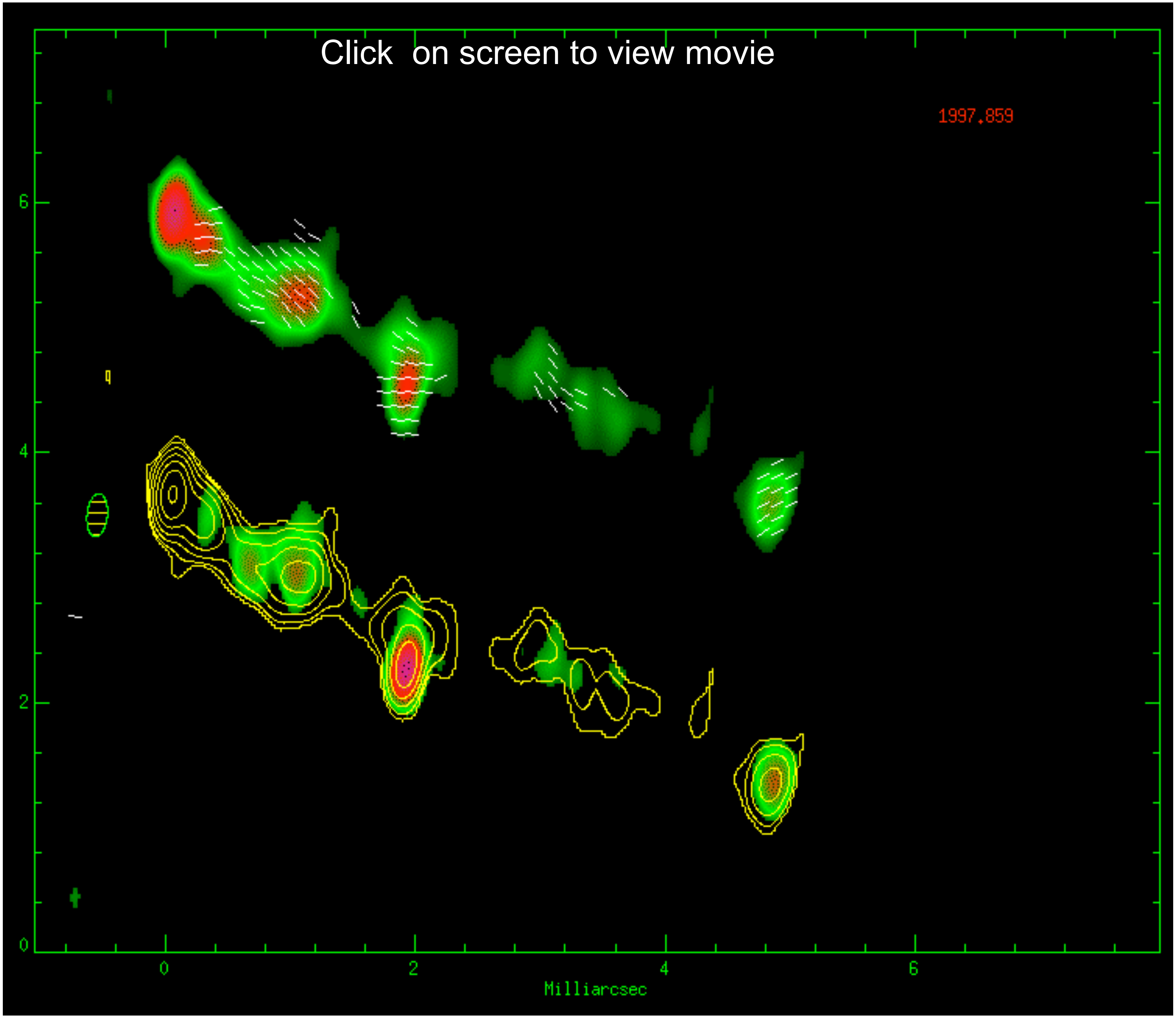
Radio core at least 1 lt-yr from black hole

Superluminal ejections follow X-ray dips

→ Similar to microquasar GRS 1915+105

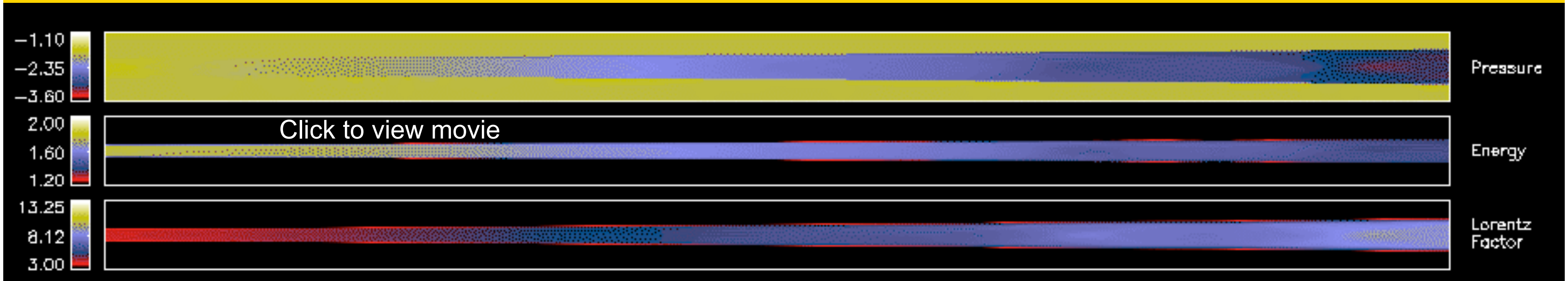





Click on screen to view movie
1997.859
6
4
2
0
0
2
4
6
Milliarcsec

Relativistic Gas Dynamics of Jets: Numerical Simulations

- Beam of relativistic gas injected from left, flow Lorentz factor Γ=4
- Perturbation initiated in form of momentary increase to Γ=11
- Shock wave forms at head of disturbance
- Notice compressions & rarefactions in wake of disturbance



Click to view movie

Click to view movie

Synchrotron emission for jet pointing 10° from line of sight, convolved by circular point-spread function

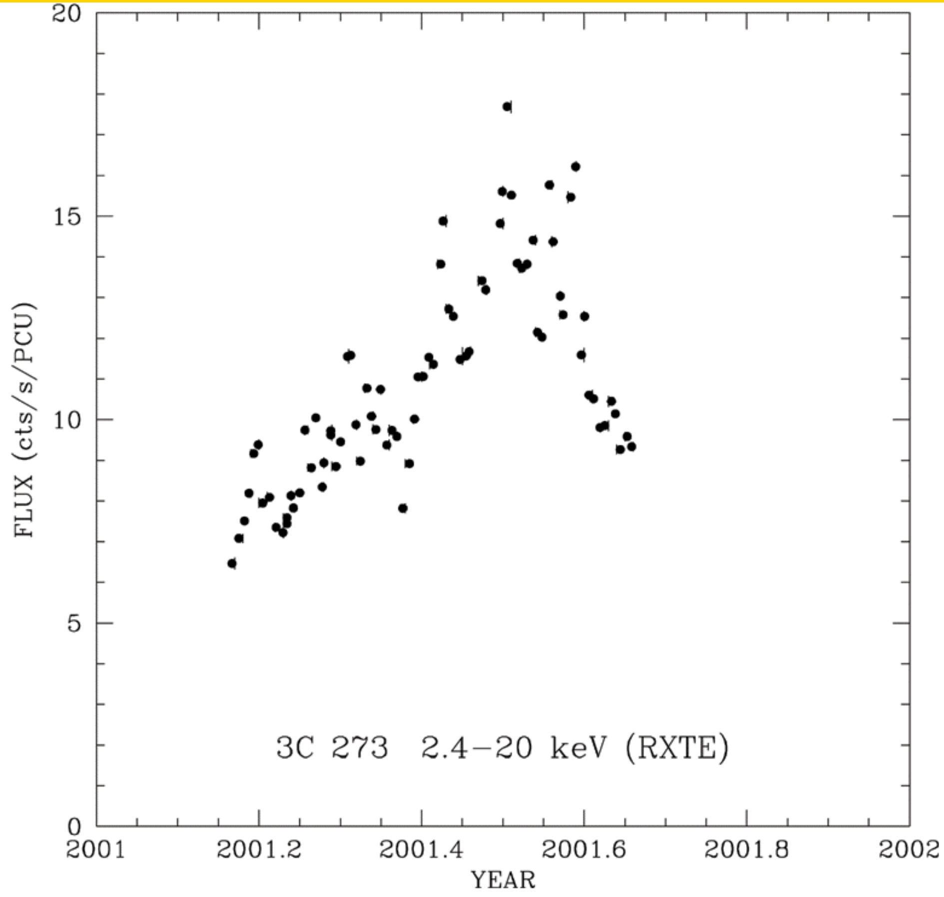
X-Rays from Relativistic Jets in Quasars

Observations by Marscher et al. using NASA's Rossi X-ray Timing Explorer (RXTE):

Several blazars observed 2-3 times per week (except for 8-week sun constraint)

X-ray flux is highly variable with wide range of amplitudes and timescales

Example (started in March 2001): 3C 273 (z=0.158), brightest quasar in visible light:



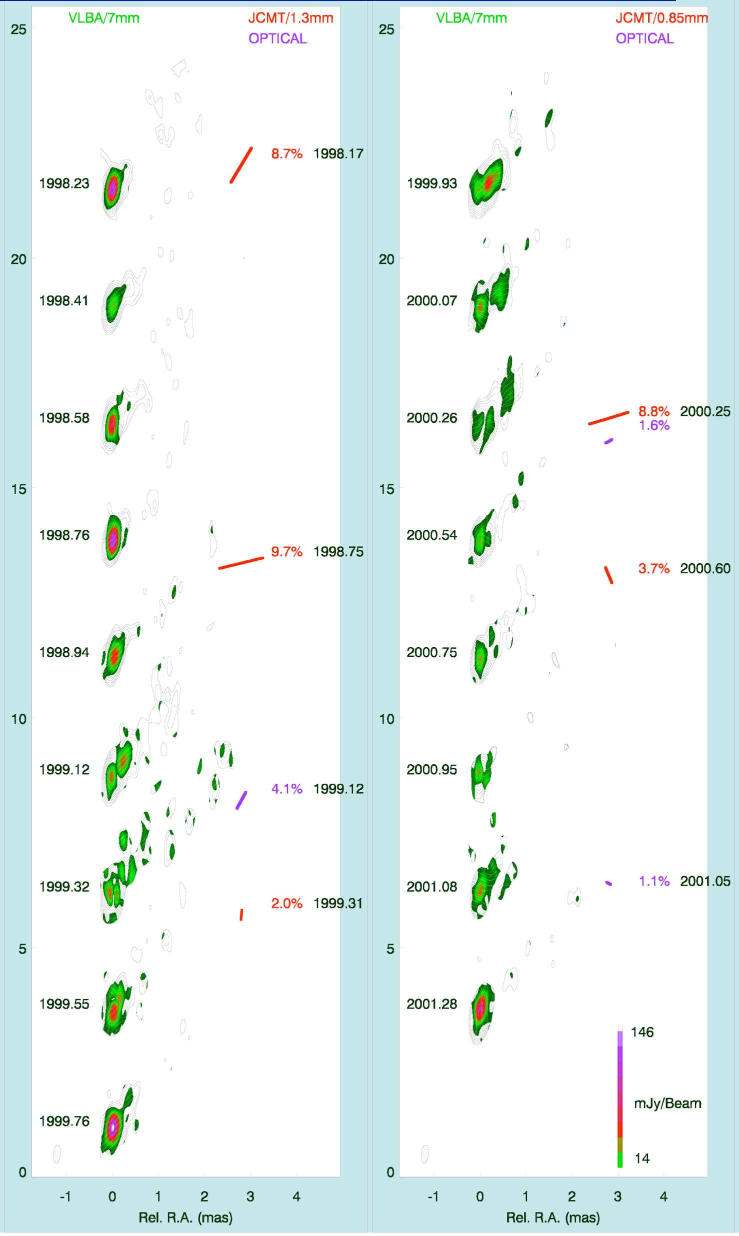
The Quasar PKS 1510-089 (z=0.361)

Scale: 1 mas = 4.8 pc = 16 lt-yr (Ho=70)

Superluminal apparent motion greater than 40c (2.1 milliarcsec/yr) (fastest confirmed speed)

Bright X-ray source with highly variable flux

Bright source of 0.1-3 GeV γ-rays

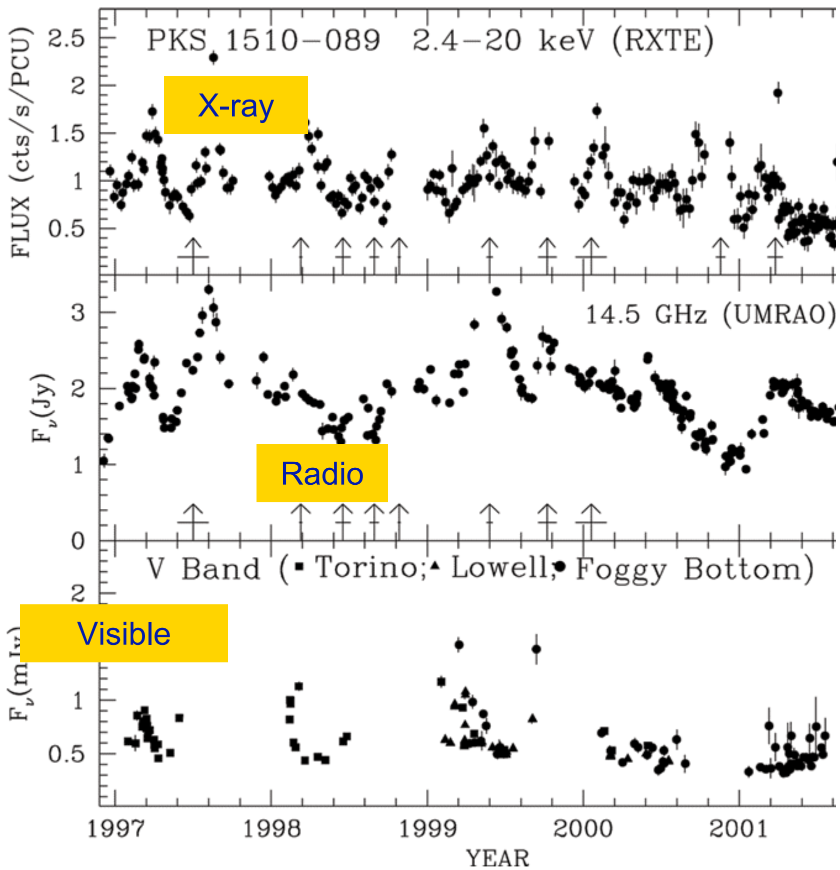


The Quasar PKS 1510-089 (cont.)

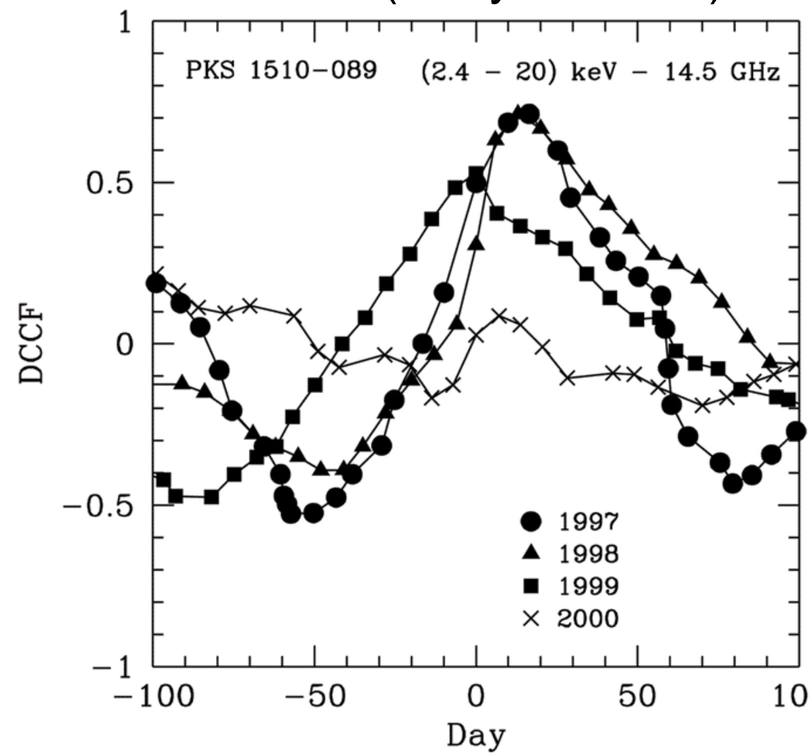
X-ray flares well-correlated with radio (14.5 GHz) in 1997 & 1998, with radio variations leading X-ray by ~ 2 weeks ("reverse time lag"); ejections of superluminal knots tend to coincide with X-ray flares

→ **X-rays come from superluminal knots in jet (not near accretion disk)**

→ delays signify frequency stratification (e^-s accelerated at shock front, highest energy e^-s "die" quickly, lower-energy ones live longer → lower ν emitted over larger vol



Discrete Cross-Correlation Coefficient (X-ray vs. radio)



Click on screen to view movie

MOVIE

ULTRA RELATIVISTIC QUASAR PKS 1510–089

Red: X-ray

Green: Visible Light

Contours: Radio (43 GHz) intensity

Colors and lines: radio polarization

ALAN MARSCHER /BU
SVETLANA JORSTAD /BU
MARGO ALLER /UMRAO
THOMAS BALONEK /COLGATE U.
IAN McHARDY /U. of SOUTHAMPTON

The Quasar 3C 279 (z=0.538)

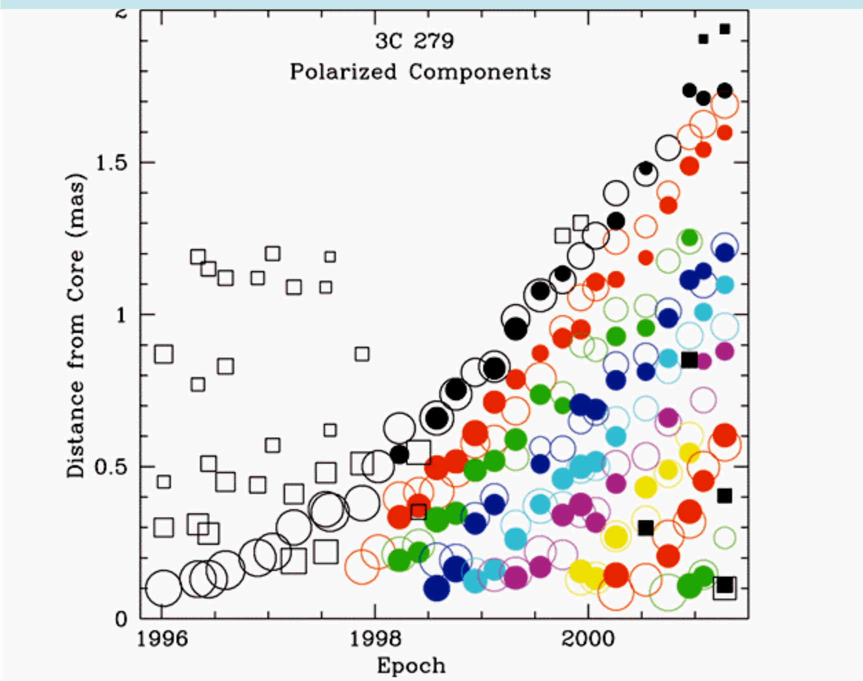
Superluminal apparent speeds, 5c – 13c

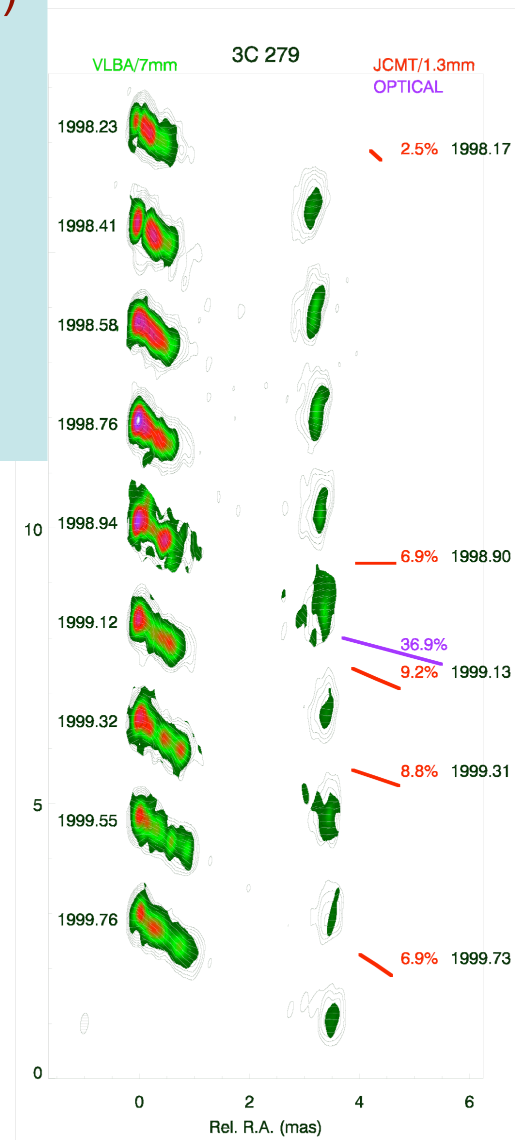
Scale: 1 mas = 6.0 pc = 19.5 lt-yr (Ho=70)

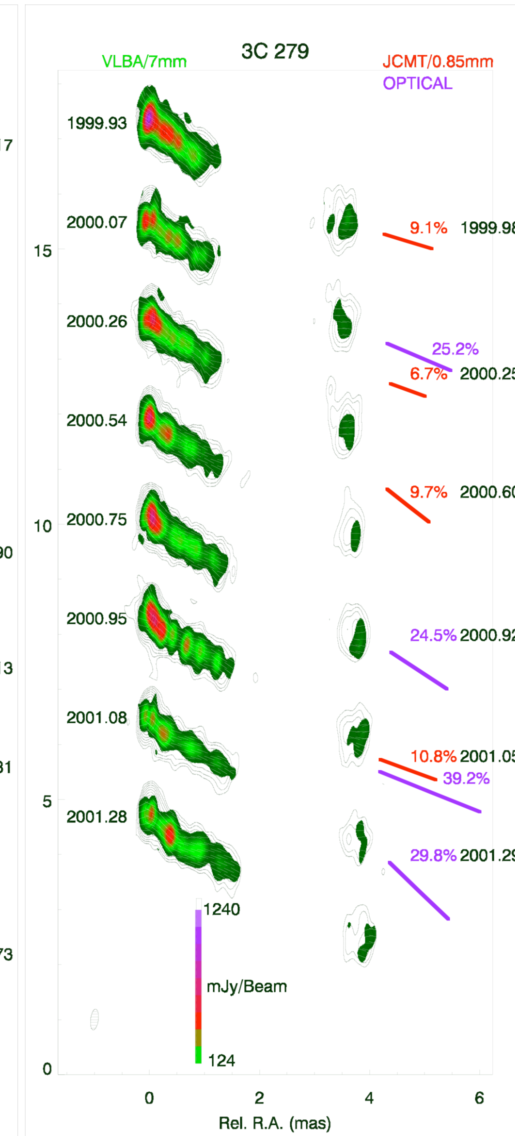
Magnetic field usually ⊥ jet axis
→ transverse shocks

Sudden change in speed at beginning of 1996

Bright, highly variable X-ray & γ-ray emission





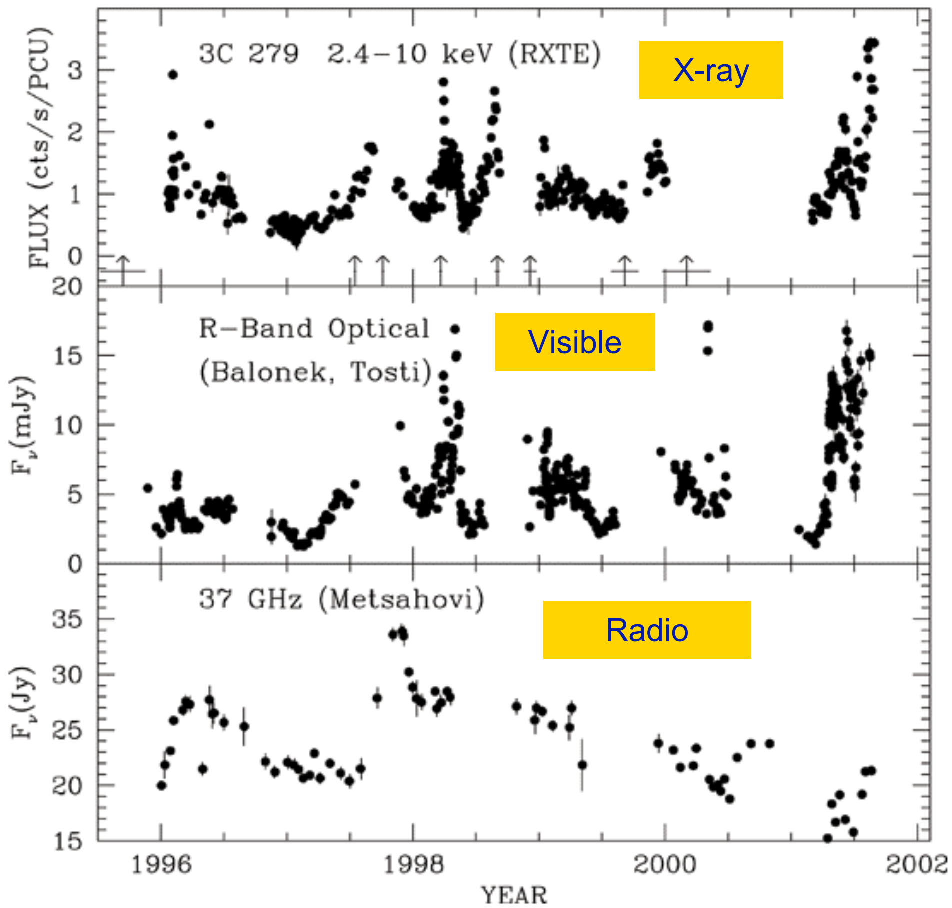


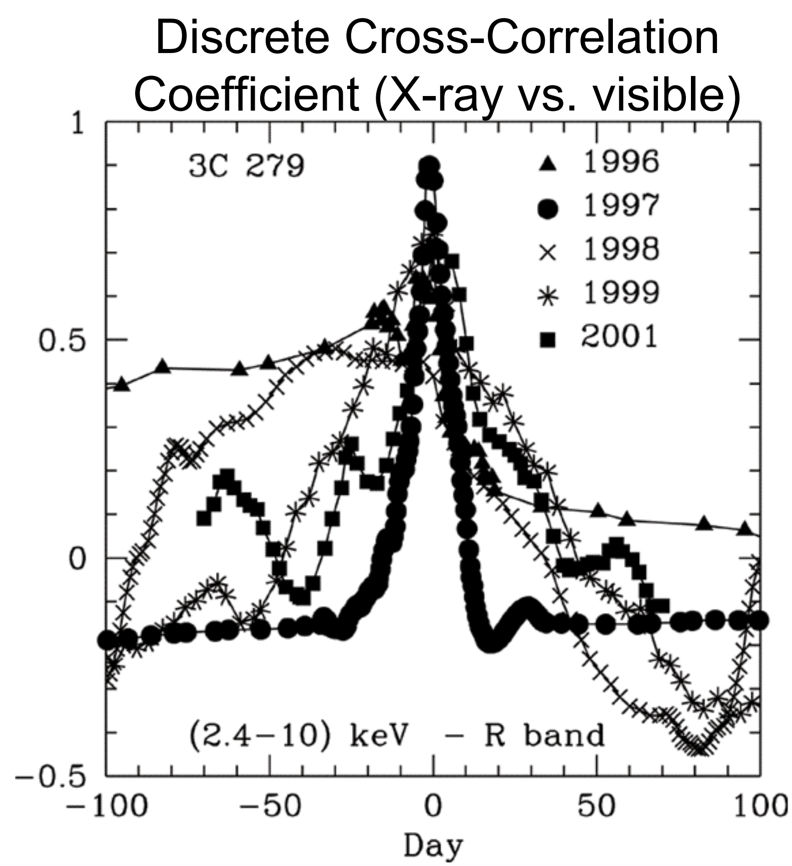
The Quasar 3C 279 (cont.)

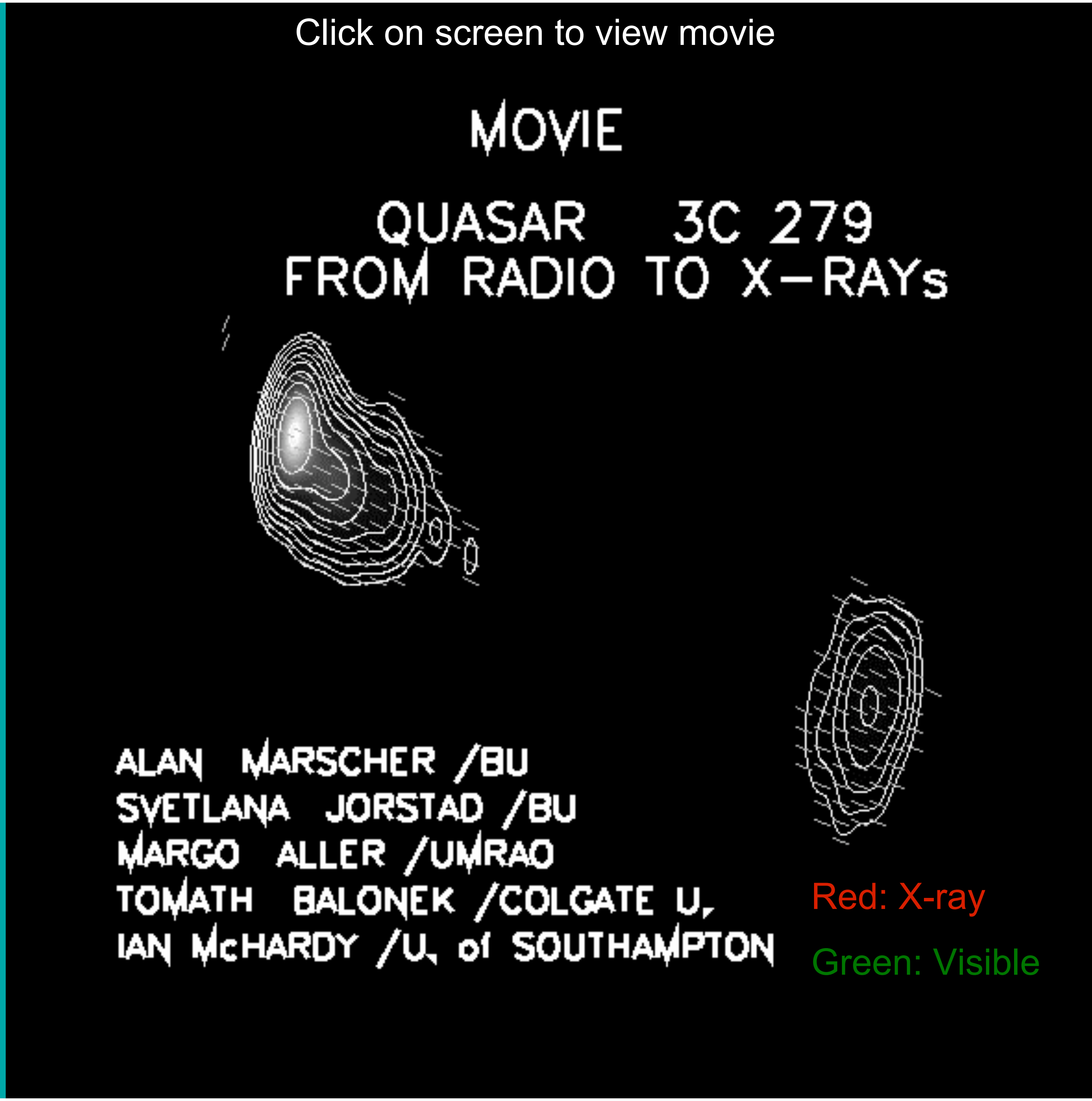
Variations in X-ray flux usually well-correlated with visible brightness, with little or no time lag; ejections of superluminal knots tend to coincide with X-ray flares

→ X-rays and visible light come from superluminal knots in jet (not near accretion disk)

Note: radio light curve is a superposition of a number of components in jet, hence there is only sometimes a correspondence between radio flares & ejections of new knots






Click on screen to view movie
MOVIE
QUASAR 3C 279
FROM RADIO TO X-RAYs
ALAN MARSCHER /BU
SVETLANA JORSTAD /BU
MARGO ALLER /UMRAO
TOMATH BALONEK /COLGATE U.
IAN McHARDY /U. of SOUTHAMPTON
Red: X-ray
Green: Visible

γ-Rays from Blazars

~70 blazars detected by Thomson, Hartman, et al. using NASA's Compton Gamma Ray Observatory (CGRO, EGRET detector, 0.1-3 GeV)

Questions: Are γ-ray blazars different from quasars not detected by CGRO?

Are γ-rays produced near the black hole or in radio-emitting section of jet ($\rightarrow$ intimately related to physics of γ-ray production)?

Our project: Observations at multiple epochs (93-97) of radio jets of 42 γ-ray blazars with the VLBA to obtain apparent velocities to estimate flow Lorentz factors that can be compared with those of the general radio-"loud" quasar population

Secondary goal: Try to determine whether superluminal ejections are related to times of especially high γ-ray flux

γ-Rays from Blazars: Main Results

Distribution of apparent velocities of radio knots in γ-ray blazars peaks at 10-12*c* while that of general radio-loud quasars is skewed toward 1-3*c*

Times of high γ-ray flux statistically associated with epochs of ejection of superluminal radio knots (needs confirmation from future γ-ray mission GLAST, which will provide much more detailed γ-ray light curves)

→ γ-rays are emitted from radio-emitting section of jet, probably from superluminal knots (<u>not from near black hole</u>; from theoretical considerations, any γ-rays emitted from close to the BH would be lost to e^+-e^- pair production off X-rays from accretion disk)

Conclusions

- The ultimate source of the luminosity and production of relativistic jets of quasars and other active galactic nuclei with jets is accretion onto supermassive black holes (see Meier et al. 2001, *Science* and **www.jpl.nasa.gov/releases/2002/release_2002_21.html** for magneto-hydrodynamical (MHD) simulations of jet production)
- X-rays and γ-rays from blazars are produced via (inverse) Compton scattering by same electrons that emit the synchrotron radiation seen at radio to visible (to X-ray in the TeV-emitting blazars) frequencies
- Site of X-ray and γ-ray emission is in the same shock waves that produced superluminal radio knots, many light-years from the black hole
- Multi-frequency monitoring & space-VLBI (iARISE) during the next generation γ-ray mission (GLAST) is surely the best way to confirm the more tentative results of our study of γ-ray blazars and, of course, to reveal new phenomena
- Relativistic jets display complex phenomena that resemble cylindrically symmetric relativistic gas dynamical simulations; as high-resolution fully 3-D gas and MHD calculations become available, such comparisons should allow us to make important inferences regarding the nature of jets