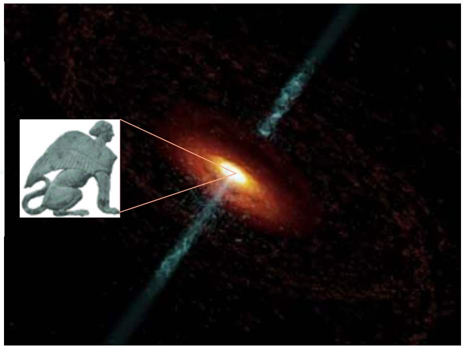

Progress (?) in Our Understanding of Blazars

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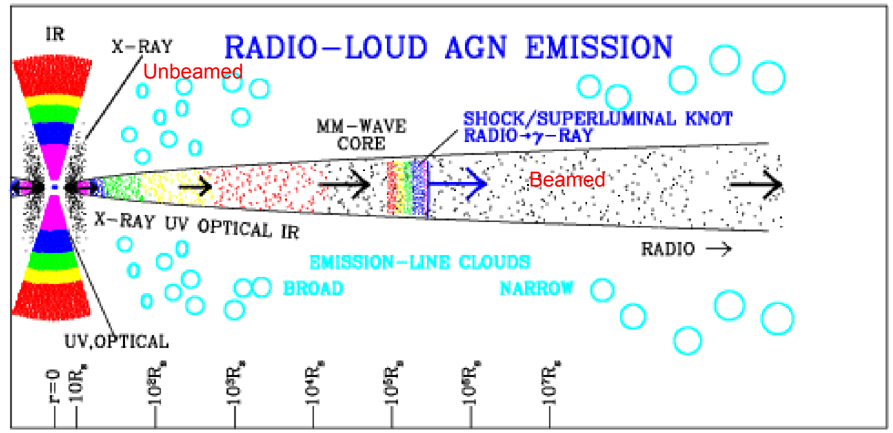
External Advisor of ENIGMA

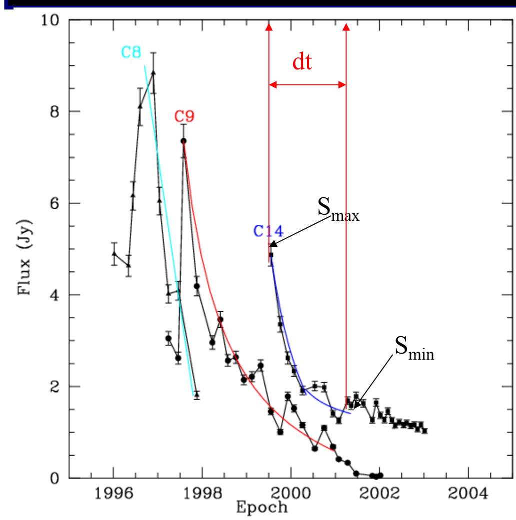
Research Web Page: www.bu.edu/blazars

We have a ~reliable cartoon picture of an AGN

Less reliable closer to black hole



New method determines Lorentz factor & Doppler factor (→ viewing angle) separately



Time Scale of Variability

Burbidge, Jones, & O'Dell 1974, ApJ , 193, 43

$\Delta t_{var} = dt/\ln(S_{max}/S_{min})$

Variability Doppler factor

$\delta_{var} = aD/[c\,\Delta t_{var}(1+z)]$

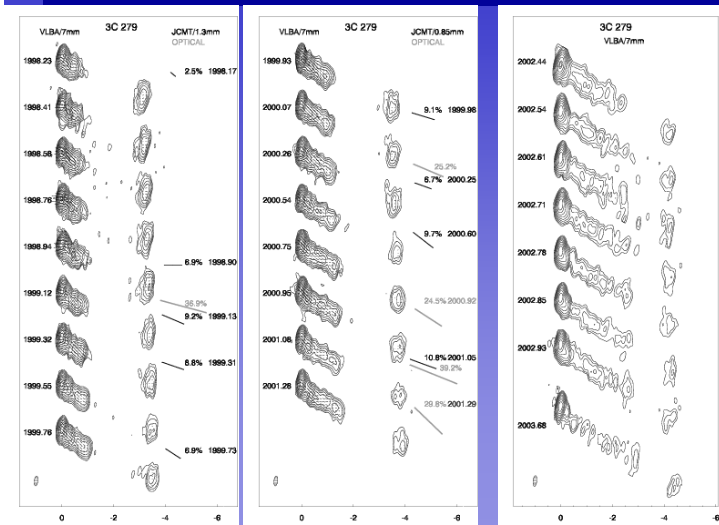
D - luminosity distance

a - VLBI size of component

c - speed of light

z - redshift

Standard jet model agrees well with basic observations

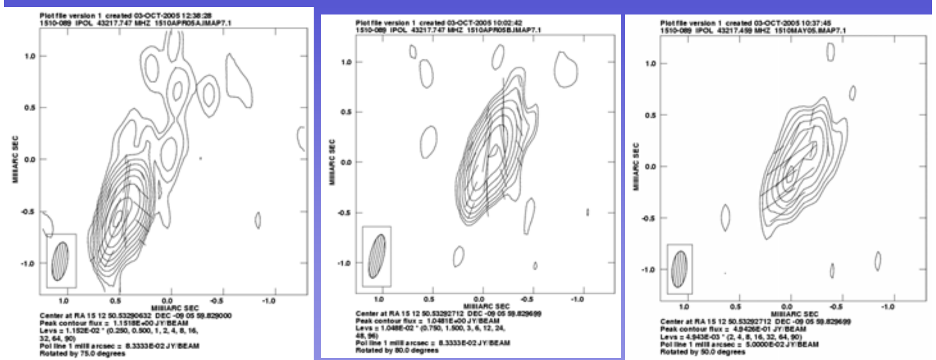


3C 279: Superluminal motion up to ~ 20*c*, bulk Lorentz factor up to ~25, Doppler factor up to ~50 → explains why it is a super blazar

Changes in apparent speed may be due solely to change in direction of jet by about ±2°

Fastest apparent speed consistent with highest variability Doppler factors

Apparent speeds up to 45c (fastest known blazar containing well-defined superluminal knots) → bulk Lorentz factor of at least 45 in jet



Statistics of radio-loud AGN population makes sense

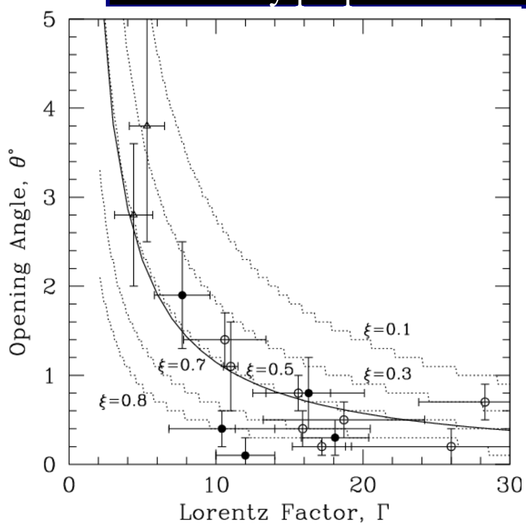
Relativistic beaming causes strong selection effect in flux-limited radio surveys → Bias toward high-Γ jets pointing almost directly along line-of-sight

Population simulation (Lister & Marscher 1997): observed apparent-motion & redshift distribution reproduced if:

1. **Radio-galaxy luminosity function measured at low *z* is valid at higher *z***
2. **Lorentz factor distribution is a power law, $N(\Gamma) \propto \Gamma^{-a}$, *a* = 1.5-1.75, with a high-Γ cutoff of 45 (highest observed β_{app})**

→ 12-17% of jets in population have Γ = 10-45
5-7% have Γ = 20-45, 2-3% have Γ = 30-45, 0.5-0.9% have Γ = 40-45

Intrinsic half opening angle of jet is inversely proportional to Lorentz factor



Side-on radio galaxies:
Opening angles typically 1-4°

$\theta \propto 1/\Gamma$ for blazars

Agrees with models in which jet is focused as it is accelerated over an extended region.(HD: Marscher 1980; MHD: Vlahakis & Königl 2004)

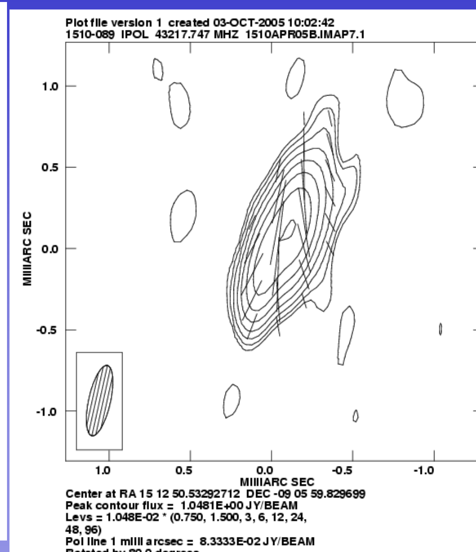
Explains why apparent opening angle is uncorrelated with apparent speed

Internal shock model for moving knots in jets seems to work well

Best-liked model: Shocks propagating down turbulent jet
Magnetic field compressed at shock front
Electrons accelerated at shock front

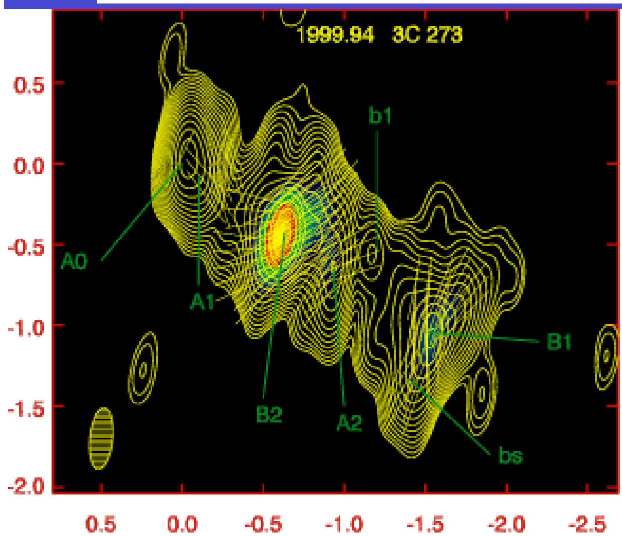
Polarization indicates that in general such shocks must be oblique, especially after correcting for aberration

Need supersonic relative motion to get shock waves → strong shocks are difficult for high-Γ flows with relativistic equation of state
- But don't need very strong shocks for substantial enhancement of radiation & polarization – 10-20% compression is usually enough



Velocity shear is present in 3C 273 where **B** is parallel to jet axis

Polarization: Most quasars have oblique or nearly perpendicular $\chi \rightarrow$ B nearly parallel to jet (after aberration taken into account)



Southern knots: $\Gamma \sim 14$
Northern knots: $\Gamma \sim 8$

The core of blazar jets might be getting clearer

Frequencies below ~ 200±100 GHz:

- $\tau \sim 1$ surface if no bright, stationary features in jet a bit farther downstream
- conical standing shock (Daly & Marscher 1988) (e.g., 1803+784 shown below)

In favor: reproduces polarization pattern if randomly oriented B field is compressed by conical shock; in some sources core position not function of wavelength

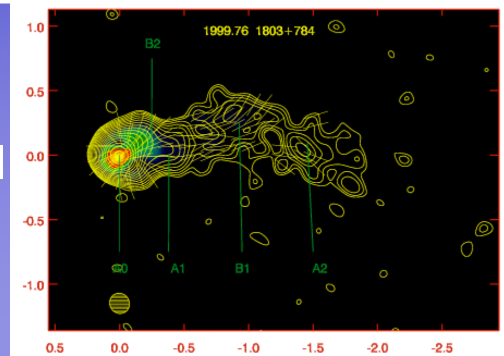
At higher frequencies:

- End of zone of accelerating flow, where Doppler factor reaches asymptotic value

But in non-blazars, beaming not important

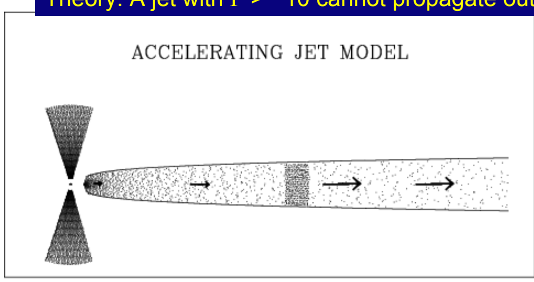
- Where high-E electrons first appear in jet

1803+784



Jet Acceleration over Extended Region

Theory: A jet with $\Gamma > \sim 10$ cannot propagate out of nuclear region (Phinney 1987)



MHD: Models under development
Vlahakis & Königl (2004, ApJ)
Jet accelerated over large distance
Γ decreases away from jet axis
No distinct boundary

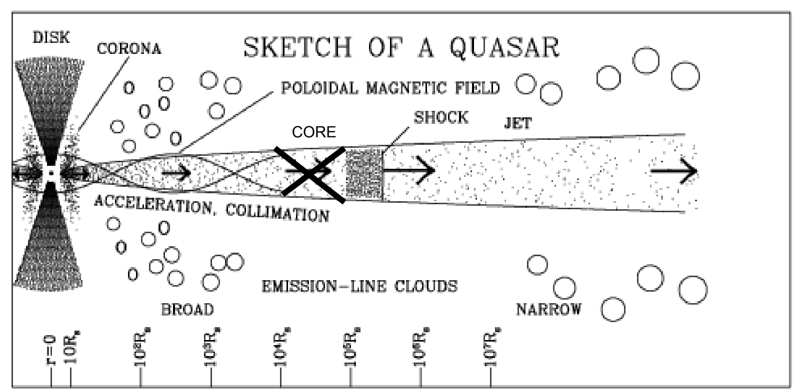
Predicts toroidal field in acceleration zone

Maybe we see this at 1 mm (Jorstad et al.2007)

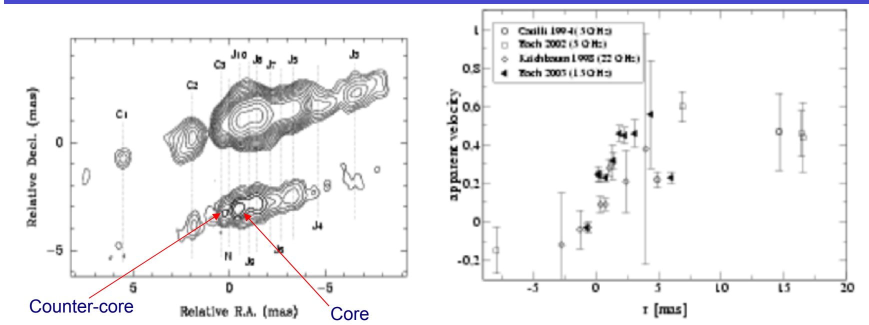
Energy density at base of jet must exceed $\sim 2\Gamma\rho c^2$

Might require a magnetosphere (pulsar or ergosphere of spinning BH)

Sketch of Physical Structure of Jet, AGN



Cygnus A (Bach et al. 2004, 2005)
FR II radio galaxy, jet at large angle to l.o.s.



Gap between core & counterjet < 0.2 mas
Apparent speed increases with distance from core

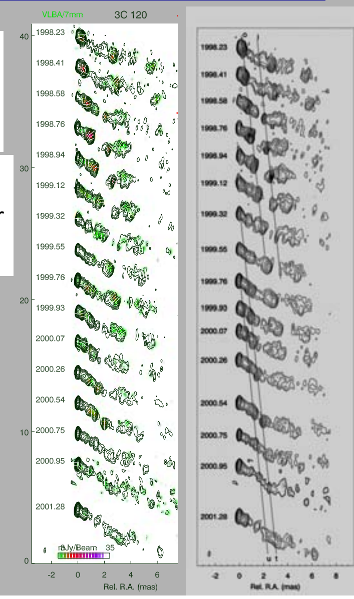
Radio galaxies show a connection between X-rays from central engine region & activity in jet, ~ as in microquasars

The FR I Radio Galaxy 3C 120 (z=0.033)

HST image (Harris & Cheung)

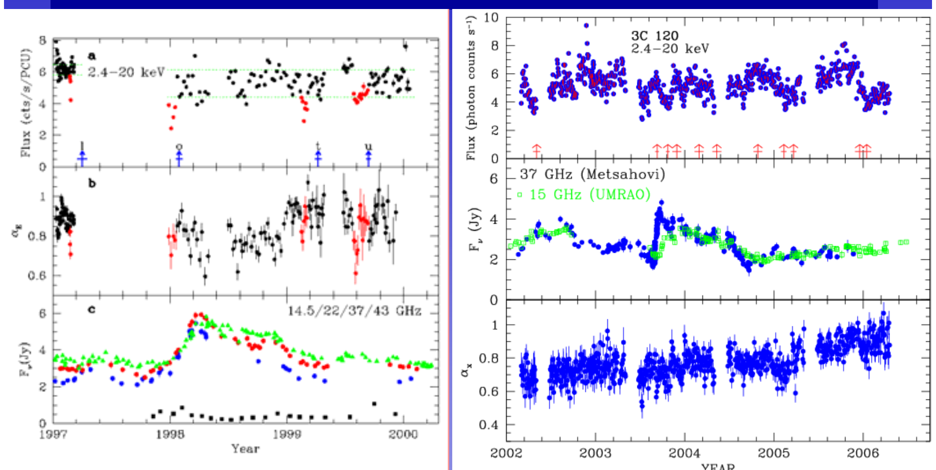
Sequence of VLBA images (Marscher et al. 2002)

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



- Superluminal apparent motion, ~5c (1.8-2.8 milliarcsec/yr)
- X-ray spectrum similar to Seyferts
- Mass of central black hole ~ $3x10^7$ solar masses (Marshall, Miller, & Marscher 2004; Wandel et al. 1999)

X-Ray Dips in 3C 120

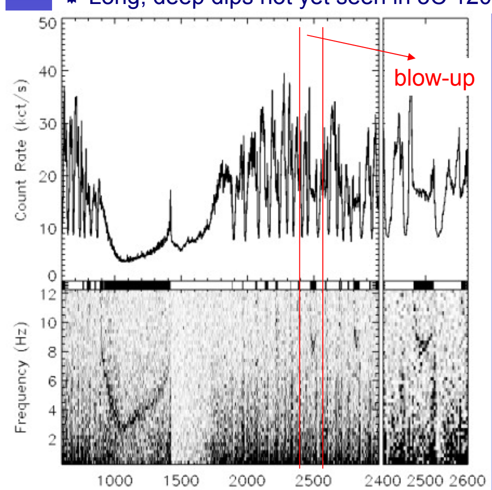


Superluminal ejections follow X-ray dips
→ Similar to microquasar GRS 1915+105

λ3mm core must lie at least 0.4 pc from black hole to produce the observed X-ray dip/superluminal ejection delay of ~ 60 days

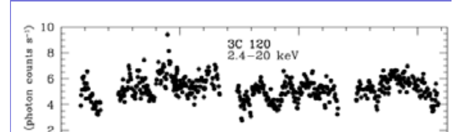
Comparison of GRS1915+105 with 3C 120 Light Curves

- BH mass of 3C 120 ~$2x10^6$ times that of GRS 1915+105, so timescales of hours to months in the former are similar to the scaled-up quasi-periods (0.15 to 10 s) & duration of short X-ray dips in the latter.
- Typical fractional amplitude of dips is also similar
- Long, deep dips not yet seen in 3C 120



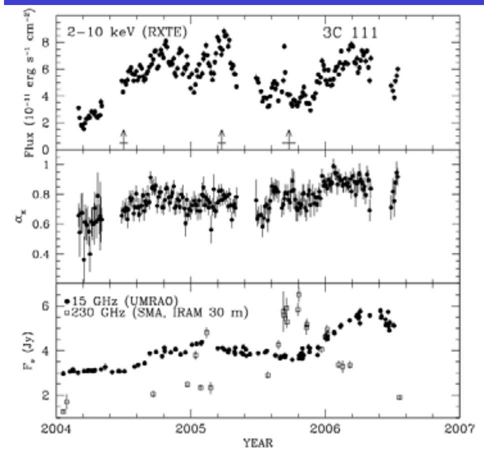
150 s of blow-up should scale up to ~10 yr in 3C 120 if timescales ∝ M_{bh}

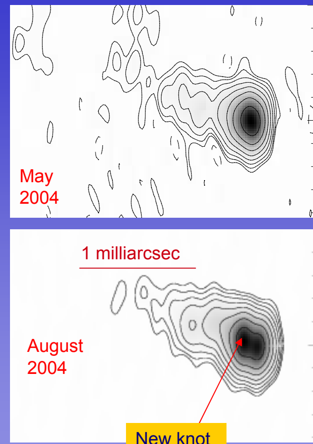
Below: X-ray light curve of 3C 120 over 2.2 yr



← GRS 1915+105 over 3000 s on 9/9/97
Light curve (top) & PSD (bottom)
(Taken from Markwardt et al. 1999 ApJL)

FR II Radio Galaxy 3C 111 (z=0.0485) Seems to Do the Same





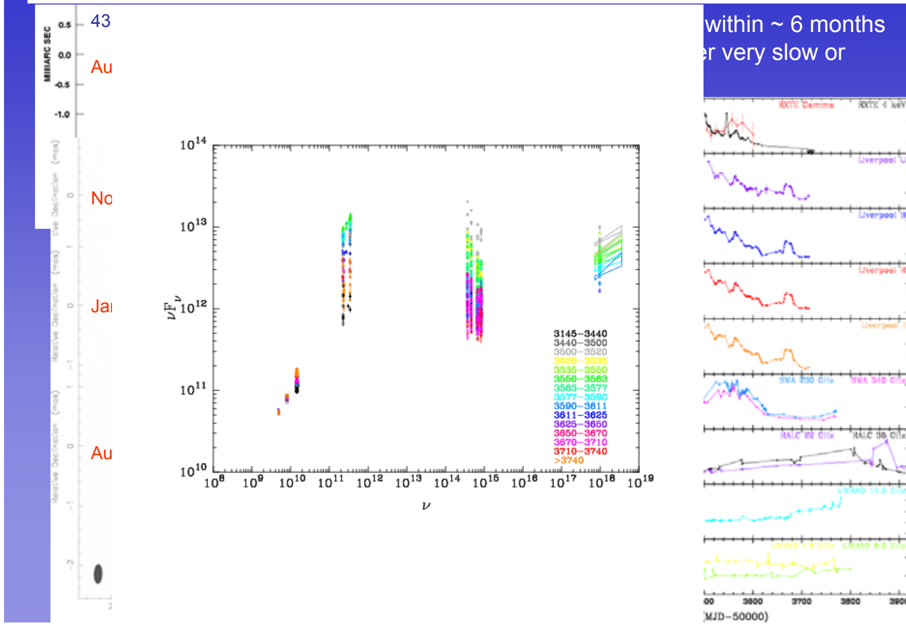
Superluminal ejection follows minimum of deep X-ray by 0.3 yr

λ3mm core must lie at least 0.4 pc from black hole to produce the observed X-ray dip/superluminal ejection delay

It appears that there are flares in the core

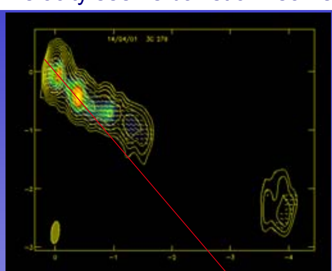
Example: Enormous outburst in 3C 454.3 in 2005-06

within ~ 6 months
r very slow or

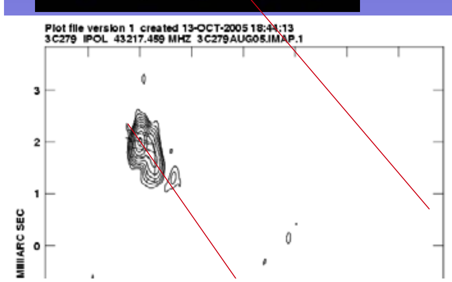


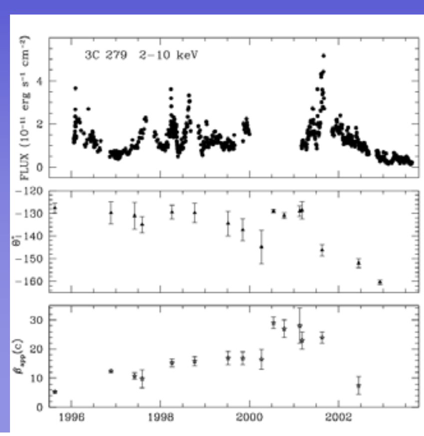
Changes in Direction

Change in apparent speed can be due solely to change in direction
Nonthermal luminosity seems to be related to direction of jet
Changes amplified greatly by projection effects
Velocity seems ballistic in some jets but seems to follow twisting jet in many others



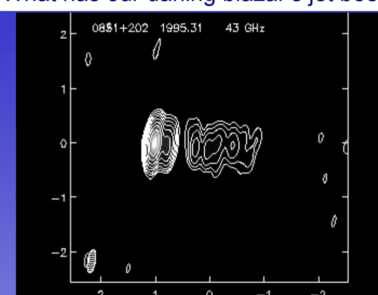
Changes in direction appear to be abrupt, unlike precession (more like an unstable firehose)

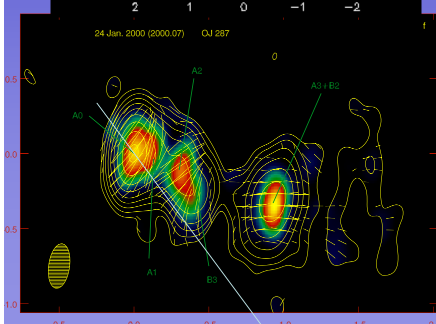


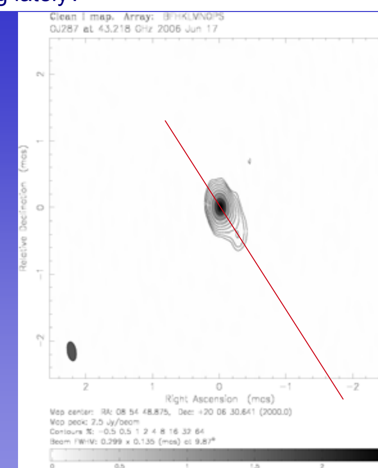


Changes in Direction: OJ 287

What has our darling blazar’s jet been doing lately?







Dramatic change in direction (~ 50° over 11 yr), might be precession

Scandals

From the Lapland Winter School (April 2004)

- No good model for core despite its prominence
- TeV BL Lac objects: slow apparent speeds, weak radio variability but need high Doppler factors
- Shock model for flares: no description of rising flux ☹
- Flare profiles sharply peaked; in models they are rounded or flat ☹
- Particle acceleration models only partially developed: how can most particles be relativistic? How can we get energies ~10-100 TeV?
- PKS 0405-385: $T_{b,min}$ ~ $2x10^{14}$ K: can δ ~200? ?
- Some deprojected opening angles <0.2^o

Scandals

[continued]

- Many prominent blazars have magnetic fields that lie parallel to the jet axis
- Models for very high γ-ray luminosities: inverse Compton scattering of photons external to jet; but mm-wave flare often precedes γ flare so outside BLR

From 2004 multiwaveband meeting in Bonn:

- We have no complete samples of quasars
- Nature keeps jets together that 3D HD simulations destroy
- Single-zone models widely applied to rapid variations

More Scandals

- No model for abrupt transition from toroidal to turbulent magnetic field in jet
- Jets contain mostly relativistic plasma; we are ignorant of physics
- Jets change direction, usually non-periodically; we don't know why ☹
- Core-sheath model gives us extra free parameters but not tested against existing statistics
- 0716+714 refuses to give us its redshift
- Enigma's external advisor is a crazy professor from the land of Bush (George II) who is even older (by several months) & crazier than Prof. Valtaoja