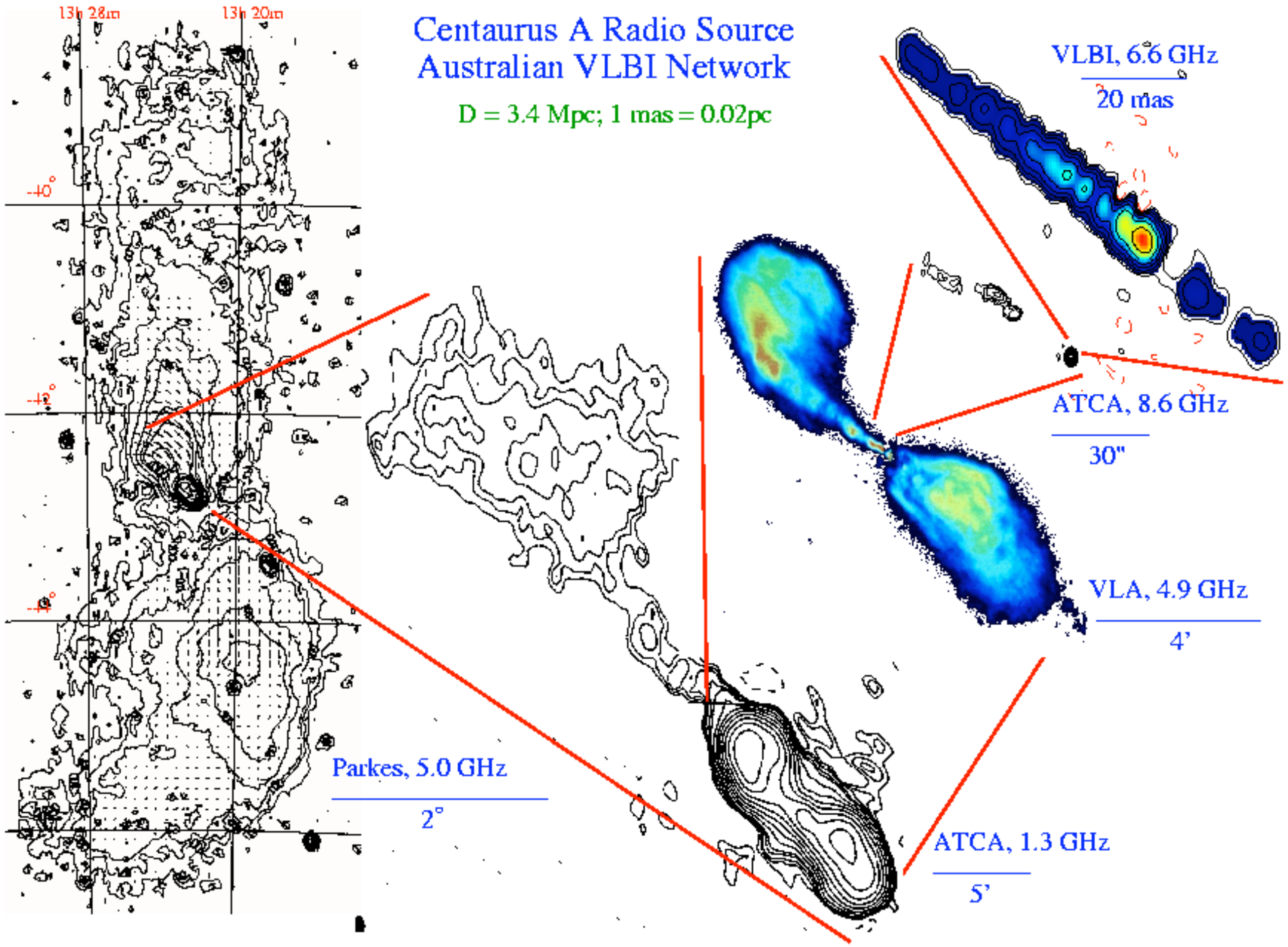
The sub-parsec-scale structure and evolution of Dunlop 482



Prof. Steven Tingay

ICRAR - Curtin University of Technology

Collaborators

Tingay, S. J. (ATNF, JPL, Swinburne, Curtin)

Jauncey, D. L., Reynolds, J. E., Tzioumis, A. K., King, E.A., Lenc, E., Edwards, P.G., Gough, R. G., Ferris, R. H., Sinclair, M. W. (ATNF)

Preston, R. A., Jones, D. L., Murphy, D. W., Meier, D. L., van Ommen, T. D. (JPL)

McCulloch, P. M., Ellingsen, S. P., Costa, M. E., Lovell, J. E. J. (University of Tasmania)

Nicolson, G. D., Quick, J. F. H., Kemball, A. J. (HartRAO)

Migenes, V., Harbison, P. (NASA)

Jones, P. A., White, G. L. (U. Western Sydney)

Blair, D., Costa, M. (University of Western Australia)

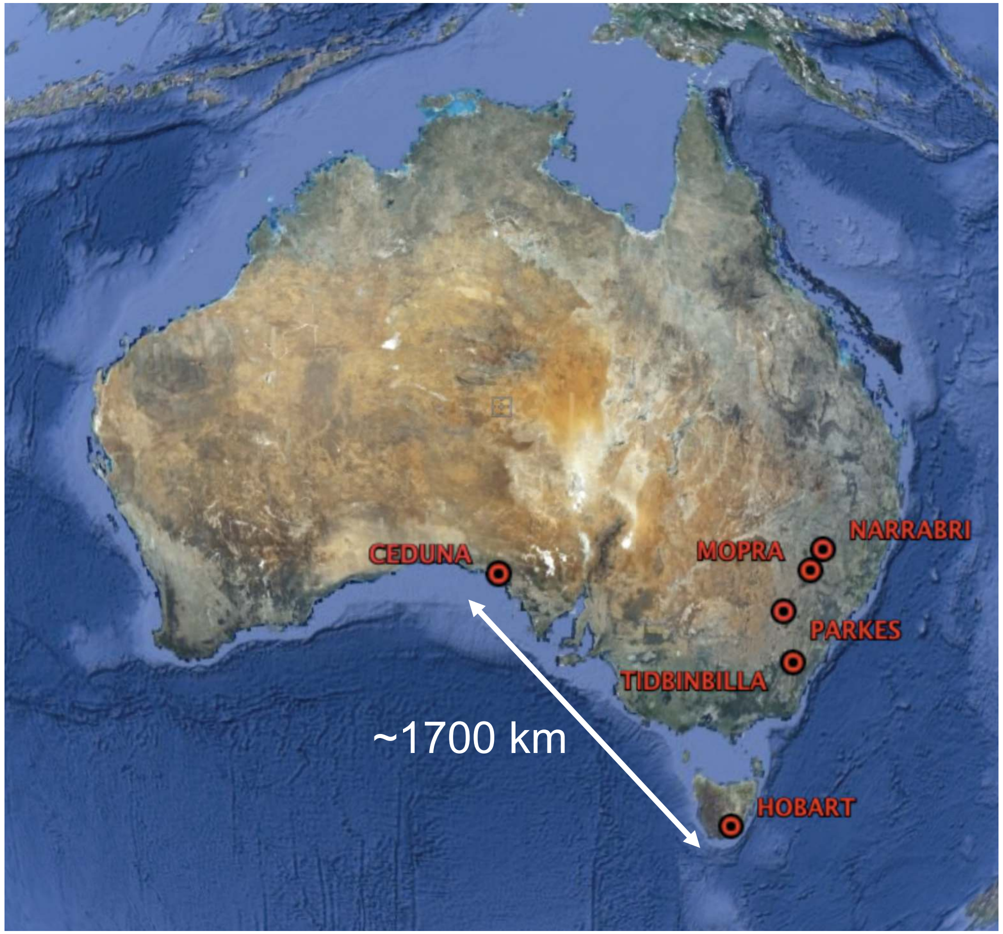
Clay, R. W. (University of Adelaide)

Outline of review

- Early observations of the parsec scale structure;
- Parsec-scale morphology;
- Time variability of the parsec-scale structure;
- Frequency variability of the parsec-scale structure;
- Results at the highest spatial resolution;
- HI and OH lines;
- Parsec-scale structure in the kiloparsec-scale jet;
- Summary.
- Bonus material: Imaging with the Murchison Widefield Array (MWA).

Very Long Baseline Interferometry

Australian Long Baseline Array



Very Long Baseline Array

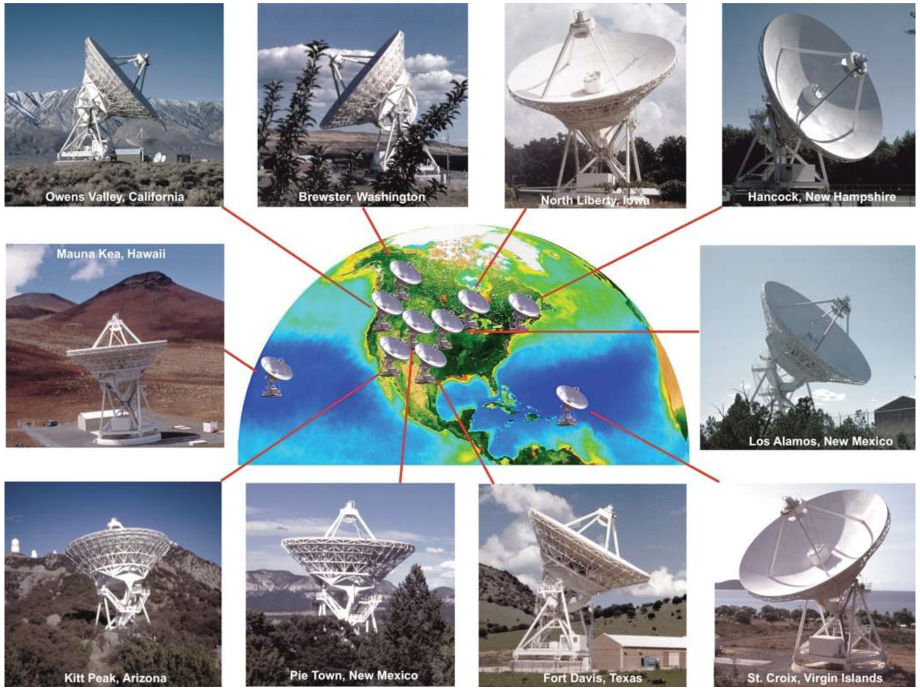


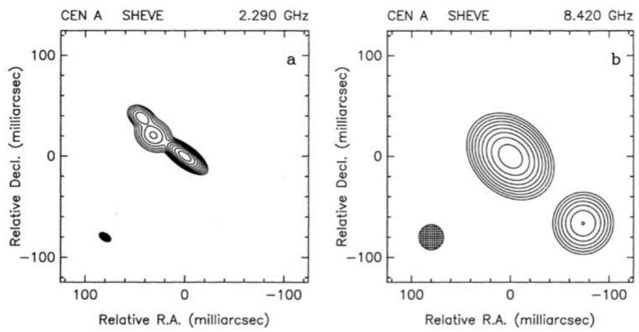
Image courtesy of NRAO/AUI and Earth image courtesy of the SeaWiFS Project NASA/GSFC and ORBIMAGE

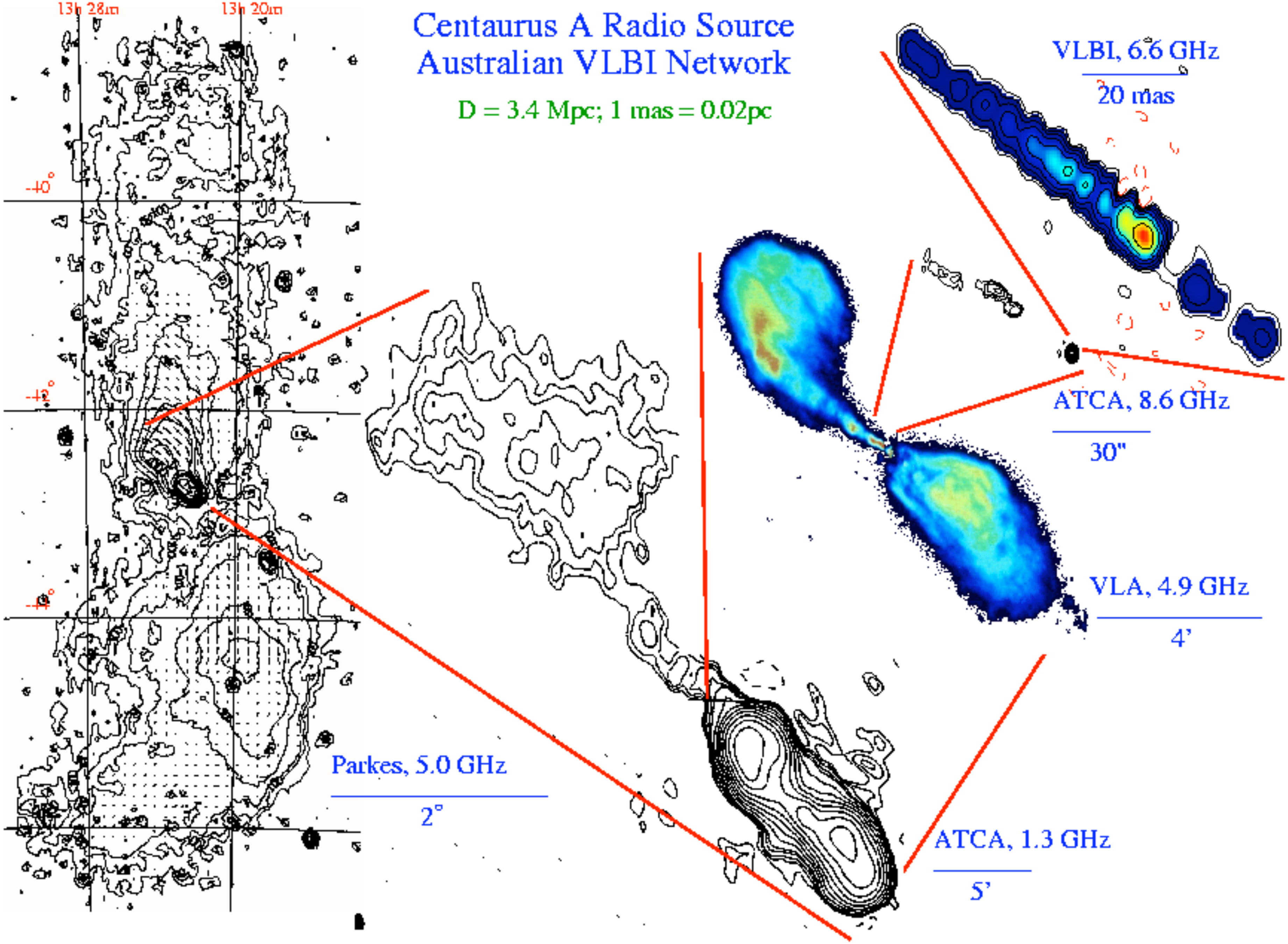
Early observations of the parsec scale structure

- Wade et al. (1971) undertook the first high-resolution radio observations of Cen A and reported a source less than 0.5" in extent (NRAO three element interferometer), noting that the inverted spectrum of the core implied a much smaller extent, <0.01 arcsec.

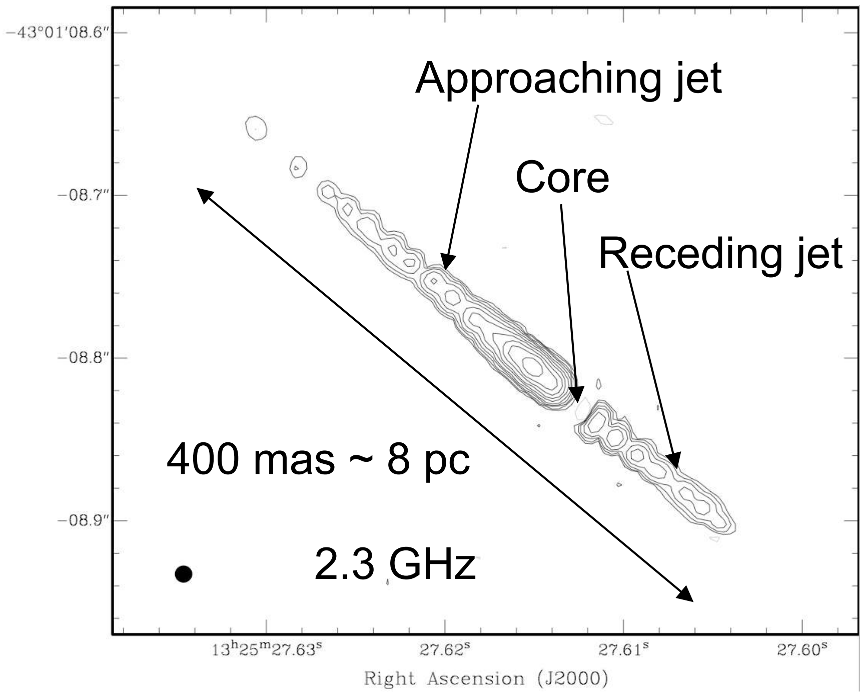
- Using VLBI observations, Preston et al. (1983) suggested a model for the nuclear radio source in Cen A that consisted of two components, a 50 mas jet that was observed with 2.3 GHz observations and a more compact component likely to be the core observed only at higher frequencies since it is highly self-absorbed at lower frequencies.

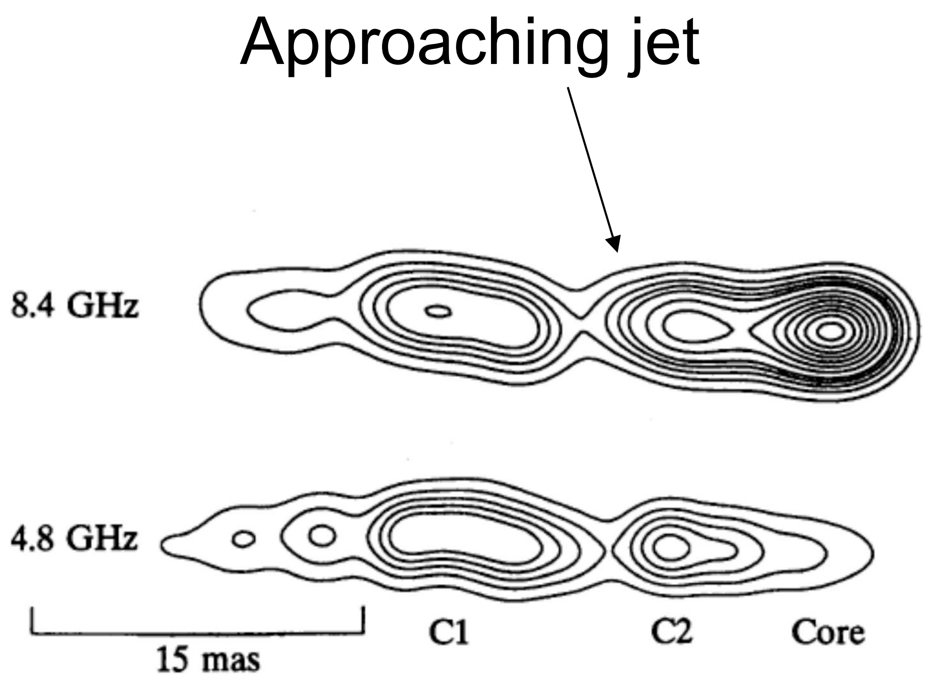
- Meier et al. (1989) proposed a model for the source that consisted of a weak self-absorbed core and an extended jet component at a PA of 51° ± 3°, in agreement with the jet position angle from VLA images of the kiloparsec-scale radio structure.




Centaurus A Radio Source
Australian VLBI Network
D = 3.4 Mpc; 1 mas = 0.02pc
13h 28m
13h 20m
-40°
-42°
-44°
Parkes, 5.0 GHz
2°
ATCA, 1.3 GHz
5'
VLA, 4.9 GHz
4'
ATCA, 8.6 GHz
30"
VLBI, 6.6 GHz
20 mas

Parsec-scale morphology





Tingay & Lenc 2009, AJ accepted

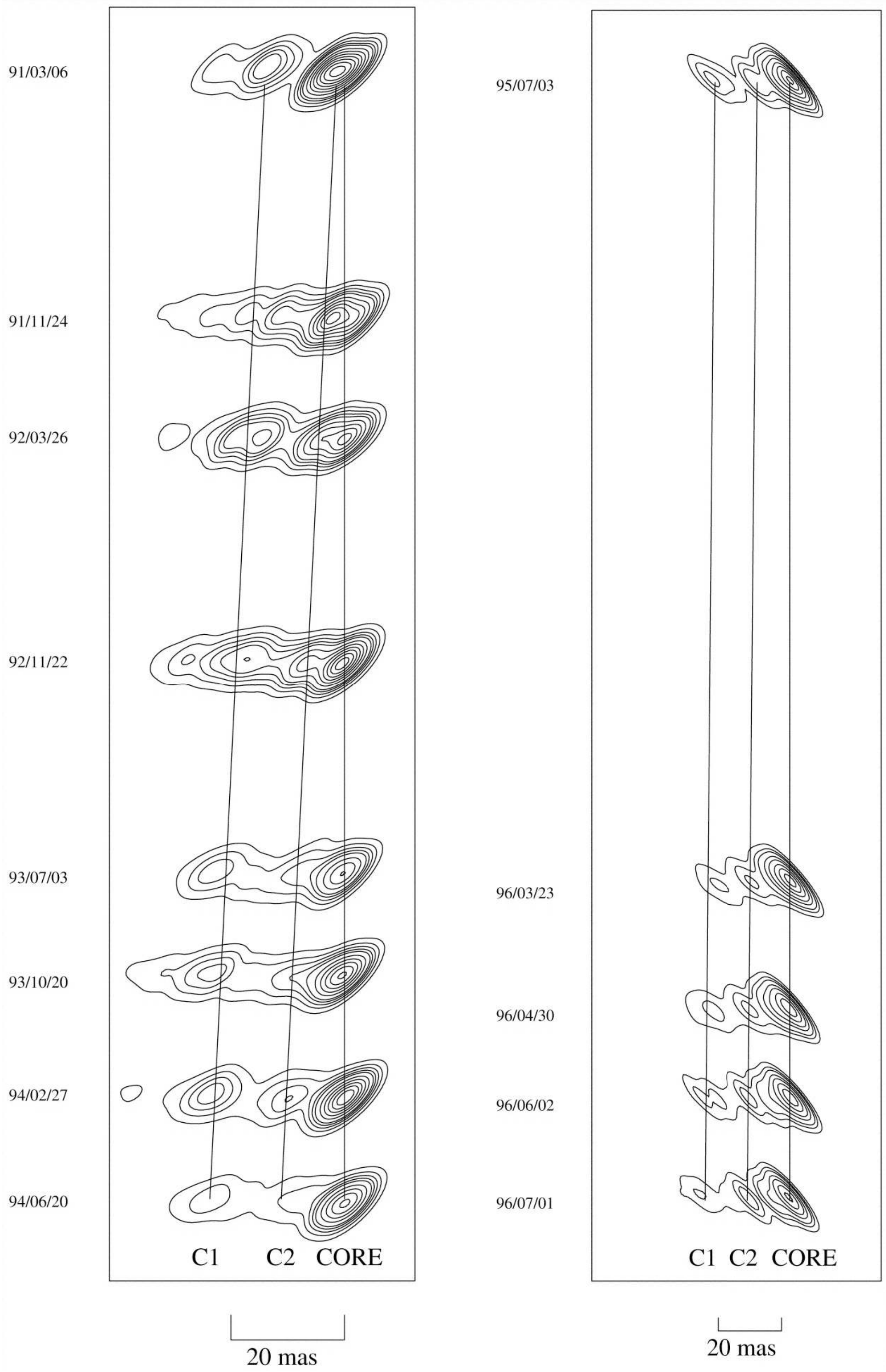
Jauncey, Tingay et al. 1995, PNAS, 9211368J

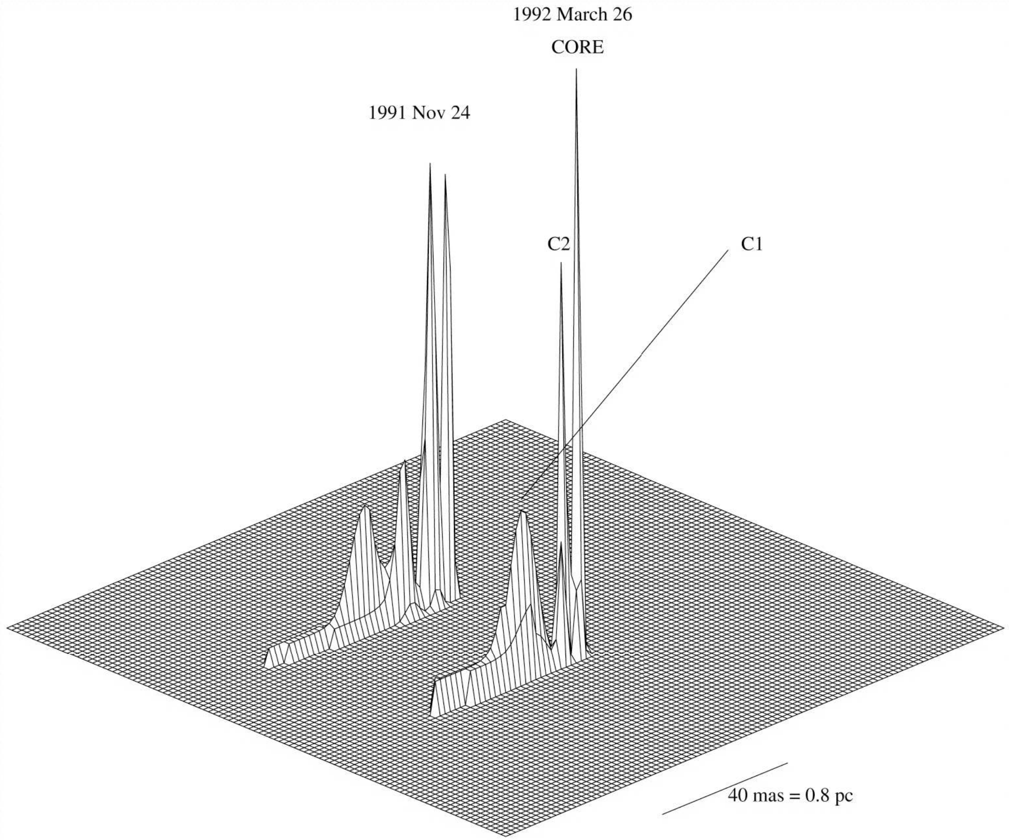
Time variability of the parsec-scale structure

Monitoring observations with VLBI can probe:

- the apparent speeds of features in the jet and counter-jet;
- the internal variability of these features;
- Place constraints on the orientation of the jet and the intrinsic speed of the jet material (under certain assumptions);
- Allow us to relate to larger scale features in Centaurus A/ NGC 5128 and multi-wavelength data;
- Reveal relativistic effects such as beamed radiation and apparent jet component motions.

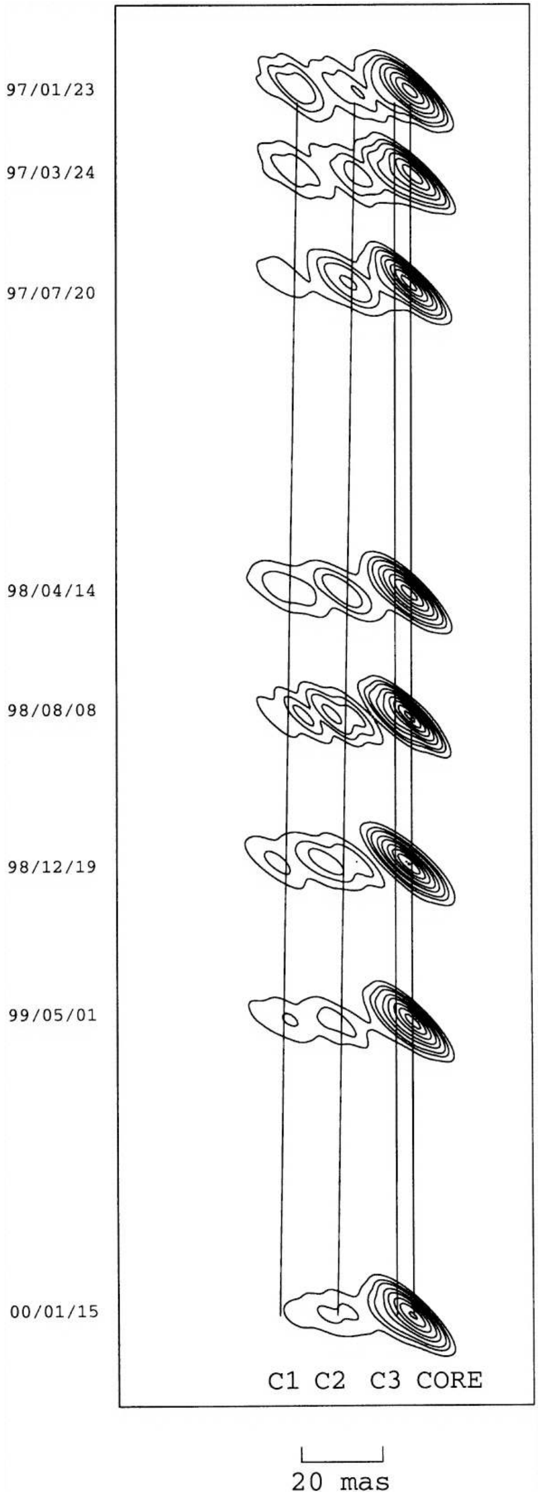
Tingay et al. 1998, AJ, 115, 960

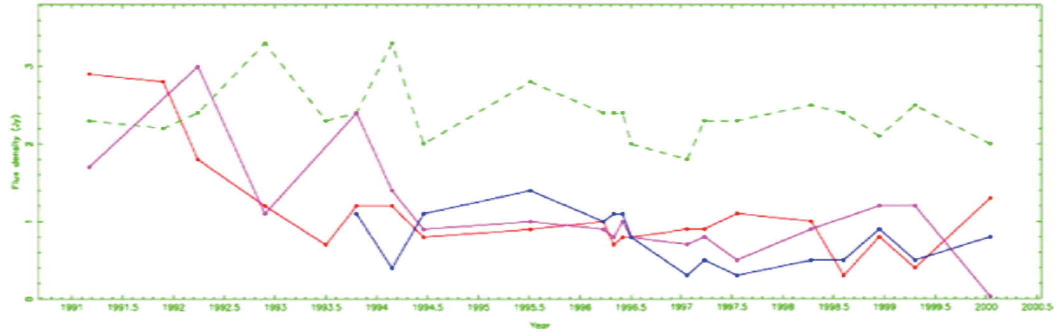


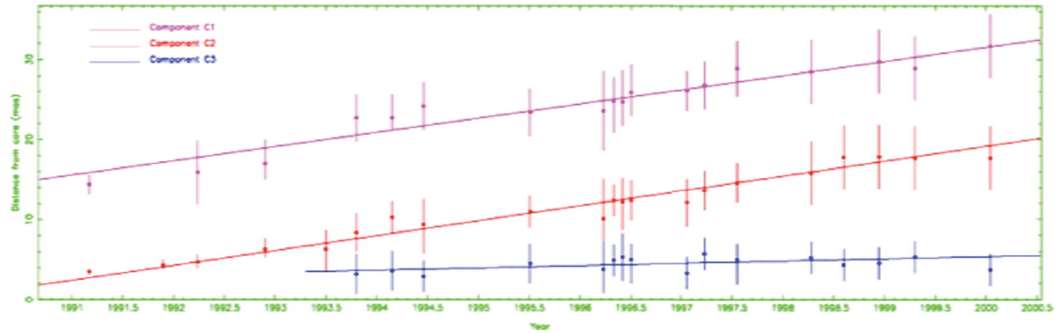


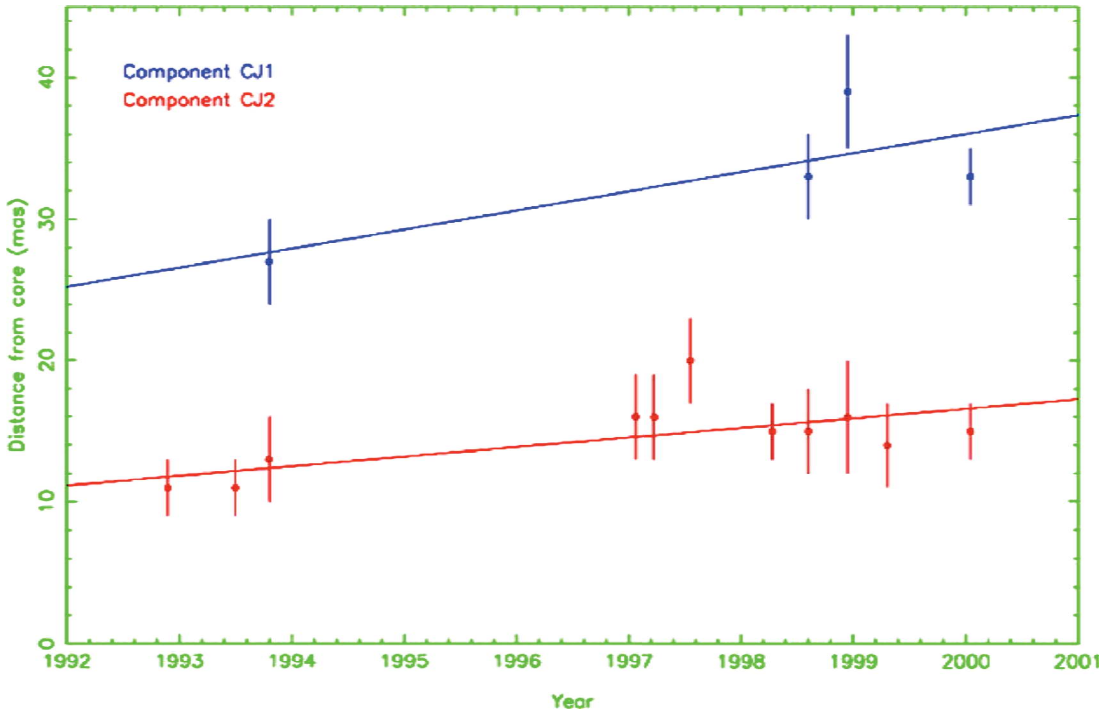
From observations of rapid variability within components such as C1, estimates of the underlying jet fluid speed give >0.45c.

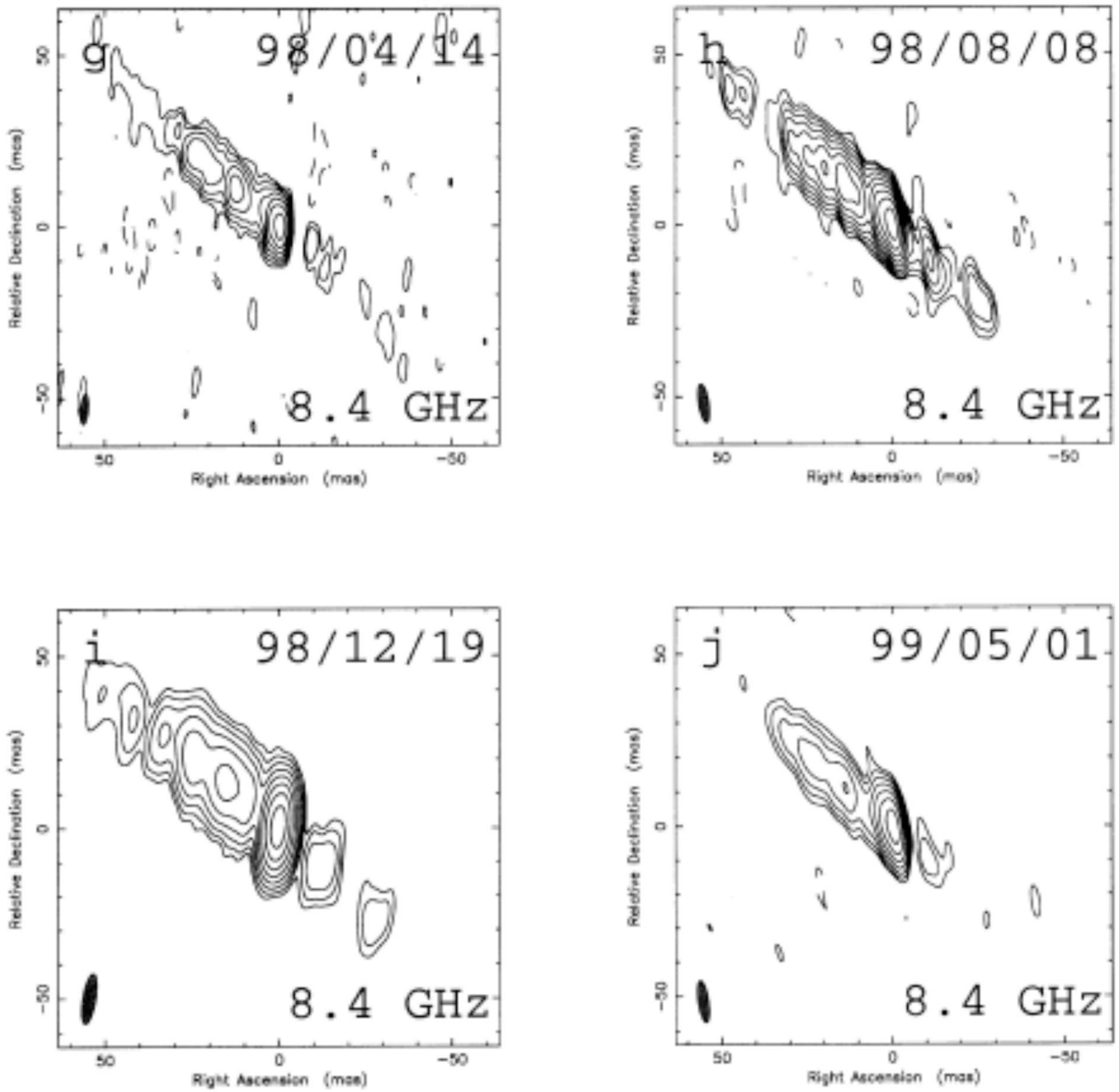
Tingay, Preston & Jauncey 2001, AJ, 122, 1697











g
98/04/14
8.4 GHz
h
98/08/08
8.4 GHz
i
98/12/19
8.4 GHz
j
99/05/01
8.4 GHz
Relative Declination (mas)
Right Ascension (mas)
50
0
-50

$$\theta = \tan^{-1}\left(\frac{2\beta^a_{\rm app}\beta^r_{\rm app}}{\beta^a_{\rm app} - \beta^r_{\rm app}}\right), \qquad \beta = \frac{\beta^a_{\rm app}}{\beta^a_{\rm app}\cos\theta + \sin\theta},$$

βa and βr are the apparent speeds of the approaching and receding components, respectively.

The data are consistent with: <u>50° < θ < 80°</u> and <u>0.1 < β < 0.2</u>

Also consistent with idea of faster underlying jet fluid (β_{fluid}>0.45c: estimated from observations of rapid variability within individual slow moving components) and observed jet to counter-jet surface brightness ratio of R = 8.

$$R = \left(\frac{1 + \beta_{fluid}\cos\theta}{1 - \beta_{fluid}\cos\theta}\right)^{3-\alpha}$$

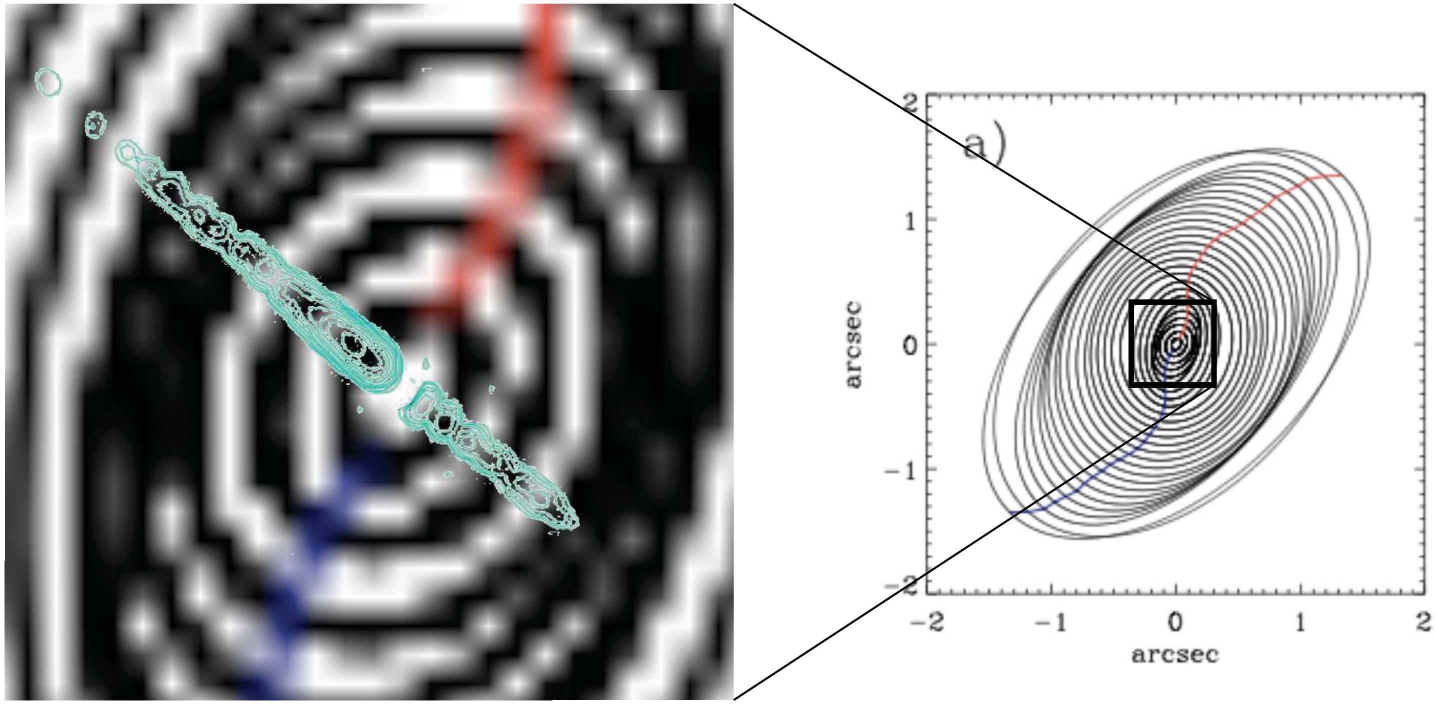
c.f. VLA data from Hardcastle et al. (2003) that shows jet features have apparent motions of ~0.5c on scales of hundreds of pc.

pc-scale	=> motion of shocks ~0.1c
pc-scale	=> motion of underlying jet fluid >0.45c
kpc-scale	=> ballistic motions of plasma ~0.5c?
kpc-scale	=> stationary plasma blobs

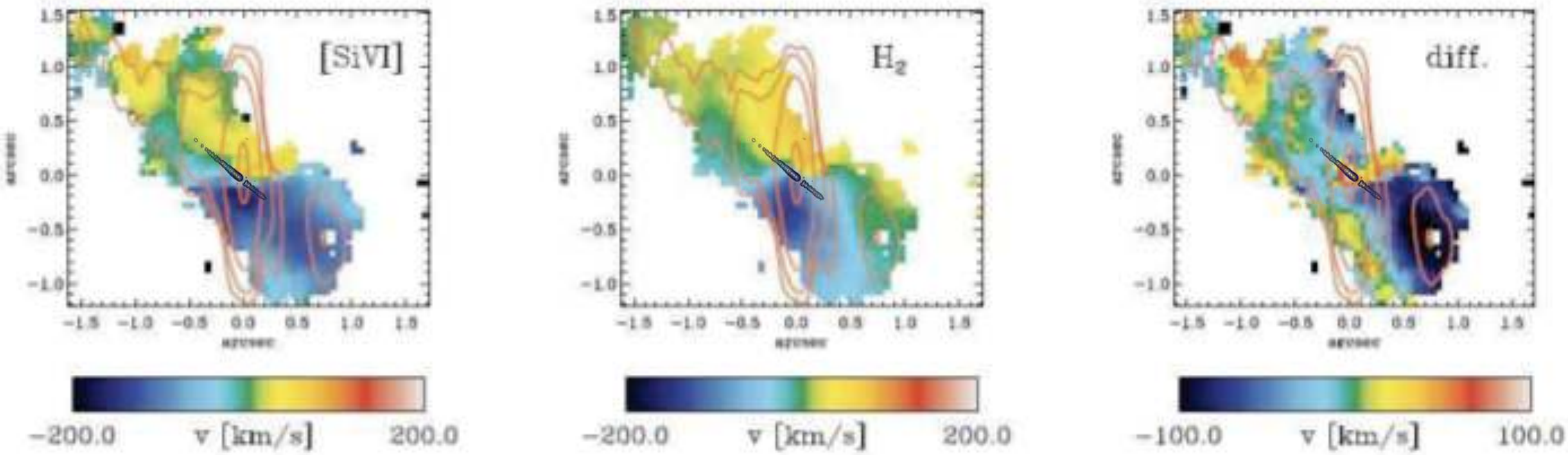
Consistent?

Skibo, Dermer, & Kinzer (1994) infer an angle to the line of sight of 61° ± 5° assuming that the 50 keV - 10 MeV emission detected by OSSE is beamed radiation that is Compton-scattered into our line of sight.

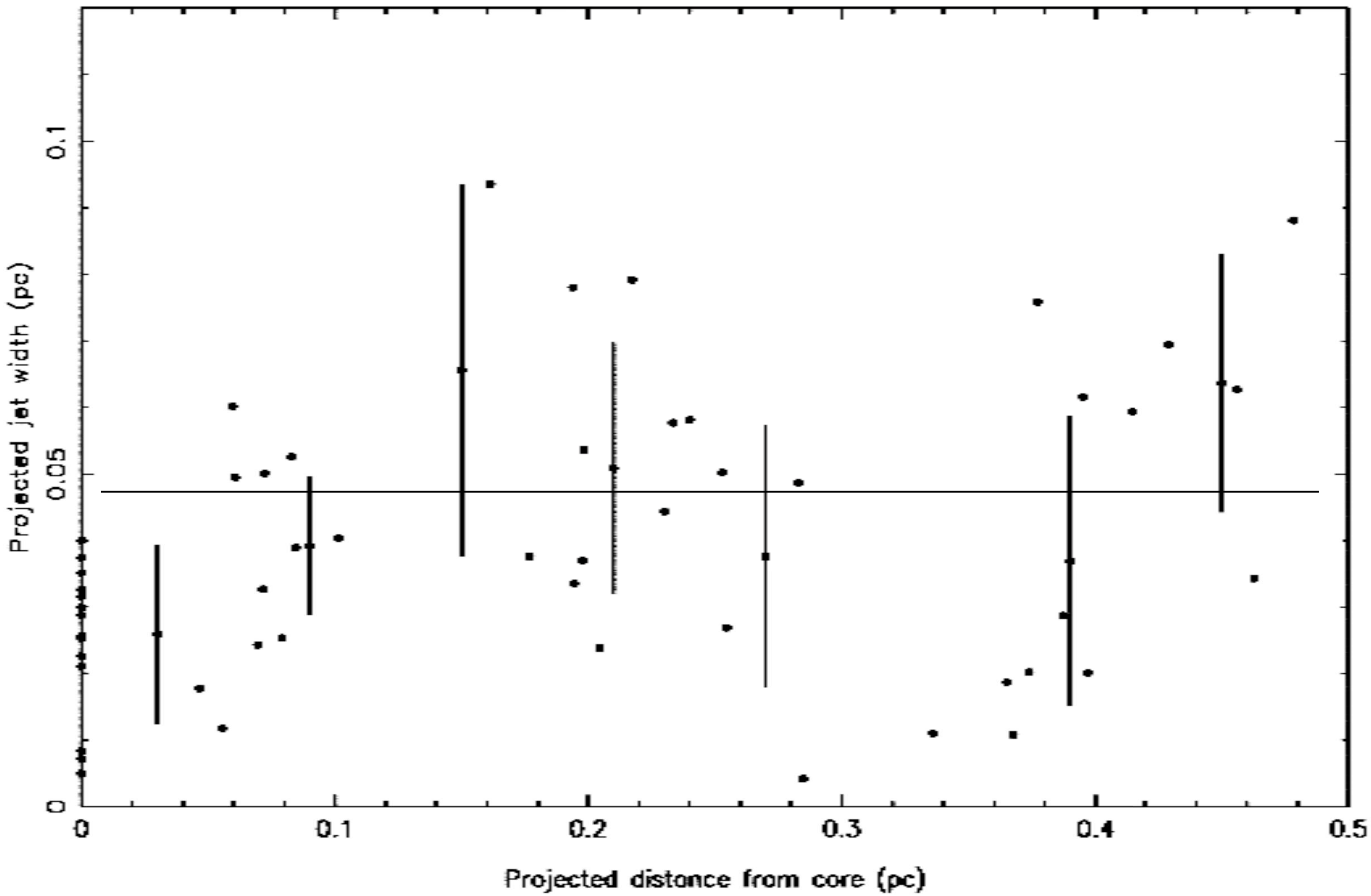
Hardcastle et al. (2003) estimate 20° < θ < 50°, based on VLA monitoring results: component motions and jet/counter-jet surface brightness ratio on scales of ~100 pc, assuming symmetry.



Neumayer et al. (2007) estimate an inclination of 45° ± 12° for a warped disk of material on sub-arcsecond scales.



Jet relative to the emission lines (Nuemayer et al. 2007) on the pc-scale



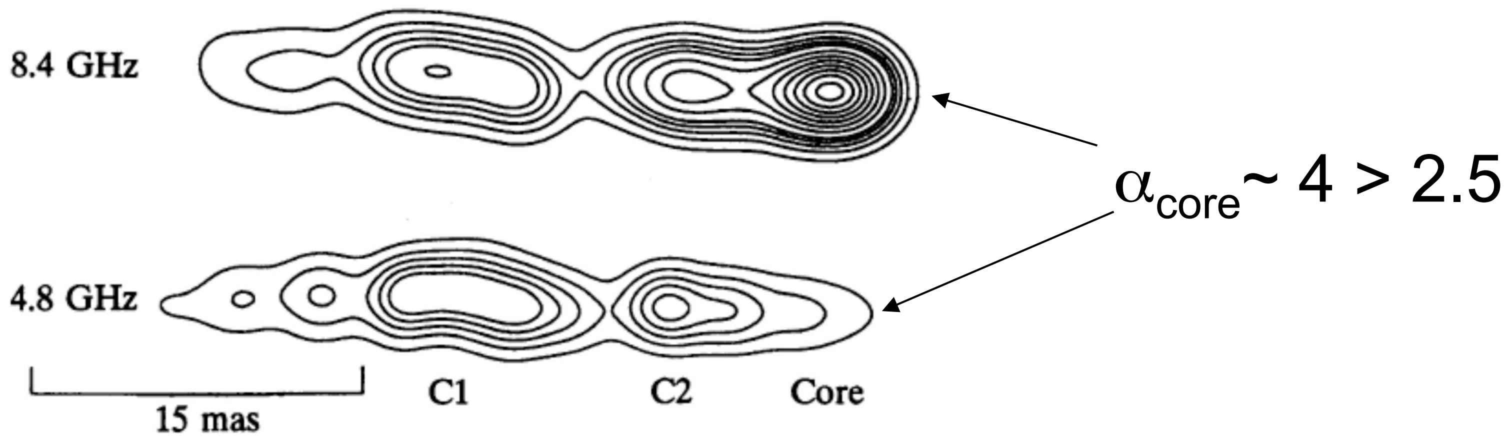
Measured jet width as a function of distance along the approaching jet, using all observations at all times.

Collimation of the jet on scales >1000 Schwarzschild radii.

Frequency variability of the parsec-scale structure

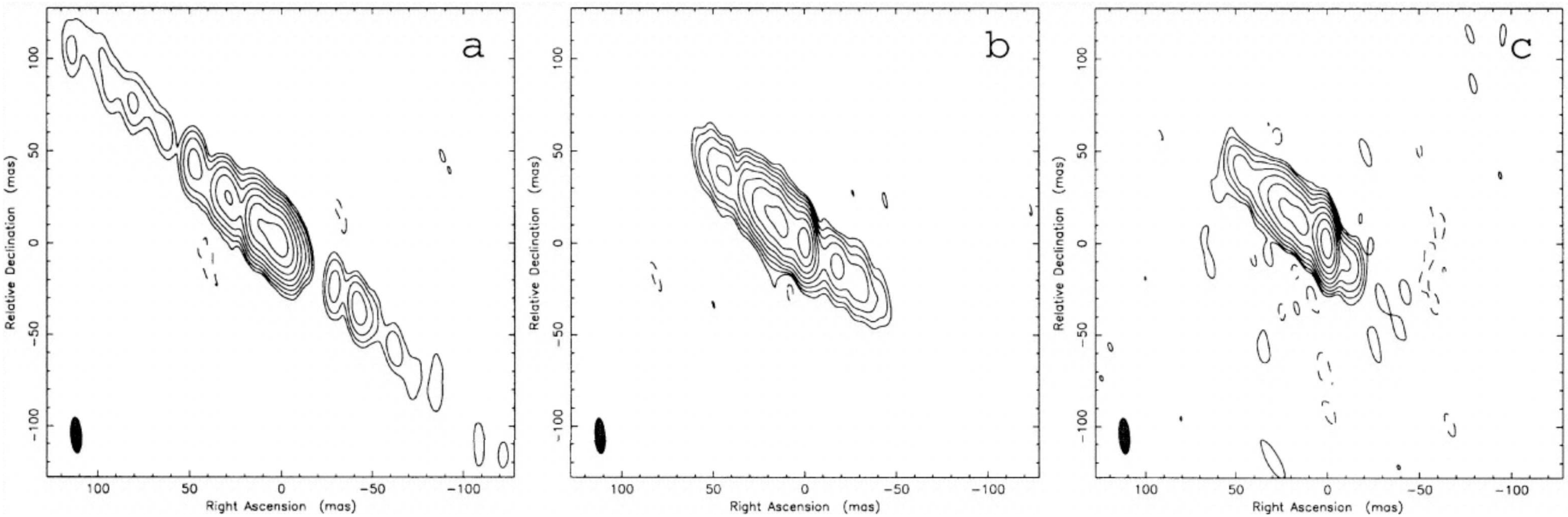
Multi-frequency observations with VLBI can probe:

- the spectral index distribution along the jet;
- Free-free and/or synchrotron self-absorption at the nucleus;

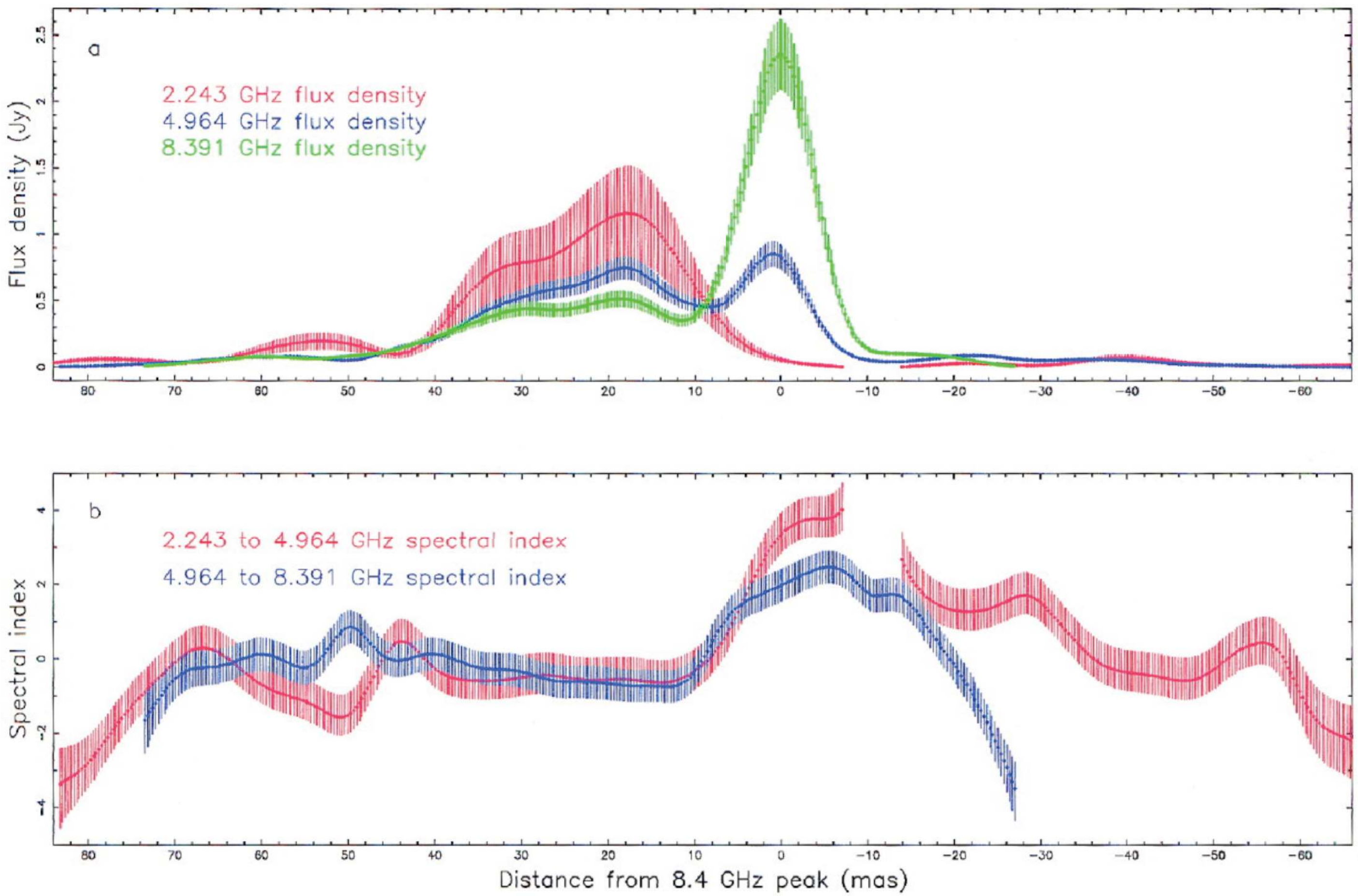


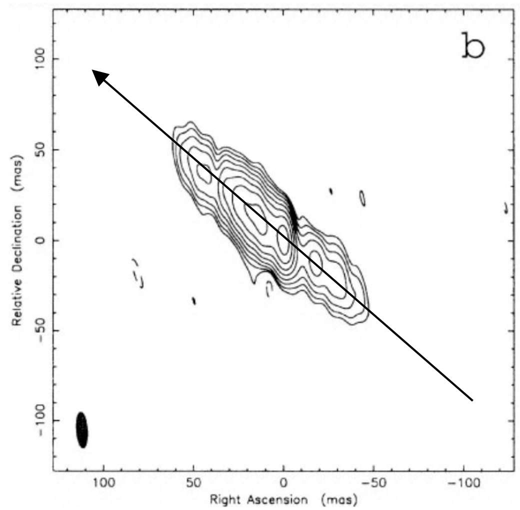
Multi-frequency, simultaneous VLBA observations at:

2.3 GHz 4.8 GHz 8.4 GHz



Tingay & Murphy 2001, ApJ, 546, 210


a
2.243 GHz flux density
4.964 GHz flux density
8.391 GHz flux density
Flux density (Jy)
b
2.243 to 4.964 GHz spectral index
4.964 to 8.391 GHz spectral index
Spectral index
Distance from 8.4 GHz peak (mas)


b
Relative Declination (mas)
Right Ascension (mas)

4.8 GHz

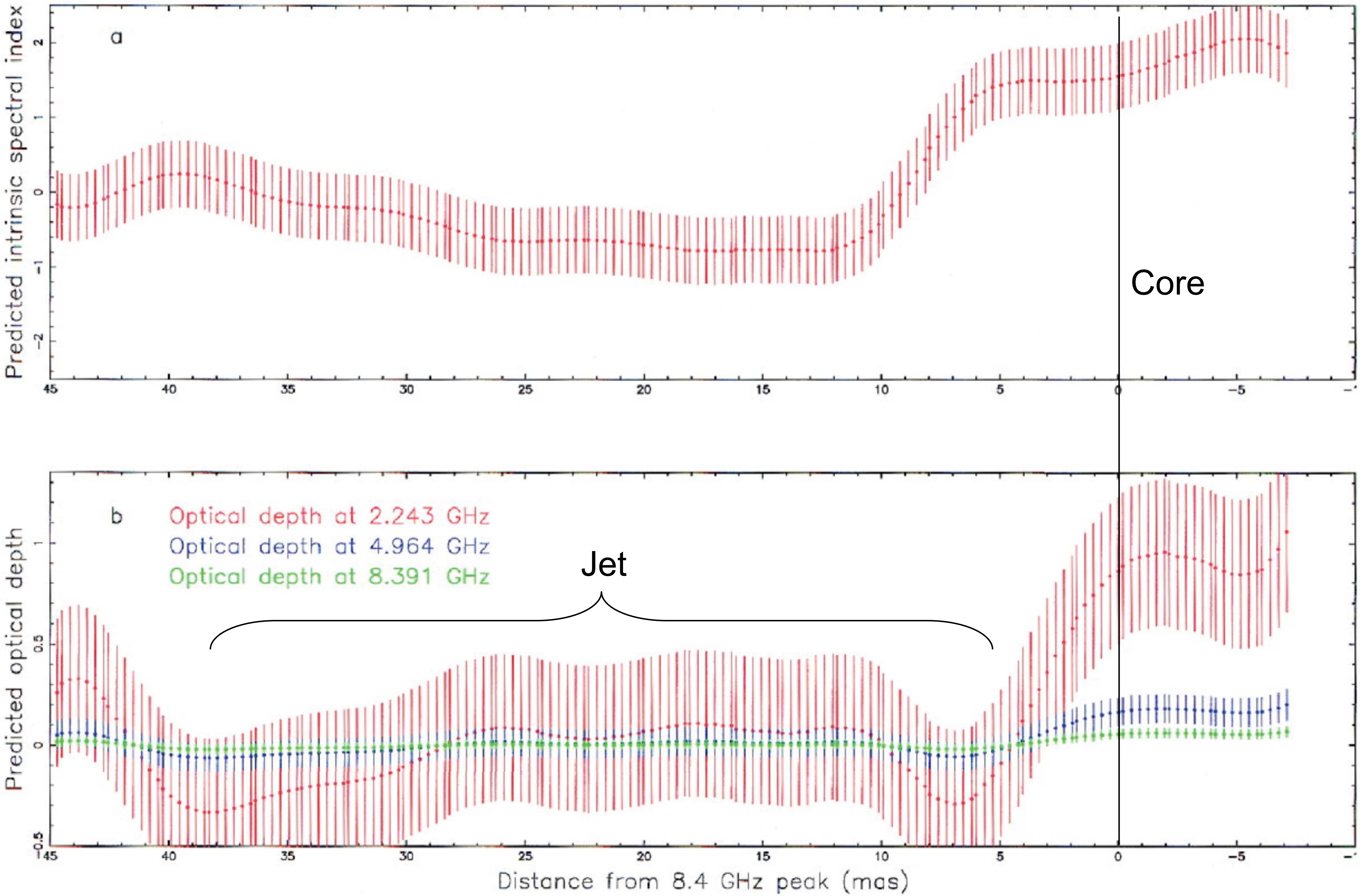
Assume a free-free absorbed power law at each point in the jet:

$$B_{\mathrm{abs}}(\nu_9, x) = \underbrace{A(x)\nu_9^{\alpha(x)}}_{\text{Synchrotron power law}} \underbrace{e^{-\tau_1(x)\nu_9^{-2.1}}}_{\text{Free-free absorption}}$$

Observations at three frequencies (ν_9= 2.3, 4.8 and 8.4) mean we can solve for:

$A(x)$, $\alpha(x)$ and $\tau(x)$,

in order to estimate the effects of free-free absorption along the jet.



Predicted intrinsic spectral index
a
Core
Predicted optical depth
b
Optical depth at 2.243 GHz
Optical depth at 4.964 GHz
Optical depth at 8.391 GHz
Jet
Distance from 8.4 GHz peak (mas)

The intrinsic spectral index toward the bright part of the jet is consistently approximately -0.7 ± 0.6

The intrinsic spectral index toward the nucleus is 2.0 ± 0.5, within a plausible range for synchrotron self-absorption.

The optical depth at 2.3 GHz is 0.9 ± 0.4 at 2.2 GHz toward the nucleus, and consistent with zero absorption toward the bright part of the jet.

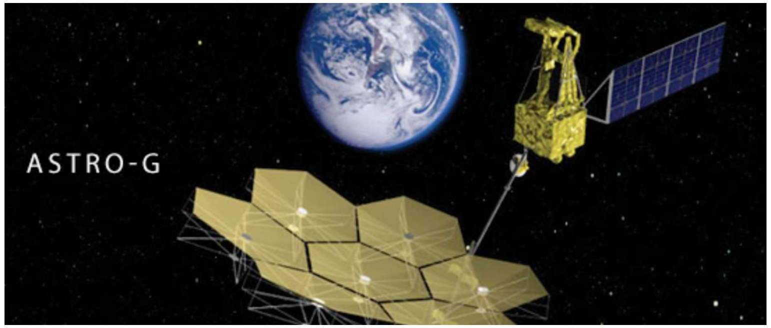
Core is < 1 mas in size [< 0.016 pc]. Adopt this as radius of absorber.

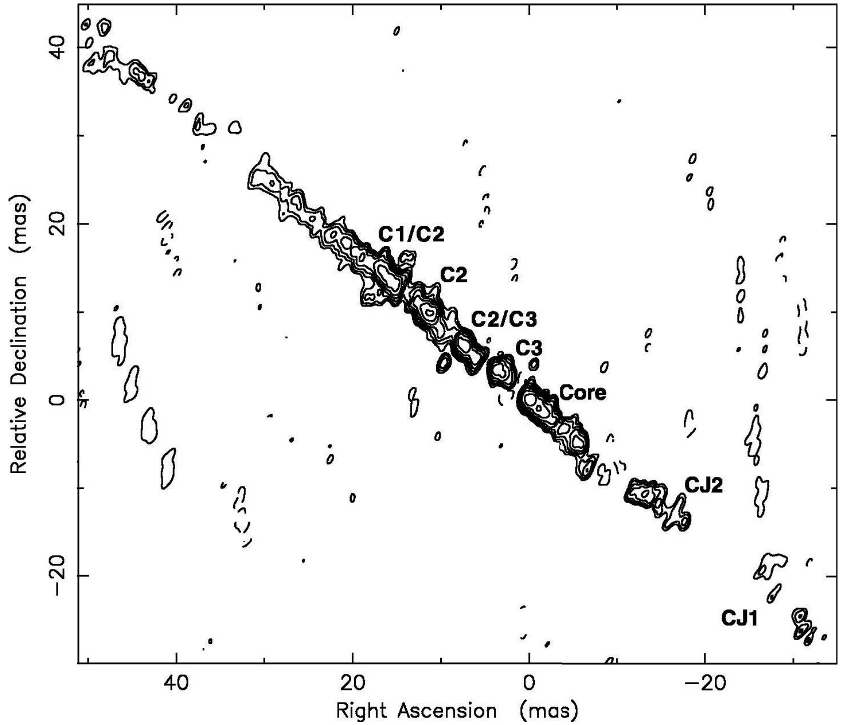
$T \sim 10{,}000$ K; $n_e \sim 10{,}000$ cm^{-3}

At the highest spatial resolution

Kellermann, Zensus, & Cohen (1997) measured a core size of 0.01 pc ~ 3 × 10^{16} cm with the VLBA at 43 GHz.

Horiuchi et al. (2006) VSOP space VLBI observation at 4.8 GHz and 0.01 pc resolution.





Centaurus A will again be a prime target for the ASTRO-G/VSOP-2 mission, at higher frequency, higher resolution and higher sensitivity.

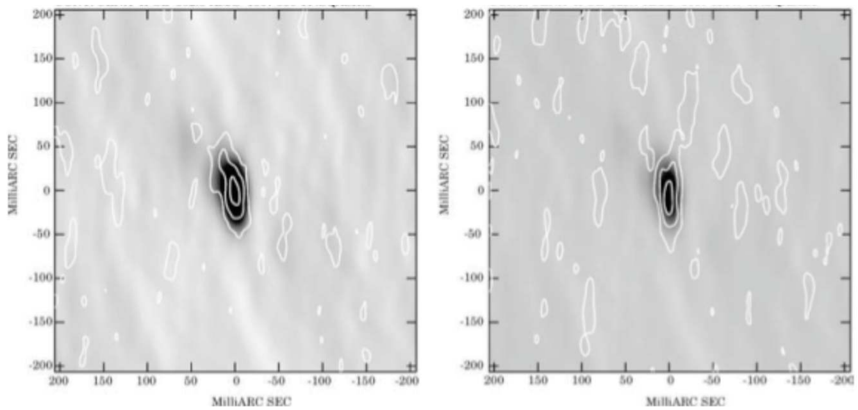
~25 - 50 Schwarzschild radii

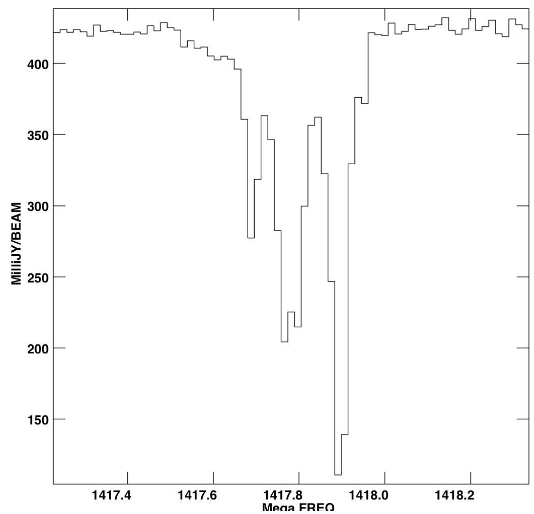
HI and OH lines

- VLBA observations of the 21 cm line by Peck & Taylor (1998) H I absorption against the pc-scale jet, but not against the core, due to free-free absorption.

- Langevelde, Philström & Beasley (2004) detected OH lines against the Centaurus A jet on the pc-scale with the VLBA, concluding that the size of the molecular clouds is less than approximately 1 pc.

- New HI study with the Australian LBA by Morganti, Argo, Struve & Tingay has detected HI against the pc-scale radio source, most likely against the jet. Consistent with results of Peck & Taylor (1998).

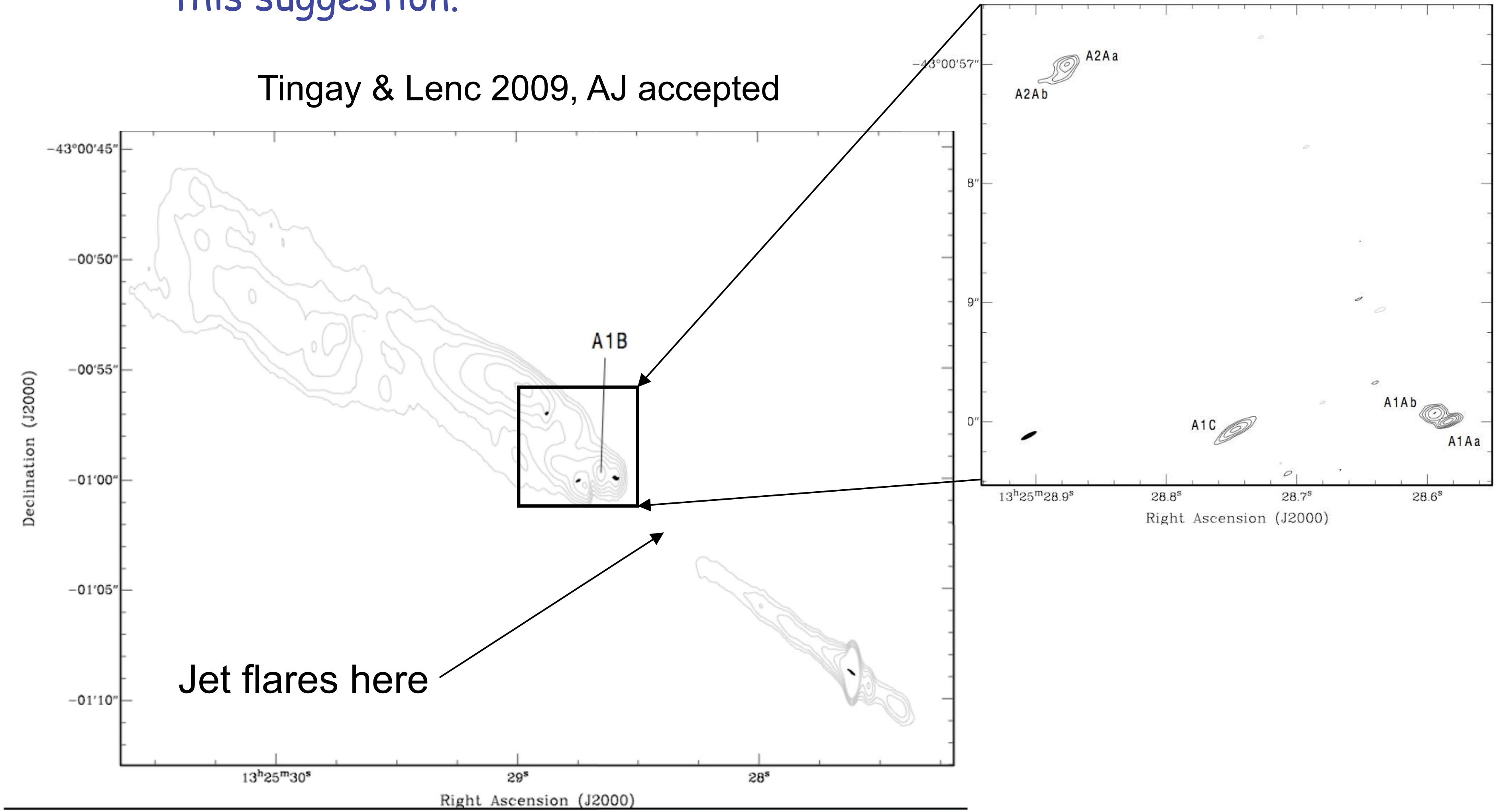




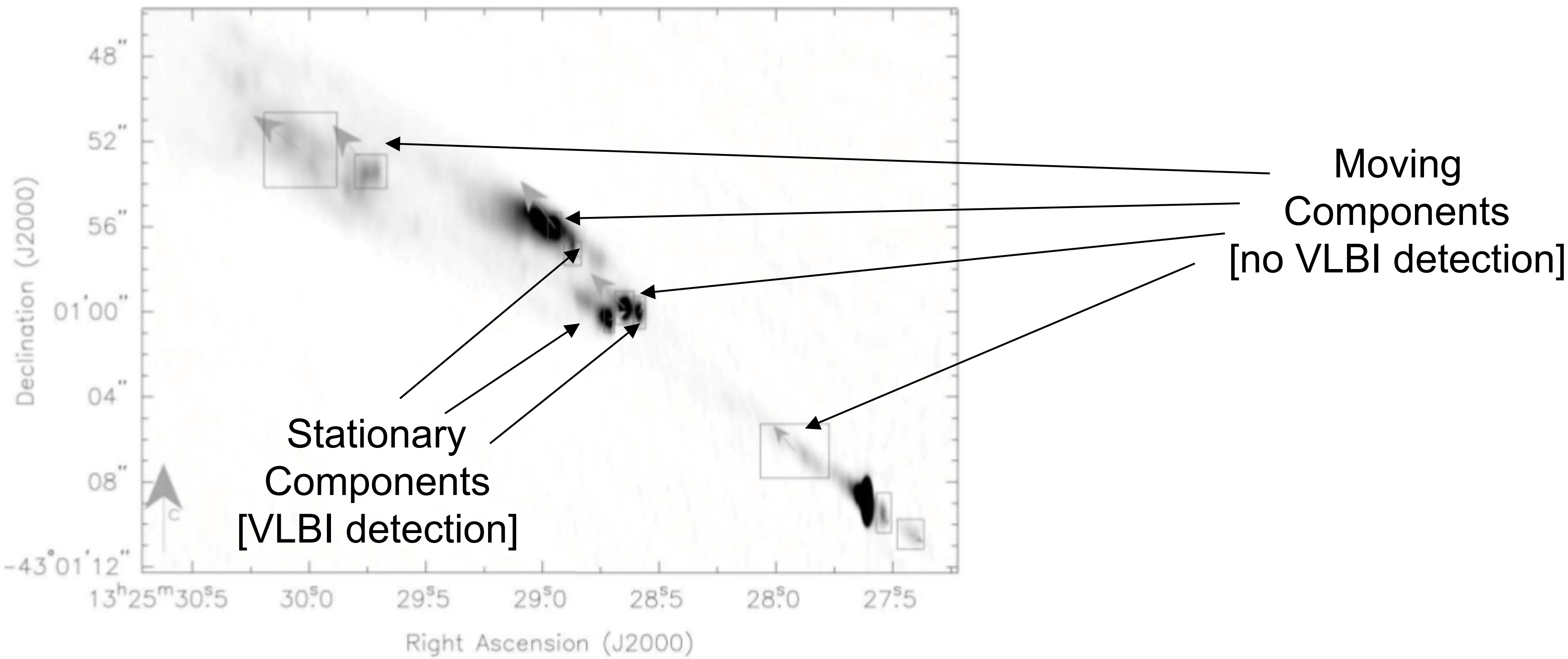
Parsec-scale structure in the kiloparsec-scale jet

Compact stationary shocks in the large scale jet? Hardcastle et al. (2003) propose interaction between jet and high mass loss stars or gas clouds as cause of stationary components. VLBI results support this suggestion.

Tingay & Lenc 2009, AJ accepted



Hardcastle et al. 2003, *ApJ* 593, 169



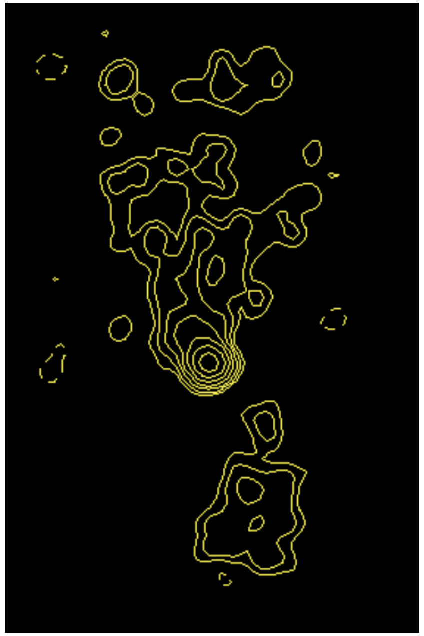
- Stationary components detected with VLBI;
- Components in motion not detected with VLBI;
- All VLBI components have strong X-ray emission;
- Component sizes of ~3 pc reduce estimated mass of obstacle by factor of ten, compared to estimates based on VLA component size estimates.

Conclusions

- Rapid variability of pc-scale components could imply jet fluid speeds of > 0.45c, consistent with jet to counter-jet surface brightness ratios;
- Slow apparent motions, ~ 0.1c, of pc-scale components could imply quasi-stationary shocks within the faster jet flow;
- Similar to observed in other well-studied FR-I radio galaxies e.g. M87;
- All broadly consistent with a jet angle to our line of sight of 50 - 80 degrees c.f. various other estimates of jet orientation. Agreement at ~50 degrees. Radio source size ~40% larger than projected size;
- Highly inverted spectrum nucleus revealed by multi-frequency VLBI images. Spectral index of ~4 explained by highly synchrotron self-absorbed nucleus + free-free absorption due to ionised material around nucleus;
- Pc-scale structure detected at the base of the kpc-scale jet, supporting suggestions of stationary shocks due to interactions with stars or gas clouds.

Rediscovering Centaurus A at ~100 MHz

Tingay, Wayth and the MWA team.



159 MHz; Stokes I; 5 min;
1.28 MHz bandwidth; 24 tiles;
20' resolution