VLBI2010:

The ASTRO–GEO CONNECTION

RICHARD PORCAS

Max-Planck-Institute for Radio Astronomy, Bonn

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The VLBI Community: Aspirations

GEO-Community: Geophysicists, Geodesists

VLBI2010
2–14 GHz
30 x 12 m–class antennas

ASTRO-Community: Astrophysicists, Astronomers

Square Kilometer Array (SKA)
0.03–20 GHz
8850 x 12 m–class antennas ?

Spacecraft tracking

32 GHz

VLBI2010 GOALS

1 mm position accuracy, 0.1 mm/year velocity accuracy over a 24h observing session

Continuous observations

Initial results within 24h

30 μas global source position accuracy ?

3 μas/year global proper motions ?

New Astrometric/Astrophysical Science enabled by VLBI2010

Mass-energy of cosmological gravitational wave background

(Limits from quasar proper-motion upper-limits)

Gwinn et al, 1997, ApJ 485, 87

Micro-arcsecond instability of the celestial reference frame

(Micro-lensing of visible Galactic stars)

Sazhin et al, 1998, MNRAS 300, 287

Anisotropic Hubble expansion of the Universe ?

(Redshift-dependence of proper-motions)

Titov, 2009, Proc. 19th EVGA

And together with GAIA

Optical quasar positions:

16 μas at 15 magnitude

70 μas at 18 magnitude

Alignment of radio and optical reference frames

Displacement of optical and radio emission regions

Active Galactic Nuclei (AGN)

Quasars, BL Lac Objects: “BLAZARS”

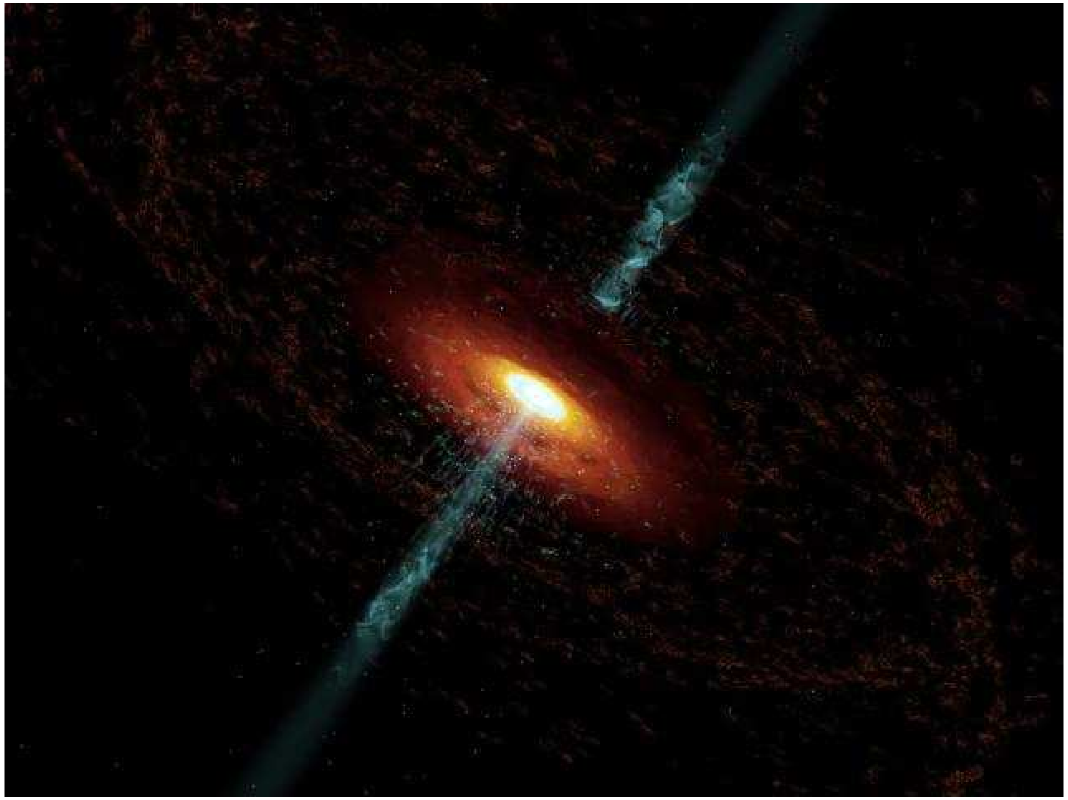
Radio emission from collimated, relativistic outflow (Γ 5–20) of plasma – “jets”

One-sided appearence due to relativistic Doppler boosting

Bright, compact feature (the “core”) at the end of jet provides obvious position reference point

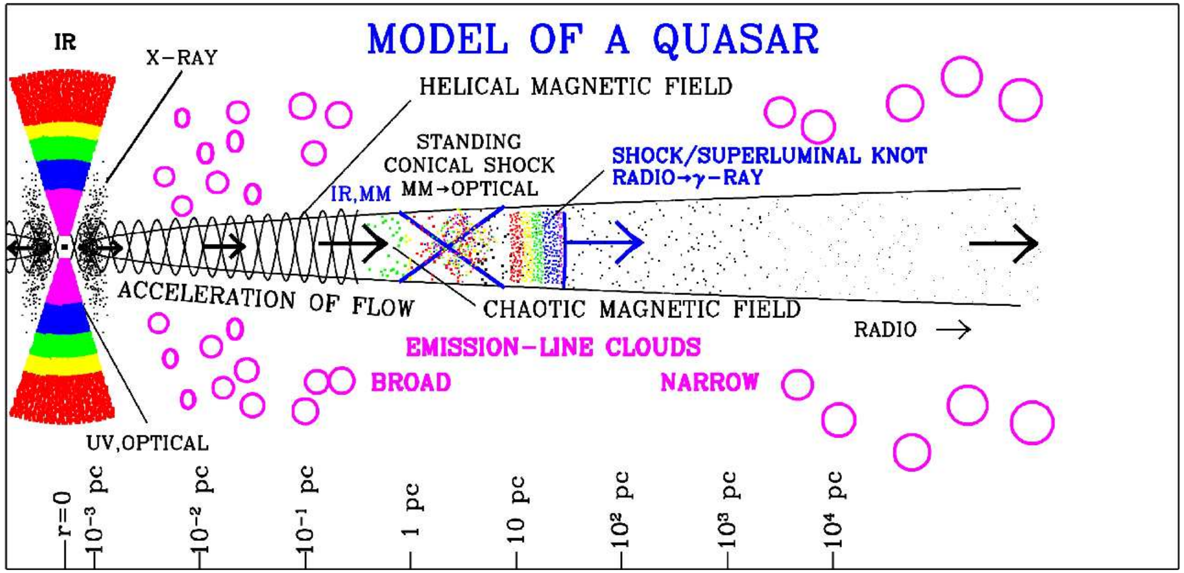
Optical emission from accretion disk or jet

Half a century of studies from radio to γ–rays



An AGN

courtesy COSMOVISION



An AGN

courtesy A.Marscher

VLBI imaging of (AGN)

Staple diet for astronomical VLBI imaging observations

MOJAVE 2 cm monitoring program for 135 sources

VLBA: 10 antennas, 25 sources per month

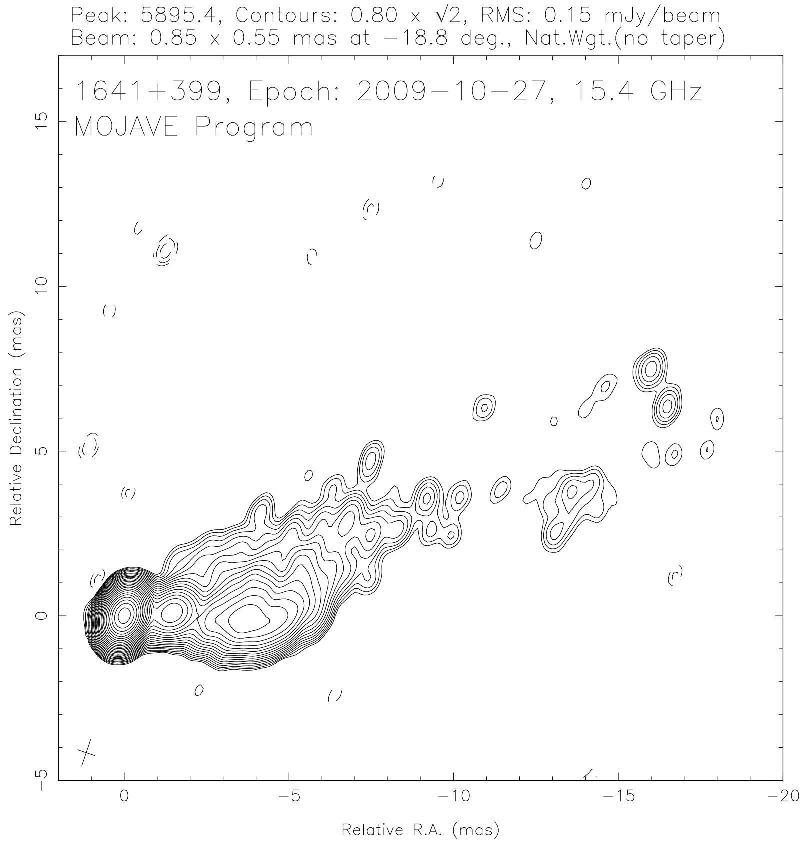
10 5-minute observations per source, 45 baselines

$\sim$ 450 visibility measurements

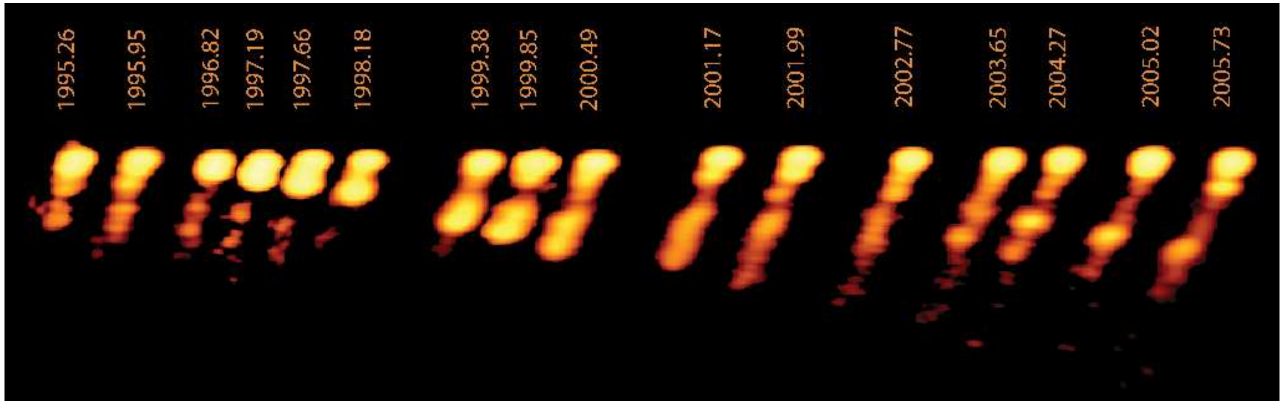
Use of interferometer relative phase:

Internal components separations with $\sim$30 μas accuracy

Internal component proper motions to $\sim$3 μas/year

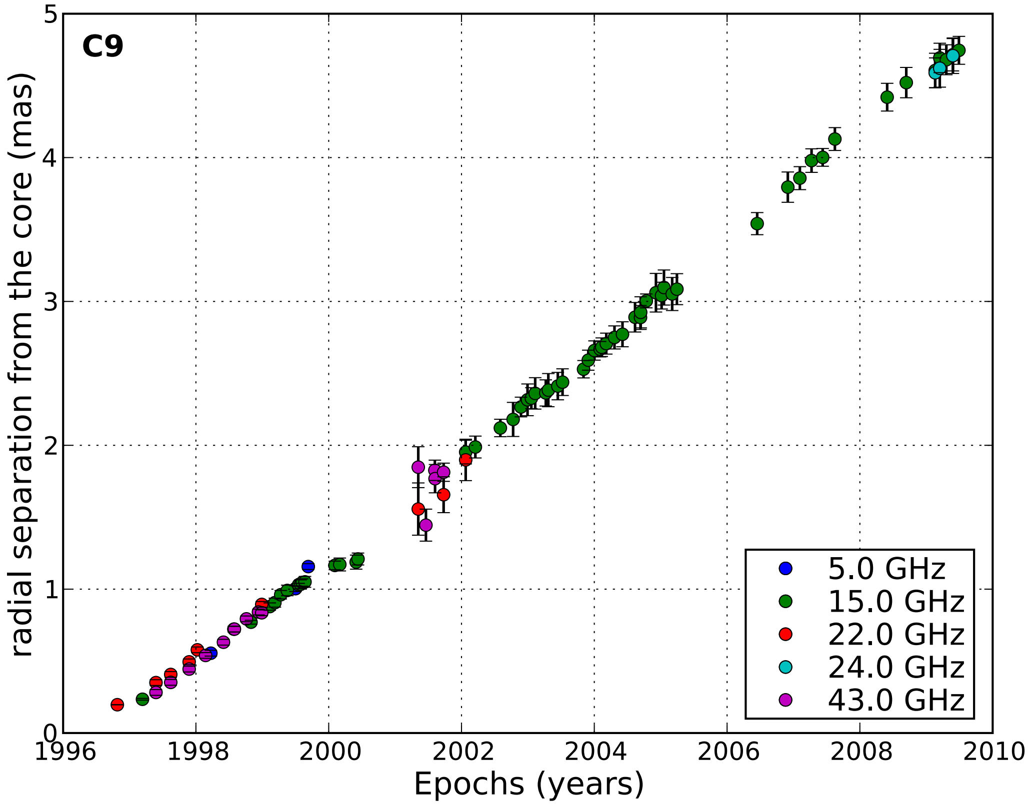


MOJAVE 2 cm image of 3C 345 from 17 October 2009



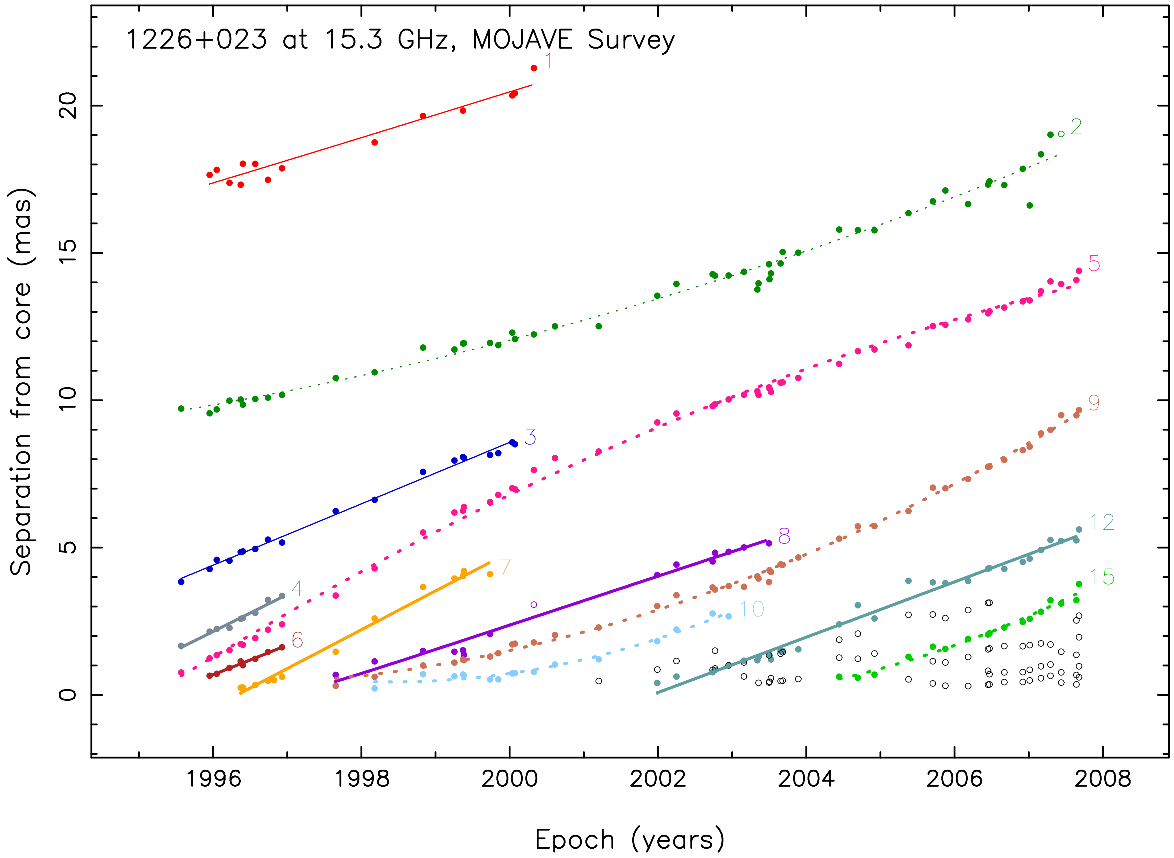
Seyfert Galaxy 3C 111 (redshift 0.0485) from VLBA 2 cm MOJAVE observations 1995–2005. Beam 0.5 x 1.0 mas. Extent (2005.73) $\sim$ 11 mas.

Kadler et al, 2008, ApJ 680, 867 (courtesy Christian Fromm)



Component 9 outward motion in 3C 345

courtesy Frank Schinzel



Component outward motions in 3C 273

Lister et al, 2009, AJ (in press); arXiv:0909.5100

Imaging sources from the IVS database

Long tradition of use for monitoring studies

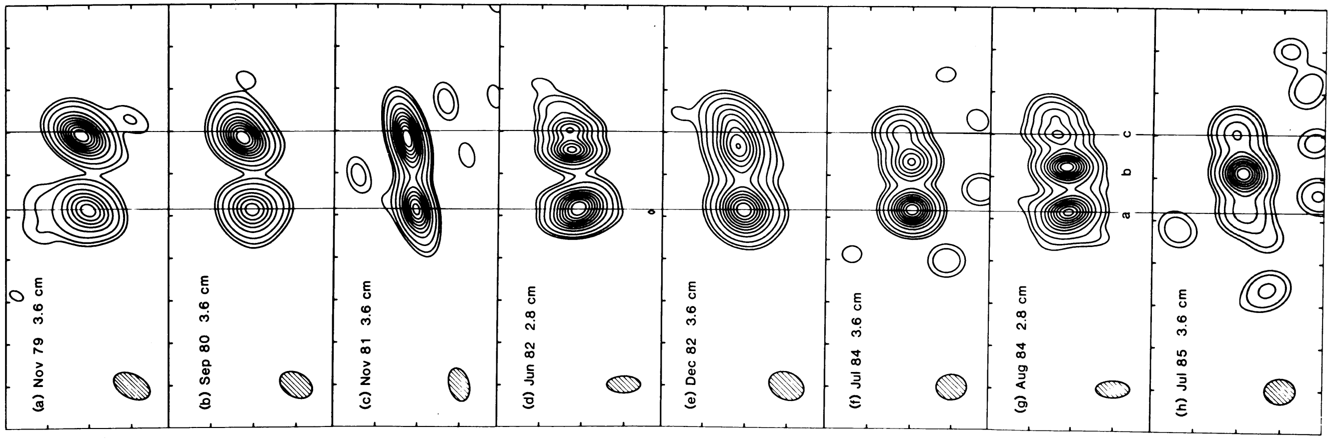
S and X-band: 230 sources

RD1 and RD4: 2 observations per week, 8 antennas

R1409: 60 sources, 1092 observations

But, use of sub-netting decreases the astronomical yield !

- Only 48 sources with any closure phase (≥ 3 antennas)
- Only 36 sources observed with 4 or more antennas
- Only 9 sources with 100 or more visibilities



X-band images of quasar 4C 39.25 (redshift 0.699), mostly NASA Crustal Dynamics Program, 1979–1985

Shaffer et al, 1987, ApJ, 314, L1

VLBI2010   METHOD ELEMENTS

Network of (30) fast-slewing antennas (12 m class)

Precision delays from 4 frequency bands 2–14 GHz

Dual polarization observing and correlating ?

Frequent source switching (15-30 s)

24 h continuous observing

24 h continuous correlating – realtime eVLBI ?

230 sources ??

Thermal and gravitational deflection of antennas

Electronic drifts

RF interference avoidance

Radio source structure

Imaging sources from the VLBI2010 database ?

Daily monitoring of (230 ?) sources in 4 frequency bands in dual polarization with 30 (?) antennas ?

Would be fantastic for astronomers........

Some potential uses:

Monitoring component outflows

Spectral evolution of jet components

Component flux-density variations on daily timescales

Short timescale positional variations of the "core"

Short timescale polarization variations ?

et cetera................

VLBI2010 ASTRONOMY TO BE CONSIDERED

SOURCE PROPERTIES

SOURCE STRENGTH, S

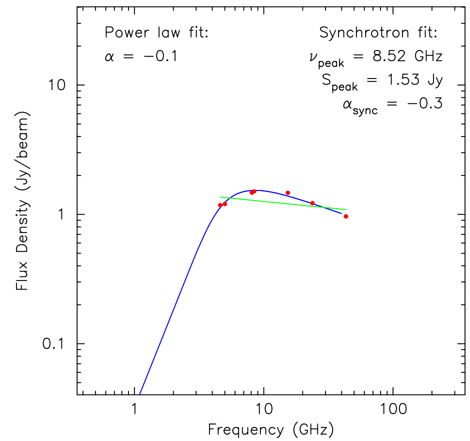
SOURCE SPECTRUM, S(ν)

SOURCE VARIABILITY WITH TIME

SOURCE STRUCTURE and “POSITION”

and any combination of these !

SOURCE STRENGTH AND SPECTRUM



VLBI2010 uses a wide frequency range (2–14 GHz; x7)

Sources are not only "flat" or "steep" spectrum

Source must be strong enough in all 4 IVS2010 bands.

Spectrum must be monitored to ensure this.

ALL SOURCES HAVE STRUCTURE !

All sources have finite size

Visibly so if comparable with beamsize

Invisible if less than the beamsize

Invisible but cannot be ignored for source position

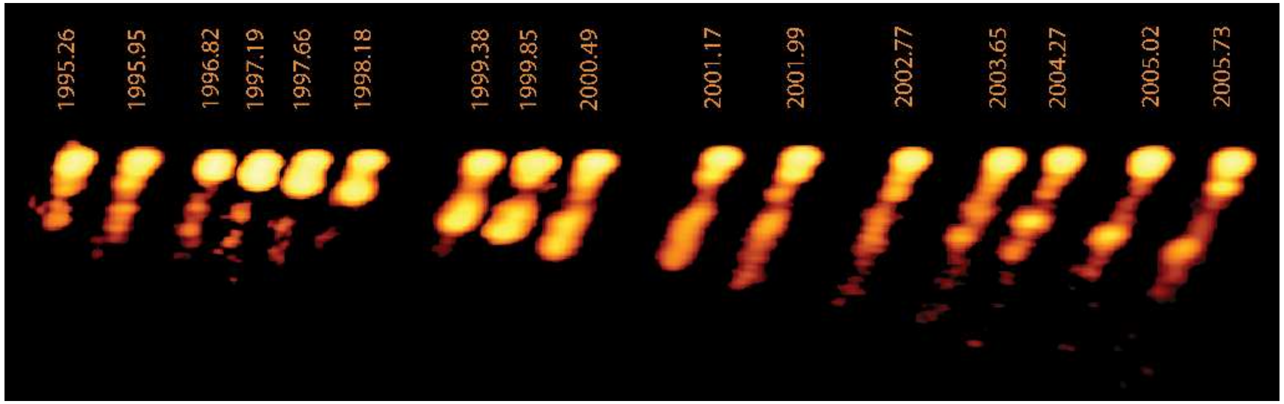
precision much less than the beamsize !

WHAT, AFTER ALL, IS IT THE POSITION OF ?

VLBI2010 leaves the regime of 250μas (1/3 beam)

and enters the regime of 1/30 beam (30 μas)

“Structure Index” (1,2,3,4) does not tell the full story



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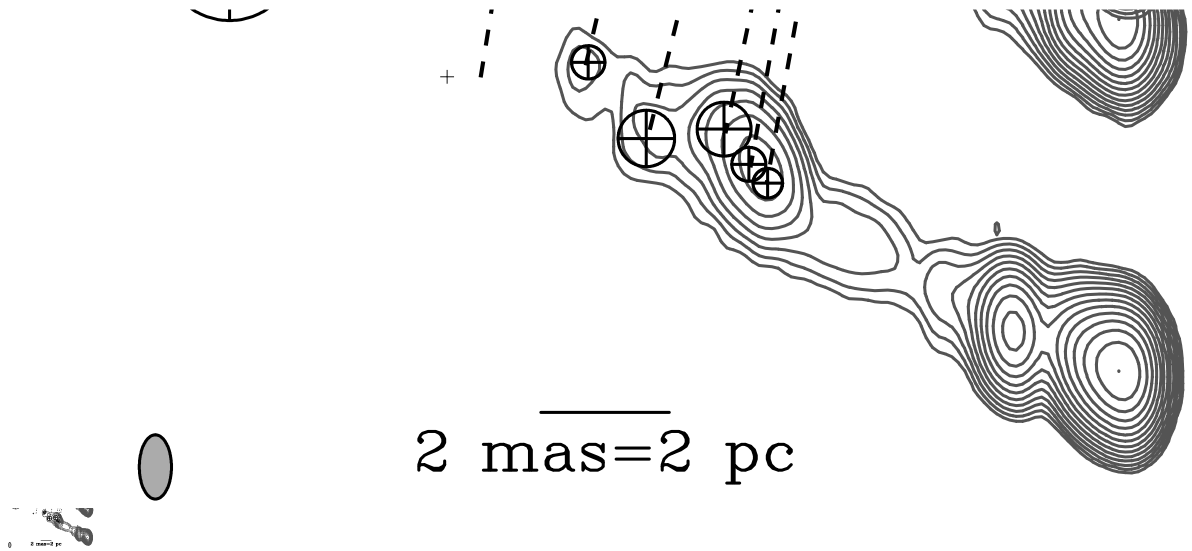
VARIABILITY OF INVISIBLE STRUCTURE



Source 3C 111 (redshift 0.048) taken to a redshift of 0.6 (bottom left). Extent of 11 mas becomes 0.9 mas.

Variable structure becomes
instability of centroid position of "core"

DEALING WITH INVISIBLE STRUCTURE

A THOUGHT

Note that source structures are roughly LINEAR

Instability of position likely in the "jet direction"

This direction roughly stable for each source

Source *a priori* position stable transverse to jet

Why not down-weight the data for baselines oriented close to the jet direction ?

Up-weight data transverse to the jet direction

Keep jet direction as part of the data base

Plan observations to avoid jet directions ?

Compare "Elevation-Dependent Weighting"
Malkin, 2008, IVS 5th GM, p178

DEALING WITH VISIBLE STRUCTURE

Structure Index: Fey & Charlot 1997

Classify structure (1,2,3,4) in all 4 frequency bands

Observe only those source with suitable classification

But structure varies with time...the index also ?

Must know structure “on the day”

Derive source structure and index from VLBI2010 observations themselves

Global Fringe-Fitting ? ... a religious debate...

Must plan observations to permit this

Source imaging part of the routine analysis

Keep updated data base for planning observations

Reject observations when structure cannot be derived

IMAGING SPARSE DATA

Is the data sufficent to determine structural delay contribution ?

Require large sub-arrays for enough closure phases

Structural delays from rapid change of ϕ with ν

Translates to rapid change of ϕ with (u, v)

Sensitive to e.g. relative flux of beating components

Imaging usually with gridded (u, v) data

Grid cell size determined by sampling theorem

But this only applies to full (u, v) coverage

...which we definitely don't have !

Can we compensate with finer-scale sampling ?

Imaging without (u, v) gridding to preserve
rapid ϕ gradients ? Better relative fluxes ?

.....Just another crazy thought !

FREQUENCY-DEPENDANT STRUCTURE

Visible structural changes from 2–14 GHz

Need structural correction in all 4 VLBI2010 bands

WHY ?

AT PRESENT: delays determined from X-band

S-band delays are "diluted" by factor $(8.4/2.3)^2$

S-band structure correction less important

NOT SO IN VLBI2010 !

Broad-band delay requires corrections in all bands

CORE SHIFTS

FREQUENCY-DEPENDENT POSITION OF INVISIBLE STRUCTURE

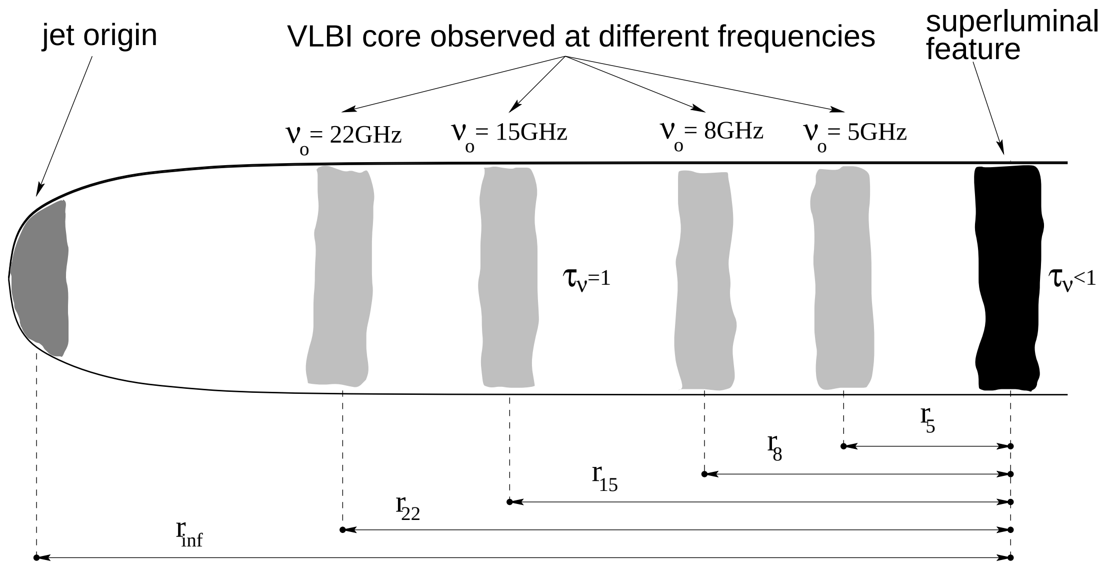
Even for apparently highly compact sources (SI = 1) both measurements and theory show that their positions will be frequency-dependent - the "core shift"

Typical shift of 440 μas between S and X-bands
Kovalev at al, 2008, A&A 483, 759

Clearly cannot be ignored in VLBI2010

Broad-band delay estimates must take account of the position change across the broad band

Frequency dependent position shift of VLBI core.



Lobanov 1998, A&A 330, 79

Frequency-dependent synchrotron opacity

MODELLING CORE SHIFTS

Shift from jet base as a power-law of λ

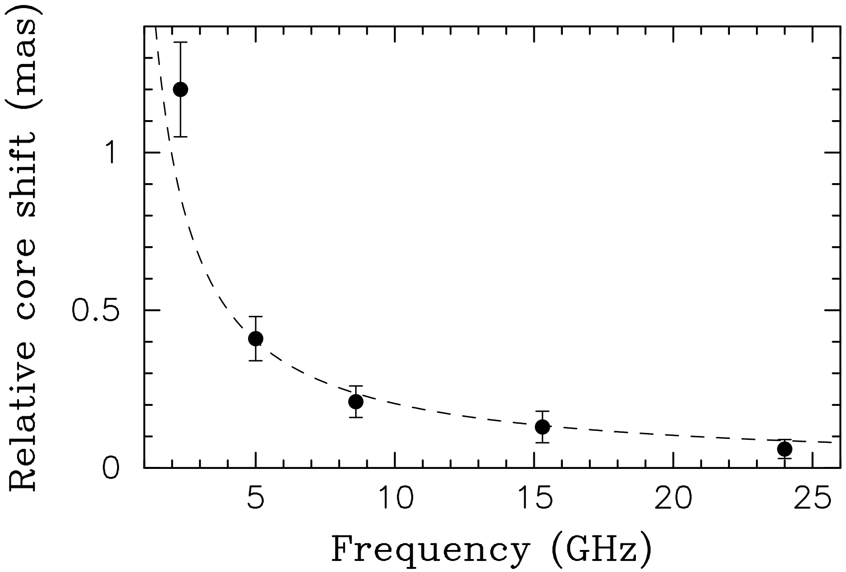
$$\Delta\mathbf{x}(\lambda) = k\lambda^{\beta}$$

$$\beta = \mathbf{1}/k_r$$

k_r **determined by physical conditions in jet**

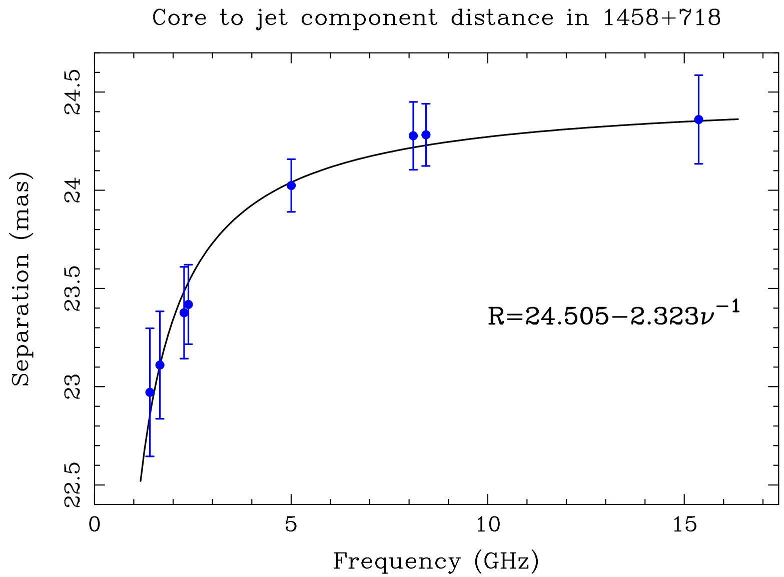
For equipartition of energy in particles and magnetic field

$k_r = 1$ **and** $\beta = 1$



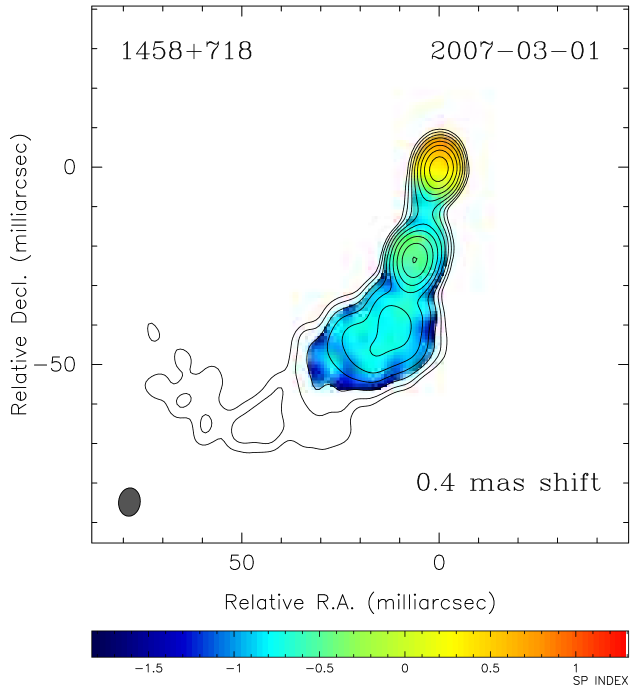
Frequency dependence of the core position of 0850+581 measured relative to its position at 43 GHz. The curve represents the best fit for the function $r_c \propto \nu^{-1/k_r}$, where $k_r = 1.1 \pm 0.1$.

Kovalev et al, 2008, MmSAI, 79, 1153



Frequency dependence of the distance between the position of the core of 1458+718 (3C 309.1) and the centroid position of a reference feature in the jet. The curve fitted to the data is for the pure synchrotron self-absorption case ($k_{\rm r} = 1$).

Kovalev et al 2008, Proc. 9th EVN Symposium, POS, 7



Spectral index α ($S \propto \nu^{\alpha}$) image between 1.4 and 2.4 GHz, 0.4 mas shift applied. Spectral index is shown by color while contours represent the 2.4 GHz CLEAN image.

Kovalev et al 2008, Proc. 9th EVN Symposium, POS, 7

CONSEQUENCES FOR GLOBAL ASTROMETRY

(Porcas 2009, A&A 505, L1)

“Core” has a frequency-dependent reference position

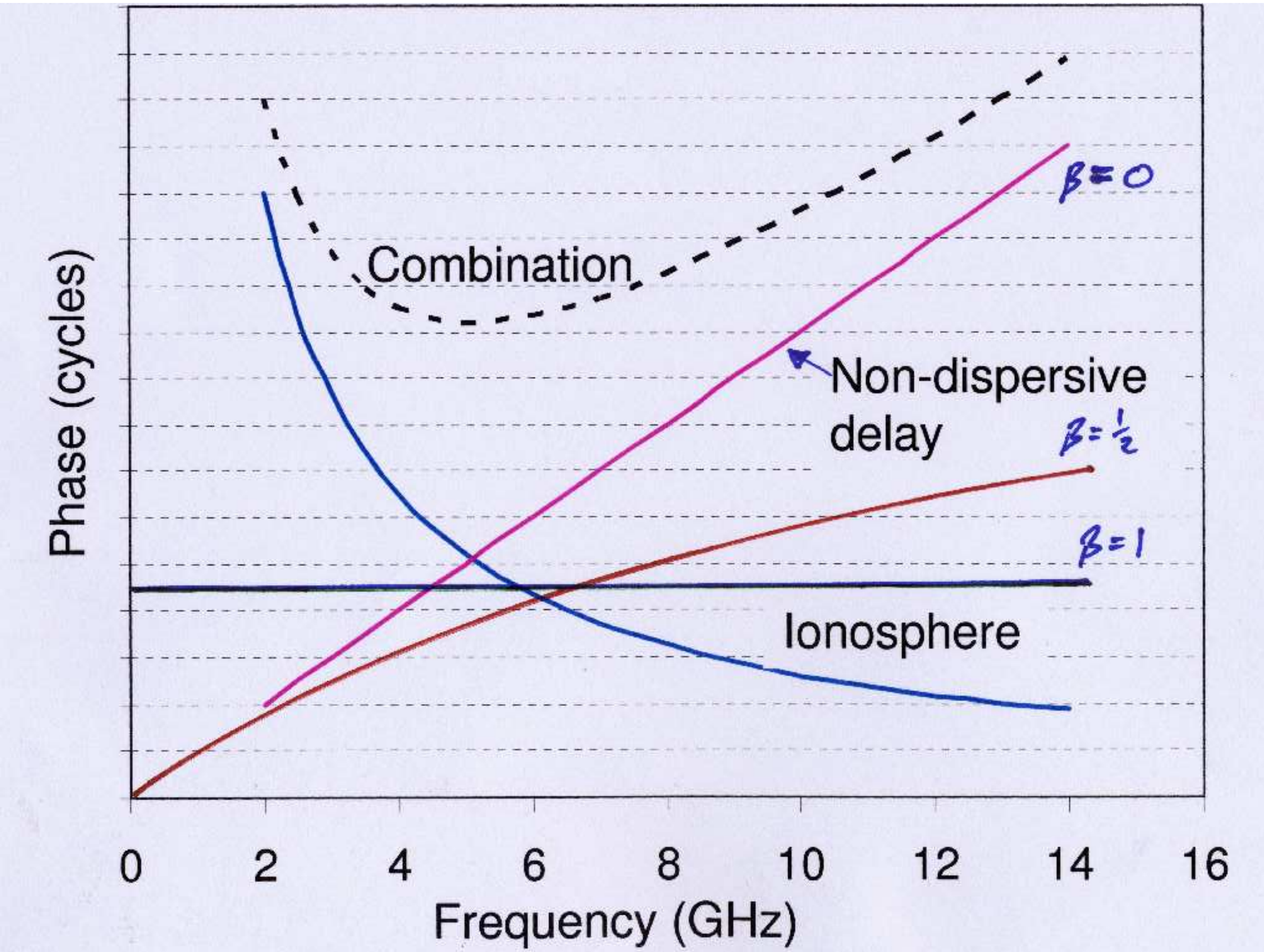
Chromatic core position introduces an additional phase across the (wide) frequency band, equivalent to a “dispersive” delay

Group delays measure a “reduced” core-shift of
$(1-\beta)\Delta\mathbf{x}(\lambda)$ **from the jet base**

For the case $\beta = 1$**:**

Group delays measure NO core shift from the jet base

The core shift gives a CONSTANT phase across the bands



Phase (cycles)
Frequency (GHz)
0
2
4
6
8
10
12
14
16
Combination
Non-dispersive
delay
Ionosphere
β=0
β=½
β=1

REFERENCE POINTS

Unfortunately, stable black holes are BLACK !

"Core" positions are frequency-dependent

But group-delay positions of cores don't measure the core position at the observing frequency

However, if β is typically close to 1, they DO measure the jet base at all frequencies !

Note that "X-band postions" of the ICRF sources and the VLBA Calibrator Survey (VCS) do not in general refer to the X-band core !

They are offset by (typically) $\sim 170\mu$as

They may be more stable than the core positions.