Jet–BLR connection in radio-loud galaxy 3C 390.3

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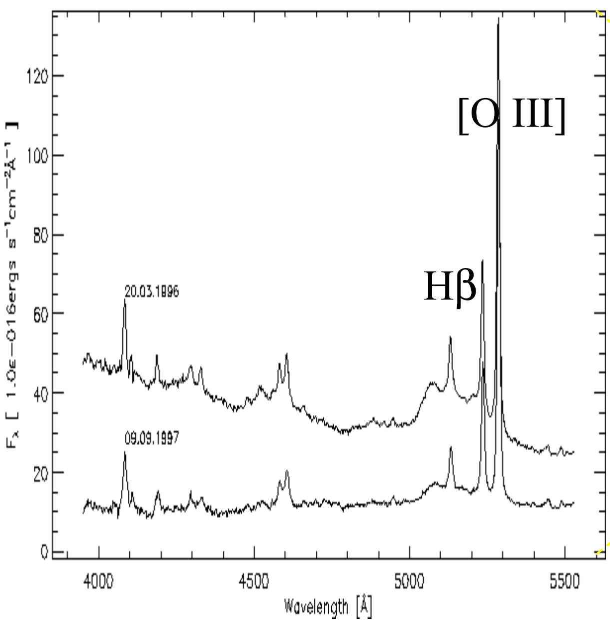
Outline

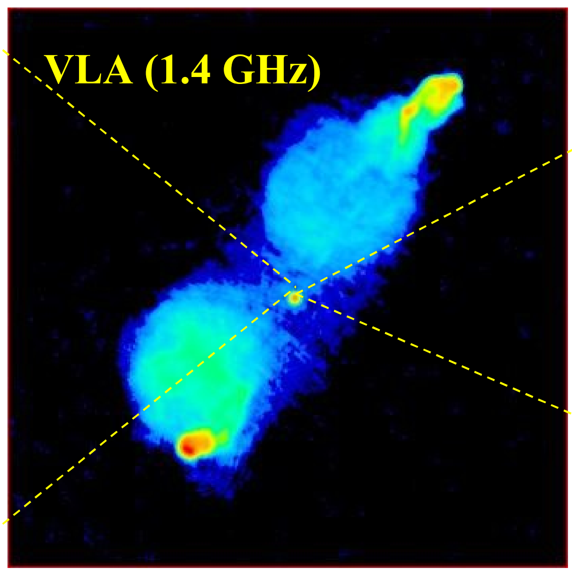
- Introduction to 3C 390.3
- Radio – optical continuum variability on sub-pc scales.
- Identification of radio components from X-ray variability
- A model for the central sub-parsec-scale region.

3C 390.3: broad-line radio galaxy (z = 0.056)



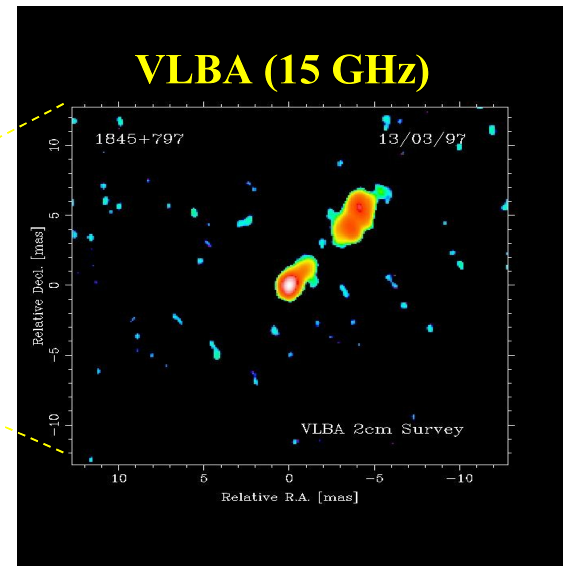
Broad double-peak Hβ emission line

Shapovalova et al. (2001)



Lobe-dominated on kpc-scales

Leahy & Perly (1995)



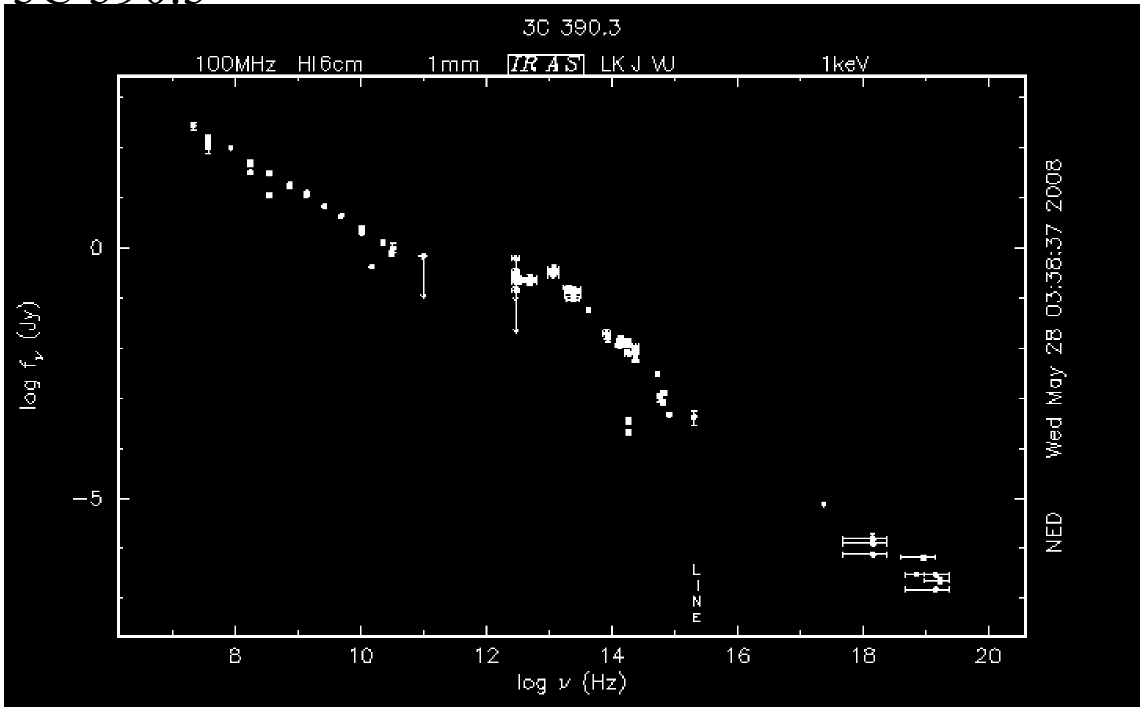
Pc-scale superluminal jet

Kellermann et al. (1998)

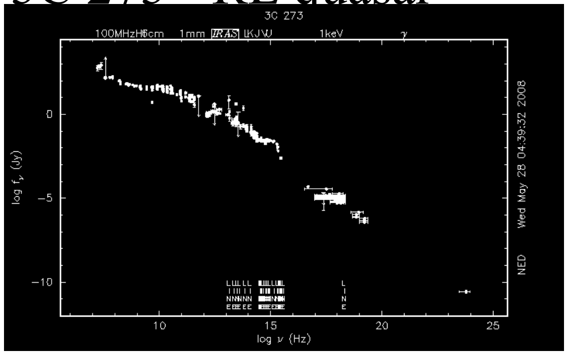
M_{BH} = 3x10^8 M_{sun} – from the reverberation mapping technique

3C 390.3: spectral energy distributiom

3C 390.3



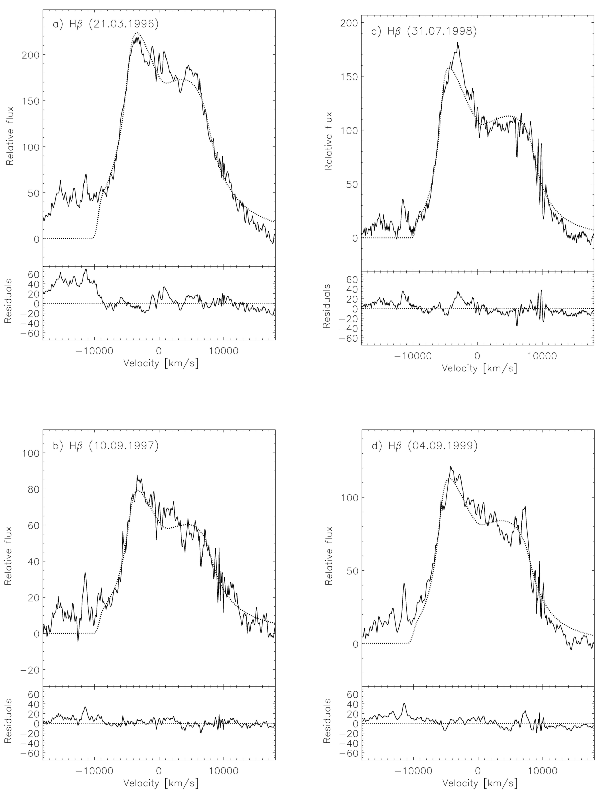
3C 273 - RL quasar



Multiwavelength data over 10 yr
optical component is likely to be opt. thin synchrotron radiation from the core of the jet (Soldi et al. 2008).

- No UV bump (the central disk is obscured)
- Non-thermal emission: radio, optical to X-ray (Wamsteker et al. 1997)

3C 390.3: Broad Line Region



Shapovalova et al. (2001)

BEL of 3C 390.3

Shape: Double-Peak, central component

Evolution:

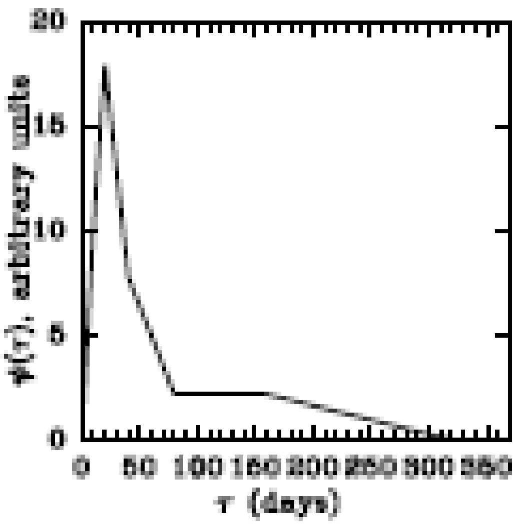
- amplitude of red and blue peaks
- distance between the peaks on long time-scales
- trailing components

Models of BLR

- Disk/disk-like models (Chen et al. 1989; Chen & Halpern 1989)
- Bipolar outflow model (Zheng et al. 1990, 1991)
- Spherical system of clouds illuminated anisotropically from the center (Goad & Wanders 1996)
- Two component BLR (Nazarova et al. 2004; Snedenn & Gaskel 2008)
- Disk and spherical BLR (Popovic et al. 2004)

Sophisticated disk BLR can not fit (Sergeev et al. 2002)

3C 390.3: Transfer function for time lags of Hb emission

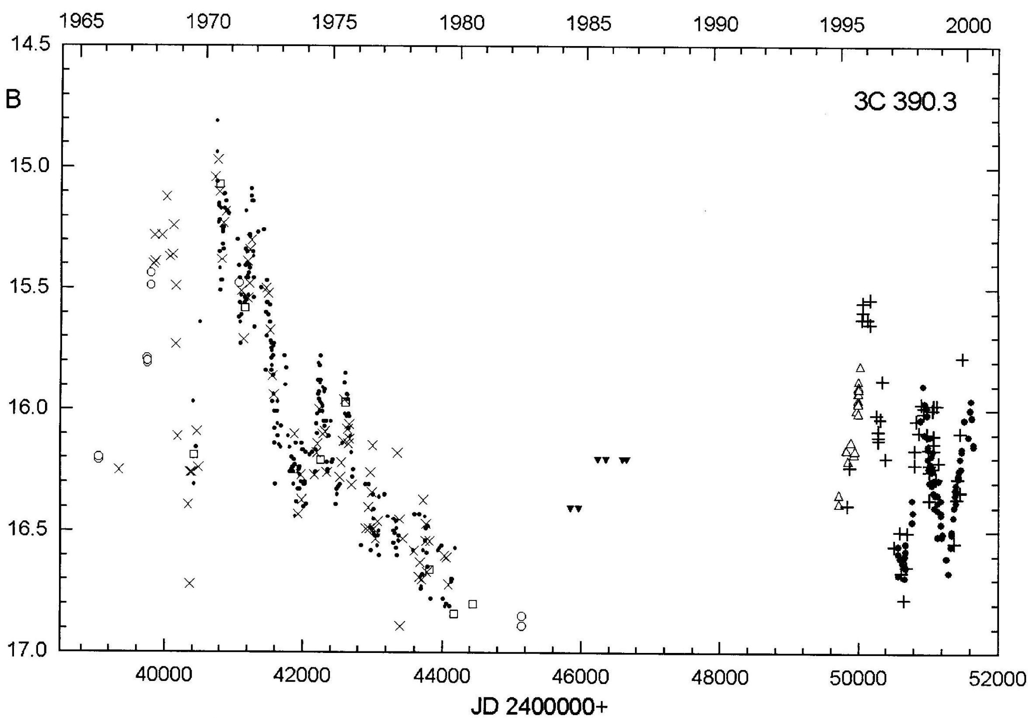


Time lag between opt. continuum and Hb line variations: 20 to 300 days

Centroid at ~ 80 days (Sergeev et al. 2002)
~100 days (Shapovalova et al. 2001)
~ 20 days (Dietrich et al. 1998)

Different patterns of the continuum variability, or multiple regions of BELs

3C 390.3: Historical light curve



Optical variability:

- Very long-term (> 3 yr)
- Long-term (flares) (~ 1-3 yr)
- Short-term (< 1 yr)

Radio variability at 15-37 GHz:

- Long-term flares ~2.5 yr

Possible periodicities:

- 8.3 yr, 5.4 yr, 3.5 yr, and 2.13 yr

(Tao et al. 2007).

Relativistic jet on pc-scales

Continuum from the jet is dominant at all energies

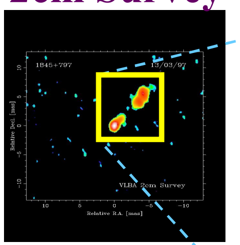
Accretion disk is partially obscured

Complex BLR with multiple different physical and geometrical emission regions

The bulk of optical continuum emission may be attributed to the jet in 3C 390.3

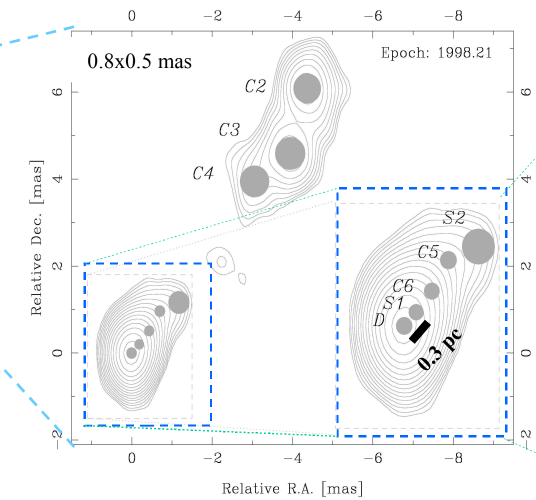
3C 390.3: sub-pc structure and kinematics of the jet

2cm Survey

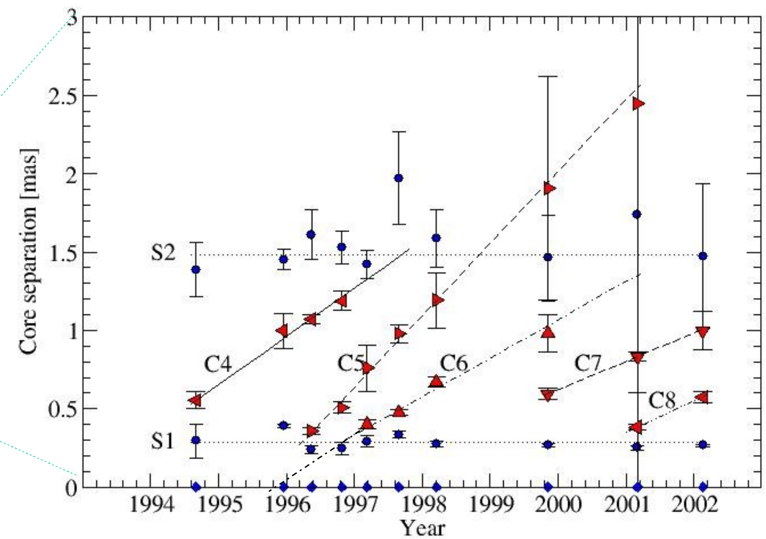


The VLBA radio map at 15 GHz

Model fitting of a **single epoch** (**1 mas = 1.09 pc**)



Separation of the jet components relative to the stationary feature **D** for **10 epochs** (1995-2001) of VLBI imaging



Jet components:

3 stationary radio features (**D**, **S1** and **S2**)

5 moving jet components (**C4-C8**, β_{app}= 0.8 to 1.5)

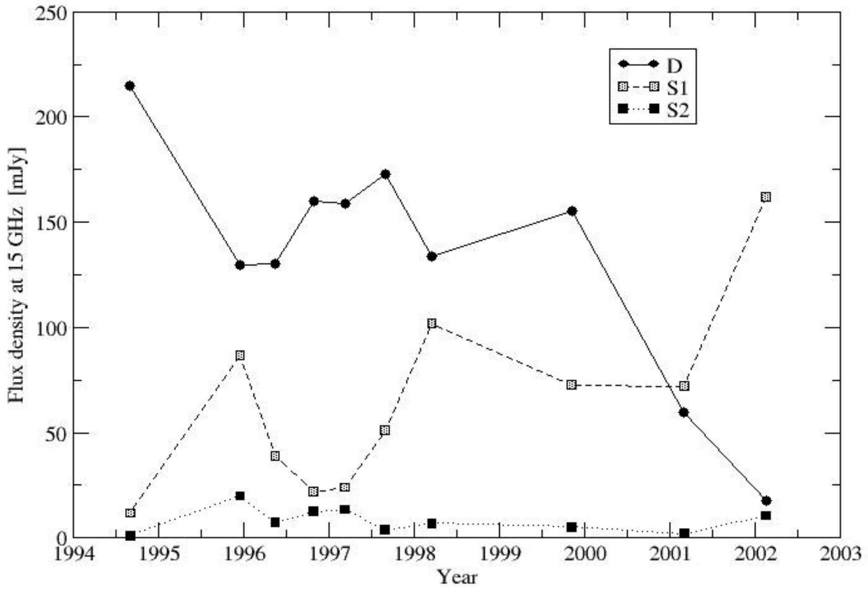
The epochs:

t_D of ejection of moving components at **D**

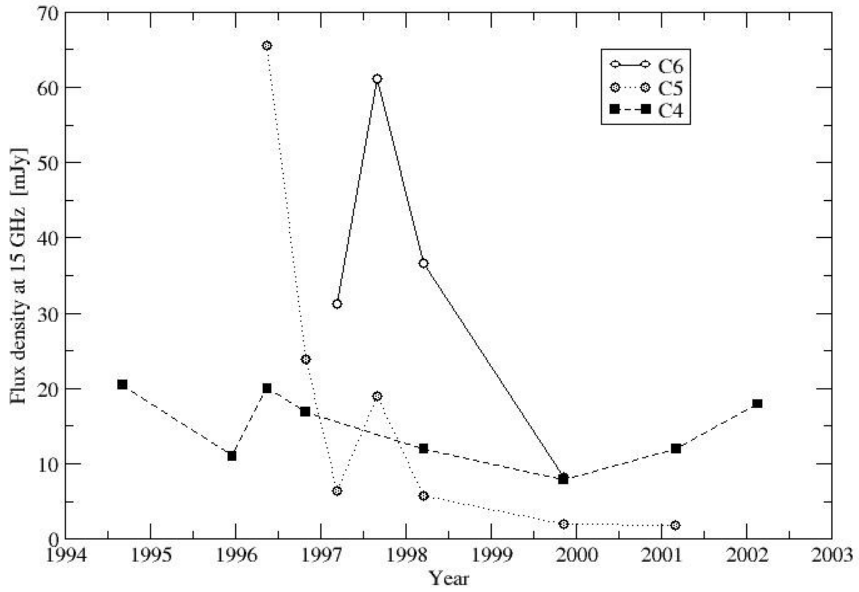
t_{S1} at which the comp. passes **S1** comp

Flux density variations of jet components at 15 GHz

Stationary components



Moving components

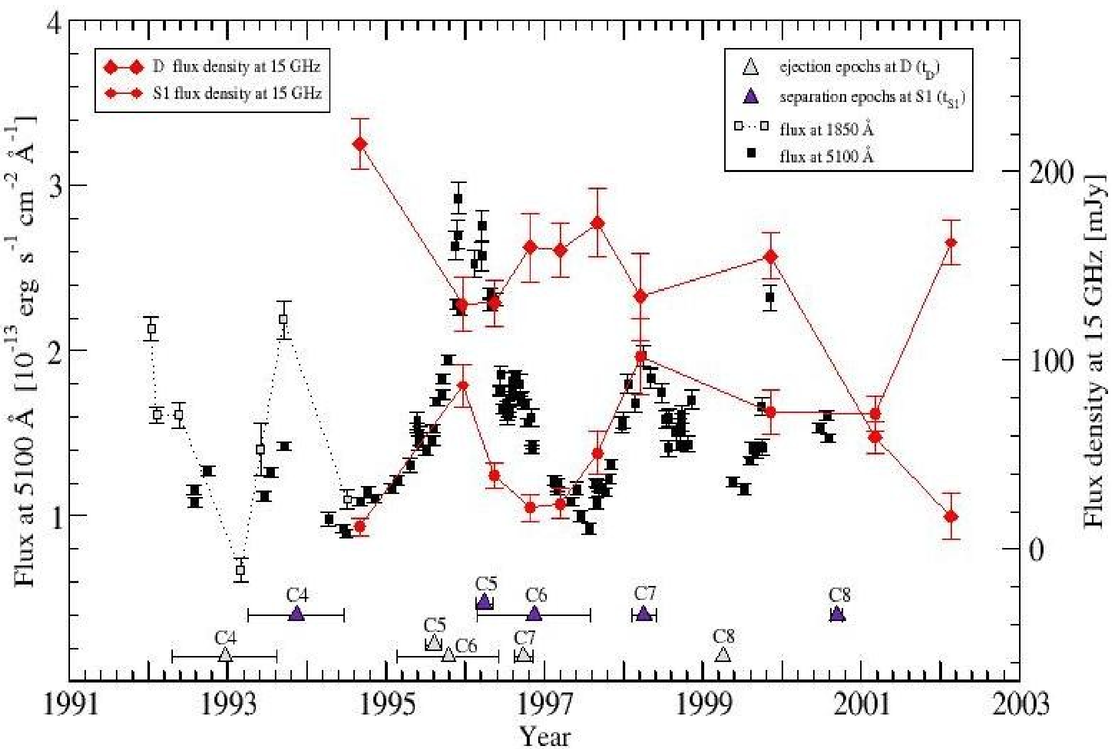


Power of VLBI monitoring:

variability of jet components
on sub-pc scales

Radio-optical variability (1994-2001)

Variations of **optical continuum (F_{opt}), radio components D** and **S1 (F_D and F_{S1})** superimposed with t_D and t_{S1}.



- Poor radio sampling (10)
- Variability time-scale: ~60 d
- F_{opt}-F_{S1}

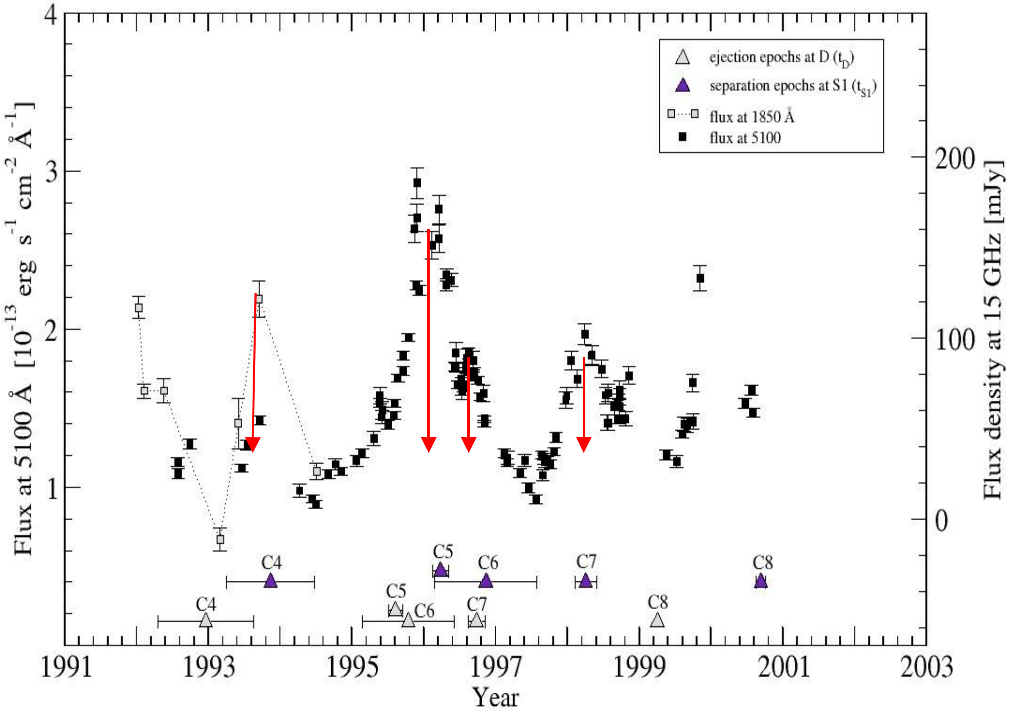
Time delay: **0.24 (+0.6 -0.2) yr**
Prob. of correlation: **~90%**

Denser sampling of radio VLBI data is needed to confirm the correlation

Optical: F_{5100A} (Shapovalova et al. 2001; Sergeev 2002); UV: F_{1850A} (Zheng 1996)

The link between the jet and optical emission

Further support for the link between **S1** component and **opt. continuum.**



The link between the jet and optical emission

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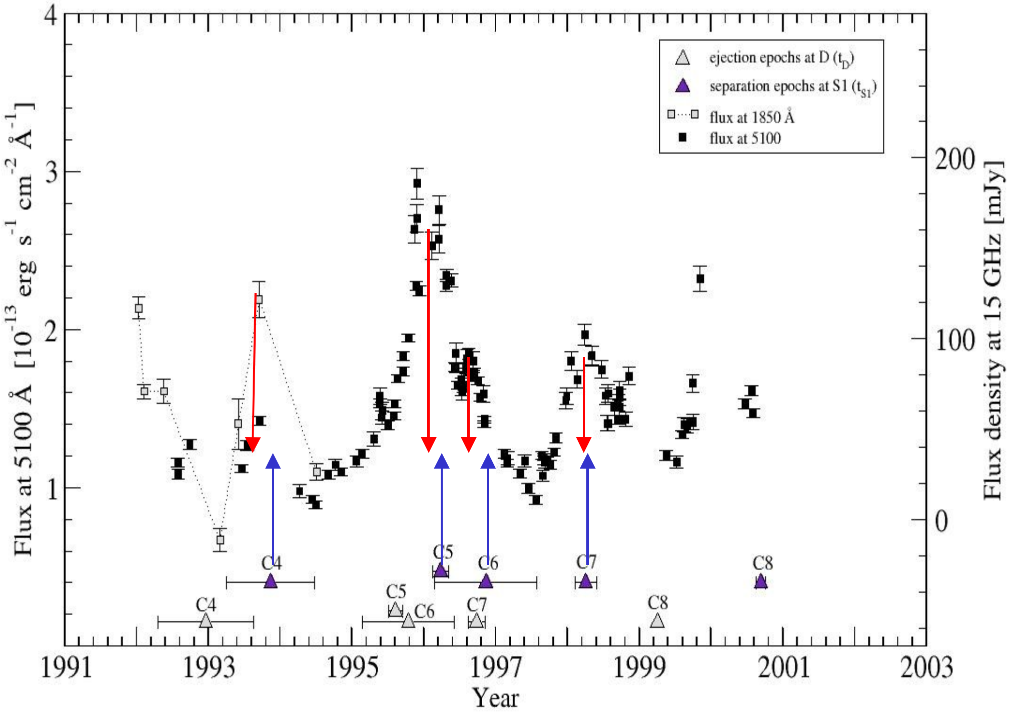
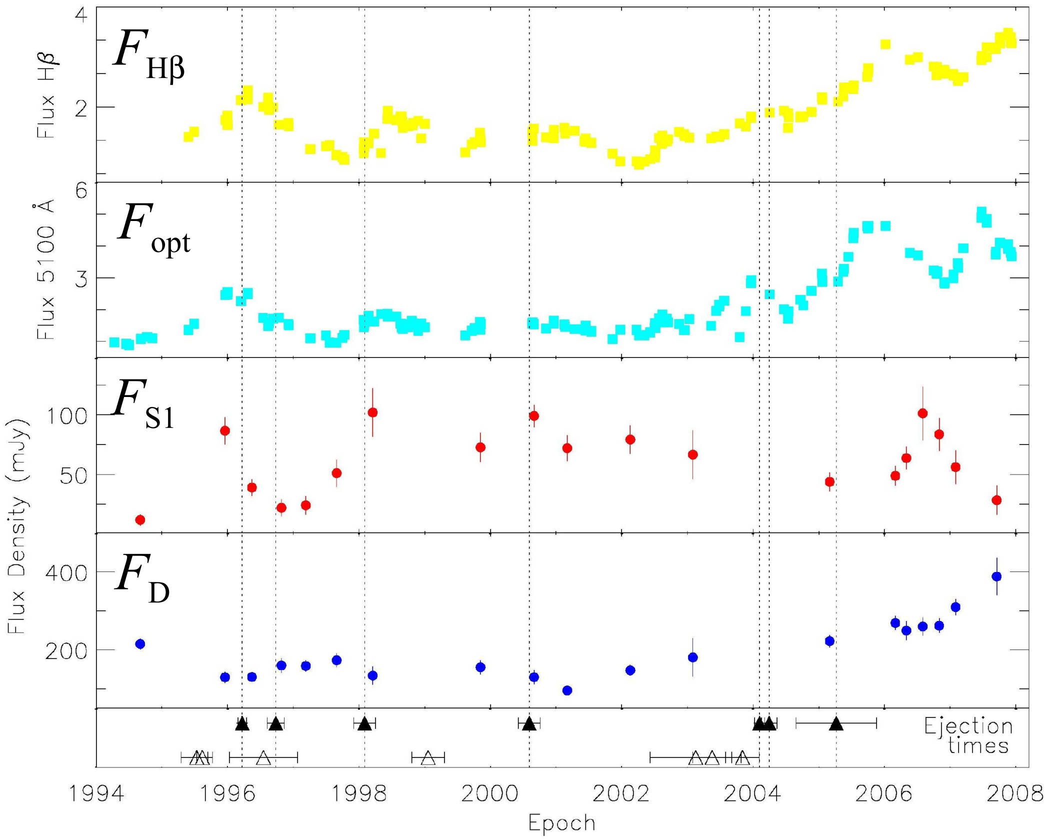


- $F_{opt,\ max} - t_{S1}$ **: 0.18±0.06 yr**
- $F_{Hb,\ max} - t_{S1}$ **: 0.01±0.06 yr**

Probability of a chance coincidence is 0.0002 (**99.98 % c.l.**).

- No correlation is found between t_D and optical continuum curve.

Radio-optical variability (1994-2008)



Tavares et al. (in prep.)

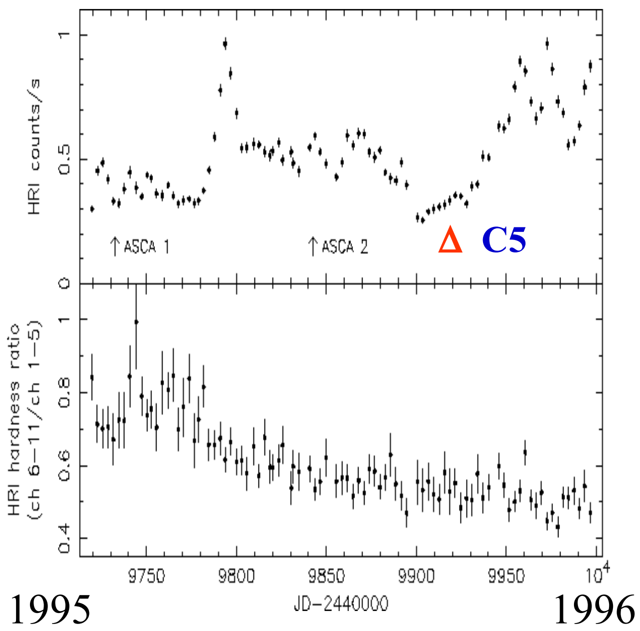
- **Variability amplitude** ~ 0.7 on time-scales of :
  ~ 2-4 yr (**S1**)
  ~ 10 yr (**D**)
- Variations from **D** ('base' of the jet) trace **very long-scale** variations of optical continuum (> 3 yr).
- Radio flares from **S1** (VLBI core) coincides with **long-scale optical** variations (2-3 yr).
- Epoch of passing the moving comp. at S1 (in 2004.3 yr) happens after the maximum in $F_{opt, max}$.

Identification of jet components D and S1

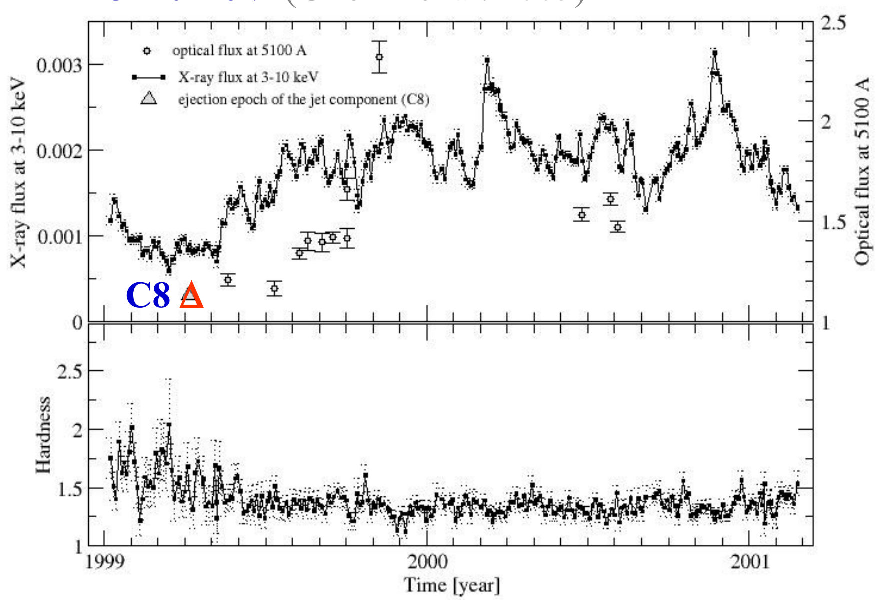
Evidence from the soft and hard X-ray data

Ejections of **C5** and **C8** components at **D** occurs after a dip in the X-ray and hardening of the spectrum (similar to 3C 120; Marscher et al. 2002).

0.5-2 keV (Lieghly et al. 1997)



3-10 keV (Gliozzi et al. 2005)



Identification of jet components D and S1

Ejecti
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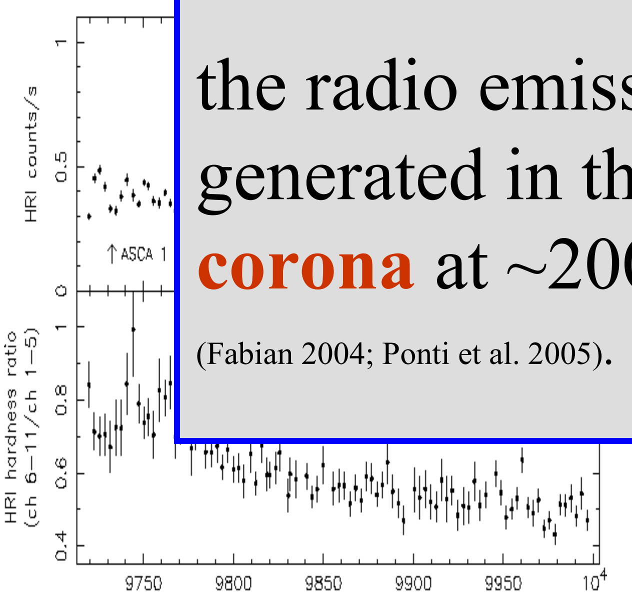
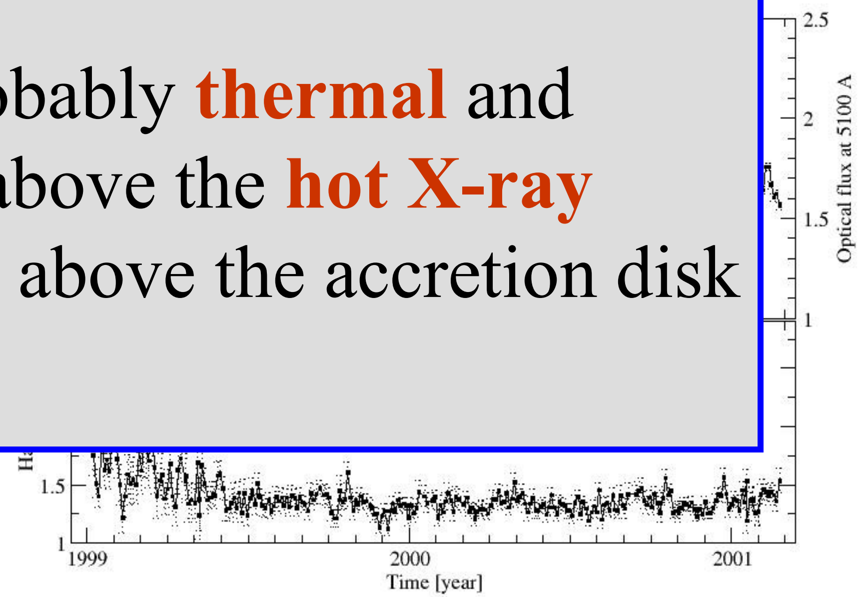
0.5-2



1995 1996



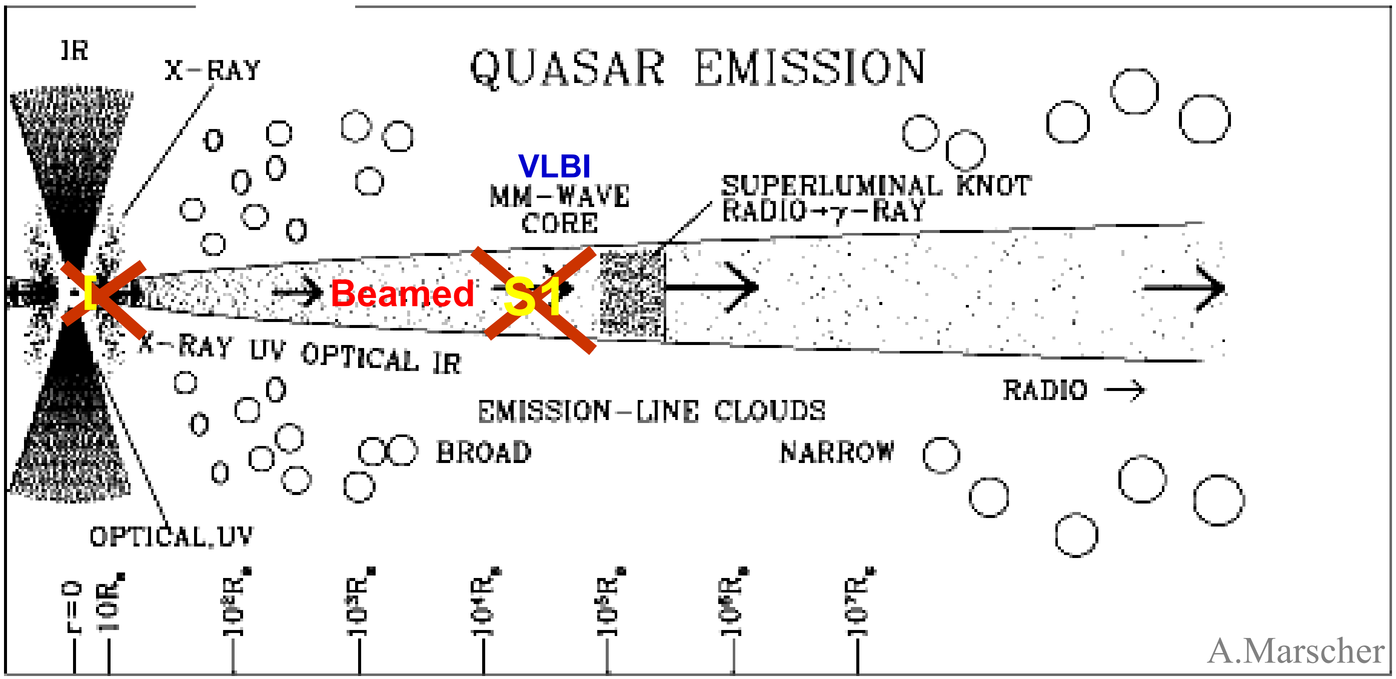
D is most likely to be associated with the central engine

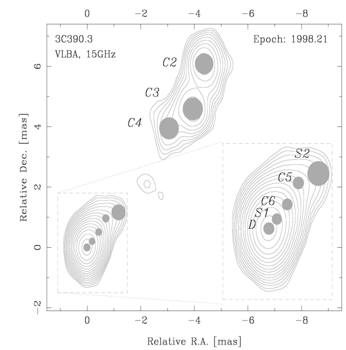
the radio emission is probably **thermal** and generated in the **AD** or above the **hot X-ray corona** at ~200-1000 R_s above the accretion disk

(Fabian 2004; Ponti et al. 2005).

Identification of jet components D and S1

Sketch of Physical Structure of Jet

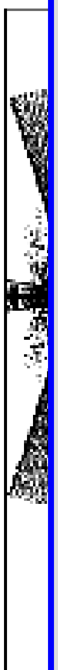




0.4 pc

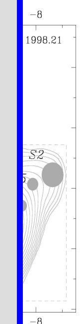
VLBI cores are detected in almost all radio-loud AGN

Identification of jet components D and S1



S1 is associated with stationary shock produced in the relativistic continuous flow (Gomez et al. 1995)

The synchrotron radio emission from the core of the jet (**S1**) is beamed in the direction of the jet.



0.4 pc

VLBI cores are detected in almost all radio-loud AGN

3C 390.3:
the nuclear region

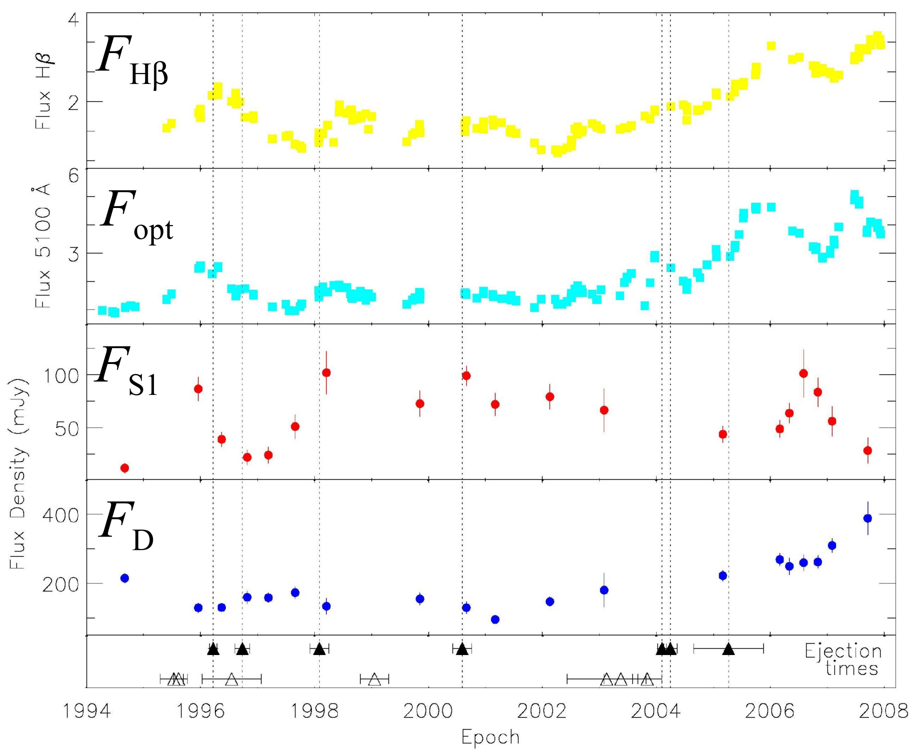
A sketch of the inner parsec

Optical continuum emission source:

- Disk/corona (**D**);
  variability – very long-term
- Near VLBI core (**S1**);
  variability – long-term (<2 yr)

Time delay between F_{opt} and F_{Hb}:

~ 60 ld – our data
~(20-100) ld – other monitorings



Tavares et al. (in prep.)

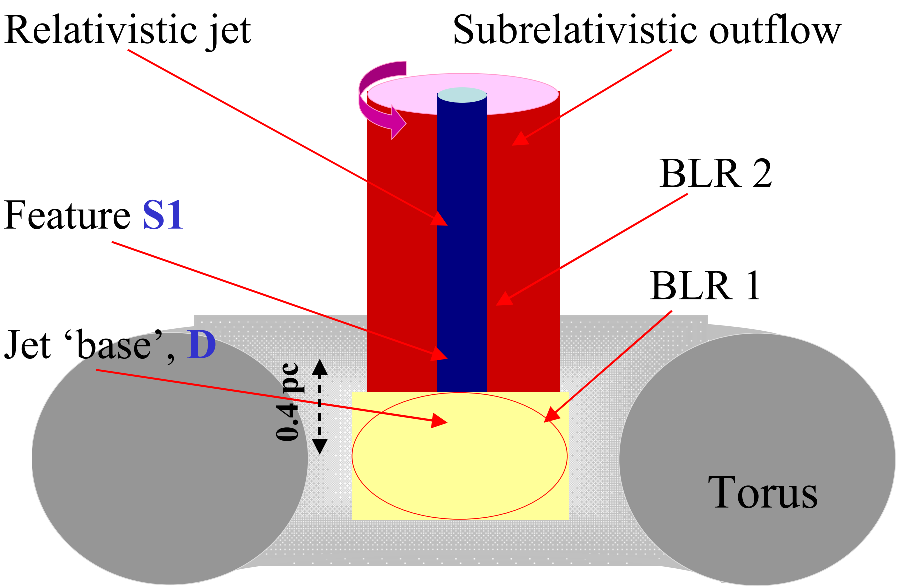
3C 390.3: *the nuclear region*

A sketch of the inner parsec

BLR - two component structure:

- **Virilized BLR1** ionized by disk/corona (**D**)
- **Outflow BLR2** ionized by the non-thermal beamed emission from the jet near the VLBI core (**S1**)

BLR1 is evident around the epochs of minima in the cont. flux (the jet contribution is small)
BLR2 may be manifested when the jet emission dominates the optical continuum.



Jet parameters

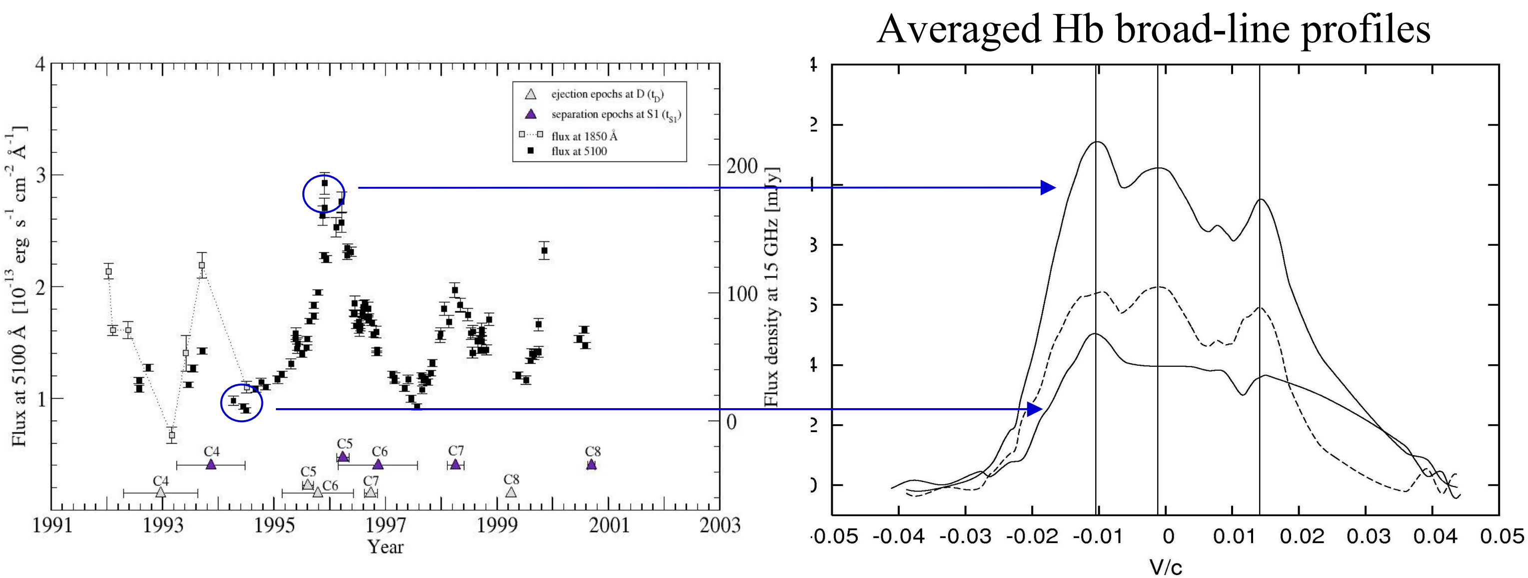
Var. Doppler factor = 1.16
Apparent speed = 1.5c
====================
Jet viewing angle ~ 50°
Lorentz factor ~2
Beaming angle ~30°
Distance ~0.4 pc=0.3/sin(50°)

3C 390.3: challenges of the BLR model

Existence of BLR2 associated with the jet questions the assumption of virilized motion of BLR and virial mass estimates of BHs in 3C 390.3

Important to understand whether this is common for all RL galaxies: long-term VLBI – optical spectral monitoring of a sample of RGs is carried out since 2005 (Lobanov and Chavushyan).

3C 390.3:
DP Hb broad-line profiles



Minimum: DP Hb profile fits well by **disk model** for BLR.
DP Hb broad-line excited by unbeamed opt. continuum of corona.
Blue and red comp. peak at -3000 km/s and +4200 km/s (no change in disk inclination)

Maximum: DP Hb + central component (-350 km/s) - hard to explain by disk only.
Central component may originate in outflow or spherical BLR (Popovic et al. 2004)
excited by beamed opt. continuum emission of the jet.

Summary

Results:

- Jet variability on sub-pc scales consists of long-term variations from the 'base' of the jet (D) superimposed with short-term radio flares (2-3 yr) of the VLBI core (S1).

- Long-term radio variations of the base of the jet correlate with long-term variations of optical continuum which originates in the disk or hot corona.

- Short term radio flares of the core seems to precede the flares in optical regime.

Proposed model of the central engine:

- We suggest that there are two sources of optical continuum emission, one near the BH (**thermal**) and one in the core of the jet (**synchrotron radiation).**

- The opt. continuum radiation ionizes two BLRs, one associated with disk/corona and one with the core jet at a distance of ~0.4 pc from the BH.