Studying the continuum spectrum of the parsec scale jets by multi-frequency VLBI measurements

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in collaboration with
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Spectral Analysis of Multi-frequency VLBI Data

Introduction

Why is it important to study the 2-D spectrum of pc scale jets?

In order...

- to study the jet physics: measuring the synhrotron self-absorption turnover and the component size gives you a handle on the important physical parameters: B and N_0. And there is no need to assume equipartition!
- to predict how much SSC X-rays one can expect from the source and from which part of the jet these come from.
- to test shock models by measuring the spectral evolution of the moving components.
- to study the possible absorption by circumnuclear gas.

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Extraction of the Spectra from Multi-λ VLBI Data

Problems:

- Target sources are typically variable ⇒ need (quasi)simultaneous multi-λ measurements. OK with VLBA
- Accuracy of flux density calibration. OK at $\nu \leq 22$ GHz, need checks at higher freqs.
- Image alignment. After phase self-cal, there is no absolute position information in the data. Can be dealt with.
- Uneven (u, v) coverage. Our new method alleviates this problem.

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Extraction of the Spectra from Multi-λ VLBI Data

Problems: Uneven (u, v) coverage

- VLBI networks cannot be scaled $\Rightarrow$ (u, v) plane coverage differs significantly at different observing frequencies
- Classic solution: match the (u, v) coverages either by throwing away long spacings at high frequencies or tapering the data to common resolution $\Rightarrow$ throw away a lot of data and lose angular resolution
- Broad frequency coverage, which is needed to observe the spectral turnover, exacerbates the problem!

Extraction of the Spectra from Multi-λ VLBI Data

Model-fitting Based Method

Solution: brightness distribution template

- Use *a priori* knowledge of the source structure from the high(est) frequency map $\Rightarrow$ fit the lower frequency data with a brightness distribution template
- Angular resolution now depends on the SNR of the visibility data $\Rightarrow$ if the data have high SNR, it is possible to derive sizes and flux densities of even those emission features that have mutual separations less than the Rayleigh limit
- Significantly relieves the problem with uneven (u, v) coverage

Extraction of the Spectra from Multi-λ VLBI Data

How Is It Done in Practice?

1. Form a model of the source brightness distribution at the frequency giving the best angular resolution and good SNR (a small number of Gaussians)
2. Transfer the model to lower frequency, keep relative positions of the components fixed (*a priori* knowledge)
3. Align the model with the data by using optically thin jet features (fine-tune the alignment, if necessary)
4. Fit the model letting S_ν and Θ to vary
5. Add new components, if new emission regions have emerged. Merge components that have mutual separation $< 1/5$ of the beam size.

Repeat $2 - 5$ for all the frequencies.

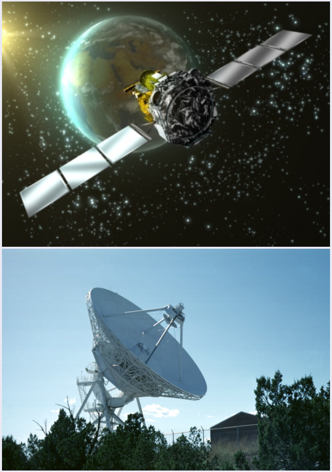
Extraction of the Spectra from Multi-λ VLBI Data

How Is It Done in Practice?

1. Assume smooth variations in component size over frequency and estimate the size-frequency relation (*a priori* knowledge)
2. Fix the size and fit the model with S_ν as the only free parameter

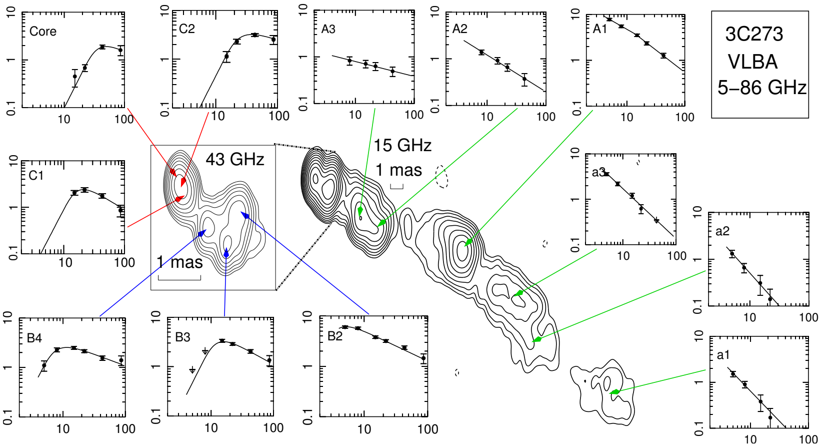
$\Rightarrow$ Final spectra

Multifrequency VLBA Observations of 3C 273

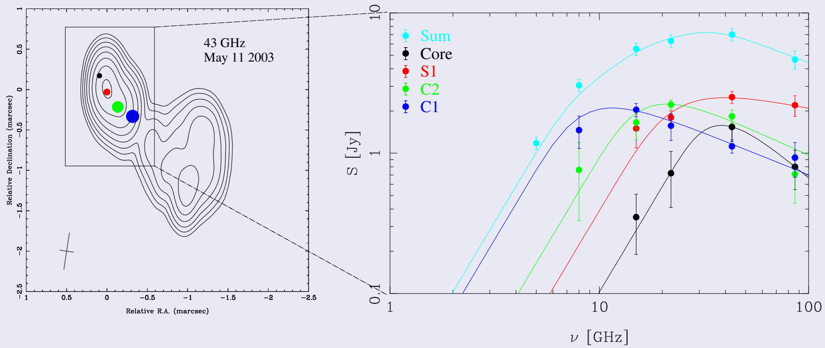


- 5-epoch multifrequency VLBA monitoring carried out concurrently with the INTEGRAL campaign in 2003 *(Courvoisier et al 2003, A&A, 411, 343)*
- Simultaneous observations at 5, 8.4, 15, 22, 43, and 86 GHz, including polarisation at every frequency

Examples of the Measured Spectra

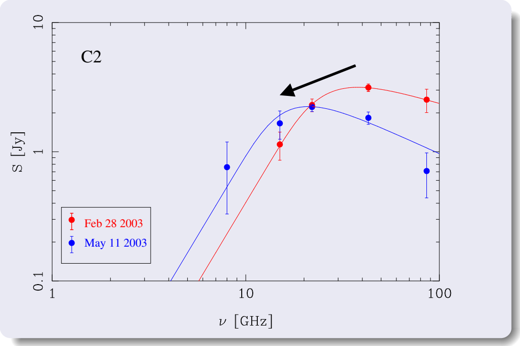


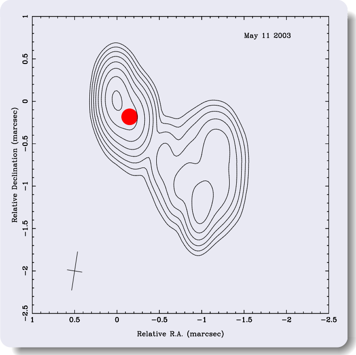
Spectral Decomposition of the Core Region



Elongated, rather flat-spectrum core can be decomposed into a series of self-absorbed synctrotron components

Spectral Evolution





- Consistent evolution gives confidence on the method!
- In some components synchotron losses dominate? In others adiabatic?

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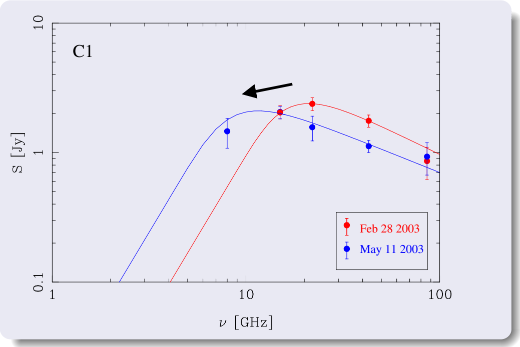

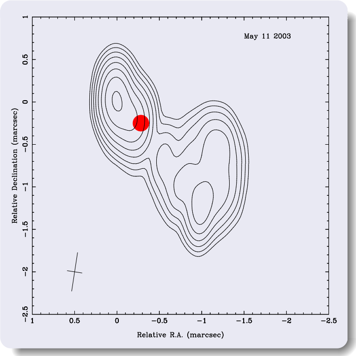

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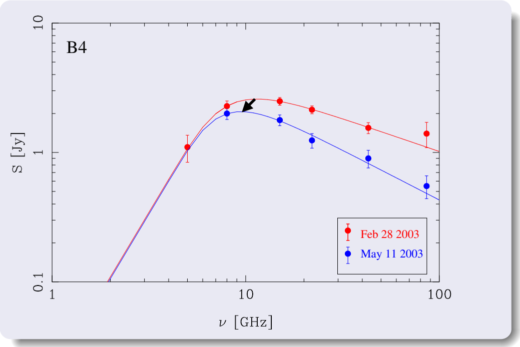

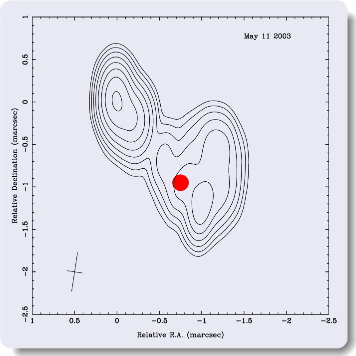

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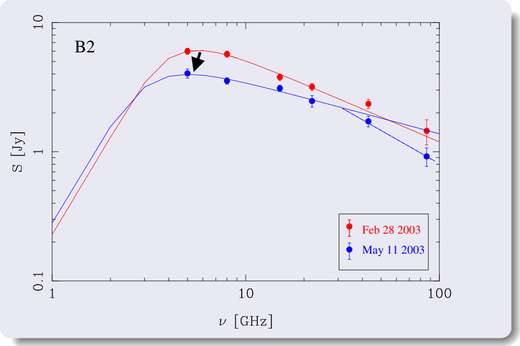

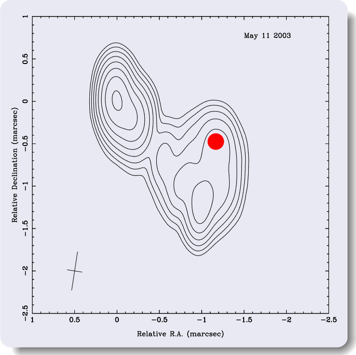

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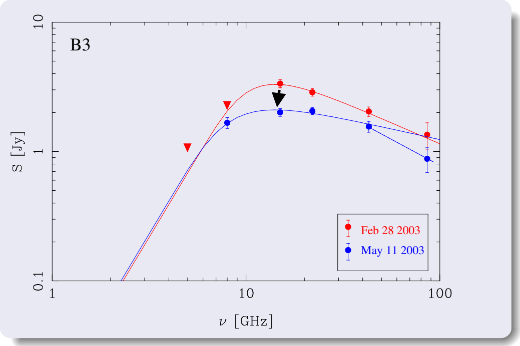

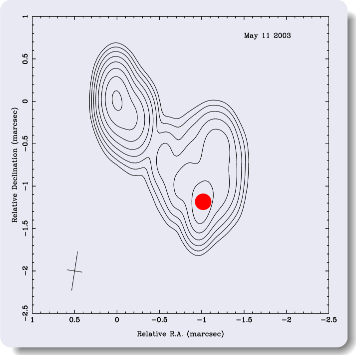

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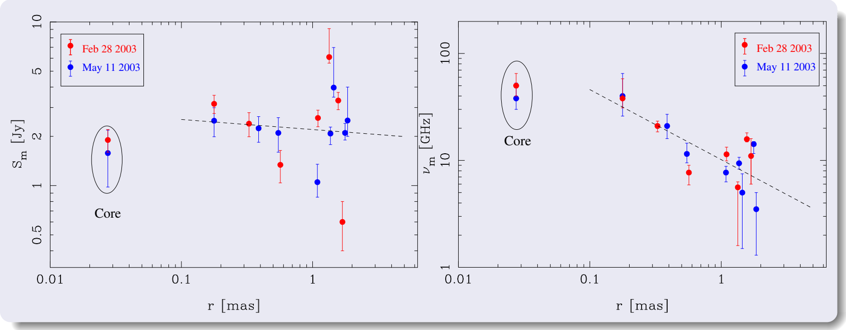
Spectral Turnover



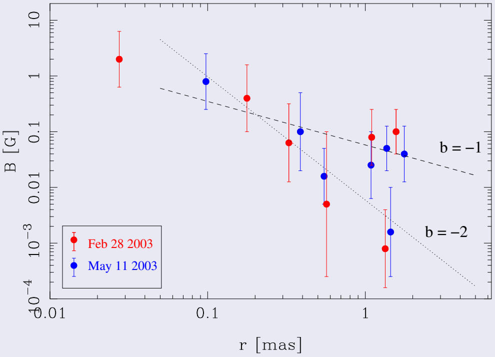
- The synchrotron peak frequency decreases as function of distance from the core: $\nu_\mathrm{m} \propto r^{-0.7\pm0.1}$
- Confirms the composite nature of the flat radio spectrum

Physical Parameters of the Plasma

- We have measured S_{m}, ν_{m}, α and Θ; Doppler factor δ is available from VLBI monitoring *(Savolainen et al. 2006, A&A, 446, 71)*
- Assuming standard synchrotron theory (e.g. *Marscher 1987, in Superluminal Radio Sources*):
  $$B = 10^{-5} b(\alpha)\Theta(\nu_{\mathrm{m}})^4 \nu_{\mathrm{m}}^5 S_{\mathrm{m}}^{-2} \frac{\delta}{1+z} \quad [\mathrm{G}]$$
  $$N_0 = n(\alpha) D_{\mathrm{Gpc}}^{-1} \Theta(\nu_{\mathrm{m}})^{-(7-4\alpha)} \nu_{\mathrm{m}}^{-(5-4\alpha)} S_{\mathrm{m}}^{3-2\alpha} \times (1+z)^{2(3-\alpha)} \delta^{-2(2-\alpha)} \quad [\mathrm{erg}^{-2\alpha}\,\mathrm{cm}^{-3}]$$
  $$U_{\mathrm{re}} \approx f(\alpha, \nu_2/\nu_1) D_{\mathrm{Gpc}}^{-1} \Theta(\nu_{\mathrm{m}})^{-9} \nu_{\mathrm{m}}^{-7} S_{\mathrm{m}}^4 (1+z)^7 \delta^{-5} \quad [\mathrm{erg\,cm}^{-3}]$$
- No need to assume equipartition!
- Highly non-linear equations:
  - Need accurate input parameters
  - Monte Carlo methods needed in estimating uncertainties

Magnetic Field Density

log(B) vs. log(r)



- In the core, $B \sim 1$ G
- Excluding B2, $B \propto r^{-1}$
- Significant B gradient across the jet at 1.5 mas from the core: Northern side $\sim$ 1 mG while Southern side $\sim$ 50 mG

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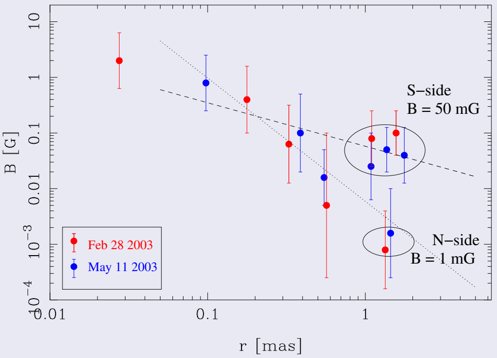
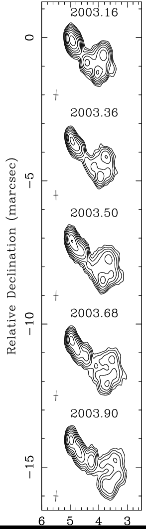


- In the core, $B \sim 1$ G
- Excluding B2, $B \propto r^{-1}$
- Significant B gradient across the jet at 1.5 mas from the core: Northern side ~ 1 mG while Southern side ~ 50 mG

Gradients in *B* and Γ across the Jet

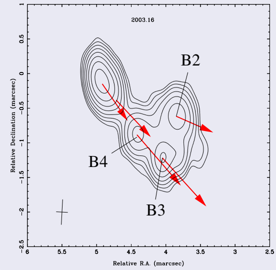


- 43 GHz VLBA monitoring: there is a velocity gradient across the jet between 1-2 mas *(Savolainen et al. 2006, A&A, 446, 71)*:
    - Northern component B2 has Γ ≈ 7
    - Southern components B3 and B4 have Γ ≈ 17
    - *Jorstad et al. (2005, AJ, 130, 1418)* report a similar velocity gradient for different components and different time; according to them knots on the northern side have Γ ≈ 8 and knots on the southern side have Γ ≈ 14

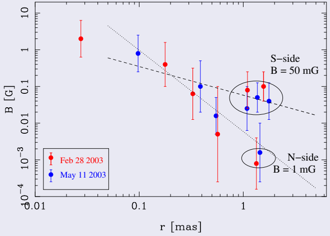
Gradients in B and Γ across the Jet

- Coincident gradients in B and Γ across the jet: Fast southern components with $\Gamma \sim 17$ have magnetic field density of ~ 50 mG while the slow northern component B2 has $\Gamma \sim 7$ and $B \sim 1$ mG; spine-sheath structure?

Velocity field (Γ)



Magnetic field density



Finally: A word of Caution

Limitations of the spectral extraction method

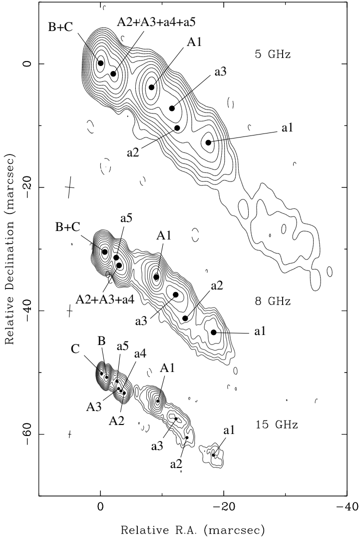
- The results are sensitive to the image alignment. Needs to be accurate!
- There is a limit to how far one can extrapolate in spatial frequencies: it depends on the SNR of the data and on the properties of the model.
- It is implicitly assumed that there are no spectral index gradients over the individual components i.e. their brightness centroids are co-spatial at different frequencies.

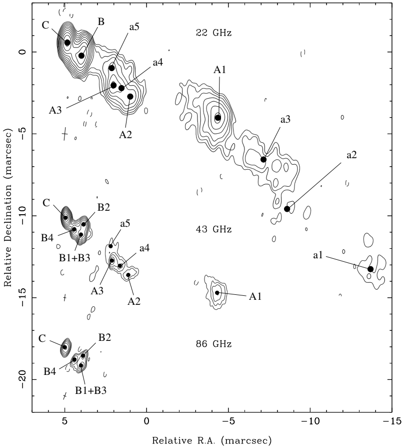
Summary

- Multifrequency VLBA observations can yield high-quality 2-D spectra of the jets in parsec scales
- Measured spectral evolution in 3C 273 is very consistent. Gives confidence on the method.
- Magnetic field density in the jet of 3C 273 was mapped within first 2 mas; in the core $B \sim 1$ G
- There are coincident magnetic field density and bulk velocity gradients across the jet at ~ 1.5 mas from the core: fast southern components have stronger magnetic field than the slow northern component; Do magnetic jet launching models predict this?

Extra Slides

Simultaneous Data at 6 Frequencies

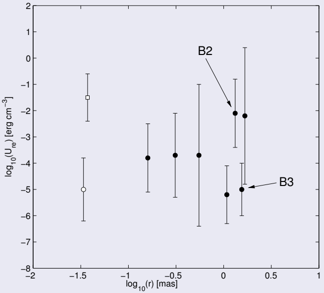




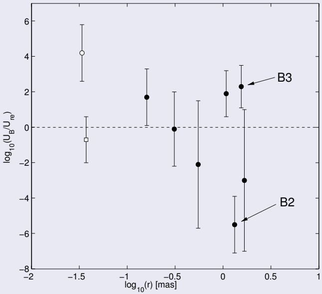
Observed on February 28, 2003

Energy Density of the Relativistic Electrons

$\log(U_{\rm re})$ vs. $\log(r)$



$\log(U_{\rm B}/U_{\rm re})$ vs. $\log(r)$



- $\langle U_{\rm re}\rangle \sim 10^{-4}$ erg cm^{-3}
- Out of equipartition: Core (*B* dom.), B2 (particle dom.)
- Limit for $\gamma_{\rm min}$: if the source is required to be rest-mass dominated beyond the core, $\gamma_{\rm min}$ must be below 10