Longitudinal and transverse velocity fields in parsec-scale jets

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Active Galactic Nuclei

Super Massive Black Hole
$10^6$ to $10^{10}$ times solar mass

Accretion disk

Jets of twin, highly collimated, and fast outflows.
Magnetic field accelerate electron and proton
Produce synchrotron radiation observable in radio
2D structure of jets

- Complex flow:
  - Relativistic
  - Stratified
  - Residual rotation
  - Instability and shocks

Accumulation

Beam

Kelvin Helmotz instabilities and/or shocks

Jet

BH
2D structure of jets

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- Current method:
  - Model fitting: 1D
  - Ridge-line analysis
  - Jet transverse profiles

A. Lobanov & A. Zensus 2001
2D structure of jets

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Margin of improvement between the information from observation and output

We need an automatic and robust tool for feature identification

A. Lobanov & A. Zensus 2001
Talk outline

- Structure analysis (WDS method):
  - Wavelet Decomposition
  - Segmentation
- Kinematic analysis: Multi Scale Cross Correlation (MSCC)
- Analysis of the velocity field of the jets of 3C273 and M87
Wavelet transform

- Time-frequency transformation
- Representation of signal as a linear combinations of a wave like function which is scaled and translated
- Provides a 2D power distribution over a range of spatial scale in the image
- Robust tool for identification of significant structural patterns (SSP)

VLA map: Owen et al. (1989)
Feature detection

1. Wavelet decomposition

2. Thresholding: Statistically significant wavelet coefficients are extracted at each scale.

3. Detection of features: Local maxima in the wavelet space are the positions of features.

4. Segmentation: Watershed segmentation is used to delimit the regions (segments) associated with those positions.

This result in a set of SSP
Feature detection

**Finest scales:**
Detailed description down to ~0.25 FWHM
Provide 2D velocity field

**Intermediate scales:**
Ridge-line detection

**Coarse scales:**
Equivalent to model-fit
MSCC detection of structural changes

- Cross Correlation of each SSP at epoch 1 vs image at epoch 2
  → **Weighted Normalized CC**

- Separation of features at scale $j \sim 2^j$
  → $j$ chosen so that expected $\Delta < 2^j$
  → CC on a $2^j \times 2^j$ window

- Features inside a same upper scale feature move in average like it:
  → **Define the location of the CC window**

> Joined analysis at all wavelet scales provide robust match of structural changes up to $\sim 5$ beam sizes
In Virgo constellation, $z \sim 0.1583$
Most luminous quasar
Transversely resolved flow (Beam $\sim 1 \times 0.5$ mas)
Observed as part of the MOJAVE survey

Monitoring Of Jets in Active galactic nuclei with VLBA Experiments
1.5 Jy Flux limited AGN sample in northern sky at 15 GHz, $\sim 300$ AGN currently monitored
Good agreement between WDS and model-fitting.
3C273

Mojave model-fit: Lister et al.

Good agreement between WDS and model-fitting
3C273

1226+023, VLBA at 15.35 GHz
Stacked images: 72 epochs from 1995-07-28 00:00:00 to 2010-10-27 00:00:00
Velocity map at scale 0.40 mas.

- 2D velocity field
- Helical patterns propagating in the flow
- Change of flow direction
3C111

Radio Galaxy, $z \sim 0.0491$
Observed as part of MOJAVE
67 epochs
from 04/1995 to 02/2013

Lister et al, 2013
Radio Galaxy, z ~ 0.033
Observed as part of MOJAVE
87 epochs from 07/1995 to 02/2013

Lister et al, 2013

0430+052, VLBA at 15.35 GHz
Stacked images: 87 epochs from 1995-07-28 00:00:00 to 2013-02-28 00:00:00
Velocity map at scale 0.80 mas.
3C274, VLBA at 43.13 GHz
Stacked images: 11 epochs from 2007-01-27 00:00:00 to 2007-08-26 00:00:00
Location of SSP at scale 0.14 mas.

3 distinct regions are detected

One of the closest radio galaxy (z = 0.0043, 1 mas ~ 0.089 pc)

11 VLBA observations between 2007/01/27 and 2007/08/26, at 43 GHz (Beam ~ 0.4 x 0.2 mas ~ 56 x 28 Rs) with 3 weeks interval (Craig Walker)
Few persistent features: **model fit not possible**
• Fast spine, slower sheath: **stratified flow**
• **Acceleration in the sheath**
• Velocity difference between northern and southern sheath: suggests **clockwise rotation** (jet or K-H instability pattern rotation)
Fast spine, slower sheath: **stratified flow**

**Acceleration in the sheath**

Velocity difference between northern and southern sheath: suggests **clockwise rotation** (jet or K-H instability pattern rotation)

Lateral displacement due to rotating pressure enhancements: visible > 3 mas
Summary

- The WDS technique provides reliable reconstruction of the velocity field in transversely resolved flows.
- This can considerably enhance the output of high resolution radio images.
- Result shows **excellent agreement** with global kinematic changes obtained from model-fit analysis of VLBI images.
- Ongoing detailed analysis of M87 velocity field promises interesting results:
  - We detect an **acceleration in the sheath**
  - Results suggest a **stratified flow** with a fast spine and a slower sheath
Summary

- The WDS technique provides reliable reconstruction of the velocity field in transversely resolved flows.
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  - We detect an acceleration in the sheath
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Thank you for your attention!

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Extra slides....
Wavelet transform: A trou (Shensa, 1992)

Advantages: stationary, isotropic and shift invariance transform

\[
s(l) = \sum_{k} c_{J,k} \phi_{J,l}(k) + \sum_{k} \sum_{j=1}^{J} w_{j,k} \psi_{j,l}(k)
\]

Result of the wavelet transformation of a Gaussian shape function of varying width, using the triangle function as scaling function.
Testing the WDS and MSCC

WDS and MSCC has been tested on simulated image with analytically defined model and:
- Gaussian noise
- Uncertainty on features positions

Input: sinusoidal velocity field

Width at base ~ 2 FWHM beam

SSP at scale 1.6 FWHM

SSP at scale 0.8 FWHM
AGN zoologies

Radio Galaxies: left FRII; right FRI