Accretion-ejection morphology of the microquasar SS 433 resolved at sub-au scale with VLTI/GRAVITY

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What is SS 433?

- SS 433 discovered in the 70’s. In the galactic plane. K=8.1!
- At a distance of 5.5 kpc, embedded in the radio nebula W50
- Eclipsing binary with Period of ~13.1 days, the secondary a A-type supergiant star and the primary may be a \( \sim 10 \ M_{\odot} \) BH.

W50 supernova remnant in radio (green) against the infrared background of stars and dust (red).
Moving Lines: Jet Signatures

- Optical/IR spectrum:
  - Broad emission lines (stationary lines)
  - Doppler (blue and red) shifted lines (moving lines)
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- Variable, periodic, Doppler shifts reaching ~50000 km/s in redshift and ~30000 km/s in blueshift

- Rapidly interpreted as signature of collimated, oppositely ejected jet (v~0.26c) precessing (162 days) and nutating (6.5 days)
**Precessing Jets**

- Collimation with opening angle $\sim 1^\circ$
- Jets mass-loss rate $> 10^{-6} M_\odot$ yr$^{-1}$
- $L_{\text{kin}} > 10^{39}$ erg s$^{-1} > 1000$ $L_{2-10 \text{ keV}}$. ($L_{X,\text{intrinsic}}$ may be much larger)
- They interact in a helical pattern with W50
- Presence of ionized heavy elements
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Stationary Lines

- Lines that do not share the large periodic Doppler shifts are called « stationary » lines
- The « stationary » lines vary in strength and profile shape during the orbital phase
- Fits with multiple-gaussians model reveal different components
Wind, accretion and Circumbinary discs

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- Two narrow remarkably constant components, one permanently redshifted and the other permanently to the blue signature of a \textbf{circumbinary ring} (the inner rim of an excretion disc?)

- Some « extra » broadening can be due to the presence of two narrow components at comparatively extreme excursions in velocity signature. Signature of a ring or \textbf{disc orbiting the compact object itself}.
The SS-433 System

- Jet precession (~164 days) and nutation (~6.5 days)
- Jet1 approaching
- Jet2 receding
- M_{\text{star}} = 24 M_{\odot}
- M_{\text{BH}} = 16 M_{\odot}
- P = 13.6 days
- 5.5 kpc
- > 300 R_{\odot} (0.2 mas)
- < 160 R_{\odot} (0.1 mas)
Basics of Interferometry

In optical range we observe interference fringe patterns.

Telescope Baselines
Basics of Interferometry

- In optical range we observe interference fringe patterns

- van Cittert-Zernike Theorem:

\[
Ve^{i\Phi} = TF\{Object\}(B/\lambda) \quad \Phi = 2\pi \frac{\vec{B}}{\lambda} \cdot \vec{s}
\]

If we collect enough V and \(\phi\) (for different \(\vec{B}\)) we can reconstruct \(I(\vec{\alpha})\)
The smaller the V amplitude, the more resolved the object is!
Basics of Interferometry

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Basics of Interferometry

The larger the $\Phi$ phase, the more dissymetric the object is!
Basics of Interferometry

\[ \delta \text{OPD} = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta}) \]

The larger the \( \Phi \) phase, the more dissymetric the object is!
GRAVITY Instrument

http://www.mpe.mpg.de/ir/gravity
First light paper: GRAVITY Collaboration: Abuter et al. (2017)

• Combines the 4 UT (8,20 m) or the 4 AT (1,80 m) since 2016

Angular resolution: 4 mas @ 2.2\(\mu\)m
by spectro-astrometry: 10 \(\mu\)as @ 2.2\(\mu\)m
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First light paper: GRAVITY Collaboration: Abuter et al. (2017)

• Combines the 4 UT (8.20 m) or the 4 AT (1.80 m) since 2016

• Devoted to the observation of the very close environment of the black hole at the galactic center

• Room for other science (AGN, stars, binaries, …): open to ESO proposals!
The SS 433 Observation

- 3.5h with the 4 UTs, the 16th July 2016
- uv-plane (coincidentally) aligned with the jet PA
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- uv-plane (coincidentally) aligned with the jet PA
- The jet precession phase at the observation date is ~0.7
Continuum Visibility

- Systematic drop versus baseline length
- No closure phase measurable
- Simple modeling with a Gaussian disk:
  - 90% from emitting region of 0.8mas
  - 10% from diffuse background (>15mas)
• $\text{Br}\gamma_\text{rest}$ is double-peaked
• $\text{HeI}$ with P Cygni profile

Stationary lines

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The GRAVITY Spectrum

Jet lines

- Emission features agree with the jet line shifts expected at the observation date
- Br$\gamma$, Hel from jet1 and jet2 and Br$\delta$ from jet1
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Normalized Visibilities

Amplitudes

Phases
Normalized Visibilities

Amplitudes

Phases

Visibility Amplitude

UT1-UT3

Normalized Visibility

Visibility drop

positive phases

negative phases

Phase

UT1-UT3
Jet line Model

**Method**: fit all jet lines (flux, vis. amplitude and phase) together assuming the same jet intensity profile moving at 0.26c
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- An exponentially decreasing intensity profile preferred to a gaussian one ($\Delta \chi^2 > 36$ for 57 dof)

$$I(z) \propto e^{-\left(\frac{z-a}{s}\right)} H(z-a)$$

- Best fit with:
  - PA = $75^\circ \pm 20^\circ$ (3σ error)
  - $s = 1.7 \pm 0.6$ mas,
  - $a = -0.15 \pm 0.34$ mas

- Transverse size < 1.2 mas
Stationary line: Brγ

- Visibilities clearly drop across the line for all the baselines.
- Deeper for longer baselines.
- Emitting region size is found to be ~1 mas.
- Phases behavior suggest East-West oriented geometry, i.e., in a direction similar to the jet one.
The SS-433 System

Jet precession (~164 days) and nutation (~6.5 days)

Jet1 approaching

Jet2 receding

5.5 kpc toward Earth

> 300 R\(_{\odot}\) (0.2 mas)

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M\(_{\text{star}}\) = 24 M\(_{\odot}\)

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The SS-433 System
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jet intensity profile

1 mas

1/e

1.7 mas

0.26c

> 15 mas
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2. 10% continuum flux left over produced by a completely resolved background on a larger scale (>15mas).

3. The Br$\gamma$ emitting region has a typical size of 1 mas with an East-West elongation, along the jet axis.
1. Most (90%) of the infrared continuum comes from a partially resolved central source of typical size ~0.8 mas.

2. 10% continuum flux left over produced by a completely resolved background on a larger scale (>15mas).

3. The Br\textgamma emitting region has a typical size of 1 mas with an East-West elongation, along the jet axis.

4. Jet with a continuous (exponentially decreasing) emitting profile. No signature of moving blobs. Jet already at 0.26c at <0.2mas (1.6 \times 10^{13} \text{ cm}) from the binary (line locking process on hydrogenoid ions for jet acceleration).
Perspectives

• Improve the uv coverage
• Days/Week/Month monitoring to follow the source on different time scales (orbital period, jet precession period)

⇒ jet stability, ejection phenomena, line substructure origin (e.g. Brγ)

New data

• A GRAVITY (5h) + XSHOOTER (2h) observation accepted for P99 in A priority (PI: I. Waisberg): data analysis in progress...
• VLBA (15-86 GHz) (PI: I. Waisberg)
Thanks!