Resolving AGN central engines with GRAVITY -
The BLR in the Quasar 3C 273

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with

I) The GRAVITY endeavour - some historical remarks

II) Spectro-differential astrometry

III) 3C 273

IV) Context: Broad Line Regions (BLRs), Reverberation Mapping (RM), and Black Hole masses

V) What dreams may come
The GRAVITY Family
Milestones:
• project kick-off: 2005-2006
• Installation on VLTI Jul.-Sept. 2015
• 1st AT light: October 2015
• 1st UT light: May 2016
GRAVITY: all over the place in VLTI!

In addition to the beam combiner:

- 4 infrared adaptive optics (CIAO)
- Metrology sensors (UTs and ATs) for high precision astrometry and phase reference imaging
What’s in the box

- Fiber coupler
- Fiber system
- Acquisition camera
- Spectrographs
- Detectors
- Integrated optics
II) Spectro-differential astrometry with the near-IR interferometer GRAVITY

Angular resolution: 3.5 mas @ 2.2 µm

GRAVITY

~ 130 m
Reminder: Signatures of (Kepler) rotation

Velocity Map

Channel Map
(Line intensity map for different channels/velocities)

→ Photocentre displacement perpendicular to the rotation axis
Model-independent photocenter map

\[ \Delta \phi(\lambda) = -2\pi \frac{r(\lambda)}{1+r(\lambda)} \left[ \vec{u}(\lambda) \cdot \vec{\epsilon}(\lambda) \right] \]

• From measured phases, fit for 2D photocenter on sky at each wavelength

• Bright quasar, $L \sim L_{\text{Edd}}$
• Radio loud: known position angle on sky

Hubble Space Telescope images and radio (Merlin) images
Jester+2006 (Chandra)
III) 3C 273 with GRAVITY

\[ \Delta \phi(\lambda) = -2\pi \frac{r(\lambda)}{1 + r(\lambda)} \left[ \vec{u}(\lambda) \cdot \vec{e}(\lambda) \right] \]

\[ PA_{\text{Jet}} = 222^\circ \]

photocenter

10µas = 0.03pc

GRAVITY collaboration+, NATURE 2018
• A spatial velocity gradient (i.e., different photocenter positions) corresponds to wavelength-dependent phase shifts.
3C 273

radial velocity (km/s)

differential phase (°)

Pa α flux

normalized flux

observed wavelength (µm)
A rotating, thick disk BLR model

- Kinematic “cloud” model fit to line profile, phases (R. Stock et al.; following Pancoast+ 2014, Rakshit+ 2015)
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radial velocity (km/s)

Pa $\alpha$ flux

differential phase ($^\circ$)

normalized flux

rms $\sim 0.05$ deg

observed wavelength (μm)
3C 273 - A rotating, thick disk BLR viewed face-on

- Kinematic “cloud” model fit to line profile, phases (R. Stock)
- $i = 12^{+/-2}$, PA = $210^{+/-10}$ deg (aligned w/ jet in 2D)

- $R_{BLR} = 46^{+/-10}$ μas * 150 +/-40 lt-d

- $M_{BH} = 2-4 \times 10^8 \ M_{\odot}$

* 10 μas = 0.03pc

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Independent check of compact BLR size:

3C 273 differential visibility amplitude (blue) averaged over all epochs and between the two longest (UT4-1, UT3-1) baselines. The amplitude increases at the spectral line (black), demonstrating that the broad line region must be much smaller in size than the hot dust continuum (R ~ 150 μas).
The kinematics of the BLR of 3C 273 is dominated by rotation

\[ R_{\text{BLR}} = 46 \pm 10 \, \mu\text{as} \quad \text{(or 150\!/\!-40 \, \text{light days, or 0.13 pc})} \]

\[ M_{\text{BH}} = 2 \times 10^8 \, M_{\text{sun}} \]

*10 \, \mu\text{as} = 0.03 \, \text{pc at the distance of 3C 273}
IV) Context: Broad Line Regions (BLRs), Reverberation Mapping (RM), and Black Hole masses
Broad Line Regions, Reverberation Mapping (RM), and Black Hole masses

Reverberation mapping: $R_{BLR} \sim c \tau$

Spectroscopy: $\Delta v \sim FWHM$

$$GM_\ast = f R_{BLR}(\Delta v)^2$$

Time delay: $\tau = (1 + \text{Cos } \theta) r/c$
Broad Line Regions, Reverberation Mapping (RM), and Black Hole masses

- This requires monitoring over long periods of time (often many years), which is laborious and time consuming.

- RM observations have established a BLR radius – AGN luminosity relation (and hence a mass – luminosity relation) as powerful diagnostic tool

\[ R_{BLR} = bL^\alpha \]
(Almost) all BH masses to date are measured like this !!
This is the only available method for measuring black hole mass in large surveys and out to high redshift

→ key role in our understanding of black hole growth over cosmic time.
Broad Line Regions, Reverberation Mapping (RM), and Black Hole masses

Comparison **GRAVITY** vs. RM for 3C273

- \( R_{\text{BLR}} = 46 \pm 10 \, \mu\text{as} \)
  - 150\(+/-40\) l.t.d
  - RM: < 100 - 380

- \( M_{\text{BH}} = 2-4 \times 10^8 \, M_{\odot} \)
  - RM: 3-8 \times 10^8

- BLR rotation dominated
• BLR kinematics and structure as well as $M_{BH}$ are consistent with RM results (for this one object); i.e. these findings support the use of virial relations to measure quasar masses.
Summary

- spectro-differential astrometry with the near-infrared interferometer GRAVITY on the VLTI reaches a precision of $10 \mu$as ($=0.03$pc at $D=550$ Mpc for 3C273)

- The BLR in 3C273 is dominated by ordered rotation

- BLR kinematics and structure as well as $M_{BH}$ are consistent with RM results (for this one object); i.e. these findings support the use of virial relations to measure quasar masses.

- Potentially a new, independent tool to understand BLR physics and to improve AGN black hole mass determinations.

- Potentially a new, powerful tool for measuring torus size and structure, etc.