High-resolution infrared observations of active galactic nuclei

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Jörg-Uwe Pott

Max-Planck Institute for Astronomy (MPIA),
Heidelberg, GER
Baselines of this talk

• Which AGN questions can be (partially) answered by IR observations at interferometric resolution?

• What is required to go beyond shear torus size estimates?

• What to expect from the next generation of instruments?
Shaping the future of AGN interferometry

- MPIA contributes to the next generation of infrared high-angular resolution technology
  - VLTI/MIDI with PRIMA-FSU K-band tracking, lead: Pott (2012)
    - water-vapor sensitive fringe tracking to optimize sensitivity, precision and accuracy of 10um measurements
  - VLTI/MATISSE (2nd gen. instrument, Co-I Th. Henning) (2016)
    - L/N-band 4-beam combiner for model-independent imaging
    - 23m-AO imaging at the LargeBinocular telescope as step towards ELT and JWST science

J-Uwe Pott (jpott@mpia.de), AGN at highest NIR resolution
AGN science: Four groups of questions

• feeding of the AGN

• feedback to the galaxy (jets, winds, ...)

• red part of the accretion disk, geometry and origin of BLR, NLR, TOR

• AGN properties as tracer for the galaxy evolution (merger history, double AGN, ...)

J-Uwe Pott (jpott@mpia.de), AGN at highest NIR resolution
AGN – host interaction

Feeding and disc wind feedback of the AGN – too large for VLTI
• gas kinematics at spatial scales of few tens of pc
• interferometric imaging is difficult because small field-of-view and imaging dynamic range (scales with the number of telescopes)
• AO assisted imaging spectroscopy is the tool of choice
  • see talks of Veilleux, Davies, van der Laan, Scharwaechter...

Launch of jets and winds – too small for VLTI
• 2nd generation VLTI-imaging (4beam combination) can image emission-line morphology on mas just outside of the launching accretion disk
• wind-morphology (equatorial vs. polar) before strong interaction (bending,...) with the host
• longer baselines, using fibre-links (G. Perrin’s ’Ohana-projects) could get to the required km-baseline
Explore the immediate AGN environment

NIR properties of AGN:

- red part of the accretion disk, geometry and origin of BLR, NLR, TOR
- size scales: few light days to few tens of parsec
Explore the immediate AGN environment

- torus is the easiest to study in IR interferometry

- origin of the torus (toroidal obscuration region, TOR) is unclear
  - AGN feeding from the circum-nuclear gas and stars (work of Davies, Schartmann, ...)
  - dust formation in non-relativistic winds from the outer accretion disk ($10^2..3 \, R_{\text{schwarz}}$, work of Elitzur, Elvis, ...)

- geometry of TORus requires few 10..1mas resolution and beyond, at moderately complex morphology

- realm of long-baseline Michelson-interferometric arrays for direct measurements (VLTI, Keck-IF)
Resolving the TORus with long-baseline IF

- last decade was dominated by pioneering the field
  - first 2um AGN fringes (Swain’03, Wittkowski’04)
  - first 10um AGN fringes (Jaffe’04)
  - first ADAF-AGN fringes (CenA, Meisenheimer’07)
  - first interferometric confirmations of the size-luminosity relation (Kishimoto’09,’11, Tristram’09,’11)
  - first torus reverberation measurement (Pott’10)
  - first sizeable 10um VLTI survey of nearby AGN (Burtscher’11, PI Meisenheimer, the MIDI AGN LP team)
Resolving the TORus with long-baseline IF

- now we search for ways to go into the details of the circumnuclear dust
  - multi-wavelength studies
    - to identify large-scale structure
  
  - high-precision measurements
    - to identify the small scale structure (clouds)

  - spatially resolved multi-\(\lambda\) reverberation
    - to understand the heating and consistency via radiative transfer models
• How does the torus react to luminosity changes
  • NGC 4151 an ideal target

• First results:
  – torus size independent of accretion status
  – but differential brightening of the accretion disk makes the combined object more compact
Resolving the TORus with long-baseline IF

- Careful interpretation of the visibilities required

- Scatter in $R \sim L^{0.5}$ due to geometric effects?

- Is there a systematic offset of 2-3x between IF measurements and V-K reverberation?

- IF size is average size, reverberation size monitor innermost clouds

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Key questions of AGN tori

• Do we see the same torus at 2um and at 10um or is there a gap

• Is there a compact source in the 10um VLTI data? What is it?

• How clumpy is the torus?

• Do we spatially resolve the dust chemistry (carbon inside of silicate)?

• Is there active dust destruction and formation, as response to accretion disk activity?

• Time variable silicate profiles?

this is work in progress...
Torus fine-structure

- Dusty RT models require self-shielding clouds
- Dust formation in the BLR / disc wind would be a natural explanation
- Resolvable clouds give large uv-plane visibility gradients
- High accuracy and precision required -> fringe tracking
how to learn more about the BLR

• BLR is with ~0.1 mas too small for NIR-VLTI imaging
• BLR geometry and kinematics from line analysis
  – Bahcall+72, Blandford & McKee 1982 to coin reverberation mapping
  – radius-luminosity relation, radial stratification, reverberation velocity delay maps (e.g. Bentz, + 2010)
  – BLR is dominated by Keplerian and turbulent motion (Kollatschny+11), but inflow of BLR gas and various geometries exist
• direct spatial constraints from spectro-interferometric astrometry
spectro-interferometric astrometry

• To get all the BLR information, you need
  • time-resolved
  • spectroscopic
    • astrometric
      • broad-band
        • interferometry

• First step: Keck-I ASTRA
  • $R \sim 2000$
  • 3-30 μas centroid precision
  • full K-band: several lines
  • decent sensitivity thanks to fringe-tracking
Spec.IF-astrometry with Keck-ASTRA

- Keck-self-phase-referencing ASTRA-SPR
  - use two fringe trackers in parallel
  - 150 km/s spectral resolution in $K$-band (at 330 pix)
  - Current sensitivity limit $K \approx 7-8$ mag
- PHASE-REFERENCING or FRINGE-TRACKING is the adaptive optics for interferometry

without phase-referencing

with phase-referencing: longer integration times

J-Uwe Pott (jpott@mpia.de), AGN at highest NIR resolution
Be star 48Lib used for science verification

- The power of spectro-interferometric astrometry
  - 150 km/s resolution (KeckI; AMBER would have also a \( R \sim 12,000 \) mode)
  - photocenter shift translates into a differential phase signal

[plot from Pott et al. 2010]
Spectro-interferometric astrometry

- The power of spectro-interferometric astrometry

- $\Delta V^2$ and $\Delta d\phi$ as observables on kinematics and dynamics

- Absolute calibration is less precise (~2-10% level), but the absolute numbers only scale the overall size of the system, most of the qualitative information is in the differential data
Spectro-interferometric astrometry

Exceptional data quality

- Spectroscopic data reduction (use of spectral templates, wavelength calibration)

- Group delay based frame selection: differential delay in air-filled delay lines creates a quadratic shape in the $d\phi$

- Stable calibration over the full band allows for line comparison at high differential precision

- $\Delta fr = 0.003$, $\Delta V^2 = 0.007$, $\Delta d\phi = 3$ mrad

- On-sky centroid shift of 3 $\mu$as -> a relative precision of $10^{-3}$

- 2 orders of mag. better than state-of-the-art single-telescope spectro-astrometry

First IF detection of Pfund series

from Pott et al. 2010
Spectro-interferometric astrometry

- Putting all the information together can reveal a lot

- Differential location of the Pfund emission confirmed

- Line location consistent with Keplerian disk, not need for an outflow / inflow scenario

- Extension comparable to the model predictions of gravitational models, but non-LTE disk emission models often predict larger disks

- Very compact disk continuum emission

- Require time resolution (more data) to confirm spiral wave directly

Information in the SPR data of 48 lib:

- 48 Lib: disk emission zones (face-on view)
- Stellar continuum: unresolved
- Disk continuum: $\Theta_{\text{FWHM}} = 1.65$ mas
- P$^*$: $V/R = 1.0$
  - $V_{\text{peak}} = +230$ km/s
  - $\langle P_{\text{fit}} \rangle = 0.9$ mas
  - $\Theta_{\text{FWHM}} = 1.7$ mas
- Bry: $V/R = 1.8$
  - $V_{\text{peak}} = +150$ km/s
  - $\langle P_{\text{fit}} \rangle = 2.1$ mas
  - $\Theta_{\text{FWHM}} = 1.6$ mas

[plot from Pott et al. 2010]
Spectro-interferometric astrometry

• Technical results from the self-phase referencing science verification (Woillez+ASTRA team, submitted to PASP)

  • 3mrad differential phase (in 70 sec) translates into 3\(\mu\)as differential astrometry, can be 10x worse at the sensitivity limit

  • Extreme differential precision at high observing efficiency due to phase-referencing

  • \(K'\) (and later L-band) technically possible

  • weak lines have a stronger SNR in the \(\Delta d\phi\) signal than in the \(\Delta V^2\)

• The brightest AGN are in technical reach, and would require minor upgrades of the current instrument setup
Unfortunately the Keck-IF story comes to an end

Bidding Aloha to the Keck Interferometer
Peter Wizinowich, Optical Systems Manager, WMKO

WMKO has reluctantly decided to halt science operations with the Keck Interferometer (KI) at the end of observing semester 2012A, leaving the European Very Large Telescope Interferometer as the only large aperture interferometer in the world.

The KI was built and operated with NASA funding. Interferometry had a high priority at NASA in the era when future space projects included the Terrestrial Planet Finder (TPF) and the Space Interferometer Mission (SIM), projects which the KI was intended to support. The KI completed its primary support mission in 2008 with the characterization of the zodiacal dust levels around nearby stars using nulling techniques at 10 μm.

Along the way, the KI became a powerful scientific tool not just for nulling but also for visibility measurements at H, K and L-band. Observing efficiency (~6 targets/hour) and up-time (>90%) are both extremely high. Thanks to an NSF MRI grant, the KI capabilities were further extended to higher spectral resolution (R~2000) and to fainter targets (K~12.5 demonstrated), with even higher sensitivity and an astrometric mode under development. Over its history the KI has been a groundbreaking instrument including the first fringes with a large aperture interferometer, the first fringe phase images, the first interferometric images of an exoplanet, and the first interferometric detection of an exoplanet (Kepler-10b).

... from the last Keck newsletter!

J-Uwe Pott (jpott@mpia.de), AGN at highest NIR resolution
and the VLTI?

• Phase-referencing at VLTI
  – was long hampered by high UT-vibration levels
  – the first ‘fringe-tracker’ FINITO was not very successful due to low sensitivity

• Future looks brighter
  – PRIMA-FSU is being commissioned
  – we startet the MIDI+FSU campaign
  – 2nd generation, multi-baseline state-of-the-art fringe tracker is being designed
Phase-referencing at VLTI: MIDI+FSU

• Pathfinder for future VLTI external fringe tracking:
  – mid- & high-resolution AMBER (and later MATISSE) observations
  – off-axis fringe tracking for faint sources
  – spectro-astrometric interferometry
  – fringe- and water vapor tracking

J-Uwe Pott (jpott@mpia.de), AGN at highest NIR resolution
Phase-referencing at VLTI: MIDI+FSU

What MIDI+FSU currently stands for:

• FSU is **Not** another FINITO
  – different band (FSU uses K vs. FINITO uses H)
  – instantaneous multi-\(\lambda\) ABCD (vs. broad-band temporal ABCD)
    • less vibration sensitive
  – water-vapor sensitive
  – better for thermal science bands
    • lower spatial resolution, and higher flux for red sources

• Much better for AGNs, when used on UTs
What can be done with MIDI+FSU

Fig. 1: **Up:** Increased OPD stability due to FSU fringe tracking during MIDI+FSU first light. **Left:** Sensitivity record of MIDI@AT thanks to FSU operation. **Right:** We plan to reobserve MIDI source with known $d\phi$ like above to demonstrate the improved $d\phi$ calibration thanks to MIDI+FSU operation.
Phase-referencing at VLTI: MIDI+FSU

• MIDI+FSU science demonstration run in few weeks with ATs
  – main goal is to verify the performance
    • precision
    • accuracy
    • wavelength-differential precision
    • final goal: 1mrad (0.05deg) for diff.phase precision

  – NGC1068 might work on shortest baselines with good weather

• MIDI+FSU@UTs could confirm the TORus dust cloud induced visibility fine-structure, or faint compact flux
Torus in 2d at high precision

- current VLTI-MIDI studies find the need to bring the dust close in
- radiative transfer modeling works only with clumpy distributions, where optically thick clouds shield each other
- torus formation models can predict geometrical thickness
- true 2d imaging with closure phase and high precision is the key to learn more about the torus and its origins
VLTI-MATISSE

- Instrument concept
  - four-beam combiner
  - MIDI-comparable 10um sensitivity
  - parallel L&N observations possible
  - FDR in March 2012
  - first light 2016
- L-band offers
  - higher angular resolution
  - filling the gap between K&N
- crucial to understand the inner torus
Now, let’s switch the resolution gear for the last few slides...
LINC: AGN in their inner galactic environment

- Michelson interferometers with large apertures (VLTI and Keck) offer the highest angular resolution, but minimal field-of-view (<100mas)
- 8-10m Adaptive optics / HST deliver imaging with >= 50-100mas resolution
- the LBT-NIR beam-combiner LINC-NIRVANA aims at combining the best of both worlds:
  - 10-20mas resolution, but 10” FoV (even larger with MCAO)
  - Dynamic range and sensitivity of imaging comparable to AO
  - Ideal to study the inner parts of active galaxies, using the AGN as guiding source
• LincNirvana is the Fizeau-type imaging interferometer of the LBT
  • broad / narrow band images in J/H/K at 10-20 mas resolution
  • about 3x better than 8-10mAO

• Adaptive Optics in two phases
  • LINC: classical on-axis SCAO
  • NIRVANA: multilayer MCAO

• OPD control to stabilize the PSF fringes
Linc-Nirvana specifics

- Homothetic imaging

- Large field of view of 60x90\" (vs. 50mas for 8m-Michelson interferometer), thanks to Fizeau interferometry and MCAO

- Both the phase-reference and the 10\"x10\" science field can be placed anywhere in this FoV

- Piston control: a single optical element for the total FoV
LINC: AGN in their inner galactic environment

- first light in 2014 for LINC mode
- throughput-performance
  - $V=16\text{-}17m$ for AO, $K=13\text{-}14m$ for FT
  - surf. bright. sensitivity at diffraction limit: $>18\text{mag/sqarcsec}$
- a few hundred AGN in the local universe observable at $5\text{-}10\text{pc-scale}$ (at $z=0.02$)
LINC – some AGN science cases

- jet in M87, location and time evolution
- dust and morphology of the extended AGN emission line region
- narrow-band imaging of ionization lines and winds
- nuclear star formation discs in ellipticals
- details of double active nuclei
- systematic study of AGN properties in Hubble-type-clean samples of statistical significance (10s-100s)
- ...

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There is a lot of exiting work and results to come in the next decade.

Thank you for your attention.