Resolving the nuclear dust structure in Centaurus A

1 July 2009
The Many Faces of Centaurus A, Sydney

Leonard Burtscher
burtscher@mpia.de

Supervisor: Klaus Meisenheimer
and with W. Jaffe, K. Tristram

Max-Planck-Institute for Astronomy, Heidelberg, Germany
## Active Galactic Nuclei

<table>
<thead>
<tr>
<th>Component</th>
<th>Physical Size</th>
<th>Angular Size in NGC 1068 (D=14 MPc)</th>
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<tr>
<td>Central SMBH</td>
<td>$10^{-5} \text{ pc} \times \frac{M_{BH}}{10^8 M_{\odot}}$</td>
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<td>0.15 milli-arcsec</td>
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*Logarithmic scale!*

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High-resolution studies of AGNs

Volume 22 of *The AGN paradigm* by Urry, Padovani 1995

- Super-Massive BH
- Accretion disk
- Broad-Line Region
- Narrow-Line Region
- Torus
- Jet (at least in some cases)

Central SMBH: $10^{-5} \text{ pc} \times \frac{M_{BH}}{10^8 M_{\odot}}$

Accretion disk: $\sim 10^{-3} \text{ pc}$

Broad Line Region: $\sim 0.01 \text{ pc}$

Torus: $\sim 2 \times 3 \text{ pc}$

Narrow Line Region: $\sim 300 \text{ pc}$

The starburst: $\sim 1 \text{ kpc}$
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The largest / closest AGN dust tori have an apparent size of less than 100 milli arcsec.
Resolution $\theta_{\text{min}}$ of a single dish telescope:

$$\theta_{\text{min}} \sim \frac{\lambda}{D}$$

(D: diameter of primary mirror)

(10\,$\mu$m @ 8m: 300 milli-arcsec)
High-resolution studies of AGNs  

2. Mid-IR Interferometric Observations

Interferometry

Resolution $\theta_{\text{min}}$ in interferometry:

$$\theta_{\text{min}} \sim \frac{\lambda}{2B}$$  
(B: separation of telescopes)

10µ @ 130m: 10 milli-arcsec (vs. 300 mas for a single-dish observation)
High-resolution studies of AGN

2. VLTI / MIDI

- MIDI: The Mid InfrareD Interferometric Instrument
- Min. 46 m (U2-U3), Max. 130m (U1-U4)
- N band (8-13 µm), R = 30, 230
- Two beams (UTs/ATs)
Interferometry

\[ V(u, v) \propto \int \frac{d\alpha}{d\beta} B(\alpha, \beta) e^{-2\pi i (\alpha u + \beta v)} \]

**Measured Quantity**: Visibility

*Source coordinates (RA, DEC)*

*The source brightness distribution (RA, DEC)*

*Fourier transform term*

The Visibility is the **Fourier Transform** of the source brightness distribution (Van-Cittert, Zernike)
Interferometry

Using the observed visibilities to reconstruct the image...

- **...works well in the radio** where phases and plenty of \( (u,v) \) points are available
- **...is not (yet) practical in the optical**
- need to model the source brightness distribution
High-resolution studies of AGNs

2. Mid-IR Interferometric Observations

Image = $\text{F.T.}^{-1}$(Visibility)

radio (6 cm) with partially completed VLA

mid-IR (8 µm) using all VLTI baselines

Sandqvist et al. 1982
High-resolution studies of AGNs

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Sandqvist et al. 1982
Image = $F.T^{-1}(\text{Visibility})$

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Raban et al. 2009
Image = F.T.\(^{-1}\) (Visibility)

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Sandqvist et al. 1982

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Raban et al. 2009
MIDI AGN programme

MIDI is the MID-infrared Interferometric Instrument (VLTI)

- **First direct Mid-IR observation of an AGN torus in NGC 1068** – Jaffe et al. 2004

- **Detailed studies**
  - NGC 1068 (Sy 2), Raban et al. 2009
  - Circinus (Sy 2), Tristram et al. 2008
  - Cen A (Radio Gal.), Meisenheimer et al. 2007

- **Snapshot survey** of 7 other, weaker galaxies, Tristram et al. 2009

- **Results:** torus exists, very different [temperature, chemical comp., orientation] in the three well-studied galaxies
High-resolution studies of AGNs

Cen A

Moonrise on Cerro Paranal (May 2008)
High-resolution studies of AGNs

Cen A

Centaurus

Moonrise on Cerro Paranal (May 2008)
High-resolution studies of AGNs

Cen A

ω Cen

Centaurus

Moonrise on Cerro Paranal (May 2008)
High-resolution studies of AGNs

Cen A

ω Cen

Centaurus

4°

Moonrise on Cerro Paranal (May 2008)
High-resolution studies of AGNs can be determined to less than 1% accuracy. This translates to a typical uncertainty in the velocity of the molecular hydrogen line of $\pm 5 \text{ km s}^{-1}$ and in the velocity dispersion of $\pm 10 \text{ km s}^{-1}$.

To allow for the best possible extraction of the gas lines the extraction window is centered on the expected wavelength. Its width is optimized iteratively to fully cover the width of the line and to make sure the extraction window covers the same range on the left and right of the line peak. An initial estimate of the Gaussian fit parameters (amplitude, central position, and width) was derived from a smoothed spectrum at a central position in the velocity field, near the AGN, and applied as a starting value throughout the field. This initial estimate is introduced in order to prevent fitting of spurious lines in the regions of bad pixels or strong continuum variation.

The signal-to-noise ratio of the spectra appears high enough for extracting the gas emission lines and drops rapidly to zero. Therefore, we do not spatially bin the data. We only consider the detection of the lines to be secure when their amplitude is a factor of 3 above the rms scatter of the spectrum. In this way we get an accurate fit to the lines over the entire field, with typical uncertainties of a few percent.

3. EMISSION-LINE GAS MEASUREMENTS

From the parameters of the Gaussian fit—peak value, mean wavelength, and width—we get the flux (or, surface brightness), the velocity, and the velocity dispersion for the considered gas species, [Si\textsc{vi}], Br\textsc{i}, [Fe\textsc{ii}], and H\textsc{2}. Since the stellar and nonstellar continua have been subtracted, the line flux is directly measured as $F_{\text{peak}}$. For the velocity, we take the recession velocity of Cen A's stellar body ($v_{\text{sys}} = 532 \pm 5 \text{ km s}^{-1}$; Marconi et al. 2001) as the reference and measure all line shifts with respect to this velocity.

3.1. Gas Kinematics

Figures 3 and 4 show the maps of total flux, velocity, and velocity dispersion for the detected lines of [Si\textsc{vi}], Br\textsc{i}, [Fe\textsc{ii}], and H\textsc{2}. These line maps illustrate vividly how the flux distribution and kinematics change when going from high- to low-excitation states. The highest excitation line, [Si\textsc{vi}], is dominated by a non-rotational component.

When comparing the velocity fields of [Si\textsc{vi}], [Fe\textsc{ii}], and H\textsc{2} (middle panel in Figs. 3 and 4), one notices that the velocity field of [Si\textsc{vi}] consists of two major components: rotational and translational motion. The velocity fields of [Fe\textsc{ii}] and Br\textsc{i} are dominated by rotation but are still distorted by a nonrotational component that is strongest to the lower right (southwest) of the field (blue component). These nonrotational motions seen in [Si\textsc{vi}], [Fe\textsc{ii}], and Br\textsc{i} are located close to the projected direction of the radio jet in Cen A ($P:A = 51^\circ$; Clarke et al. 1992; Fig. 3).
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High-resolution studies of AGNs

Centaurus A

MIDI observations

Credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)
Centaurus A

MIDI observations

- total: 18 (u,v) points collected with MIDI in 2005 (4) and 2008 (14)
- resolution ~ 7 mas at 8 µm
- scale: 0.019 pc / mas (D = 3.8 Mpc)
High-resolution studies of AGNs

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High-resolution studies of AGNs

Correlated flux $F_\nu$ [Jy]

wavelength $\lambda$ [\mu m]

130 m, 40°

113 m, 80°

major axis of the dust disk 148.5°

jet axis 51°
Centaurus A

- only weakly emitting dust disk ($L_{dust} \sim 0.02 \ L_{dust}$, Circinus), no geometrically thick torus
- disk $\perp$ VLBI jet axis
- disk size: $\sim 0.6 \ \text{pc} \times 0.2 \ \text{pc}$ ($\sim 70^\circ$ inclined thin disk?)
- point source flux ratio $\sim 50\%$ (synchrotron core)

bolometric luminosity of the disk (from excess over synchrotron radiation): $L_{dust} \sim 3 \times 10^{34} \ W$

(cf. Circinus: $L_{dust} \sim 2 \times 10^{36} \ W$)

resolution of the VLTI radio core (unresolved)

10.8 mas

0.2 pc

Meisenheimer et al. 2007

Burtscher et al. 2009 (in preparation)
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High-resolution studies of AGNs

Centaurus A
Connection to larger scales?

jet axis
51°

major axis of the dust disk
148.5°

10.8 mas
0.2 pc

from axis ratio
6/2: inclination
~ 70°

P.A. ~145°

R (arcsec)

i ~ 38°

Neumayer et al. 2007
Centaurus A

Extinction

- dust extinction to the core: $A_V = 14$

- After correction for extinction ($A_V \sim 14$) by dust, the mid-IR spectrum of the unresolved source fits well to the overall synchrotron SED

Meisenheimer et al. 2007
The point source unresolved MIDI point source is \( \approx 3 \) mas = 0.01 pc

\[ F_{\nu} \sim \nu^{-0.36} \]

**MIDI**
(unextinction corrected)

**MIDI**
(uncorrected)

**SSC model:**
- \( B = 26 \, \mu T \) (260 mG)
- \( \gamma_{\text{max}} = 8500 \)
- \( t_{\text{acc}} = 4 \) days
- \( \delta \sim 1; \Gamma_{\text{jet}} < 2.5 \)

Meisenheimer et al. 2007
Summary

• To test the unified model we observe the dusty torus of nearby Active Galactic Nuclei with mid-infrared interferometry

• Detailed observations of the nearest radio galaxy Centaurus A have revealed a thin $0.2 \times 0.6$ pc dust disk of low luminosity $\perp$ VLBI jet axis (work in progress...)

• About half of the MIR emission in Cen A on scales $< 1$ pc is synchrotron radiation

• Outlook: Studies of more AGNs will allow us to get statistical information, further modelling (hydro + rad. transfer) will give more physical insight