First infrared VLTI fringes on Galactic Center sources

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Abstract. We present the first VLTI observations of targets in the Galactic Center region. The encouraging results are establishing the scientific capabilities of infrared interferometry in the outstanding but – for interferometric means – distant and faint dust obscured Central Parsec. We successfully combined the light of two 8m-class telescopes in K and N band with ESO’s AMBER and MIDI beam combiners. The enigmatic dust-forming and spectrally featureless source IRS 3 could be clearly resolved into two components with different physical properties. We estimated lower limits of the 10 µm sizes of the most prominent Northern Arm bow-shocks IRS 1W, 10W, and 8. Investigations on the suitability of IRS 7 as a phase reference for long baseline interferometry at NIR wavelengths are underway.

1. Introduction
The Central Parsec of the Milky Way is due to its proximity a unique place to study star formation and evolution close to a supermassive black hole (Sgr A\textsuperscript{*}: 3.6 M\textsubscript{☉}, 7.6 kpc; Eisenhauer et al. 2005). The so-called paradox of youth in the Galactic Center (GC) describes the existence of numerous massive, young stars in the central stellar cluster, indicating an active star forming history despite the strong gravitational forces, dominated by the black hole (Genzel et al. 2003; Eckart et al. 2004; Moultaka et al. 2004). Observed dust-forming stellar phases are short-lived (e.g., massive Wolf-Rayet stars form dust for not more than 10\textsuperscript{5}–6 yr). The presence of many such sources indicates that star formation took place just a few Myr ago. The detailed study of the formation, evolution and kinematics of the circumstellar dust distribution in the GC can reveal and trace mass loss, stellar wind interaction zones, and properties of the underlying enshrouded stellar population.

Since very recently, the VLTI Interferometer (VLTI)\textsuperscript{2} offers measurements at an angular resolution on scales of a few to tens of milliarcsec (mas) in several near and mid infrared atmospheric transmission windows. The present sensitivity of the VLTI is sufficient for the investigation of the stellar dust envelopes and bow-shocks of the some sources. In the mid-infrared a two-telescope beam combiner measures the visibility modulus of the source with

\textsuperscript{1} Based on observations collected at the European Southern Observatory, Paranal, Chile (programs 073.B-0249, 075.B-0113, and 076.B-0863).
\textsuperscript{2} http://www.eso.org/projects/vlti/
respected to the used projected baseline length and position angle. The modulus can constrain
the one dimensional extension of simple target brightness distributions of circular or elliptical
shape with a constant or Gaussian radial intensity profile at a resolution of e.g. 20 mas using
a 130 m baseline length and an observing wavelengths of 10 μm. In the near-infrared three
VLTI baselines can be combined at the same time, enabling the measurement of the closure
phase in addition to the visibility moduli. This property gives valuable information about the
source asymmetry at high precision, unaltered by atmospheric and instrumental influences. We
employed the NIR instrument to analyze the properties of IRS 7. This bright supergiant is to
be used as an off-axis fringe tracking reference star for the observations of weak sources in the
central arcseconds of the GC, as soon as the star separator facility of the PRIMA instrument will be available.

2. Observations

MIDI, the Mid-Infrared Interferometric Instrument of the VLTI, combines the light of two
telemes and measures spectrally dispersed fringes in the 8-13 μm regime. We recorded the
correlated and total flux at a spectral resolution of R∼30 using the high-sensitivity mode of
MIDI. The observations of the brightest MIR-excess sources in the Central Parsec (IRS 3, 1W,
10W, 2L, 8) were conducted in June 2004 with the shortest baseline UT2-UT3 (46m). The most
compact source IRS3 was re-observed in ESO period 75 in 2005 with the UT3-UT4 baseline.
Its orientation is nearly perpendicular to UT2-UT3. Thus the new dataset complements the
uv-coverage of the previous one and enables the detection of pronounced source asymmetries.
The complete N-band flux of IRS 3 was resolved out by observations with the longest baseline
UT1-UT4 (130 m).

In March 2006 we could observe the Galactic Center for the first time in the NIR with an
optical long baseline interferometer. The AMBER instrument is capable to record spatially
dispersed fringes of a telescope- and baseline triple instantaneously. Due to technical problems,
we were capable to track fringes continuously only on the intermediate baseline of the used triple
(UT1-UT3-UT4).

3. Local dust formation around IRS 3

We presented the first fringes on IRS 3 in Pott et al. (2005). This interesting source eludes any
spectral classification so far (Tanner et al. 2006). From the late seventies on it is known to be
a hot and compact dusty source. Rieke et al. (1978) estimated a luminosity of 5·10^4 L⊙ and
a blackbody temperature of the de-reddened spectrum of about 400 K. Becklin et al. (1978)
characterized IRS 3 to be the only dusty source within the Central Parsec with intrinsic silicate
absorption of an optical depth of at least 1.3. Viehmann et al. (2006) found four other nearby
MIR sources with intrinsic silicate absorption. IRS 3 appears to show similar broadband spectral
properties as dust-enshrouded (super-)giants. AGB stars and red supergiants have been shown
to have mass loss rates in the range of 10^{-7} to 10^{-3} M⊙ yr^{-1} and stellar wind velocities of
10-20 km s^{-1} (van Loon et al. 1999). These authors have shown, that a few 10-20 carbon-rich
super-giants and AGB stars at the very tip of the AGB can dominate the mass loss of an entire
sample of thousands of mass losing stars. This underlines the importance that a few individual
stars may have for the understanding of mass loss and dust formation at the center of the Galaxy.

Viehmann et al. (2005) have observed a sharp interaction zone in the L- and M-band, where
the outer dust shell of IRS 3, resolvable with a beamwidth of a single 8m-class telescope, appears
to collide with an outflow from the central arcseconds, possibly due to the fast winds of the He-

3 http://www.eso.org/projects/vlti/instru/prima/index_prima.html
4 http://www.eso.org/instruments/midi/; Leinert et al. (2003)
5 http://www.eso.org/instruments/amber/; Petrov et al. (2003)
Figure 1. Interpretation of MIDI data of IRS 3. A model of two circular Gaussian brightness distributions fits the data best. The parameters of the model are the absolute size and the flux ratio of both components. Stars and diamonds are indicating 8 and 12 μm data, respectively. Note the relative flux increase of the larger component with wavelength. Assuming a blackbody as radiating source, this can be translated into absolute temperatures (right panel).

Figure 2. The model of the dust distribution around IRS 3, which fits the data best (Fig. 1). The intensity is plotted in logarithmic greyscale. The model consists of the sum of two circular Gaussian, as shown by the radial profiles in the right panel.

An important outcome of the spectrally dispersed visibility data is, that the wavelength dependence of the visibility modulus cannot be fitted by a single uniform disc model. The minimum requirement to a successful model are two different components of different angular size. We fitted two blackbodies to the data, representing two dust shells around the embedded stellar source. The flux distribution in each component has a radial decline of Gaussian shape. We cannot derive a relative phase shift between both components from the single-baseline data, due to the lack of most of the phase information. Thus both Gaussian components are centered on top of each other (2). Since we fit a circular-symmetric model, the visibility data can be azimuthally averaged and plotted over the uv-radius (left panel of Fig. 1). This approach is justified by the fact, that we did not observe any significant dependence of the visibility modulus.
Both figures show the maximum Fourier amplitude of the MIDI fringe search data. A fringe detection is indicated by a significant peak (left: visibility calibrator HD165135). This peak is well above the 3σ level of the search data of IRS 1W as indicated by the two horizontal lines in the right panel. Note the reduced ordinate-scale in the right panel.

Table 1. Upper correlated flux limits give lower limits of the source size at 10 μm.

| Sources with existing bow-shock models: | IRS 1W | IRS 10W |
|----------------------------------------|--------|---------|
| Total flux at 8.6micron (VISIR), (extinct. Av=25) [Jy] | 4.6 | 2.7 |
| Upper limit of the correlated flux density [Jy] | < 0.3 | < 0.25 |
| Visibility limits [1] | < 0.06 | < 0.09 |
| Width of bow-shock models [mas/AU] | > 30/240 | > 20/160 |

| Sources without existing bow-shock models: | IRS 2 | IRS 8 |
|------------------------------------------|-------|------|
| Upper limit of the correlated flux density [Jy] | < 0.4 | < 0.35 |

on the baseline position angle. We overplotted the model visibility with indicated FWHM sizes of 20 mas (160 AU) for the inner and 50 mas (400 AU) for the outer component. An important fit parameter is the wavelength-dependent flux-ratio of both components. Together with the size-ratio the flux-ratio can be translated into absolute temperatures unambiguously, if we adopt a blackbody SED for each component. The resulting temperatures are (918±100) K for the hotter inner component and (510±50) K for the cooler outer component. These simple blackbody components result in bolometric luminosities exceeding $5 \cdot 10^5 L_\odot$, which suggest that the embedded source is a massive supergiant. The results of detailed radiative transfer calculations leading to a physically self-consistent model of the circumstellar dust distribution and its chemical composition will be published soon.

4. The Northern Arm bow-shocks
A different species of strong MIR emitters is found along the northern mini-spiral. In a few arcsec distance to SgrA*, these deeply embedded sources could indicate young stellar objects and sites of star formation. But recently Tanner et al. (2005) found bow-shock-like morphologies in a NIR AO-added imaging experiment. Such bow-shocks can be created by stellar winds of evolved massive stars ($v_\infty \leq 1000$ km s$^{-1}$), moving through the ISM of the Minispiral. For the estimation of the underlying stellar parameters the morphology of the bow-shocks has to be known as well as possible.

We investigated the sizes of the bow-shocks in the MIR with MIDI. We did not detect any fringes on the bow-shocks IRS 1W, 8, and 10W or on IRS 2L. Since no technical failure of the
VLTI was apparent and we found fringes on calibrator sources regularly throughout the night, we interpret these non-detections of the correlated flux as low visibilities. That is, the sources are too extended and upper limits on the correlated flux are leading to lower limits on the extension of the bow-shocks at the observing wavelengths.

To derive $3\sigma$ upper limits on the correlated flux we investigated and flux-calibrated the fringe-search data of the MIDI experiment. The peak of the Fourier transform along the wavelength dependence of the spectrally dispersed interferometric data indicates the group delay. Its amplitude is proportional to the correlated flux of the source, if the group delay is zero and the amplitude is maximum over the scanned optical path difference range. We used this maximum Fourier amplitude of a calibrator source to flux-calibrate the fringe search data of the bow-shocks (Fig. 3). To transform the thus estimated correlated flux limits into lower limits on the bow-shock size, we added to the NIR bow-shock model of Tanner et al. (2005) a one-dimensional parameter scaling the radial FWHM of the bow-shocks. Comparing the visibility moduli of these scalable models to the measured upper limits results in lower limits of the width of two bow-shocks at 10 $\mu$m (Table 1). Furthermore we could derive an overall extension of IRS 1W by deconvolution of the acquisition image. The entire bow-shock structure extends to $\sim$350mas and indicates a significant increase of the MIR emitting bow-shock with respect to the NIR findings.

5. Phase referencing capabilities of IRS 7
The phase and closure phase of the complex visibilities bears important imaging information. A shift in image space transforms into a linear phase slope in the Fourier space of the complex visibilities. Thus in addition to full image reconstruction on the basis of a complete uv-dataset, already a few visibility phases of an unresolved target give a precise distance measurement with respect to a phase reference center. Fringe tracking and phase referencing using off-axis guide stars within an extended 2 arcmin field-of-view will become available with the star separator systems.

Within this distance, the brightest NIR source IRS 7 is the prime target for phase referencing. Its 5.5 arcsec distance to SgrA* minimizes the distance dependent atmospheric deterioration of such interferometric experiments which will possibly allow to study the accretion disc in its flaring phase at unprecedented angular resolution. Blum et al. (1996) estimated a spectral classification of M1I for IRS 7 and gave a $T_{\text{eff}} = 3600$ K. This leads to a stellar radius of about 0.5 mas at the distance to the GC, still unresolved for AMBER – a 50m projected baseline length gives an angular resolution of 8mas at 2$\mu$m and a linear scale of 8 AU/mas at the GC. Lack of an infrared excess around IRS 7 indicates the lack of a significant extended dust structure in the NIR, which would decrease the signal-to-noise ratio of interferometric measurements. Thus a visibility modulus very close to 1 and a correlated magnitude of more than K=6.6 (Ott et al. 1999) can be expected.

We observed IRS 7 with AMBER and MIDI in March and June 2006 and recorded successfully fringes in both the 2 $\mu$m and the 10 $\mu$m wavelength regimes. The publication of the flux calibrated data in underway and will clarify the suitability of IRS 7 as phase referencing source in the central parsec.

6. Outlook
The case of IRS 3 presents the capabilities of MIDI in the investigation of dusty sources at the Galactic Center. A full radiative transfer model of IRS 3 could be used to estimate its physical properties. With the upcoming external fringe tracker FINITO, the sensitivity of MIDI will increase significantly and enable us to study in detail several sources in that outstanding region. The interferometric data are constraining the dust distribution and its energetics uniquely. The first detection of fringes with AMBER on IRS 7 without external fringe tracking successfully
opens the epoch of NIR-interferometric GC observations. Different interstellar absorption as well as distinct emission properties between the NIR and the MIR domains will lead to complementing data on the stellar and dusty interstellar structures in the center of our Galaxy at highest angular resolutions.

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