

A feasibility study of future observations with MIDI and other VLTI science instruments: The example of the Galactic Center

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ABSTRACT

Interferometry with the Very Large Telescope Interferometer (VLTI) will allow imaging of the Galactic Center and the nuclei of extragalactic sources at an angular resolution of a few milliarcseconds. VLTI will be a prime instrument to study the immediate environment of the massive black hole at the center of the Milky Way. With the MID infrared Interferometric instrument (MIDI) for example the enigmatic compact dust embedded MIR-excess sources within the central parsec should be resolvable. Further the observations of external galactic nuclei will allow unprecedented measurements of physical parameters (i.e. structure and luminosity) in these systems. With the exception of a few 'self-referencing' sources these faint-target observations will benefit from the available off-axis wavefront-correction system STRAP, working on suitable guide stars (GS).

To fully exploit the use of VLTI within this context, the following questions have to be addressed among others: How feasible is blind-pointing on (faint) science targets? Are VLTI observations still efficiently feasible if these faint science targets exceed the usual angular distance (≤ 1 arcmin) to a GS candidate, enabling a standard closed-loop tip-tilt correction? How is the fringe-tracking procedure affected in densely populated regions such as the Galactic Center? What preparatory steps have to be performed to successfully observe these non-standard targets with the VLTI?

In this contribution, we present aspects for the preparation of VLTI observations, which will be conducted in the near future. Considering these example observations of the Galactic Center region, several details of observing modes are discussed, which are necessary to observe such science targets. The final goal is the definition of observational strategies that are optimized for the discussed classes of targets, which provide properties touching the limits of VLTI observability.

Keywords: Interferometry, Very Large Telescopes, Very High Angular Resolution, VLTI, MIDI, AMBER, Galactic Center, infrared stars

1. INTRODUCTION

The construction of the VLTI has progressed step by step over the past years. Since the recent start of the regular science observations with MIDI, it has entered the final phase: The usage of the VLTI as an ordinary telescope facility, providing the astronomer with the extraordinary capabilities of an optical/infrared interferometer. Although the first scientific results, based on the publicly available data of commissioning and science

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demonstration runs (for a summary see¹) are very encouraging, most of the observed targets are bright, isolated and compact sources, thus ideal targets for interferometry.

There is still only few workaday experience made with fainter targets. E.g. a number of scientifically interesting targets (deeply embedded young or evolved stars, active galactic nuclei) are too faint in the optical wavelength regime to enable the use of the Adaptive Optics devices STRAP and MACAO. In these cases the off-axis observation of a Guide Star is foreseen to enable wave-front correction and efficient target acquisition and tracking. But such a Guide Star is not always available. Also crowded fields with several sources within the field-of-view of the interferometric science instruments may bear difficulties for the standard observability and the applied fringe tracking mechanisms. Of especial interest for the general astronomical community is the question of how easy and straight forward VLTI observations close to the limiting technical capabilities can be conducted.

Thus a feasibility study is needed to test the usage of the VLTI under such adverse conditions. As described in the following sections, the region of the Galactic Center provides numerous scientifically interesting targets, which fulfill one or more of these conditions. It is therefore reasonable to extract from foreseen scientific observations of the GC region with the VLTI information and experiences for such a feasibility study. The different science cases of these observations are presented, dependent on the foreseen VLTI beam combining instrument (MIDI or AMBER for the near-infrared). As a first result of this study the capabilities of VLTI/MIDI are discussed in detail with respect to the successful preparation of similar observations.

2. VLTI ON THE GALACTIC CENTER

The Galactic Center is due to its proximity (8 ± 0.5 kpc;² a unique region to observe the surroundings of a supermassive black hole (³⁻⁵).⁶ have given a general overview of the scientific potential for interferometric observations of the center of our galaxy. Several issues can be addressed by the reduction of interferometric datasets at (near)infrared wavelengths. Even the most recently observed infrared flares from the accretion disk around the black hole itself (⁷) are within reach of the upcoming interferometers (the VLTI*, the LBT[†] and the Keck Interferometer[‡]).

A central question is the understanding of the (apparently ongoing) starformation in the central parsec. One scenario for the formation of the found massive stars is the infall of a massive dense cloud less than 10^7 yr ago (⁸). Such a cloud would have been highly compressed and became gravitationally unstable.⁹ discussed within their article different morphologies of the molecular gas such as a clumpy disk and a spiral-arm like geometry. They showed that both can lead to the ongoing star formation in the Galactic Center as observed (e.g.,^{10 11}).

2.1. MIDI

MIDI is the mid-infrared two-beam combining facility at the VLTI. It was developed by an international consortium under the leadership of the Max-Planck Institut für Astronomie in Heidelberg, Germany. The first commissioning phase has been finished successfully. The data of the Science Verification Programme are publicly available in the ESO data archive[§]. And although the number of commissioned capabilities and observing modes are still limited with respect to the final variety of possible fields of application, already the first extragalactic target (NGC 1068) has been observed several times and led to intriguing results (¹²).

In April 2004 for the first time the usage of MIDI was offered to the whole astrophysical community. To give an idea of the (at the moment) possible astrophysical applications, some key values are listed in Table 1. In the next section MIDI observations of sources in the Galactic Center are presented. The observations will be conducted in July 2004, when the GC is well visible from Cerro Paranal. Because these targets are close to MIDI's (current) instrumental requirements, valuable experience in observing faint targets, within a crowded field of several sources, and with possible position uncertainties will be made (cf. Sect. 2.1.2).

*Very Large Telescope Interferometer at ESO's Paranal Observatory; <http://www.eso.org/projects/vlti/>

†Large Binocular Telescope in Arizona, <http://medusa.as.arizona.edu/lbto/>

‡atop Mauna Kea; http://planetquest.jpl.nasa.gov/Keck/keck_index.html

§<http://archive.eso.org/>

Wavelength coverage	N-band (8-13 μ m)
Limiting magnitude ¹	1 Jy
Available baselines	UT2-UT3(47 m), UT3-UT4(63 m), UT2-UT4(89 m)
Interferometric resolution in N-band	40 mas with 50 m projected baseline length
Target acquisition FOV	2 arcsec
Fringe spectral dispersion	Prism (R=30), Grism (R=230)
Slit for spectral dispersion	Width=0.52 arcsec on sky
Spectral filtering	entire N-band
Fringe acquisition mode	Fourier Mode: 5 points/fringe, 10 fringes/scan (indicative)
Fringe tracking	Internal (coherencing from data in Fourier mode)
tip-/tilt correction	STRAP unit in Coudé focus of the UT's
tip-/tilt requirements	V \leq 16; off-axis (max 1') Guide Star possible

Table 1. The offered MIDI observing modes in ESO's Period 74 (Oct.'04-Mar.'05). More and most recent information on these continuously changing data are presented on the web: <http://www.eso.org/instruments/midi/index.html>.

¹: refers to the correlated flux of the observed target, i.e. the radiated flux density reduced by the interferometric visibility, which depends on the observing wavelength, baseline and the target's brightness distribution

2.1.1. Mid-infrared Sources

Beside the population of young massive HeI stars (cf. Sect. 2.3) there have been found at least half a dozen dust embedded sources with featureless K-band spectra within the central parsec. The nature of these strong 10 μ m sources (IRS 21, IRS 1W, IRS 10W, IRS 3, etc.) is rather unclear. Initially¹³ suggested IRS 21 to be an externally heated, high-density dust clump. Until recently the observational findings let them appear to be young stellar objects. More properties were published, such as the strong polarization (17% at 2 μ m;^{10, 14}), the MIR excess and featureless K-band spectra. Thus¹⁰ and¹⁵ proposed to classify IRS 21 rather as protostar or embedded early-type star.

Recently published diffraction-limited 2 – 25 μ m images suggest that IRS 21 is possibly a Wolf-Rayet star (¹⁶). They and¹⁷ observed with single-telescope observations extended infrared structures, which not necessarily have to be explained by young stars, still embedded in their natal molecular clouds. To understand more about these enigmatic objects, it turned out, that it is crucial to investigate the connection between the intrinsic source and its surroundings. Therefore mid-infrared observations at highest angular resolution are needed.

During summer 2004 we will observe some of these targets with the mid-infrared interferometric beam-combiner MIDI of the VLTI. The results of this observing run will show, if a bow-shock like structure (¹⁷ can be observed and confirmed in the N-band in a direct (interferometric) measurement, without deconvolution of single aperture images. From the orientation and size of this bowshock the relative motion of the embedded source within the (moving) surrounding gas/dust of the so called Northern Arm can be derived.

The involved dynamical calculations are described in some detail in (¹⁸ and references within). They obtained with the GEMINI North Telescope high resolution images of IRS 8 which has comparable properties to the other infrared sources, embedded in the Northern Arm, but is located farther away ($\sim 30''$ from GC) from the central cluster. They could derive from the morphology of the bowshock the stellar proper velocity. This can be done with similar calculations for the targets of our observations.

Thus the precise observation of a bow-shock, produced by strong stellar winds of fast moving stars in a dense gaseous medium can complement or even replace (at lower accuracy) the dynamical information of emission lines, which are not present for the discussed sample. The study of objects like IRS 1W and IRS 3 helps us to understand the physical conditions at the Galactic Center. These are dominated by the presence of the massive black hole, the star formation, the evolution of massive stars, and the properties of the interstellar gas in the extreme environment of the Galactic center. Providing the bow-shock hypothesis, these sources compress the more tenuous gas and dust of the central streamers and may therefore have vice versa an influence on the star formation.

2.1.2. VLTI/MIDI capabilities, required and tested by the Galactic Center observations

Several properties of IRS 1W, IRS 3 and the other dust embedded sources in the GC region are classifying the MIDI observations as non-standard ones, which therefore have to be carried out in visitor mode. Because of the lack of larger experience with such non-standard MIDI observations we present here as the example of our Galactic Center observations some topics of general interest for the observer of non-standard MIDI targets.

- The targets are only bright in the mid-infrared range. What does this imply for the observability?

All optical observations of the Galactic Center suffer from very high extinction at optical wavelengths (about 30 magnitudes) due to the high amount of interstellar dust along the line of sight. But also other interesting mid-infrared sources are often deeply dust-embedded and not visible in the optical, because mostly thermally heated dust and gas is radiating at $10\ \mu\text{m}$. This complicates both the target acquisition and the tip-/tilt correction, done by the STRAP unit in the Coudé-foci of the Unit Telescopes (see¹⁹ for an introduction into the Adaptive Optics system of the VLTI).

The best solution is given by a natural Guide Star within the 2 arcmin FOV of the UT's Coudé-focus[¶], fulfilling the $V \leq 16$ mag requirement of the STRAP unit. Then the tip-/tilt correction ensures, that MIDI is illuminated constantly with a coordinate precision of ~ 0.05 arcsec, whereas without correction the reimaged image will move around due to atmospheric turbulences and lower the coordinate precision down to about 0.2 arcsec.

Fortunately there is such a Guide Star within reach of the Galactic Center. But several tests have shown, that also if the STRAP unit cannot be used to stabilize the image, the target can be successfully acquired by MIDI, if the target coordinates are precise enough.

- How are deficient coordinates affecting the target acquisition?

This again may be an important issue for several MIDI observations, because often the mid-infrared data are relying on low-resolution observations^{||}. Only most recently high-resolution mid-infrared imagers at 8-meter class telescopes are upcoming in the Southern Hemisphere (VISIR at ESO's VLT and T-Recs at GEMINI South). But both are still under comissioning or inaugurated most recently.

Also without matching the STRAP requirements the VLT's field stabilization is tracking the source coordinates with $\leq 0.1''$ accuracy. Therefore the major problem is the small FOV of 2 arcsec of the VLTI. If the deficiency of target coordinates are surpassing this limit, the target cannot be seen on the MIDI detector. Then a successful target acquisition can only be performed by a time consuming search on the sky, which is strongly exacerbated, if the science target is visible only at mid-infrared wavelengths^{**}. This case should *always* be excluded by the astronomer by pre-imaging the source at the highest available resolution to avoid waste of the given time, which is especially valuable, because until now an uncalibrated visibility measurement takes 20-30 minutes.

Another stumbling block to a successful fringe measurement is the limiting magnitude requirement of the target itself (Tab. 1).

- Does the *correlated* flux density of the target surpass 1 Jy?

In general this issue leads to the same advice as the previous one: Only from modern high-resolution single-telescope observations there is a reasonable chance to derive the expected visibility at the needed level of accuracy to predict the correlated flux^{††}. To explain this important observation preparation we present in Fig. 1 the procedure in some detail at the example of Galactic Center sources IRS 1W and IRS 3. The panel *c* shows linear cuts through the seeing limited images. The comparison with the totally unresolved source IRS 7 shows

[¶]i.e. the limiting distance between science target and source is about 1 arcmin

^{||}e.g. IRAS Sky Survey Atlas shows images with a resolution of 4-5 arcmin; cf. <http://irsa.ipac.caltech.edu/IRASdocs/issa.exp.sup/>

^{**}the technical CCDs in the Nasmyth/Coudé foci of the UT's are blind in N-band

^{††}which is the product of the visibility and the flux

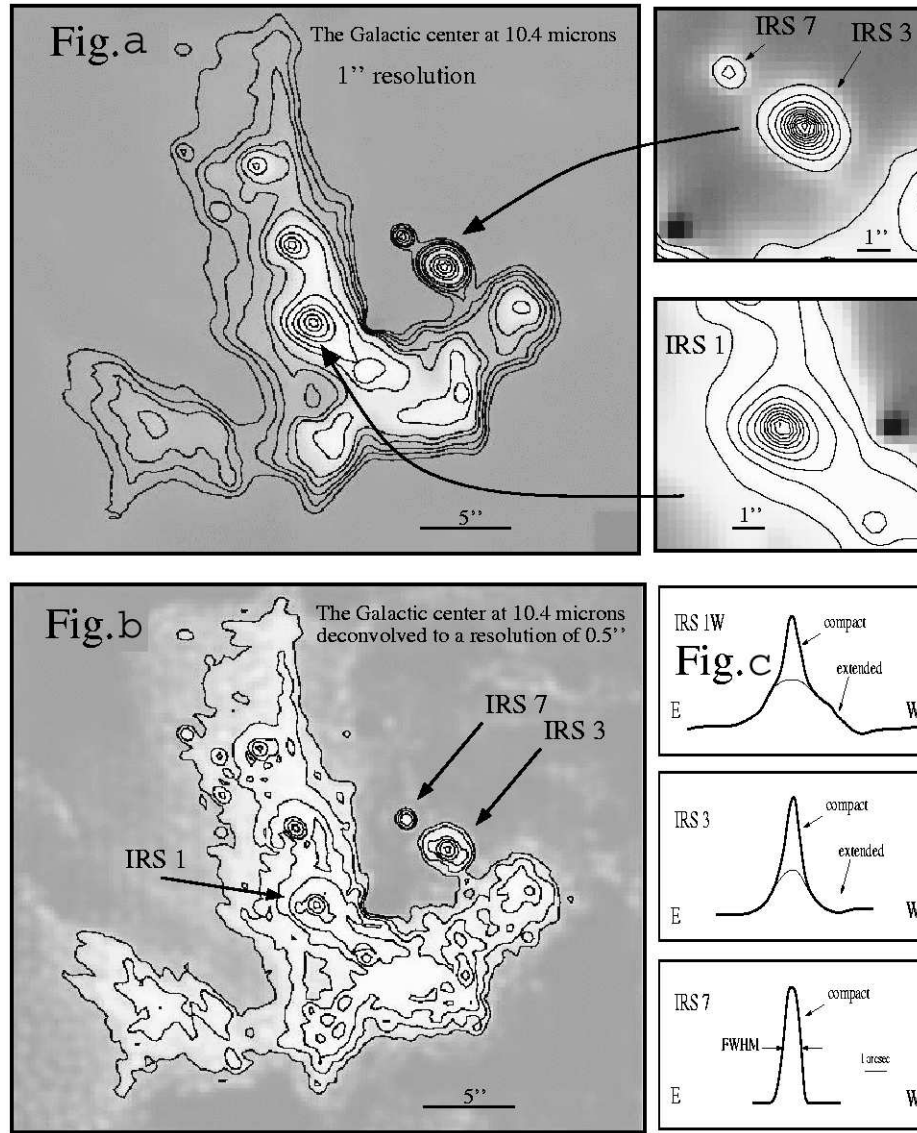


Figure 1. a: $10.4\mu\text{m}$ 1 arcsec resolution image of the Galactic Center obtained at the UKIRT (2.5, 3.75, 5, 7.5, 10, 17.5, 25, 37.5, 50, 75, 100 % of the peak brightness). The total mid-infrared flux of IRS 1W, which contains within its extension of $\sim 2.5''$ the brightest compact MIR source within the entire central cluster, rises over the N-band from 35 Jy at $8.3\mu\text{m}$ up to 71 Jy at $12.4\mu\text{m}$ (¹³). Panels to the right show the region around IRS1W and IRS3; **b:** The same image deconvolved to a resolution of about 0.5'' with the Richardson-Lucy deconvolution algorithm; **c:** RA cuts through IRS1W, IRS3, and IRS7 in the seeing limited image. All three images show that there are compact $\leq 0.3''$ source components at the centers of IRS1W and IRS3. Here we have indicated the compact components in comparison to the unresolved source IRS 7. For IRS 1W and IRS 3 we show the compact and extended flux distributions separately.

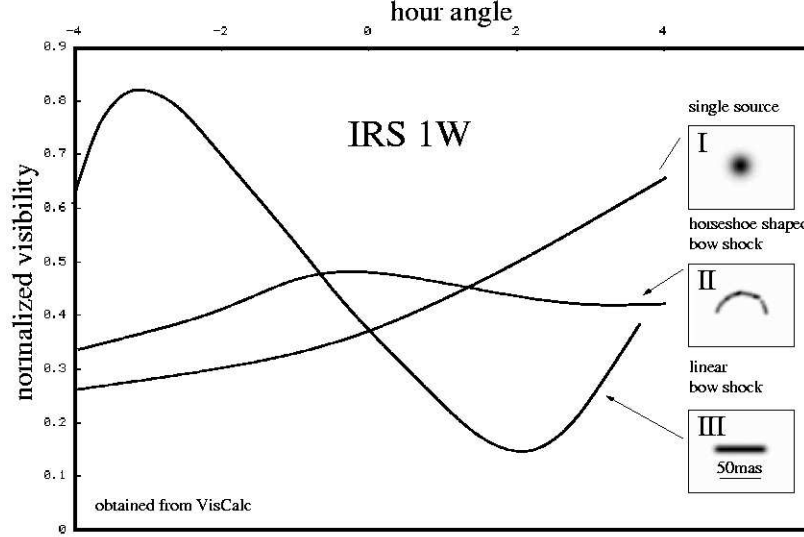


Figure 2. Calculation of the change of modelled visibilities with the hour angle. The used parameters are: Baseline UT2-UT3, source coordinates of IRS 1W and observation in July.

that our targets are composed of an extended and a compact component with respect to the UKIRT PSF at $10.4 \mu\text{m}$. Components of arcsec-extension will be fully resolved by MIDI at all available baselines and will not contribute to the measured fringe contrast. The question of the correlated flux is transformed to the extension of the compact component. Of course single-telescope observations can only lead to upper limits of source size, detectable by MIDI.

In our example both IRS 1W and IRS 3 contain compact components of less than $0.3''$ angular size. Sometimes further hints on the MIR size of sources may be deducible from NIR data sets. But this has to be done very carefully and cannot replace a mid-infrared pre-imaging. In most cases the intrinsic physical radiation processes which account for the observed radiation are rather different in both wavelength-regimes.

The last step is to calculate the visibility from the expected source size. The online-tool *VLTI Visibility Calculator* is created for this task and is available on the webpages of the European Southern Observatory^{††}.

This is what the astronomer can do before the observation. If the brightness distribution of the source will result in fringe detections by MIDI, can only definitively be shown by the observation itself. To demonstrate to the general astronomer, presumably a novice in interferometry, how strongly the visibility (and therefore the interferometric detectability) still depends on the source structure, we calculated different scenarios of IRS 1W on the estimated source size order of magnitude (Fig. 2). Further the figure shows immediately that *no* fringe detection at the beginning of the night not necessarily means: *no* fringes at all! This fact always has to be taken into account to fully exploit the given MIDI time.

Further questions may be interesting and can be answered by the presented observations:

- How can the system handle crowded fields like the GC region, where several sources within the Coudé-field-of-view are present.
- Can the observer efficiently handle the complex VLTI system to rapidly switch between the scientific target and reference sources?

^{††}<http://www.eso.org/observing/etc/>

Name	Central wavelength (μm)	FWHM (μm)	Comment
[<i>ArIII</i>]	9.00	0.14	PAH1
[<i>SIV</i>]	10.48	0.16	
N11.3	11.28	0.61	PAH2
[<i>NeII</i>]	12.80	0.22	
N8.6	8.6	0.43	PAH1
N8.7	8.78	1.75	Short N-band
SiC	11.81	2.36	
Nband	10.40	5.25	Wide N-band

Table 2. Different spectral filters, which can be used in the MIDI target acquisition mode to record images with one UT.

At the current state of preparatory work, these questions cannot be answered extensively. But it was recently verified, that during the target-acquisition phase with closed tip-/tilt loop an R.A./Decl. offset within the 2 arcmin FOV of the Coudé foci can be performed easily within less than 10 min. And the observer can offset even further if the decreased image quality is accepted due to the loss of the tip-/tilt correction.

Finally two issues are interesting for the observation of faint MIR targets:

- How feasible/fruitful is a fringe measurement, if the tip/tilt correction in the Coudé-focus is not working? Either because of a lacking Guide Star or because of thin cirrus inhibiting the applicability of such a guide star.
- And last but not least, how to use efficiently the MIDI time, if the correlated source flux is below the detection limit.

Of course there is no general answer to this topic. But if the correlated flux density of the science target is in general high enough for MIDI, often also without tip/tilt-correction a fringe measurement has been proven to be feasible. Further, if no fringes are detectable due to low intrinsic source visibility, the high-quality state-of-the-art equipment of MIDI offers currently the possibility, to record target acquisition images with the MIDI science detector applying wide- and different narrow-band filters (see Table 2). The FWHM of the single-telescope PSF can be expected to be about 250 mas.

The concrete strategies to fully exploit the actual MIDI capabilities as discussed above will be fixed and the outcome will lead to 'Notes for MIDI astronomers' which should help in the preparation and conduction of non-standard observations, due to the faint and/or complex source structure. A first version is already available at the Paranal Observatory. For more information or a copy please contact J.-U. Pott.

2.2. AMBER

The near infrared focal instrument AMBER of the VLTI combines three beams in J, H and K band (1-2.5 μm). Without external fringe tracker the limiting K-band magnitudes are $K \sim 13$ for the use of the 8 m Unit Telescopes (UT) and $K \sim 10$ for the use of the 1.8 m Auxiliary Telescopes (AT). If a bright ($H < 13$) reference star is present within 1 arcmin distance to the science target, the limiting magnitudes may rise up to $K \sim 20$ (UTs) and $K \sim 16$ (ATs), depending on the observing mode. The maximum spectroscopic resolution is foreseen to reach 10 000. While AMBER is currently under commissioning, the public scientific usage is foreseen to start in April 2005. Details on the current instrument status are given in²⁰ and references therein.

In the next section we present VLTI observations of the Galactic Center region in the near infrared. They will test the capabilities of AMBER in the densely populated GC region in a similar way as pointed out in detail Sect. 2.1.2 for the MIDI observations.

2.2.1. Stellar Orbits

The actual measurements of mass and density of the supermassive black hole in the Galactic Center are based on dynamic measurements of the stars orbiting the black hole (e.g.^{5,21}). The high angular resolution data was obtained using Speckle techniques (res~100 mas in K, Sharp at the NTT) and later on Adaptive Optics (res~60 mas in K, NACO at the VLT-UT4). The precision of the orbital parameters, derived from the maps and spectra, can be significantly improved by K-band interferometric images, obtained with the 3-beam combining device AMBER. Using closure phases the original brightness distribution can be restored. Within the AMBER field-of-view of $\sim 0.25''$ at $2\mu\text{m}$, employing the ATs (the FOV is given by the size of the Airy Disks of the single telescopes), a number of sources can be observed in the Galactic Center region. Even the infrared flares of the accretion disk around the black hole at maximum emission were shown to be as bright as some of the stars⁷ and therefore well above the magnitude limit for AMBER observations with an available bright off-axis reference source.

With the maximum AT separation of about 200 m the interferometric angular resolution in K-band will be about 2 mas. Thus the resolution may rise about one order of magnitude employing the VLTI. With higher precision in the stellar motion data the ambiguity between Keplerian and non-Keplerian orbit fits to the data may be resolvable (cf.²²). Thus the investigation of the central gravitational potential will benefit a lot from the application of VLTI-AMBER.

2.3. The cluster of massive stars

The luminosity of the entire central parsec of our Galaxy is dominated by a cluster of massive stars, formed only a few million years ago (e.g.²³). They observed strong stellar winds ($\dot{M} \sim (5 - 80) \cdot 10^{-5} M_{\odot}/\text{yr}$) with relatively small outflow velocities ($V \sim 300$ to 1000 km/s). These findings together with effective temperatures ($17\text{-}30 \cdot 10^3 \text{K}$) and strong enhanced helium abundances ($N_{\text{He}}/N_{\text{H}} > 0.5$) let them conclude, that the observed HeI emission line stars are evolved blue supergiants. These stars appear to be close to the Ofp9/Wolf-Rayet evolutionary stage and power the central cluster. Because of the huge source density in the central stellar cluster, single-telescope resolutions of a few hundred mas cannot distinguish between close double/multiple stars systems. The linear scale of $(0.5'' \sim 20 \text{ mpc} \sim 4 \cdot 10^3 \text{ AU}$ at a Distance of $\sim 8 \text{ kpc}$) is huge with respect to the stellar radii of HeI stars. The K-band resolution of AMBER is needed to resolve these sources, if they are in binary systems (e.g. IRS 16SW in²⁴). The correct number of stars is needed to derive the number of ionizing photons and thus understand, if the massive stars can account for the entire observed HeI continuum radiation of the Galactic Center. Binarity and mass transfer between components would also help to explain the unexpectedly large number of He-stars at the center.

3. SUMMARY

It was shown, that in the Galactic Center region numerous scientifically interesting targets exist. Their observation will at the same time reveal unprecedented scientific results as well as test the capabilities of VLTI on faint, embedded targets, partially providing properties, which are not ideal for interferometric observations. Thus valuable experience for future VLTI observations will be made.

We presented the preparation of VLTI/MIDI observations of the enigmatic dust embedded sources in the Galactic Center in detail and discussed thereby different stumbling blocks, which may hamper or even inhibit successful observations of non-standard targets. The results were rather encouraging. It was shown, that blind target acquisition is efficiently feasible, if coordinates of intermediate precision (subarcsec resolution is provided by all modern MIR observation with large single-telescope observations) are given. Several other aspect were mentioned to give the reader an idea of the feasibility of VLTI observations, close to the offered capabilities.

The experiences with MIDI observing faint targets will help to conduct observations on extragalactic targets in the near future, because the properties of extragalactic targets are as well close to MIDI's (current) instrumental capabilities.

Because of the permanent expansion of the VLTI in general and of the ongoing commissioning runs of the science instruments and other VLTI facilities, the capabilities of the VLTI, offered to the astronomical community, will be enhanced continuously. Therefore interested astronomers are requested to contact the authors and respective instrument responsables for most recent information.

ACKNOWLEDGMENTS

We thank Anders Wallander and Sebastien Morel for substantial discussions. This work has been partly supported by the Deutsche Forschungsgemeinschaft (DFG) via SFB494 at the University of Cologne.

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