Interferometric Observations of the Galactic Center: LBT and VLTI

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ABSTRACT

Current and future opportunities for interferometric observations of the Galactic Center in the near- and mid-infrared (NIR/MIR) wavelength domain are highlighted. Main emphasis is being put on the Large Binocular Telescope (LBT) and the Very Large Telescope Interferometer (VLTI). The Galactic Center measurements of stellar orbits and strongly variable NIR and X-ray emission from Sagittarius A* (SgrA*) at the center of the Milky Way have provided the strongest evidence so far that the dark mass concentration at this position is associated with a super massive black hole. Similar dark mass concentrations seen in many galactic nuclei are most likely super massive black holes as well. High angular resolution interferometric observations in the NIR/MIR will provide key information on the central massive black hole and the stellar cluster it is embedded in. These observations have already started: Recent results on the luminous dust enshrowded star IRS3 using MIDI at the VLTI are presented and future scientific possibilities in the GC using MIDI at the VLTI in the MIR and GRAVITY in the NIR are highlighted. As a NIR wide field interferometric imager offering an angular resolution of about 10 milliarcseconds LINC/NIRVANA at the Large Binocular Telescope will be an ideal instrument for imaging galactic nuclei including the center of the Milky Way.

Keywords: Instruments: MIDI/VLTI, LINC/NIRVANA, GRAVITY/VLTI, Telescopes: LBT, VLTI, Sience: The Galactic Center

1. INTRODUCTION

The proximity of the Galactic Center means that it is the ideal laboratory for studying the central super-massive black hole at the position of SgrA* (Sagittarius A*) as well as the stellar populations, dynamics, and stellar interactions within the environment of this super-massive object. Interferometric observations at NIR/MIR wavelengths will allow us to carry out detailed investigations on the distribution and kinematics of stars, gas and dust in this area on the smallest scales.

2. MIDI - VLTI

The VLTI allows sensitive interferometric observations with a very large collecting area and a number of high-throughput beam combiner instruments*. In the MIR MIDI (MID-infrared Interferometric instrument; Leinert et al. 1998) is the interferometric VLTI camera for N-band (8 to 13 μm) interferometry. MIDI is operational with an angular resolution of 20 mas on a 100 m baseline. The limiting magnitudes are N=4 and 5.8 (with reference source). The field of view (FOV) is of the order of $\pm$1". MIDI is a two-beam combiner giving wavelength dependent values of fringe visibility moduli (samples in the (u,v) plane) with a spectral resolution of R=30 or R=230.

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3. LINC/NIRVANA - LBT

As a near-infrared (NIR) wide field interferometric imager offering an angular resolution of about 10 milliarcseconds LINC/NIRVANA† at the Large Binocular Telescope (LBT) will be an ideal instrument for imaging of galactic nuclei including the center of the Milky Way. The Galactic Center measurements of stellar orbits and strongly variable NIR and X-ray emission from Sagittarius A* have provided the most convincing evidence for the presence of a 3.7 million solar mass black hole at the position of SgrA* (Eckart & Genzel 1996, 1997, Ghez et al. 1998, 2003 Eckart et al. 2002, Genzel et al. 2003, Schödel 2002, Eisenhauer et al. 2004, see also Eckart, Schödel & Straubmeier 2005 for a review). Observations with LINC/NIRVANA will allow simultaneously to investigate the stellar dynamics of the entire central cluster, to determine the amount of extended mass within the cusp region, and to monitor the activity of the black hole at separations of only about 10 light hours or 15 Schwarzschild radii.

The LBT consists of two 8.4m diameter mirrors in one single mount over a fixed baseline of 14.4m. The Telescope is located on Mt.Graham near Tucson, Arizona. Virtually all baselines ranging from 0 to 22.8m are sampled by the 110m^2 collecting area and the resolving power at 1.25μm wavelength will be $\sim$9mas. The NIR beam combination will be carried out by LINC (Herbst et al. 2003, Straubmeier et al. 2003, Straubmeier et al. 2004a, 2004b, 2004c, Bertram et al. 2004, 2005, Beckmann et al. 2004, Eckart et al. 2004). As a Fizeau interferometer the LBT will have an exceptionally large imaging FOV of the order of at least 1 arc-minute. Using MCAO techniques (multi conjugate adaptive optics; LBT: Ragazzoni et al. 2003, 2005, Egner et al. 2004) this will be extended to at least 2 arcminutes.

The NIR is a sensitive tracer of the mass dominating (older) stellar populations in galaxies. Compared to optical wavelengths the NIR is also less affected by extinction, but still sensitive to the distribution and contribution of dust. Studying the detailed morphology, dynamics and composition of the sources within the central stellar cluster is therefore ideally done in the NIR. The extinction towards the Galactic Center is of the order of A_V=27 in the optical and $A_K \sim 0.1 \times A_V$=2.7 in the infrared.

Several challenging technical requirements will have to be fullfilled by LINC/NIRVANA in order to efficiently observe the Galactic Center. The Adaptive Optics will have to work at low elevations (best down to 20^o; at the location of the LBT the culmination of the Galactic Center will be around $\delta \sim 30^o$). Currently the AO will operate with optical guide stars. The best suited optical reference star is located at a distance of about 30" NNE of SgrA* with R=13.2. In NIRVANA-mode a variety of reference stars can be used within a $\sim$1' field. For the Galactic Center NIR wavefront sensing would be best using IRS7 K$\sim$7 located 5.5" N of SgrA*. In order to carry out deep investigations of stellar populations narrow band filters in JHK bands are required - both at line and continuum wavelengths. The central He-stars are bright - exposures longer than of the order of a second in JHK broad band will be difficult in combination with full AO correction. For imaging narrow band filters could be used for the central regions and wider band filters for the outer regions of the central stellar cluster. Polarization measurements are highly desirable. They require two Wollaston prisms positioned orthogonally to each other. Polarization calibration could be done within the target field on stars in the central cluster.

4. GRAVITY - VLTI

GRAVITY is a NIR second generation NIR beam combiner camera for the VLTI (Eisenhauer et al. 2005). To fully exploit the interferometric capabilities of an upgraded VLTI system an IR AO assisted, two-object beam-combiner instrument is needed. Consequently, the second generation instrument GRAVITY has been proposed‡. For a variety of astronomical key measurements this instrument will open an unique window for interferometric observations. As one of the key scientific projects GRAVITY will for the first time allow to directly probe the regimes of strong gravity close to the SgrA* black hole. Its top level requirements in the context of the VLTI facility will go beyond those of the first generation of instruments and the upcoming PRIMA facility (Delplancke et al. 2000; see also Wilhelm et al. (2002) and Delplancke 2004b).

†LBT: medusa.as.arizona.edu/lbto/; LBT/Köln: www.ph1.uni-koeln.de/workgroups/astro-instrumentation/LINC/; LBT/LINC: www.mpia-hd.mpg.de/LINC/index.html;

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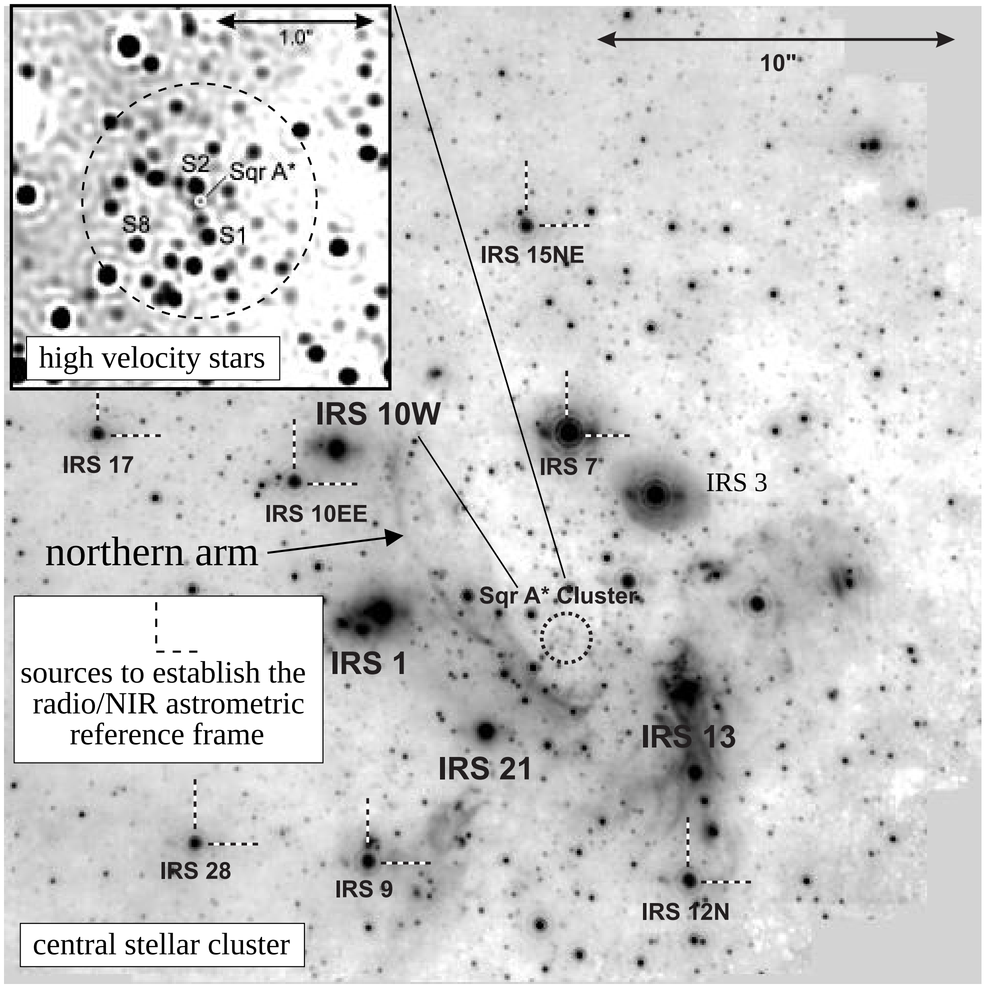

Figure 1. L-band (3.8μm wavelength) image of the Galactic Center region with a K-band (2.2μm) zoom into the central arcsecond. The images were taken with the NACO system at the ESO VLT UT4.

In order to efficiently observe the Galactic Center certain functional requirements of the interferometric system have to be fulfilled. It has to be optimized for NIR wavefront sensing for observations of red objects and has to provide improved capabilities for simultaneous astrometry using multiple baselines. For this the availability of Star Separator Systems (STSs) is essential. These systems allow for a simultaneous interferometric observation of the science target and a brighter references source (Strehl $\simeq$ 50% for $m_K \geq 10$). Two of the four 8.2m diameter Unit Telescopes (UTs) will be equipped with STSs by the European Southern Observatory (ESO). For the remaining two STSs full financial resources have been put forward by the MPE Garching and the University of Cologne[§]. With four fringe sensing units (FSUs) and differential delay lines (DDLs) the VLTI facility will be fully operational in the NIR. The two channel STSs will then allow to perform phase-referenced imaging on six baselines ($m_K \geq 19$ in one hour observing time). Such a system will be able to perform narrow-angle astrometry ($\simeq$ 10 μas accuracy) for distances less than two arcseconds and beyond (Eisenhauer 2006 and references therein).

[§]provided by University of Cologne, the Federal State of North-Rhine Westfalia and BMBF national science resources

5. SCIENCE CAPABILITIES OF LINC/NIRVANA AND GRAVITY FOR THE GALACTIC CENTER

5.1. The Central Arcsecond

The high velocity stars in the central cusp allow us to probe the immediate surroundings of the super-massive black hole (Fig. 1). Studying the kinematics of the inner stars enables us to determine the central mass and mass density with high accuracy. A significant fraction of the stars in the cusp are apparently early type stars (Eckart & Genzel 1997, Gezari et al. 2002, Genzel et al. 2003a, 2003b, Ghez 2003a). The updated estimate of the distance to the Galactic center from the S2 orbit fit is $R_o = 7.62 \pm 0.32$ kpc, resulting in a central mass value of $(3.61 \pm 0.32) \times 10^6 M_\odot$.

Unsolved questions are - how these young objects can be present there - how the stellar population in the cusp evolves, and - how this population of stars and its evolution is linked to the stellar content of the cluster at larger radii. To determine the nature of these cusp stars it is essential to obtain high quality high resolution spectra of them. This is difficult since they are all located within 2" from the center. High angular resolution techniques are needed to separate them from each other and from the gas of the mini-spiral which emits contaminating Hydrogen and Helium recombination lines.

Following the first low resolution speckle spectroscopy spectra for a few bright objects by Ott et al.(1997), Gezari et al. (2002) and Ghez et al. (2003) presented the first high resolution K-band spectra with $\lambda / \Delta\lambda \sim 2600$ of some of the $K = 14 - 16^m$ high velocity stars in the central cusp. For the first time they applied adaptive optics in combination with spectroscopy on this target using the AO system at the 10 m Keck telescope and the Near-Infrared Camera 2 (McLean & Sprayberry 2003). Eisenhauer et al. (2003, 2005) report on 75 mas resolution, NIR imaging spectroscopy within the central 30 light-days of the Galactic center, using the adaptive optics assisted integral-field spectrometer SINFONI (Eisenhauer et al. 2003) on the ESO VLT. To a limiting magnitude of $K \sim 16^m$ 13 of 17 stars out to 0.7" from the central black hole have spectral properties of B0-B9 main-sequence stars. These stars appear to have properties similar to solar neighborhood stars. Based on the 2.1127 μm He I line width, all brighter early-type stars have normal rotation velocities. Eisenhauer et al. (2003, 2005) combine the new radial velocities with SHARP/NACO astrometry to derive improved three-dimensional stellar orbits for six of these high velocities stars in the central cusp. Their orientations in space appears to be random. Their orbital planes are not co-aligned with those of the two disks of massive young stars 1"-10" from Sgr A* (Genzel et al. 2003). It appears implausible that the cusp stars have been located/formed in these disks and then migrated inward. It appear to be more likely that these stars were brought into the central light-month by strong stellar scattering events. Using the LBT and VLTI we plan to explore the physics and time evolution of stellar dynamics in this enigmatic region. The high stellar density makes stellar passages in the immediate vicinity (less than 50 AU) of the MBH very likely.

$\odot$ Key scientific target therefore is the investigation of stellar dynamics at the very center with the goal to discover and monitor the motions of stars in the immediate vicinity of SgrA*. A further project is to search for signs of Newtonian and/or relativistic precession.

5.2. The Black Hole at the position of SgrA*

The identification of SgrA* in the NIR allows us to perform multi-wavelength studies of its variability and the accretion process of this low luminosity galactic nucleus in detail.

5.2.1. NIR polarization and NIR/X-ray variability measurements

Variable polarized NIR emission and simultaneous radio/NIR/X-ray observations of SgrA* in 2003-5 have revealed deep insights into the relativistic physics within a few 10-100 Schwarzschild radii of the super-massive black hole associated with SgrA*. We found simultaneous NIR/X-ray flare variations (Eckart et al. 2004, 2005), indications of quasi-periodicity within the NIR flares (Genzel et al. 2003a, 2003b, Eckart et al. 2006, Ghez 2003b), and highly polarized emission peaks (Eckart et al. 2006; Fig. 2). However, the radio/sub-mm/NIR observations also indicate adiabatic expansion within an SSC model and emission from a jet still has to be excluded (Eckart et al. 2005, 2006).

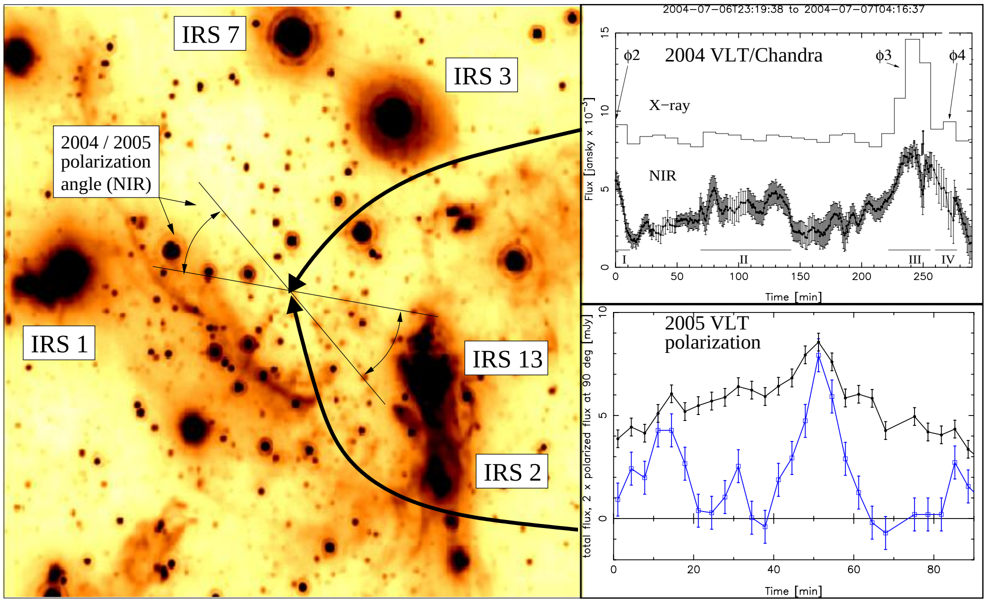

Figure 2. An image of the central 0.5×0.5 square parsec (1 arcsec $\sim$ 0.039 parsecs) of the Galactic Center at a wavelength of 3.8μm using the NACO adaptive optics system at the VLT. In addition to the stars the dust emission from the mini-spiral can be seen. The two lines centered at the position of SgrA* enclose the range over which the polarization angle varied on the sky during the 2005 and 2006 observing sessions (Eckart et al. 2006). Top right: The X-ray and NIR light curves plotted with a common time axis (Eckart et al. 2005). Bottom right: Polarized emission from the NIR counterpart SgrA*. The total de-reddened flux density light curve (black) and the de-reddened flux density at polarization angle 90^o (East over North; lower curve) corrected for the flux density measured at a PA of 0^o at which the sub-flares cannot be seen (Eckart et al. 2006).

⊙ Key scientific target: Monitor the flux density variability of SgrA* - if possible in coordinated campaigns (radio/mm/MIR/X-ray) and in polarized radio/NIR emission. In case of jet activity measurable positional shifts should occur due to the motion of NIR luminous jet components (see Paumard et al. 2005).

The new polarization measurements of the variable near-infrared emission of the SgrA* counterpart reported by Eckart et al. (2006) have been carried out using the NACO adaptive optics (AO) instrument at the ESO VLT[¶]. They find that the variable NIR emission of SgrA* is highly polarized and consists of a contribution of a non- or weakly polarized main flare with highly polarized sub-flares. The flare activity shows a quasi-periodicity of 20±3 minutes consistent with previous observations (Genzel et al. 2003a, 2003b). The highly variable and polarized emission supports that the NIR emission is non-thermal. The observations can be interpreted in a jet or temporary disk model. In the disk model the quasi-periodic flux density variations can be explained due to spots on relativistic orbits around the central MBH. Alternative explanations for the high central mass concentration involving boson or fermion balls are increasingly unlikely.

⊙ Key scientific target: Use high precision astrometric capabilities as provided through the combination of the VLT Interferometer and GRAVITY in order to measure the positional shifts due to the relativistically orbiting gas that gives rise to the observed NIR flares.

5.3. Stellar Populations

The population of the nuclear star cluster in the central half-parsec can be studied down to about three solar masses with current AO instruments, such as NACO/VLT. An increased angular resolution will decrease crowding

[¶]Based on observations at the Very Large Telescope (VLT) of the European Southern Observatory (ESO) on Paranal in Chile; Program: 271.B-5019(A).

and LINC/NIRVANA will provide observations of stars near SgrA* down to one solar mass, simultaneously over large portions of the central stellar cluster.

A main goal of the program is to solve the paradox of youth whereby a surprising number of young, massive stars lie very near the super-massive black hole SgrA*. There is now clear evidence for the presence of young, massive main sequence stars in the immediate environment of the super-massive black hole Sgr A* at the center of our Galaxy. The currently best (and very recent) explanation is formation of these stars in previously present heavy accretion disks (e.g. Nayakshin, Cuadra, Sunyaev 2004). Observations and theory indicate a top-heavy IMF. However, it is not yet clear how the S-stars, B-type main sequence stars within less than 0.05 pc of Sgr A* could form and/or whether they are part of the disks of young massive stars (see above). Progress in our understanding can be reached by classifying stars down to one solar mass into early/late type. The imaging that will be possible within the wide field of view of LINC/NIRVANA will allow us to study the colors of 10^4 to 10^5 stars with the help of narrow/intermediate band filters and provide a preliminary identification (young/hot - cool/CO-absorption bands - dust enshrowded) of the stellar population in the entire central 1 pc diameter stellar cluster.

⊙ Key scientific target is the investigation of the stellar populations at the GC with an unprecedented statistical quality supported by imaging spectroscopy. The NIR color approach (with narrow and intermediate band filters) will be 1 to 2 magnitudes more sensitive than the spectroscopic approach. Also stellar variability studies will be carried out with very high precision due to the large number of secondary reference sources in the field.

5.4. Bright stars

Bright stars are the ones for which NIR/MIR interferometric studies can be carried out most straight forwardly. For IRS 3 first results with MIDI at the VLTI have already been obtained.

5.4.1. Bow Shock sources

The unusually large number of massive, young stars in the stellar cluster at the GC (e.g. Tanner et al., 2002, 2003, 2005; Genzel et al. 2003a; Eckart et al. 2004; Moultaka et al. 2004, 2005, Viehmann et al. 2005, 2006) are indicative of an active star formation history despite the tidal forces exerted by the gravitational potential of the central SMBH. The most recent star formation episode took place not more than a few million years ago. This is indicated by the presence of numerous stars in short-lived phases of their development, such as the bright He-stars and early IR luminous giants. IRS 21, IRS 1W (Ott et al. 1999, Tanner et al. 2002, 2005) and IRS 3 (see below; Moultaka et al., 2004, 2005, Viehmann et al., 2005, 2006; Pott et al. 2005) with its 1-2 arcsec extended mid infrared (MIR) excess is one of the most prominent of these sources.

⊙ Key scientific target is the investigation of sizes, shape, kinematics, and excitation of the dust shells associated with luminous stars. The results are essential for the understanding of the physics of the stars and the GC interstellar medium (ISM).

5.4.2. Multiplicity

The upper cut-off in the mass function of stellar clusters is one of the most critical parameters in the description of the evolution. Binary stars are ideal objects for the determination of stellar masses, and eclipsing binaries can be studied comparatively easily in distant stellar systems, since they can be identified via their characteristic light curves. For the Galactic Center such a study is in progress. First results were obtained by Ott et al. (1999ApJ) through aperture photometry on deconvolved images using three different deconvolution methods. With the time coverage provided by the multi-epoch Galactic Center observations, the authors were able to show that IRS 16SW is an eclipsing binary with a period of 9.72 days. The symmetrical shape of the light curve and a hint for a second local minimum suggest that this star is indeed an eclipsing binary.

⊙ Key scientific target is the identification of additional binaries and the exploration of the hypothesis that all or most bright He-stars might be binaries. Furthermore Wolf-Rayet (i.e. hot luminous stars similar to the Galactic Center He-stars) binary systems are prime candidates for dust-formation and ideal sources for interferometry.

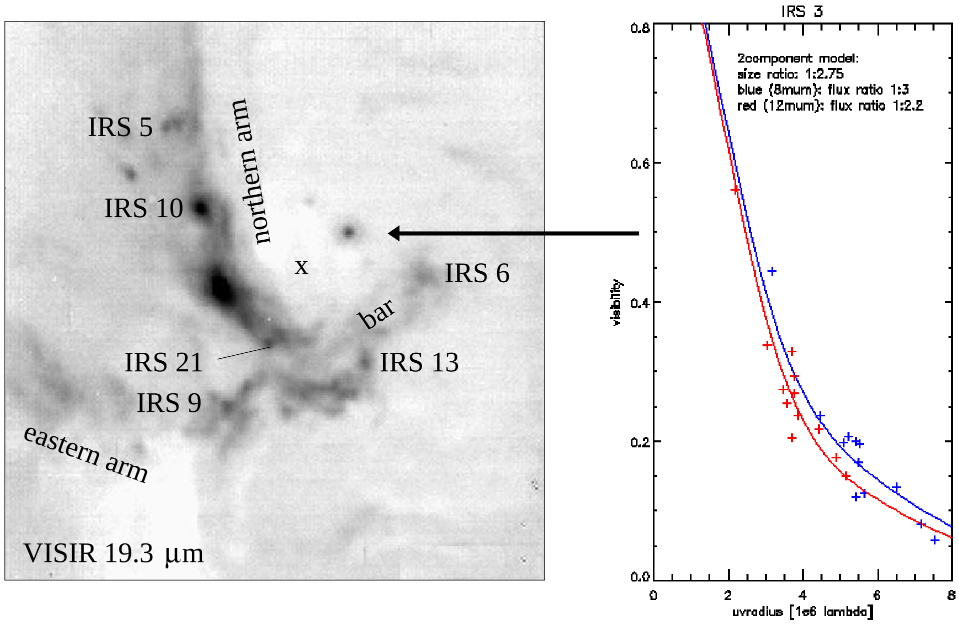

Figure 3. Left: MIR images of the central 0.5×0.5 pc^2 as taken by VISIR (Viehmann et al. 2006). Right: Visibilities of IRS 3 as obtained by MIDI at the ESO VLTI facility at 8.2μm (blue) and 12μm (red) (Pott et al. 2005 and 2006). We also show a possible two component Gaussian model with given model size and flux density ratios (compact vs. extended). Two Gaussians give a slightly better fit than two disks.

5.4.3. MIDI VLT Interferometry on IRS 3

The dust enshrowded star IRS 3 in the central light year of our galaxy was partially resolved in a recent VLTI experiment (Fig. 3). This observation is the first step in an interferometric investigation of individual sources in particular and the stellar population of the Galactic Center in general. In the late '70s (Rieke, Telesco,& Harper 1978 and Becklin et al. 1978) it was argued that IRS 3 is a dust enshrowded supergiant with a compact circumstellar dust shell. Gezari et al. (1985) identified IRS 3 as the most compact and (together with IRS 7) hottest MIR source (T$\sim$400 K) in the central cluster, with total integrated flux densities of about 30 Jy at 8 μm to 12 μm. Viehmann et al. (2005) provided evidence that the IRS 3 dust shell is interacting with the GC ISM. NIR/MIR images show a sharp interaction zone of the outer part of the dust shell with the wind arising from the IRS 16 cluster of hot, massive Helium stars.

In the recently performed VLTI experiment with MIDI we investigated the dust shell of IRS 3. The lower spectroscopic resolution used (R=30) offers dispersed visibility data over the entire N-band, as well as a spectrum of the uncorrelated flux density. The first VLTI detection of IRS 3 was achieved in June 2004: We partially resolved IRS 3 on the 47 m UT2-UT3 baseline. In 2005 we obtained data on the UT3-UT4 (62 m) and UT1-UT4 (130 m) baselines (Fig. 3). About $\sim$25% of the flux density of IRS 3 is concentrated in a compact component with a size of $\leq$40 mas (i.e. $\leq$300 AU). This agrees with the interpretation that IRS 3 is a luminous compact object in an intensive dust forming phase.

In addition, the remaining six of the seven brightest (N-band) MIR excess sources in the GC were observed (IRS 1W, 2, 8, 9, 10, 13) with the same instrumental setup (see Pott et al. 2006). Most of them are located in the Northern Arm of the ISM or associated with the mini-spiral of ionized gas and warm dust (Fig. 1). Until now none of these sources has been detected interferometrically indicating that they are more extended and/or contain fainter compact components compared to IRS 3.

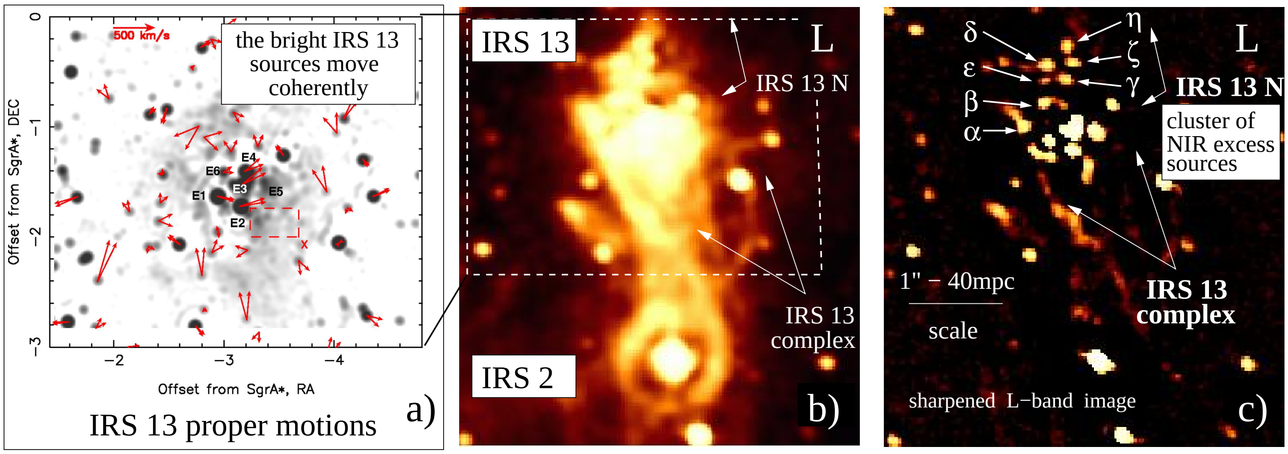

Figure 4. L' band images of the IRS 13/IRS 2 region. The image scale is given in (b). Ring structures around the brighter stars n panel (a) are artifacts of the deconvolution algorithm. Panel (b) is a high pass filtered L'-image which shows the locations of individual stars, including the newly discovered L'-band excess sources α through η. The blue source κ is located between ζ and δ (Eckart et al. 2004).

5.4.4. IRS13

The IRS 13E complex is an unusual concentration of massive, early-type stars at a projected distance of ∼0.13 pc from the Milky Way's central super-massive black hole Sagittarius A* (Sgr A*) (see Fig. 4). It has recently been suggested that IRS 13E may be the remnant of a massive stellar cluster containing an intermediate-mass black hole (IMBH) that binds its members gravitationally in the tidal field of Sgr A*. This statement is based on their similar proper motion and their common nature as massive, young stars (Maillard et al. 2004). Schödel et al. (2005) present an analysis of the proper motions in the IRS 13E region combining the currently best available data with a time line of 10 years. The authors find that an IMBH in IRS 13E must have a minimum mass of $<10^4$ $M_\odot$ if one assumes that the source complex is gravitationally bound. Two facts make it very unlikely that an IMBH exists in IRS 13E: 1) the high-mass limit derived by the proper motions and 2) the lack of a compelling evidence for a non-thermal radio and X-ray source in IRS 13E.

IRS 13E is located at a projected distance of ∼3.5 mpc or ∼130 mpc from the 3.5×10^6 $M_\odot$ black hole Sgr A*. It appears to be possible that it is associated with the counter-rotating disk of young stars (Genzel et al. 2003). In this case, it is likely to be positioned ∼120 mpc behind the plane of the sky in which SgrA* is located. With a radius of ∼0.25", a mass of roughly 1000 $M_\odot$then would be sufficient to protect the system from tidal disruption. However, as the analysis above shows, the real constraints for binding IRS 13E gravitationally result from the intrinsic proper motions of the sources in this complex. Schödel et al. (2005) took into account the unknown location of the hypothetical black hole and various possibilities for the systemic motion of IRS 13E in the gravitational potential of Sgr A*. In the most conservative case, that lead to a minimum mass to bind IRS 13E gravitationally of 7000±1800 $M_\odot$. This would confine the IMBH to a narrow region ∼0.1" northwest of E1. Outside this region, the required mass is greater than 10^4 $M_\odot$.

5.4.5. IRS13N

In addition to the bright infrared excess sources there are also fainter sources with similar colors. Eckart et al. (2004) present results from diffraction-limited L'-band spectroscopy and H, K, and L'-band imaging of the IRS 13 region in the Galactic Center performed with the adaptive optics camera NAOS/CONICA at the ESO VLT. Just about 0.5 arcsec north of IRS 13 the authors have discovered a small (∼0.13 light year diameter) cluster of compact sources with strong IR excesses due to T>500 K dust. MIR spectroscopy and additional photometry using ISAAC and VISIR at the VLT is provided by Moultaka et al. (2004, 2005) and Viehmann et al. (2006). Until now the nature of the IRS 13N sources is unclear. As a most likely and most conservative interpretation a low luminosity bow-shock nature of these sources has to be considered. They may also be a cluster of highly extincted stars that heat the local environment of the mini-spiral. One can also consider an explanation that involves the presence of young stars at evolutionary stages between YSOs and Herbig Ae/Be with ages of about 0.1-1 million years. This scenario would imply more recent star formation in the GC than previously suspected. A detailed discussion is presented in Eckart et al. (2004) and Moultaka et al. (2005).

⊙ Key scientific target is the interferometric investigation of a larger number of individual stars and their shells (like IRS 3 and IRS 1) as well as stellar aggregates and their relative proper motions (like IRS 13 and IRS 13N) in the MIR/NIR.

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