NIR Observations of the Galactic Center

R. Schödel, A. Eckart, C. Straubmeier & J.-U. Pott

I.Physikalisches Institut
Universität zu Köln, Zülpicher Str.77, 50937 Köln
rainer@ph1.uni-koeln.de
www.ph1.uni-koeln.de

Abstract

High-resolution near-infrared observations of the central parsec of the Milky Way are currently revolutionizing our understanding of this nearest galactic nucleus. In this contribution we review some recent results of this research. Via the observation of stellar dynamics it has by now delivered ironclad evidence that the central radio source, Sagittarius A, is associated with a supermassive black hole. NIR monitoring of the flux from Sagittarius A* allows to study the accretion and emission mechanisms in this extremely sub-Eddington system. Coordinated observations of the near-infrared and X-ray quasi-quiescent and flaring emission from Sagittarius A* show that the emission is most likely produced via synchrotron or synchrotron-self Compton processes. There are numerous young, massive stars present in the central stellar cluster. In fact, star formation may be even a still ongoing process: A group of deeply embedded sources north of the IRS 13 complex of bright stars may represent young stars. Compact MIR sources close to the northern arm of the mini-spiral are further potential candidates for young stars, or may be, alternatively, witnesses of the close interaction of stellar winds with the ISM. Very recently. the first successful interferometric observations of a stellar source in the galactic center have been carried out at mid-infrared wavelengths.*

1 Introduction

The recent advent of adaptive optics instrumentation on 8-10 m-class telescopes has been a major breakthrough for near-infrared (NIR) observations of the center of the Milky Way. Due to its proximity (8 kpc, see, e.g., Reid, 1993; Eisenhauer et al., 2003) it is the only galaxy in which the central cluster can be resolved observationally and the stellar population and the dynamics of gas and dust examined in detail. Observations of the Galactic Center (GC) have delivered evidence beyond doubt for the existence of supermassive black holes. This evidence was obtained mainly through the observation of stellar proper motions and orbits near the central black hole (e.g., Eckart & Genzel, 1996; Ghez et al., 1998; Genzel et al. 2000; Ghez et al., 2000; Eckart et al. 2002; Schödel et al., 2002; Ghez et al., 2003) and through

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radio interferometric observations of the radio source Sagittarius A* (Sgr A*) that is associated with the black hole (e.g., Reid et al., 2004).

In this contribution we present a brief overview of recent research carried out with high-resolution near- and mid-infrared observations of the central parsec of the Milky Way. In particular we highlight the following results: The study of stellar dynamics near Sgr A* has delivered stringent constraints on its nature by showing that all models for its nature are extremely implausible with the exception of a massive black hole. Coordinated, simultaneous NIR/X-ray observations of Sgr A* allow us to gain insight into the accretion and emission processes near this supermassive black hole. The stellar population in the GC has been found to be characterized, surprisingly, by the presence of numerous massive, young stars. In this context, we discuss a recently discovered complex of infrared-excess sources, close to Sgr A*, that are potential candidates for young stars and report on newly discovered compact mid-infrared (MIR) excess sources. Finally, we introduce the results of the first MIR interferometric observations of a stellar source in the GC. These VLTI observations open a new era of exploration at the highest angular resolutions.

2 Stellar dynamics and the nature of Sgr A*

High-resolution NIR imaging with speckle interferometry (and adaptive optics since about 2000) led to the first clear evidence that the gravitational potential in the central parsec of the Milky Way is dominated by a point mass (e.g., Eckart & Genzel, 1996; Ghez et al., 1998). Continued observations revealed the first detection of stellar acceleration near Sgr A* (Ghez et al., 2000; Eckart et al., 2002). Finally, a unique solution for the orbit of the star S2 could be determined after the observation of its peri-center passage in spring 2002 (Schödel et al., 2002; Ghez et al., 2003). The Keplerian orbit of S2 indicates that a mass of $3.6 \pm 0.6 \times 10^6\,M_\odot$ is located within a sphere of radius 0.6 mpc around Sgr A* (Eisenhauer et al., 2003). This enormous mass density excludes the possibility that a ball of heavy, degenerate fermions ("neutrino ball") is responsible for the central mass concentration of the Milky Way. As concerns the hypothesis of a cluster of dark astrophysical objects (e.g., neutron stars), the lifetime of such a configuration with the required high density would be less than 10^5 yrs. This leaves a supermassive black hole as the only plausible explanation for the nature of Sgr A*. In Figure 1 we show the orbits of six stars around Sgr A* as determined by Schödel et al. (2003).

Figure 2 illustrates the scales near Sgr A* that are probed by observations of stellar dynamics and of variable emission from Sgr A*. Stellar dynamics, especially the orbits of individual stars, probes the gravitational potential on the scale of several light hours down to several light days ($\approx$ 1.2 light days correspond to one mpc). On the left hand side of Fig. 2, the core radii of two hypothetical dense clusters (Plummer models) with total masses of $\sim 3.5 \times 10^6\,M_\odot$, as derived from the orbit of S2, are indicated: A cluster of $3\,M_\odot$ black holes with a life time of 10^7 yr, marked by a dashed line, and a dark cluster that could marginally fit the gravitational potential as constrained by the orbit of S2. The latter cluster, marked by a dotted line, would have a life time of less than 10^5 yr. The radius of a neutrino ball, composed of

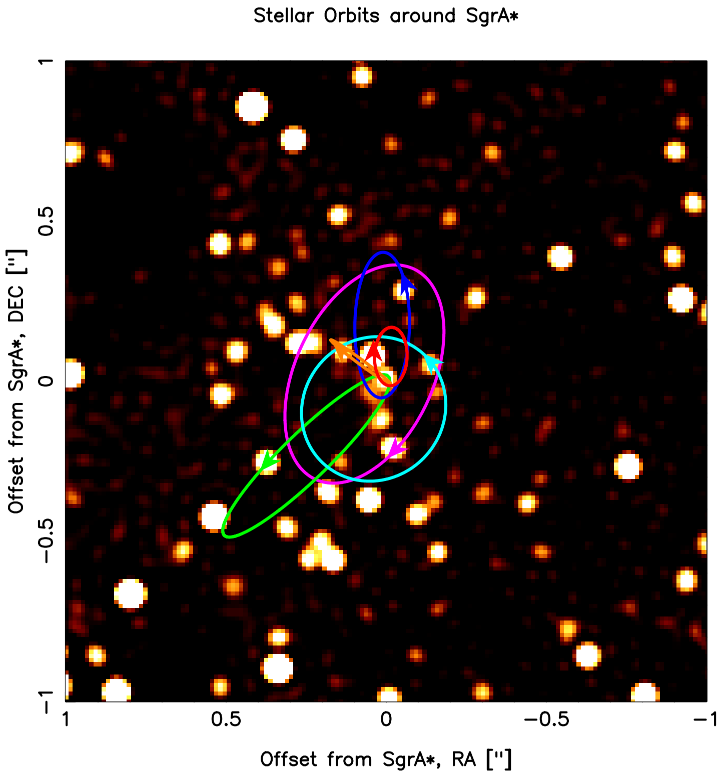

Figure 1: Stellar orbits around Sgr A* as determined by Schödel et al. (2003). The orbits are shown on the background of a Lucy-Richardson deconvolved and beam restored K-band image (NACO/VLT) of a region within $1''$ of Sgr A*.

degenerate 17 keV neutrinos, is indicated by a circle with a straight line. All these models are excluded by the observed orbit of S2 and the requirement that a given configuration should have a life time comparable to the life time of the galaxy. The right hand side of Fig. 2 illustrates a zoom into a region with the size of a few tens of Schwarzschild radii that is probed by radio/mm observations and observations of the variability of the X-ray/NIR emission (see below) from Sgr A*. Indicated are the size constraints due to the duration of the observed X-ray and NIR flares with a duration of the order 60 min (outer circle, marked by "flares:duration"), the size inferred from 7 mm interferometry (Bower et al., 2004), the size limit imposed by the variability time (rise-and-fall time, $T_{\rm Var}$) of the flares (dotted line), and the Schwarzschild radius, R_S, of a 3.6×10^6 $M_\odot$ black hole.

3 Coordinated NIR/X-ray observations of Sgr A*

Sgr A* is a very weak X-ray and NIR source (see, e.g., Melia & Falcke 2001). When it could be finally detected unambiguously with instruments capable of high-

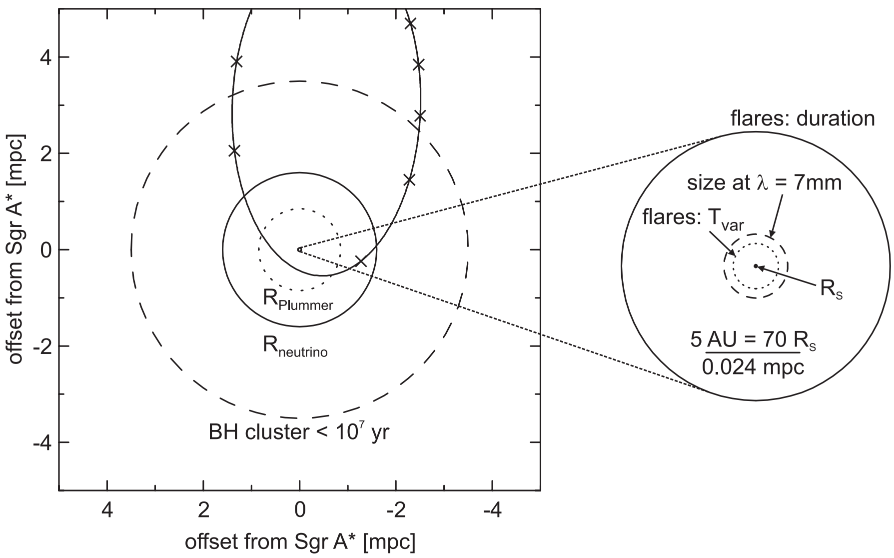

Figure 2: Illustration of the scales near Sgr A* that have been probed by observations.

resolution imaging at the corresponding wavelengths, such as *Chandra* (X-rays) and NAOS/CONICA at the ESO VLT (NIR), the emission from Sgr A* turned out to be highly variable at these wavelengths. X-ray flares, during which the emission from Sgr A* rises by factors of a few tens up to one hundred, were first detected by Baganoff et al. (2001). NIR flares were detected by Genzel et al. (2003) and Ghez et al. (2004). During NIR flares the emission from Sgr A* increases by a factor of a few in this wavelength regime. Both at X-ray and NIR wavelengths the flares show variability on time scales of just a few minutes. This points to very compact source regions of not more than a few tens of Schwarzschild radii in size.

In order to understand the nature of these flares, coordinated simultaneous observations at the different wavelengths are necessary. The first successful simultaneous near-infrared and X-ray detection of the Sgr A* counterpart, was carried out using the NACO adaptive optics (AO) instrument at the European Southern Observatory's Very Large Telescope and the ACIS-I instrument aboard the *Chandra X-ray Observatory* (Eckart et al., 2004). A flare was detected at X-rays that was covered simultaneously in its decaying part by the NIR observations (Fig. 3).

Eckart et al. (2004) find that the flaring state can be conveniently explained with a synchrotron self-Compton (SSC) model involving up-scattered sub-millimeter photons from a compact source component, possibly with modest bulk relativistic motion. The size of that component is assumed to be of the order of a few times the Schwarzschild radius. A conservative estimate of the upper limit of the time lag between the ends of the NIR and X-ray flares is of the order of 15 minutes. The simultaneity of the flares at NIR/X-ray also confirms clearly that the X-ray source seen by *Chandra* is indeed associated with Sgr A*.

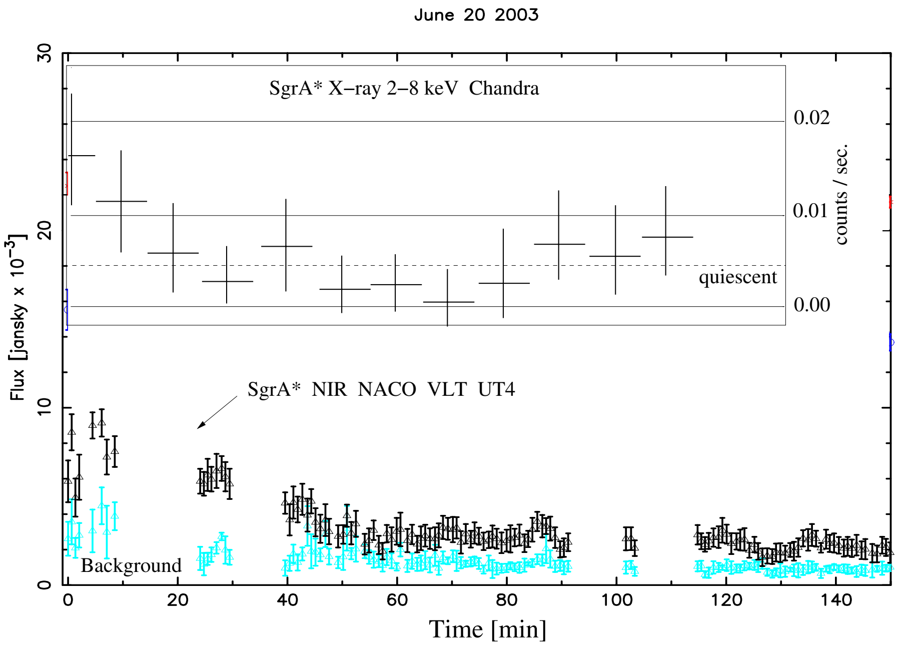

Figure 3: Sgr A* flare observed simultaneously at NIR/X-ray wavelengths (Eckart et al., 2004). The X-ray and NIR light curves are plotted with a common time axis. Straight solid lines in the inserted box represent the 0.00, 0.01, and 0.02 counts per second levels. The straight dashed line represents the X-ray quiescent-state flux density level. The NIR observations started on 19 June 2003 at 23:51:15 (AT), just 0.38 minutes before the midpoint of the highest X-ray measurement.

New coordinated NIR/X-ray observations were successful in observing several flares simultaneously at NIR/X-ray wavelengths (Eckart et al., 2005, in preparation). They show that the variability at the two wavelengths is closely related, i.e., that the time lag between the events at the two different wavelengths is close to zero. Both direct synchrotron emission and SSC emission appear to contribute in varying amounts to the emission from NIR flares, while at X-ray wavelengths only the SSC process is important. This may also be the reason why flares in the NIR regime are a factor of ∼2 more frequent than at X-ray wavelengths.

4 Embedded/MIR excess sources

Numerous young, massive stars found in the central parsec of the GC are witnesses of star formation episodes in the GC that occurred not more than a few million years ago. There are, e.g., the hot, massive so-called He-stars, mainly concentrated in the IRS 16 and IRS 13 associations (e.g., Krabbe et al. 1995; Paumard et al. 2001). The so-called S-stars, located within just a few milli-parsecs of the central black hole,

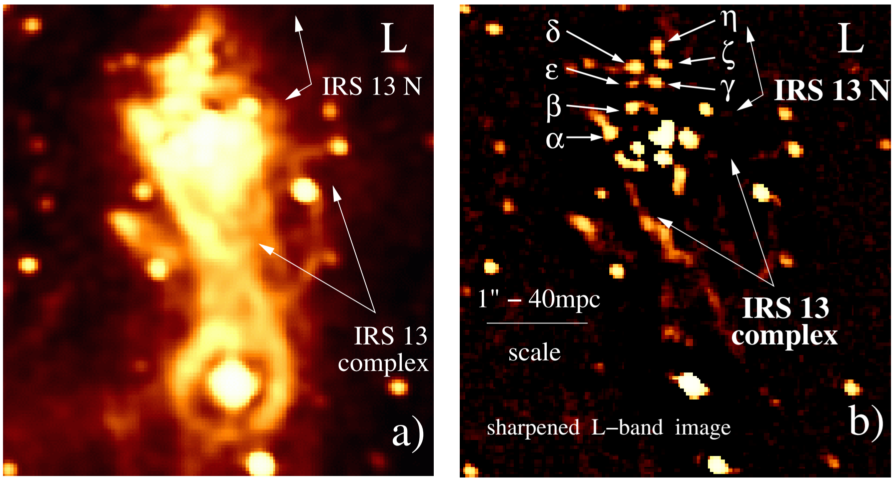

Figure 4: L' band images of the IRS 13/IRS 2 region. The image scale is given in (b). Ring structures around the brighter stars in panel (a) are artifacts of the deconvolution algorithm. Panel (b) is a high pass filtered L'-image which shows the locations of individual stars, including the newly discovered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

have been identified as B-type main sequence stars (e.g., Ghez et al. 2003; Eisenhauer et al. 2005). The existence of these massive, young stars so close to the central supermassive black hole is a very enigmatic finding because in the light of current astrophysical knowledge they could not have formed near the black hole nor have migrated there from larger distances within their life times (see, e.g., discussions in Ghez et al. 2003; Genzel et al. 2003a). However, the existence of these young stars raises the question whether star formation may still be an ongoing process near Sgr A*. Highly reddened sources, such as IRS 21, were previously regarded as potential young stellar objects. However, newer, higher-resolution observations show that these stars are rather massive windy stars that interact with the local ISM (Tanner et al. 2002, 2005).

New candidates for potentially very young stars were discovered by Eckart et al., (2004a), who identified a small (0.13 lt-yr diameter) cluster of compact sources about $0.5''$ north of IRS 13 with strong IR excess due to T > 500 K dust (see Fig. 4). The nature of the sources is still unclear. They may be a cluster of highly extincted stars that heat the local ISM. Eckart et al. (2004a) also consider an explanation that involves the presence of young stars at evolutionary stages between young stellar objects and Herbig Ae/Be objects with ages of about 0.1 to 1 million yr. This scenario would imply more recent star formation in the GC than previously suspected. The AO observations also resolve the central IRS 13 complex. In addition to the previously known bright stars E1 and E2, the K- and L-band images for the first time resolve object E3 into two components, E3N and E3c. The latter one is close to the 7/13 mm Very Large Array radio continuum source found at the location of the

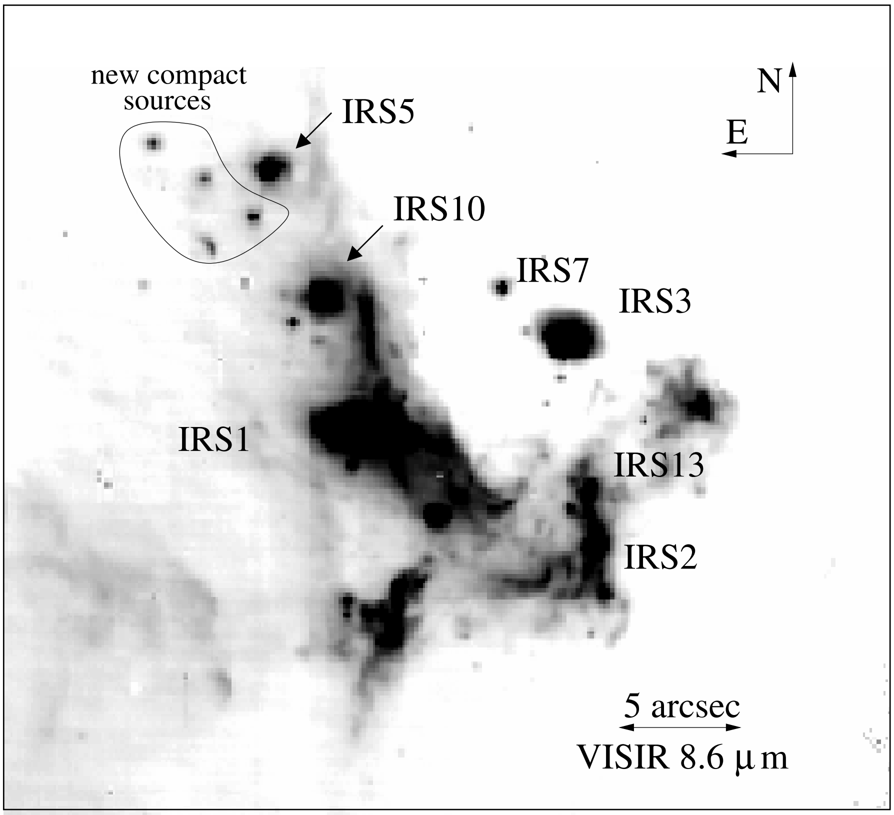

Figure 5: VISIR 8.6 µm image with the previously unknown compact sources close to the Northern Arm, indicated by the thin black line.

IRS 13 complex (Zhao & Goss 1998). E3c may therefore be associated with a dusty Wolf-Rayet like star at that location.

Recent images of the Galactic Center in the N-band (8.6 µm) with the new instrument VISIR at the VLT clearly show four compact sources located to the east of the bright Northern Arm source IRS 5 (Fig. 5). These sources are exceptional because of their compactness: All other 8.6 µm emission sources in the central parsec are extended and associated with the mini-spiral of ionized gas and warm dust, with the clearly extended luminous, dusty sources like IRS 1, 5, 10, 21, 3, or with the extended IRS 13/IRS 2 complex. Only the supergiant IRS 7 has a comparable point-like appearance on all MIR images. While the brighter 8.6 µm sources such as IRS 1, 5, 10, or 21 are now interpreted as bow-shock type interactions between hot emission-line stars with strong winds and the dusty mini-spiral ISM (Tanner et al. 2002, 2005), the nature of the four newly discovered compact sources is unclear. These sources are MIR bright and clearly discernible in M- and L-band images, and can be identified in the K-band, too. High-resolution NAOS/CONICA K- and L-

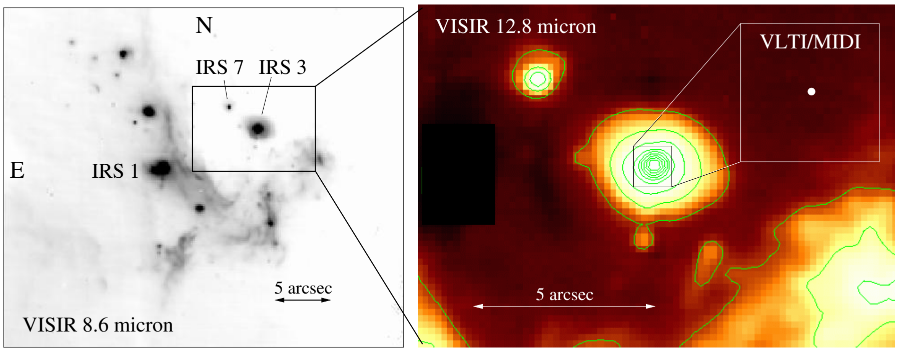

Figure 6: VISIR MIR image and an inset demonstrating the scale on which the current UT2-UT3 VLTI/MIDI data detected a compact source with a visibility of about 30%.

band images reveal that the southernmost of the four sources, which appears *slightly* extended (∼0.2”; compared to IRS7) at longer wavelengths, is in fact double, consisting of a blue point source to the east and a fainter point source to the west, which shows a tail-like structure that appears to be the main source of emission at longer wavelengths. This is an intriguing case of possible interaction, either of the two sources with each other (if they lie spatially close together), or of the western component with the surrounding ISM.

There are two plausible possibilities to explain the nature of the compact MIR sources: They may be low-luminosity counterparts of the more luminous bow-shock sources, such as IRS 21. In that case they could be a more dispersed group of stars similar to the IRS13N complex described by Eckart et al. (2004a). Alternatively, they might be young stars that have been formed while falling into the central parts of the stellar cluster. These objects could be bright in the MIR since they are still surrounded by their proto-stellar dust shells or disks.

5 VLTI observations of IRS 3

In June 2004, IRS 3, the brightest compact MIR source in the GC was detected and partially resolved with VLTI using MIDI (N-band, 8-12 micron) on the 47 m UT1-UT2 baseline (Pott et al. 2005, in preparation). These are the first interferometric observations of an object in the GC at infrared wavelengths. About ∼30% of the flux density were found to be in a compact component with a size of less than 40 mas (i.e. less than 300 AU). This agrees with the interpretation that IRS 3 is a luminous compact object in an intensive dust forming phase. Therefore, IRS 3 is the hottest and most compact bright source of MIR emission within the central stellar cluster. All other MIR sources at the GC were resolved at a 2 Jy flux level (see Figure 6, Pott et al., in preparation).

In general, the visibility amplitude of IRS 3 was found to be smaller (0.23 ± 0.06) at shorter and larger (0.28 ± 0.04) at longer wavelengths. Although the uncertainty of a single visibility value seems at first glance to be too large to identify such a trend, in fact the uncertainty of the slope of a visibility dataset over the N-band was found to be of the order of 1%. Thus, the estimated trend is indicating that the compact portion of the IRS 3 dust shell is extended and only partially resolved on the UT2-UT3 baseline. We also find indications for a narrower width of the 9.3 μm silicate line towards the center, indicating the presence of 'fresh', unprocessed small grains closer to the central star in IRS 3 (van Boekel et al., 2003).

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