The Galactic Centre: The Flare Activity of SgrA* and High-Resolution Explorations of Dusty Stars[1]

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We summarise the most recent efforts to investigate the properties of the Galactic Centre making extensive use of the instrumental capabilities of the Paranal observatory.

The Galactic Centre is one of the most exciting targets in the sky. At a distance of ~ 8 kpc it is about one hundred times closer than the second nearest nucleus of a similar galaxy such as M31 and therefore the closest Galactic Nucleus that we can study. As has been proven convincingly by the analysis of stellar dynamics the central stellar cluster harbours a $(3.7 \pm 0.3) \times 10^6 M_\odot$ black hole at the position of the compact radio source Sagittarius A* (SgrA*). SgrA* represents the largest Schwarzschild radius projected on the sky and provides us with unique information to understand the physics and possibly the evolution of these objects (see also Eckart, Schödel and Straubmeier 2005 and references therein).

Compelling evidence for a massive black hole at the position of Sgr A* is also provided by the observation of variable emission from that position both in the X-ray and the near-infrared domain. Here NACO observations provided the infrared data for the first simultaneous NIR/X-ray flare detections. Repeated measurements have shown that to within less than 10 minutes the brighter X-ray flares occur simultaneously to the NIR flare events. Recent near-infrared polarimetric observations with NACO at the VLT UT4 (Yepun) have revealed that some of the one to two hour flares from SgrA* show a surprising fine structure in the form of polarised sub-flares that have a width of only about 7–10 minutes and are spaced by about 18 ± 3 minutes from peak to peak. These features can successfully be interpreted as emission from hot spots that are on relativistic orbits around the central black hole.

In the near future infrared interferometry with the VLT – which is already possible for the bright and dusty stars at the Galactic Centre – will allow us to determine the emission mechanism and to model the accretion flow onto the Milky Way's central black hole.

Polarised sub-flares from SgrA*

Using the NACO adaptive optics (AO) instrument at the ESO VLT in 2004 and 2005 we have obtained new polarisation data of the variable NIR emission of SgrA* (Eckart et al. 2006a; see also Yusef-Zadeh et al. 2006a). The new data reveal that some of the typically 100 minute long infrared flares are modulated by highly polarised sub-flares with durations of only about 10 minutes (Figure 1 left). These polarised sub-flares have been observed in both years and have an overall degree

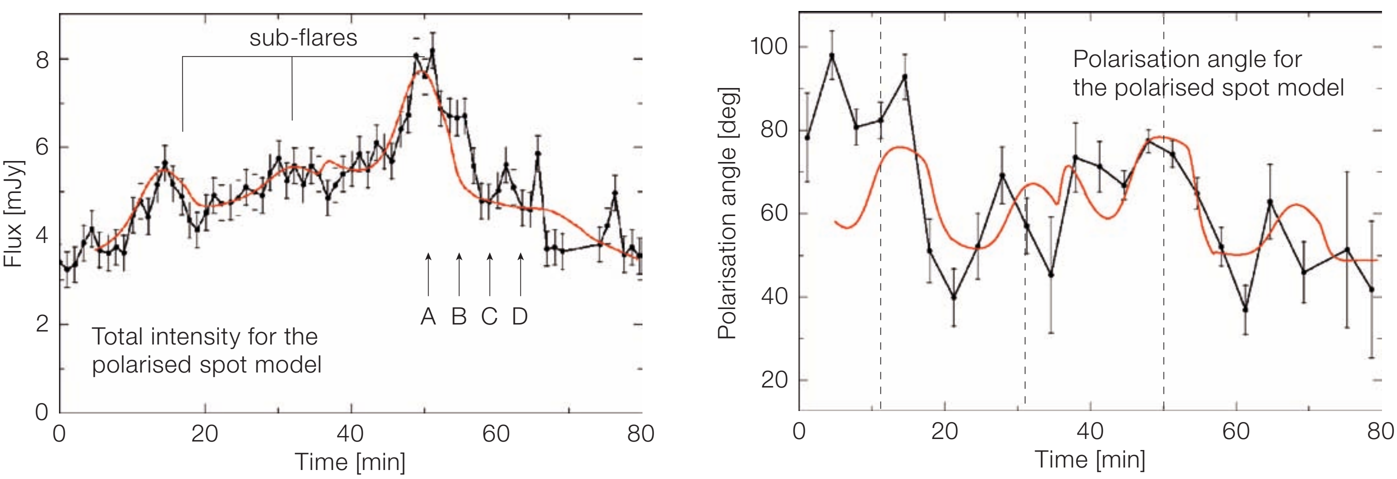

Figure 1: Comparison between model results of an orbiting spot model (red lines) for July 2005 and the measured total flux density (left) and polarisation angle (right). The vertical dashed lines indicate the times at which sub-flares occurred. For details see Eckart et al. 2006b. The model calculations show the compatibility of the orbiting spot model with the NIR polarisation data.

[1] Based on observations with CHANDRA and ESO VLT observations 271.B-5019, 073.B-0249, 75.B-0093, 075.B-0113, 076.B-0863, and 077.B-0028.

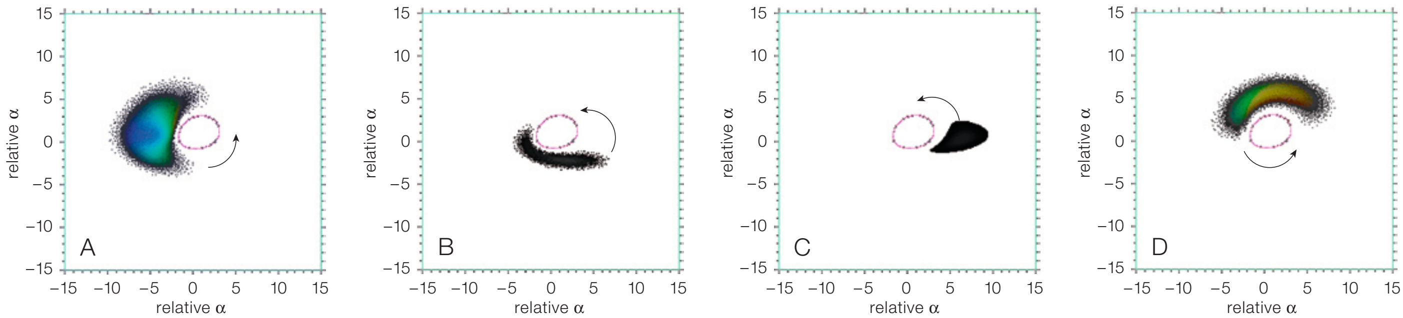

Figure 2: Apparent images of an orbiting hot spot as seen from the observer. The images have been calculated for a case of $i = 60°$, $a = 1$ for a spot at a distance of four gravitational radii (R_g) from the SgrA* black hole (Dovciak, Karas and Yaqoob 2004). This model compares well to best χ^2 fits to the recent polarisation data. (Meyer et al. 2006, submitted to A&A). Colours indicate the energy shift, the blackest structures correspond to the faintest spot images. The labels A to D correspond to the appearance of the spot model at the times labelled for a single flare in Figure 1. Lables are given in R_g at the location of SgrA*.

of polarisation of the order of 20 %. In 2005 the main underlying flare was long enough to observe a minimum of three consecutive sub-flares that are consistent with a quasi-periodicity of 18 ± 3 minutes similar to the value of 17 ± 2 minutes found in previous NACO observations (Genzel et al. 2003; see also Gillessen et al. 2005). A similar periodicity has recently also been reported for a bright X-ray flare (Bélanger et al. 2006). The rapid variation of polarised emission is most likely indicative of synchrotron radiation by relativistic electrons. The intrinsic polarisation of the sub-flares could therefore be up to 60 %.

A preferred model that is used to explain the quasi-periodic polarised flux density variabilities is that of a faint temporal disc as part of which a hot spot is orbiting the central black hole (Figure 2). Details of the exact modelling we used are given in Dovciak, Karas and Yaqoob (2004). In this model the temporal variations are explained due to a relativistic apparent flux density increase and decrease when the spot is approaching and receding from the observer. At the same time formation of partial Einstein rings due to gravitational lensing decreases the overall polarisation of the hot spot. All these effects are a function of the spot properties as well as the spin parameter of the black hole and the spin orientation with respect to the spot orbit. Another model parameter is the orientation of the magnetic field. A toroidal B-field will result in a rotating apparent E-field vector. As an alternative the B-field arrangement of the spot may be such that the apparent E-field is perpendicular to the disc. The minimum spin parameter of $a \sim 0.5$ is given by the observed quasi-periodicity. If the spot is at the last stable orbit its period will be about 3 minutes for a prograde orbit around a black hole with maximum spin ($a = 1$) and close to 30 minutes for a stationary non-rotating black hole ($a = 0$). The χ^2 fits show the consistency between the model and the data. (Figure 1). We find a tendency for high inclinations, spot radii larger than the last stable orbit and spin parameters larger than $a = 0.5$ (Meyer et al. submitted to A&A).

As an unexpected surprise the position angle of the mean E-field vector on the sky during the sub-flare has a similar value of about 60 ± 30 degrees for the two flares in 2004 and 2005. This suggests a preferred orientation of the overall black hole/disc arrangement with respect to the observer. Observations of further polarised flare events are needed to determine how stable the orientation of the polarisation vector is. Given that we have not included other possibly important facts that can have an influence on the observed light curve, like tilts and warps of the accretion disc, there is a surprisingly good agreement between the data and the highly idealised model. Future simultaneous observations covering the near-infrared, radio millimetre and sub-millimetre domain should provide a clear discrimination against explanations involving jets. However, near the last stable orbit a short jet with a length of only a few Schwarzschild radii (of the order of or larger than the width of the jet base, i.e., nozzle) emerging from a disc may likely look almost indistinguishable from a case involving a pure disc or orbiting spots. Here new NACO polarisation observations to be taken in the upcoming years as well as planned future simultaneous radio/NIR/X-ray observing runs will be needed to confine the models.

Simultaneous observations of flares in the NIR and X-ray domain

Following the first successful experiment between the VLT and the Chandra satellite during which simultaneous X-ray and near-infrared flare emission has been detected (Eckart et al. 2004) new simultaneous NIR/sub-millimetre/X-ray observations of the SgrA* counterpart were recently presented by Eckart et al. 2006b (Figure 3). In addition to NACO, the Chandra X-ray Observatory as well as the Submillimeter Array on Mauna Kea, Hawaii, and the Very Large Array in New Mexico were involved. For a total of four near-IR flares we found an upper limit for a time lag between the X-ray and NIR flare of ≤ 10 minutes – mainly given by the required binning width of the X-ray data. The NIR/X-ray flares from SgrA* can be explained with a synchrotron self-Compton (SSC) model involving up-scattered submillimetre photons from a compact source component. Inverse Compton scattering of the THz-peaked flare spectrum by the relativistic electrons then accounts for the X-ray emis-

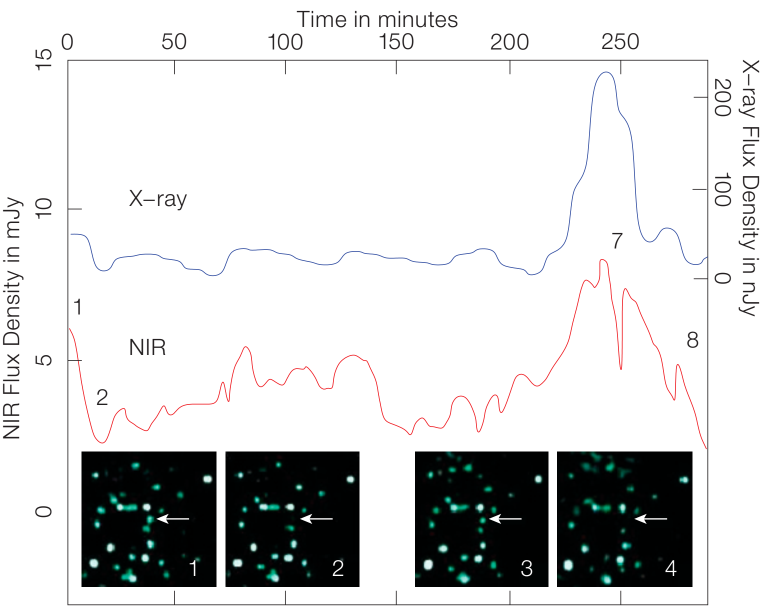

Figure 3: The 6–7 July VLT/Chandra observations as described by Eckart et al. 2006a. The X-ray and NIR light curves plotted with a common time axis. For the labelled times we show 1.3″ × 1.2″ *K*-band images of the Galactic Centre region with SgrA* in its bright and dim state.

sion. This model is in full agreement with the relativistic orbiting spot model described above. In addition – as a consequence of the possible IR turnover of the synchrotron spectrum (see Eckart et al. 2006b) – the flare rates at longer IR wavelengths may be higher than those at shorter NIR wavelengths. The excess flux densities detected in the radio and submillimetre may be linked with the NIR flare activity via cooling through adiabatic expansion of a synchrotron component (see also Marrone et al. 2006, Mauerhan et al. 2005). A similar behaviour was recently found in dual wavelength radio data by Yusef-Zadeh et al. (2006b).

The NIR *K*-band is the ideal wavelength band to study the flare emission from SgrA*. In combination with adaptive optics systems it provides the highest angular resolution and the lowest amount of contamination by dust emission. Future progress will mainly depend on further successful simultaneous observing campaigns – especially between the NIR and submm(mm)-domain, since until now there was only a few hour overlap between the NIR/X-ray data and the VLA and SMA data. Extensive simultaneous data are not available so far. Further polarisation data from the NIR to the radio as well as (sub-)mm-VLBI and NIR interferometric experiments are also highly desirable to study the details of the accretion process in SgrA*.

VLTI and the Galactic Centre: MIDI and AMBER results

In the future a particularly strong emphasis will also be put on measurements of the Galactic Centre using infrared interferometers like the Very Large Telescope Interferometer (VLTI), as well as comparisons to properties of other low-luminosity galactic nuclei. Infrared interferometry has already started with the observations of the luminous dust-enshrouded star IRS 3 using MIDI at the VLTI (Pott et al. 2005, 2006). In 2005 we obtained data on the UT3–UT4 (62 m) and UT1–UT4 (130 m) baselines. In Figure 4 we plot measured visibilities together with a two-component model with a FWHM size of 20 mas (160 AU) for an inner and 50 mas (400 AU) for an outer component. The wavelength dependent flux density ratios of the two components can be used to estimate blackbody temperatures. We find 920 ± 100 K and 510 ± 50 K for the hotter inner and the cooler outer components, respectively. This agrees well with the interpretation that IRS 3 is a luminous compact object in an intensive dust-forming phase. In fact sources like IRS 3 may contribute substantially to the dust content in the overall Galactic Centre region. While most of the other MIR bright GC sources like IRS 1W, 2, 8,

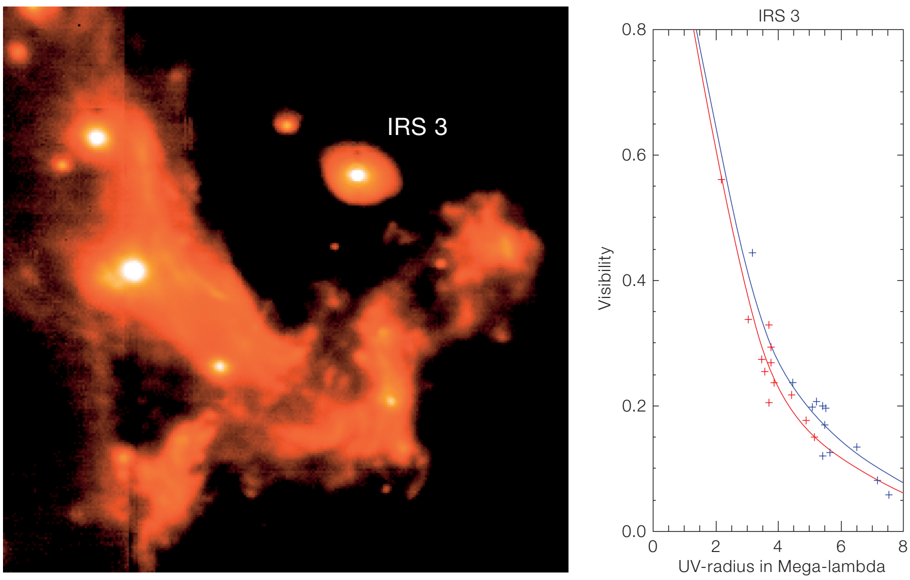

Figure 4: **Left:** A 20″ × 20″ VISIR image of the Galactic Centre at a wavelength of 8.6 μm taken in June 2006. SgrA* is located at the centre of the image. IRS 3 is labelled. **Right:** Visibilities of IRS 3 as obtained by MIDI at the ESO VLTI facility on the UT2–UT3 baseline in 2004 and the UT3-UT4 baseline in 2005 at a wavelength of 8.2 μm (blue) and 12 μm (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 versus extended). Two Gaussian intensity profiles give a slightly better fit than uniform discs.

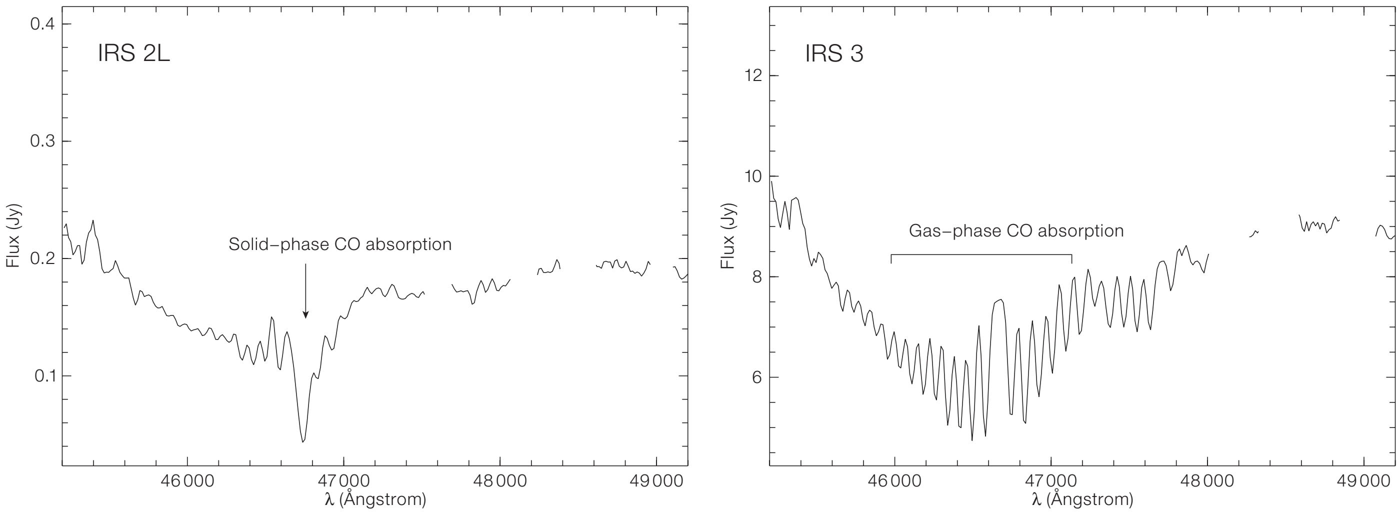

Figure 5: *M*-band spectra of the IRS 2S and IRS 3 Galactic Centre sources. The CO gas- and solid-phase absorptions are indicated, too. Telluric lines longward of 4.75-μm wavelength have been blanked.

9, 10, 13W are more extended and remain currently undetected by MIDI we recently succeeded in obtaining fringes on the compact supergiant IRS 7 in the *N*-band with MIDI on UT2–UT3 (47 m) and in the *K*-band with AMBER on UT1–UT3 (102 m) and UT3–UT4 (62 m). The compactness of the supergiant IRS 7 is of special importance since it can serve as a fringe tracker in future experiments at longer NIR/MIR wavelengths. AMBER observations will be especially suited to study apparent and physical binaries in the Galactic Centre (1 mas ~ 8 AU). A thorough analysis of the diffuse emission and the dust enshrouded sources at the Galactic Centre is essential to parameterise the ISM in the central parsec. Here ISAAC and VISIR have recently contributed in the thermal infrared.

The Galactic Centre in the thermal infrared: recent ISAAC and VISIR observations

During the past few years we have also carried out extensive observations of the central parsec of our Galaxy in the thermal infrared (Moultaka et al. 2004, 2005, Viehmann et al. 2005, 2006). Spectroscopic observations with ISAAC allowed us to build the first *L*-band data-cube of the central region corrected for foreground extinction. This led to the discovery of three Wolf-Rayet stars, all of which show a prominent 3.09 μm He II line without showing the He II line at 2.189 μm in emission. The presence of hot, He II line emitting stars is indicative of ongoing star formation within the central cluster. The data-cube also allows us to study the distribution of water ice and hydrocarbon absorption features in the central parsec. Through recent ISAAC *M*-band spectroscopic observations of a number of bright sources in the central parsec a detailed study of the CO gas- and solid-phase distribution is possible and in progress (Moultaka et al. in prep.; Figure 5). NACO NIR photometry was also combined with VISIR *N*- and *Q*-band MIR photometry obtained in May 2004 (see also Lagage et al. 2004). For an unprecedentedly large number of over 60 compact sources – most of which are giants and/or young stars enshrouded in the Galactic Centre gas and dust – the observed spectra cover the *H*- to *Q*-band, i.e., 1.6 μm–19.5 μm wavelength. The combined data indicate that a significant portion of the absorption features can be associated with the individual sources and therefore most probably occur in the local Galactic Centre medium close to or even within the dust shells around the objects. Detailed Brα and Pfγ emission line maps also demonstrate that the physical conditions of the more extended Galactic Centre ISM are not uniformly the same in the observed region of the minispiral, especially at the edges of the minicavity. We can clearly distinguish between luminous Northern Arm bow shock sources, lower luminosity bow shock sources, hot stars, and cool stars. For the first time a high angular resolution distribution of *L*-band water ice and hydrocarbon absorption features was determined. A significant contribution to these features also appears to be closely associated with the individual sources at the Galactic Centre.

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