Sagittarius A* in the Infrared

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Abstract. The central black hole of the Milky Way, Sagittarius A* (SgrA*) is, in terms of Eddington luminosity, the weakest accreting object of its class accessible to detailed observations. It is therefore key to the refinement of theoretical models of radiatively inefficient accretion. Unfortunately, our knowledge of the mean SED of Sgr A* is very limited. Current models rely almost exclusively on cm to mm mean flux measurements and only on upper limits at infrared to soft X-ray wavelengths. Here, we present a new analysis of imaging data of the Galactic center (GC) at 2.2 to 8.6 microns, obtained with NACO and VISIR at the ESO VLT. We used the VISIR burst mode combined with a novel implementation of the holographic image reconstruction algorithm to obtain mid-infrared images with a Strehl ratio $\gtrsim 90\%$ even under conditions of $\sim 2-3\arcsec$ seeing in the visual. No counterpart of Sgr A* is detected at 8.6 microns. At this wavelength, Sgr A* is located right on top of a dust ridge, which considerably complicates the search for a potential point-source. Based on the available data, it is argued that Sgr A* cannot be detected in the MIR with currently available instruments, not even during flares. At 3.8 and 4.8 $\mu$m SgrA* is detected at all times. We measure the time-averaged mean fluxes of Sgr A* at these wavelengths. From the literature there is evidence that SgrA* is also detected at 2.2 $\mu$m most of the time. The new measurements of the mean, quiescent emission of SgrA* fill a gap of almost 6 orders of magnitude in its known mean SED and provide novel constraints on accretion/emission models.

1. Introduction
The black hole at the center of the Milky Way, Sagittarius A* (SgrA*), has a mass of about $4 \times 10^6 M_\odot$ and is located at a distance of 8 kpc. The combined systematic and statistical uncertainties of these values are about 10% for its mass and 5% for its distance [e.g. 1–3]. The electromagnetic emission from SgrA* is powered by accretion, but, as inferred from measurements of Faraday rotation, the actual accretion rate is lower than $2 \times 10^{-7} M_\odot$, possibly by up to two orders of magnitude [4]. This low accretion rate is intimately connected to a low efficiency in converting the accreted mass to radiation. Accretion onto SgrA* is generally described with so-called Radiatively Inefficient Accretion Flow (RIAF) models, that have efficiencies orders of magnitude below the 10% efficiency of a canonical thin-disk accretion flow [5]. Radiating at $\sim 10^{-9}$ Eddington luminosities [6], SgrA* is thus the weakest black hole accessible to detailed measurements and is thus of special interest for the theory of accretion, emission, and outflow in compact objects.

Unfortunately, the Galactic center is located behind 30 – 50 magnitudes of visual extinction [7; 8] and characterized by an extreme source density at all wavelengths, which creates great observational difficulties in measuring the mean SED of SgrA*. Although being of fundamental importance for theoretical models, the SED of SgrA* is only known well at radio to millimeter
Figure 1. Left: SSA reconstruction of 8.6 µm burst mode data taken with VISIR on 23 May 2007. Right: Holographic reconstruction.

wavelengths. In the X-ray domain, SgrA* is a relatively weak source, that is embedded into extended X-ray emission from the gas within its Bondi radius [9]. At far- to mid-infrared wavelengths, only upper limits on SgrA* could be established so far [e.g. 10]. In the near-infrared (NIR), on the other hand, SgrA* is an extremely variable source, with hour-long flares occurring several times per day. A large number of observing campaigns was focused on these flares in the past years [e.g. 11–15], but the questions whether there is a permanently detectable NIR source at the position of SgrA* and what is its mean flux were neglected. However, it is the mean flux at a given wavelength that provides fundamental constraints for theoretical models.

2. NIR and MIR Imaging of the Galactic center

The Galactic center has been observed numerous times with VISIR/VLT at mid-infrared (MIR) wavelengths, often within the framework of multi-wavelength campaigns on SgrA*. The MIR emission in the central parsec of the GC is dominated by the warm dust in the mini-spiral, which is roughly composed of three streams of (partially) ionized gas and dust [e.g., 16; 17]. Both stars as well as numerous ISM features can be seen in MIR images within 1” of SgrA* [10]. When searching for a MIR counterpart of SgrA* one should therefore use the highest possible spatial resolution. The wavelength-dependence of the FWHM of a point source in seeing-limited observations can be approximated with the Roddier formula: 

$$FWMH \propto \lambda^{-0.2}$$

which leads to 

$$FWMH_{8.6\mu m} \approx 0.5''$$

with a seeing of ~0.8”. The diffraction limit of the VLT is, however, ~0.25” at 8.6 µm. Therefore, with standard imaging techniques, the diffraction limit at short MIR wavelengths can only be exploited during exceptionally good seeing conditions. This situation has changed with the implementation of the burst mode at VISIR, that allows the observer to store individual exposures. The typical exposure time with VISIR is 0.02 s, i.e. much shorter than the coherence time of the atmosphere. Speckle imaging techniques can thus be applied for optimal image reconstruction. Typically, a simple shift-and-add (SSA) algorithm is applied because it is easy to use and implement [e.g. 18]. However, this algorithm is only efficient if the speckle clouds of the sources are dominated by a single speckle, but some of the observations used for this work were obtained under visual seeing of 2 – 3”, so that this requirement was not
filled. Therefore, the more complex, but more efficient holography algorithm was used for image reconstruction [19]. The great performance of holography is illustrated in Fig. 1, where an SSA image image from 23 May 2007 is compared to a holographic reconstruction, which has a Strehl ratio \( \gg 90\% \).

For the observations in the NIR, the ESO archive was used to access the great amounts of observations of SgrA* with NACO/VLT at \( L' (3.8 \mu m) \), between 2006 and 2009, and at \( M' (4.8 \mu m) \), in 2003, 2004, and 2006. Data reduction was standard. For further details on the data used and on their reduction, see [20].

3. Results

No counterpart of Sgr A* could be detected at 8.6 \( \mu m \), where Sgr A* lies atop a dust ridge (see Fig. 2). This \( SgrA^*\)-Ridge limits considerably the point-source sensitivity at the position of Sgr A*. Therefore, to determine an upper limit to the emission from Sgr A* it was first necessary to estimate the background flux density from the ISM at its position. For this purpose, the flux in a circular area centered on Sgr A* was estimated for the image of each observing epoch by interpolation from surrounding pixels. This approximate background was then subtracted and the remnant emission corrected for aperture effects [for a more detailed description of the methodology, see 20]. Four epochs with very low upper limits were excluded from the measurements because they may have been affected by systematic uncertainties due to chopping into bright sources. The weighted mean and error of the remnant flux in the images from the remaining 8 epochs is 7.1 \( \pm 0.9 \) mJy, leading to a 3 \( \sigma \) upper limit of 9.8 mJy for the emission from Sgr A* at 8.6 \( \mu m \). Assuming an extinction of \( A_{8.6} = 2.0 \pm 0.3 \) [21], this leads to a de-reddened 3 \( \sigma \) upper limit of 84 mJy, which includes the uncertainty of the extinction correction.

In the \( M' \)-band, at 4.8 \( \mu m \), a counterpart of Sgr A* was detected in the images from all epochs. Due to the relatively low resolution at this wavelength (FWHM \( \approx 0.135'' \)), Sgr A* is confused with a dust blob located about 0.094" to the southeast [22; 23]. It therefore appears as an elongated source, which could be approximated well by a combination of two point sources that were fitted simultaneously in order to estimate the emission from Sgr A*. The emission from the dust blob is 1.2 \( \pm 0.3 \) mJy and the emission from Sgr A* is 1.5 \( \pm 0.3 \) mJy, where the uncertainty includes the statistical uncertainty from the various measurements as well as a
possible systematic uncertainty from contamination by stellar sources. The extinction-corrected mean flux from Sgr A* at 4.8 \( \mu m \) is 3.8 \( \pm \) 1.3 mJy, taking the uncertainty of the extinction correction into account.

The \( L' \)-band, centered at 3.8 \( \mu m \), is probably the best band to estimate the mean emission from Sgr A* in the NIR because of an optimal trade-off between relatively high angular resolution, on the one hand, and relatively low contamination from surrounding stars and ISM, on the other hand. Sgr A* was detected in all epochs, with a de-reddened mean flux density of 5.0 \( \pm \) 0.6 mJy, including the uncertainty from the extinction correction.

In order to examine short timescales, the imaging data at \( L' \) were divided into subsets, comprising 800 s of observations. Sgr A* could be detected in all of the resulting images of 800 s integration time. The corresponding histograms of the measured flux densities of Sgr A* and of the nearby star S2 are shown in the right panel of Fig. 2. The width of the histogram for the star S2 indicates the measurement uncertainty. The histogram for Sgr A* shows a broader distribution, with a distinct tail towards high flux densities.

In the \( K \)-band, at wavelengths around 2.1 – 2.2 \( \mu m \), the situation is complicated by the intrinsic faintness of the extremely red source Sgr A* and the extreme stellar confusion at its position [24]. Nevertheless, the available literature indicates that a (highly variable) counterpart

Figure 3. Combined jet-ADAF model for the SED of Sgr A*. See [28] for a description of the model and of the radio and X-ray data. The 3 \( \sigma \) upper limit at 8.6 \( \mu m \) and the mean near-infrared emission from the work described in this article is indicated by red points [20].
of Sgr A* can be detected at all times, with a flux density of $0.5 - 2.5 \text{ mJy}$ [25–27].

4. Discussion
The new infrared measurements of Sgr A* are indicated by red points in Fig. 2, along with a jet-ADAF model of its SED [28]. The new upper limit at $8.6 \mu m$ is the tightest one obtained so far at this wavelength. The detection of Sgr A* in the MIR is hindered considerably by the low angular resolution in this wavelength regime, combined with the strong background emission from the ISM near Sgr A*, and the general difficulty of observing in the MIR due to the strong thermal background from sky and telescope. The long integration times necessary to reach the required sensitivity of a few mJy are on the order of 1 hour or longer, which means that any bright flares will be diluted. An analysis of images with about 19 min time resolution indicates that it is probably not possible to detect Sgr A* with currently existing instrumentation, not even during a bright flare [20].

This is the first time that a permanently detectable counterpart of Sgr A* is reported in the NIR. The new data close a previously existing gap of about 6 orders of magnitude in our knowledge of its SED. The measurements of the mean emission from Sgr A* in the NIR agree rather well with the model shown in Fig. 2 and also with a different kind of RIAF model [29], while published models based on relativistic hydrodynamics simulations generally under-predict the newly derived infrared flux densities [20; 30]. It has to be kept in mind, however, that all published models so far are purely based on radio to millimeter and X-ray measurements.

As can be seen in Fig. 2, tighter limits in the MIR can help to constrain models that include a jet component. Finally, the mean flux at $\sim 2.2 \mu m$ appears somewhat high. It is rather possible that this is due to contamination by confusion with stars at the position of Sgr A*.

It appears that the $L'$-band is the best wavelength to monitor the emission from Sgr A* in the NIR. The histogram of flux densities measured in images of 800 s integration time at $L'$ indicates that Sgr A* spends most of the time in a state of low emission with a well defined mean. This state could be termed the quiescent state of Sgr A*, with a flaring state marked by the tail toward high flux densities [see also 27].

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