The infrared emission of the dust clouds close to Sgr A*

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Abstract. Since about an half-decade, adaptive optics (AO) on 8-10m class telescopes has been a key instrumentation for our understanding of Sgr A*. In this article, we first remind the performances of the AO-fed NACO/VLT, with its infrared wavefront sensor, comparing them to other systems worldwide. We then present results obtained in imaging with NACO, on the dust clouds close to Sgr A*, more particularly on the closest one, Sgr A*-f, whose emission could result from a jet from Sgr A*. We finally describe the spectroscopic observations of these dust clouds, performed very recently, using the low resolution prism mode of NACO.

1. Available modes and compared performances of NACO/VLT
NACO has been the first AO-assisted spectro-imager installed at VLT, in late 2001. It is made of the AO system NAOS [1] and the camera CONICA [2]. The main advantage of NAOS for Galactic Centre (GC) observations is its infrared (IR) wavefront sensor (WFS), which is locked on IRS 7 (K=6.5), located 5.5" from Sgr A*. When equipped with visible WFS, AO systems have to be locked on a R∼14 star located about 20" away from Sgr A*, which limits their performances. Even laser-guide star AO systems need an additional guide star for tip-tilt correction, with lower constraints than the classical guide star of visible WFS AO, and thus face the paucity of bright stars in the optical around Sgr A*. As a conclusion, under comparable atmospheric conditions, NAOS-CONICA provides the best correction and image quality for Sgr A* observations (Table 1).

| AO systems                  | Strehl ratio at K (2.1 μm) | Strehl ratio at L’ (3.8 μm) |
|-----------------------------|-----------------------------|-----------------------------|
| NAOS+IRWFS                 | ∼50%                        | ∼80%                        |
| Visible WFS (e.g. Keck [3])| <10%                        | ∼35%                        |
| Laser guide star (e.g. Keck [3]) | ∼30%                      | ∼70%                        |

The CONICA camera is provided with several observing modes: imaging from J (1.2 μm) to M’ (4.8 μm), spectroscopy from J to M’, Fabry-Perot at K, polarimetry and coronography.
2. Infrared imaging of the dusty clouds close to Sgr A* [4]

2.1. Observations and results

We have performed L′-band (3.8 μm, 0.0271″/pixel) observations of the GC region during five 2004 nights (hereafter Night 1, 2, 3, 4 and 5 respectively) with NACO.

**Figure 1.** 1.4″×1.4″ Night 3 images of the central stellar cluster during Sgr A*/L′ flare (pair of images on the left) and quiescent (pair of images on the right) states. Each couple of images is made of a 105 s integration time reduced image and the corresponding deconvolved one, obtained with 40 iterations of the maximum likelihood deconvolution IDL procedure.

**Figure 2.** Left: Distance of Sgr A*/L′ from the dynamical centre (DC) of the S2 orbit as a function of the Sgr A*/L′ magnitude. Crosses, stars, diamonds, triangles, squares and filled circles are Night1, 2, 3/part1, 3/part2, 4, 5 data points respectively. Right: Sgr A*/L′ positions with respect to DC. Crosses are positions for 12.2≤L′(Sgr A*/L′)<12.6, diamonds for 12.6≤L′(Sgr A*/L′)<13.0, stars for 13.0≤L′(Sgr A*/L′)<13.4, triangles for 13.4≤L′(Sgr A*/L′)<13.8.

We observe a clear, reproducible, correlation between the Sgr A*/L′ flux and the Sgr A*/L′ position (Fig. 1, 2). This modulation is actually due to the combined and spatially unresolved emissions of SgrA*/IR (the IR counterpart of Sgr A* itself) and Sgr A*-f, a nearby dusty cloud. Hence, we point at a dual mechanism for the Sgr A*/L′ emission (the 3-5 μm emission of Sgr A*): one traced by the flaring state, unresolved and associated to Sgr A*/IR itself and another one associated to the quiet state due to Sgr A*-f. Sgr A*-f has the following characteristics: extended (∼130 mas), distance from Sgr A*/IR: 75 mas, unobserved at K and K−L′>3.

2.2. Origin of the Sgr A*-f emission

We consider here the different possible emission mechanisms for Sgr A*-f and their likelihood:

- **dust cloud on the line of sight, heated by a nearby/embedded star:** this mechanism has been invoked by [3, 5] and is of course a possible explanation;
- **stellar emission:** this mechanism is unlikely given the large observed K−L′ colour, the extended emission and the lack of detection at K;
- **dust cloud close to Sgr A*, heated by the accretion disk:** the colour temperature $T_c$ of the Sgr A*/L′ quiescent emission, derived from the optically thin case equation $F_\nu(K)/F_\nu(L') = Q_{abs}(K)/Q_{abs}(L') \times B_\nu(T_c, K)/B_\nu(T_c, L')$ (where $Q_{abs}$ is the absorption cross section coefficient,
\( B_\nu(T, \lambda) \) the Planck function, \( F_\nu(K)=1.9 \text{ mJy} \) [6] and \( F_\nu(L')=3 \text{ mJy} \), is comprised, for dust grain sizes from 0.01 to 0.1 \( \mu \text{m} \), between 1110 K and 1130 K for silicate grains, between 870 K and 930 K for graphite grains. On the other hand, the maximum equilibrium temperature \( T_e \) of dust grains heated by Sgr A* itself can be derived from:

\[
\int_0^\infty \frac{L_\lambda}{4\pi r^2} \pi a^2 Q_{\text{abs}}(\lambda) d\lambda = \int_0^\infty 4\pi a^2 Q_{\text{abs}}(\lambda) \right\} B_\lambda(T_e, \lambda) d\lambda,
\]

where \( L_\lambda \) is the Sgr A* flux density, \( a \) the dust grain size and \( r=600 \text{ UA} \), ie about 75 mas. Since the smallest wavelengths dominate the first term, we approximate \( L_\lambda \) by the Sgr A* quiescent state power law found by [7] and usually adopted to constrain the Sgr A* emission models: \( L_\lambda = 7.1 \times 10^{-35} \left( \frac{\lambda}{3.1 \times 10^{-10}} \right)^{-0.8} \). For dust grain sizes ranging from 0.001 to 0.1 \( \mu \text{m} \), we obtain an equilibrium temperature between 70 K and 90 K for silicate grains, between 80 K and 110 K for graphite grains. About one order of magnitude is then found between the quiescent IR color temperature \( T_c \) of Sgr A*/\( L' \) and the temperature \( T_e \) expected if the accretion disk emission was the dust heating source at the Sgr A*-f location. This latter process is therefore excluded.

- dusty cloud close to Sgr A*, heated by a jet: the kinetic power delivered by a jet from Sgr A*, assuming an equipartition between ions and electrons, is given by \( P_{\text{jet}}=\dot{M}_{\text{jet}} \times m_e/m_p \times (\beta c)^2 \), where \( m_e \), \( m_p \), \( \beta \) are the mass of electron, the mass of proton and the electron to light speed ratio, respectively. \( \beta=0.95 \) [8]: hence, \( P_{\text{jet}}=1.2 \times 10^{35} \text{ erg/s}=32 \text{ L}_\odot \). On the other hand, the total luminosity corresponding to the observed \( L' \)-band luminosity \( L_{\text{tot}} \), given by:

\[
L_{\text{tot}} = \frac{\int_0^\infty Q_{\text{abs}}(\lambda) B_\lambda(T_e, \lambda) d\lambda}{\int_0^{L'} Q_{\text{abs}}(\lambda) B_\lambda(T_e, \lambda) d\lambda} \times L_{L'}, \text{ is } L_{\text{tot}}=12 \text{ L}_\odot \text{ for silicate grains at } T_e=1120 \text{ K and } L_{\text{tot}}=6 \text{ L}_\odot \text{ for graphite grains at } T_e=900 \text{ K, whatever the grain size from from 0.001 to 0.1 } \mu \text{m.}
\]

These luminosities are of the same magnitude order as the kinetic power delivered by the jet \( P_{\text{jet}} \). The energy transfer of this jet power to Sgr A*-f through collisions can therefore be a possible mechanism to explain the Sgr A*-f emission.

2.3. Connection between IR dusty clouds and gaseous HII regions

Radio observations have shown the presence of a ridge of emission made of a chain of gaseous clouds from Sgr A* to the mini-cavity [9]. These HII coulds could have been formed by the gravitational collimation of the IRS 16 cluster stellar winds by Sgr A* [10, 11]. Alternatively, a jet from Sgr A*, similarly to our scenario, has been proposed as the wind source [12].

These gaseous HII clouds, taking into account their estimated proper motions and their fairly extended sizes [13, 14], are close to red IR extended sources (Fig. 3), which could suggest a common origin, if not an identification.

![Figure 3. Encircled HII cloud positions on a 2.4"×2.4" L' NACO image. From left to right: HII 5D, HII 5C, source \( \epsilon \), source \( \xi \) [13, 14]. The circle diameter is the 0.1" radio resolution.](image-url)
3. Infrared spectroscopy of the dusty clouds close to Sgr A*

3.1. Observations
During the night of 30 March 2006, we have performed with NACO spectroscopic observations of few dust red clouds close to Sgr A*. For that purpose we have used the NACO spectroscopic mode made of a low resolution prism which allows one to cover at once from J to M′ (1 to 5.4 μm). Its resolution varies from ∼60 at 3 μm to 200 at 5 μm. Actually, two configurations are available when using this mode: either with a filter introducing a cut-off at 2.5 μ to cover only from J to K, or a full J-to-M′ coverage, the latter having been used for our observations.

![Figure 4](image)

**Figure 4.** Left: Slit position. Middle and right: raw ”spectra” of a B2V and G0V stars.

3.2. Calibration and preliminary results
This observing mode, with its large covered spectral domain, is tricky to use: apart from the lack of signal at the shortest wavelengths for red sources when preventing from saturating the largest wavelengths, calibration is complex, in particular wavelength calibration (given the lack of calibration lines for the available calibration lamps) and telluric feature correction.

![Figure 5](image)

**Figure 5.** Telluric features. Left column: from the G0V star. Middle: from the B2V star. Right: from [15]

Wavelength calibration and telluric correction have been done simultaneously using the 1-5 μm atmospheric transmission from [15]. Figure 5 presents this calibration of the L′ and M′ atmospheric transmissions, with the observed telluric features from the B2V and G0V calibration stars.
The data is still under data reduction/analysis processes. Still, we can already infer few results (cf. Fig. 6):
- the signal to noise ratio we have obtained on Sgr A*-f is low;
- a Sgr A* flare may have occurred during the observations (from control acquisition images) but it will be probably difficult to extract a spectrum of Sgr A* itself;
- we have achieved a good signal to noise ratio for the other dusty clouds

4. Conclusions
We will most probably be unable to derive a 3-5.4 μm spectrum of Sgr A* during the flare that has occurred during our observations. Though, the derivation and comparison of the dust temperatures and possible spectral features (hydrogen recombination lines, PAH) of the different dusty clouds should help us to test the nature of Sgr A*-f and our shock/jet hypothesis.

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