Ices in the Galactic Center?

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Abstract. We present for the first time, an infrared data-cube of the central parsec of our Galaxy in the 2.8 to 4.2 micron range. This spectral band (the L-band) harbors important signatures of the interstellar and circumstellar medium, since the water ice absorption feature at 3 micron traces the dense medium and the hydrocarbon absorption at 3.4 micron is only observed in the diffuse gas.

Thanks to a calibrator spectrum of the foreground extinction in the L-band derived in a previous paper, we corrected our data-cube for the line of sight extinction. Our observations performed with ISAAC spectrograph at the VLT-ESO telescope suggest that part of the absorption features takes place in the local environment of the Galactic center. This induces the presence of very low temperatures in the central parsec.

1. Introduction

The Galactic Center (GC) is the ideal place where one can study at high angular resolution the direct environment of a central galactic super massive black hole (SMBH). In this work, we present the first results of our study of the half parsec diameter area around the central SMBH SgrA* of our Galaxy (Schödel et al. 2002, Ghez et al. 2003). This study is conducted in spectroscopy in the mid-infrared, from about 2.8 to 5.1 µm.

The present spectral region is of great interest since it harbors prominent absorption features and emission lines that are signatures of the interstellar and circumstellar media (ISM and CSM, respectively). The ISO SWS spectrum of the central region (Lutz et al 1996) shows that the features are actually present in that direction towards SgrA*. Studying the distribution of these features allows to derive valuable information on the physics of the region.

In the L-band domain (from 2.8 to 4.2µm), in addition to the Hydrogen and Helium emission lines that are signatures of the ionized gas and Wolf-Rayet stars, one can distinguish a broad feature at 3µm, due to the presence of water ices in the dense ISM. This feature has been often observed towards Young Stellar Objects (YSOs) (e.g. Ishii et al. 1998). Hydrocarbon absorption features at 3.4µm and 3.48µm, can also be distinguished in this spectral domain. They are generally observed exclusively in the diffuse medium.

In the M-band domain (from 4.4 to 5.1µm), the integrated spectrum of the Galactic center shows also Hydrogen recombination lines as well as two other absorption line complexes attributed to
the $^{12}$CO and $^{13}$CO in gas phase and an absorption line of the $^{12}$CO in its solid phase at 4.676$\mu$m. Moreover, a broad feature at 4.62$\mu$m called XCN, is attributed to CN bonds. 

Paradoxically, the central parsec has been very little studied in these bands although the latter harbor important signatures from the ISM and CSM. The only few studies that were made, were done either at low spatial resolution (e.g. Moneti et al. 2001), or at low spectral resolution (e.g. McFadzean et al. 1989). In all cases, only a small number of individual sources were observed (Chiar et al. 2000, 2003). In general all previous studies resulted in the idea that the previous absorption features arise from molecular clouds along the line of sight towards the Galactic Center.

2. Observations and extinction calibration
Some years ago, we initiated L- and M- band observations of the central parsec of our Galaxy using the capabilities of ISAAC spectrograph located at the UT3-VLT-ESO telescope. We observed a larger number of sources than already studied in these bands, at higher spatial resolution or smaller apertures and in most of the cases, at higher spectral resolution. We mapped the central half parsec in these two bands and finished our program last August 2011. Here we show the first results of our L-band mapping that needed 26 slit positions in order to cover the whole desired central region. This allowed us to build the first L-band data-cube of the central half parsec of our Galaxy.

In a former paper (Moultaka et al. 2004), we used the L-band spectrum of a ”CO star” (a late type star showing CO band-heads in its K-band spectrum) in order to calibrate the foreground extinction towards the central parsec at these wavelengths. Since this star is at an almost 13" angular distance from the center (i.e. it is close enough to the studied region but outside the mini-spiral area), it is located at the edge of the SgrA* west region and does not show excess emission in the L-band spectrum. Hence we assumed that it is free from local extinction and that its spectrum is only affected by the line of sight extinction. Thus dividing its spectrum by a blackbody spectrum of 3600 K temperature, we derived the L-band line of sight extinction spectrum (see Fig. 1).

![Figure 1. L-band spectrum of the foreground extinction towards the Galactic Center. The x-axis is in Ångström units and the y-axis is the optical depth of the extinction.](image)

Thanks to this calibrator, we derive the first data-cube corrected for the foreground extinction in the L-band (see the integrated L-band maps corrected and non corrected for the line of sight extinction in Figs. 2 and 3, respectively).
These maps show that we manage to reproduce the region very well even though ISAAC is not an integral field spectrograph.

In Fig. 4 we overlay our non-corrected map of the L-band integrated emission (in contours) over a NAOS/CONICA (NACO) L-band image of the central parsec. This figure shows again that our mapping is very successful in reproducing the stellar field and that the positions are accurate to within better than a fraction of an arcsecond.

3. Validation of the line of sight extinction calibration

In our previous work (Moultaka et al. 2004) we derived the intrinsic spectra of a dozen of bright sources in the region. All spectra could be fitted by spectra of blackbodies with temperatures equal to the known temperatures of the sources or of the dust they are embedded in (see Moultaka et al. 2004). This shows that our calibration of the line of sight extinction spectrum is correct at least for the area defined by these sources.

In the present work, use blackbody continua to fit a number of spectra of early-type stars located all around the central half parsec region and outside the mini-spiral. The stars are shown in red in Fig. 5 as well as their spectra and the continua fitted with an appropriate blackbody. All of them were fitted by blackbody spectra of about 26000 K temperature which is in agreement with the temperature of such stars. This result also validates our calibration of the line of sight extinction spectrum.
Figure 4. NAOS-CONICA L-band image of the central parsec with contours of our integrated L-band emission image obtained with our data-cube.

Figure 5. L-band spectra corrected for the foreground absorption of a dozen of early-type stars which locations are shown in red dots and arrows.

4. Results
Given that we validated our foreground extinction spectrum and consequently our extinction corrected data-cube, we are now confident to derive maps of the optical depths of the water ice and hydrocarbon absorptions in our data-cube.

We assume that the continuum of the hydrocarbon absorption can be approximated by a straight line going from 3.32\(\mu\)m to 3.77\(\mu\)m and the absorption of the water ice feature by a
straight line going from 2.84\(\mu m\) to 3.77\(\mu m\). The optical depths are calculated via the definition 
\[ \tau = -\ln\left(\frac{F_{\text{obs}}}{F_{\text{cont}}}\right), \]
where \(F_{\text{obs}}\) is the integrated observed flux over the absorption feature and \(F_{\text{cont}}\) is the integrated continuum flux along the spectral feature. The optical depths of the water ice absorption were obtained by subtracting the hydrocarbon absorption. The advantage in using optical depths is that these are independent of the continuum intensity, so one can compare directly all luminosity class objects.

**Figure 6.** Optical depth map of the water ice absorption feature built with our extinction corrected data-cube. Contours are also shown for clarity.

**Figure 7.** Optical depth map of the hydrocarbon absorption feature at 3.4 \(\mu m\) built with our extinction corrected data-cube. Contours are also shown for clarity.

The corrected and non corrected optical depth maps for foreground extinction are very similar in both cases of the water ice absorption feature and of the hydrocarbon feature. This suggests that we do not over-correct our features for the line of sight extinction and do not overestimate the line of sight absorption since we don’t get negative values. In Figs 6 and 7, we show the extinction corrected optical depth maps of the water ice and hydrocarbon absorptions. Our resulting maps show that the features take place locally and can be associated with the neighboring infrared sources.

Moreover, in Figs. 8 and 9 we overlay the K-band extinction map derived by Schödel et al. (2009) on our optical depth maps. We find no correlations between the K-band and the water ice and hydrocarbon extinction maps. This again, stresses the fact that water ice and hydrocarbon absorptions we map are not primarily produced in the foreground material.

The water ice and hydrocarbon absorptions trace the mini-spiral region but also the dusty sources like IRS3, 7 and north of IRS 13. If we compare our maps with figure 5 from Mužič et al. (2007) showing the dusty filaments in the central parsec, we find that the absorption optical
depths peak at the same positions as the dusty filaments tracing well these high density regions.

In Figs. 10 and 11 we show the optical depth maps with contours of the integrated L-band emission overlaid. One can notice in these figures that the minima of the optical depth coincide with the positions of the infrared sources and that peaks of the optical depth are located in the neighboring regions. We interpret these observations as being the resulting shape of mass losing stars interacting with the local ISM and thereby enhancing their surrounding dust emission (possibly by piling up the local dust).

From the L-band extinction spectrum along the line of sight shown in Fig. 1, we derive an optical depth of about 0.55, this corresponds to an \( A_L \sim 0.6 \) mag which is consistent with an \( A_K \sim 1.52 \) mag. This is less than the value obtained by Schödel et al. (2009) of 2.46 mag. We conclude that the absorption features do not account alone for the foreground extinction but an important contribution comes from the continuum as well.

Since there is no direct relation between the optical depths of the features and the optical depth of the overall extinction along the L-band, we build a new optical depth map taking into account the absorption line (i.e. both features) and the continuum contribution within the entire wavelength band. The smoothed version of this map is shown in Fig. 13. We find that the optical depths vary from 0 to 1 in the whole region. This means that \( A_L \) varies from 0 to 1.08 mag corresponding to a variation of \( A_K \) from 0 to 2.3 mag. This is much higher than the 0.5 mag variation along the line of sight derived by Schödel et al. (2009). This result implies that the absorption features we observe take place locally. The presence of water ices
in the Galactic Center implies temperatures of the order of 60K. This is consistent with our finding that (Moultaka et al. 2009) that CO ices are probably present in the region as well. We showed in Moultaka et al. (2009) that, given the complexity of the region with the presence of bow-shock sources, narrow dust filaments and dust embedded YSOs, one cannot discard the presence of high-density pockets and high-optical depths where very low temperatures can also be present. These compact dusty structures can persist and survive while traveling through the central parsec since we showed that the travel time is shorter than the evaporation time of molecular clumps and disks in similarly harsh environments.

Finally, we find a weak correlation between the water ice and the hydrocarbon optical depths with a correlation coefficient of 0.38 (see Figs. 12 and 14). This correlation suggests that the ISM presents itself as a mixture (possibly clumpy) of a dense and a diffuse medium.

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Figure 12. Optical depth map corrected for the foreground extinction of the water ice absorption with contours of the hydrocarbon absorption corrected optical depth map.

Figure 13. Optical depth map of the extinction along the whole L-band corrected for the foreground extinction.

Figure 14. Optical depth of the hydrocarbon versus the ice absorption features. This figure plots the intensities of all pixels of the water ice and hydrocarbon corrected optical depth maps, at which the S/N ratio in the integrated L-band map, is higher than 10. In red, the best linear fit.

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