Radial distribution of the carbonaceous nano-grains in the protoplanetary disk around HD 169142

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ABSTRACT

Context. HD 169142 is part of the class of (pre-)transitional protoplanetary disks showing multiple carbon nanodust spectroscopic signatures (aromatic, aliphatic) dominating the infrared spectrum. Precise constraints on the spatial distribution and properties of carbonaceous dust particles are essential to understanding the physics, radiative transfer processes, and chemistry of the disk. The HD 169142 disk is seen almost face-on and thus offers a unique opportunity to study the dust radial evolution in disks.

Aims. We investigate the spatial distribution of the carriers of several dust aromatic emission features of the disk across a broad spatial range (10–200 AU) as well as their properties.

Methods. We analysed imaging and spectroscopic observations in the 8–12 µm range from the VLT Imager and Spectrometer for Mid-Infrared (VISIR) at the Very Large Telescope (VLT), as well as adaptive optics spectroscopic observations in the 3–4 µm range from the Nasmyth Adaptive Optics System – Near-Infrared Imager and Spectrograph (NACO) at VLT. The data probe the spatial variation of the flux in the 3.3 µm, 8.6 µm, and 11.3 µm aromatic bands. To constrain the radial distribution of carbonaceous nano-grains, the observations were compared to model predictions using The Heterogeneous dust Evolution Model for Interstellar Solids (THEMIS), which is integrated into the POLARIS radiative transfer code by calculating the thermal and stochastic heating of micron- and nanometer-sized dust grains for a given disk structure.

Results. Our data show predominant nano-particle emission at all radii (accessible with our resolution of about 0.1” or ~12 AU at 3 µm and ~0.3”, 35 AU at 10 µm) in the HD 169142 disk. This unambiguously shows that carbonaceous nano-grains dominate radiatively the infrared spectrum in most of the disk, a finding that has been suggested in previous studies. In order to account for both VISIR and NACO emission maps, we show the need for aromatic particles distributed within the disk from the outermost regions to a radius of 20 AU, corresponding to the outer limit of the inner cavity derived from previous observations. In the inner cavity, these aromatic particles might be present but their abundance would then be significantly decreased.

Key words. protoplanetary disks – radiative transfer – methods: data analysis – techniques: imaging spectroscopy

1. Introduction

The solid carbon content of protoplanetary disks is of primary importance for improving the understanding of circumstellar disk evolution and planet formation. Öberg et al. (2011) linked the initial carbon content of the region of formation of planetesimals to the composition and chemistry of the atmosphere of the evolved planet. Eistrup et al. (2018) showed that the chemical composition of forming planets depends on the physical conditions and the location of planetesimals in the disk, emphasising the necessity of taking chemical evolution into account in planetary formation models. Hence, an accurate and complete knowledge of the physical properties of primordial solid carbon reservoirs through the disk is essential for describing the formation and evolution paths and predicting the probability distribution of the properties of evolved planets (e.g. Öberg et al. 2011).

If the solid carbon in disks has been extensively studied at large separations, it is only recently that investigations in planet-forming regions, namely, those below ~50 AU, were made possible through high-resolution observations. In tracking down carbonaceous emission lines with the MATISSE interferometer, Kokouлина et al. (2021) were able to probe the distribution of solid carbon below 10 AU in the disk around HD 179218. Recently, Boutuéraon et al. (2019) investigated the spatial distribution of carbon nano-grains down to 0.1” in protoplanetary disks around multiple stars, including HD 100546 and HD 169142.

In this paper, we study HD 169142, a well-known Herbig Ae star (A5Ve; Keller et al. (2008)), at a distance of 117 ± 4 pc (Manoj et al. 2006; Grady et al. 2007; Gaia Collaboration 2016, see stellar properties in Table 1). The star is surrounded by an almost face-on (pre-)transitional disk, with an inclination ~13° (Panić et al. 2008). The gas and dust spatial
distributions observed with SPHERE and ALMA hint at the presence of multiple (giant) protoplanets shaping the disk structure via dynamical clearing (dust cavity and gap) and dust trapping (double ring dust distribution). The protoplanetary system shows an inner disk between 0.2 and 0.5 AU, two annular gaps (from 1 to 20 AU and from 32 to 56 AU), and an outer disk extending to 250 AU (Quanz et al. 2013; Osorio et al. 2014; Ligi et al. 2018; Momose et al. 2015; Fedele et al. 2017; Bertrang et al. 2018; Honda et al. 2012; GRAVITY Collaboration 2019). The radial structure of the disk used in this work is summarized in Fig. 1. It assumes the gap radial extension derived by Ligi et al. (2018) from the results of Quanz et al. (2013), using the corrected value of 117 pc for the distance to Earth.

HD 169142 is one of the few Herbig Ae/Be stars for which planet candidates have been detected via direct imaging in the near-infrared (Biller et al. 2014; Reggiani et al. 2014; Osorio et al. 2014; Quanz et al. 2015). One of the point sources detected around HD 169142 (Biller et al. 2014; Reggiani et al. 2014) was shown to be related to an inhomogeneous ring structure in the inner region of the disk at 0.18″ by Ligi et al. (2018). These authors also found that an additional compact structure detected at about 0.1″ projected separation could possibly be related to an additional ring structure at the given separation. Furthermore, the system shows near infrared flux decreasing in the past decades (by 45%), which may have resulted from modifications of the inner disk structure due to accretion or sculpting by planets undergoing formation (Wagner et al. 2015).

The HD 169142 global spectrum presents very rich and intense infrared carbon nano-dust spectroscopic features (aromatic, aliphatic) between 3 and 13 μm (Meeus et al. 2001; Sloan et al. 2005; Acke et al. 2010; Boutéraon et al. 2019; Seok & Li 2017). The carriers of these bands can be attributed to carbon nano-grains containing aromatic domains, for instance, astronomical polycyclic aromatic hydrocarbons (PAH) or amorphous hydrocarbons a-C:H that are undergoing stochastic heating. HD 169142 is one of the few disks with a very large amount of aromatic species (Woitke et al. 2016) and very high normalised aromatic infrared bands to UV luminosity ratio L_{AIB}/L_{UV} (Acke & van den Ancker 2004; Maaskant et al. 2014). In this study, we present spatially resolved observations of the 3.3, 8.6, and 11.3 μm aromatic bands.

The disk of HD 169142 has been observed at different wavelengths, using ISO, Spitzer, and ground-based spectroscopy. The detection of [OI] (Acke et al. 2005), Hα (Dunkin et al. 1997), and Brγ (Garcia Lopez et al. 2006) emission indicates the presence of gas in the inner parts of the disk. The carbonaceous aromatic nano-particles are strongly coupled to the gas in proto-planetary disks and are thus expected to follow the radial distribution of gas in the disk. Given the detected distribution of gas, it is then natural to wonder about the presence of aromatic carbonaceous nano-particles in the inner regions of the disk.

Habart et al. (2006); Boutéraon et al. (2019) detected the 3–4 μm aromatic features in the inner parts of the disk. These features are spatially extended, with a FWHM of 0.3″ or ~30 AU. Both the spatial extension of carbonaceous nano-grains in the HD 169142 disk and their presence in the optically thin inner cavity have also been suggested by Maaskant et al. (2014) and Seok & Li (2016). Furthermore, Seok & Li (2016) performed a comprehensive modelling of the SED with a mixture of porous dust and astronomical-PAH and found that three dust populations and relatively small PAH with an ionization fraction of 0.6 can explain the entire SED. Backing up those observations, Klarmann et al. (2017) compared the extended continuum flux measured at 1.3 μm with PIONIER (Lazareff et al. 2016) and the aromatic infrared bands to UV luminosity ratio in multiple circumstellar objects and found an extended hot emission in the cavity of the HD 169142 disk, which they linked to stochastically heated carbonaceous particles. Finally, based on resolved Keck NIRC2 data in the 3.4–4 μm region Birchall et al. (2019) suggested the presence of a ring of emission at ~0.06″ (7 AU). They conclude that, in contrast with the historical view of pre-transitional discs (e.g. Espaillat et al. 2007), the ‘gap’ region is radiatively dominated by emission from very small grains and very small, likely carbonaceous, nano-particles.

In this paper, we use high angular-resolution data obtained with the NACO and VISIR instruments to investigate the spatial distribution of the carriers of the aromatic infrared bands at 3.3, 8.6, and 11.3 μm in the HD 169142 disk. We focus on the distribution of the carriers in the most evolved, innermost regions of the disk (inner cavity and gap, below 60 AU). We model the data using The Heterogeneous dust Evolution Model for Interstellar Solids1 (THEMIS, Jones et al. 2017) integrated in the radiative transfer code POLARIS (Reissl et al. 2016) to constrain the spatial distribution of carbonaceous nano-particles and to compare it with the distribution of micron- to millimeter-sized dust grains derived in the literature. The data are presented in Sect. 2 and analysed in Sect. 3. The radiative transfer modelling is described in Sect. 4. Section 5 compares it to the data and constrains the radial distribution of aromatic carbon grains. We discuss and summarize our findings in Sect. 6.

2. Observations and data reduction

We analysed the distribution of the carriers of aromatic infrared bands in the HD 169142, making use of VISIR imaging (Sect. 2.1) and spectroscopic observations (Sect. 2.2), as well as NACO spectroscopic data (Sect. 2.3).

2.1. VISIR imaging data

HD 169142 was observed by the ESO mid-infrared instrument VISIR installed on the VLT (Paranal, Chile) in the imaging mode in the PAH1 and PAH2 filters, which probe the aromatic infrared bands at 8.6 and 11.3 μm. In addition, the source was observed in the adjacent continuum (ArIII and SIV filters at 9 and 10.5 μm respectively). The observations were obtained in 2005 as part of the VISIR GTO program on circumstellar

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1 https://www.ias.u-psud.fr/themis/
Table 1. HD 169142 stellar properties.

| Parameter | Value | Source |
|-----------|-------|--------|
| Mass ($M_\odot$) | 2; 1.65 | [1], [2], [4], [5], [8] |
| Age (Myr) | 5.4; 3–12; 6; 12 | [1]; [4]; [5]; [8] |
| Distance (pc) | 145; 117; 151 | [1], [2], [4], [5], [6]; [7]; [8] |
| Radius $R_*$ ($R_\odot$) | 2.2; 1.6 | [1], [2], [5], [8] |
| Temperature (K) | 8 100; 8250; 8400; 6500; 7800 | [1], [2], [5], [6]; [8] |
| Spectral type Herbig Ae/Be | A5Ve; A7V; A7Vz | [1], [2], [5], [6]; [4]; [8] |

Notes. Values are taken from [1] Manoj et al. (2006), [2] Monnier et al. (2017), [3] Quanz et al. (2013), [4] Biller et al. (2014), [5] Seok & Li (2016), [6] Dunkin et al. (1997), [7] Ligi et al. (2018), [8] Blondel & Djie (2006). The values chosen for the current study are in bold font.

Table 2. Characteristics of the VISIR imaging observations.

| Filter | PAH1 | ArIII | PAH2 | SIV |
|--------|------|-------|------|-----|
| Wavelength (µm) | 8.6 | 8.99 | 11.3 | 10.4 |
| On source obs. time (min) | 10 | 10 | 20 | 20 |
| Std star | HD 167121 | HD 151680 | HD 151680 | HD 151680 |

Table 3. Full width at half maximum in arcseconds, measured with the use of Gaussian fitting on the VISIR 2D maps in the PAH1 and PAH2 filters (1st column) and the PSF of the observations (second column).

| Filter | FWHM (arcsec) | PSF FWHM (arcsec) |
|--------|---------------|-------------------|
| PAH1   | 0.41          | 0.26              |
| PAH2   | 0.47          | 0.30              |

Disks, and partly from the VISIR archive (ESO program 099.C-0794(A) on 07/21/2017). All observations were obtained under fair conditions of seeing (less than 1″ DIMM monitor) and precipitable water content smaller than 5 mm (Table 2). Under good seeing conditions, close to diffraction-limited imaging is obtained in the $N$ band (8–13 µm) with an angular resolution of about 0.3″ around 10 µm. A standard quadrangular (8″ offsets) chopping-nodding technique was used to remove the high thermal background. All observations except in the ArIII filter used the burst mode, which allows for one image to be stored every ~15 ms. A dedicated pipeline was then used to perform lucky imaging (Law et al. 2006) and image registration to minimize the effect of tip-tilt smearing. Typical achieved Strehl ratios are of the order of 0.5. Standard calibration stars were also observed in the same modes in order to perform the photometric calibration and determine the instrument PSF (Table 2).

Data taken in PAH2, ArIII, and SIV filters have a pixel scale of 0.075″. They are re-binned to the PAH1 pixel size of 0.046″ which corresponds to the upgraded VISIR instrument pixel scale after 2015. The emission maps probe the disk from 0″ to 3″. However, this study is limited to the range [0″, 2″] (see Fig. 2) as the signal-to-noise ratio (S/N) drops at larger radii.

2.2. VISIR spectroscopic data

The spectroscopic observations were performed on the night of 18–19 June 2005 (ESO program 60.A-9234(A)). The observing conditions were fair at less than 0.8″ optical seeing and relatively low humidity. The low-resolution spectroscopic mode of VISIR was used ($R \approx 220$). The 0.75″ slit was north–south aligned. The entire $N$ band is split into four grating settings. In this paper, we focus only on the ones centred on the aromatic features at 8.6 and 11.3 µm, with the other ones affected by rather strong telluric transmission errors. The on-source observing time
for each setting was about ten minutes, which corresponds to a median sensitivity of about 50 mJy arcsec$^{-2}$. Chopping and nodding were performed parallel to the slit for all observations. The standard star used for photometric calibration and telluric correction was HD 177716 (Cohen et al. 1999).

VISIR resolved spectra are measured from 0″ to 1.5″, with a pixel size of 0.127″. However, only the data under 1″ is used (Fig. 3) because the S/N drops below a value of two at higher radii.

2.3. NACO data

Observations of the HD 169142 disk were performed between 3.2 and 3.76 μm using a long slit with the adaptive optics system NACO at the VLT. The on-sky projection of the slit is 28″ long and 0.086″ wide, which corresponds to the diffraction limit in this wavelength range. The spectral resolution is $R = \lambda/\Delta \lambda \sim 1000$. Nine slit positions were taken, one centred on the star and the other slits shifted by half a slit width. Nine slit positions allowed to extract a spectral cube on an area of 2″ × 0.354″ centred on the star. The dataset ESO program ID is 075.C-0624(A). Observations properties and data reduction are summarised in Boutéraon et al. (2019).

The aromatic and aliphatic emission features at 3.3 and 3.4 μm are detected near the star, down to a distance of 0.1″, but with a low S/N at such small separations (Boutéraon et al. 2019). We focus on regions were the features are clearly detected, from 0.168″ to 0.4″ (20–47 AU) from the star. This corresponds to the transition region between the inner ring and the gap (Fig. 1). For each pixel, the continuum is interpolated by a first-degree polynomial and substracted from the spectrum. To create the pure band emission map and emission profiles at 3.3 μm shown in Fig. 4, the spectral region associated to the telluric band between 3.309 and 3.322 μm is removed, and the flux is spectrally integrated between 3.2 and 3.35 μm.

3. Analysis of the spatial distribution of the AIB and underlying continuum emission

3.1. Spatial distribution of AIB carriers

Figure 3 shows the VISIR resolved spectra from 0″ to 1.02″ as well as the HD 169142 spectra integrated over the entire disk, measured by Spitzer, and computed from the VISIR observations. All spectra include both aromatic band emission and dust-continuum emission. The aromatic infrared nano-particles dominate the infrared emission in HD 169142, as already been reported by Boutéraon et al. (2019). We focus on regions were the features are clearly detected, from 0.168″ to 0.4″ (20–47 AU) from the star. This corresponds to the transition region between the inner ring and the gap (Fig. 1). For each pixel, the continuum is interpolated by a first-degree polynomial and substracted from the spectrum. To create the pure band emission map and emission profiles at 3.3 μm shown in Fig. 4, the spectral region associated to the telluric band between 3.309 and 3.322 μm is removed, and the flux is spectrally integrated between 3.2 and 3.35 μm.

Figure 2 (left) compares the total emission maps (continuum included) of HD 169142 in the VISIR PAH1 and PAH2 filters to the associated PSF. The full widths at half maximum,
computed by a 2D Gaussian model fitting, are shown in Table 3 for the PAH1 and PAH2 filters, along with the associated PSF. The emission in the PAH1 and PAH2 filters is spatially more extended than the PSF. Similar observations can be made based on the centro-symmetrically averaged profiles (Fig. 2, right, neglecting the disk inclination of $\sim 13^\circ$). This hints towards an intrinsically extended aromatic emission up to at least 2$''$ (234 AU). The rather flat behaviour of the emission profiles towards the star, and the absence of any side-lobes in the emission maps and profiles also suggest the need for an inner region (radii below 0.2$''$), producing relatively low levels of emission in these two bands. A strongly peaked emission towards the inner parts of the disk would indeed lead to noticeable PSF modulations, as described in Sect. 5.1.

Figure 4 shows the spatial distribution of the emission of HD 169142 observed with NACO, integrated over the 3.3 $\mu$m feature (continuum-subtracted, see details in Sect. 2.3), shown in the upper panel. The inner and outer edge of the gap are shown in with dashed lines. The flux is not computed below 0.168$''$ and above 0.4$''$, due to low S/N. The associated azimuthally averaged emission profile is shown in the lower panel. The black solid line is the radial emission profile at 3.3 $\mu$m and the grey line is the associated PSF. The grey fill indicates the location of micron- and millimeter-sized grain dust that has been taken from the literature.

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**Fig. 4.** Spatial distribution of the emission of HD 169142 observed with NACO, integrated over the 3.3 $\mu$m feature (continuum-subtracted, see details in Sect. 2.3), shown in the upper panel. The inner and outer edge of the gap are shown in with dashed lines. The flux is not computed below 0.168" and above 0.4", due to low S/N. The associated azimuthally averaged emission profile is shown in the lower panel. The black solid line is the radial emission profile at 3.3 $\mu$m and the grey line is the associated PSF. The grey fill indicates the location of micron- and millimeter-sized grain dust that has been taken from the literature.

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3.3. AIB emission versus the continuum

In this section, we make use of the derivation of the underlying continuum emission in the PAH1 and PAH2 filters (described in Sect. 3.2) to compare the spatial distributions of the infrared band emission and the continuum emission at 8.6 and 11.3 $\mu$m. As can be seen in Fig. 2 (right) the total emission (band + continuum) at 8.6 and 11.3 $\mu$m and the underlying continuum emission have very similar spatial distributions. The discrepancy between the FWHM of the observational PSF in the PAH1 and PAH2 filters and in the associated continuum filters is smaller than 10%. Therefore, the comparison between the profiles of the total emission in the PAH1 and PAH2 filters and the underlying continuum can safely be interpreted in terms of the spatial distribution of the emission of the disk. The similarity between the distribution of the total flux and the underlying continuum suggests that the continuum emission at 8.6 and 11.3 $\mu$m is dominated by the aromatic infrared band carriers everywhere in the disk. This is in agreement with the dominating aromatic infrared bands in the spatially resolved spectra (Fig. 3).

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3.4. AIB carriers properties

Maaskant et al. (2014) interpreted the HD 169142 spectrum in the mid-infrared (5–13 $\mu$m) using an interstellar-PAH model to accurately evaluate the continuum flux under each band, $I_{cont,8.6}$ and $I_{cont,11.3}$, (ii) from the same spectra, at the same radii, we measure the flux at the wavelength corresponding to the ArIII and SIV filters, $I_{ArIII}$, $I_{SIV}$; (iii) we compute the correcting factors for radius, $r_i$, as $f_{k,8.6}(r_i) = \frac{I_{k,8.6}(r_i)}{I_{cont,8.6}(r_i)}$ and $f_{k,11.3}(r_i) = \frac{I_{k,11.3}(r_i)}{I_{cont,11.3}(r_i)}$; (iv) by interpolating the sets $\{f_{k,8.6}(r_i)\}$ and $\{f_{k,11.3}(r_i)\}$ over the range of [0, 2$''$], we derive the correcting factors at all radii $f_k(r_i)$, $f_{k,11.3}(r)$.

Those factors are then used to compute the underlying continuum maps in the PAH1 and PAH2 filters shown in Fig. 2. These maps are estimated by multiplying the ArIII and SIV filters flux by the correcting factors at each radius : $I_{cont,PAH1}(r) = f_{k,8.6}(r_i)f_{ArIII}(r) \text{ and } I_{cont,PAH2}(r) = f_{k,11.3}(r_i)f_{SIV}(r)$, where $I_k(r)$ is the flux in the filter $k$ at a radius $r_i$. 

3.2. Estimation of the underlying continuum emission

To gain more insight in the intrinsic distribution of the AIB carriers, we aimed at disentangling the pure band emission at 8.6 and 11.3 $\mu$m. In HD 169142, the characteristics of the continuum are discussed in Sect. 3.2. It is due to the increasing thermal emission of the micronic grains at larger distance to the star between 0$''$ and 1$''$, and constant ratios at larger distance. The low ratio values closer to the star are mostly due to the increasing thermal emission of the micronic grains at thermal equilibrium (contributing as continuum emission). On the contrary, the flat band-to-continuum ratios in the HD 169142 disk indicate that carbonaceous nano-grains strongly contribute to the infrared spectra at all radii.

Overall, our data provides evidence of the domination of carbonaceous nano-grains in the infrared emission of the HD 169142 disk at all radii. This is to be linked with the presence of an inner cavity in the disk below 0.17$''$ (20 AU), resulting in a lack of hot micronic grains, which were observed to dominate the continuum emission in, for instance, HD 100546 Habart et al. (2021).
account for the aromatic infrared bands and showed that the spectrum is intermediate between fully neutral, for which the 11.3 μm feature dominates over the 6.2, 8, and 8.6 μm features as well as the fully ionized interstellar PAH, showing predominant 6.2, 8, and 8.6 μm features over the 11.3 μm band (Peeters et al. 2002). Following their interpretation, we note that the VISIR spectra show intermediate features between fully ionized and fully neutral at all radii (Fig. 3). Nevertheless, as the radius increases, the slope at 8.6 μm flattens, which might suggest a higher neutral fraction in the outer regions of the disk. To highlight this effect, we spatially integrate the spectra within a 0.3″ (35 AU) and outside of a 0.3″ separately (see Fig. 3, upper panel). The spectrum of the inner regions shows a stronger slope at 8.6 μm than that of the outer regions, hinting towards a higher ionization fraction in the inner parts of the disk.

According to Maaskant et al. (2014), the spectrum corresponding to a fully optically thin cavity should show completely ionized features. Nonetheless, it is not the case for the spectrum at 0″ (Fig. 3), which probes the inner cavity up to 0.128″ (15 AU). The observed neutral carriers emission could originate from the optically thick inner ring of the disk, and be mixed with the emission within 0.128″ (15 AU) due to the PSF of the observation. However, it should be noted that the evolution of the spectrum may reflect other effects linked to the irradiation condition (spectral shape and intensity of the UV field) or variations in the properties of the aromatic band carriers, such as their size or their structure (see Sect. 5.2).

4. Radiative transfer modelling

In the following, we use the radiative transfer code POLARIS (Reissl et al. 2016), coupled to the grain model THEMIS (Jones et al. 2017) to derive the emission of the disk from a given distribution of small dust grains in HD 169142. Our objectives are to draw better constraints on the distribution of carbonaceous nanoparticles in the disk, and to confirm the first preliminary trends provided by the a priori analysis in Sect. 2. We mainly focus on the comparison between the radial distribution of carbonaceous nano-grains and that of bigger grains derived from the literature. In particular, we try to constrain the presence of carbonaceous nano-particles in the inner cavity and towards the outer disk.

4.1. THEMIS dust grain model

The grain optical properties are modelled using THEMIS, which is an evolutionary core-mantle dust model designed to allow variations in the dust structure, composition, and size according to the local density and radiation field (Jones et al. 2013, 2017). The a-C(H) nano-particles, are modelled as hydrogenated aromatic-rich carbonaceous nano-particles with mixed aromatic, aliphatic, and olefinic domains. It is applied, in particular, to the modelling of dust in the diffuse and dense ISM (Ysard et al. 2015, 2016; Saajasto et al. 2021), near-infrared to sub-millimeter observations of nearby galaxies (Chastenet et al. 2017; Viaene et al. 2019), the near-infrared observations of protoplanetary disks (Boutéraon et al. 2019; Habart et al. 2021), and in photon-dominated regions (Schirmer et al. 2020, 2021).

For the study of the HD 169142 disk, we assume the dust composition and size distribution used by Habart et al. (2021) in their modelling of the HD 100546 disk. It corresponds to the THEMIS diffuse-ISM dust model developed by Jones et al. (2013); Köhler et al. (2014). The dust is modelled as a-C nanoparticles populations with different size distributions (a-C1, a-C2, VSG), amorphous carbon dust grains of radius ~20 nm (amC), and silicates, modelled as a balanced mix of amorphous pyroxene-type and olivine-type silicate grains (SiIl, SiI2) (see Habart et al. (2021) for more details). The properties of each dust population are given in Table 4. The Habart et al. (2021) model corresponds to a weighted mix of the a-C1, a-C2, VSG, and SiI2. It is used in the outer regions of the HD 169142 disk.

The SiI2 dust component is used to model the emission of the HD 169142 inner disk. Similar to Chen et al. (2018), we use large grains in the inner structure, with sizes from 10^{-2} to 10^{3} μm, and a power-law distribution with exponent −3.5 (see Table 4). The higher amount of large grains has already been suggested in inner disk regions, for instance, in the HD 100546 disk by Tatulli et al. (2011), who used 5 μm-sized dust grains, as well as Miley et al. (2019), who suggested that grain populations could reach millimeter to centimeter sizes in the inner hot regions of the disk. It is thought to be due to the sublimation of smaller grains in such intense radiation field and temperature conditions (Tatulli et al. 2011). This assumption is physically supported by the fact that the smallest grains are also the hottest ones and are thus more prone to destruction by sublimation.

4.2. POLARIS radiative transfer code

POLARIS is a three-dimensional radiative transfer code (Reissl et al. 2016) which solves the radiative transfer problem self-consistently using the Monte Carlo method. POLARIS has been developed to simulate polarised emission and Zeeman splitting due to magnetic fields in dusty media. We used the recent updates of the code, which allow for the modelling of the emission of protoplanetary disks by considering complex structures and varying dust populations in space, and take into account the stochastic heating of nanometer-sized grains, including single as well as multi-photon absorption. In particular, feeding POLARIS with optical properties of small carbon grains from THEMIS...
allows us to build a detailed model of the infrared emission in the HD 169142 disk.

The stellar parameters, $R = 1.6 R_\odot$ and $T = 7800$ K, are taken from previous works (Table 1). We use an axis-symmetrical, cylindrical grid. The gas density distribution is computed assuming hydrostatic equilibrium in the disk (Hayashi 1981):

$$n(r, z) = n_0 \left( \frac{r_0}{r} \right)^\alpha \exp \left( - \frac{1}{2} \left( \frac{z}{h(r)} \right)^2 \right), h(r) = h_0 \left( \frac{r}{r_0} \right)^\beta,$$

where $\alpha = -2.09$, yielding decrease in the density with radius slightly steeper than squared, and $\beta = 1.1$, corresponding to a flared disk, are taken from Monnier et al. (2017). We make the commonly used assumption of an approximate $1/10$ ratio for the disk scale height, we set $r_0 = 1$ AU, $h_0 = 0.07$ AU in the inner disk and we set $r_0 = 100$ AU, $h_0 = 15$ AU in the outer regions. The dust model does not include grains bigger than 5 $\mu$m, as large grains do not contribute substantially to the thermal emission below 13 $\mu$m. The small inclination of the disk is neglected, and the system is modelled face-on, as observed by Panić et al. (2008), for instance.

Models featuring an empty gap (0.27–0.48″, 32–56 AU) or no gap (full disk from 0.17″, 20 AU) resulted in similar profiles after convolving with the VISIR PSF, showing that the VISIR data does not have a high enough angular resolution to study the gap properties (see PSF in Table 3). Because of the very narrow gap region probed by the NACO data, neither did it allow to distinguish between both cases. For simplicity the gap from 30 to 55 AU is therefore not taken into account in our simulations and the outer region from 20 to 250 AU is modelled as a full disk. Both Osorio et al. (2014) and Monnier et al. (2017) place the inner disk between 0.2 AU and 0.5 AU, and we follow this choice. The mass of the inner disk is chosen small enough to create an optically thin structure which does not contribute significantly to the disk emission (see Table 5), in agreement with the absence of silicate bump in the HD 169142 spectrum.

The spatial distribution of each type of dust is given in Table 5. We modeled the dust in the outer regions of the disk from 0.17″ (20 AU), according to the dust model used by Habart et al. (2021). It only features dust grains smaller than 5 $\mu$m as a mix of a-C, a-C$_1$, a-C$_2$, VSG, and Sil1 dust populations (Table 5, third column). The inner disk, below 0.5 AU is modelled as pure silicate dust, with grain sizes up to 1 mm (Table 5, first column). The properties of the dust populations are detailed and discussed in Sect. 4.1. Finally, the model allows the addition of carbonaceous nano-particles below 0.17″ (20 AU) starting from an inner radius $R_{cav}^{\text{C}}$ and following the gas density distribution given in Eq. (1) with values for $\alpha$, $\beta$, $r_0$, and $h_0$ identical to the outer disk. This new component is composed only of carbonaceous nanoparticles (a-C$_1$, a-C$_2$, Table 5, second column) with a density depleted by a factor $f$ compared to the outer disk, resulting in a total carbon nano-particles mass $M_{cav}^{\text{C}}$ between $R_{cav}^{\text{C}}$ and 20 AU. The numerical values used for the model parameters $(h_0, R_{cav}^{\text{C}}, M_{cav}^{\text{C}})$ are given in Table 6 and will be discussed in Sect. 5.1.

### 4.3. Predicted intensity profiles

POLARIS outputs are obtained as data cubes: 2D intensity maps computed at regularly spaced wavelengths (150 values between 7 and 13 $\mu$m). To account for the spectral width of VISIR PAH1 and PAH2 filters in our simulations, the maps are spectrally averaged over the filter widths. The resulting images are then convolved with the observed PSF (given in Fig. 2) and azimuthally averaged to compute the profiles shown in Fig. 6. The continuum maps and profiles are computed first by a two-degree polynomial interpolation of the continuum around 8.6...
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Fig. 6. VISIR radial profiles (black full line), compared to simulated results (dotted, dashed, dash-dash-dotted, and dash-dot-dotted lines) for the PAH2 filter and associated continuum on the top panels, and the PAH1 filter and continuum on the bottom panels. For a description of the different models, we refer to Table 6. The grey fill indicates the location of micron- and millimeter-sized grain dust.

and 11.3 µm on the initial POLARIS cube, resulting in a continuum cube, from which the continuum profiles are then similarly derived.

Similar work has been done to reproduce the NACO maps and profiles to account for the spectral width of the aromatic band at 3.3 µm. The simulated spectral cube (100 wavelengths between 3 and 4 µm) is first spectrally integrated between 3.2 and 3.35 µm, ignoring the region between 3.309 and 3.322 µm, which corresponds to a telluric band. Ignoring the telluric band results in a underestimation of the modelled integrated band flux by less than 0.5%. We then extract a 1D flux profile and convolve it with the PSF (1D, see Fig. 4) of the observation, integrated in the same way around 3.3 µm. The resulting profiles are compared with NACO data in Fig. 7.

5. Comparison between model and data

5.1. Constraining the nano-grain distribution in the disk

We first compared the data with the standard disk model described in Sect. 4.2, having no carbonaceous nano-particles below 0.17” (20 AU), as shown in model M0 in Table 6 and Fig. 6. Figure 6 (top) compares the resulting profiles with the VISIR imaging data in the 11.3 µm PAH2 filter. We focus mainly on the model-data comparison in this filter, because it is less affected by the state of charge of the carriers. The VISIR flux is overestimated at 11.3 µm in the entire disk by a factor of 1.8 to 2.2, both for the continuum and the total emission, resulting in an overestimation of the band flux by a factor of 1.9 over the full disk (Table 7).

This overestimation at all radii can be linked to the presence of a spatially unresolved component showing very strong emission from all dust populations in the inner regions in our model. Such a component would indeed contribute as an additional, almost unresolved flux at every radius in the disk. We lower the value of the disk height in the whole disk by decreasing h₀ from 15 to 5 AU at r₀ = 100 AU. This allows to reduce the amount of hot dust close to the star and recover the VISIR total flux level in the PAH2 filter also as the associated continuum (model M1 in Table 6 and Fig. 6) and the integrated continuum-subtracted emission in the band (Table 7). The slope of the modelled profile agrees with the VISIR data in the PAH2 band for radii higher
than 0.2″ (Fig. 6) and the absolute flux at 11.3 μm is well reproduced. However, the modelled flux in the 11.3 μm feature drops by 20% (1.8 Jy as⁻²) below the VISIR error bars at radii smaller than 0.2″ (23 AU).

Adding a very small amount of carbonaceous nano-particles in the inner cavity leads our model to match the entire observed profile within the error bars (model M3 in Table 6 and Fig. 6). However, a degeneracy is observed between the inner radius, RCav, and the depletion factor, f, of the carbonaceous nano-grains in the cavity. This is because models using (RCav = 0.128″ or 15 AU; f = 100), (RCav = 0.09″ or 10 AU; f = 1000) and (RCav = 0.04″ or 5 AU; f = 3000) account similarly well for the VISIR profiles at 11.3 μm, the ISO, and the Spitzer spectra. A model having non-depleted carbonaceous nano-grains in the cavity from 0.04 to 0.17″ (5 AU to 20 AU) strongly overestimates the flux of the aromatic infrared bands (model M2 in Table 7). The associated profile at 11.3 μm overestimates the band flux near the star, and shows Airy side-lobes (Fig. 6). The much better agreement achieved between model M3 and the data thus supports the need for depletion of carbonaceous nano-particles in the cavity.

In summary, the comparison between our models and the VISIR data at 11.3 μm hints towards depleted carbonaceous nano-grains in the cavity below 0.17″ (20 AU). It could be due to photo-destruction of the grains in the strongly irradiated inner regions. The photo-destruction and depletion of small dust grains has been observed, for instance, in the interstellar photon dominated regions by Schirmer et al. (2020). However, this study faces strong degeneracy due to the limited angular resolution of the data. A higher angular-resolution is required to better quantify the level of depletion as well as the spatial distribution of the band carriers in the cavity.

5.2. Carbonaceous nano-particles properties

5.2.1. Analysis of the 8.6 μm band

None of the models have satisfactorily reproduced the VISIR 8.6 μm band profile (Fig. 6). Both the M1 and M3 models, which optimally reproduce the data at 11.3 μm, underestimate the flux at 8.6 μm by a factor 2 in the entire disk, as well as in the integrated spectra (Fig. 8).

This could be explained considering the charge state of the band carriers. Using an interstellar-PAH description of the aromatic infrared band carriers, the 8.6 μm feature is expected to be stronger for ionised PAH. The underestimation of the emission at 8.6 μm would then suggest the need for a higher ionisation fraction in the HD 169142 disk than what is considered in our model. Indeed, THEMIS includes no charge dependence of the aromatic particles, while Seok & Li (2016) derived an ionization fraction of 0.6 for the PAH in HD 169142 from SED fitting.

In addition, all simulated VISIR profiles at 8.6 μm are too flat near the star and show a strong slope between 0.2″ and 0.5″ (20–60 AU). In order to better fit the data, the predicted emission of the 8.6 μm feature should be stronger below 0.17″ (20 AU) and quickly decrease when entering the disk. It is in agreement with the evolution of the 8.6 μm slope observed in the VISIR resolved spectra (see Fig. 3 and Sect. 3.4). In the interstellar-PAH framework, as the 8.6 μm to 11.3 μm ratio is higher for ionised PAH, it thus suggests the need for a greater amount of ionised emission near the star in our disk models. As the POLARIS/THEMIS models assume no variations of the ionisation fraction, the comparison to the data would then hint towards an increasing ionisation fraction towards the irradiated inner regions. Maaskant et al. (2014) associated the emission from ionized PAH to optically thin inner disk regions where the UV field is high and the electron density is low; whereas optically thick outer disk regions would be dominated by neutral PAH emission with little variation with radius. This is in agreement with the trend found in our observations.

However, the interpretation of the spectral signatures at 7.7, 8.6, and 11.3 μm is not unequivocal, and could be as well explained, for instance, by varying size distribution of carbonaceous nano-grains. The underestimation of the flux at 8.6 μm, and the need for a steeper radial slope near the star would, within this framework, suggest the need for a higher abundance of bigger carbonaceous dust grains in the inner regions. This is consistent with stronger photo-destruction of smaller grains in optically thin, strongly irradiated media and is supported by the work of Schirmer et al. (2020, 2021) on dust evolution in photon dominated regions.

5.2.2. Analysis of the 3.3 μm band profile

The standard model M0 as well as models M1 and M3 are consistent with the NACO absolute flux in the 3.3 μm band (Table 7). Yet, none of the simulated flux distributions agree with the NACO radial profile shown in Fig. 7. The 3.3 μm is produced by very small carbon grains, with radii smaller than 0.7 nm. A stronger depletion of this population of grains in the innermost regions could explain the discrepancy between the data and the model. Such a depletion could originate from photo-destruction of the smaller grains in the irradiated regions, as was observed in the interstellar photon dominated regions by Schirmer et al. (2020).

6. Conclusion

We investigated the carbonaceous nano-grains emission in the HD 169142 disk by comparing high angular observations with model predictions. We analysed the imaging and spectroscopic data (VLT/VISIR, 8–12 μm, angular resolution 0.3″) as well as the adaptive optics spectroscopic data (VLT/NAOS-CONICA,
both observations and model predictions are summarised below:

3–4 μm, angular resolution 0.1′′. Our main results derived from both observations and model predictions are summarised below:
1. Probing the emission in the HD 169142 disk in the 3.3, 8.6, and 11.3 μm aromatic infrared bands, we were able to provide new strong evidence of the extended nature of the distribution of carbonaceous nano-particles populations and their domination in the infrared emission of the disk at all radii, in agreement with previous studies, for instance Seok & Li (2016);
2. The flattening VISIR spatial emission profiles near the star, the absence of Airy side-lobes in the VISIR imaging data and the faint aromatic feature detection by NACO below 20 AU points towards a fairly large depletion of PAH inside the 20 AU cavity;
3. To gain more insight in the spatial distribution of carbonaceous nano-particles in the disk, we modelled the distribution of small dust grains using the POLARIS radiative transfer code coupled to the THEMIS model for the emission of carbonaceous nano-grains. The VISIR radial profile at 11.3 μm is reproduced within the error bars, assuming a continuous radial distribution of micronic grains and carbonaceous nano-grains from 20 to 250 AU, as well as carbonaceous nano-grains decreased in abundance in the inner cavity between 0.5 and 20 AU. The precise amount of carbon nano-grains needed in the cavity and their inner radius are strongly degenerate and could not be derived from our modelling. Nonetheless, the comparison between simulations and the emission profile at 11.3 μm shows the need for strongly depleted carbonaceous nano-grains below 20 AU. This result supports previous studies from Maaskant et al. (2013) and Seok & Li (2016), which hinted at the presence of interstellar PAH in the cavity and offers evidence of their depletion;
4. The VISIR spectra clearly shows a spectral evolution from the inner regions towards the outer regions. In the interpretation framework of interstellar PAH, this evolution can be explained by a transition between dominating ionized PAH in the optically thin internal regions to neutral PAH in the optically thick outer disk media. The discrepancy between our models and the VISIR profiles at 8.6 μm seems to support this interpretation. It first suggests that the ionization which has be considered in the model is too small (full neutrality was assumed). As the emission at 8.6 μm shows more radial variations in the data than in the model, it also suggests the need for ionization variations throughout the disk. However, the interpretation of the spectral signatures at 8.6 and 11.3 μm as indicators of the ionization fraction of the PAH is not unequivocal. The evolution of the spectrum may reflect other effects linked to the irradiation condition (spectral shape and intensity of the UV field) or the size or structure of the band carriers. The evolution of the HD 169142 spectrum towards the center could also be consistent with a higher abundance of larger grains in the inner cavity;
5. Finally, the NACO radial slope is strongly overestimated. This could be linked to a depletion in very small carbonaceous nano-particles towards the most irradiated regions, caused by a strong photo-dissociation of small particles (Schirmer et al. 2020).

Our understanding of the evolution of carbonaceous nano-grains in disks is expected to make significant progress thanks to upcoming spatially resolved observations with the VLTI/MATISSE interferometer, the JWST integral-spectrograph, and the ELT/METIS high-resolution spectrograph and high-contrast imager. Interferometric measurements using MATISSE would provide valuable and precise information on the distribution of carbon nano-grains in the innermost regions, namely, the inner cavity and the inner disk (1 < r < 15 AU). On the other hand, observations with the JWST covering a complete spectral domain between 0.6 and 28 μm will mainly probe the dust content with a spectral resolution of ~3000–4000, a spatial resolution of 10–100 AU, and for distances up to 500 AU. Spatially resolved spectroscopy of the aromatic and aliphatics sub-features will be obtained and allow for a better identification of the nature and properties of the bands carriers. Finally, ELT-METIS will achieve a combination of high spatial resolution with a large field-of-view and a spectral resolution allowing the detection of aromatic infrared bands.

**Table 7.** Continuum-subtracted band fluxes in 10^{-14} W m^{-2}, integrated over the disk in the three aromatic bands, computed for the different POLARIS models.

| Model | Band | Data | Model |
|-------|------|------|-------|
|       | 3.3 μm | 8.6 μm | 11.3 μm |
| ISO   | 0.89 ± 0.01 | 2.55 ± 0.5 | 2.08 ± 0.01 |
|       | 1 ± 0.2 | 2.2 | 1.1 |
| M0 : R_{cav}^a = 20, h_0 = 15 | 0.55 | 1.3 | 0.92 |
| M1 : R_{cav}^a = 20, h_0 = 5 | 0.26 | 0.64 | 1.5 |
| M2 : R_{cav}^a = 5, h_0 = 5, f = 1 | 1.7 | 3.5 | 7.8 |
| M3 : R_{cav} = 5, h_0 = 5, f = 3000 | 0.87 | 0.92 | 1.5 |

**Notes.** The modelled values are compared to the fluxes computed on ISO data (Acke & van den Ancker 2004) and Spitzer data (Acke et al. 2010).

**Fig. 8.** ISO and Spitzer spectra, compared to the simulated results. For a description of the different models, we refer to Table 6.
thus providing an great opportunity to probe the dust content in the gap region (0.27”–0.48” or 32–56 AU). Furthermore, combining dust models with new high-resolution data could allow a more detailed analysis of the local properties of the particles (charge, size, excitation). This would help to break some of the degeneracies encountered in this work, differentiate between the various proposed disk compositions, and study more precisely the distribution of aromatic dust populations in the gaps.

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