SF2A 2025
A. Siebert, K. Baillié, M. Béthermin, F. Cantalloube, E. Josselin, N. Lagarde, J. Malzac, J. Richard, L. Selliez, O. Venot (eds)

DISK THICKNESS AS AN ALTERNATIVE TO SATURATED WATER-ICE BANDS FOR DETERMINING ICE ABUNDANCES IN HIGHLY INCLINED DISKS

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Abstract. Ices are assumed to play a key role in planetary formation and have been commonly detected in protoplanetary disks. The shape of ice bands is used to provide information on the ice properties. The James Webb Space Telescope now enables the spectral study of ices in more detail, and it is necessary to correctly interpret these ice bands. However, the spatial distribution of ices is currently not considered and the saturation of ice bands in too highly inclined disks precludes the determination of ice abundances.

In preparation for future spectral observations by JWST, we studied the dependence of water-ice absorption bands on disk inclination and disk location from which spectra are extracted. Based on a standard protoplanetary disk model composed of a spatially homogeneous dust and amorphous water ice mixture around a T Tauri star, we used the radiative transfer code MCFOST. We also propose a method to circumvent the saturation in spectra of highly inclined disks to determine the ice abundances in these disks.

We found that the observed properties of water-ice bands depend on two parameters independently of the type of ice or the grain size distribution: inclination of the system as well as location within the disk. In particular, even with only amorphous water ice, the wavelength minimum of the bands can change by up to $0.2\,\mu$m, comparable to the difference expected between amorphous and crystalline ices assumed in previous studies. This phenomenon stems from a balance between absorption and scattering linked to a shift between absorption and scattering opacity curves and must be taken into account in detailed modeling of spatially resolved infrared spectroscopy of ices. We also predict the same phenomenon for CO and CO_2 ices based on the shift of their opacity curves. Finally, we show that the thickness of the disk may be a good quantitative tracer to determine the ice abundance in highly inclined disks.

Keywords: scattering, protoplanetary disks, stars: variables: T Tauri, Herbig Ae/Be

1 Introduction

Ices form in the cold regions of protoplanetary disks and are involved in many processes leading to planetary systems. In particular, water ice plays a crucial role in the growth of grains and in planetary formation. In previous studies, the shape and minimum position of the band is used to provide information about ices properties like the distinction between amorphous or crystalline water ice (Boogert et al. 2015).

Ices are also assumed to be ubiquitous in protoplanetary disks and have been detected in some disks to date. These detections have been done through imaging and photometry in low inclinations disks (Betti et al. 2022) without spectroscopic information, precluding a detailed analysis of ice properties. However, spectroscopic observations have revealed the presence of ices in a few highly inclined disks (Sturm et al. 2023). The James Webb Space Telescope now enables the spectral study of ices with unprecedented sensitivity and angular resolution but the spatial distribution of ices in protoplanetary disks is yet poorly constrained. Thus, we need to improve our knowledge in view of upcoming JWST programmes.

In this study, we explore the importance of the viewing angle and light propagation path on the shape of water-ice spectra which depend on the inclination of the system as well as the location within the disk. We also propose a method to determine the ice abundance within the disks.

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2 Methods

Our model follows the one described in Martinien et al. (2025), composed of a uniform disk with a mixture of dust and amorphous water ice. Inclinations range from 60°to 90°to see their effect on the behavior of water-ice bands. The spectra are extracted from synthetic total intensity images between 2.0 and 4.0 microns at two different locations: at the outer edge of the disk and at the central point source.

3 Results

3.1 Spatially-varying water ice spectra

Fig. 1 shows the extracted spectra at the edge of the disk (framed in blue dotted line) and at the central point source (framed in red solid line). The spectra at the edge of the disk have the same relative depth and the bands are similarly saturated for all inclinations. However, the shape of the bands at the central point source is different from those at the disk edge, with a strong dependence on inclination. The minimum of the band is shifted from the longer to the shorter wavelengths, from the lowest to the highest inclinations respectively. There is also a bump on the blue side of the band for intermediate inclinations, called the grazing-angle inclinations, which is caused by scattering by grains of the order of a few microns. Interestingly, this blue bump has been recently observed in CO and CO_2 ices band JWST spectra in a grazing angle disk in Orion (Potapov et al. 2025). The bands become saturated for the highest inclinations, making it impossible to determine the abundance of ice when the disks are too highly inclined. This difference in behavior between the two locations in the disk can be explained by the wavelength dependence of the scattering and absorption opacities combined with the path of photons that depends on the viewing geometry.

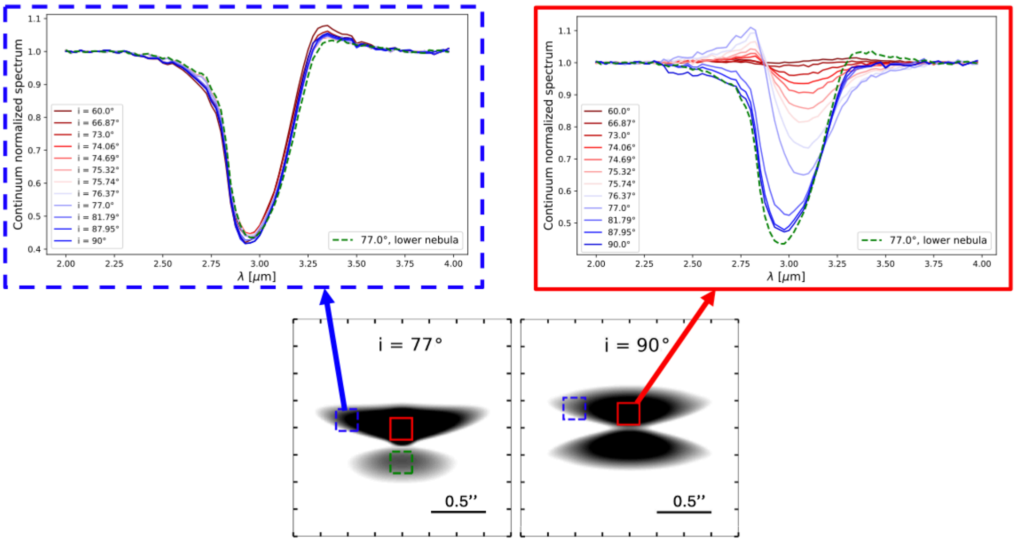

Fig. 1. Synthetic spectra at two locations in the disk for different inclinations, adapted from Martinien et al. (2025).

3.2 Light propagation path in different disk inclinations

Fig. 2 illustrates the importance of the observer's viewing angle. In low inclination disks, like IM Lup, the stellar photosphere remains visible and the observer's line-of-sight to the central star is dust free, with some (small) additional contribution from light scattering off the disk surface. In high inclination disks, like HH 30, the observer's line-of-sight to the star is optically thick. Stellar photons cannot reach the observer directly. The observer therefore dominantly receives scattered photons. This leads to scattering-dominated spectra as well as a rapidly saturated water-ice band. However, an intermediate case exists, the grazing angle inclination, like PDS 453, in which the disk partially masks the star. This results in non negligible absorption and scattering components, both contributing to the spectrum. This geometry is unique and is the only one for which we can observe both scattering and absorption.

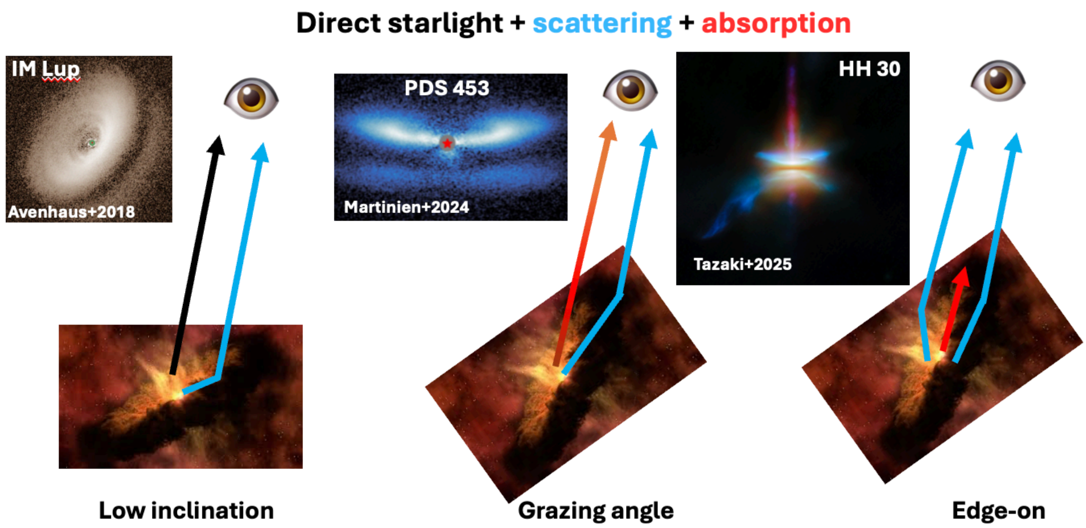

Fig. 2. Sketch of the light propagation path from the star to the observer at different viewing geometry.

3.3 *A consequence of scattering and absorption opacities*

The difference in behavior of water-ice spectra between the two locations can be explained by the opacity law of the mixture, as well as the viewing geometry. The left panel of Fig. 3 shows the minimum position of the band as a function of inclination. For the spectra at the edge of the disk, the minimum only barely shifts between the lowest and the highest inclinations. However, for the spectra at the central point source, the minimum increases from the lowest to the grazing angle inclinations until reaching $\sim$3.1 μm and then decreases until $\sim$2.9 μm for the highest inclinations. The difference of 0.2 μm is similar to the difference often associated to amorphous and crystalline water-ice in the literature. However, our model contains only one type of water-ice, amorphous, and yet it yields different minimum positions of the band with changes in inclination.

This phenomenon is a result of the shift between the minimum and maximum position of the scattering and absorption opacity curves, respectively, as illustrated in the right panel of Fig. 3. Indeed, for the lowest and highest inclinations, the bands are scattering dominated because the minimum position of the bands is around 2.9 μm. However, for the grazing angle inclinations, the minimum is around 3.1 μm and correspond to a regime where the absorption component is significant. Thus, the correct interpretation of ice spectra requires a complete consideration of all radiative transfer effects.

The same phenomenon can be expected for CO and CO_2 ice bands because a shift similar to water ice is observed between the scattering and absorption opacities. The expected phenomenon possibly being even more pronounced compared to H_2O ice.

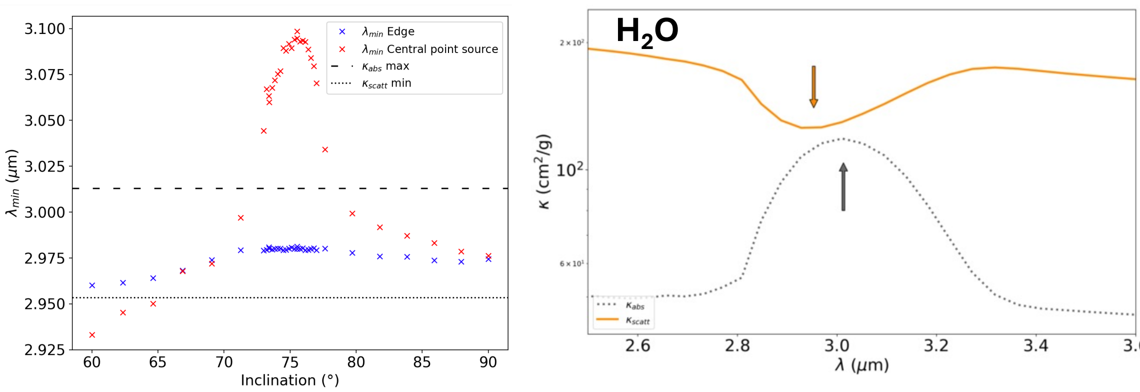

Fig. 3. Left: Minimum position of the bands as a function of inclination. **Right:** Scattering and absorption opacities curves of H_2O ice. Figures are adapted from Martinien et al. (2025).

4 The thickness of the disk as a tracer of the ice abundance

We showed that for high inclination disks, it is impossible to determine the abundance of ices from spectra because both the band and adjacent continuum are seen via optically thick scattering. This band saturation was observed several times in models of highly inclined disks (Sturm et al. 2023; Martinien et al. 2024, 2025).

However, the thickness of the disk across the absorption band, measured as separation between the two scattering nebulae, can be used to overcome this problem. Fig. 4, left panel, shows the distance between the two nebulae in the edge-on model in Martinien et al. (2025), which is directly connected to the disk mass and dust opacity (Watson & Stapelfeldt 2004). For dust continuum scattering, the distance decreases with wavelength because the dust opacity also decreases. However, adding ice increases the dust opacity over specific ranges of wavelengths and a bump appears at 3.1 μm corresponding to water ice. Consequently, the height of the scattering surface is elevated in the ice band. The increased disk thickness can be directly linked to the abundance of ice in the disk, without saturation. The disk thickness will increase more at the band center as the abundance of ice increases. We will quantify this with models in a separate paper (Martinien et al., in prep.).

Interestingly, the phenomenon is also conspicuous in JWST observations. Fig. 4 shows the distance between the two nebulae in two edge-on disks: HH 30 and Tau 042021. As the opacity decreases with wavelength, so does the separation except at the position of ices, at 3.1 μm, 4.2 μm and 4.6 μm, corresponding to H_2O, CO_2 and CO ices. This unambiguously confirms the presence of all three ice species of ices within these disks. It will thus be possible to determine the abundance of ice by fitting models to the observed distance between the two nebulae. Moreover, we can expect the same phenomenon of disk thickness increasing in other optically thick spectral features affected by scattering such as the silicate bands, the PAH bands and some gas lines.

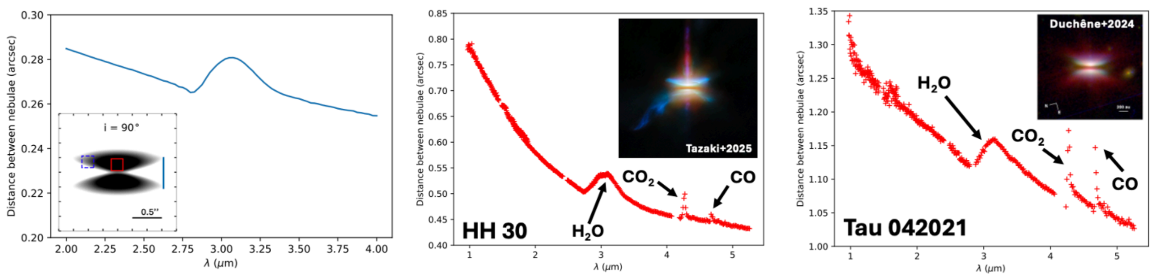

Fig. 4. Distance between the two nebulae as a function of wavelengths. **Left:** In edge-on disk model of Martinien et al. (2025). **Middle and right:** In JWST/NIRSpec observations of HH 30 and Tau 042021 (Martinien et al. in prep.).

5 Conclusions

In addition to physical parameters (e.g., grain size and composition), water-ice spectra observed in protoplanetary disks depend on two other parameters: the inclination of the system and the location in the disk, even for a uniform dust distribution. This is due to a balance between absorption and scattering. Future models should therefore account for scattering to avoid misinterpretation of ice band behaviors to accurately constrain ice properties within disks. The thickness of the disk can provide insights on ices abundance in edge-on disks, which is impossible to achieve otherwise, because of the saturation of the band at high inclinations.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon Europe research and innovation program (grant agreement No. 101053020, project Dust2Planets, PI: F. Ménard).

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