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STUDY OF THE VERTICAL AND RADIAL STRUCTURE OF THE EDGE-ON PROTOPLANETARY DISK SSTTAU042021

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Abstract. We present observations of the edge-on protoplanetary disk 2MASS J04202144+2813491 (SST-Tau042021) combining archival ALMA data with new NOEMA observations. Using the tomographic method, we have reconstructed the two-dimensional brightness temperature distribution $T_\mathrm{b}(r, z)$ for several molecules (^{12}CO, ^{13}CO, C^{18}O, and HCO$^+$). This analysis is coupled with a parametric radiative transfer modeling using the DiskFit code. The combination of these approaches allowed us to quantitatively characterize the vertical stratification of the molecular layer. We have been able to determine the temperatures of the disk mid-plane, the molecular layer, and the upper disk atmosphere, providing new constraints on the vertical thermal structure of this edge-on disk.

Keywords: protoplanetary disks – edge-on disks – astrochemistry

1 Introduction

Most protoplanetary disks are observed with an inclination, and even with ALMA, studying their vertical and radial gas and dust structure remains challenging due to limited sensitivity and angular resolution. In such inclined systems, the Keplerian shear complicates the determination of the vertical location of the molecular layer, which often requires complex thermo-chemical models based on assumptions that are difficult to verify, unlike in edge-on disks, where this structure can be more directly constrained.
We exploit the ALMA archive and NOEMA data to investigate the dust and gas properties of the edge-on disk surrounding 2MASS J04202144+281349, a TTauri star located in Taurus. We apply the tomographic method from (Dutrey et al. 2017) to investigate the properties of this edge-on disk. We derive the CO temperature using parametric models to determine the vertical temperature gradient. We investigate the column density using the optically thinner isotopomers of CO. We also analyse the dust emission in order to determine the dust distribution, temperature and mass.

2 Observations

2.1 Source presentation

The SSTTau042021 disk is observed almost perfectly edge-on, with an inclination of $90.6 \pm 0.4°$. It is located in the Taurus cloud and has a low-mass star of $\sim 0.27 M_\odot$ (Simon et al. 2019). This T Tauri star is surrounded by a Class II edge-on disk (Villenave et al. 2020), which is one of the largest millimeter disks known among edge-on systems, extending up to 260 au. ALMA observations also reveal a large CO disk with a radius of approximately 700 au.

2.2 Disk wind with JWST observations

This disk was also observed with the JWST, in particular in Arulanantham et al. (2024), which revealed a significant H_2 disk wind. We therefore superimposed the molecular line contours obtained with ALMA and NOEMA on the H_2 disk wind (Fig.1).

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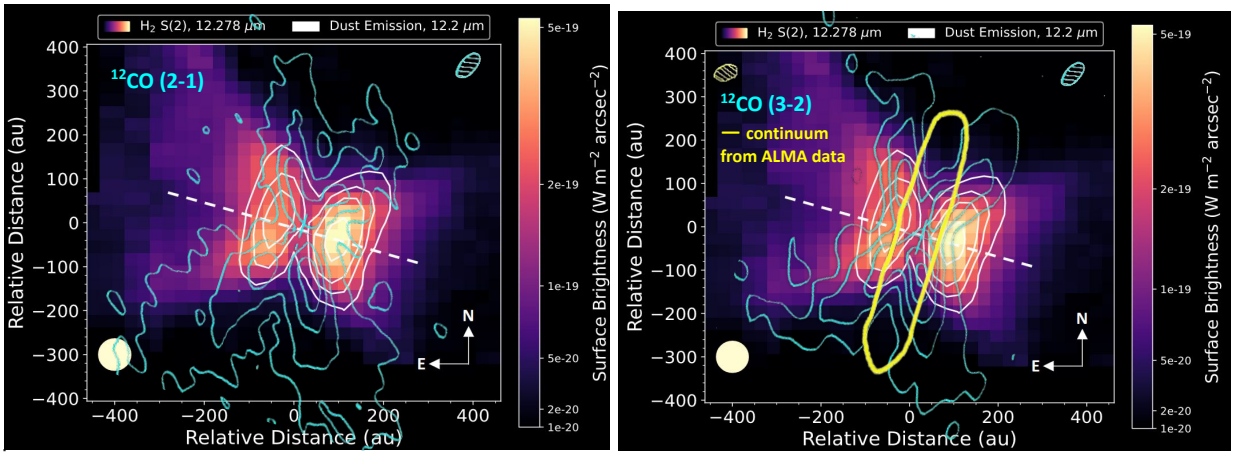

Fig. 1. Montage of JWST and interferometric data for SSTTau042021. MIRI MRS images from JWST reveal H_2 S(2) emission at 12.278 μm (Arulanantham et al. (2024)). White contours indicate the mid-infrared scattered-light continuum at 12.2 μm, and the white dashed line marks the rotation axis of the disk at PA = 73.5°. From archival ALMA data, cyan contours show molecular emission lines of ^{12}CO (2-1), and ^{12}CO (3-2), while yellow contours represent the 0.85 mm continuum emission at 1 mJy/beam. Beige circles in the bottom left corner of each panel represent the average theoretical FWHM of the PSF for JWST data, calculated from the relationship reported in Law et al. (2023), and the beam of the molecular line emission is shown as a cyan ellipse in the top-right corner of each panel (Foucher et al. submitted).

The ^{12}CO (2-1) emission exhibits a significant vertical extension, revealing complex structures in the outer regions of the disk. In particular, two velocity channels highlight the presence of toroidal features located symmetrically above and below the disk plane. These CO rings are detected at altitudes corresponding to approximately four scale heights from the midplane.

Such structures may trace gas entrained by the molecular H_2 wind previously detected with JWST, suggesting a possible connection between disk winds and the vertical distribution of CO. However, deeper and more sensitive CO observations are required to better constrain the kinematics of this extended emission and to confirm its physical origin.

2.3 Tomographies

The tomography method is a construction of a 2D image of the gas brightness temperature as a function of radius and height by averaging the observed intensity along lines in the PV diagram (each line corresponding to a disk radius) in the regions where the signal is sufficiently resolved both spectrally and spatially (Dutrey et al. 2017). We use this tomography method on the SSTtau042021 (column a in Fig.2) and put in evidence with a direct view that CO has a much higher abundance than ^{13}CO and C^{18}O. Thus, it allows us to trace the entire disk, unlike ^{13}CO and C^{18}O, which trace mostly the densest part of the disk, corresponding to the molecular layer.

3 Modeling

We combine the study of our observations with a simple parametric disk model, DiskFit (see Piétu et al. (2007)) in which the disk is characterized by several parameters, for which error bars can be derived. Temperature radial and vertical profiles are modeled following Dartois et al. (2003) and Dutrey et al. (2017). The disk atmosphere temperature is given by:

$$T_{atm}(r) = T^0_{atm}\left(\frac{r}{r_0}\right)^{-q_{atm}} \tag{3.1}$$

while the mid-plane temperature corresponds to:

$$T_{mid}(r) = \min\left(T_{atm}(r), T_0\left(\frac{r}{r_0}\right)^{-q_0}\right) \tag{3.2}$$

In between, for an altitude of $z < z_q H(r)$, the temperature is defined by:

$$T(r,z) = (T_{mid}(r) - T_{atm}(r)) \left(\cos \left(\frac{\pi z}{2 z_q H(r)} \right) \right)^{2\delta} + T_{atm}(r) \tag{3.3}$$

An analysis of CO data with this model inside the UV-plane reveals the vertical extents of the CO isotopologues and allow a proper derivation of the thermal structure.
We derived best models for ^{12}CO, ^{13}CO, C^{18}O, and HCO$^+$ which provide the 2D gas kinetic temperature profile because the transitions are optically thick and thermalized.

4 Results & Conclusions

Thanks to the comparison between the tomographic observations and the best-fit models (Fig 2), we have gained important insights into the structure of both the dust and gas.

4.1 Continuum

Our analysis reveals that the dust disk around SSTTau042021 is extended, cold (with temperatures around 10 K), and shows no evidence of a central cavity. The temperatures derived from both dust and gas tracers are consistent, indicating thermal coupling in the dense midplane (8-10 K). A potential gap between 70 and 150 au is detected in the dust continuum at 150 and 330 GHz, but remains undetected in CO and HCO$^+$ emission, highlighting the need for additional molecular line observations to confirm its presence.

The disk appears to be relatively young, with a surface density that follows a power-law distribution with a flat radial index and a small vertical scale height. These characteristics suggest partial vertical settling of large dust grains toward the midplane, possibly marking an early stage of disk evolution and planetesimal formation.

4.2 Molecular observations

Our combined analysis of ALMA and NOEMA data reveals a vertically stratified gas structure in the edge-on protoplanetary disk SSTTau042021. We identify a well-defined molecular layer with a temperature of approximately 17 K, lying above a colder midplane (∼8-12 K) and below a warmer CO-rich atmosphere reaching ∼31 K at 100 au. CO and HCO$^+$ emission extend well beyond the dust disk radius (∼300 au for the dust against ∼750 for the gas).

From the detection and thermalization of the HCO$^+$ (3-2) line, we infer that the H_2 density in the molecular layer exceeds 3×10^6 cm^{-3} at 100-200 au. Finally, we derive a total disk mass of ∼0.05 M$_\odot$ from the continuum emission.

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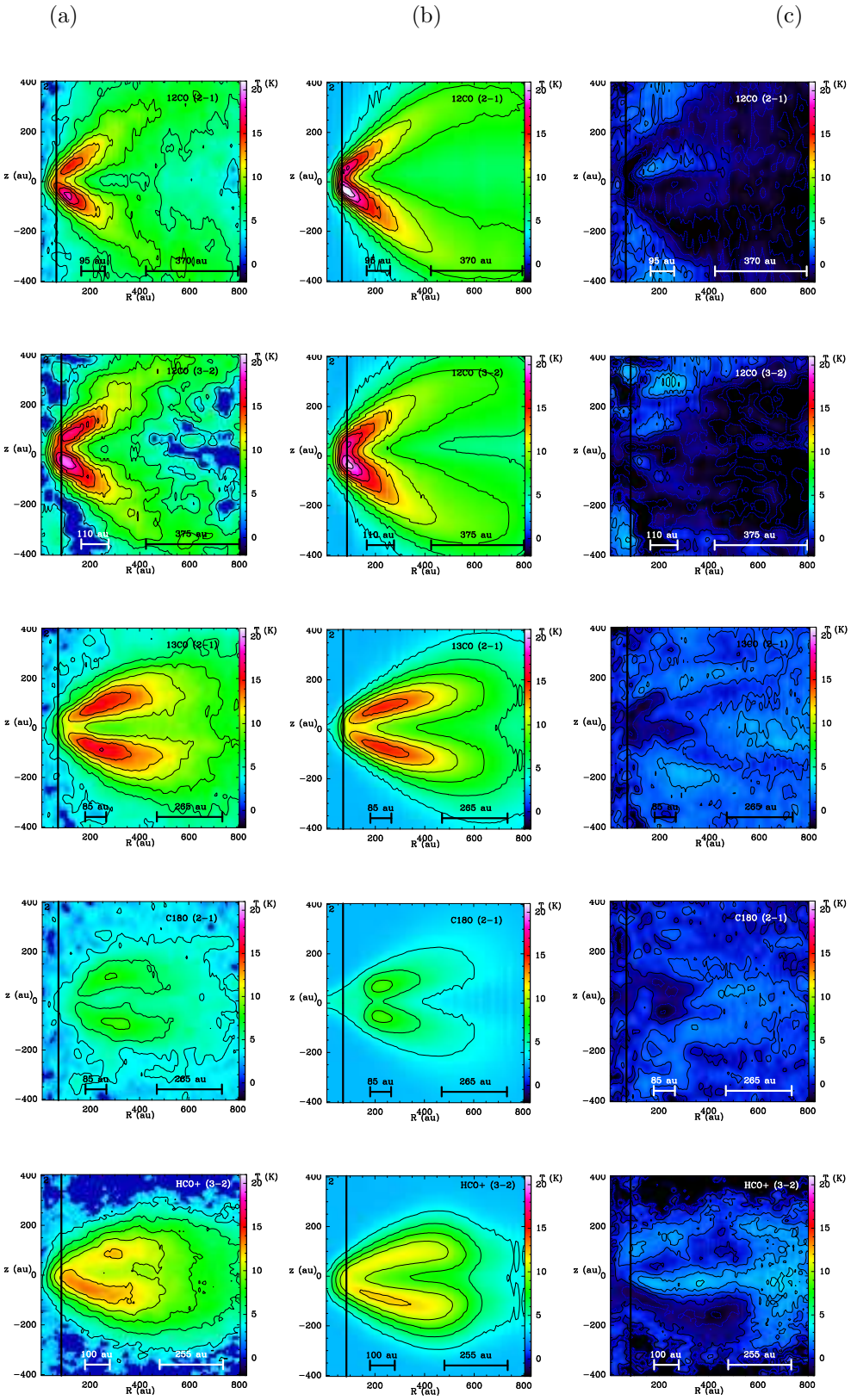

Fig. 2. From top to bottom: Tomographically Reconstructed Distribution (TRD) of ^{12}CO (2-1), ^{12}CO (3-2), ^{13}CO (2-1), C^{18}O (2-1) and HCO$^+$ (3-2) : (a) TRD of the observations (b) TRD of the final result of the models (c) difference between the observations and models TRD. The vertical black line represents the effective resolution and two error bars show the widening of the beam as a function of radius caused by the TRD method. (Foucher et al. submitted)