Tomographic Reconstruction of the Vertical Temperature Structure in Edge-On Disks

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Abstract:

Protoplanetary disks are the sites of planet formation, and their vertical structure plays a key role in regulating temperature, chemistry, and irradiation. However, this structure is difficult to constrain observationally due to projection effects in moderately inclined systems. Highly inclined (edge-on) disks offer a unique opportunity to directly probe their vertical stratification. We apply the tomographically reconstructed distribution (TRD) method [2,3] to ALMA CO spectral lines data obtained within the DISKSTRAT Large Programme (PI: R. Le Gal, Co-PI: F Ménard) [1], with the aim of recovering the brightness temperature distribution in cylindrical coordinates, ($T(R, Z)$). This technique exploits the Keplerian velocity field to map emission from position-velocity space into disk-centric coordinates, providing a relatively model-independent view of the disk structure. We present TRD maps for a sample of edge-on disks and the reconstructed distributions reveal a vertically stratified structure, characterized by a warm molecular layer located above a colder midplane, consistent with expectations from thermo-chemical disk models. Radial temperature gradients are also observed, reflecting stellar heating or external heating. These results demonstrate the potential of tomographic reconstruction, combined with high-quality ALMA observations from DISKSTRAT[1], to provide new constraints on the vertical thermal structure of protoplanetary disks and to inform models of disk evolution and planet formation.

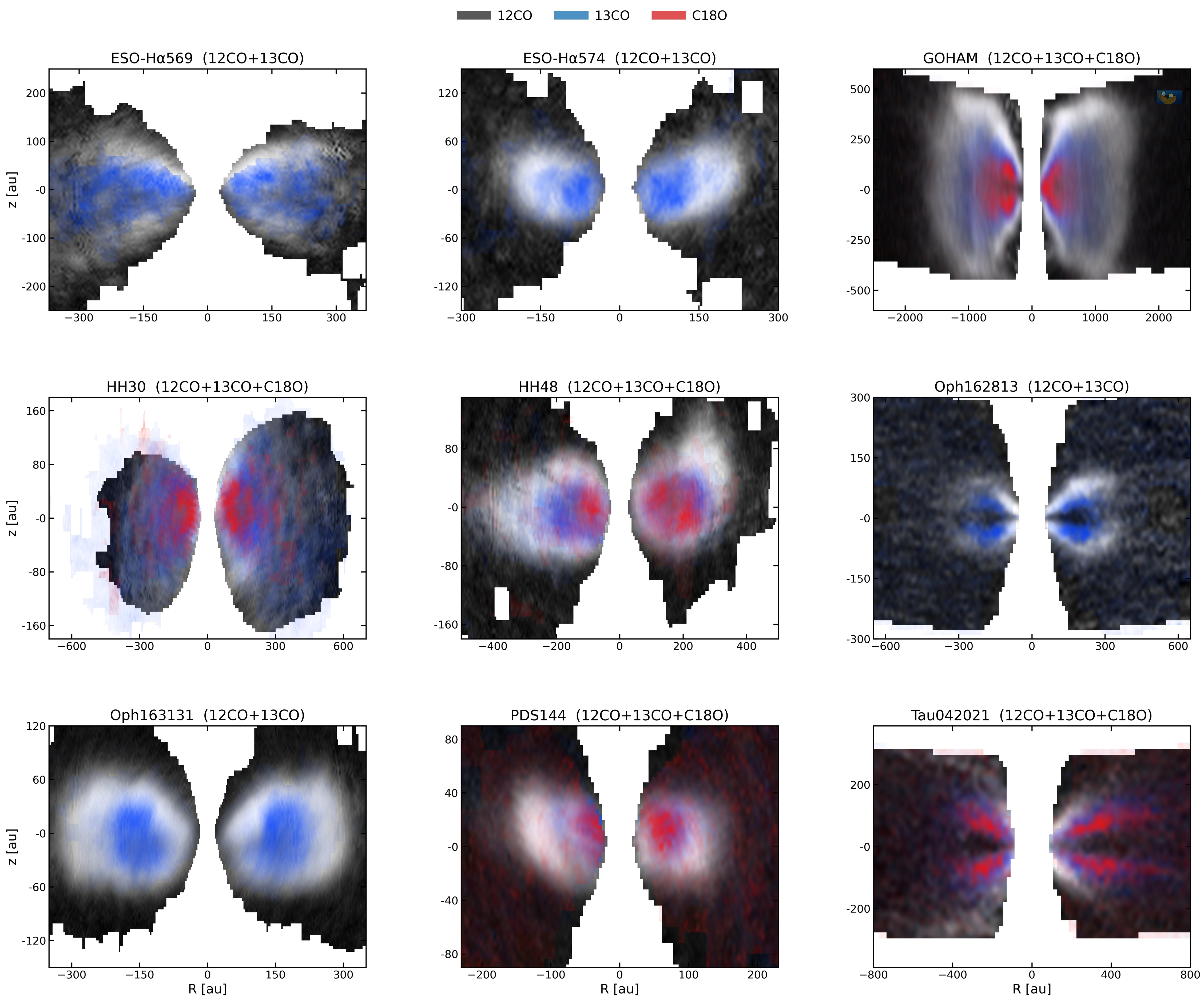

Figure 1:

Composite TRD maps of the CO isotopologues in nine highly inclined disks. Gray shows ^{12}CO, blue shows ^{13}CO, and red shows C^{18}O.
The maps reveal a nested vertical structure, with ^{12}CO tracing the extended molecular atmosphere, ^{13}CO probing lower-altitude gas, and C^{18}O tracing the deepest detected molecular layer.

Summary of the results:

The composite TRD maps in Fig.1 reveal a clear vertical stratification of CO isotopologue emission across the sample of nine highly inclined disks. In nearly all sources, ^{12}CO is the most extended tracer, outlining the warm molecular atmosphere above and below the disk midplane. ^{13}CO is more compact and is concentrated at lower altitudes, while C^{18}O, when detected, is confined closest to the midplane.
This nested structure is especially clear in GoHam, Tau 042021, and Oph 163131. GoHam shows the largest reconstructed molecular structure, with ^{12}CO extending over several hundred au in height and several thousand au in radius. Tau 042021 also shows vertically extended ^{12}CO emission, while Oph 163131 displays one of the most symmetric stratified morphologies. More compact systems, such as ESO-Hα574, HH 48, and PDS 144 N, show the same ordering of tracers but over smaller spatial scales.
The reconstructed brightness temperatures also decrease from the abundant to the rarer isotopologues. Across the sample, ^{12}CO reaches the highest brightness temperatures, typically ~20-45 K, consistent with emission from a warm, optically thick disk atmosphere. ^{13}CO is cooler, usually reaching ~11-19 K in most disks, although GoHam reaches higher values. C^{18}O is fainter still, with reconstructed brightness temperatures of order ~8-16 K in the detected subset.
The vertical observed layering likely reflects a combination of optical depth, excitation, freeze-out, and UV-driven chemistry. In the warm disk atmosphere, ^{12}CO remains optically thick and bright, while the rarer isotopologues trace deeper layers where the gas is denser and better shielded. In dust-depleted outer regions, external UV photons may penetrate more deeply and contribute to CO photodesorption from icy grains, helping to maintain gas-phase CO outside the colder midplane. This mechanism was proposed for Oph 163131 [2], but in the present sample this might be a possible explanation, since disk winds, outflows, cloud contamination, and differences in dust opacity can also affect the reconstructed ^{12}CO morphology.

References:

1- ALMA programme 2024.1.01212.L. (PI R. LeGal)
2- Flores, C., et al. 2021, AJ,161:239,21pp
3- Dutrey, A., et al. 2017, A&A,607.A130

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