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Probing planet forming zones with rare CO isotopologues

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The properties of the midplane of planet-forming protostellar disks remain largely unprobed by observations due to the high optical depth of common molecular lines and the continuum. However, rotational emission lines from rare isotopologues may have optical depths near unity in the vertical direction, so that the lines are strong enough to be detected, yet remain transparent enough to trace the disk midplane. Here we present a chemical model of an evolving T-Tauri disk and predict the optical depths of rotational transitions of CO isotopologues. CO does not freeze out in our modeled region within 70 AU around a sunlike star. However, the abundance of CO decreases because of the formation of complex organic molecules (COM), producing effect that can be misinterpreted as the "snow line". The optical depths of low-order rotational lines of $C^{17}O$ are around unity, which suggests it may be possible to see into the disk midplane using $C^{17}O$. With our computed $C^{17}O/H_2$ abundance ratio, such ALMA observations would provide estimates of the gaseous disk masses by measuring the intensity of $C^{17}O$ emission.

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1. Introduction and Methods

The mass and surface density of the inner 30 AU of protoplanetary disks are critical parameters that control disk evolution and planet formation. Disk masses are currently determined by (sub)millimeter observations of dust [4]. However, observations begin to lose sensitivity to grains as they grow beyond the observing wavelength; millimeter wave observations may thus underestimate solid masses in the inner disk, where dust settling and higher densities lead to more rapid growth [3]. On the other hand, commonly observed molecular lines often suffer from high optical depth, and are therefore unable to probe gas near the midplane. Here we seek a molecule that can be used to probe the conditions in planet-forming midplanes with rotational transitions observable from the ground.

We construct chemical evolution models of T-Tauri disks including C, H, O, N, and different C and O isotopes. The model is built upon an Magnetorotational Instability - active disk (MRI [1]) from Landry et al. 2013 [2], which include a viscosity prescription for accretion driven by MRI turbulence. The chemical networked is extended based on the UMIST database RATE06 [5]. The reaction network contains 13116 reactions, including gas-phase reactions, grain-surface reactions, freezeout, thermal desorption, and reactions triggered by UV, X-rays and cosmic rays, such as isotope-selective photodissociation. The carbon isotopic chemistry network was developed by Woods & Willacy [6] and was extended to include oxygen isotopes for this work.

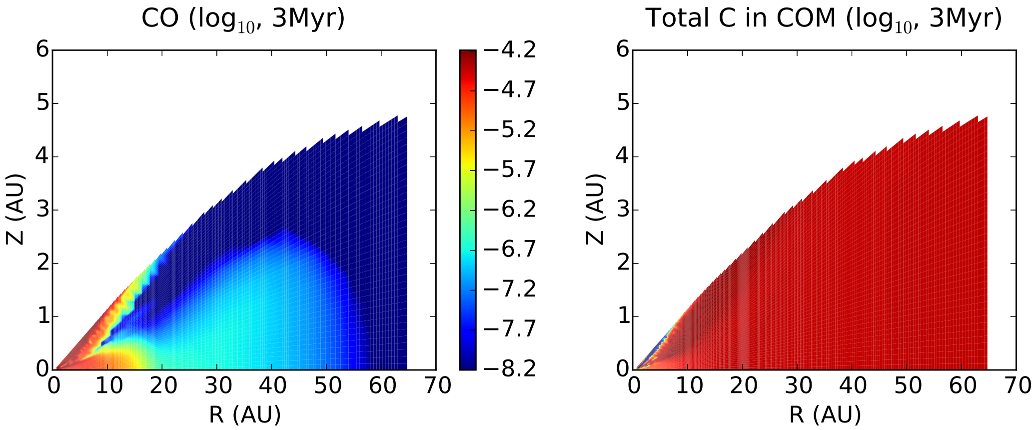

Figure 1: Fractional abundances at the end of the 3Myr evolution (the number density with respect to the number density of hydrogen nuclei, $n_H + 2n_{H_2}$). The color scale is in logarithm. Left: CO exists in a large abundance for r< 15AU; Right: Abundance of all complex organic molecules including C_2H_2 (acetylene), C_2H_5, CH_3CHO (acetaldehyde), CH_3OH (methanol), and H_2CCO (ketene).

2. Results and Summary

Due to efficient heating from the central star, CO does not freeze out in our modeled region—the inner 70 AU of the disk—at any time in our 3 Myr of evolution. However, the abundance of CO drops beyond 15 AU because carbon is tied up in hydrocarbons, methanol, and ketene (complex organic molecules or COMs), mimicking the effect of CO freezeout. Contour plots of abundances of CO and COM are shown in Fig. 1. The depletion of CO is initiated by ionization of He by cosmic rays and X-ray, which happens at a million-year time scale.

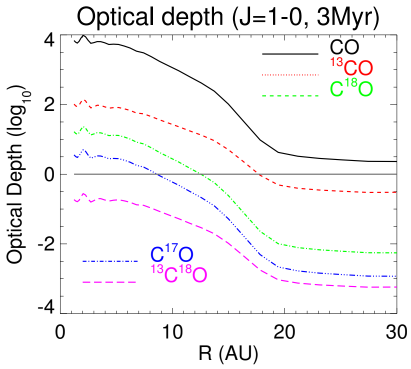

Figure 2: Optical depth of CO 1-0 lines (3 Myr)

We calculate the optical depth of CO rotational emission lines at each disk radius by integrating the absorption efficiency through the disk. The optical depths of J= 1 → 0 lines for CO isotopologues at the end of the 3 Myr evolution are shown in Figure 2. We can immediately see that $C^{17}O$ traces the disk midplane outside 8 AU, and $C^{18}O$ traces the midplane outside 12 AU. The optical depth remains above one out to about 18 AU for ^{13}CO, and 42 AU for CO. ALMA observations of this line would provide estimations of the disk midplane temperature if the CO ice lines were spatially or spectrally resolved. Additionally, with our computed $C^{17}O/H_2$ abundance ratio, observers would be able to measure the disk masses by measuring the intensity of gas emission.

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