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Hydrostatic Equilibrium Does Not Solve the $C^{18}O$ Flux Problem in Protoplanetary Disks

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Abstract

ALMA observations have shown that there is discrepancy between the disk mass estimate from CO emission and disk masses estimated from other tracers. This discrepancy has been interpreted as lower than expected CO abundance in the warm, surface layers of the disk. Recent work by Ruaud et al. claims that the low observed $C^{18}O$ fluxes can be explained with a ISM abundance of CO, that is 10^{-4} w.r.t. H_2 by including hydrostatic equilbrium in the model density setup. We show that the Ruaud et al. low CO fluxes are due to an unrealistic temperature structure in the outer disk, due to an interaction of their dust model and hydrostatic equilibrium at their inner model edge. Furthermore, we show with our own modeling that a parametric model does a better job at matching the measured outer disk temperature structure.

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1. Introduction

The advent of ALMA, and the increase in protoplanetary disk observations, opened a new window on the gas-rich phase. Whereas the expectation was that gas disk mass measurements with ALMA would be straightforward using CO isotopologues, reality is more complex. Different disk mass measurements, based on dust continuum emission, dust physics, accretion rates, gravitational potentials, hydrogen deuteride, and N_2H^+, consistently overpredict the CO derived gas masses. A flurry of theoretical and modeling work has tried to explain this discrepancy, which also exists for H_2O and other carbon-tracers. Most of these focus on either dynamical processes that lower the total abundance of carbon in the surface layers or chemical processes that transform the CO into other, unobservable species (e.g., CO_2 and CH_3OH ice). Both processes decrease the CO emission, but only by invoking them in tandem does the CO abundance drop enough to explain CO fluxes (see Miotello et al. 2022, for a review).

Recent work by Ruaud et al. (2022) claims that the low observed $C^{18}O$ fluxes can be explained without having to invoke a dynamical process that lowers total available carbon and oxygen in the surface layers of the disk. In their models they are able to reproduce the low fluxes by including CO conversion into CO_2 and a vertical structure that follows hydrostatic equilibrium (HEq), with the latter being the driving force for the low CO fluxes.

2. Analysis

To test the hypothesis of Ruaud et al. (2022) that HEq combined with CO to CO_2 conversion lowers CO fluxes we ran a set of DALI models (Bruderer et al. 2012; Bruderer 2013) solving for HEq using a setup similar to that of Ruaud et al. (2022). Specifically, the same gas mass (0.05 $M_\odot$) surface density profile (γ=1), overall gas-to-dust ratio (100) and stellar spectrum (TW Hya, Herczeg et al. 2004) are adopted. Our initial parametric model assumes a height of h=0.1 at 100au, and a flaring angle of ψ= 0.3. We tracked the evolution of the CO isotopologue J=3–2 line flux through the iterations of gas temperature and HEq calculations using the DALI standard network that does not include conversion of CO into CO_2. After the 25 iterations we removed all the CO at temperatures below 30 K to simulate the optimal case of the conversion scheme outlined by Ruaud et al. (2022). The model structures and flux progression can be seen in Figure 1. It is clear that with just these processes the decrease is only a factor of 4, clearly not the order of magnitude or more that is required to match observations. Furthermore, the impact of HEq on the observed flux is small when compared to chemical conversion. These effects agree with previous studies. Specifically, in a comparison between parameterized and HEq models it was found that inclusion of HEq drives up the CO flux and that a parameterized model was a better fit to the SED, ^{12}CO ladder, and atomic oxygen lines (Woitke et al. 2016).

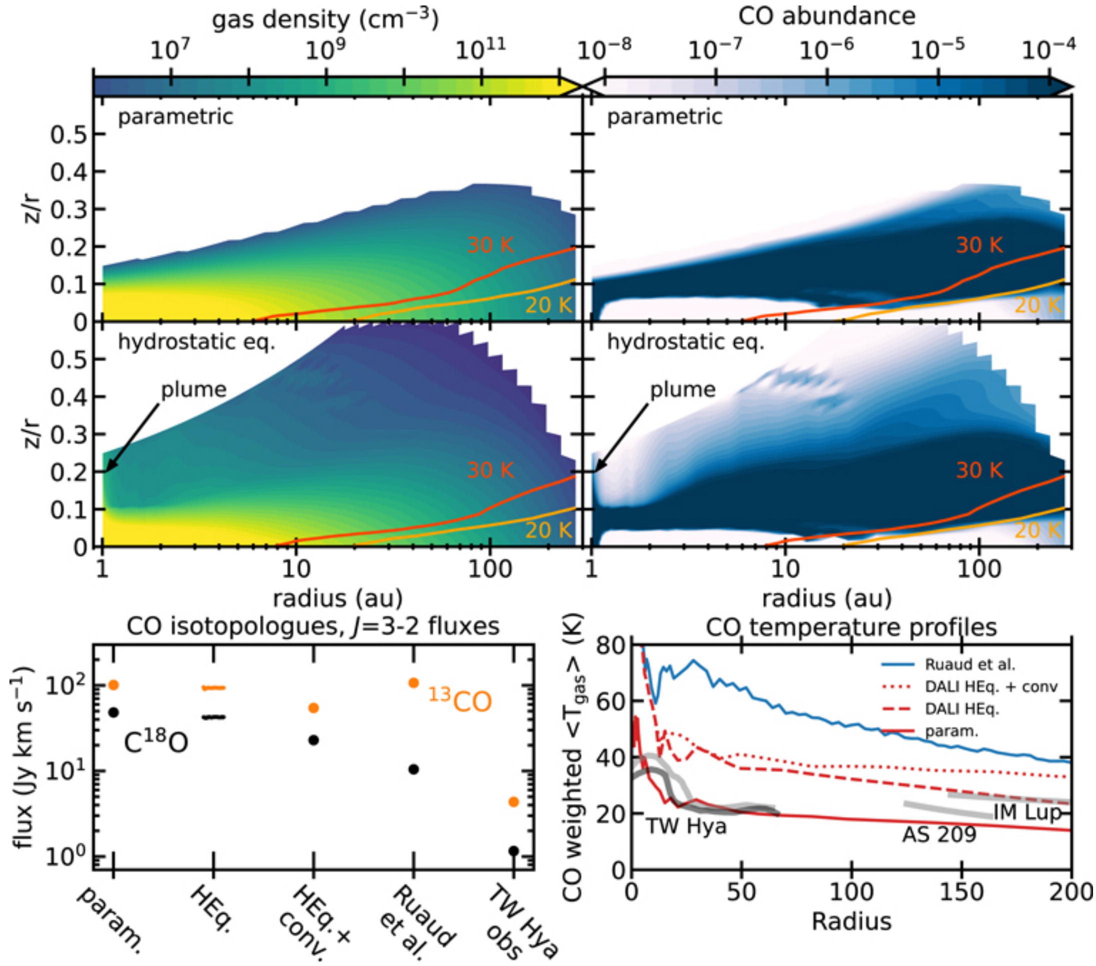

Figure 1. DALI models showing density, CO abundance, CO isotopologue fluxes and CO temperature profiles. The top two panels show a parametric model while the middle two panels show a model after 25 iterations of solving for HEq. Orange and red lines show T_{dust}=20 and 30K, respectively. These roughly correspond to the freeze-out temperature of CO and the maximal temperature at which CO can be converted to CO_2 in chemical models. The isotopologue fluxes are shown for the original parametric models, for all 25 iterations of the HEq. The last iteration is shown again separately, but now with all gaseous CO under 30 K removed to mimic optimal CO conversion. These fluxes are compared with the fluxes from the Ruaud et al. (2022) model as well as the TW Hya observations. In the bottom right, CO abundance weighted temperature profiles are shown for the Ruaud et al. (2022) model as well as three DALI models: parametric, HEq and HEq with CO conversion. These are compared with measured CO temperatures from TW Hya (Schwarz et al. 2016), AS 209 and IM Lup (Law et al. 2021). Temperatures are measured from optically thick ^{13}CO (gray) and $C^{18}O$ (black).

So why does the Ruaud et al. (2022) model produce integrated fluxes that are significantly lower than other models in the literature? The reason can be found in the interaction between their dust model and the HEq calculation. In the inner region of the model, directly behind the inner edge of the model at 1au, there is a plume of material with a very high vertical extent. Features like this are consistent between in HEq models, but they do not agree with observational constraints (Figure 1 McClure et al. 2013; Woitke et al. 2016). In the Ruaud et al. (2022) model the effect is amplified by the dust model, which links grain size and density structure. The lower midplane density leads to a lower maximum grain size and more small grains, which are lofted vertically. This increases the amount of starlight that is reprocessed, creating an plume that is optically thick to the bulk of the stellar radiation field up to a $z/r\sim0.15$, which shadows the disk to very large radii. This is the z/r range that contains a large fraction of disk mass at T=20–40K in the parameterized DALI and HEq models. The shadow cools the gas and dust, especially impacting the atmosphere between 20 and 40 K that is responsible for the bulk of disk emission, lowering the temperature in this layer to below 20 K. As such, a larger fraction of CO is frozen out and emission is suppressed in the Ruaud et al. (2022) models compared to previously published parametric models (Miotello et al. 2016) as well as our HEq models.

The small amount of mass in the 20–40 K region in the Ruaud et al. (2022) models is in contradiction with CO gas temperature measurements, which independently find that the bulk of the CO gas is close to the freeze-out temperature of 20 K (Pinte et al. 2018; Schwarz et al. 2018; Law et al. 2021). The Ruaud et al. (2022) as well as the DALI HEq model do not match these observations (Figure 1). Only the parametric model has enough cold CO gas to match these observations. Therefore we conclude that a parametric model with a lower CO abundance is still a better match to observations than HEq models.