



Universiteit
Leiden
The Netherlands

Hydrostatic equilibrium does not solve the C18O flux problem in protoplanetary disks

Bosman, A.D.; Trapman, L.; Sturm, J.A.; Bergin, E.A.; Booth, A.S.; Calahan, J.K.; ... ; Zhang, K.

Citation

Bosman, A. D., Trapman, L., Sturm, J. A., Bergin, E. A., Booth, A. S., Calahan, J. K., ... Zhang, K. (2022). Hydrostatic equilibrium does not solve the C18O flux problem in protoplanetary disks. *Research Notes Of The American Astronomical Society*, 6(9). doi:10.3847/2515-5172/ac8e69

Version: Publisher's Version











License: [Creative Commons CC BY 4.0 license](#)

Downloaded from: <https://hdl.handle.net/1887/3562007>

Note: To cite this publication please use the final published version (if applicable).

OPEN ACCESS

Hydrostatic Equilibrium Does Not Solve the C¹⁸O Flux Problem in Protoplanetary Disks

Arthur D. Bosman¹ , Leon Trapman² , Ardjan Sturm³ , Edwin A. Bergin¹ ,
Alice S. Booth³ , Jenny K. Calahan¹ , Ewine F. van Dishoeck^{3,4} ,
Melissa K. McClure³ , Anna Miotello⁵ , and Ke Zhang² 

Published September 2022 • © 2022. The Author(s). Published by the American Astronomical Society.

Research Notes of the AAS, Volume 6, Number 9

Citation Arthur D. Bosman *et al* 2022 *Res. Notes AAS* **6** 176

DOI 10.3847/2515-5172/ac8e69

arbos@umich.edu

¹ University of Michigan, LSA astronomy, 1085 S University, Ann Arbor, MI 48109, USA;
arbos@umich.edu

² Department of Astronomy, University of Wisconsin-Madison, Madison, WI 53706, USA

³ Leiden Observatory, Leiden University, P.O. box 9513, 2300 RA Leiden, The Netherlands

⁴ Max Planck Institute for Extraterrestrial Physics, Giessenbachstrasse 1, D-85748 Garching, Germany

⁵ European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany

Arthur D. Bosman  <https://orcid.org/0000-0003-4001-3589>

Leon Trapman  <https://orcid.org/0000-0002-8623-9703>

Ardjan Sturm  <https://orcid.org/0000-0002-0377-1316>

Edwin A. Bergin  <https://orcid.org/0000-0003-4179-6394>

Alice S. Booth  <https://orcid.org/0000-0003-2014-2121>

Jenny K. Calahan  <https://orcid.org/0000-0002-0150-0125>

Ewine F. van Dishoeck  <https://orcid.org/0000-0001-7591-1907>

This site uses cookies. By continuing to use this site you agree to our use of cookies. To find out more, see our [Privacy and Cookies policy](#).



Anna Miotello  <https://orcid.org/0000-0002-7997-2528>

Ke Zhang  <https://orcid.org/0000-0002-0661-7517>

1. Received August 2022
2. Accepted September 2022
3. Published September 2022

Protoplanetary disks; Astrochemistry

 Journal RSS

Create or edit your corridor alerts

What are corridors? 

Create citation alert

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 C¹⁸O fluxes can be explained with a ISM abundance of CO, that is 10⁻⁴ w.r.t. H₂ by including hydrostatic equilibrium 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.

Export citation and abstract

[BibTeX](#)

[RIS](#)

◀ **Previous** article in issue

Next article in issue ▶



Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

This site uses cookies. By continuing to use this site you agree to our use of cookies. To find out more, see our [Privacy and Cookies policy](#).



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 N₂H⁺, consistently overpredict the CO derived gas masses. A flurry of theoretical and modeling work has tried to explain this discrepancy, which also exists for H₂O 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., CO₂ and CH₃OH 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 C¹⁸O 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 CO₂ 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 CO₂ 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_⊙) surface density profile ($\gamma=1$), 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 $\psi=0.3$. 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 CO₂. 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

fact one of us clearly not the order of magnitude or more that is required to match
out more, see our Privacy and Cookies policy.



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).



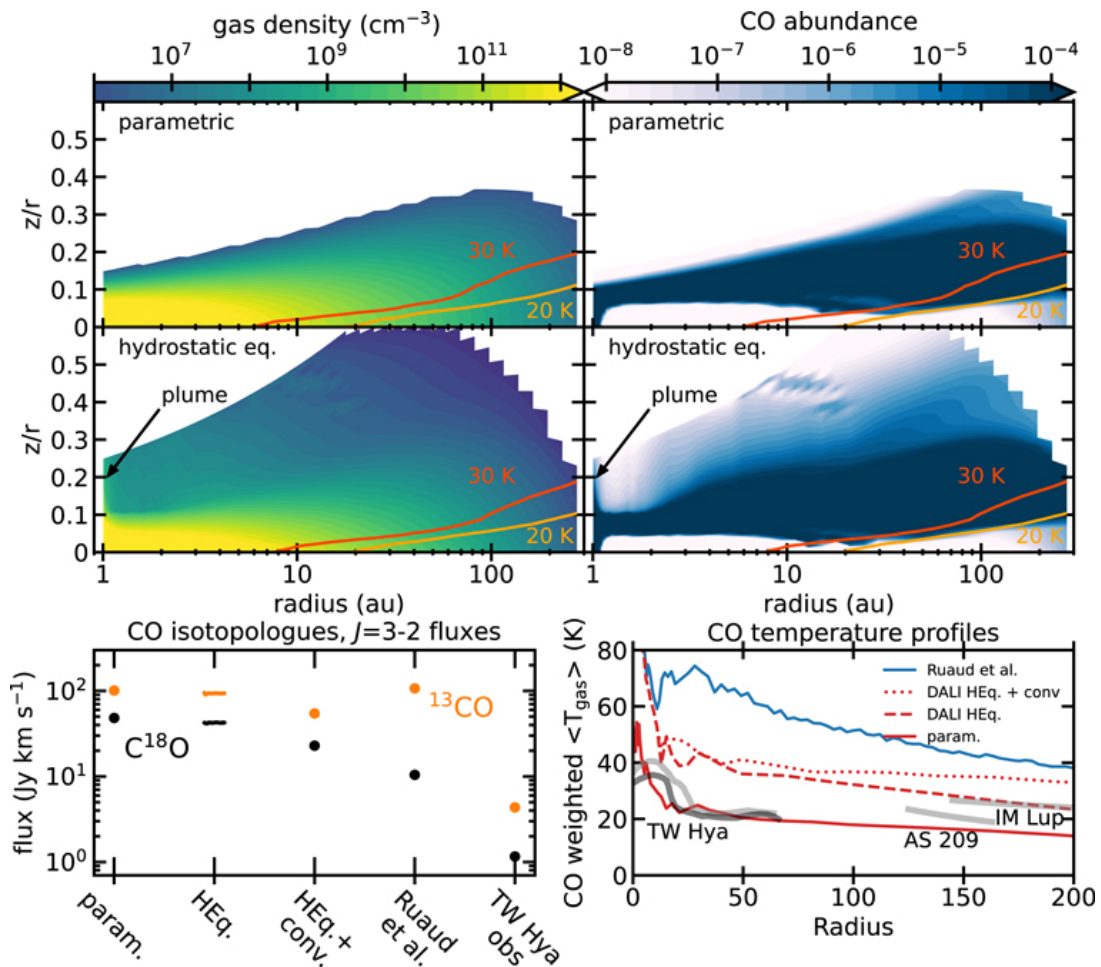


Figure 1. DALI models showing density, CO abundance, CO isotopologue fluxes and CO temperature profiles. The top two panels show a parametric model while the middle two panels show a model after 25 iterations of solving for HEq. Orange and red lines show $T_{\text{dust}}=20$ and 30K, respectively. These roughly correspond to the freeze-out temperature of CO and the maximal temperature at which CO can be converted to CO₂ 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 ¹³CO (gray) and C¹⁸O (black).

So why does the Ruard 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 1 au, 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 Ruard 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 $z/r \sim 0.15$, which shadows the disk to very large radii. This is the z/r range that contains a large fraction of disk mass at $T=20\text{--}40\text{K}$ 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 Ruard 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 Ruard 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 Ruard 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.

