

THE ROLE OF ICE COMPOSITIONS AND MORPHOLOGY FOR SNOWLINES AND THE C/N/O RATIOS IN ACTIVE DISKS

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ABSTRACT

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1. INTRODUCTION

Background info. Importance of volatiles in disks and planetary atmospheres, detections of snowlines in disks, C/O ratios etc. State again the importance of radial drift and gas accretion on the snowline locations, and that a systematic study of the combination of these two particular effects across the disk has not been done before. Then transition to the fact that we provide such a systematic study in Paper I and in this paper. Here, we expand the model of Paper I by making three additions: (1) we add N and CH₄ in the static chemistry model, and explore how different abundances of CH₄ and of the N main carriers (N₂ and NH₃) affect the C/O and N/O ratios, (2) we quantify the effect of radial drift and gas accretion on the N₂, CH₄ and NH₃ snowline locations, and (3) we explore how different binding energies of CO and N₂ affect their snowline locations.

2. COUPLED DRIFT-DESORPTION MODEL REVIEW

We begin with a brief review of Paper I's model for the effect of radial drift and viscous gas accretion on volatile snowline locations. We review our disk model assumptions and relevant timescales in Section 2.1, and summarize our findings in Section ??.

2.1. Disk Model and Important Timescales

We first assume a static disk, which is only irradiated by the central star and does not experience redistribution of solids or radial movement of the nebular gas. To quantify the effects of radial drift and gas accretion, we use a viscous disk with a spatially and temporally constant mass flux, \dot{M} . The viscous disk takes into account radial drift, gas accretion onto the central star, as well as accretion heating. We prefer this disk model to an irradiated or evolving disk (see Paper I) because it includes all the dynamical and thermal processes we are interested in for the scope of this paper, and therefore it is the most realistic one.

We model the static disk as a minimum mass solar nebula (MMSN), using a prescription for the gas surface density, Σ , and disk midplane temperature, T , similar to that of Chiang & Youdin (2010):

$$\Sigma = 2000 (r/\text{AU})^{-1} \text{ g cm}^{-2} \quad (1a)$$

$$T = 120 (r/\text{AU})^{-3/7} \text{ K}, \quad (1b)$$

where r is the semimajor axis. Based on observations of protoplanetary disks (Andrews et al. 2010), we choose a flatter surface density than the one assumed by Chiang & Youdin (2010), where $\Sigma \propto r^{-3/2}$.

We use the Shakura & Sunyaev (1973) steady-state disk solution to model the viscous disk. Solving the Equation set of Appendix A in Paper I yields an expression for the temperature profile in a steady-state disk:

$$T_{\text{act}} = \frac{1}{4r} \left(\frac{3G\kappa_0 \dot{M}^2 M_* \mu m_p \Omega_k}{\pi^2 \alpha k_B \sigma} \right)^{1/3}. \quad (2)$$

Here G is the gravitational constant, $\kappa_0 = 2 \times 10^{-6}$ is a dimensionless coefficient in the opacity law $\kappa = \kappa_0 T_{\text{act}}^2$, $M_* = M_\odot$ is the mass of the central star, $\mu = 2.35$ is the mean molecular weight of the nebular gas, m_p is the proton mass, $\Omega_k = \sqrt{GM_\odot}/r^3$ is the Keplerian angular velocity, $\alpha = 0.01$ is a dimensionless coefficient (see below for details), k_B is the Boltzmann constant, and σ is the Stefan-Boltzmann constant. The final midplane temperature profile is computed as

$$T^4 = T_{\text{act}}^4 + T_{\text{irr}}^4, \quad (3)$$

where $T_{\text{irr}} = T$ from Equation (1b). We use this expression because in addition to accretion heating, stellar irradiation also contributes to the disk thermal structure.

The steady-state disk has an α -viscosity prescription, where the kinematic viscosity is $\mu = \alpha c H$. Here $c \equiv \sqrt{k_B T / (\mu m_p)}$ is the isothermal sound speed (with T from Equation 3), and $H \equiv c / \Omega_k$ is the disk scale height. We can then determine the gas surface density for a viscous disk as (Shakura & Sunyaev 1973; see also Paper I for a more detailed explanation of these calculations):

$$\Sigma = \frac{\dot{M}}{3\pi\nu}. \quad (4)$$

We choose $\dot{M} = 10^{-8} M_\odot \text{ yr}^{-1}$, consistent with mass flux observations in disks (e.g., Andrews et al. 2010).

In what follows, we summarize the timescales that are

Review disk models, desorption model, relevant timescales. State that we use a steady-state disk for the coupled drift-desorption evolution, since it is the most realistic, therefore only summarize the static and steady-state (viscous) disk. Summarize the findings of Paper I, i.e. particles of certain sizes desorb instantaneously and at a fixed particle size dependent location.

3. CH₄ AND C/O RATIOS

Discuss observed abundances for CH₄ and the choices that we make (no CH₄, median value, maximum value).

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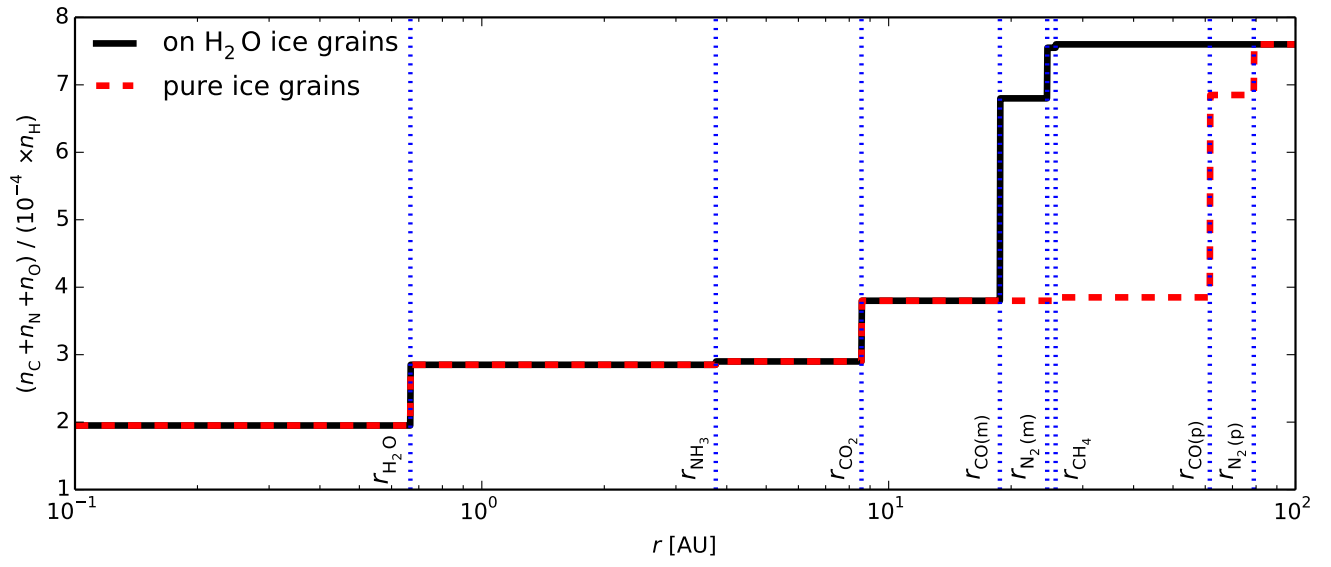


FIG. 1.— CNO abundance in grains...

State that desorption energies for H_2O , CO_2 and CH_4 are well constrained experimentally, and that the CO_2 and CH_4 binding energies are only weakly dependent on whether it's pure CO_2/CH_4 or combined with H_2O , but that is not the case for CO (and N_2 as we will show in the next section). Present new binding energies for CO as pure ice and mixed with water. Show Figure 1 and discuss how different CH_4 abundances and binding energies affect snowline locations and C/O ratio: $\text{CO-H}_2\text{O}$ mixture (though I think it's rather CO layered on top of H_2O) moves the CO snowline inward by ~ 40 AU (will calculate percentages too); the maximum reasonable abundance of CH_4 changes the C/O ratio by less than 10%. Show Figure 2 and quantify the effect of drift and accretion on the CH_4 snowline compared to a static disk. While CH_4 has only a modest effect on the C/O ratio in a static disk, this effect may be larger in a viscous disk, as the C gas abundances inside the CH_4 snowline may be enhanced due to the differential motion of the desorbed ices and overall nebular gas (refer to Paper I). In this study, however, we neglect these effects and therefore do not include CH_4 in estimating the C/O ratio (as an aside, the figures that include CH_4 in the C/O ratio with drift and desorption are quite messy due to snowlines overlapping). Show Figure 3 and estimate the difference between $\text{CO-H}_2\text{O}$ and CO pure ice snowlines in the case of drift and accretion, as well as the comparisons for the static disk for the CO snowline.

4. NITROGEN CARRIERS AND N/O RATIOS

Similar to the previous section, but with more details. Discuss that nitrogen is abundant in the solar system and disks and primarily found as N_2 . Due to the high volatility of N_2 , the gas phase N/O ratio in the outer disk may be even more enhanced than the C/O ratio. A fraction of the nitrogen abundance may be also carried by NH_3 . Discuss NH_3 observed abundances and the choices that we make (no NH_3 , median, maximum). State that the NH_3 desorption energy is only weakly dependent on whether it's pure NH_3 or combined with H_2O , but that is not the case for N_2 . Present new binding energies for N_2 as pure ice and combined with water. Show Figure 4 and discuss how different nitrogen abundances and binding energies affect snowline locations and N/O ratio: N_2 combined with H_2O moves the N_2 snowline inward by ~ 50 AU (will calculate percentages too); the maximum reasonable abundance of NH_3 changes the N/O ratio by $\sim 15\%$. In the outer disk, the N/O ratio is enhanced by a factor of ~ 4 compared to the solar value, twice as much as the C/O enhancement. Show Figure 5 and quantify the effect of drift and accretion on the NH_3 snowline compared to a static disk. While NH_3 does not have a significant effect on the N/O ratio in a static disk, this effect may be larger in a viscous disk, as the N gas abundance inside the NH_3 snowline may be enhanced due to the differential motion of the desorbed ices and overall nebular gas (refer to Paper I). In this study, however, we neglect these effects and therefore do not include NH_3 in estimating the N/O ratio (again, N/O ratio figure with drift is quite messy when including NH_3 and does not add any information that is not already shown in Figures 4 and 5). Show Figure 6 and estimate the difference between $\text{N}_2\text{-H}_2\text{O}$ and N_2 pure ice snowlines in the case of drift, as well as the comparisons for the static disk for the N_2 snowline. State that

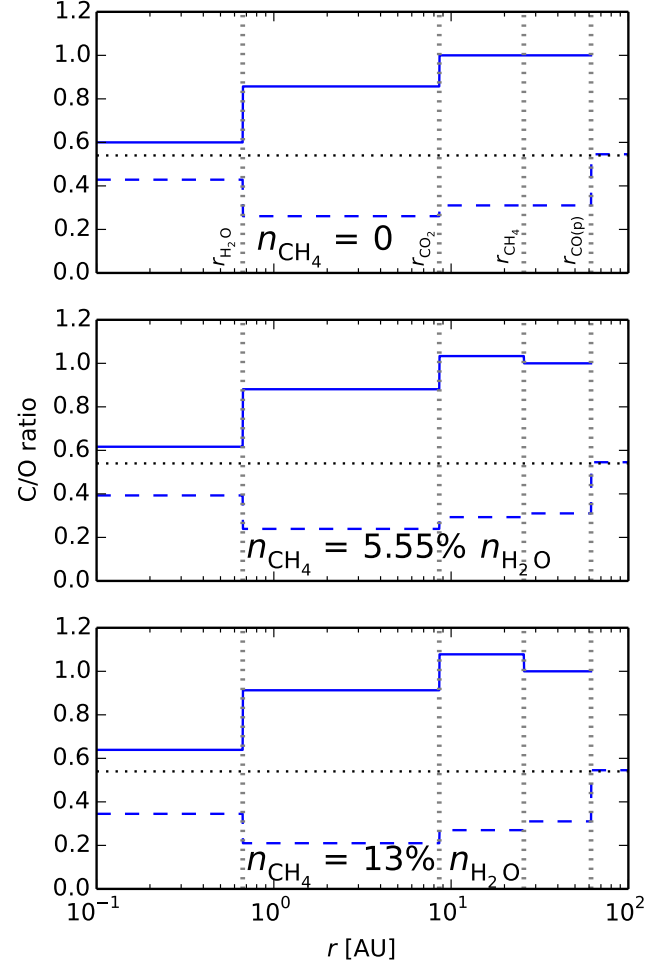


FIG. 2.— C/O ratio in a static disk for different CH_4 abundances and CO binding energies...

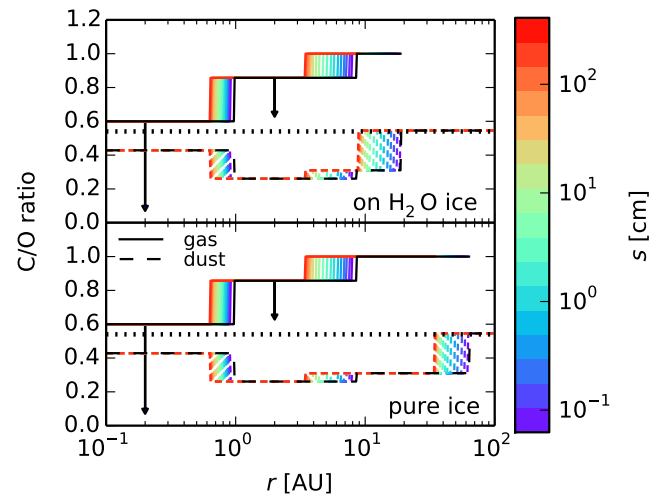


FIG. 3.— C/O ratio as function of semimajor axis for CO combined with H_2O (top panel) and pure CO ice (bottom panel).... Drift and gas accretion move the CO snowlines inward by $x\%$ and $y\%$, respectively.

there will be an overabundance of gas-phase N/O between the CO and N₂ snowlines, as there is no oxygen gas in this region.

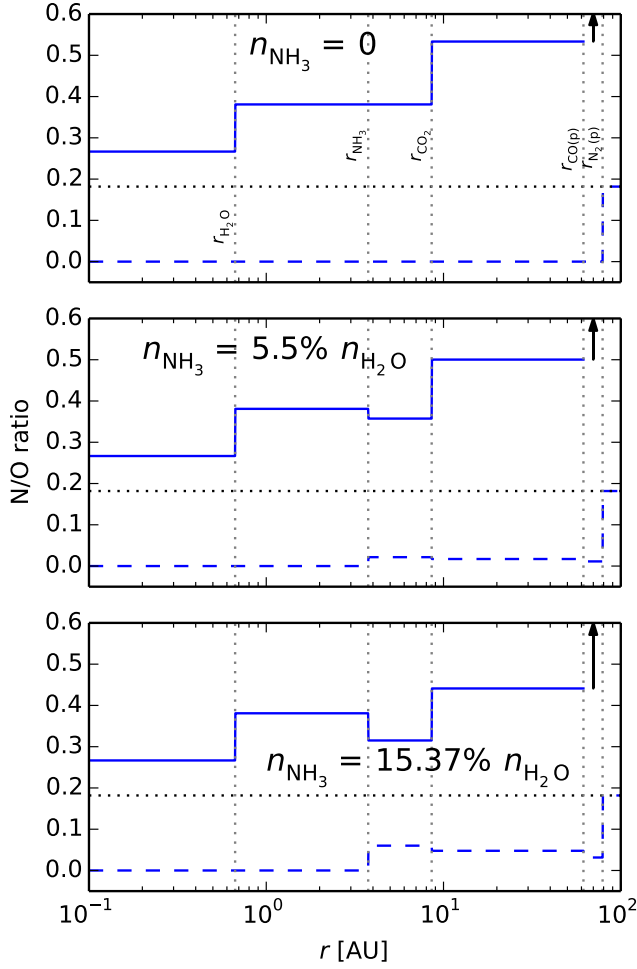


FIG. 4.— N/O ratio in a static disk for different NH₃ abundances and N₂ binding energies...

5. DISCUSSION

Discuss how entrapment of volatiles by H₂O affects volatile abundances and C/O ratios. Re-emphasize the fact that the C/O and N/O ratios are upper estimates, and that CH₄ and NH₃ might matter in a viscous disk. State that we plan to address this in a future paper. More TBD.

6. SUMMARY

Maybe we can include the summary in the discussion section?

REFERENCES

- Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2010, *ApJ*, 723, 1241
 Chiang, E., & Youdin, A. N. 2010, *Annual Review of Earth and Planetary Sciences*, 38, 493
 Shakura, N. I., & Sunyaev, R. A. 1973, *A&A*, 24, 337

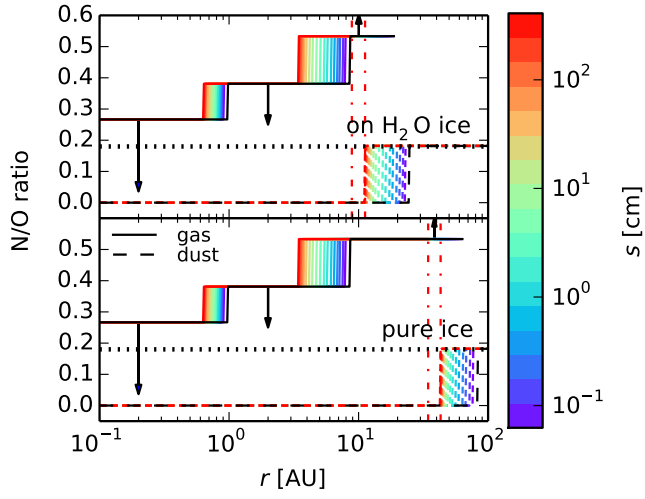


FIG. 5.— N/O ratio as function of semimajor axis for N₂ combined with H₂O (top panel) and pure N₂ ice (bottom panel).... Drift and gas accretion move the N₂ snowlines inward by $x\%$ and $y\%$, respectively. Overabundance of gas-phase N/O between the CO and N₂ snowlines, marked by the vertical red dash-dotted lines for the largest drifting particles in our model.