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C/O IN PROTOPLANETARY DISKS: THE EFFECT OF RADIAL DRIFT AND VISCOUS ACCRETION

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ABSTRACT

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1. INTRODUCTION

Background topics: importance of atmospheric chemistry in providing constraints on the formation of giant planets; C/O ratio as important signature of atmospheric chemistry; C/O ratios observationally determined are different from interstellar — one explanation is the different abundance in gas and dust form of the main C and O carriers, H_2O, CO_2 and CO, between their respective snowlines (cite Öberg et al. 2011).

Main sequence stars commonly host giant planets (refs). The chemical composition of gas giant atmospheres can provide important constraints on their formation, accretion and migration history. In recent years, the onset and development of sensitive infrared and (sub)millimeter spectroscopic observations has facilitated the detection of organic molecules in the outer regions of protoplanetary disks (e.g., Öberg et al. 2010, Öberg et al. 2011c, Öberg et al. 2011b, ...). Of particular importance are volatile compounds, since the location of their snowlines determines their relative abundance in gaseous and solid form in the protoplanetary disk, and thus the chemical composition of nascent giant planets.

Notably, an important signature of giant planets atmospheric chemistry is the carbon to oxygen (C/O) ratio. Spectroscopic observations of gas giants such as WASP-12b have found atmospheric C/O ratios close to unity, substantially different from the Solar value of 0.54 (Madhusudhan et al. 2011). One explanation for this discrepancy was proposed by Öberg et al. (2011a), who considered the fact that the main carries of carbon and oxygen, i.e. H_2O, CO_2 and CO, have different condensation temperatures. This changes the relative abundance of C and O in gaseous and solid form as a function of the snowline location of the volatiles mentioned above. Öberg et al. (2011a) calculated analytically the C/O ratio in gas in dust as a function of semimajor axis for passive protoplanetary disks and reproduced a gas C/O ratio of order unity between the CO_2 and CO snowlines, where oxygen gas is highly depleted.

In order to obtain more realistic estimates for C/O ratios across protoplanetary disks, dynamical processes and the disk evolving chemistry have to be taken into account. In this paper, we enhance the model of Öberg et al. (2011a) considering two additional dynamic effects: (1) the radial drift of solids throughout the protoplanetary disk, and (2) the viscous accretion of the disk gas onto the host star. Our goal is two-fold: (1) to quantify the effect of radial drift of solids of different sizes on the location and shape of H_2O, CO_2 and CO snowlines, and (2) to calculate the resulting C/O ratio in gaseous and solid form throughout an actively accreting protoplanetary disk as a function of the grain size distribution and the evolutionary time of the nebula.

This paper is organized as follows: *(section summaries).*

2. MODEL ASSUMPTIONS

We describe our analytic model for the radial drift of solids in section 2.1. In section 2.2, we present our protoplanetary disk model, as well as our prescription for the gas and dust surface density evolution in an active disk. Finally, we summarize our ice desorption model in section 2.3.

2.1. *Radial Drift*

2.2. *Evolutionary Disk Model*

2.3. *Volatile Desorption*

Describe disk model — both passive MMSN and active self-similar solution with α prescription for viscosity. Describe the model for evolving the surface density profile of planetesimals following Birnstiel et al. (2012). Describe temperature profile — currently power-law, but may change. Describe desorption model and parameters following Hollenbach et al. (2009). Mention that the solids are perfect spheres composed of a single volatile. Perhaps this subsection needs to be split into subsubsections.

2.4. *Relevant timescales*

Calculate timescale for radial drift following Chiang & Youdin (2010). Calculate desorption timescale following Hollenbach et al. (2009). Estimate gas accretion timescale for a given α. Important: mention that, for simplicity and illustrative purposes, these calculations are performed for a passive disk. Show plot with the timescales as a function of particle size at different snowlines to show the regime in which drift matters.

3. SNOWLINE LOCATIONS

Present the equation set that you are solving, $dr/dt = \dot{r}$, $ds/dt = ...$ I don't think it is necessary to describe in detail the numerical method of solving the equations since it's pretty straightforward. Present the pretty rainbow plots side by side for passive and active disks, and highlight the differences. Insert the plots that shows that for the intermediate size particles, the desorption distance can be estimated analytically with good accuracy.

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Maybe also include the plot showing the desorption distance as a function of particle size, both for passive and active disk. Split into subsections?

4. RESULTS FOR THE C/O RATIO

Present the plots analogous to Fig. 1 in Öberg et al. (2011) for different particle sizes, based on the snowline locations obtained in the previous section, both for passive and active disk. Perhaps show it at different times in the gas disk evolution (i.e., not just at 3 Myr) for the active disk. Then assume a particle size distribution and show the interpolated result for the C/O ratio. Generalize the result using a transition disk (this part might also fit in the discussion section).

5. DISCUSSION AND MODEL LIMITATIONS

Present the diagram that shows all the effects that can modify snowline location. For model limitations, include: non-inclusion of turbulence, assumption of perfect spheres when in fact they may have cracks, particles composed of a single volatile when in reality they are likely to be mixed, etc. Discuss uncertainty of initial conditions and estimate how much they matter. ....

6. SUMMARY AND FUTURE WORK

Summarize results. Mention inclusion of N_2 as a first expansion. Mention the implementation of time-dependent chemical models in the drift calculation.

APPENDIX

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Right now it's unclear to me what could go in an appendix, if anything. Maybe discuss a bit the algorithm to evolve $\Sigma_{\rm p}$ (although it is already explained in detail in the appendix of Birnstiel et al. 2010). Maybe show some example profiles of $\Sigma_{\rm p}$ at different times and for different particle sizes.

REFERENCES

Madhusudhan, N., Harrington, J., Stevenson, K. B., Nymeyer, S., Campo, C. J., Wheatley, P. J., Deming, D., Blecic, J., Hardy, R. A., Lust, N. B., Anderson, D. R., Collier-Cameron, A., Britt, C. B. T., Bowman, W. C., Hebb, L., Hellier, C., Maxted, P. F. L., Pollacco, D., & West, R. G. 2011, Nature, 469, 64

Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011a, ApJ, 743, L16

Öberg, K. I., Qi, C., Fogel, J. K. J., Bergin, E. A., Andrews, S. M., Espaillat, C., van Kempen, T. A., Wilner, D. J., & Pascucci, I. 2010, ApJ, 720, 480

Öberg, K. I., Qi, C., Fogel, J. K. J., Bergin, E. A., Andrews, S. M., Espaillat, C., Wilner, D. J., Pascucci, I., & Kastner, J. H. 2011b, ApJ, 734, 98

Öberg, K. I., Qi, C., Wilner, D. J., & Andrews, S. M. 2011c, ApJ, 743, 152