

Reviewer's Comments:

The paper describes the location of the water, carbon monoxide, and carbon dioxide snow lines under the influence of radial drift and inward viscous gas accretion. Numerical models are presented for four different disk models, highlighting different aspects that influence the location of the snow line. The main result is that the snow lines move in by up to 50-60% for most particle sizes when considering the inward gas and dust flow.

The paper is well-written and the outlined approach is clear. The conclusions seem fairly robust given the context in which they are presented, with the exception of the assumption of inward radial gas flow, which may not be valid under all circumstances and this may change some of the conclusions. There are also a number of other issues that need to be addressed before publication.

The paper merits publication in ApJ, provided the following issues are addressed:

MAJOR

The paper assumes the radial flow of gas is directed inward, towards the star (Eq. 13), in contrast with Ali-Dib et al. 2014 that assume an outward flow. Since this is a critical assumption in the paper, this issue needs to be addressed. An inward flow may be a reasonable assumption for the water snow line that is close to the star, but this is not immediately clear for CO/CO₂ snow lines that are located further out. In reality, the movement of gas is likely a diffusive process, but with a net flow that is inward in the inner disk and outward in the outer disk. The authors need to investigate whether the expected direction of the gas flow is indeed inward for each of the snow lines and discuss how this assumption affects their conclusions if this is not (always) the case.

The inward movement of the water snow line is significantly smaller in a viscous disk than in a passive disk (Figure 5). Since the former is the most likely scenario, the quoted number of 60% in the abstract seems overstated. In general, a location of 0.7 AU for the water snow line in a disk model based on the minimum mass solar nebula seems unrealistic, so care should be taken with conclusions based on the model that does not include viscous heating. The actively heated model should be preferred as being the most complete one, and at least mentioned in the abstract. It is also not clear why this model is not shown in figures 2 and 3. There were a number of papers published this year on the location of the water snow line in viscous+irradiated disks that could be used for guidance: Baillié et al., Mulders et al., Bitsch et al.

The calculated gas C/O ratios (colored lines in figure 5) are not correct. Between the static and dust snow line, gas-phase abundances are modified by the release of additional gas through desorption of drifting solids, not by additional adsorption onto dust grains. Inside the CO₂ and H₂O snow line, this drives the C/O ratios down, not up as is shown. The assumption in section 4 that "the abundance relative to hydrogen for each volatile is fixed" cannot be used in conjunction with radial drift. Two possible solutions are evident: calculating the amount of vapor released by drifting grains (equation 18a+b) or finding an approximation that reflects that the C/O ratios go down, not up.

THROUGHOUT PAPER

"the disk": Protoplanetary disk properties evolve in time and their properties vary from star to star. It is fine to pick a fiducial disk model for this investigation, but one should be aware that some of the conclusions will depend on the chosen disk model. In particular, the grain sizes quoted in abstract and conclusions are model-dependent and this should be clearly articulated, unless they can be expressed in a dimensionless size that is independent of the chosen disk structure. This same holds for the respective locations of the snow lines.

The term "active disk" for an evolving irradiated disk without viscous heating is confusing. In the current manuscript, the terms "active" and "passive" refer to both heating (eq. 8) and dynamics (disk models), and are not defined in the abstract. The authors should try to find less ambiguous terms. I would suggest "viscous" and "(ir)radiated" when referring to heating mechanisms. Perhaps "irradiated", "evolving", and "viscous" are terms that better reflect both geometry and heating mechanisms for the "passive", "active", and "accretionally heated" models, respectively.

The ("active disk") does not take into account time-dependencies in the mass accretion rate and

irradiated mid-plane temperature (through evolving surface density and stellar luminosity). Inclusion of these effects will lead to the inward movement of the snow lines throughout the disk lifetime. It is not clear from the current draft how this effects conclusions that snow line locations are independent of time. The water snow line may move fast at early times. The authors could verify that the timescales for moving the snow line in through drift are shorter than its intrinsic movement.

MINOR

Introduction:

- It would be good to also mention the Alma DCO+ observations of the snow line.
- "This 'conveyor belt' model is also used by Ciesla & Cuzzi (2006)". The current paragraph doesn't reflect that much of the work is based on the pioneering work by Ciesla & Cuzzi and also Cuzzi & Zahnle 2004. Please rephrase.
- "These observations are currently lacking an interpretive framework that takes into account all important dynamical and chemical processes." Since the paper does not present such a framework or outlines a way towards one, it is not clear how the work presented here fits in to this bigger picture.
- The claim of super-stellar C/O ratio in WASP-12b by Madhusudhan et al. 2011 are no longer supported by the available observations. The text should reflect that there is currently no unambiguous evidence for super-stellar C/O ratios in hot jupiters.
- "One combination that has not yet been considered is the combination of radial drift and viscous gas accretion" This contradicts earlier statements about the work in the Ali-Dib et al. (2014) paper. Maybe the authors mean INWARD gas accretion?

Section 2:

Disk model ordering: it would make sense to list disk models in order of increasing complexity: static, passive, active, active heated. The static and passive disk are identical in terms of density and temperature, they could be combined in one heading in section 2.1. This would also make it more clear that the choice of density and temperature for the passive disk is based on that in Oberg et al. 2011.

Passive disk: One could also note here that a slope flatter than $r^{-1.5}$ is more consistent with the temperature profile for a steady state gas disk.

It is not clear if the active disk has the same surface density profile as the static/passive disk. A plot comparing the two surface densities would be helpful, or a statement at what time the active disk surface density matches the passive disk.

Eq 4 & 5: T is used for time, but is already used for temperature in the rest of the paper.

"Calculating the mid-plane temperature self-consistently for an active disk is non-trivial." This statement is not correct. It is in fact irradiation that is non-trivial, see for example Chambers 2009.

Active disk: the equations presented here do not take into account two time-dependencies: mass accretion rate and irradiated temperature. This should be clearly stated.

After eq 14: please cite original references for binding energies.

Last paragraph: Text would be clearer if the second sentence "In these case ..." was moved before (1) and (2)

What about the time scales at which the snow line moves in due to changes in accretion rate and stellar luminosity? How do these compare?

Section 3:

Footnote 4: This is an important caveat: these statement is not true for the water snow line in a

viscous disk. This should be in the main text.

Last sentence: This statement is only true if also ignoring time dependence of the mass accretion rate, disk temperature, and stellar luminosity.

Section 4:

"If grains have grown to radii larger than ~ 7 m, then the 7m snowline applies" This does not seem to be the case for significantly larger particles (Figure 2). Please clarify.

"snowline in all disks is significantly closer to the host star compared with Solar system models". The snow line location depends mainly on the mass accretion rate and dust opacity, see for example Min et al. 2011 for a comparison between different models. A different choice may have yielded a value that better matches the solar system snow line. On the other hand, Mulders et al. 2015 find that typical sun-like stars may have snow lines closer in than our solar system.

"moving the snowline location outwards" -> "... inwards"

The TW Hya snow line matches that for small grains: This may indicate that coagulation and fragmentation is important. It would be interesting to compare the coagulation-fragmentation time scale with that of the desorption time scale to see if this is the case. Alternatively, the flow may not be inward at 30 AU, see also major point.

Section 5:

paragraph 2&3: Mention that the conclusion pertaining disk age and mass are only valid if the snow line itself doesn't move with time or disk mass.

Discussion:

1. "grain growth will eventually push the snowline location outwards" If grains grow to sizes where they don't drift or sublimate, the snow line is successfully 'frozen in' to the planetesimal population, and stops moving. It is not clear from the text why this implies an outward movement of the snow line.

2. "Turbulence causes eddies and vertical mixing, which are likely to reduce the radial drift velocity of the solids" This is not immediately clear from the text. Please expand or add a reference.

3. Is it possible to estimate the fragmentation time scale and compare it to the drift and desorption time scale? Perhaps in Section 2?

4. "outward" -> "less far inward" or "outward with respect to"

6. "cavities significantly depleted of gas" Given that most transitional disk observations probe dust, it might be good to add a reference for the gas. For example, van der Marel et al. 2015.

7. The mass accretion rate is a dominant factor in setting the location of the water snow line, and some more discussion on this choice is warranted. In particular, how does this value compare to accretion rate measurements of solar mass stars, and what is the age where the disk reaches 10^{-8} ?

Summary:

It would be good to explicitly state what "the model" or "fiducial model" is, since the mentioned grains sizes depend upon it.

1. add that movement is inward

2. "Thus for each particle size there is a fixed and uniquely determined H₂O, CO₂ or CO snowline."

This conclusion is at direct odds with that of Baillié et al 2015, who identify snow regions. please clarify or rephrase.

3. Specify what kind of numerical simulations

6. Add that the drift of the water snow line is less than 60% for a viscously heated disk.

7. Is conclusion 7 new? If this is just a confirmation of Oberg et al. 2011, this should be stated, and what this paper adds to this conclusion. Mention this is C/O ratio of gas. Also mention the direction and magnitude of the change in C/O when taking into account radial movement of gas, reflecting the changes made to figure 5 and section 2.

8. mention this is assuming a constant \dot{M} and L_{star} .

FIGURES

1: not color-blind friendly. This is a very complex plot, is it possible to split it into three separate panels?

Would it be possible to show a cut a given radius (at the snow line or a few different radii) showing final semi-major axis as a function of particle size as an intermediary between figure 1 and 2?

2: Line colors are hard to distinguish since a large section of the color bar is not used. Is it possible to increase the contrast?

Why is the heated disk not shown? Also for figure 3.

Could skip a few axes tick labels in Figure 1 and 4. Bold tick labels in figure 2 & 3 like in other plots would improve readability.

4: There is only one labeled tick in the top right panel

Left hand panels would be clearer if particle size at $t=t_{\text{disk}}$ would not go to zero

5: Can the caption be shorter? A lot of information is included that is better explained in the main text. The arrows are not explained. Curves exterior to the static snow line could simply be replaced by the static snow line.