THE MEASURED COMPOSITIONS OF URANUS AND NEPTUNE FROM THEIR FORMATION ON THE CO ICE LINE

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ABSTRACT

The formation mechanisms of the ice giants Uranus and Neptune, and the origin of their elemental and isotopic compositions, have long been debated. The density of solids in the outer protosolar nebula is too low to explain their formation, and spectroscopic observations show that both planets are highly enriched in carbon, very poor in nitrogen, and the ices from which they originally formed might have had deuterium-to-hydrogen ratios lower than the predicted cometary value, unexplained properties that were observed in no other planets. Here, we show that all these properties can be explained naturally if Uranus and Neptune both formed at the carbon monoxide ice line. Due to the diffusive redistribution of vapors, this outer region of the protosolar nebula intrinsically has enough surface density to form both planets from carbon-rich solids but nitrogen-depleted gas, in abundances consistent with their observed values. Water-rich interiors originating mostly from transformed CO ices reconcile the D/H value of Uranus’s and Neptune’s building blocks with the cometary value. Finally, our scenario generalizes a well known hypothesis that Jupiter formed on an ice line (water snow line) for the two ice giants, and might be a first step toward generalizing this mechanism for other giant planets.

Key words: planets and satellites: atmospheres – planets and satellites: composition – planets and satellites: formation – planets and satellites: interiors – protoplanetary disks

1. INTRODUCTION

Uranus and Neptune are the outermost planets of the solar system. Formation at their current positions poses the problem of how a large density of solids could have existed that far out in the protosolar nebula (hereafter PSN), since gas density is thought to decrease with inverse heliocentric distance (Pollack et al. 1996). A large solid surface density is needed to form the planetary cores quickly enough to accrete gas within a timescale consistent with the presence of the gaseous protoplanetary disk in the currently accepted models of giant planet formation (Helled & Bodenheimer 2014).

With atmospheric C/H ratios measured to be enhanced by factors of ∼30–60 times the solar value (Fegley et al. 1991), both planets appear highly enriched in carbon. In comparison, the C/H ratios in Jupiter and Saturn have been measured to be about 4 and 7 times the solar value, respectively (Wong et al. 2004; Fletcher et al. 2009), and are thought to be consistent with some core-accretion formation models.

The nitrogen abundance is also surprising, since both planets have probably very low N/H ratios (~1% of the solar value; de Pater & Richmond 1989; de Pater et al. 1989; Gautier & Owen 1989). Jupiter and Saturn, on the other hand, are enriched in nitrogen by a factor of ~4 compared to the solar value (Wong et al. 2004; Fletcher et al. 2009). This large difference motivated several studies that tried to explain the N depletion in Uranus and Neptune, with little success (Fegley et al. 1991; Atreya et al. 1995). This differential enrichment found in Uranus and Neptune, in contrast with the uniformly enriched Jupiter and Saturn, hints at differences in the initial composition of their formation locations.

The deuterium to hydrogen (D/H) ratio, which is strongly temperature-dependent and considered an indicator of the ice formation location (Mousis et al. 2000), is also problematic for Uranus and Neptune. This ratio was measured in both atmospheres. These measurements were coupled to models of planet interiors (Helëld et al. 2011) to obtain the D/H ratios for the original water proto-ices that contributed to forming the planets (hereafter proto-ices). By making the assumption that the water in their interiors originated entirely from nebular H2O ice, its D/H value was found to be ~6–8 times lower than the cometary values in both Oort cloud and Jupiter family comets (Lis et al. 2013). This is surprising, because Uranus and Neptune are supposed to have formed in the region of the comets, and thus their proto-ices should have cometary D/H.

Here, we show that we can explain all these unique properties at once if Uranus and Neptune formed at the CO ice line with the N2 ice line a short distance outward. In Section 2, we present the dynamical multi-snow-line volatile transport model we used to calculate the CO ice line properties. In Section 3, we discuss the results and show how this model explains the aforementioned observations. Caveats and implications of our results are discussed in Section 4, and we conclude in Section 5.

2. THE VOLATILE DISTRIBUTION MODEL

In order to calculate the composition and properties of the CO ice line, we used the dynamical volatile transport and distribution model from (Ali-Dib et al. 2014, hereafter AD14). It tracks the evolution of CO and N2 solids and vapor in a standard model of the PSN. This model takes into account the major dynamical and thermodynamical effects relevant to volatiles: turbulent gas drag (Stepinski & Valaège 1996; Hughes & Armitage 2010) and sublimation (Supulver & Lin 2000) for solids, in addition to gas diffusion (Stevenson & Lunine 1988) and condensation (Ros & Johansen 2013) (RJ13) for vapors. We used the same modules and parameters as AD14 unless otherwise stated. The main modification is the replacement of the dust coagulation module used in AD14 with the timescales of the more effective growth due to the condensation obtained.
by RJ13. In this model, condensation and sublimation are simulated in a Monte Carlo scheme where solid particles diffuse following turbulence, leading some of them to cross an ice line and sublimate. The resulting vapor recondenses onto already existing particles, leading to pebble growth. For a minimum mass solar nebula and $\alpha = 0.01$, millimetric dust is found to grow into pebbles in $10^3 \Omega_{K^{-1}}$. We used the equilibrium vapor pressure for N$_2$ from (Giauque & Clayton 1933). The results for each module are presented in Table 1.

For the rest of this work, we will use the disk properties at $10^5$ yr. The disk is presumed to be stationary since the planetesimal formation timescale is shorter than the disk evolution timescale. The initial conditions of the disk model are those inferred by (Hueso & Guillot 2005, HG05) for the DM Tau system: $M_{\text{cloud}} = 0.53 M_\odot$, $\Omega_{\text{cloud}} = 23 \times 10^{-14}$ s$^{-1}$, $T_{\text{cloud}} = 16$ K, $M_{0,\text{star}} = 0.01 M_\odot$, and $T_{\text{star}} = 4700$ K, but $\alpha = 0.01$ (the value used by Hughes & Armitage (2010) instead of $\alpha = 0.02$ as in HG05). At $10^5$ yr, this leads to a star–disk system with respective masses of 0.5 and 0.03 $M_\odot$. We chose these initial conditions leading to a system less massive than our protosolar nebula for consistency. These parameters provided a best fit for the typical protoplanetary disk DM Tau, and using a more massive disk will not change the qualitative results of this work since we are discussing abundances normalized with respect to solar value, so we preferred using consistent parameters instead of tweaking them. The obtained disk properties are shown in Figure 1.

In our model, volatile concentrations are presumed to be initially homogeneous throughout the PSN; CO and N$_2$ are supposed to be the main carriers of C and N (Prinn 1993),

**Table 1**

| Size (cm) | N$_2$ | Velocity (cm s$^{-1}$) | $\Delta t$ (yr) | $\Delta R$ (AU) | CO | Velocity (cm s$^{-1}$) | $\Delta t$ (yr) | $\Delta R$ (AU) |
|----------|------|------------------------|------------------|-----------------|----|------------------------|------------------|-----------------|
| $10^{-1}$ | ...  | $4.3 \times 10^4$      | ...              | ...             | ...| $3.3 \times 10^4$      | ...              | ...             |
| 1        | $-787.3$ | $1.3 \times 10^4$     | $-22.5$          | $-463.6$        | $-2754.3$ | $3.7 \times 10^4$     | $-19.0$          | $-20.8$         |
| 10       | $-2647.0$ | $4.1 \times 10^3$    | $-23.8$          |                  |    |                        |                  |                 |

**Notes.** Negative velocities mean inward drifts. $\Delta t$ is the time taken by 1 and 10 cm particles to drift from their starting positions until sublimation and for millimetric dust to grow into pebbles through vapor condensation (in this case $\Delta t \equiv t_{\text{grow}}$). $\Delta R$ is the distance traveled by particles drifting inward from their ice line to their sublimation location. The particles are placed initially on their ice line. Millimetric dust velocities and transport in RJ13 are dictated by turbulence and gas drag.
and hence their abundances are set to the carbon and nitrogen solar abundances. Solids are assumed to be decimetric “pebbles” at their respective ice line.\textsuperscript{3} Centimetric pebbles are observed in large quantities in disks (Wilner et al. 2005). Interestingly, pebbles are found by models to have an optimal size for effective concentration in vortices and for accretion (Lambrechts & Johansen 2012). Inside the ice lines there is only vapor. Since the sublimation temperatures for CO and $N_2$ are respectively 25 and 24 K (Fray & Schmitt 2009), their ice lines are located in our model at 28 and 32 AU. The CO ice line’s position is comparable to that recently inferred at $\sim$30 AU in the solar analogue TW Hya (Qi et al. 2013). The exact sublimation temperature of these ices does not affect our scenario, it is only the difference between the two temperatures that is key to our results. The model then tracks the subsequent evolution of the system as a function of time and location.

A typical simulation starts with a decimetric pebble ($N_2$ or CO) near its corresponding ice line. This particle is large enough to decouple from gas. It will drift inward due to gas drag at the velocity determined by the transport module, and starts sublimating. The time needed for sublimation and the distance traveled before it happens are calculated by the sublimation module. These values are communicated to the vapor diffusion module through the source function. This module then evolves the vapor concentration inside the ice line. The vapor will diffuse outward along its concentration gradient due to the existence of the ice line. The removed vapor will condense with time at the ice line into decimetric pebbles. These will get decoupled and start drifting inward, repeating the cycle. The distribution of volatiles in our model is hence controlled by the balance of these two effects: the outward diffusion of the vapor and the ice’s inward migration followed by sublimation.

\section{3. RESULTS}

\subsection{3.1. Qualitative Results Discussion}

In our model, the outward diffusion of vapor is shown to be faster than its replenishment inside the ice lines by sublimating ices. This leads to depletion in vapors inside the ice lines and a concentration of solids at the ice line positions. This result is of capital importance for this work. Since CO is the major C-bearing volatile in the PSN, its ice line should be very rich in solids, explaining the origin of the high volumetric density of solids needed to form the planets. The high CO abundance in the building blocks implies that planets forming in this region should be very rich in carbon in bulk.

On the other hand, the $N_2$ ice line is located slightly outward (4 AU) of the CO ice line. The proximity of the two ice lines leads to a natural depletion in $N_2$ vapor at the CO ice line, since the vapor diffusion depletes the area immediately inward of an ice line quicker than that farther away. Therefore, planets forming at the CO ice line should also be significantly depleted in nitrogen compared to the solar $N/H$ abundance.

Finally, coupling the D/H observations in Uranus and Neptune with our model, where only a small fraction of the water present in the planets’ interiors is of nebular origin, and the rest originated from the transformation of CO into $H_2O$, leads to a higher D/H ratio for the proto-ices that formed the planets. The value found is compatible with internal structure models and the formation location of the planets in the same region as comets.

\subsection{3.2. Solid Densities and Elemental Abundances}

Figure 2 represents the evolution of CO and $N_2$ vapors inside their respective ice lines. In the final steady state at $1.6 \times 10^5$ yr, there is little vapor left inside these condensation fronts. All the missing vapor has been condensed into solids that concentrated at the ice line locations. We note that the minor difference between this figure and its analogue in AD14 is due to a minor numerical correction from the latter.\textsuperscript{4} Figure 3 shows the evolution of the solid CO normalized density as a function of time in the region near the ice line where all the CO ices concentrated. To quantify the solid surface density $\Sigma_c$ at the CO ice line, we need first to calculate the length scale over which most of the diffused CO vapor condenses. We follow the prescription of Stevenson & Lunine (1988) in expressing this length scale as

$$X_c = \delta \times \ln(\sqrt{D \times t / \delta}) ,$$

(1)

where $t$ is the diffusion characteristic time and $\delta$ is a parameter that measures the distance over which the saturation vapor

\footnotetext[3]{The region in protoplanetary disks where temperature becomes low enough to condense a volatile vapor.}

\footnotetext[4]{See Erratum in preparation.}
The roughly 40 times solar CO enrichment in the planet formation zone, presented in Figure 3, is thus the integral of the CO vapor concentration removed from the entire inner region with 0.5 AU as the integration step. Now we calculate the gas/solid \(G/S\) mass ratio and the solid surface density \(\Sigma_s\) in that region:

\[
G/S = \frac{\Sigma_s \mu^s n^s}{\sum_i \mu^i n^i},
\]

where \(\mu\) is the mean molecular weight of a species and \(n\) is the molar abundance of gases \((g)\) and solids \((s)\). Taking into account CO and \(H_2O\) as solids, we obtain

\[
G/S = \frac{\mu_{H_2} n_{H_2}}{\mu_{CO} n_{CO} + \mu_{H_2O} n_{H_2O}},
\]

We use \(n_{H_2O}/n_{H_2} = 7 \times 10^{-4}\), as found by Cyr et al. (1999) from chemical equilibrium calculations. We also chose \(n_{CO}/n_{H_2O} = 43 \pm 0.77\), which is the value observed in the inner region of AA Tauri’s atmosphere (Carr & Najita 2008) multiplied by the calculated enrichment factor. This value is higher than in comets, but lower than in the interstellar medium (Mumma & Charnley 2011). Finally, this gives \(G/S = 3\) and \(\Sigma_s = \Sigma_s/G/S = 9 \text{ g cm}^{-2}\) (for \(\Sigma_s = 27 \text{ g cm}^{-2}\)). Figure 4 shows the mass fractions of solids at the CO ice line before and after the CO vapor condenses. The \(\Sigma_s\) is more than one order of magnitude higher than the initial value obtained for \(G/S = 72\). This \(G/S\) value is more than enough to form the cores through gravitational collapses (Youdin 2011).

Moreover, Dodson-Robinson & Bodenheimer (2010) calculated that \(6 < \Sigma_r < 11 \text{ g cm}^{-2}\) is the best value to fit the formation timescales of Uranus and Neptune, although the value we found is limited to a 0.5 AU wide zone. It should also be mentioned that the formation models of Dodson-Robinson et al. (2009); Dodson-Robinson & Bodenheimer (2010) predict very large quantities of methane ices in the outer solar nebula, which is not observed in comets (Mumma & Charnley 2011), but the authors stated that the CO/CH\(_4\) ratio is not critical for their results. Moreover, in these models, Uranus and Neptune are formed with large amounts of ammonia, implying a large nitrogen abundance in their atmospheres, which is not observed (but not completely excluded).

After core formation and the subsequent gas envelope accretion (Pollack et al. 1996), the accreted CO will dissolve and transform into gaseous \(H_2O\) and \(CH_4\) following

\[
CO + 3H_2 \rightarrow CH_4 + H_2O,
\]

resulting in the observed highly enriched atmospheric gaseous \(CH_4\). This nebular gas origin for the hydrogen in \(CH_4\) is also consistent with the low \(CH_3D\) abundance measured in both planets (Feuchtgruber et al. 2013; Irwin et al. 2014). Hence, the \(C/H\) and \(O/H\) ratios increase to more than 40 times the solar abundance. The predicted \(C/H\) matches within the uncertainties the measured values of \(34_{-11}^{+15}\) and \(48_{-13}^{+31}\) \(\times\) solar for Uranus and Neptune, respectively (Baines et al. 1995 using the solar abundances of Asplund et al. 2009).

Figure 2(b) shows that at the CO ice line location, \(N_2\) vapor is depleted by more than a factor of 50 with respect to solar value after \(2 \times 10^5\) yr. This implies that any planet forming in this region should be naturally poor in nitrogen by factors similar to those inferred in Uranus and Neptune.

### 3.3. The Deuterium-to-Hydrogen Ratio

To calculate the proto-ice \(D/H\) ratio in a manner consistent with the Uranus and Neptune internal structures, previous works supposed that primordial water ice (and thus with a cometary \(D/H\) value) can represent up to \(\sim 90\%\) of the planet’s mass (Helley et al. 2011; although it might be less due to the contribution of rocks). This required the value of the proto-ice \(D/H\) to be \(\sim 5 \times 10^{-5}\), a factor six lower (and can get up to an order of magnitude in some models) than the average cometary

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Figure 3. Density of solid CO at its ice line, normalized with respect to solar value. Solid CO density increases as a function of time due to vapor diffusion from the inner nebula. In \(2 \times 10^5\) yr, the density and chemical composition of this region become compatible with Uranus and Neptune.

Figure 4. Mass fractions of solids at the CO ice line for \(t = 0\) yr (left) and \(10^5\) yr (right). The left panel also describes the mass fractions between the CO and \(N_2\) ice lines (beyond the density peak) at any time. \(SiO_2\) was included to represent silicate grain contribution with solar Si abundance (Asplund et al. 2009). At \(t = 10^5\) yr, the mass distribution is almost completely dominated by CO ices.
D/H value of $\sim 2.4 \times 10^{-4}$ (Feuchtgruber et al. 2013). This led to speculation on the origin of their proto-ices and their interior structure. Using the observed planetary D/H for Uranus and Neptune, we perform the same calculations but assuming that most of the H$_2$O in the interior has CO as the origin. Following Feuchtgruber et al. (2013) and assuming fully mixed envelopes, we can write

$$\frac{(D/H)_{\text{ices}}}{(D/H)_{\text{planet}}} = \frac{(D/H)_{\text{ices}} - x_{\text{H}_2} (D/H)_{\text{gas}}}{(1 - x_{\text{H}_2})},$$

where $(D/H)_{\text{planet}}$ is the value measured in Uranus and Neptune, $(D/H)_{\text{ices}}$ is the value of the proto-ices accreted by these planets, and $(D/H)_{\text{gas}}$ is the value of the PSN H$_2$ gas, supposedly equal to the value in Jupiter’s atmosphere. $x_{\text{H}_2}$ is the molar ratio of gas and ice defined as

$$x_{\text{H}_2} = \frac{1}{1 + \left(\frac{1 - f_{\text{H}_2}}{m_{\text{H}_2^0}/m_{\text{H}_2} \times f_{\text{H}_2}}\right)}.$$

where $m_{\text{H}_2^0}$ and $m_{\text{H}_2}$ are the molar masses of H$_2$O and H$_2$, respectively. $f_{\text{H}_2}$ is the molar ratio of H$_2$ defined as

$$f_{\text{H}_2} = \frac{0.747 M_{\text{H}_2^0}}{0.747 M_{\text{H}_2^0} + M_{\text{ice}}}.$$

where $M_{\text{ice}}$ is the total ice mass in the planet’s interior (assumed to be H$_2$O), and $M_{\text{H}_2^0}$ is the total mass of hydrogen and helium. Calculating $(D/H)_{\text{ices}}$ requires a prior knowledge of $x_{\text{H}_2}$, and therefore of the ice/gas ratio in the planets. In our model, the core accreted initially was dominated by CO ice. This CO then transforms into CH$_4$ and H$_2$O under the conditions obtained in the envelopes of Uranus and Neptune. For these two reasons, respectively, to calculate $(D/H)_{\text{ices}}$ inferred from our model, we use interior models of the planets from Helled et al. (2011; H$_2$O model case 2) to determine $f_{\text{H}_2}$ and $x_{\text{H}_2}$, but we divide $M_{\text{ice}}$ (corresponding to the ice mass fraction $Z$ given in Helled et al. 2011) by 34, since Z corresponds to the contribution of oxygen originating from both the protoplanetary CO and H$_2$O ices, while only the latter contributes to the D/H value. Assume $Z = Z_1 + Z_2$, where $Z_1$ and $Z_2$ are respectively the CO and H$_2$O ice contributions to $Z$. $Z_1 = 43 \times Z_{\text{CO}}^{\text{solar}} = 43 \times 0.77 \times Z_{\text{H}_2O}^{\text{solar}}$ since in our protoplanetary disk CO is enriched 43 times over the solar value, and $n_{\text{CO}}^{\text{solar}} / n_{\text{H}_2O}^{\text{solar}} = 0.77$ as mentioned in the previous subsection. Again, we make the reasonable approximation that CO and H$_2$O are the dominant C and O bearing species. This leads to $Z_1 = 33 \times Z_2$ and $Z_2 = Z/(33 + 1)$. $Z_2$ is finally equal to $Z/34$. Hence, we replace $Z$ in the original calculations by our $Z_2$ to calculate the D/H only for minor cometary water contribution to the global D/H ratio.

We then obtain for Uranus and Neptune $f_{\text{H}_2} = 0.70$ and 0.73, giving $x_{\text{H}_2} = 0.954$ and 0.960, respectively. For $(D/H)_{\text{planet}} = 4.2 \times 10^{-5}$ and $(D/H)_{\text{gas}} = 2.25 \times 10^{-5}$, we can deduce $(D/H)_{\text{ices}} = 4.4$ and $5.1 \times 10^{-4}$ for Uranus and Neptune, respectively, values just slightly above the cometary D/H (Feuchtgruber et al. 2013). These calculations are a proof of concept, and can be improved using better interior models and initial water abundance estimates. The methane contribution to the ice mass should also be taken into account for more precise calculations, instead of supposing that all ices are H$_2$O as in this work. We should also mention that an alternative explanation for the D/H problem might be found in the new model of Yang et al. (2013), where a non-monotonic D/H gradient is inferred.

It should be noted that acquiring H$_2$O through CO transformation implies a higher initial X/Z ratio. By reversing the problem, we get $X' = 0.230$, $Y' = 0.024$, and $Z' = 0.746$ initially during the planet formation. $X'/Y'$ is different from the solar value used by Helled et al. (2011). The origin of this discrepancy is unclear and should be investigated.

4. DISCUSSION

4.1. Consistency with Dynamical Models

The presence and initial positions of Uranus and Neptune are important for the Nice model, which explains the orbital structure of the solar system (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005). An important component in the Nice model is the initial compact configuration of the giant planets, where Uranus and Neptune are at 15 and 12 AU, respectively, much closer than the CO ice line. There are two possible ways to reconcile this with our model. The first is that Uranus and Neptune probably migrated inward during the era of the gaseous disk from their formation location to the locations required by the Nice model. Planets of the mass of Uranus and Neptune are expected to undergo a type I migration due to their interaction with the disk gas. The characteristic timescale of type I migration is $10^4$ yr, and its usual direction is inward, although recent works showed that under some circumstances it can be outward (Guilet et al. 2013). This migration will be halted when the ice giants enter a mean motion resonance (MMR) with Saturn and then each other. These are some of the initial conditions for the Nice 2 model (Morbidelli & Crida 2007; Morbidelli et al. 2007; Levison et al. 2011). Another possible solution is the migration of the CO and N$_2$ ice lines themselves (due to the cooling of the gaseous disk over time), along with the accumulated matter, to these new locations prior to the formation of Uranus and Neptune. On the other hand, the presence of Uranus and Neptune has minimal effects on the Grand tack scenario dealing with the solar system dynamics prior to disk dissipation (Walsh et al. 2011). Finally, we should mention the alternative model of Thommes et al. (2002), where Uranus and Neptune form between the orbits of Jupiter and Saturn. This scenario, though, cannot explain the chemical compositions of the planets.

4.2. The Model Predictions

The main prediction of the model we presented is the bulk O/H ratio in Uranus and Neptune. Since most of the oxygen is accreted in the form of CO, O/H should be $\sim$C/H. Our prediction would imply primarily an external source of the observed stratospheric CO (steady micrometeorite influx or a kilometric-sized cometary impact), a scenario consistent with recent observations (Lellouch et al. 2010; Luszcz-Cook & de Pater 2013; Cavaatch et al. 2014; Irwin et al. 2014). An internal source necessitates a C/O ratio $\sim$0.1 (implying O/H $\geq$ 400 $\times$ solar value Lodders & Fegley 1994), in contrast with our model, where C/O $\sim$ 1. A future definitive observation of tropospheric CO, on the other hand, might imply C/O $\sim$0.1 according to the standard interpretation. This would apparently contradict the D/H measurement. All formation scenarios enriching O by such large fractions rely on accreting large cometary water ice quantities. This in turn leads to a high D/H for the planets, in contradiction with the observed values. The scenario of Horsant et al. (2004), for example, interprets the measured abundances of Uranus and Neptune using a clathrates trapping model. Since almost six water molecules are needed for each gaseous volatile to be trapped, this model predicted...
4.3. Effects on Jupiter and Saturn

Our model predicts a moderate depletion in gaseous CO and N$_2$ in the 3–6 AU Jupiter–Saturn formation region (Walsh et al. 2011), but this does not necessarily contradict some formation models. For example, in Lodders (2004), carbon in Jupiter is typically found in 2D viscous disks simulations and $\alpha \sim 0.01$. Recent MHD (magnetohydrodynamics) simulations showed that the midplane might be an MRI (magnetorotational instability) inactive deadzone (Gammie 1996; Dzyurkevich et al. 2013; Martin & Livio 2014), resulting in much weaker turbulence (and hence a smaller $\alpha$) and an almost static gas. A lower $\alpha$ value decreases the diffusion rate ($D \sim \nu x$) due to lower viscosities, but also significantly decreases the particles growth rate (RJ13). To simulate this aspect of dead zones, we run our model using $\alpha = 10^{-4}$ (in all modules). Results are presented in Figure 5 showing the persistence of the solid enhancement effect even for weak turbulence.

Another important component in our model is that both planets formed at the same location in a narrow 0.5 AU sized region, although not necessarily simultaneously. It might be possible for the growth of the first planet to be truncated by migration, leaving enough solids behind to form the second. Another possibility would be the first planet formation and migration, before all the CO vapor is diffused throughout the CO ice line, allowing the second to form later from solids originating from the remaining vapor. The formation timescales are an obvious problem for this scenario, although the presence of a dead zone might significantly increase the CO ice concentration timescale. Using an evolving disk is an important step in this direction. A third possible solution would be if the diffused CO vapor condenses over a larger length scale $X_c$ (as those reported in RJ13), giving enough space for both planets to form simultaneously without interference. Finally, advanced disk simulations that include the deadzone and gravitational instability effects (Martin & Livio 2012) show that the temperature gradient profile in protoplanetary disks might not be monotonous, allowing the possibility of having multiple ice lines for the same species at some stages of disk evolution, and thus hinting at another possible solution for this problem.

Finally, by interpreting the measured abundances of the ice giants as bulk compositions, we assumed first that the reason for detecting the low NH$_3$ abundance is the intrinsically low bulk abundance. An alternative interpretation is that NH$_3$ condenses beyond the observable level. The second assumption is that both atmospheres are well mixed. This might not be the case for Uranus, since its low heat flux indicates that it might not be fully convective, although this is unlikely for the more dynamic Neptune (Lunine 1993).

5. CONCLUSIONS

In this paper, we showed how the formation of Uranus and Neptune on the CO ice line resolves many issues related to these planets. The diffusive redistribution of vapor across the ice lines increases the local solid density, allowing the formation of these planets from carbon-rich solids but nitrogen-poor gas, and leads to planetary interiors consistent with recent D/H measurements.

Our scenario follows from previous models (Stevenson & Lunine 1988), where Jupiter is formed on the H$_2$O ice line, a hypothesis to be firmly tested by Juno. It expands this hypothesis to other planets and shows how this mechanism can solve certain longstanding problems. If it is true that most of the giant planets in our solar system were formed on ice lines, it is difficult not to speculate that the same holds true for the formation of giant planets in general. In the last decade, hundreds of exoplanets have been discovered, with Neptune-mass bodies more abundant than Jovian-mass ones. In this work, we gave a specific interpretation of a “Neptune-like” planet as one that formed on the CO ice line, and is thus enriched with carbon with respect to the stellar value, regardless of its mass. This might allow a future generation of telescopes to better classify planets with ambiguous masses and to disentangle mini-Neptunes and superEarths. It is possible that several mechanisms make Neptune-mass planets, and that those formed on the CO ice line and migrated inward are a subset of the total. Only those that are very enriched in carbon are Neptune-like, according to this definition. Testing this hypothesis will require compositional
data on the atmosphere of such planets, which we anticipate obtaining with the James Webb Space Telescope.

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