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RESOLVING THE INCONSISTENCY BETWEEN THE ICE GIANTS AND COMETARY D/H RATIOS

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Abstract. The properties and chemical compositions of giant planets strongly depend on their formation locations. The formation mechanisms of the ice giants Uranus and Neptune, and 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 within a timescale consistent with the presence of the gaseous protoplanetary disk, 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 had deuterium-to-hydrogen ratios lower than the predicted cometary value, unexplained properties 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 iceline location, namely the region where this gas condensates in the protosolar nebula. 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 observed in Uranus and Neptune with the cometary value.

Keywords: Planets formation, Uranus, Neptune, volatiles enrichment

1 Introduction

Uranus and Neptune are the outermost planets of the solar system. Dynamical evolution simulations show that they should have formed in the cold outer protosolar nebula (hereafter PSN), in contrast with Jupiter and Saturn that formed in the inner relatively warm regions (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005). This poses the problem of how did large density of solids exist that far out in the disk, since it is thought to decrease with the inverse heliocentric distance (Pollack et al. 1996). A large solids surface density is needed to form the planetary cores quickly enough to accrete gas in the currently accepted models of cores formation (Helled & Bodenheimer 2014).

With atmospheric C/H ratios measured to be enhanced by factors of $\sim$30 to 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 very low N/H ratios ($\sim$ 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 $\sim$ 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 to different formation mechanisms.

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The Deuterium to Hydrogen (D/H) ratio, strongly temperature dependent and considered an indicator of ices formation location, is also problematic for Uranus and Neptune. This ratio was measured in both atmospheres. These measurements were coupled to planets interiors models (Helled et al. 2011) to obtain the D/H ratios for the original water proto-ices that contributed in forming the planets (hereafter proto-ices). By making the assumption that the water in their interiors originated entirely from nebular H_2O ice, its D/H value was found ~ 6 times lower than the cometary values (Feuchtgruber 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. This led to speculations on the origin of their proto-ices and the interiors of Uranus and Neptune (Feuchtgruber et al. 2013).

2 Qualitative solution

We explain all these unique properties at once with our scenario where Uranus and Neptune form at the CO iceline. An iceline is a region in protoplanetary disks where the temperature becomes sufficiently low for a specific species to condense into ices. The CO condenses at ~ 25 K (Fray & Schmitt 2009), placing its iceline in the outer disk at ~ 30 AU (Qi et al. 2013). The surface densities of the solids are known to increase substantially on icelines due to the outward diffusion and the subsequent condensation of the inner disk vapor at the narrow iceline location (Stevenson & Lunine 1988). Since CO is the major C-bearing volatile in the PSN (Prinn 1993), its iceline should be very rich in solids. This implies that planets forming in this region should be very rich in carbon.

On the other hand the iceline for N_2 (the major N bearing species in PSNs (Prinn 1993)) is located slightly outward of the CO iceline (Fray & Schmitt 2009). The proximity of the two icelines leads to a natural depletion in N_2 vapor at the CO iceline since the vapor diffusion depletes the area immediately inward of an iceline more quickly than that further away (Stevenson & Lunine 1988). Therefore planets forming at the CO iceline 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 originating from the conversion 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.

3 Quantitative discussion

To quantify this scenario, we used a dynamical volatiles transport and distribution model tracking the evolution of CO and N_2 solids and vapor in a standard model of the PSN (Hueso & Guillot 2005). This model (Ali-Dib et al. 2014) takes into account the major dynamical and thermodynamical effects relevant to volatiles: turbulent gas drag (Stepinski & Valageas 1996; Hughes & Armitage 2010) and sublimation (Supulver & Lin 2000) for solids, in addition to gas diffusion (Stevenson & Lunine 1988) and condensation (Ros & Johansen 2013) for vapors. A simulation (Ali-Dib et al. 2014) starts with matter distributed homogeneously throughout the PSN with CO and N_2 abundances set to the C and N solar abundances, respectively. Solids are assumed to be decimetric pebbles (Ros & Johansen 2013) at their respective iceline. Inside the icelines there is only vapor. Since the sublimation temperatures for CO and N_2 are respectively 25 and 24 K (Fray & Schmitt 2009), their icelines are located in our model at 28 and 32 AU. 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.

The distribution of volatiles is controlled by the balance of two important effects: the outward diffusion of the gas and the ices inward migration followed by sublimation. The diffusion is induced by the concentration gradient due to the existence of the iceline, and the inward drift is caused by the solid particles losing energy due to gas friction. In our model the diffusion of vapor is shown to be much faster than its replenishment inside the icelines by sublimating ices. This leads to depletion in vapors inside the icelines and concentration of solids at the iceline positions. Figure 1 represents the evolution of CO and N_2 vapors inside their respective icelines. In 1.6×10^5 years, there is very little vapor left inside the icelines. All the missing vapor has been condensed into

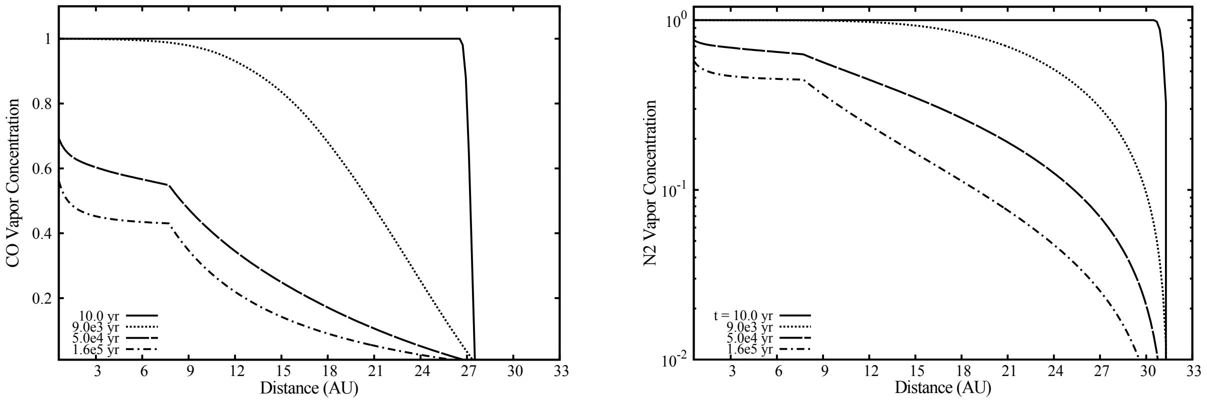

Fig. 1. Vapors concentrations of CO (left panel) and N_2 (right panel). The concentrations are normalized with respect to solar value. Vapors evolution is tracked inside their respective icelines as a function of time and distance to the star. In both cases there is a gradual location dependent depletion in the concentration due to gas diffusion being faster than replenishment through solid particles drift. N_2 is depleted by up to two orders of magnitude on the CO iceline.

solids at the icelines. Figure 2 shows the evolution of solid CO normalized density as a function of time in the region near the iceline where all the CO ices concentrated. This solids density increases along with the decrease in the CO vapor concentration. In 1.6×10^5 years the surface density at the CO iceline increases to a minimum of $\sim$ 12 g cm^{-2}, a value consistent with the estimations of the density of solids needed to form the cores of Uranus and Neptune (Dodson-Robinson & Bodenheimer 2010). 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, resulting in the observed highly enriched atmospheric gaseous CH_4. Hence, the C/H and O/H ratios increases to $\sim 52\times$ solar value. The predicted C/H value matches the measured values (Fegley et al. 1991; Baines et al. 1995) and the O/H ratio is consistent with observations, provided that the CO observed in the upper stratosphere of both planets comes primarily from an external source, a scenario consistent with recent observations (Luszcz-Cook & de Pater 2013; Cavalié et al. 2014; Irwin et al. 2014). Figure 1b shows that at CO iceline location, N_2 vapor is depleted by a factor up to 100 with respect to solar value. This implies that any planet forming in this region should be impoverished in nitrogen by factors similar to these inferred in Uranus and Neptune.

To calculate the proto-ices D/H ratio in a manner consistent with Uranus and Neptune internal structures, previous works supposed that primordial water ice (and thus with cometary D/H value) represents up to $\sim$ 90% of the planets mass (Helled et al. 2011). This required the value of the to proto-ices D/H to be $\sim 5\times10^{-5}$ (Feuchtgruber et al. 2013), a value a factor 5 (and can get up to an order of magnitude in some models) lower than the average cometary D/H value of $\sim 2-4\times10^{-4}$ (Feuchtgruber et al. 2013). There is no obvious reason why this should have been so. Using the observed planetary D/H for Uranus and Neptune, we perform the same calculations but assuming that most of the H_2O in the interior has CO as origin and is thus irrelevant to D/H calculations. By restricting the contributing proto-ices to solar H_2O abundance, we obtained D/H(proto-ices) $\sim$ 3.7 and 4.1×10^{-4} respectively for Uranus and Neptune, very close to the average cometary D/H ratio. Our scenario is found consistent with the dynamical models of the solar system evolution.

Finally, our scenario follows on from previous models (Stevenson & Lunine 1988), where Jupiter is formed on the H_2O iceline, a hypothesis to be firmly tested by *Juno*. It expands this hypothesis to other planets and shows how this mechanism can solve certain long standing problems.

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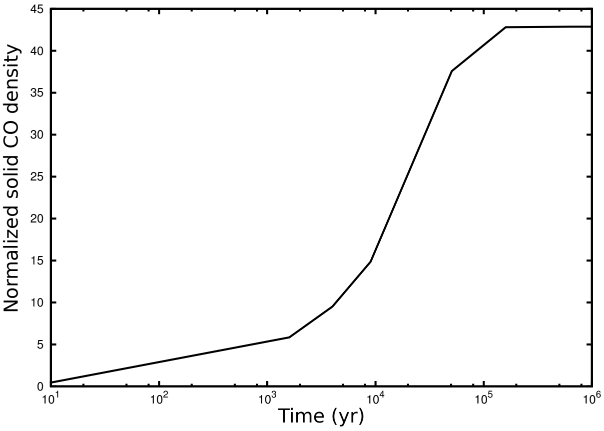

Fig. 2. The density of solid CO at its iceline. The density is normalized with respect to solar value. Solid CO density increase as a function of time due to vapor diffusion from the inner nebula. In 2×10^5 years, The density and chemical composition of this region becomes compatible with Uranus and Neptune.

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