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Uranus and Neptune's formation on the CO iceline

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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, both are very rich in carbon, poor in nitrogen, and their D/H ratios appear to be inconsistent with the cometary values. Using a novel volatiles transport model, we calculate the properties of the CO iceline and show how Uranus and Neptune's formation at this region can solve all the above mentioned problems.

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 where the solids density is not enough for their formation in timescales consistent with the presence of a gaseous protoplanetary disk. With atmospheric C/H ratios measured to be enhanced by factors of 30 to 60 times the solar value both planets appear highly enriched in carbon [1], much more than Jupiter and Saturn (respectively 3 and 10 times solar). The nitrogen abundance is also surprising, since both planets have very low N/H ratios (1% of the solar value) [2]. Finally, D/H value measurements in their atmospheres, coupled to interior structure models, inferred D/H ratios for their building blocks of 6 times lower than the cometary values [3]. 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.

In the following we use a volatiles transport model to show how the properties of the CO iceline is compatible with all the observed properties of these planets.

2. Methods

We use a transport model of major gaseous and solid C, O, and N bearing volatiles that is based on the simultaneous dynamical evolution of their snowlines [4]. The model takes into account the effects of aerodynamics of solid particles in presence of turbulence, in addition to the processes of diffusion, sublimation and condensation. The coupling of this transport model to a turbulent accretion disk model allows tracking of the solid particles and gases of CO and N_2 (major C- and N-bearing volatiles) and the evolution of their respective snowlines. This allows us to compute the composition of the CO iceline.

3. Results

Figure 1 represents the evolution of CO and N_2 vapors inside their respective icelines. In 1.6e5 years, there is very little vapor left inside these condensation fronts. All the missing vapor has been condensed into solids that concentrated at the icelines locations. This implies the presence of a solids density peak at the CO iceline, giving it 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 [5].

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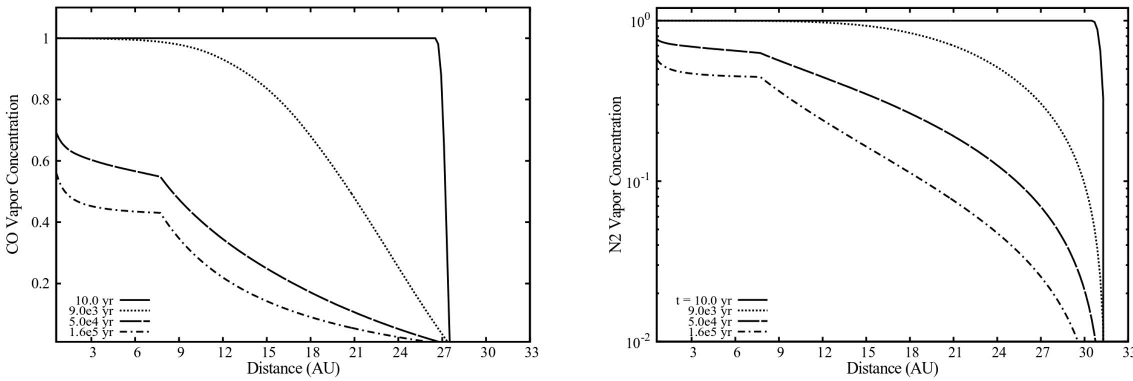

Fig. 1 The vapors concentrations of CO (left panel) and N_2 (right panel) inside their respective icelines as a function of time and distance to the star. In both cases there is a gradual depletion in the concentration due to diffusion being faster than replenishment. In 10^5 years, the CO iceline becomes very rich in CO ices but very poor in N_2 vapor.