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Constraints on the origin of the Uranian satellite system from chemical and isotopic measurements

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Abstract

We study the thermodynamic conditions existing in the Uranian subnebula from which the regular satellites were presumably formed, assuming it was produced by an earth-sized body impact on proto-Uranus. Two evolutionary turbulent models of the Uranian subnebula are constructed, each of them providing a distinct chemical composition which depends on the assumed origin of the subdisk's material (proto-Uranus or impactor ejected material). Moreover, the evolution of the chemistry of C and N compounds is examined in order to assess the nature of major volatiles trapped into the ices of regular satellites. The temporal evolution of the D/H ratio in water is also explored in the Uranian subdisk, as a function of the gas phase composition. Such an analysis may provide constraints on the origin of the material which led to the formation of the regular satellite system.

1 Introduction

Here we use a 1D accretion disk model [1, 2] to investigate the thermodynamic conditions existing in the protosatellite accretion disk surrounding Uranus, assuming it was produced by the giant collision. Given the uncertainties on the origin of the material forming the Uranian subnebula (proto-Uranus or impactor originating material), we consider two turbulent models, each of them providing a different chemical composition. These models allow us to explore the evolution of carbon and nitrogen gas-phase chemistries in the Uranian subnebula and to deduce the nature of C and N volatiles trapped into icy planetesimals from which the regular satellites were presumably formed. The evolution of the D/H ratio in the vapor phase of water is also examined in the Uranian subnebula. Indeed, since it strongly depends on the chemical composition of the subdisk, such an analysis is susceptible to provide constraints on the origin of the material that formed the Uranian satellites.

2 Composition of the impact-generated subnebula

The first model (*water-rich subnebula*), is based on the assumption that the chemical composition of the initial gas phase of the Uranian subnebula should be close to that of Oort comets. In these conditions, CO, CH_4, and NH_3 gases are supposed to be the main C and N compounds in the subdisk, with abundances relative to H_2O not exceeding $\sim$15% for CO, and 1.5% for both NH_3 and CH_4. In this case, C and N chemical conversions are impossible because the subnebula medium is dominated by water in vapor phase. This involves that at any epoch and as long as they stay in the gas phase, CO, CH_4, and NH_3 should remain the main C and N species in this subnebula, with the same initial abundances.

The second model (*water-poor subnebula*), is based on the hypothesis that a part of the giant planet's envelope was ejected into orbit to produce a satellite disk. In this scenario, the H_2-He-CH_4-H_2O atmosphere of proto-Uranus was shocked, involving the complete chemical conversion of the expelled CH_4 into CO [3]. As a consequence of this conversion, some oxygen was associated with carbon and reduced the quantity of water in the subnebula. Furthermore, assuming that NH_3 exists in solar proportions in the atmosphere of Uranus, its conversion into N_2 also occurred in the expelled part of the envelope, as a result of the heating due to the shock [4]. In the case of the water poor subnebula, its hydrogen-dominated medium lead us to check the possibility of CO $\rightarrow$ CH_4 and N_2 $\rightarrow$ NH_3 conversions. However, the investigation of the kinetics of these conversions suggests that they are clearly inhibited due to the dramatically long conversion times which exceed by far the lifetime of the subdisk.

3 Evolution of the D/H ratio in water in the Uranian subnebula

Two different cases of deuterium enrichments (compared to protosolar D/H), can be found in the H_2O ices formed in the Uranian subnebula, each of them depending on the initial abundance of hydrogen. The enrichment factor f, defined as the ratio of D/H in deuterated water to D/H in hydrogen, is given by:

$$f = \frac{1/2}{1/2} \frac{\mathrm{HDO/H_2O}}{\mathrm{HD/H_2}}. \quad (1)$$

In the case of the *water-rich subnebula*, the main reservoir of deuterated molecule is H_2O. As a consequence of the weak abundance of hydrogen in the subdisk, the isotopic exchange in vapor phase with deuterated hydrogen molecules is restricted to a very limited amount of H_2O molecules. In such conditions, the global D/H enrichment in water ice is almost equal to the initial value present in the ices of the impactor before it collided with the proto-Uranus.

In the case of the *water-poor subnebula*, the situation is quite different because hydrogen is the most important deuterium reservoir in the subdisk. The enrichment factor $f(R,t)$ is thus obtained by integrating a diffusion equation [5, 6]. Our scenario implies that, at the time of the collision with the impactor, the temperature following the impact was high enough to decompose in elements all the volatiles presents in the expelled material. Therefore, if the molecules have been exclusively produced from the recombination of elements in the initially hot water-poor Uranian subnebula, there is no initial fractionation between D/H ratios in water and molecular hydrogen (f = 1). Setting $f(R)$ = 1 at t = 0 when integrating the diffusion equation reveals that, as shown on the figure, $f(R,t)$ never exceeds 1.3 at the level of the regular satellite system in the life of the water poor Uranian subnebula.

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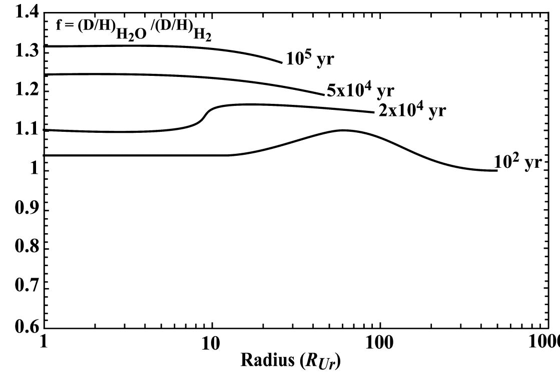

Figure 1: Calculated deuterium enrichment factor f in H_2O as a function of uranocentric distance R_{Ur}, at various epochs in years, in the case of the water poor subnebula. The initial enrichment factor $f(R) = f_0$ at t = 0 is equal to 1. The integration of the equation of diffusion is calculated until the condensation radius of water is reached. When condensation occurs, the value of the enrichment is fixed.

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