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Origin of Titan and its Atmosphere: New Lights from Cassini-Huygens

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Introduction

The origin of Titan and its atmosphere dominated by nitrogen and methane is still uncertain. A puzzling feature of the satellite's atmosphere is the non-detection of the primordial noble gases krypton and xenon by the Huygens probe, present in the atmosphere of Jupiter and presumably Saturn. The carbon monoxide to methane ratio is $\sim 10^{-3}$ in Titan's atmosphere, which also places a strong constraint on the satellite's origin, since carbon monoxide should have been more abundant than methane in the primitive nebula. Here we present a model for the origin of Titan consistent with these observations: Titan was formed from planetesimals initially produced in the primitive nebula that were partially devolatilized during their migration within Saturn's satellite-forming subnebula. In contrast with krypton and xenon which remained trapped, most of the carbon monoxide and argon was lost from icy planetesimals during their migration within the subnebula. The observed deficiency of Titan's atmosphere in krypton and xenon could result from various sequestration processes that may have occurred prior or after the satellite's completion. On the basis of our model, we predict that all regular satellites interiors to the orbit of Titan are depleted in primordial carbon monoxide and nitrogen.

Formation of ices in Saturn's feeding zone

The process by which volatiles are trapped in icy planetesimals, illustrated in Fig. 1, is calculated using the stability curves of hydrates, clathrates and pure condensates, and the thermodynamic path detailing the evolution of temperature and pressure at 10 AU. The cooling curve intercepts the stability curves of the different ices at some given temperature and pressure conditions. For each ice considered, the domain of stability is the region located below its corresponding stability curve. The clathration process stops when no more crystalline water ice is available to trap the volatile species. Note that, in the pressure conditions of the Solar nebula, CO_2 is the only species that crystallizes at a higher temperature than its associated clathrate. In addition, we have considered only the formation of pure ice of CH_3OH in our calculations since, to our best knowledge, no experimental data concerning the stability curve of its associated clathrate have been reported in the literature.

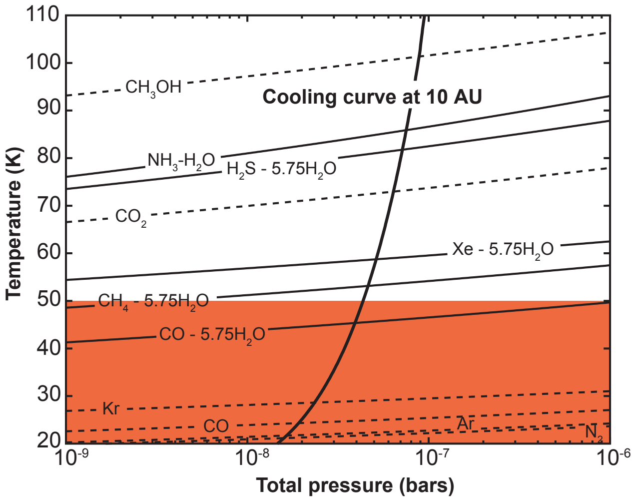

Figure 1: Stability curves of hydrate (NH_3-H_2O), clathrates (X-5.75H_2O) (solid lines), and pure condensates (dotted lines), and cooling curve of the Solar nebula at the heliocentric distance of 10 AU. Species remain in the gas phase above the stability curves. Below, they are trapped as clathrates or simply condense. The red area characterises the different ices heated to 50K during their migration and accretion in Saturn's subnebula to form proto-Titan. We assume that CO:CO_2:CH_3OH:CH_4 = 70:10:2:1 and N_2:NH_3 = 1:1 in the gas phase of the Solar nebula.

As a result of the assumed solar gas phase abundance for oxygen, Fig. 1 shows that ices formed in the outer Solar nebula are composed of a mix of clathrates, hydrates and pure condensates which are, except for CO_2 and CH_3OH, produced at temperatures ranging between 20 and 50 K. Once formed, the different ices agglomerated and incorporated into the growing planetesimals.

Multiple guest trapping in clathrates

We calculate here the relative abundances of guests that can be incorporated in H_2S, Xe and CH_4 dominated clathrates at the time of their formation in the Solar nebula. In our calculations, any volatile already trapped or condensed at a higher temperature than that of the considered clathrate is excluded from the coexisting gas phase composition. We use a statistical model which relates the macroscopic thermodynamic properties of clathrates to the molecular structure and interaction energies [1]. Table 1 gives the fraction of volatiles incorporated in H_2S, Xe and CH_4 dominated clathrates relative to their initial fraction available in the nebula gas. Our calculations show that CO, N_2 and Ar are poorly trapped in clathrates. On the other hand, we note that substantial amounts of Xe and Kr can be trapped in H_2S and CH_4 clathrates, respectively.

Table 1: Abundance of volatile i in clathrate relative to initial abundance at 10 AU in the nebula.

Species	H_2S clathrate	Xe clathrate	CH_4 clathrate
CO_2	1.6×10^{-6}	–	–
Xe	0.1424	–	–
CH_4	2.9×10^{-5}	1.1×10^{-5}	–
CO	1.5×10^{-8}	1.2×10^{-10}	2.3×10^{-5}
Kr	1.3×10^{-5}	8.5×10^{-7}	1.17
Ar	1.6×10^{-8}	6.4×10^{-11}	2.3×10^{-5}
N_2	1.6×10^{-7}	8.3×10^{-9}	3.0×10^{-4}

Partial devolatilization of the planetesimals that formed Titan

In order to yield Titan from the Saturn's accretion disk, we assume that solid material has been supplied essentially by direct transport of gas-coupled solids into the disk with the gas inflow during the first phase of the subnebula's evolution or by capture of heliocentrically orbiting solids as they pass through the disk [2,3]. Once embedded in the subnebula, planetesimals originating from Saturn's feeding zone can be altered if they encounter during their migration gas temperature and pressure conditions high enough to generate a loss of volatiles.

We favor this mechanism to explain the carbon monoxide and argon deficiencies in the atmosphere of Titan. Indeed, as Figure 1 shows, if planetesimals ultimately accreted by Titan experience intrinsic temperatures of $\sim$50 K during their migration in Saturn's subnebula, they are expected to release most of their argon and carbon monoxide. Note that, in this scenario, a higher sublimation temperature of planetesimals is excluded since it would imply the dissociation of methane clathrate from solids accreted by Titan, a result in conflict with the large abundance of methane in the satellite's atmosphere. On the other hand, since Kr and Xe are incorporated at higher temperatures than $\sim$50 K in clathrates produced in the nebula, they cannot be eliminated via the partial sublimation mechanism only.

However, several noble gases trapping processes, which occurred either in the solar nebula gas phase before the formation of solids ultimately accreted by Titan or at the satellite's surface, may explain the deficiencies of Kr and Xe observed in its atmosphere. In particular, it has been proposed that the presence of H_3^+ ion in the outer Solar nebula may induce the trapping of Xe and Kr in the form of stable complexes XH_3^+ (with X = Kr and Xe) [4,5]. Once formed, these complexes would remain stable, even at low temperature, and their presence in the outer nebula gas phase would induce the formation of Kr and Xe-poor bodies that are then delivered to Titan [5]. Alternatively, it has been shown that if large amounts of Kr and Xe were initially present in Titan's atmosphere, they could have been efficiently trapped as clathrates by crystalline water ice located on the satellite's surface [6]. It has been also proposed that the atmospheric noble gases of Titan could be removed by their trapping in its haze [7]. Hence, each of these two mechanisms would act as sinks of Xe and Kr in the atmosphere of Titan.

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