A PARTIAL SUBLIMATION OF THE PLANETESIMALS THAT FORMED TITAN.

O. Mousis[1], J. I. Lunine[2], C. Thomas[1], M. Pasek[2], U. Marboeuf[1], Y. Alibert[1], V. Ballenegger[1], Y. Ellinger[3], F. Pauzat[3] and S. Picaud[1], [1]Université de Franche-Comté, Institut UTINAM, CNRS-UMR 6213, France (olivier.mousis@obs-besancon.fr), [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, [3]Laboratoire de Chimie Théorique, CNRS-UMR 7616, Université Pierre et Marie Curie, France.

Introduction: The exploration of Titan by the *Cassini-Huygens* spacecraft has provided new constraints on its formation, as well as on the origin of Saturn's satellite system. The measurements made by the Gas Chromatograph Mass Spectrometer (GCMS) aboard the *Huygens* probe have confirmed that the atmosphere of Titan is dominated by N_2 and CH_4, with only a tiny abundance of CO, in agreement with previous determinations [1]. The abundance of Ar was also found to be very low and those of Kr and Xe were too weak to be determined [2]. These latter measurements are at odd with the detection of noble gases in the atmospheres of Mars and Venus [3,4], in some meteorites [5], and in the atmosphere of Jupiter, where their abundances are found to be over-solar [6].

We describe here a scenario of the formation of Titan matching the constraints derived from its atmospheric composition, as revealed by the *Huygens* probe. We propose that Titan was formed from icy planetesimals initially produced in the feeding zone of Saturn and that were partially vaporized during their migration/accretion in the subnebula [7]. The volatile fraction of these solids was formed from a mix of multiple guest clathrates, hydrates and pure condensates. Most of carbon monoxyde and argon were lost during the migration or accretion of planetesimals within the subnebula, due to the increasing temperature. The deficiency of Titan in krypton and xenon may result from either their trapping in the form of XH_3^+ complexes in the solar nebula gas phase prior their incorporation in the forming planetesimals [8], or from an efficient sink of these noble gases in clathrates located on the surface of Titan [9].

Formation of ices in the feeding zone of Saturn: We assume that the abundances of all elements, including oxygen, are solar [10] and consider both refractory and volatile components. Refractory components include rocks and organics. Rocks contain 23% of the total oxygen in the nebula [10]. The fractional abundance of organic carbon is assumed to be 55% of total carbon [11], and the ratio of C:O:N included in organics is supposed to be 1:0.5:0.12 [12]. 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 evolutionary tracks detailing the evolution of temperature and pressure at 10 AU for $CO:CO_2:CH_3OH:CH_4$ = 70:10:2:1 and $N_2:NH_3$ = 1:1 in the gas phase. S is only present as H_2S and other refractory sulfur components [13]. The cooling curve intercepts the stability curves of the different ices at some given temperature, pressure and surface density conditions. Note that, during the cooling of the Solar Nebula, CO_2 is the only species that crystallizes as a pure condensate prior to being trapped by water to form a clathrate hydrate. Hence, we assume here that solid CO_2 is the only existing condensed form of CO_2 in these environments. In addition, we have considered only the formation of pure ice of CH_3OH in our model since, to our best knowledge, no experimental data concerning the stability curve of its associated clathrate have been reported in the literature.

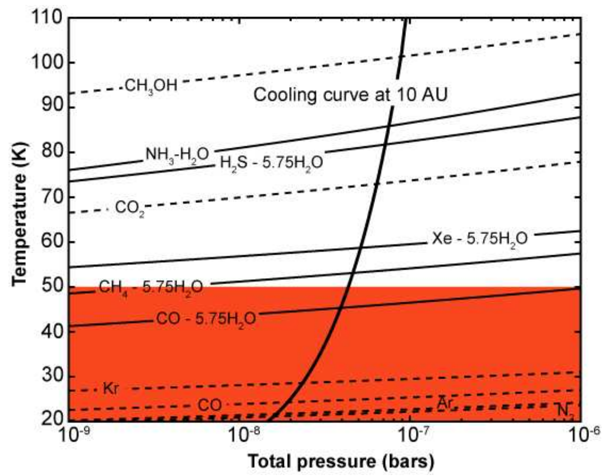

Figure 1: Stability curves of hydrate (NH_3-H_2O), clathrates (X-5.75H_2O) (solid lines), and pure condensates (dotted lines), and cooling curve of the Solar nebula at the heliocentric distance of 10 AU. Species remain in the gas phase above the stability curves. Below, they are trapped as clathrates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

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. As a result of the adoption of a solar gas phase abundance for oxygen, Fig. 1 shows that ices formed in the outer solar nebula are composed of a mix of clathrates and hydrates and pure condensates essentially produced at lower temperatures (but still greater than 20 K). Note that the abundances of volatiles observed in the envelopes of Jupiter and Saturn can be reproduced by using solar abundances for all elements in the Solar nebula, and that, with this assumption, the calculated amount of heavy elements remains in agreement with internal structure models [14].

We have quantified the fractions of other guests that can be trapped during the formation of H_2S, Xe and CH_4 clathrates in the nebula, with the use of a statistical thermodynamic model [15,9]. Our calculations show that CO, N_2 and Ar are poorly trapped in these structures. On the other hand, substantial amounts of Xe and Kr can be trapped in H_2S and CH_4 clathrates, respectively.

Partial sublimation of the planetesimals that formed Titan: Once embedded in the subnebula, the planetesimals originating from Saturn's feeding zone can be altered if temperature and pressure conditions within the subdisk are 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. Thus, as Fig. 1 shows, if planetesimals ultimately accreted by Titan experience intrinsic temperatures of the order of 50 K during their migration in Saturn's subnebula, they are expected to release most of their argon and carbon monoxyde. Note that, in this scenario, a higher sublimation temperature is excluded since it would imply the loss of methane from solids accreted by Titan.

Discussion: Since Kr and Xe are trapped at higher temperatures in clathrates produced in the nebula (see e.g. Fig. 1 and discussion about the trapping of Xe and Kr as supplementary guests in clathrates), they cannot be eliminated via the partial sublimation of planetesimals in Saturn's subnebula, in contrast with CO and Ar. However, additional processes that occurred either before or after the formation of Titan, combined with our scenario, may explain the deficiencies of Kr and Xe 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 XH_3^+ complexes (with X = Kr and Xe) [8]. Once formed, these complexes would remain stable [16], even at low temperature, and their presence in the outer nebula gas phase would induce the formation of noble gas-poor planetesimals that could ultimately take part to the formation of Titan. Alternatively, it has been shown that if large amounts of Kr and Xe were initially present in Titan's atmosphere, they could be efficiently trapped by clathrates located on the satellite's surface [9]. As such, clathrates would act as sinks of Xe and Kr on the surface of Titan.

References: [1] Gautier D. & Raulin F. (1997) *ESASP*, 1177, 359. [2] Niemann H. B. et al. (2005) *Nature*, 438, 779-784. [3] Biemann K. et al. (1976) *Science*, 194, 76-78. [4] Donahue T. M. et al. (1981) *Geophys. Res. Let.*, 8, 513-516. [5] Marty B. et al. (2006) *Meteor. Planet. Sci.*, 41, 739-748. [6] Owen T. et al. (1999) *Nature*, 402, 269-270. [7] Alibert Y. & Mousis O. (2007) *Astron. Astrophys.*, 465, 1051-1060. [8] Mousis O. et al. (2008) *Astrophys. J.*, in press. [9] Thomas C. et al. (2007) *Astron. Astrophys*. 474, L17-L20. [10] Lodders K . (2003) *Astrophys. J.*, 591, 1220-1247. [11] Pollack J. B. et al. (1994) *Astrophys. J.*, 421, 615-639. [12] Jessberger E. K. et al. (1988) *Nature*, 312, 691-695. [13] Pasek M. et al. (2005) *Icarus*, 175, 1-14. [14] Mousis O. et al. (2008) *Astrophys. J.*, to be submitted. [15] Lunine J. I. & Stevenson D. J. (1985) *Astrophys. J. Supp. Ser.*, 58, 493-531. [16] Pauzat F. & Ellinger Y (2007) *J. Chem. Phys.*, 127, 014308-014308-13.