

A DUAL ORIGIN FOR THE DEUTERIUM ENRICHMENT IN THE ATMOSPHERE OF TITAN. D. Cordier^{1,2}, O. Mousis³, J. I. Lunine⁴, and A. Moudens¹, ¹Institut de Physique de Rennes, CNRS-UMR 6627, Campus de Beaulieu, 35700 Rennes, France; ²Ecole Nationale Supérieure de Chimie de Rennes, Campus de Beaulieu, 35700 Rennes, France; ³Université de Franche-Comté, Institut UTINAM, CNRS-UMR 6213, France; ⁴Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: The interpretation of the D/H ratio measured in methane in the atmosphere of Titan is not straightforward. The most recent determination of D/H derived from Cassini/CIRS infrared spectra indicates values of the order of $1.32_{-0.11}^{+0.15} \times 10^{-4}$ [1], substantially higher than the protosolar value, namely the value in the hydrogen of the solar nebula, but less than the values in water in the Earth's oceans (SMOW) and in comets. The cause of this enhancement is still under some debate. It could be the result of isotopic exchange between methane and molecular hydrogen within the early Solar nebula, prior the formation of the icy planetesimals that were ultimately accreted by Titan [2]. An alternative interpretation suggests that the initial methane reservoir was larger than what is seen today in the atmosphere of Titan. The D/H enhancement would then result from atmospheric escape, photochemistry, and consequent isotopic fractionation [3,4]. In this work, we reinvestigate this latter scenario in light of the recent Cassini/CIRS determination of D/H [1]. We also use rate coefficients for methane loss reactions derived from recent photochemical models of the atmosphere of Titan [5].

Photochemical model: We define R as the ratio of the total mass of methane outgassed from the interior of Titan during a timescale τ to the current atmospheric mass of methane. R is related to the deuterium enrichment factor f via the following analytic relationship [3,4]:

$$R = f^{\frac{1}{1-q}}. \quad (1)$$

The D-enrichment factor f is defined as the ratio of D/H in the considered deuterated species to protosolar D/H ($(D/H)_{\text{protosolar}} = 2.35 \times 10^{-5}$). q is the ratio of k_2 over k_1 , namely the respective standard rate constants for CH_3D and CH_4 destruction, and has to be larger than 0.75, 1.0 being the limit value [3,4].

R can be independently expressed as follows [3,4]:

$$R \simeq \frac{g m_{\text{CH}_4} F \tau}{x_{\text{CH}_4}^{(s)} P^{(s)}} \quad (2)$$

where g is the Titan's surface gravity, m_{CH_4} the mass of a methane molecule, $x_{\text{CH}_4}^{(s)}$ the methane

surface mole fraction [9] and $P^{(s)}$ the pressure at the surface of Titan. The quantity F is the net rate of destruction of CH_4 referred to the Titan's surface ($F = 4.8 \times 10^{13} \text{ m}^{-2}\text{s}^{-1}$ [5]).

Figure 1 shows that, assuming no initial deuterium enrichment in methane, its destruction rate is not efficient enough to allow a sufficient increase of the atmospheric D/H to match the observed one, even if an outgassing timescale of 4.5 Gyr is considered. A higher D/H ratio than the protosolar value must then be advocated in the methane of Titan prior its outgassing from the crust, in order to explain the observed one. Following the different outgassing scenarios, a range of values of the initial D-enrichment f_0 can be determined. If the atmospheric methane of Titan is replenished since 4.5 Gyr from the interior, the initial D-enrichment f_0 must be at least of ~ 2 for $q = 0.75$. On the other hand, if the actual atmospheric methane of Titan results from a more recent outgassing event [6], the required initial D-enrichment f_0 should be somewhat higher. For example, assuming that the methane of Titan is replenished since 0.6 Gyr only [6], the minimum initial D-enrichment f_0 is ~ 3 for $q = 0.75$.

Discussion: An appropriated mechanism to explain the [1.9–3.1] minimum range of values for the initial D-enrichment acquired by the methane reservoir in Titan is the isotopic thermal exchange of molecular hydrogen with CH_3D in the gas phase of the solar nebula. In this case, CH_3D originates from interstellar methane highly D-enriched ices that vaporized when entering the nebula [2]. During the cooling of the nebula, methane was subsequently trapped in crystalline ices around 10 AU in the form of clathrates formed at about 60 K, and incorporated into planetesimals that took part to the formation of Titan [7,8]. The atmospheric methane of Titan, owning the D/H ratio acquired in the Solar nebula, subsequently outgassed from the decomposition of the clathrates located in the interior.

We conclude that the two afore-mentioned D-enrichment processes, namely the isotopic fractionation in the atmosphere of Titan and the isotopic exchange in the Solar nebula, are complementary to explain the observed D/H value in methane.

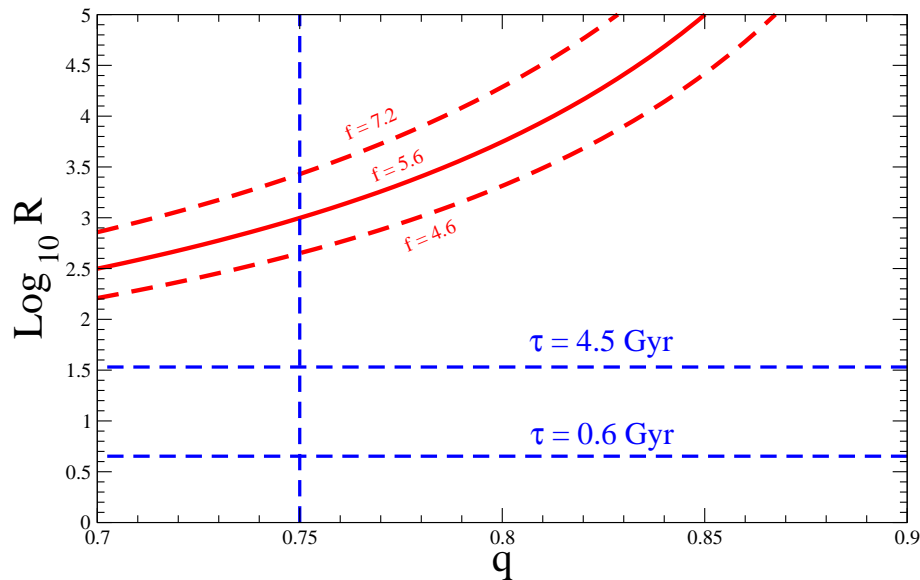


Figure 1: The atmosphere of Titan: fractionation of deuterium in methane photochemistry. Drawn is R the ratio of the total mass of methane outgassed from the interior of Titan during a timescale τ to the current atmospheric mass of methane, as a function of the relative dissociation rates q of deuterated and normal methane. The solid curve corresponds to the central value derived from Cassini/CIRS and the dashed curves are related to extreme values obtained when uncertainties are taken into account [1]. The horizontal lines show estimations for R from Eq. 2 in cases of two assumptions: $\tau = 4.5$ Gyr and $\tau = 0.6$ Gyr. The vertical line at $q = 0.75$ indicates the lower limit of the allowed range for q .

The relative importance of these two mechanisms depends on the epoch from which started the actual outgassing event.

Acknowledgements: This work was supported in part by the French Centre National d'Etudes Spatiales.

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