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D/H ratio of Titan and Enceladus atmospheres: some cosmochemical conclusions for moon's formation

V. A. Dorofeeeva
Vernadsky Institute of Geochemistry and Analytical Chemistry RAS, Moscow
dorofeeva@geokhi.ru

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«Cassini-Huygens» spacecrafts in 2005-2010 performed the detailed studies of the Saturnian moon system. The quantitative data were firstly obtained in relation to the atmospheric and isotopic composition of Titan atmosphere along with new «Cassini» discovered Enceladus aqueous plumes. It was found the Titan atmosphere consisting of only two macrocomponents: $N_2 \geq 95$ mol. % ($^{15}N/^{14}N = 5.99\times10^{-3}$) [*Owen, Niemann,* 2009] and CH_4, the latter being about 1% at 50 km altitude and as high as 5% near the moon surface [*Niemann*, 2005]. D/H ratio of molecular $CH_4 = 1.58\times10^{-4}$ [*Abbas et al.,* 2010] showed extraordinary agreement with the standard D/H value of terrestrial oceanic water = 1.56×10^{-4} (VSMOW-Vienna Standard Mean Ocean Water) as well as with D/H in hydroxile (OH^-) of carbonaceous chondrites (mean D/H value varies from 1.3×10^{-4} up to 1.7×10^{-4} [*Robert*, 2006]). At the same time D/H value in molecular hydrogen of the Enceladus aqueous plumes was found as $2.9^{+1.5}_{-0.7}\times10^{-4}$ [*Waite et al.*, 2009] being near to D/H of five comets (from $(2.9\pm1)\times10^{-4}$ up to $(4.7\pm1.1)\times10^{-4}$ [*Villanueva et al.*, 2009]) (Fig. 1).

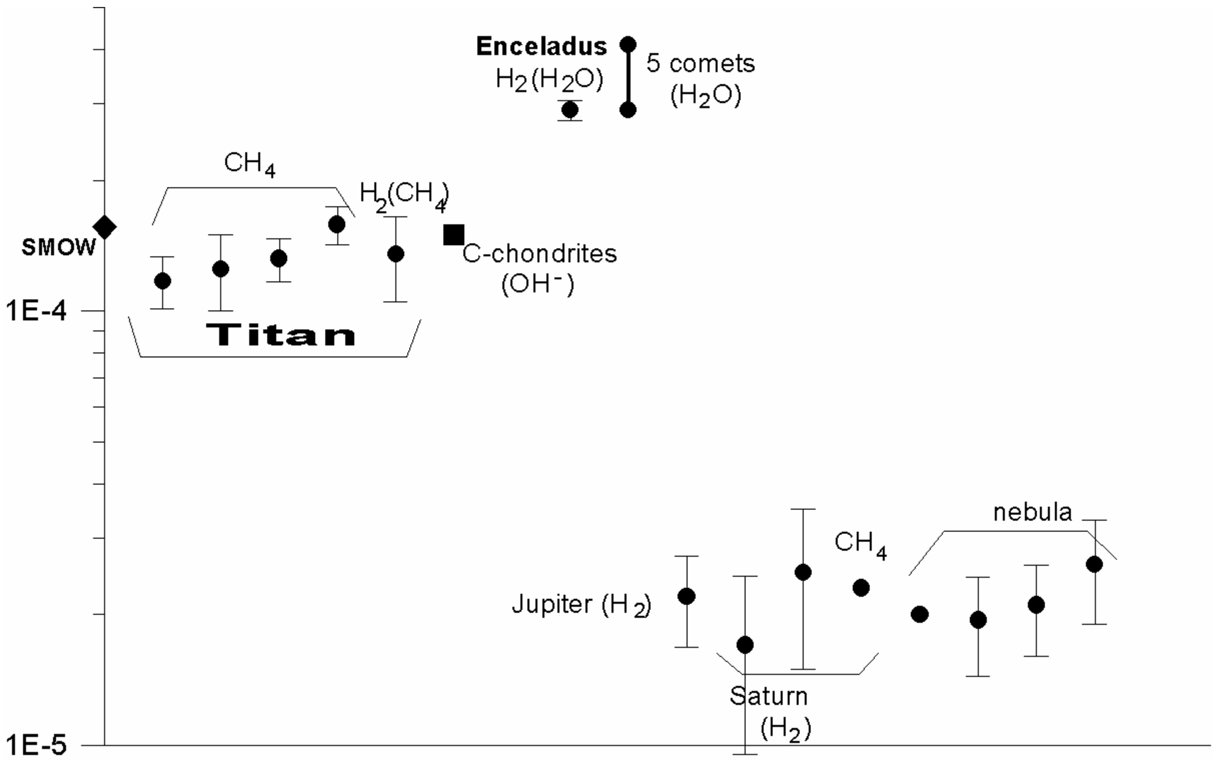

Fig. 1. D/H ratios of some Solar system objects.

It should be noted that above mentioned H_2 is interpreted as a product of H_2O molecule dissociation.

Before the «Cassini» new data were obtained, it was abundantly assumed that ice planetesimals formed in the nebula (solar gas-dust protoplanetary disc), could serve as a source of volatiles for all Jovian and Saturnian moons including Titan and Enceladus. Such planetesimals were assumed to contain rock component, H_2O and CO_2 ice as well as some other gases in a form of solid clathrates which could be formed in the process of appropriate nebular regions cooling up to temperature lower then ~ 80 K. The contemporary bulk elemental and isotopic composition of Jovian and Saturnian atmospheres could be in some sense analogous to their "ancient" composition. But in any case the relations between the main volatile elements, such as C, N, O, incorporated in various chemical compounds (NH_3:N_2; CH_4:CO:CO_2) as well as carbon fraction in the solid organic matter was remained undetectable. The clathrate composition of the ice planetesimals also was undistinguished. Some volatiles were dissipated from the Saturnian protosatellite disc (sub-nebular) but the experimental data indicating to the appropriate thermodynamical conditions are absent. All these circumstances make the problem of regular Saturnian satellite system origin to be highly complicated. New information on the hydrogen isotopic composition of Titan and Enceladus atmospheres is just very valuable in such matter.

The Titan atmosphere is characterized by the absence of heavy noble gases (Xe and Kr), as their clathrates could be formed in the protoplanetary disc only at $T \leq 60$K. This peculiarity imposes the constraints to the molecular nitrogen formation in the Titan atmosphere. It is known that nitrogen clathrate formation temperature is very low ($T \leq 40$K). Such temperatures were likely not achieved in the feeding zone" of the Titan ice-rock planetesimals, so the most probable nitrogen source in the Titan atmosphere could be only the ammonium clathrate ($NH_3 \cdot H_2O$).

The are two main hypotheses of CH_4 origin in the Titan atmosphere, the former being the second abundant atmospheric component. (1) CH_4 could be formed as the product of interaction of CO_2 dissolved in water with the hydrogen. It is assumed that CO_2 could be considered as one of probable carbon-bearing phases accreted by Titan. The hydrogen could be evolved as a product of silicate interaction with aqueous solutions (serpentinisation reaction). (2) The thermodynamical conditions of the nebula and the Saturnian sub-nebula allowed to accrete CH_4 as well as CO_2, the former being introduced to the satellite atmosphere.

The agreement of D/H values of CH_4 in Titan atmosphere with that of SMOW hardly could be occasional, thus water should be involved in methane formation, so the first version is mostly plausible and CO_2 could be assumed as a source of methane. This conclusion leads to another consequence: H_2O ice in the Solar disc (nebula) was evaporated in the space in the region up to $r \sim 10$ A.U. if even not to longer radial distances. It could be very probable that D/H values in water molecules primarily being near to the comet ratios varied as a result of isotopic exchange with the molecular hydrogen, the isotopic composition of the latter being near to the Jovian (Fig. 1). As a result the newly detected D/H values are peculiar of the inner planetary regions ($r \leq 10$ A.U.). This conclusion could be supported by the computer modeling of the protoplanetary disc inner structure (Dorofeeva, Makalkin, 2004). According to this study water existed in gaseous phase even at the Saturnian radial distance as a product of the probable proceeding of the reaction:

$$HDO + H_2 = H_2O + DH$$

H_2O ice incorporated in Enceladus was presumably not evaporated, thus Enceladus was presumably formed not within the Saturnian protosatellite disc but in the Solar nebula at the radial distances above 10-15 A.U.. The temperature of this region was substantially lower, so the Enceladus could be accrete some more fugitive gases than H_2O and CO_2 in a form of clathrates. The absence of Kr and Xe in the Enceladus water plumes is highly surprising and it is difficult to explain this phenomenon.

New «Cassini-Huygens» data on the hydrogen isotopic composition of the Titan atmosphere and Enceladus water plumes are compared with the analogous information on CI-chondrites, SMOW value, comets, Jovian and Saturnian atmospheres. It is shown that H_2O molecules could be considered as the most probable hydrogen source of the Titan atmospheric CH_4 and the Enceladus water plumes. This water probably was accreted in a form of ice in the process of proto-satellite body formation. We assume that the Enceladus water ice in contrast to that of Titan was formed at the radial distance above 10-15 A.U. where it could not be evaporated and accreted in the amorphous state. This conclusion was performed at the base of contemporary estimates of the characteristic time intervals of gas-dust disc evolution around the solar type stars, as well as the same values of planetesimals formation and differentiation within the outer part of the Solar nebula and models of thermal and dynamical conditions of the Saturnian sub-disc.

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