EPSC Abstracts,
Vol. 4, EPSC2009-611-3, 2009
European Planetary Science Congress,


# Formation conditions of Enceladus and origin of its methane reservoir

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## Abstract

We describe a formation scenario of Enceladus in which, similarly to Titan [1], the satellite formed from icy planetesimals that were partly devolatilized during their migration within the Kronian subnebula. In our scenario, at least primordial Ar, CO and $N_2$ were devolatilized from planetesimals during their drift within the subnebula, due to the increasing temperature and pressure conditions of the gas phase. The origin of methane is still uncertain since it might have been either trapped in the planetesimals of Enceladus during their formation in the solar nebula or produced via hydrothermal reactions in the satellite's interior. If the methane of Enceladus originates from the solar nebula, then Xe/$H_2O$ and Kr/$H_2O$ ratios are predicted to be equal to $\sim 7 \times 10^{-7}$ and $7 \times 10^{-6}$ in the satellite's interior. On the other hand, if the methane of Enceladus results from hydrothermal reactions, then Kr/$H_2O$ should not exceed $\sim 10^{-10}$ and Xe/$H_2O$ should range between $\sim 1 \times 10^{-7}$ and $7 \times 10^{-7}$ in the satellite's interior. Future spacecraft missions, such as *Titan Saturn System Mission*, will have the capability to bring new insights on the origin of Enceladus by testing these observational predictions.

## Introduction

We propose that Enceladus formed from icy planetesimals initially produced in the solar nebula that, once embedded in the subnebula of Saturn, have been partly devolatilized due to the increasing gas temperature and pressure conditions during their migration inwards the subdisk. Here, we aim at providing observational tests that may allow characterization of the importance of the devolatilization undergone by the building blocks of Enceladus during their migration within Saturn's subnebula. Our attention is focused on the origin of $CH_4$, which is directly tied to the magnitude of this devolatilization. We show that the fractions of Kr and Xe trapped in the interior of Enceladus can vary as a function of the $CH_4$ origin, i.e. trapping in the solar nebula or production via serpentinization reactions in the interior of Enceladus. This is because these noble gases have the ability to be incorporated in $H_2S$- and $CH_4$- dominated clathrates initially trapped in the building blocks of Enceladus at the time of their formation.

## Formation of Enceladus' building blocks

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 9.5 AU in the solar nebula, corresponding to the actual position of Saturn. The cooling curve intercepts the equilibrium curves of the different ices at particular temperatures and pressures. For each ice considered, the domain of stability is the region located below its corresponding equilibrium curve. The clathration process stops when no more crystalline water ice is available to trap the volatile species. As a result of the assumed solar gas phase abundance for oxygen, ices formed in the outer solar nebula are composed of a mix of clathrates, hydrates and pure condensates. Once formed, the different ices agglomerated and incorporated into the growing planetesimals.

## Noble gases trapping in Enceladus as a function of methane incorporation

Here, we investigate the fraction of noble gases that can be incorporated in Enceladus at the time of its formation, provided that Ar, Kr and Xe were in solar abundances in the initial gas phase of Saturn's feeding zone. These results can be useful to constrain the formation of Enceladus because the nature of the trapped species in the interior of the satellite will depend on the temperature at which its building blocks have been devolatilized within the subdisk. We have determined the fraction $F_i$ of volatiles incorporated in $H_2S$, Xe and $CH_4$ dominated clathrates relative to their initial fraction available in the nebula gas [1]. Our calcu-

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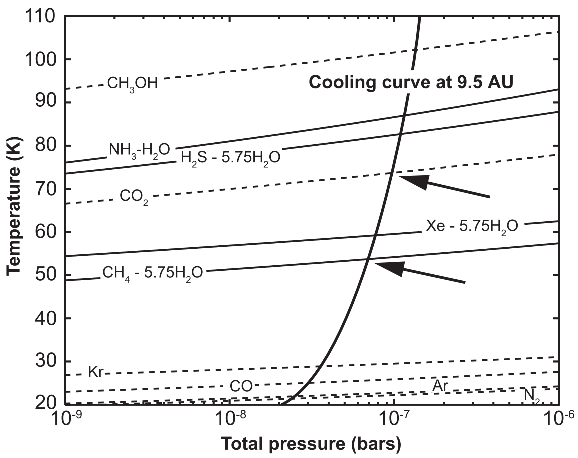


Figure 1: *Formation sequence of the different ices in Saturn's feeding zone.* The bottom and top arrow designate respectively the maximum temperatures at which the building blocks of Enceladus can be heated during their migration within the Saturn's subnebula if methane observed in the plumes is primordial or if it is produced in the satellite.

lations show that CO, $N_2$ and Ar are poorly trapped in clathrates because their relative abundances in these structures are orders-of-magnitude lower than those found in the solar nebula. On the other hand, substantial amounts of Xe and Kr are trapped in $H_2S$- and $CH_4$-dominated clathrates, respectively. In particular, because the Kr/$CH_4$ ratio is larger in $CH_4$-dominated clathrate than in the solar nebula ($F_{\rm Kr} > 1$), most of Kr is incorporated in this clathrate, thus preventing the formation of its pure condensate at lower temperature.

Two different maximum devolatilization temperatures can be envisaged for the building blocks of Enceladus. In the first case, similarly to Titan we assume that the methane detected in the plumes is primordial. This corresponds to the hypothesis that the devolatilization temperature of planetesimals never exceeded $\sim 50$ K during their drift within the subdisk. In the second case, we assume that methane is not primordial and has been produced in the interior of the satellite. Here, the maximum devolatilization temperature is then of $\sim 75$ K because a higher value would not be compatible with the presence of primordial $CO_2$ in Enceladus (see Fig. 1). In the first case, we infer that Xe/$H_2O$ and Kr/$H_2O$ ratios are respectively equal to $\sim 7 \times 10^{-7}$ and $7 \times 10^{-6}$ in Enceladus if methane is primordial. In the second case, Kr/$H_2O$ should not be higher than $\sim 10^{-10}$ in Enceladus because $CH_4$-dominated clathrates have been dissociated during the migration of the planetesimals within the subdisk. On the other hand, depending on the value of the devolatilization temperature of planetesimals, which translates into the preservation or not of the Xe-dominated clathrates, the Xe/$H_2O$ ratio in Enceladus should range between $\sim 1 \times 10^{-7}$ and $7 \times 10^{-7}$.

## Discussion

Recent INMS measurements during the October 9, 2008 encounter with the best signal quality to date have shown no clear sign of Kr in the Enceladus' plume. Instrument sensitivity and observed signal-to-noise constrain the determination of Kr/$H_2O$ to an upper limit of $< 10^{-5}$. However, subsequent encounters with Enceladus' plume may enhance the signal-to-noise to a level at which Kr can be identified without ambiguity. On the other hand, the INMS instrument is unable to directly measure Xe as its observable mass range is capped at 100 Da. This measurement will have to wait for a future spacecraft mission, such as the *Titan Saturn System Mission* actually studied by NASA and ESA.

## References

[1] Mousis, O., et al. 2009, *The Astrophysical Journal*, 691, 1780–1786.