Key Atmospheric Signatures for Identifying the Source Reservoirs of Volatiles in Uranus and Neptune

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EGU 2020

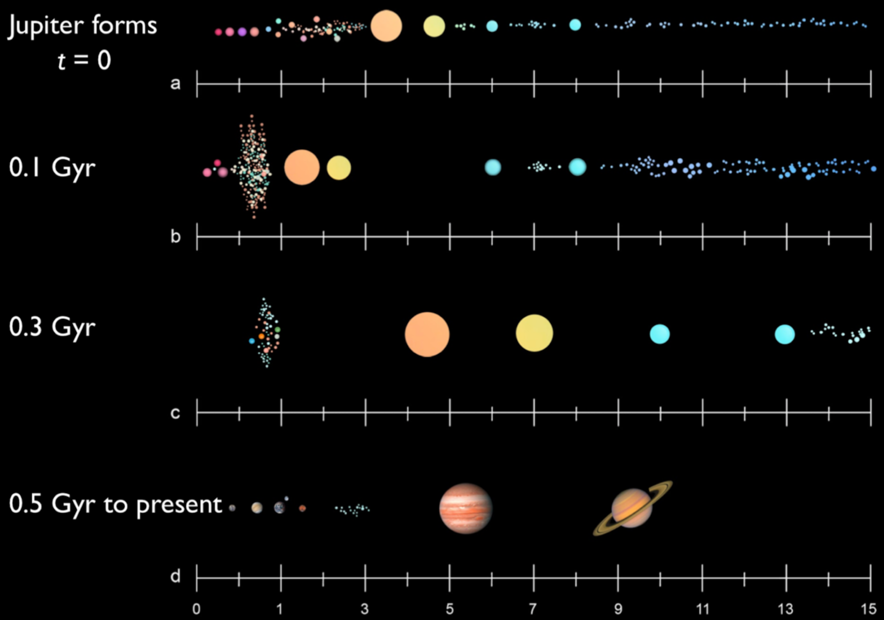
07 May 2020

IMPORTANCE OF KEY ELEMENTAL AND ISOTOPIC COMPOSITION MEASUREMENTS

- Giant planets have played a **significant role in shaping the architecture of our planetary system and the evolution of the smaller, inner worlds**.

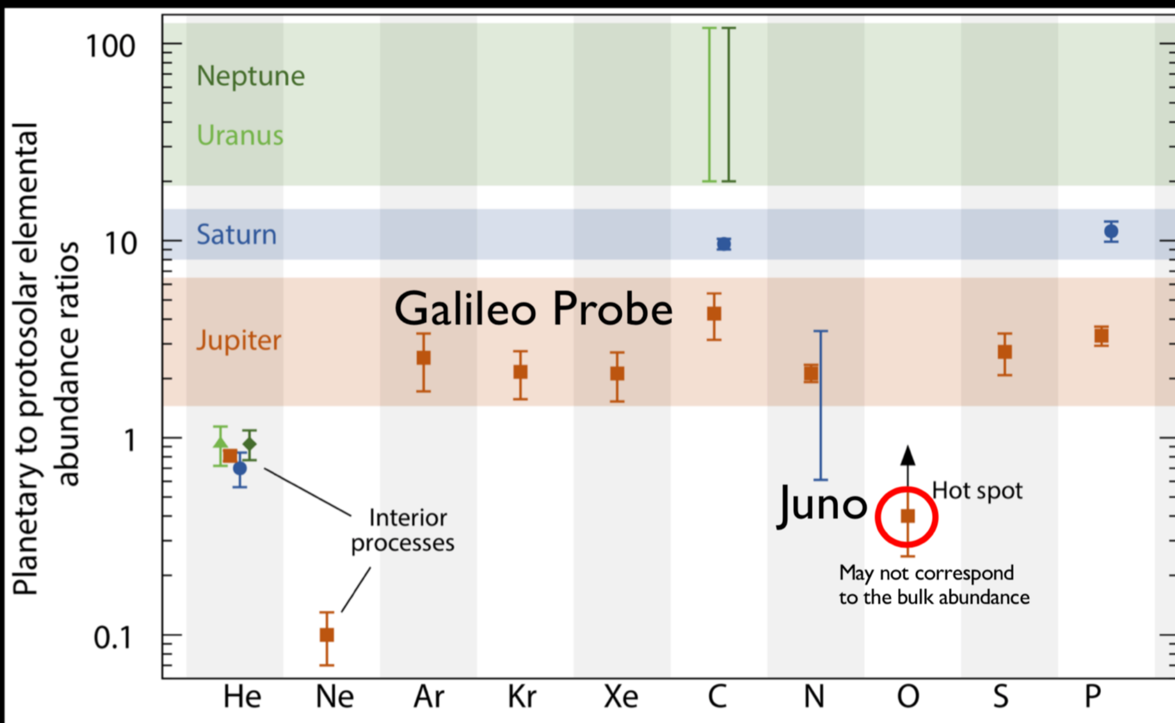
- Elemental and isotopic composition measurements allow to retrieve the history of the formation/migration of giant planets starting from the protosolar nebula, and the effects of their migration on the overall architecture of the solar system.

Planet Migration & Scattering in the Early Solar System



Grand Tack model
(Walsh et al. 2011; Batygin & Laughlin 2015)

ADVANTAGES OF IN SITU MEASUREMENTS



Atreya et al. (2018), Mousis et al. (2018)

Delivery of Volatiles to the Giant Planets – Solids

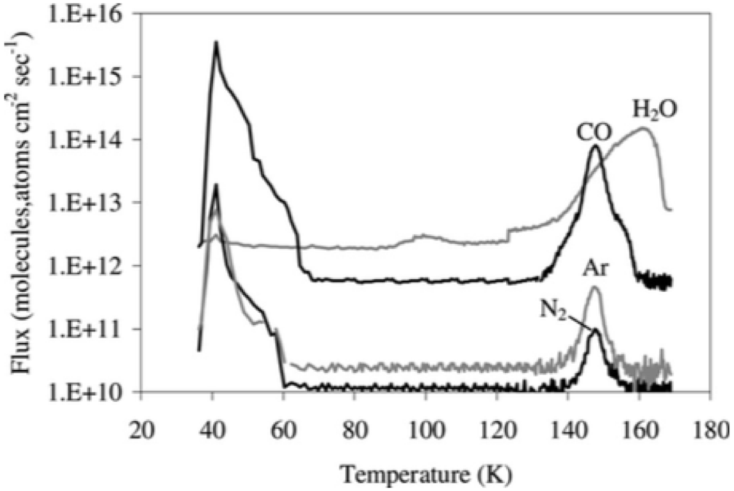
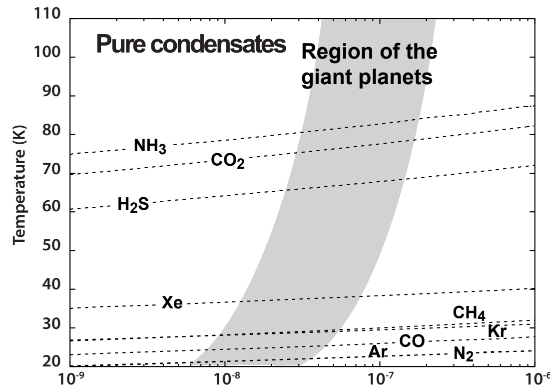


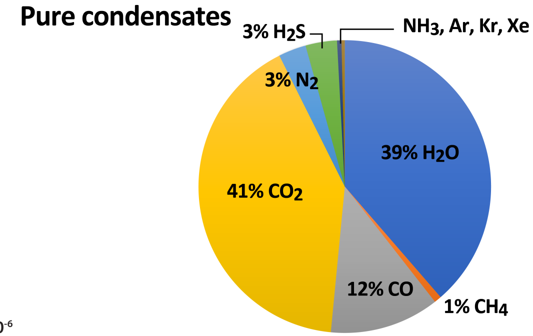
Fig. 1. A plot of the fluxes of evolved CO, N_2, Ar and water during warming up of 0.1 μm ice layer. The gas-laden ice was deposited at 27 K from a H_2O:CO:N_2:Ar = 100:100:14:1, at a rate of 5×10^{-4} μm min^{-1}. At 35–65 K the gas frozen on the ice sublimates. The internally trapped gases are released at 135–160 K during the transformation of the amorphous ice into a high viscosity "liquid" with cubic domains.

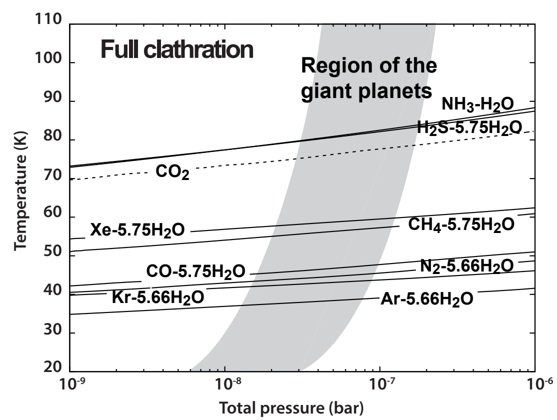
Amorphous ice

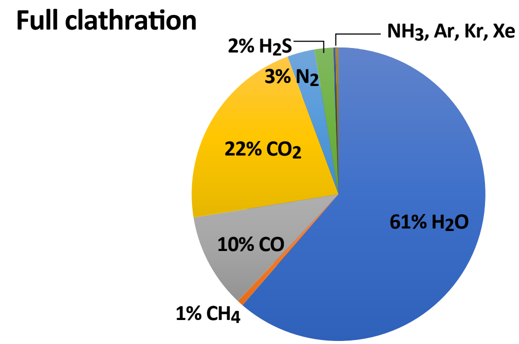
Owen et al. (1999),

Bar-Nun et al. (2007)





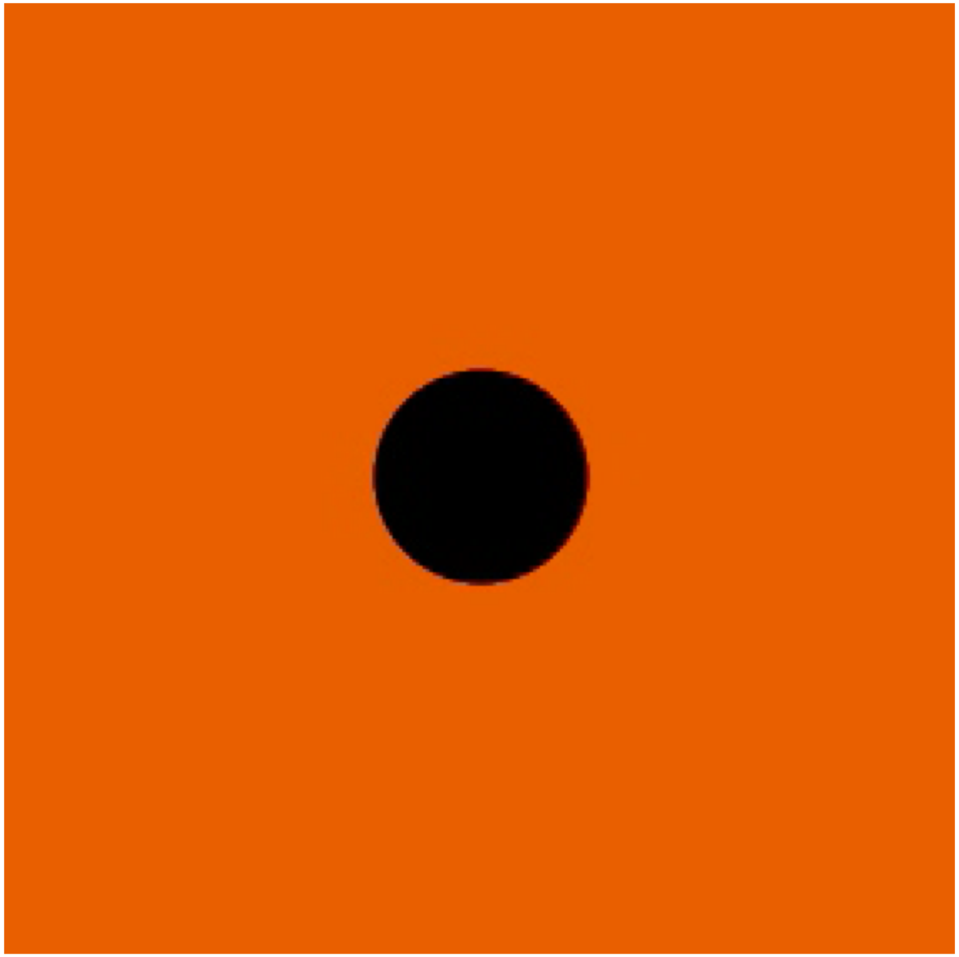




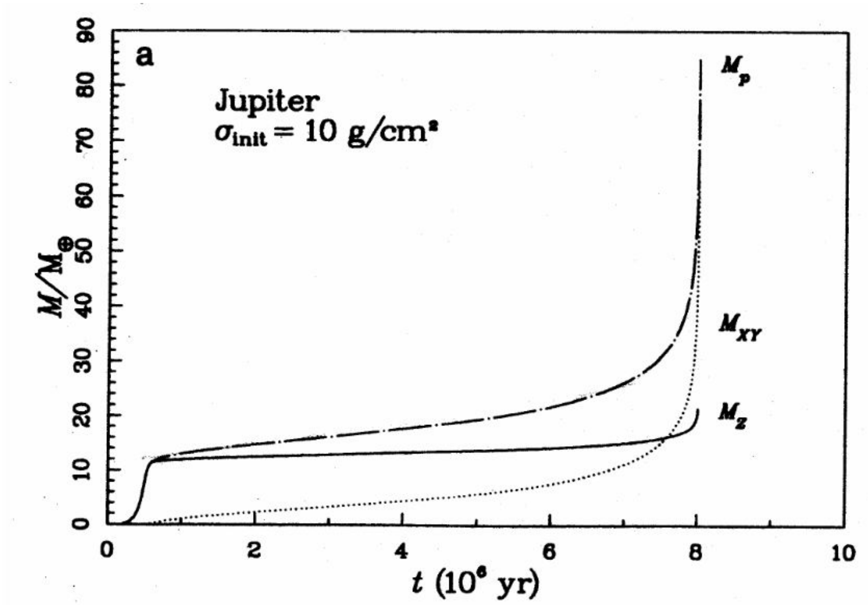
Clathrates + pure condensates

Gautier et al. (2001), Mousis et al. (2009, 2012)

Gas opening and consequence for the accretion of pebbles/planetesimals



Crédit. F. Masset

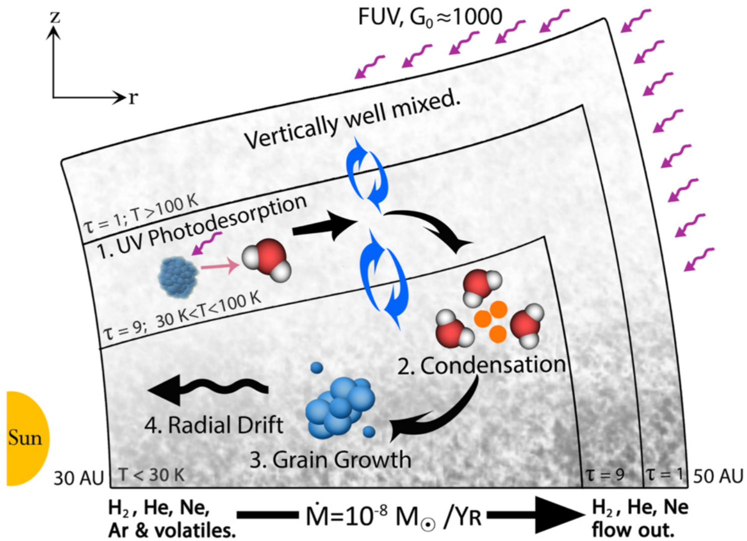


Pollack et al. (1996)

Gap formation halts the accretion of pebbles -> Giant planets supersolar metallicities cannot be acquired during the growth of the envelope!!

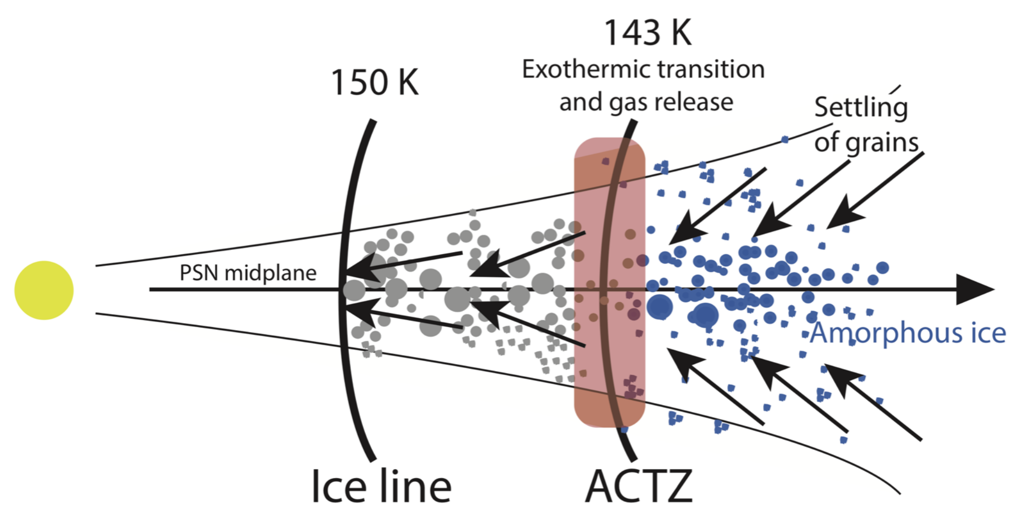
(Lambrechts & Johansen 2014)

Delivery of Volatiles to the Giant Planets – Vapors

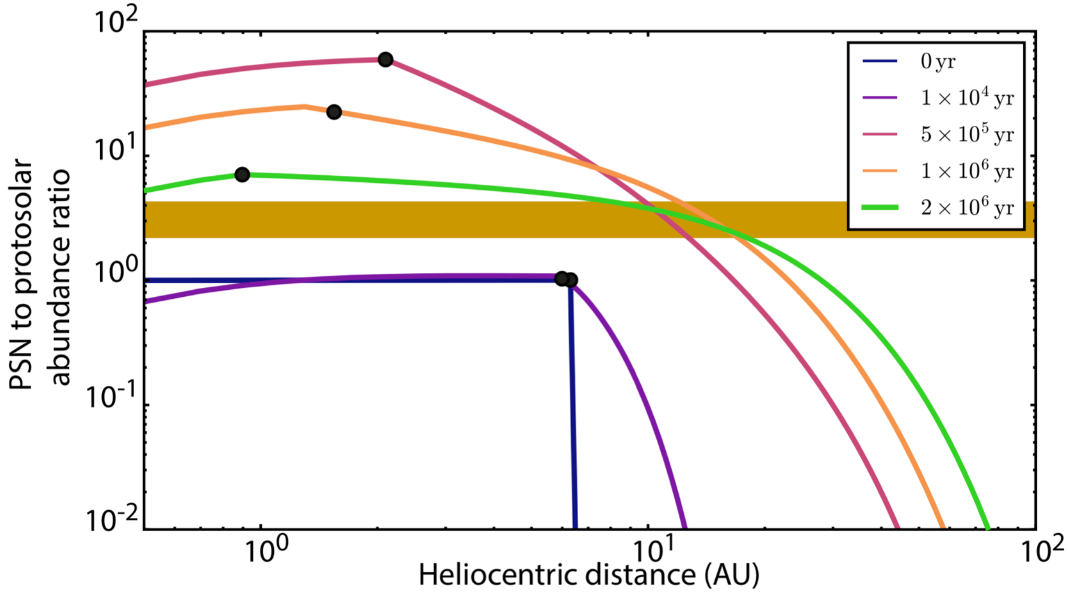


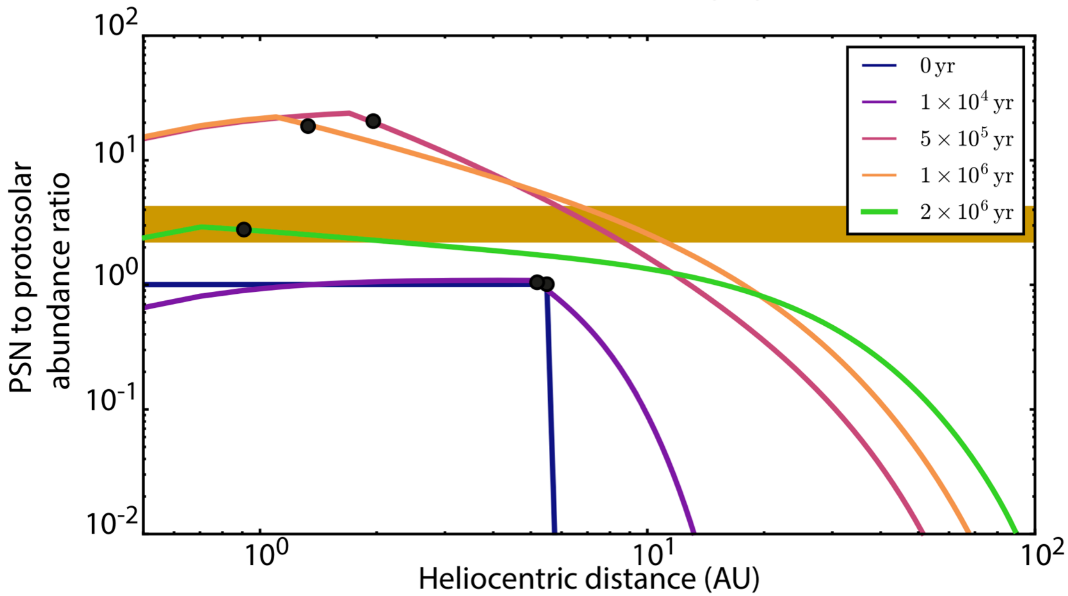
Production of **amorphous ice** via photoevaporation (Monga & Desch 2015)

Release of volatiles at the ACTZ
(Mousis, Ronnet, & Lunine 2019)



Release of volatiles from the ACTZ: delivery of enriched gases vs protosolar toward Jupiter's formation zone

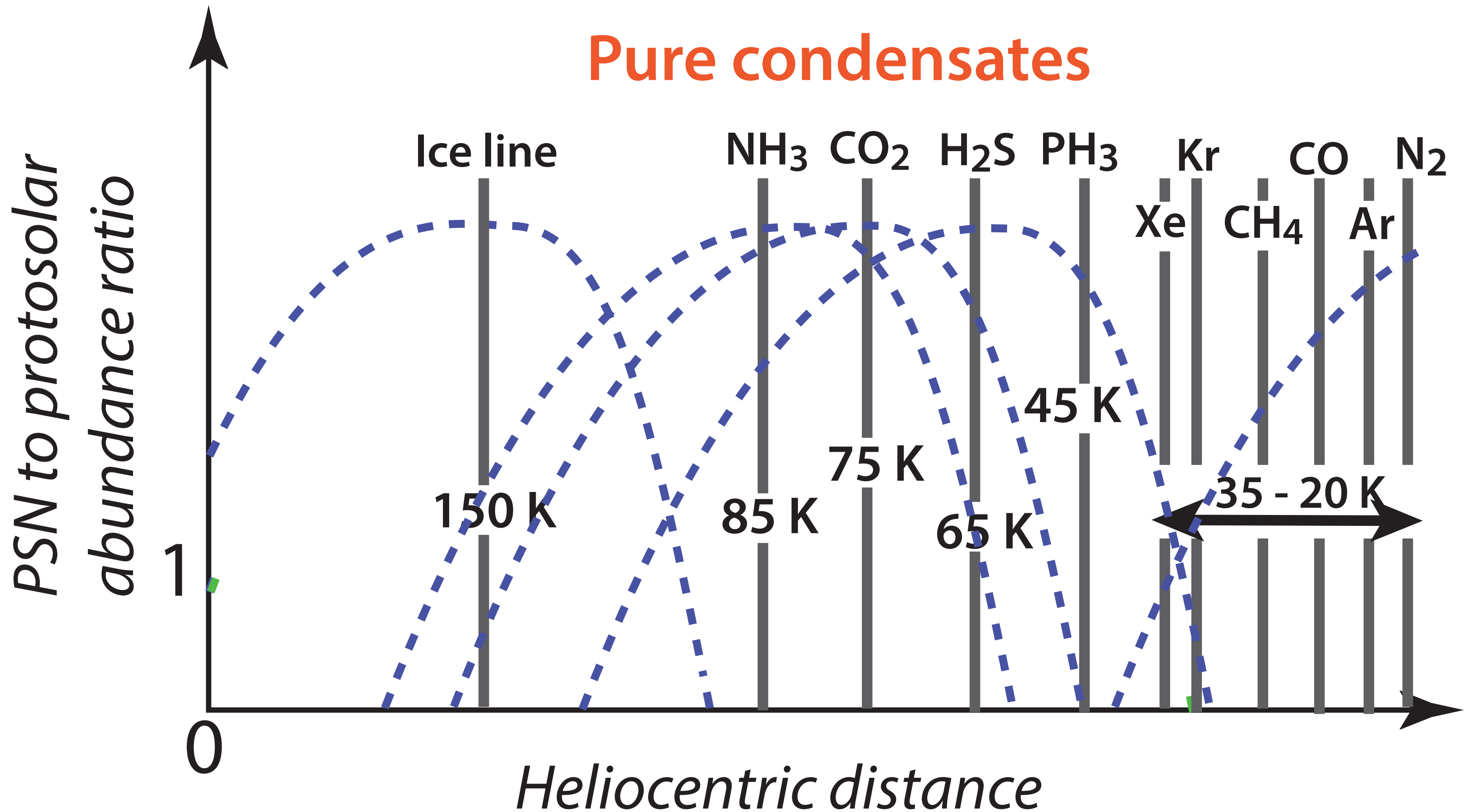




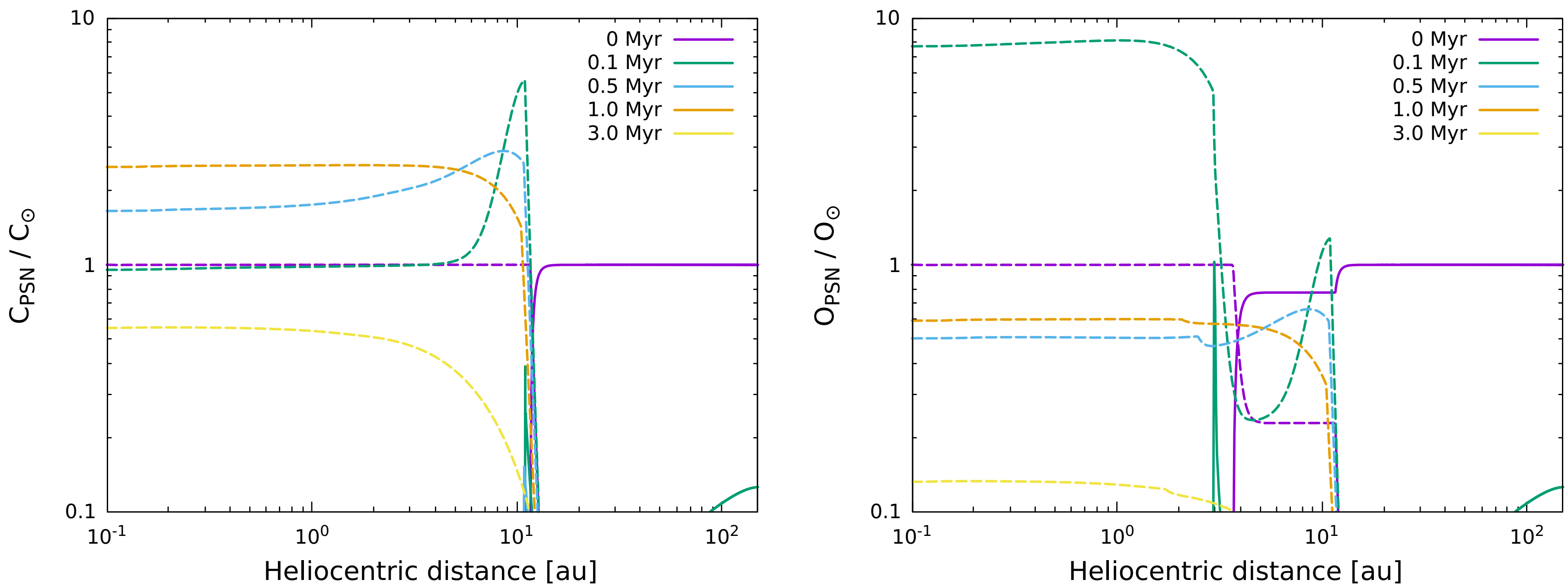
Evolution of the disk's gas phase metallicity

Mousis, Ronnet & Lunine (2019)

Release of volatiles from various snowlines: the case of pure condensates



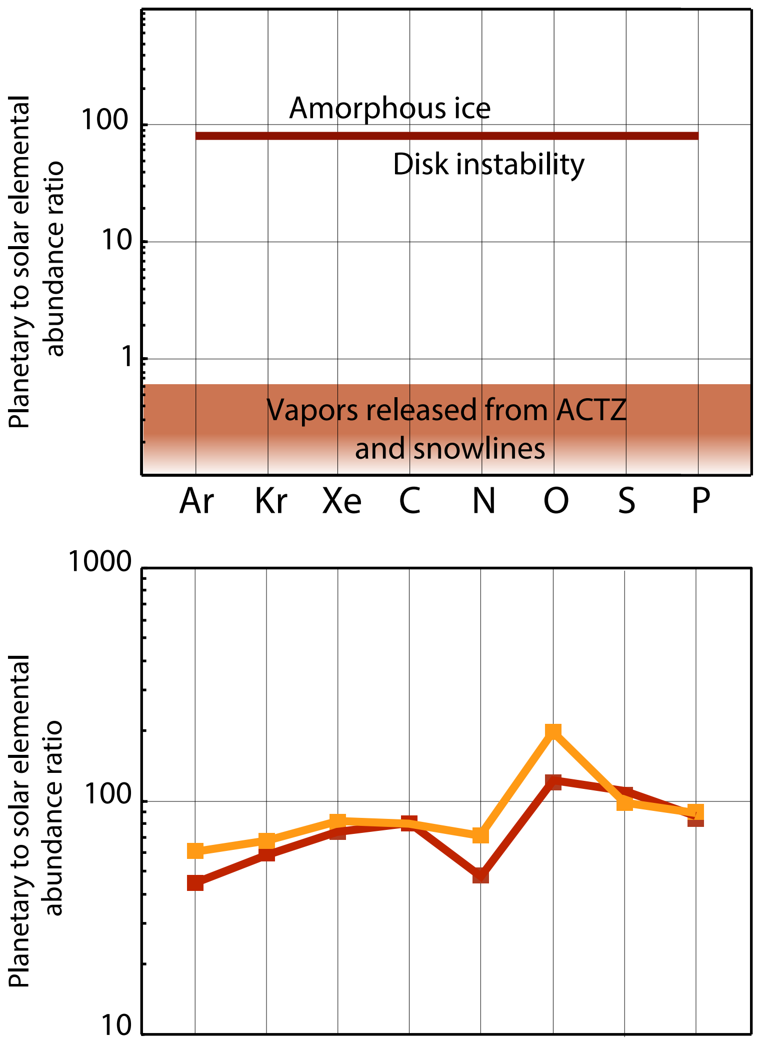
Release of volatiles from various snowlines: the case of pure condensates



Time evolution of radial profiles of C (left panel) and O (right panel) in the PSN, normalized to their respective protosolar abundances. Solid and dashed lines are used to identify the trace species in solid and gaseous phases, respectively.

Mousis et al. (2020), SSRv

Signatures of the different scenarios of volatiles delivery in the envelopes of Uranus and Neptune



Mousis et al. (2020)

Assumptions of i) homogeneous mixing and ii) measured C abundances are representatives of the bulk values.

Calibration is done on a C abundance assumed to be 80 times protosolar.

<u>Top panel:</u> volatiles delivered via disk instability or amorphous planetesimals in the framework of the core accretion model Volatiles delivered as vapors desorbed from the ACTZ or resulting from the sublimation of pure condensates at their respective snowlines display subsolar abundances in the envelopes.

<u>Bottom panel:</u> atmospheric signatures of volatiles accreted in the ice giants in forms of pure condensates (red lines) or clathrates (orange lines).

Conclusions

- There is no unique scenario of delivery of volatiles to the giant planets
- Volatiles may be supplied to the giant planets in solid form, gaseous form, or in both forms!
- The in situ measurement of the noble gases in Uranus and Neptune should, in principle, shed light on the delivery mechanisms that were at play during formation
- The delivery mechanisms that were at work in the cases of Jupiter and Saturn may have been different from those in the cases of Uranus and Neptune –> link between the mass of the planet and gap formation