Thesis subject

Laboratory: Laboratoire d'Astrophysique de Marseille

Thesis supervisor: Olivier Mousis

Title of the thesis subject: Investigating the Primordial Composition and Evolution of the Hydrospheres of the Galilean Moons

Description of the thesis subject:

Research Objectives

The primary objective of this PhD thesis is to assess the primordial composition of the hydrospheres of the Galilean moons in the context of the ESA JUICE and NASA Europa-Clipper missions. The term "primordial hydrosphere" refers to the reservoir comprising all volatile species incorporated by these moons during their formation, prior to subsequent evolution via exchange or alteration processes. This study aims to provide a comprehensive understanding of the initial volatile content of these bodies, offering insights for subsequent investigations into their geological and chemical evolution. To achieve this, the research will address the following tasks:

1. Determination of Volatile Content in Jupiter's Feeding Zone: using advanced disk and transport models, this task will focus on deriving the volatile composition of solids that condensed in Jupiter's feeding zone, both beyond and below the snowline (Aguichine et al., 2022; Mousis et al., 2023).

2. Exploration of Density Gradients Among the Galilean Moons: Simulations will assess how the volatile content of solids can explain the observed density variations among the Galilean moons. Particular attention will be given to Io's volatile depletion and Callisto's approximately 50% volatile content.

3. Alternative Formation Scenarios: This task will evaluate whether the moons formed from similar initial building blocks, with density gradients shaped by atmospheric escape driven by high-energy impacts during accretion. This scenario will consider the implications of atmospheric instability on the moons' hydrosphere stability and volatile retention.

Data from the Juno mission, including measurements of the oxygen-to-nitrogen ratio in Jupiter's atmosphere (Li et al., 2024) and elemental abundances from previous missions (Mahaffy et al., 2000; Wong et al., 2004), will serve as critical inputs for this study. The results of this research, particularly the determination of the primordial hydrosphere compositions, will inform subsequent investigations into the evolution of these moons' hydrospheres and their potential habitability.

Research Methodology

The methodology combines advanced numerical modeling with data analysis from key space missions to simulate the formation and evolution of the Galilean moons' hydrospheres.

1. Disk and Transport Modeling in the Protosolar Nebula (PSN): A disk and transport model validated in multiple frameworks (Schneeberger et al., 2023; Mousis et al., 2024) will simulate the transport of dust and vapors within the PSN. Key processes, including sublimation, condensation, clathrate formation, and volatile delivery via amorphous ice, will be incorporated alongside a dust and pebble transport module. Molecular abundance profiles in Jupiter's feeding zone will be derived, with a focus on variations across condensation and clathration lines. By varying disk and thermodynamic parameters, the model will produce solid and vapor abundance profiles, which will be compared to Jupiter's envelope composition using data from the Juno mission and Galileo probe.
2. Modeling Volatile Transport in the Circumplanetary Disk (CPD): A two-dimensional disk model (Schneeberger & Mousis 2024) will simulate the transport of solids and vapors within Jupiter's CPD, from which the Galilean moons likely formed. This will include time-dependent modeling of rock-to-volatile ratios in dust and pebbles to align with observed compositional gradients among the moons.
3. Accretion and Atmospheric Escape Modeling: Coupled accretion models (Bennacer et al., 2024) will explore the influence of accretion energy, radiogenic heating, and Jupiter's irradiation on hydrosphere stability. The impact of large impactors, previously overlooked in studies of hydrosphere evolution (Bierson & Nimmo, 2020), will also be incorporated to evaluate their role in altering the moons' volatile content.
4. Integration of Observational Data: Data on elemental abundances and isotopic ratios from Juno and Galileo missions will be used to validate model outputs. This integration will help refine hypotheses regarding the primordial volatile content and the role of atmospheric escape in shaping the observed density gradients.

By synthesizing data and simulations, this PhD thesis will provide a robust framework to reconstruct the formation and evolution of the Galilean moons' hydrospheres, offering insights into their early history and potential for harboring subsurface oceans.

Expected Contributions

This research will:

- Deliver a comprehensive understanding of the primordial composition of the Galilean moons' hydrospheres.
- Provide novel insights into the mechanisms driving density gradients and volatile distribution among the moons.
- Advance methodologies for simulating planetary formation and evolution in gas giant systems.
- Inform future investigations into the habitability of icy moons in the Solar System and beyond.

References :

Aguichine, A., Mousis, O., Lunine, J.I. 2022. The Possible Formation of Jupiter from Supersolar Gas. The Planetary Science Journal 3. doi:10.3847/PSJ/ac6bf1

Bennacer, Y., Mousis, O., Monnereau, M., Hue, V., Schneeberger, A. Assessing the thermal evolution of the Galilean moons during their accretion phase. Planetary Science Journal, submitted

Bierson, C.J., Nimmo, F. 2020. Explaining the Galilean Satellites' Density Gradient by Hydrodynamic Escape. The Astrophysical Journal 897. doi:10.3847/2041-8213/aba11a

Li, C. and 14 colleagues 2024. Super-adiabatic temperature gradient at Jupiter's equatorial zone and implications for the water abundance. Icarus 414. doi:10.1016/j.icarus.2024.116028

Mahaffy, P.R. and 7 colleagues 2000. Noble gas abundance and isotope ratios in the atmosphere of Jupiter from the Galileo Probe Mass Spectrometer. Journal of Geophysical Research 105, 15061–15072. doi:10.1029/1999JE001224

Mousis, O. and 8 colleagues 2024. Insights on the Formation Conditions of Uranus and Neptune from Their Deep Elemental Compositions. The Planetary Science Journal 5. doi:10.3847/PSJ/ad58d8

Mousis, O., Schneeberger, A., Lunine, J.I., Glein, C.R., Bouquet, A., Vance, S.D. 2023. Early Stages of Galilean Moon Formation in a Water-depleted Environment. The Astrophysical Journal 944. doi:10.3847/2041-8213/acb5a4

Schneeberger, A., and Mousis O. 2024. Impact of Jupiter’s heating and self-shadowing on the Jovian circumplanetary disk structure. Astronomy & Astrophysics, in press.

Schneeberger, A., Mousis, O., Aguichine, A., Lunine, J.I. 2023. Evolution of the reservoirs of volatiles in the protosolar nebula. Astronomy and Astrophysics 670. doi:10.1051/0004-6361/202244670

Wong, M.H., Mahaffy, P.R., Atreya, S.K., Niemann, H.B., Owen, T.C. 2004. Updated Galileo probe mass spectrometer measurements of carbon, oxygen, nitrogen, and sulfur on Jupiter. Icarus 171, 153–170. doi:10.1016/j.icarus.2004.04.010