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FORMATION OF COMPLEX ORGANIC MATTER IN THE PROTOSOLAR NEBULA AND DELIVERY TO THE GALILEAN MOONS

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Abstract.
Carbonaceous material is thought to exist on the surface of various celestial bodies in the outer solar system, such as the Galilean moons. We aim to investigate the accretion of complex organic molecules from the protosolar nebula during the formation of moons. We have developed a two-dimensional model describing the transport of pebbles and dust particles during the protosolar nebula evolution, employing a Lagrangian scheme. Based on experimental studies that have confirmed that UV irradiation and thermal processing of icy grains can generate complex organic molecules, we constrain their formation in the protosolar nebula. Assuming a cold circumplanetary disk as the environment for moon formation, particles from the protosolar nebula would contribute directly as building blocks for the formation of moons. We present preliminary results showing a range of disk conditions that support the survival of complex organic molecules across the protosolar nebula, allowing them to persist until they reach the formation region of the Jovian system. Of the 500 particles of 1 μm size that we simulate, only ~ 20 % succeed in forming complex organic molecules and delivering them to Jupiter to be used as primary material for the moons.

Keywords: Protoplanetary disks, numerical method, astrobiology, astrochemistry, planets and satellites: composition and formation

1 Introduction

Protoplanetary disks (PPDs) are the sites of planet formation, and they harbour complex chemistry as well, in particular the synthesis of complex organic molecules (COMs) composed of more than 6 atoms of carbon, hydrogen, oxygen, and/or nitrogen (Belloche et al. 2009; Tenelanda-Osorio et al. 2022). Ices found in molecular clouds and circumstellar disks (van Dishoeck 2004; Boogert et al. 2015) serve as potential reservoirs for COMs formation (Ciesla & Sandford 2012), as supported by experimental studies (Moore et al. 1991; Nuevo et al. 2011; Bossa et al. 2008; Tenelanda-Osorio et al. 2022). COMs have been observed in comets and star-forming regions (Briggs et al. 1992; Bisschop et al. 2007), highlighting their importance in understanding prebiotic molecules in planetary systems. Similarly, moons formation within giant planet systems is debated, particularly whether moons form in circumplanetary disks (CPDs) that are massive (Keith & Wardle 2014; Szulágyi et al. 2016) or not (Canup & Ward 2002; Sasaki et al. 2010). If moons formed in low-mass CPDs, their compositions may largely reflect the primordial materials from the protosolar nebula (PSN) without significant alteration. Since interior models predict that up to 17-26% of the Galilean moons composition could be made of COMs (Reynard & Sotin 2023), the low-mass CPD scenario suggests that those COMs are directly inherited from the PSN. Furthermore, the presence of COMs in the primordial composition of the Galilean moons can significantly impact the primordial state of the moon's hydrosphere, and as a consequence, the volatile inventory stored in nowadays subsurface ocean (Amsler Moulanier et al. Submitted). Using a time-dependent PPD model (Aguichine et al. 2020) and a Lagrangian particle-tracking model (Benest Couzinou et al. Submitted), we aim to compare the experimental data (Bossa et al. 2008) with the temperature and irradiation conditions of the particles in the PPD, to constrain the COMs formation and their delivery to the Galilean moons' formation region.

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2 Methodology

This section describes both the experimental conditions taken from Bossa et al. (2008) on which we base our study, and the modules used for the numerical simulations of the PPD and the particles.

Our modelling is guided by the parameters of the experimental set-up, such as the approach described in Bossa et al. (2008). To sum up, a binary 1:1 NH_3 and CO_2 ice mixture was heated from 10 K. Above 80 K, two species were formed: ammonium carbamate $[NH_2COO^-][NH_4^+]$, and neutral carbamic acid NH_2COOH. Both species were present in similar quantities, i.e. the carbamate:carbamic acid ratio was 1:1 at 140 K, and they sublimated between 230 and 260 K. The experiments also considered the VUV irradiation of the NH_3:CO_2=1:1 ice at 10 K, with an irradiation dose of 4.32×10^{19} photons cm^{-2}, which lead to the formation of species such as carbamic acid, ammonium carbamate, and ammonium formate $[HCOO^-][NH_4^+]$ (the details are given in Bossa et al. (2008)). 86% of the newly formed molecules are carbamic acid, 6% are ammonium formate, and 3% are ammonium carbamate, resulting in a carbamate:carbamic acid ratio of 1:28.

The evolution of the α-viscous disk (Shakura & Sunyaev 1973) is based on a model from Lynden-Bell & Pringle (1974). For a comprehensive overview of the disk evolution model, we refer the reader to Aguichine et al. (2020) and Schneeberger et al. (2023), where it is described in detail.

Assuming the disk is vertically isothermal, we can derive its vertical density profile and the corresponding irradiation in a two-dimensional disk model (Ciesla 2010, 2011; Ciesla & Sandford 2012). Particle transport is modeled following the approach of Ciesla (2010, 2011); Ciesla & Sandford (2012), which enables us to compute the radial and vertical trajectories of particles while accounting for random contributions from turbulence in the fluid. Consequently, the flux experienced by a particle along its trajectory depends on its radial and vertical position. We then compare these accumulated irradiation doses with experimental data to draw conclusions. We refer the read to Benest Couzinou et al. (Submitted) to a complete overview of the particle transport model.

3 Discussion and conclusion

We show on Fig. 1 the results for 500 simulated particles with a size of 1 μm released at 7 AU. The upper panel shows that the particles accumulate great irradiation (up to $\sim 10^{19}$ photons cm^{-2}), but do not reach the experimental irradiation dose needed to form COMs (at $\sim 4^{19}$ photons cm^{-2}),. However, they reach the disk region where the temperature is hot enough to form COMs from thermal processing. After 500 kyr, $\sim$ 20 % of the particles succeed to create COMs and bring them to the Jupiter CPD. It's important to note that larger particles won't ascend to such high altitudes and will thus be exposed to less irradiation. Additionally, they will undergo faster inward radial drift. Another key factor is the initial release point of the particles: those released closer to Jupiter can more easily reach its location, while particles released farther out will struggle to reach Jupiter's CPD but will be subjected to increased irradiation due to the lower gas density at greater distances from the star. These various scenarios will be explored in future studies.

In this study, we show that COMs can form in the PSN and subsequently be delivered to the Galilean moons. We propose that nitrogen, among other elements, could be transported to Jupiter's moons via nitrogen-bearing COMs. The presence of nitrogen in the primordial composition of the moons can lead to significant changes, especially in the distribution of partial pressures in the moon's primordial atmosphere. Indeed, as shown in (Amsler Moulanier et al. Submitted), the chemical equilibrium taking place between NH_3 and CO_2, will impact the sustainability of a CO_2–rich atmosphere, depending on the amount of ammonia delivered to the moon and the pH of the ocean. While alternative scenarios, such as ion or electron bombardment or secondary UV irradiation, might explain other origins for COMs and various species, our primary scenario must be considered. In our study, we assumed a low-mass CPD, minimizing thermal processing, and assumed rapid accretion of COMs by protomoons, leading to negligible irradiation within the CPD, where the moons formed. To validate this hypothesis, however, future studies of particle evolution in a CPD would be valuable. In addition, several assumptions have been made in our study, such as the complete accretion of molecules at Jupiter's CPD without desorption, the constant size of particles despite expected growth in the disk, and the comparison of experimental irradiation with interstellar levels, even though particles in the disk are likely to experience lower irradiation rates, resulting in reduced chemical transformation. Our results indicate that the delivery of nitrogen-bearing COMs to the Galilean moons is a complex process with limited success, especially considering that the actual amount of COMs reaching the Galilean moons is likely to be even smaller considering the processes we have omitted.

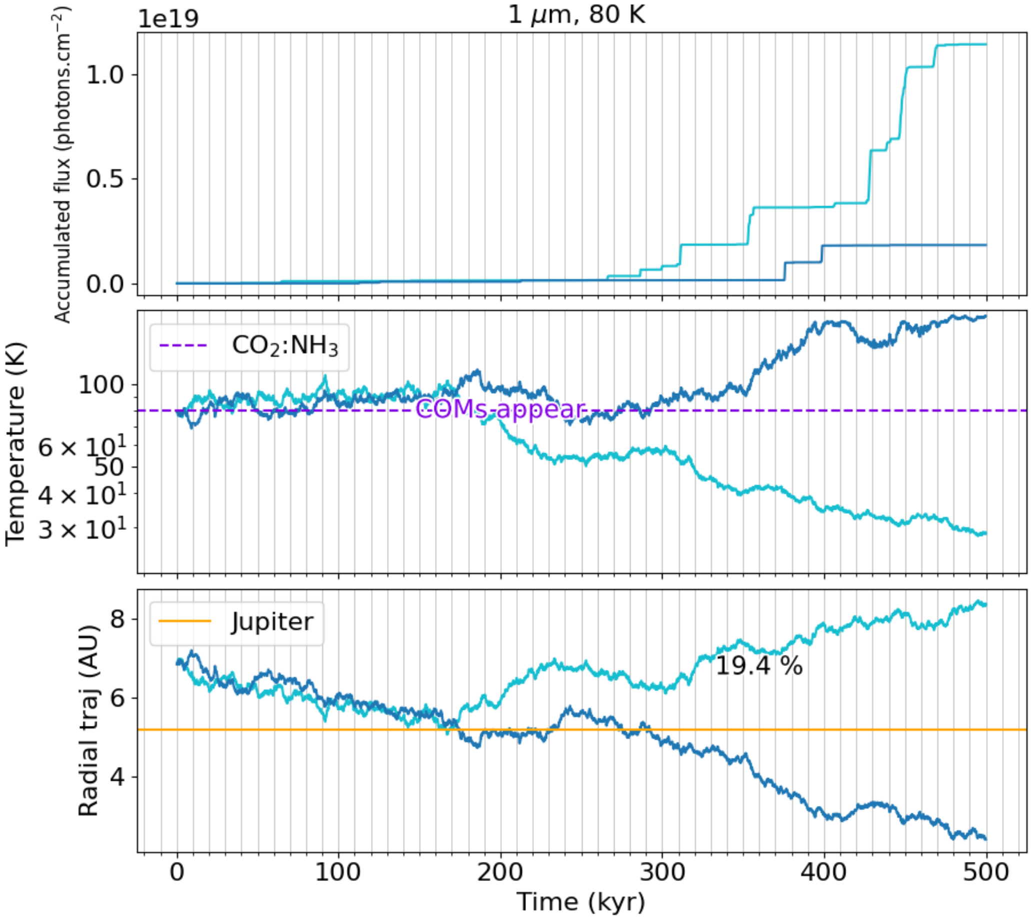

Fig. 1. Top panel: Irradiation accumulated by the particles, and the experimental irradiation doses in horizontal lines. **Middle panel**: Temperature encountered by the particles, and the temperature range that allows COMs formation in purple lines, based on experiments. **Bottom panel**: Radial trajectory of the particles, with the Jupiter location in orange. Of all the 1 μm-sized particles released at 7 AU which create the COMs and bring them to the region where the Galilean moons form (i.e. ∼20% of the 500 simulated particles), the two most extreme trajectories are shown in blue, over 500 kyr.

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