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The Chemical Inheritance of Icy Moons

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Abstract

Large icy exomoons may represent a ubiquitous habitable environment yet remain on the fringes of detectability. Despite decades of progress in theoretical work, the nature and origin of the solids which form the building blocks of satellites remains a topic of debate. We utilize a radiation-thermochemical disk modeling code to study the time-dependent chemical evolution of volatiles prior to their incorporation into moons. We trace the evolving ice fraction and composition throughout an ensemble of disk models to match their evolving chemical state to solar system observables. We find that the expected evolutionary timescales of viscously evolving circumplanetary disks (10^3-10^5 yr) are not generally sufficient to allow chemical equilibrium to be reached, and that some degree of chemical inheritance from the circumstellar disk may be necessary in the form of meter-sized boulders which retain their volatiles during shock heating or even larger objects.

Introduction

Icy satellites and minor bodies are the most prevalent of the Solar System worlds known or suspected to host oceans of liquid water [1]. The bulk composition of the satellite ices may contain chemical impurities ranging from 0.1-15% by mass fraction [2]. The melting point of ice mixtures can be depressed by the presence of Ammonia, Methanol, or salts. Hence the composition of the volatile reservoir from which icy satellites form is of relevance to the presence of subsurface oceans, their geothermal and -physical evolution [3], the interpretation of in-situ measurements [4], and the eventual atmospheric composition [5].

The exact process by which moon formation occurs in circumplanetary disks (CPDs) is still a matter of debate. A general feature of regular satellite formation scenarios is that the CPD consists of circumstellar material accreted from within the vicinity of the planet [6]. Modeling of the outer solar circumstellar disk suggests a possible ammonia fraction relative to water $NH_3/H_2O = 0.14$, with as much as 80% of the nitrogen locked into NH_3 [7].

Once a sufficiently massive planet has opened a gap in its circumstellar disk, accretion onto the CPD slows but does not stop as circumstellar material continues to flow into the vicinity of the planet [8]. Gas falling supersonically onto the CPD may pass through one or more accretion shocks and could be heated to >1000 K [9][10] destroying molecules in the accretion flow and potentially altering the eventual composition of satellites in a "reset" scenario.

The potentially short viscous timescale in which CPDs radially transport material suggests that they may be unable to reach chemical equilibrium before solid material is lost or incorporated into satellites. We must consider the time-dependant chemical evolution of the CPDs to determine whether inheritance may be necessary to reproduce the observed bulk composition of the icy satellites. If inheritance is necessary, CPDs may need to acquire their solids in larger (> 1 m) boulders able to retain their volatiles during gap crossing and shock heating.

Methodology

We aim to investigate the consequences of a chemical reset on the final composition of ices in chemically evolving circumplanetary disks by expanding the network of chemical reactions previously considered and taking into account the relatively short period in which chemical evolution can occur prior to moon formation. We will analyze the CPD time-dependant chemistry and determine the timescales for chemical equilibration relative to viscous diffusion, and extract bulk volatile satellite compositions given a variety of plausible disk properties. We will determine which scenarios are consistent with in-situ coeval formation of satellites and which suggest sequential formation and migration. Additionally We will determine whether limits on the CPD viscosity, accretion rate, and dust-to-gas ratio can be determined by the relevant timescales of chemical evolution versus radial transport. We use a radiation thermo-chemical disk model *ProDiMo* (PROtoplanetary DIsk MOdel) to explore the resulting abundance of various ices in a model grid of CPDs [11][12][13].

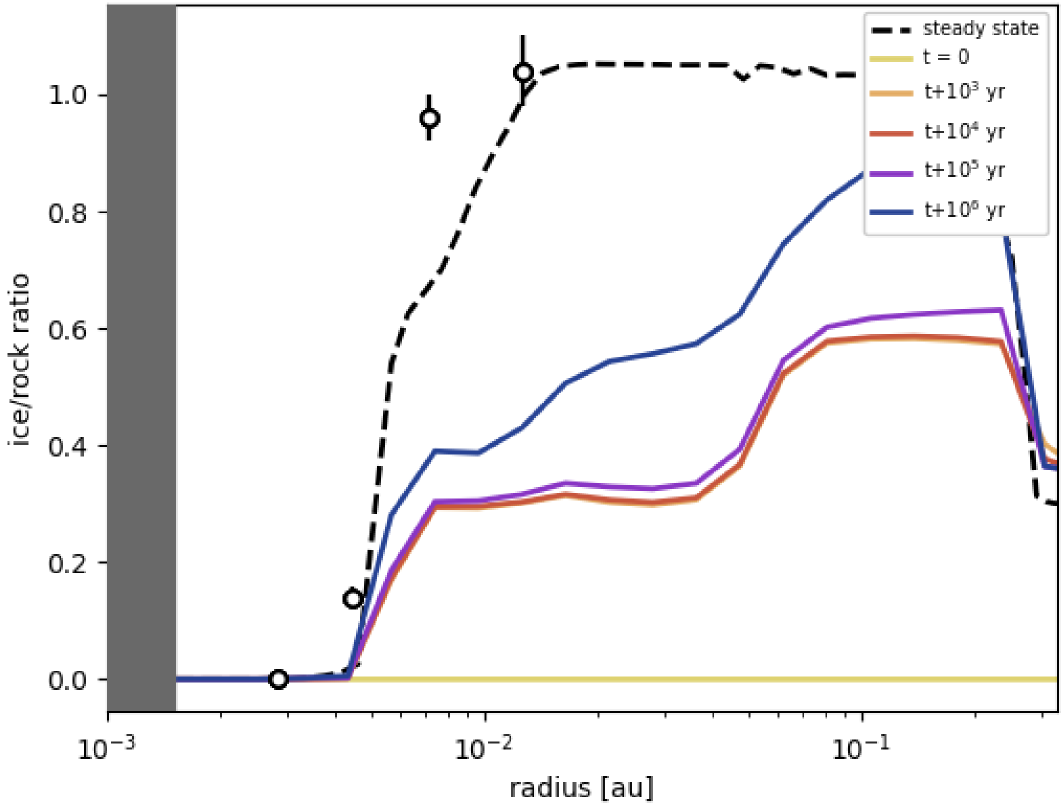

Figure 1: The radial ice-to-rock ratio in a Jovian circumplanetary disk model. The black dashed lined indicates the a steady-state chemical equilibrium , while the colored lines trace the evolving ice-to-rock ratio over 10^6 years. The black circles indicate the radial location and ice content of the

Galilean satellites.

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