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Evolution of the protolunar disk: Dynamics, cooling timescale and implantation of volatiles onto the Earth

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ABSTRACT

It is thought that the Moon accreted from the protolunar disk that was assembled after the last giant impact on Earth. Due to its high temperature, the protolunar disk may act as a thermochemical reactor in which the material is processed before being incorporated into the Moon. Outstanding issues like devolatilisation and istotopic evolution are tied to the disk evolution, however its lifetime, dynamics and thermodynamics are unknown. Here, we numerically explore the long term viscous evolution of the protolunar disk using a one dimensional model where the different phases (vapor and condensed) are vertically stratified. Viscous heating, radiative cooling, phase transitions and gravitational instability are accounted for whereas Moon's accretion is not considered for the moment. The viscosity of the gas, liquid and solid phases dictates the disk evolution. We find that (1) the vapor condenses into liquid in $\sim$10 years, (2) a large fraction of the disk mass flows inward forming a hot and compact liquid disk between 1 and 1.7 Earth's radii, a region where the liquid is gravitationally stable and can accumulate, (3) the disk finally solidifies in 10^3 to 10^5 years. Viscous heating is never balanced by radiative cooling. If the vapor phase is abnormally viscous, due to magneto-rotational instability for instance, most of the disk volatile components are transported to Earth leaving a disk enriched in refractory elements. This opens a way to form a volatile-depleted Moon and would suggest that the missing Moon's volatiles are buried today into the Earth. The disk cooling timescale may be long enough to allow for planet/disk isotopic equilibration. However large uncertainties on the disk physics remain because of the complexity of its multi-phased structure.

1. Introduction

The Earth's Moon is believed to have formed in the aftermath of the last giant impact on the proto-earth. Whereas numerous works treating the giant-impact have been published, the subsequent evolution of the protolunar disk is only poorly known. The main challenge is to couple in a single framework both the dynamical and thermodynamical evolution of the disk material. Kokubo and Ida (2000) have simulated the re-accretion of a protolunar disk into a proto-moon from solid particles and neglected thermodynamics. The system was found to collapse into a disk and form a satellite at the Roche Limit in $\sim$100 orbits. Once the particulate disk is completely cold, if it contains about 1% of the mass of the Earth, gravitational instabilities lead to the formation of a single moon only (Kokubo and Ida, 2000; Crida and Charnoz, 2012). Machida and Abe (2004) have studied the evolution of a two-phase disk but neglected cooling and vapor condensation as well as time evolution. Salmon and Canup (2012) have studied the accretion of the Moon from a Roche interior fluid disk assuming that the disk acts as a reservoir with a radially constant surface density; its outflow is prescribed assuming that viscous heating perfectly balances radiative cooling as suggested in Thompson and Stevenson (1988). The vertical structure of a vapor/liquid magma disk at thermodynamical equilibrium is described by Ward (2012) and its evolution investigated analytically in Ward (2014a) assuming several simplifying assumptions such as a steady-state radial flux. Hence, in all previously mentioned work, the coupling between the disk dynamics and thermal evolution (radiative cooling, viscous heating and phase transitions) is not treated in a time dependent way. Impact simulations show that the disk is initially very hot (>3000 K) and, in order to become gravitationally unstable and assemble into a moon, it must cool down first. During this cooling phase, a major restructuration is expected.

The cooling timescale of the protolunar disk is actively debated as it determines the period during which the lunar material can be processed chemically as well as isotopically, before being incorporated

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into the Moon (Pahlevan and Stevenson, 2007). A simple computation of the cooling timescale (internal energy divided by black body emission power) that ignores any dynamical evolution gives a timescale of a few 10 to a few 100 years. However, as noted by Thompson and Stevenson (1988) and Ward (2012), if the disk is gravitationally unstable it should heat up rapidly due to a large effective viscosity induced by gravitational instabilities and this heating should increase the cooling timescale. It is even possible that viscous heat production may, at some point, perfectly balance the energy loss due to black-body emission, lengthening by orders of magnitude the cooling timescale of the disk (Thompson and Stevenson, 1988; Ward, 2012). However Ward (2014a) seems to reach an opposite conclusion based on steady state models of disks. So, depending on the study, the cooling timescale may extend from ~10 years to several thousands of years.

These uncertainties have important consequences on the subsequent composition of the lunar material. Many measurements suggest a significant processing of the disk material before being incorporated into the Moon. On a three-isotope plot ($\delta^{17}O$ versus $\delta^{18}O$), different samples from different planetary bodies are all aligned on a unique fractionation line, characteristic of the body, with a slope close to 0.5. Thus, if the Moon is mainly made of impactor's material, as it is the case in the so-called canonical impact (Canup, 2004), it may leave its imprint on the protolunar disk and the Moon (see e.g. Canup, 2004, Pahlevan and Stevenson, 2007). However, the oxygen fractionation line of the Moon is either indistinguishable from the terrestrial line (Wiechert et al., 2001) or, at most, differs by a very small fraction (Herwartz et al., 2014). In an attempt to reconcile the canonical impact model with the identical oxygen isotopic composition of the Earth and the Moon, Pahlevan and Stevenson (2007) suggested that turbulence in the disk may allow isotopic equilibration of the disk with the proto-earth and erase any isotopic difference. The Moon is also substantially depleted in volatile elements compared to the Earth's mantle, by a factor of 10 for moderately volatile elements like potassium and almost by a factor of 100 for highly volatile elements like Zinc (Taylor and Wieczoreck, 2014). In addition Zinc isotopes are strongly enriched in their most heavy species (Paniello et al., 2012) arguing for an efficient volatile removing process. An incomplete condensation of the Moon was suggested by Stewart et al. (2013) but hydrodynamical escape of volatile elements may not be efficient enough to explain Moon's depletion because of the high concentration of oxygen atoms in the disk and possibly its short lifetime (Nakajima and Stevenson, 2014b). The processes by which the lunar material has become depleted in volatile elements are thus still questioned.

In order to make progress in our understanding of the disk, the present work aims to build a numerical model of a time-evolving protolunar disk.

In their pioneering work, Thompson and Stevenson (1988) described the complex physical processes at play in the protolunar disk making it particularly exotic compared to many other astrophysical disks. The disk is likely to be constituted by a two-phase media, with a liquid and a vapor phase. The disk cools from its upper atmosphere and generates heat through viscous dissipation in the midplane. The vapor phase condenses in liquid droplets that sediment in the midplane. Whereas Thompson and Stevenson (1988) assumed that the disk is made of an intimate mixture of gas and droplets, more recent works suggest that the disk is indeed stratified with a condensed layer in the midplane (liquid or solid) topped by a vapor atmosphere. Machida and Abe (2004) have shown that the droplets sediments in less than 10^{-2} years. Recently, Nakajima and Stevenson (2014a) proposed scaling relations for estimating the disk vapor fraction in good agreement with SPH simulations, assuming such a vertically stratified disk at hydrostatic equilibrium.

Unfortunately there is no numerical code today that can grasp all the physical ingredients of the protolunar disk as described in Thompson and Stevenson (1988) and compute the disk evolution over a cooling timescale (>100 years).

Here we propose a model for a two-phases, vertically stratified protolunar disk. Our central idea is to use technics developed for the study of protoplanetary disks and adapt them to the case of the protolunar disk to account in particular for the presence of two phases, which imposes major changes compared to all published protoplanetary disk models. We numerically track the evolution of the protolunar disk, just after the giant impact, and over hundreds of thousands of years with a simple, but non-trivial, one dimensional and two-phase model. On the contrary to Machida and Abe (2004), we allow for mass exchanges between the vapor and liquid phases (due to cooling and condensation), consider a time evolving temperature and account for radiative cooling and viscous heating. We emphasize the role of viscosity as the main driver of the disk evolution over long timescales (i.e. timescales $\gg$ orbital period which is ~10 h on average), and of phase transition effects. To make the computation tractable, we assume that the disk is always in hydrostatic equilibrium and locally vertically isothermal. The aim of the present study is to focus on the disk evolution. The growing of a proto-moon and its back-reaction onto the disk are not considered. Taking this process into account may imply significant modifications of our (already complex) code. In order to precisely understand the effects of each process on the disk evolution, we choose a step-by-step approach. We leave the effect of a proto-moon for a future work, whereas a simplified case is presented in Section 3.3.3 and in Section 3 of the supplementary online material.

The paper is organized as follows: in Section 2 the physics and the algorithm that couple the dynamical evolution, thermodynamical equilibrium, heating and cooling are described. A special care is given to the computation of viscosities that are key ingredients. In Section 3 we present the evolution of a disk, first neglecting the disk's dynamical evolution (in order to illustrate the basic effects of the cooling and heating processes involved) and then considering the disk full thermodynamical and dynamical evolution. Cases with fully separated phases and with some degrees of mixing are compared. In Section 4, the evolution of the disk content in volatile and refractory species is presented and we show that it is possible to devolatilize the disk rapidly if the vapor layer is abnormally viscous. In Section 5 the results are commented in the context of different Moon formation scenarios. In Section 6 we summarize our results and conclude on their possible implications regarding Moon's formation.

2. The model

2.1. Overall structure of the model

We solve for the one dimensional time evolution of the condensed phase (liquid or solid) and the vapor phase, in terms of surface density and temperature as a function of distance to the proto-earth. This approach is inspired from one-dimensional codes developed for the study of protoplanetary disks or rings (see e.g. Hueso and Guillot, 2005; Charnoz et al., 2011; Yang and Ciesla, 2012; Baillie and Charnoz, 2014), the main difference being the taking into account of two phases (Fig. 1). For simplicity, the two layers of the disk are assumed to be in local hydrostatic equilibrium and the disk is assumed to be vertically isothermal. In fact, the vapor layer is probably everywhere in equilibrium with the condensed phase and should lie on the Clapeyron curve (Ward, 2012). But the structure and energy budget of an isothermal vapor layer is very close to the case of a Clapeyron atmosphere (see