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Note

Fossilized condensation lines in the Solar System protoplanetary disk

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ABSTRACT

The terrestrial planets and the asteroids dominant in the inner asteroid belt are water poor. However, in the protoplanetary disk the temperature should have decreased below water-condensation level well before the disk was photo-evaporated. Thus, the global water depletion of the inner Solar System is puzzling. We show that, even if the inner disk becomes cold, there cannot be direct condensation of water. This is because the snowline moves towards the Sun more slowly than the gas itself. Thus the gas in the vicinity of the snowline always comes from farther out, where it should have already condensed, and therefore it should be dry. The appearance of ice in a range of heliocentric distances swept by the snowline can only be due to the radial drift of icy particles from the outer disk. However, if a planet with a mass larger than 20 Earth mass is present, the radial drift of particles is interrupted, because such a planet gives the disk a super-Keplerian rotation just outside of its own orbit. From this result, we propose that the precursor of Jupiter achieved this threshold mass when the snowline was still around 3 AU. This effectively fossilized the snowline at that location. In fact, even if it cooled later, the disk inside of Jupiter's orbit remained ice-depleted because the flow of icy particles from the outer system was intercepted by the planet. This scenario predicts that planetary systems without giant planets should be much more rich in water in their inner regions than our system. We also show that the inner edge of the planetesimal disk at 0.7 AU, required in terrestrial planet formation models to explain the small mass of Mercury and the absence of planets inside of its orbit, could be due to the silicate condensation line, fossilized at the end of the phase of streaming instability that generated the planetesimal seeds. Thus, when the disk cooled, silicate particles started to drift inwards of 0.7 AU without being sublimated, but they could not be accreted by any pre-existing planetesimals.

1. Introduction

The chemical structure of a protoplanetary disk is characterized by a condensation front for each chemical species. It marks the boundary beyond which the temperature is low enough to allow the condensation of the considered species, given its local partial pressure of gas. If one assumes that the disk is vertically isothermal and neglects pressure effects, the condensation front is a vertical straight-line in (r, z) space. This is the reason for the wide-spread use of the term "condensation line". However, the vertical isothermal approximation is in many cases a poor proxy for the thermal structure of the disk (see below), so that in reality the condensation "line" is a curve in (r, z) space, like any other isothermal curve (Isella and Natta, 2005).

Probably the most important condensation line is that for water, also called the ice-line or the snowline. In the Solar System water accounts for about 50% of the mass of all condensable species (Lodders, 2003). The fact that the inner Solar System objects (terrestrial planets, asteroids of the inner main belt) are water poor, whereas the outer Solar System objects (the primitive asteroids in the outer belt, most satellites of the giant planets and presumably the giant planets cores, the Kuiper belt objects and the comets) are water rich, argues for the importance of the snowline in dividing the protoplanetary disk in two chemically distinct regions.

Thus, modeling the thermal structure of the disk has been the subject of a number of papers. There are two major processes generating heat: viscous friction and stellar irradiation. Chiang and Goldreich (1997), Dullemond et al. (2001, 2002) and Dullemond (2002) neglected viscous heating and considered only stellar irradiation of passive disks. They also assumed a constant opacity (i.e. independent of temperature). Chiang and Goldreich demonstrated the flared structure of a protoplanetary disk while the Dullemond papers stressed the presence of a puffed-up rim due to the face illumination of the disk's inner edge. This rim casts a shadow onto the disk, until the flared structure brings the outer disk back into illumination. Hueso and Guillot (2005), Davis (2005), Garaud and Lin (2007), Oka et al. (2011), Bitsch et al. (2014a, 2015a) and Baillié et al. (2015) considered viscous heating also and introduced temperature dependent opacities with increasingly sophisticated prescriptions. They demonstrated that viscous heating dominates in the inner part of the disk for $\dot{M} > 10^{-10} M_\odot/y$ (Oka et al., 2011), where $\dot{M}$ is the radial mass-flux of gas (also known as the stellar accretion rate) sustained by the viscous transport in the disk. In the most sophisticated models, the aspect ratio of the disk is grossly independent of radius in the region where the viscous heating dominates, although bumps and dips exist (with the associated shadows) due to temperature-dependent transitions in the opacity law (Bitsch et al., 2014a, 2015a). The temperature first decreases with increasing distance from the midplane, then increases again due to the stellar irradiation of the surface layer. The outer part of the disk is dominated by stellar irradiation and is flared as predicted earlier; the temperature in that region is basically constant with height near the mid-plane and then increases approaching the disk's surface.

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As a consequence of this complex disk structure, the snowline is a curve in the (r, z) plane (see for instance Fig. 4 of Oka et al., 2011). On the midplane, the location of the snowline is at about 3 AU when the accretion rate in the disk is $\dot{M} = 3\text{—}10 \times 10^{-8} M_\odot/y$. When the accretion rate drops to $5\text{–}10 \times 10^{-9} M_\odot/y$ the snowline on the midplane has moved to 1 AU (Hueso and Guillot, 2005; Davis, 2005; Garaud and Lin, 2007; Oka et al., 2011; Baillié et al., 2015; Bitsch et al., 2015a). Please notice that a disk should not disappear before that the accretion rate decreases to $\dot{M} \lesssim 10^{-9} M_\odot/y$ (Alexander et al., 2014). The exact value of the accretion rate for a given snowline location depends on the disk model (1 + 1D as in the first four references or 2D as in the last one) and on the assumed dust/gas ratio and viscosity but does not change dramatically from one case to the other for reasonable parameters, as we will see below (Eq. (9)).

The stellar accretion rate as a function of age can be inferred from observations. Hartmann et al. (1998) found that on average $\dot{M} = 10^{-8} M_\odot/y$ at 1 My and $\dot{M} = 1\text{–}5 \times 10^{-9} M_\odot/y$ at 3 My. The accretion rate data, however, appear dispersed by more than an order of magnitude for any given age (possibly because of uncertainties in the measurements of the accretion rates and in the estimates of the stellar ages, but nevertheless there should be a real dispersion of accretion rates in nature). In some cases, stars of 3–4 My may still have an accretion rate of $10^{-8} M_\odot/y$ (Hartmann et al., 1998; Manara et al., 2013).

The Solar System objects provide important constraints on the evolution of the disk chemistry as a function of time. Chondritic asteroids are made of chondrules. The ages of chondrules span the ~3 My period after the formation of the first solids, namely the calcium–aluminum inclusions (CAIs; Villeneuve et al., 2009; Connelly et al., 2012; Bollard et al., 2014; Luu et al., 2015). The measure of the age of individual chondrules can change depending on which radioactive clock is used, but the result that chondrule formation is protracted for ~3 My seems robust. Obviously, the chondritic parent bodies could not form before the chondrules. Hence, we can conclude that they formed (or continued to accrete until; Johansen et al., 2015) 3–4 My after CAIs.

At 3 My (typically $\dot{M} = 1\text{–}5 \times 10^{-9} M_\odot/y$) the snowline should have been much closer to the Sun than the inner edge of the asteroid belt (the main reservoir of chondritic parent bodies). Nevertheless, ordinary and enstatite chondrites contain very little water (Robert, 2003). Some water alteration can be found in ordinary chondrites (Baker et al., 2003) as well as clays produced by the effect of water (Alexander et al., 1989). Despite these observations, it seems very unlikely that the parent bodies of these meteorites ever contained ~50% of water by mass, as expected for a condensed gas of solar composition (Lodders, 2003).

One could think that our protoplanetary disk was one of the exceptional cases still showing stellar accretion $\gtrsim 10^{-8} M_\odot/y$ at ~3 My. However, this would not solve the problem. In this case the disk would have just lasted longer, while still decaying in mass and cooling. In fact, the photo-evaporation process is efficient in removing the disk only when the accretion rate drops at $\lesssim 10^{-9} M_\odot/y$ (see Fig. 4 of Alexander et al., 2014). Thus, even if the chondritic parent bodies had formed in a warm disk, they should have accreted a significant amount of icy particles when, later on, the temperature decreased below the water condensation threshold, but before the disk disappeared.

The Earth provides a similar example. Before the disk disappears ($\dot{M} \sim 10^{-9} M_\odot/y$), the snowline is well inside 1 AU (Oka et al., 2011). Thus, one could expect that plenty of ice-rich planetesimals formed in the terrestrial region and our planet accreted a substantial fraction of water by mass. Instead, the Earth contains no more than ~0.1% of water by mass (Marty, 2012). The water budget of the Earth is perfectly consistent with the Earth accreting most of its mass from local, dry planetesimals and just a few percent of an Earth mass from primitive planetesimals coming from the outer asteroid belt, as shown by dynamical models (Morbidelli et al., 2000; Raymond et al., 2004, 2006, 2007; O'Brien et al., 2006, 2014). Why water is not substantially more abundant on Earth is known as the *snowline problem*, first pointed out clearly by Oka et al. (2011). Water is not an isolated case in this respect. The Earth is depleted in all volatile elements (for lithophile volatile elements the depletion progressively increases with decreasing condensation temperature; McDonough and Sun, 1995). Albarède (2009), using isotopic arguments, demonstrated that this depletion was not caused by the loss of volatiles during the thermal evolution of the planet, but is due to their reduced accretion relative to solar abundances. Furthermore, a significant accretion of oxidized material would have led to an Earth with different chemical properties (Rubie et al., 2015). Mars is also a water-poor planet, with only 70–300 ppm of water by mass (McCubbin et al., 2012).

Thus, it seems that the water and, more generally, the volatile budget of Solar System bodies reflects the location of the snowline at a time different from that at which the bodies formed. Interestingly and never pointed out before, the situation may be identical for refractory elements. In fact, a growing body of modeling work (Hansen, 2009; Walsh et al., 2011; Jacobson and Morbidelli, 2014) suggests that the disk of planetesimals that formed the terrestrial planets had an inner edge at about 0.7 AU. This edge is required in order to produce a planet of small mass like Mercury (Hansen, 2009). On the midplane, a distance of 0.7 AU corresponds to the condensation line for silicates (condensation temperature ~1300 K) for a disk with accretion rate $\dot{M} \sim 1.5 \times 10^{-7} M_\odot/y$, typical of an early disk. Inside this location, it is therefore unlikely that objects could form near time zero. The inner edge of the planetesimal disk at 0.7 AU then seems to imply that, for some unknown reason, objects could not form there even later on, despite the local disk's temperature should have dropped well below the value for the condensation of silicates. Clearly, this argument is more speculative than those reported above for the snowline, but it is suggestive that the snowline problem is common to all chemical species. It seems to indicate that the structure of the inner Solar System carries the *fossilized* imprint of the location that the condensation lines had at an early stage of the disk, rather than at a later time, more characteristic of planetesimal and planet formation; hence the title of this Note. Interestingly, if this analogy between the silicate condensation line and the snowline is correct, the time of fossilization of these two lines would be different (the former corresponding to the time when $\dot{M} \sim 1.5 \times 10^{-7} M_\odot/y$, the latter when $\dot{M} \sim 3 \times 10^{-8} M_\odot/y$).

The goal of this Note is to discuss how this might be understood. This Note will not present new sophisticated calculations, but simply put together results already published in the literature and connect them to propose some considerations, to our knowledge never presented before, that may explain the fossilization of the condensation lines, with focus on the snowline and the silicate line.

Below, we start in Section 2 with a brief review of scenarios proposed so far to solve the snowline and the 0.7 AU disk edge problems. In Section 3 we discuss gas radial motion, the radial displacement of the condensation lines and the radial drift of solid particles. This will allow us to conclude that the direct condensation of gas is not the main process occurring when the temperature decreases, but instead it is the radial drift of particles from the outer disk that can repopulate the inner disk of condensed species. With these premises, in Section 4 we focus on the snowline, and discuss mechanisms for preventing or reducing the flow of icy particles, so to keep the Solar System deficient in ice inside ~3 AU even when the temperature in that region dropped below the ice-condensation threshold. In Section 5 we link the inner edge of the planetesimal disk to the original location of the silicate condensation line and we attempt to explain why no planetesimals formed inside this distance when the temperature dropped. A wrap-up will follow in Section 6 and an appendix on planet migration in Appendix A.

2. Previous models

The condensation line problem is a subject only partially explored. For the snowline problem, Martin and Livio (2012, 2013) proposed that the dead zone of the protoplanetary disk piled up enough gas to become gravitationally unstable. The turbulence driven by self-gravity increased the temperature of the outer parts of the dead zone and thus the snowline could not come within 3 AU, i.e. it remained much farther from the star than it would in a normal viscously evolving disk. This model, however, has some drawbacks. First, it predicts an icy region inside of the Earth's orbit, so that Venus and Mercury should have formed as icy worlds. Second, from the modeling standpoint, the surface density ratio between the deadzone and the active zone of the disk is inversely proportional to the viscosity ratio only in 1D models of the disk. In 2D (r, z) models (Bitsch et al., 2014b) the relationship between density and viscosity is non-trivial because the gas can flow in the surface layer of the disk. Thus, the deadzone may not become gravitationally unstable.

Hubbard and Ebel (2014) addressed the deficiency of the Earth in lithophile volatile elements. They proposed that grains in the protoplanetary disk are originally very porous. Thus, they are well coupled with the gas and distributed quite uniformly along the vertical direction. The FU-Orionis events, that our Sun presumably experienced like most young stars, would have heated above sublimation temperature the grains at the surface of the disk. Then, the grains would have recondensed, losing the volatile counterpart and acquiring a much less porous structure and a higher density. These reprocessed grains would have preferentially sedimented onto the disk's midplane, featuring the major reservoir of solids for the accretion of planetesimals and the planets. Planetesimals and planets would therefore have accreted predominantly from volatile depleted dust, even though the midplane temperature was low. This model is appealing, but has the problem that the phase of FU-Orionis activity of a star lasts typically much less than the disk's lifetime. Thus eventually the devolatilization of the grains would stop and the planetesimals and planets would keep growing from volatile-rich grains. Also, it neglects the radial drift of icy particles on the mid-plane from the outer disk.

Concerning the inner edge of the planetesimal disk at 0.7 AU, an explanation can be found in Ida and Lin (2008). The authors pointed out that the timescale for runaway growth of planetary embryos decreases with heliocentric distance. Because the radial migration speed of embryos is proportional to their mass (Tanaka et al., 2002), the innermost embryos are lost into the star and are not replaced at the same rate by embryos migrating inward from farther out. This produces an effective inner edge in the solid mass of the disk, that recedes from the Sun as time progresses (see Fig. 2 of Ida and Lin, 2008). The major issue here is whether planets and embryos can really be lost into the star. The observation of extrasolar planets has revealed the existence of many "hot" planets, with orbital periods of a few days. Clearly, these planets would be rare if there had existed no stopping mechanism to their inward migration, probably due to the existence of an inner edge of the protoplanetary disk where the Keplerian period is equal to the star's rotation period (Koenigl, 1991; Lin et al., 1996), acting like a planet-trap (Masset et al., 2006). The presence of planet-trap would change completely the picture presented in Ida and Lin (2008) (see for instance Cossou et al., 2014).