Rocklines as Cradles for Cosmic Spherules

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ABSTRACT

In our solar system, terrestrial planets and meteoritical matter exhibit various bulk compositions. To understand this variety of compositions, formation mechanisms of meteorites are usually investigated via a thermodynamic approach that neglect the processes of transport throughout the protosolar nebula. Here, we investigate the role played by rocklines (condensation/sublimation lines of refractory materials) in the innermost regions of the protosolar nebula to compute the composition of particles migrating inward the disk as a function of time. To do so, we utilize a one-dimensional accretion disk model with a prescription for dust and vapor transport, sublimation and recondensation of refractory materials (ferrosilite, enstatite, fayalite, forsterite, iron sulfur, kamacite and nickel). We find that the diversity of the bulk composition of cosmic spherules can be explained by their formation close to rocklines, suggesting that solid matter is concentrated in the vicinity of these sublimation/condensation fronts. Although our model relies a lot on the number of considered species and the availability of thermodynamic data governing state change, it suggests that rocklines played a major role in the formation of small and large bodies in the innermost regions of the protosolar nebula. Our model gives insights on the mechanisms that might have contributed to the formation of Mercury’s large core.

Keywords: planets and satellites: composition, planets and satellites: formation, protoplanetary disks, methods: numerical

1. INTRODUCTION

Meteorites and terrestrial planets show varying proportions of silicates and metallic iron, with Fe being distributed between Fe alloys and silicates (Nittler et al. 2000; Folco & Cordier 2015). Chondrites are the most common meteoritical bodies found on Earth, whose unaltered structure gives valuable information on their formation conditions. Ca-Al-rich inclusions (CAI) that are found in carbonaceous chondrites are believed to be the first kind of refractory matter that formed in the early Solar System, with the oldest known CAI being 4568.22 ± 0.17 Myr old (Bouvier & Wadhwa 2010; Connolly et al. 2012). As a result, chondrules present in carbonaceous chondrites are thought to be the building blocks of the solar system, reflecting its early time composition. Another source of meteoritical matter are cosmic spherules (CS), which are micrometeorites formed by the melting of meteoritical matter during atmospheric entry, they are sorted by families and types, each one presenting its own structures and compositions (Sohl 2015; Taylor et al. 2000; Alexander et al. 2002; Cordier et al. 2011). Recent studies explored the link between CS and chondrites, showing that it is possible to associate one CS to its chondritic precursor based on its composition (Rudraswami et al. 2015; van Ginneken et al. 2017).

These composition differences are often attributed to the cooling of the inner disk where high temperature materials condense first (Grossman 1972; Taylor, & Scott 2001, 2004). However, the composition difference observed in meteoritic matter can also result from the temperature gradient within the PSN, where more refractory materials form at closer distances from the Sun. Abundances of materials both in solid and gaseous...
phases are ruled by the chemical status of the disk and by the location of their condensation/sublimation fronts (Dražkowska & Alibert 2017; Öberg & Wordsworth 2019; Pekmezci et al. 2019). Significant increases of the abundances of solid materials can be generated at the location of these transition lines, due to the dynamics of vapors and grains (Cyr et al. 1998, 1999; Bond et al. 2010; Ali-Dib et al. 2014; Desch et al. 2017; Mousis et al. 2019). These processes potentially explain the metallicity of Jupiter through its formation near the water snow-line (Mousis et al. 2019), as well as the high density of Mercury whose building blocks could have formed in regions where the abundances of Fe-bearing species are prominent (Taylor, & Scott 2004; Vander Kaaden et al. 2019).

Here, we use a coupled disk/transport model to investigate the role held by rocklines (the concept of snowlines extended to more refractory solids) of the most abundant solids into the shaping of Mg, Fe, and Si abundances profiles in the inner part of the PSN. The radial transport of solid grains through the different rocklines, coupled to the diffusion of vapors, leads to local enrichments or depletions in minerals and imply variations of Mg-Fe-Si composition of dust grains in the inner regions of the PSN. We discuss our results in light of the relative abundances and compositions of minerals observed in meteoritic matter and planetary bulk compositions. Our approach can be used to derive the formation conditions of the primitive matter in the PSN, and to give insights on the origin of Mercury as well as Super-Mercuries (Santerne et al. 2018; Brugger et al. 2019).

2. MODEL

2.1. Disk evolution

Our time-dependent PSN model is ruled by the following second-order differential equation (Lynden-Bell & Pringle 1974):

\[
\frac{\partial \Sigma_g}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left[ r^{1/2} \frac{\partial}{\partial r} \left( r^{1/2} \Sigma_g \nu \right) \right].
\]  

This equation describes the evolution of a viscous accretion disk of surface density \( \Sigma_g \) of dynamical viscosity \( \nu \), assuming hydrostatic equilibrium in the \( z \) direction. This equation can be rewritten as a set of two first-order differential equations coupling the gas surface density \( \Sigma_g \) field and mass accretion rate \( \dot{M} \):

\[
\frac{\partial \Sigma_g}{\partial t} = \frac{1}{2\pi r} \frac{\partial}{\partial r} \left( \frac{1}{2\pi r} \frac{\partial M}{\partial r} \right),
\]

\[
\dot{M} = 3\pi \Sigma_g \nu (1 + 2Q),
\]

where \( Q = \frac{d \ln (\Sigma_g \nu)}{d \ln r} \). The first equation is a mass conservation law, and the second one is a diffusion equation. The mass accretion rate can be expressed in terms of the gas velocity field \( v_g \) as \( \dot{M} = -2\pi r \Sigma_g v_g \).

The viscosity \( \nu \) is computed using the prescription of Shakura & Sunyaev (1973) for \( \alpha \)-turbulent disks:

\[
\nu = \alpha \frac{c_s^2}{\Omega_K},
\]

where \( \Omega_K = \sqrt{GM_\odot/r^3} \) is the keplerian frequency with \( G \) the gravitational constant, and \( c_s \) is the isothermal sound speed given by

\[
c_s = \sqrt{\frac{RT}{\mu_g}}.
\]

In this expression, \( R \) is the ideal gas constant and \( \mu_g = 2.31 \text{ g.mol}^{-1} \) is the gas mean molar mass (Lodders et al. 2009). In Eq. 4, \( \alpha \) is a non-dimensional parameter measuring the turbulence strength, which also determines the efficiency of viscous heating, hence the temperature of the disk. The value of \( \alpha \) typically lies in the range \( 10^{-4} - 10^{-2} \), from models calibrated on disk observations (Hartmann et al. 1998; Hueso & Guillot 2005; Desch et al. 2017).

The midplane temperature \( T \) of the disk is computed via the addition of all heating sources, giving the expression (Hueso & Guillot 2005):

\[
T^4 = \frac{1}{2\sigma_{sb}} \left( \frac{3}{8} \tau_R + \frac{1}{2\tau_T} \right) \Sigma_g \nu \Omega_K^2
\]

\[
+ T^4_{\odot} \left[ \frac{2}{3\pi} \left( \frac{R_\odot}{r} \right)^3 + \frac{1}{2} \left( \frac{R_\odot}{r} \right)^2 \left( \frac{H}{r} \right) \left( \frac{d \ln H}{d \ln r} - 1 \right) \right]
\]

\[
+ T^4_{\text{amb}}.
\]

The first term corresponds to the viscous heating (Nakamoto & Nakagawa 1994), where \( \sigma_{sb} \) is the Stefan-Boltzmann constant, and \( \tau_R \) and \( \tau_T \) are the Rosseland and Planck mean optical depths, respectively. For dust grains, we assume \( \tau_T = 2.4\tau_R \) (Nakamoto & Nakagawa 1994). \( \tau_R \) is derived from Hueso & Guillot (2005):

\[
\tau_R = \frac{\kappa_R \Sigma_g}{2},
\]

where \( \kappa_R \) is the Rosseland mean opacity, computed as a sequence of power laws of the form \( \kappa_R = \kappa_0 \rho^a T^b \), where parameters \( \kappa_0 \), \( a \) and \( b \) are fitted to experimental data in different opacity regimes (Bell, & Lin 1994) and \( \rho \) denotes the gas density at the midplane. The second term corresponds to the irradiation of the disk by
the central star of radius $R_\odot$ and surface temperature $T_\odot$. It considers both direct irradiation at the midplane and irradiation at the surface at a scale height $H = c_s/\Omega_K$. The last term accounts for background radiation of temperature $T_{\text{amb}} = 10$ K.

At each time step, $\Sigma_g$ is evolved with respect to equation (2). Then equation (6) is solved iteratively with Eqs. (4), (5), (7) to produce the new thermodynamic properties of the disk. Finally, the new velocity field is computed following (3). The time-step is computed using the diffusion timescale in each bin $\Delta t = 0.5 \text{ min}(\Delta r^2/\nu) \simeq 0.1$ yr, where $\Delta r$ is the spatial grid size, and the factor 0.5 is taken for safety. The spatial grid is formed of 500 bins scaled as $r_i = (r_{\text{min}} - r_{\text{off}}) \times i^\beta + r_{\text{off}}$, giving a non-uniform grid in which parameters $r_{\text{off}}$, an offset, and $\beta$ allow to control the number of points located in different regions of the disk. We compute the sum of the mass lost from both limits of the simulation box ($\int M(r_{\text{min}}) dt$ and $\int M(r_{\text{max}}) dt$) along with the mass of the disk itself at each time. This quantity remains constant within $10^{-11}\%$, which is typically induced by the precision of the machine.

The initial condition is the self-similar solution $\Sigma_g \nu \propto \exp(-r/r_c)^{2-\nu}$ derived by Lynden-Bell & Pringle (1974). Choosing $\nu = \frac{3}{2}$ for an early disk, we derive the initial surface density and mass accretion rate as follows:

$$
\begin{cases}
\Sigma_{g,0} = \frac{M_{\text{acc},0}}{3 \pi \nu} \exp \left[ - \left( \frac{r}{r_c} \right)^{0.5} \right], \\
M_0 = M_{\text{acc},0} \left( 1 - \left( \frac{r}{r_c} \right)^{0.5} \right) \exp \left[ - \left( \frac{r}{r_c} \right)^{0.5} \right].
\end{cases}
$$

(8)

To compute the numerical value of $\Sigma_{g,0}$, we solve iteratively equation (6) with the imposed density profile in the first member of equation (8). $r_c$ regulates the size of the disk, and from the second member of equation (8) we see that it matches, at $t = 0$ to the centrifugal radius.

The value of $r_c$ is computed by dichotomy, assuming a disk mass $M_d$ of 0.1 $M_\odot$. For $\alpha = 10^{-3}$, $r_c$ is equal to 1.83 AU, and 99% of the disk's mass is encapsulated within $\sim 100$ AU. We assume the initial mass accretion rate onto the central star $M_{\text{acc},0}$ to be $10^{-7.6}$ (Hartmann et al. 1998). The resulting density and temperature profiles are shown in Figure 2 at different epochs for $\alpha = 10^{-3}$.

2.2. Size of dust particles

The size of dust particles used in our model is determined by a two-populations algorithm derived from Birnstiel et al. (2012). This algorithm computes the representative size of particles through the estimate of the limiting Stokes number in various dynamical regimes. We assume that dust is initially present in the form of particles of sizes $a_0 = 10^{-7}$ m, and grow through mutual collisions on a timescale (Lambrechts & Johansen 2014):

$$
\tau_{\text{growth}} = \frac{a}{a_0} = \frac{4 \Sigma_g}{\sqrt{3 \epsilon_g \Sigma_d \Omega_K}},
$$

(9)

where $a$ is the size of dust grains and $\Sigma_d$ is the dust surface density. We set the growth efficiency parameter $\epsilon_g$ equal to 0.5 (Lambrechts & Johansen 2014). The size of particles that grow through sticking is thus given by $a_{\text{stick}} = a_0 \exp(t/\tau_{\text{growth}})$. However, this growth is limited by several mechanisms preventing particles from reaching sizes greater than $\sim 1$ cm. The first limit arises from fragmentation, when the relative speed between two grains due to their relative turbulent motion exceeds the velocity threshold $u_\ell$. This sets a first upper limit for the Stokes number of dust grains, which is (Birnstiel et al. 2012):

$$
\text{St}_{\text{frag}} = 0.37 \frac{1}{3 \alpha \epsilon_g^2},
$$

(10)

where we set $u_\ell = 10$ m.s$^{-1}$ (Birnstiel et al. 2012; Mousis et al. 2019).

A second limitation for dust growth is due to the drift velocity of grains, i.e. when grains drift faster than they grow, setting another limit for the Stokes number (Birnstiel et al. 2012):

$$
\text{St}_{\text{drift}} = 0.55 \frac{\Sigma_d \nu_K^2}{\Sigma_g c_s^2} \frac{d \ln P}{d \ln r}^{-1},
$$

(11)

where $\nu_K$ is the keplerian velocity, and $P$ is the disk midplane pressure.

Equation (10) only considers the relative turbulent motion between grains that are at the same location, but the fragmentation threshold $u_\ell$ can also be reached when dust grains drift at great velocities, and in the process collide with dust grains that are on their path. In that case, we obtain a third limitation for grains’ size (Birnstiel et al. 2012):

$$
\text{St}_{\text{df}} = \frac{1}{(1 - N) \epsilon_g} \frac{u_\ell \nu_K}{c_s^2} \left( \frac{d \ln P}{d \ln r} \right)^{-1},
$$

(12)

where the factor $N = 0.5$ accounts for the fact that only particles of bigger size fragment during collisions.
The relation between Stokes number and dust grains size depends on the flow regime in the disk (Johansen et al. 2014):

\[
St = \begin{cases} 
\sqrt{\frac{2\pi a^2 \rho_b}{\Sigma}} & \text{if } a \leq \frac{9}{4} \lambda \\
\frac{8 a^2 \rho_b c_s}{\Sigma} & \text{if } a \geq \frac{9}{4} \lambda,
\end{cases}
\]  

where \(\rho_b\) is the bulk density of grains. The first case correspond to the Epstein’s regime, occurring in the outermost region of the disk, and the second case corresponds to the Stokes regime. The limit between the two regimes is set by the mean free path \(\lambda = \sqrt{\pi/2} \cdot \nu/c_s\) (computed by equating both terms of Eq. (13)) in the midplane of the disk. One can compute sizes \(a_E\) and \(a_S\), and Stokes numbers \(St_E\) and \(St_S\) in Epstein and Stokes regimes (respectively) separately, and as shown by the sketch in Figure 1 the representative size and Stokes number become

\[
a = \min (a_E, a_S),
\]

\[
St = \max (St_E, St_S).
\]  

In the following, two end-cases are considered. In case A, we assume that all trace species are entirely independent, i.e. a run with several species is equivalent to several runs with a single traces species at a time. In case B, we assume that at each orbital distance, dust grains are a mixture of all available solid matter at that distance. For this case, the considered dust surface density is the sum over all surface densities \(\Sigma_d = \sum_i \Sigma_{d,i}\) and the bulk density \(\rho_b\) of resulting grains is the mass-average of the bulk densities of its constituents (given in Table 1):

\[
\rho_b = \frac{\sum_i \Sigma_{d,i} \rho_{b,i}}{\sum_i \Sigma_{d,i}}
\]  

Case B is favored from a dynamical point of view, as dust grains of different composition mix over long timescales, whereas case A is favored from a thermodynamic point of view, since sublimation and condensation tend to separate species into their pure forms. Since we focus on rocklines, whose positions are all at distances \(\leq 1\) AU, we consider our disk volatile-free. In our model, the closest iceline would be that of \(H_2O\) and located around 4 AU, which we consider far enough to ignore its impact on processes at play around rocklines.

2.3. Evolution of vapors and dust

We follow the approaches of Desch et al. (2017) and Drażkowska & Alibert (2017) for the dynamics of trace species in term of motion and thermodynamics, respectively. The disk is uniformly filled with seven refractory species considered dominant (see Table 1), assuming protosolar abundances for Fe, Mg, Ni, Si and S (Lodders et al. 2009), similar Fe/Mg ratios in olivine and pyroxene, and that half of Ni is in pure metallic form while the remaining half is in kamacite.

Sublimation of grains occurs during their inward drift when partial pressures of trace species become lower than the corresponding vapor pressures. Once released, vapors diffuse both inward and outward. Because of the outward diffusion, vapors can recondense back in solid form, and condensation occurs either until thermodynamic equilibrium is reached or until no more gas is available to condense. Over one integration time step \(\Delta t\), the amount of sublimated or condensed matter is

\[
\Delta \Sigma_{\text{subl},i} = \dot{Q}_{\text{subl},i} \Delta t
\]

\[
= \min \left( \frac{6\sqrt{2\pi}}{\pi \rho_b a} \sqrt{\frac{\mu_i}{RT} P_{\text{sat},i} \Sigma_{d,i} \Delta t}, \Sigma_{d,i} \right)
\]

Figure 1. Visual sketch showing the Stokes number St dependency with respect to the particle size \(a\), in both considered flow regimes. When \(a < 9\lambda/4\), particles follow Epstein regime. When \(a > 9\lambda/4\), particles follow Stokes regime. In both cases, the relevant size is the smallest among the two, and the relevant Stokes number is the greatest, which are depicted as the red dot-dashed line.
where $\mu_i$ is the molar mass of a given trace species, $P_{\text{sat},i}$ its saturation pressure and $P_{v,i}$ its partial pressure at a given time and place in the PSN. The second term of the min function ensures that the amount of sublimated (resp. condensed) matter is at most the amount of solid and vapor of a given species $i$ are equal. Species exist mostly in solid forms at greater heliocentric distances than their rocklines while they essentially form vapors at distances closer to the central star. Figure 3 shows the locations of the considered rocklines as a function of time in the PSN for both cases. No gas phase chemistry is assumed in the disk.

The motion of dust and vapor, who coexist as separate surface densities $\Sigma_{d,i}$ and $\Sigma_{v,i}$, is computed by integrating the 1D radial advection-diffusion equation (Birnstiel et al. 2012; Desch et al. 2017):

$$\frac{\partial \Sigma_i}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \left( \Sigma_i v_i - D_i \Sigma_g \frac{\partial}{\partial r} \left( \frac{\Sigma_i}{\Sigma_g} \right) \right) \right] + \dot{Q}_i = 0. \quad (19)$$

This equation holds for both vapor and solid phases since the motion is determined by the radial velocity $v_i$ and the radial diffusion coefficient $D_i$ of species $i$, $\dot{Q}$ being the source/sink term. When a species $i$ is in vapor form, we assume $v_i \simeq v_g$ and $D_i \simeq \nu$. When this species is in solid form, the dust radial velocity is the sum of the gas drag induced velocity and the drift velocity (Birnstiel et al. 2012):

$$v_d = \frac{1}{1 + St} v_g + \frac{2St}{1 + St} v_{\text{drift}}, \quad (20)$$

where the drift velocity is given by (Weidenschilling 1977; Nakagawa et al. 1986):

$$v_{\text{drift}} = \frac{c_s^2}{c_k} \frac{\ln P}{\ln r}. \quad (21)$$

This expression usually holds for a population of particles sharing the same size. However, we work here with the two-population algorithm from Birnstiel et al. (2012), i.e. the dust is composed of a mass fraction $f_m$ of particles of size $a$, and a mass fraction $1 - f_m$ of particles of size $a_0$. The dust radial velocity can be then approximated by a mass-weighted velocity:

$$v_i = f_m v_{d,\text{size } a} + (1 - f_m) v_{d,\text{size } a_0}, \quad (22)$$

where $v_{d,\text{size } a/a_0}$ is calculated with respect to Eq. (20), $St$ is computed for both populations at each heliocentric distance, and $f_m$ depends on the size limiting mechanism (Birnstiel et al. 2012):

$$f_m = \begin{cases} 0.97 \text{ if } St_{\text{drift}} = \min(St_{\text{frag}}, St_{\text{drift}}, St_{\text{df}}) \\ 0.75 \text{ otherwise.} \end{cases}$$

Due to the low Stokes number of dust grains ($St < 1$), we make the approximation $D_i = \frac{v_i}{1+St_i} \simeq \nu$.

3. RESULTS

Figures 4 and 5 represents the time evolution of the composition of refractory particles evolving throughout the PSN in a Mg-Fe-Si ternary diagram (left panels) and as Fe wt% (right panels). Solid particles start with a protosolar composition which changes during their drift throughout the innermost regions of the PSN, due to the successive sublimation of minerals. Because alloys, which contain only Fe, S and Ni, are the first to sublimate (see Fig. 3), solid particles loose a substantial amount of iron, from $\sim 50\%$ to $\sim 20\%$, but not Mg and Si, so that in the ternary diagram the composition profiles shift toward the Mg-Si axis with an unchanged Mg/Si ratio. Closer to the Sun, Ferrosilite and Fayalite begin to sublimate until no Fe remains in solid form. In this case, the composition profiles in ternary diagrams are located on the Mg-Si axis, and because some silicon is vaporized too, the Mg/Si ratio increases. Finally, if the temperature is high enough to melt Forsterite, only Enstatite remains in solid particles, with an atomic ratio (Mg/Si)$_{\text{at}} = 1$ corresponding to 46 wt% of Mg. In case A, different trace species are allowed to migrate at different velocities, leading to a slightly wider range of possible compositions in the PSN, but the differences between the two runs are minor from a compositional point of view.

Top panels of Fig. 7 show the radial profiles of the disk’s metallicity (defined as $Z = \Sigma_d/\Sigma_g$) at different epochs of its evolution. As expected, solid matter is concentrated at the position of rocklines. The composition of the PSN around the first cluster of rocklines (iron sulfur, kamacite and nickel) corresponds to the 30-60 wt% Fe part of curves in ternary diagrams and Fe wt% profiles, which matches the S-BO type (barred olivine).
spherules compositions. The composition of the PSN around the second cluster of rocklines (fayalite and ferrosilite) corresponds to the 10-30 wt% Fe part of curves in the ternary diagram and Fe wt% profiles, matching the S-V type (glass) spherules compositions. In the same manner, we would expect chondrules to be formed in the innermost regions, were sufficient amount of material is present due to continuous drift from outwards. However, the physics of our model are limited and do not allow to reduce the inner bound of the computational box. At $t = 10^5 \text{ yr}$ and 0.67 AU (rockline of iron sulfur), the PSN has 56 wt% and 58 wt% of Fe in case A and case B, respectively. This increase of the Fe wt% leads to compositions of the PSN richer in Fe than the protosolar value.

Finally, bottom panels of Fig. 7 show the Stokes number of dust grains in the disk. Because case A has many independent species evolving, we only follow forsterite, fayalite and iron sulfur, namely the most, least, and intermediate refractory materials considered in our particles. In case B, all grains are mixed together, giving a single Stokes number at each heliocentric distance. Using Eqs. (10), (11) and (12), we expect i) $S_{\text{frag}} \propto 1/T$, ii) $S_{\text{drift}} \propto Z/(rT)$ and iii) $S_{\text{diff}} \propto 1/(\sqrt{T})$ (assuming $|\frac{\text{dln} P}{\text{dln} T}|^{-1} \propto 1$). In the innermost region, dust size is limited by fragmentation up to $\sim 5$ AU. In the 5-10 AU range, a competition between drift and drift-limited fragmentation sets the dust grains size. Beyond 10 AU dust is in the growth phase.

In case A, variations in limiting sizes only come from the difference in bulk densities of grains. As a result, different species display the same Stokes number during most of their drift throughout the PSN (see bottom left panel of Fig. 7). However, because the amount of solid matter decreases below 10 AU, as a result of sublimation and/or radial drift, the Stokes number diminishes as well. In case B, minor species embedded in large grains are transported more efficiently toward their rocklines. Hence, higher metallicities are found around the rocklines in case B compared to case A, at early epochs. In turn, the PSN becomes depleted in solid matter in shorter timescales in case B compared to case A.

As stated in section 2.1, $\alpha$ is a free parameter, whose value can change with time and heliocentric distance. For this disk model, an increase in $\alpha$ leads to a greater centrifugal radius $r_{c}$, which in turn leads to a larger disk. For trace species, a greater value of $\alpha$ leads to a greater diffusion coefficient $D_{\alpha} = \nu$. As a consequence, vapors diffuse outward faster and enrich the solid phase more evenly. This results in peaks of abundance (as those observed in right panels of Figs. 4 and 5) wider, but smaller in size. For the extreme case $\alpha = 10^{-2}$, the peaks of abundance are not observable anymore. This shows that the choice on $\alpha$ is critical for both the PSN and trace species evolution. However, results of simulations with non-uniform $\alpha$ show that $\alpha$ is increasing with heliocentric distance, and takes values of $\sim 10^{-3}$ at 1 AU (Kalyaan et al. 2015, see). Since we are mostly interested in the dynamics of the inner PSN, we choose $\alpha = 10^{-3}$ as a mean value valid for the inner PSN.

4. DISCUSSION AND CONCLUSION

Our model shows that the diversity of the bulk composition of cosmic spherules can be explained by their formation close to rocklines, suggesting that solid matter is concentrated in the vicinity of these sublimation/condensation fronts. However our model is limited to the study of pebbles only, and additional physical ingredients are required to form planetesimals and compute their effect on dust grains. Formed planetesimals will have the same composition as trace species in the PSN, but their interaction is of gravitational nature. Finally, we need to invoke dynamical models such as the Grand Tack or Nice models to explain how these planetesimals, with compositions shaped by rocklines, have been redistributed in the solar system to the location where they are today.

Interestingly, these high concentrations do not allow the triggering of streaming instability. The smallest metallicity $Z_{c}$ required to trigger a streaming instability for low Stokes number regimes ($St < 0.1$) is (Yang et al. 2017):

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### Table 1. Trace species present in the disk with corresponding initial abundances and references for saturation pressures $P_{\text{sat}}$.

| Type   | Name         | Formula     | $n_{i} = (X_{i}/H_{2})$ | $\rho_{i}$ (g.cm$^{-3}$) | $P_{\text{sat}}$ |
|--------|--------------|-------------|--------------------------|--------------------------|-----------------|
| Pyroxene | Ferrosilite  | FeSiO$_{3}$ | $9.868 \times 10^{-6}$  | 3.95                     | Nagahara et al. (1994) |
|        | Enstatite    | MgSiO$_{3}$ | $4.931 \times 10^{-5}$  | 3.20                     | Tachibana et al. (2002) |
| Olivine | Fayalite     | Fe$_{2}$SiO$_{4}$ | $2.897 \times 10^{-6}$  | 4.39                     | Nagahara et al. (1994) |
|        | Forsterite   | Mg$_{2}$SiO$_{4}$ | $1.452 \times 10^{-5}$  | 3.22                     | Nagahara et al. (1994) |
| Alloys  | Iron sulfur  | FeS         | $3.266 \times 10^{-5}$  | 4.75                     | Ferro & Scardala (1989) |
|        | Kamosite     | Fe$_{0.9}$Ni$_{0.1}$ | $1.875 \times 10^{-5}$  | 7.90                     | Alcock et al. (1984) |
| Nickel  | Ni           | Ni           | $1.875 \times 10^{-6}$  | 8.90                     | Alcock et al. (1984) |
log $Z_c = 0.10 (\log St)^2 + 0.20 \log St - 1.76.$ \hspace{1cm} (23)

Figure 7 shows that the highest disk metallicity computed with our model, i.e. at $t = 10^7$ yr and $r = 0.1$ AU in case B, is $Z = 4.4 \times 10^{-3}$, way below $Z_c = 2.7 \times 10^{-2}$, suggesting our model does not allow the triggering of a streaming instability. However, the decoupling of dust grains from gas at greater Stokes numbers or the back-reaction of dust onto the gas could slow down the drift of particles in the pile-up regions, thus increasing the local dust-to-gas ratio.

Other origins for chondrules have been proposed, such as high temperature bow shocks around planetesimals (Boley et al. 2013). However, the drift of dust grains induce both depletion in the outermost regions and concentration around rocklines. The scenario of matter processed by rocklines has the advantage of making processed matter the dominant component. Although the spread in bulk compositions of CS can be well explained by alteration during atmospheric entry (Rudraswami et al. 2015), the two scenarios are not exclusive. Further investigation is required to answer this question such as the computation of compositions of a population of grains, which could be the aim of a future work.

Although our model relies a lot on the number of considered species and the availability of thermodynamic data governing state change, it suggests that rocklines played a major role in the formation of small and large bodies in the innermost regions of the PSN. For example, even if the large amount of iron in Mercury (83 wt% in the ternary diagram) cannot be explained with this model alone, the increased proportion of Fe in the PSN (62 wt% at most in the vicinity of rocklines; see Figs. 4 and 5) from the protosolar value (47 wt%) might have contributed to the accretion of Mercury’s large core by forming Fe-rich regions. As our model only tracks the evolution of dust grains in the early PSN, it is compatible with any planetary formation mechanism. The relevant PSN composition in terms of PSN age and heliocentric distance must then be chosen accordingly to the considered formation scenario. In particular, it is compatible with a collisional evolution of Mercury, lowering the constraints on collisional parameters and the size of the impactor for currently existing models that assume initial protosolar composition of early Mercury (Chau et al. 2018), making them more likely. This conclusion is strengthened by the fact that at greater heliocentric distances we recover a protosolar composition of the PSN (mainly for case B), which is in agreement with the bulk composition of Earth and Venus derived from interior structure models.

In the context of extrasolar planetary systems, this study suggests that Mercury-like planets, dense planets that are believed to have a high iron content, are a rule rather than an exception. The presence, or absence, of Mercury-like planets would be ruled by the amount of available matter to form the Fe-rich planets. Although the temperature profile and thus the position of rocklines is model-dependent, their relative position is model-independent. As a result, in a very massive protostellar nebulae it would be possible to form Fe-poor planets, prior to the iron sulfur and kamacite rocklines. This could be a lead to explain why Mercury-like planets are not always the first in extrasolar systems. Such a system could also be massive enough to produce planets known as super-Earths, using the matter concentrated around rocklines. Finally, the results presented here are for moderately turbulent disks ($\alpha = 10^{-3}$). It is very likely that other systems, especially those with very active protostars, are more turbulent, and thus evolve faster, which leads to a greater diversity of possible extrasolar planetary systems.

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Figure 2. From top to bottom: disk’s surface density and temperature profiles at different epochs of its evolution, assuming $\alpha = 10^{-3}$.

Figure 3. Time evolution of the locations of rocklines in the PSN. Solid and dashed lines correspond to cases A and B, respectively (see text). Only minor differences between the two cases are observed, resulting from changes in radial drift velocities of particles.

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**Figure 4.** Left pannel: composition of refractory matter in a Mg-Fe-Si ternary diagram expressed in mass fraction between $t = 10^4$ and $2 \times 10^6$ yr of the PSN evolution with $\alpha = 10^{-3}$ and for case A (all trace species independent). Purple triangles correspond to glass cosmic spherules (S-V type) (Taylor et al. 2000), suggesting they were formed by condensation in the vicinities of Fe oxides rocklines. Green circles correspond to barred olivine spherules (S-BO type) (Cordier et al. 2011) that potentially formed via mixing in the region of iron alloys rocklines. Green squares represent porphyritic spherules (S-P type) from the same collection. Yellow triangles correspond to a random selection of chondrules from various samples studied in Hezel & Palme (2010). Sun and Earth symbols correspond to protosolar and Earth bulk compositions, respectively (Sotin et al. 2007). The red circle represents Mercury’s bulk composition (Brugger et al. 2018).

Right pannel: corresponding iron wt% in solids profiles as a function of heliocentric distance. The different colorboxes correspond to rough iron content of chondrules (0-10%), glass cosmic spherules (10-30%) and porphyritic and barred olivine cosmic spherules (30-60%).

**Figure 5.** Same as figure 4, but for case B.

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Figure 6. Ternary diagram showing profiles from figure 4, with compositions of chondrules, matrixes and mean chondritic types. Chondrules (yellow triangles) and matrix (grey squares) composition are taken from Hezel & Palme (2010). Mean bulk chondrites compositions are taken from ?. 

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Figure 7. Local metallicity $Z = \Sigma_d/\Sigma_g$ (top panels) and Stokes number (bottom panels) computed as a function of time and heliocentric distance. Left and right panels are results for case A and case B, respectively (see text). Stokes number is shown at $t = 10^6$ yr for a few representative species (left panel) and at different epochs of the PSN evolution (right panel). Dashed lines in top panels show the lowest metallicity $Z_c$ required to trigger streaming instability (see text).