



Chemical composition of Earth-like planets

M. P. Ronco^{1,2}, A. Thiabaud³, U. Marboeuf³, Y. Alibert^{3,4}, G. C. de Elía^{1,2} & O. M. Guilera^{1,2}

¹ *Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Argentina*

² *Instituto de Astrofísica La Plata, Consejo Nacional de Investigaciones Científicas y Técnicas - Universidad Nacional de La Plata, Argentina*

³ *Physics Institute and Center for Space and Habitability, University of Bern, Switzerland*

⁴ *Observatoire de Besançon, France*

Contact/ MPR: mpronco@fcaglp.unlp.edu.ar

Resumen / Los modelos de formación planetaria se enfocan principalmente en el estudio de los procesos de acreción y evolución dinámica de los planetas sin tener en cuenta su composición química. En este trabajo, calculamos la secuencia de condensación de los diferentes elementos químicos para un disco protoplanetario de baja masa alrededor de una estrella tipo solar. Incorporamos esta secuencia de elementos químicos (materiales refractarios y moléculas volátiles) en nuestro modelo semianalítico de formación planetaria que calcula el proceso de formación de un sistema planetario durante su etapa gaseosa. Los resultados de este modelo, distribución final de embriones y planetesimales, son utilizados como condiciones iniciales para desarrollar simulaciones de N cuerpos que computan la formación post oligárquica de planetas tipo terrestres. Los resultados de nuestras simulaciones indican que la composición química de los planetas que permanecen en la zona de habitabilidad presenta características similares a la composición química de la Tierra aunque existen diferencias que pueden deberse al ambiente dinámico en el cual se formaron.

Abstract / Models of planet formation are mainly focused on the accretion and dynamical processes of the planets, neglecting their chemical composition. In this work, we calculate the condensation sequence of the different chemical elements for a low-mass protoplanetary disk around a solar-type star. We incorporate this sequence of chemical elements (refractory and volatile elements) in our semi-analytical model of planet formation which calculates the formation of a planetary system during its gaseous phase. The results of the semi-analytical model (final distributions of embryos and planetesimals) are used as initial conditions to develop N-body simulations that compute the post-oligarchic formation of terrestrial-type planets. The results of our simulations show that the chemical composition of the planets that remain in the habitable zone has similar characteristics to the chemical composition of the Earth. However, exist differences that can be associated to the dynamical environment in which they were formed.

Keywords / Planets and satellites: terrestrial planets — formation — composition

1. Introduction

Alibert et al. (2005, 2013) developed a model to calculate the structure and evolution of a protoplanetary disk solving the vertical structure of the disk at each radial distance from the central star. Defining the mass of the central star, the mass of the disk, and the initial surface density profile, this model allows us to calculate the initial radial profiles of the temperature and pressure of the disk. These thermodynamic parameters are then used to calculate the condensation sequence of the different chemical elements assuming chemical equilibrium*. The distribution of chemical elements includes information about the abundance of the most important elements, the formation of refractory material and the condensation of volatile molecules, as H₂O, CO, CO₂, CH₄, H₂S, N₂, NH₃ and CH₃OH, along the disk. All this information is incorporated in our semi-analytical model of planet formation (Brunini & Benvenuto, 2008;

Guilera et al., 2010), which calculates the formation of a planetary system, considering the *in situ* formation of the embryos, during the gaseous phase of the disk. The final distributions of embryos and planetesimals calculated by the semi-analytical model are used as initial conditions to carry out N-body simulations to compute the post-oligarchic formation of terrestrial-type planets. The results of the N-body simulations allow us to study the collisional history of each body in the system and thus, we can determine the final chemical composition of each planet, specially those that remain in the habitable zone (HZ).

2. Initial conditions

Following our previous work (Ronco & de Elía, 2014), we adopted a disk of mass $M_d = 0.03 M_\odot$ with an initial gas surface density profile given by

$$\Sigma = \Sigma_0^g \left(\frac{R}{R_c} \right)^{-\gamma} e^{-(R/R_c)^{(2-\gamma)}}, \quad (1)$$

* To do this we used the comercial software HSC Chemistry for refractory species and the cooling curve of the disk (Marboeuf et al., 2014) for volatile molecules.

where $R_c = 50$ AU is a characteristic radius of the disk, $\gamma = 1.5$ is the slope of the profile and Σ_0^g is a constant of normalization which is function of γ , R_c and the mass of the disk.

Using Eq. 1, the model of Alibert et al. (2005) calculated the initial radial profiles of the temperature and the pressure. The thermodynamic profile allowed us to calculate the condensation sequences of refractory and volatile elements assuming that the disk is initially chemically homogeneous everywhere (see Figure 1). Assuming that the chemical composition of the planetesimals is given by the condensation sequences, we thus computed the initial planetesimal surface density. It is worth noting that in this work, the snow line is shifted a little bit outside (3 AU according to Marboeuf et al. (2014)) compared to our previous work (2.7 AU according to Hayashi 1981). The amount of solid material due to the condensation of water beyond the snow line is lower (about 1.75) compared to our previous work (4 following Hayashi 1981).

We incorporated these initial surface density profiles (gas and planetesimals) in our semi-analytical model of planet formation and we calculated the initial distribution of embryos: the first embryo is located at the inner radius of the disk (0.5 AU) and the rest of the embryos are separated by 10 mutual Hill radii (the mutual Hill radius between two bodies of semimajor axis a_1 and a_2 and masses M_1 and M_2 is defined by $R_{H,m} = 0.5(a_1 + a_2)[(M_1 + M_2)/(3M_\odot)]^{1/3}$) until they reached 5 AU; the mass of each embryo is the corresponding to the transition mass between runaway and oligarchic growth (Ida & Makino, 1993). Then, the system evolves until the gas has disappeared (3 Myr). As in de Elía et al. (2013) and in a new work in preparation, embryos grow by the accretion of other embryos (when the distance between two embryos becomes lower than 3.5 mutual Hill radii we consider perfect merging) and planetesimals. Since embryos are formed in situ, their chemical composition will be, for simplicity, the same composition of the accreted planetesimals at a given distance from the central star. Therefore, after 3 Myr of evolution, we obtain the distributions of embryos and planetesimals when the gas in the disk is dispersed (Figure 2). These final distributions are considered as initial conditions for the N-body simulations to calculate the post-oligarchic growth of the system. From these initial conditions, we generated four simulations distributing randomly the orbital elements of the embryos and planetesimals. We used the MERCURY code (Chambers, 1999) using an integration time-step of 6 days in order to calculate with enough precision the most inner orbit. Since terrestrial planets in our solar system might have formed in 100 Myr - 200 Myr we integrated each simulation for at least 200 Myr.

3. Results

All our simulations present planets in the optimistic HZ (Kopparapu et al., 2013) with masses ranging from $1.52M_\oplus$ to $4M_\oplus$. The planets incorporate between 6.37% and 16.41% of volatile material according to their total mass. Water is the most abundant specie,

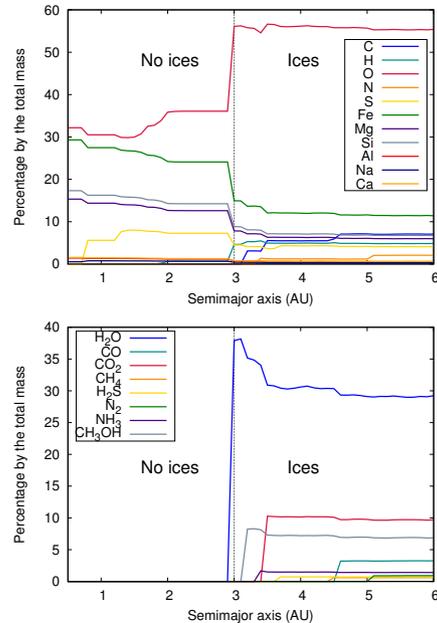


Fig. 1: Top panel: Total abundances of the most significant chemical elements that result from the condensation sequence. Bottom panel: Distribution of the most significant volatile molecules (in percentage by mass) product of the condensation sequence. The solid material necessary to complete the total of the mass at each radial distance remains in refractory material. This means that there are not condensed volatile molecules in the inner region delimited by the snow line (located at ~ 3 AU and represented by the dashed line).

with values ranging from 4.29% to 13.19% by mass (Figure 3). In general, the final abundances of the chemical elements obtained in the HZ planets are similar to those derived by Kargel & Lewis (1993) (see Table 1) for the Earth. However, the planets that remain in the optimistic HZ show a mark deficit in the final amount of iron as well as an excess of oxygen and carbon.

It is interesting to analyze both, similarities and differences, obtained in the final abundances of chemical elements between the resulting HZ planets in our simulations and the Earth. On the one hand, the equivalences obtained may suggest similarities in the initial distribution of chemical elements in the protoplanetary disk. On the other hand, the differences could be at-

Table 1: Planetary abundances in % by mass of Mercury and Venus (Morgan & Anders, 1980), the Earth (Kargel & Lewis, 1993), Mars (Lodders & Fegley, 1997) and the range of values for the planets in the HZ in our simulations.

	Mercury	Venus	Earth	Mars	Simulations
Fe	64.47	31.17	32.04	27.24	21.34 - 24.70
O	14.44	30.9	31.67	33.75	35.23 - 41.93
Mg	6.5	14.54	14.8	14.16	11.17 - 12.93
Al	1.08	1.48	1.43	1.21	1.03 - 1.19
Si	7.05	15.82	14.59	16.83	12.61 - 14.59
Ca	1.18	1.61	1.6	1.33	0.56 - 0.65
C	0.0005	0.05	0.004	0.29	0.55 - 1.03
Na	0.02	0.14	0.25	0.57	1.14 - 1.31

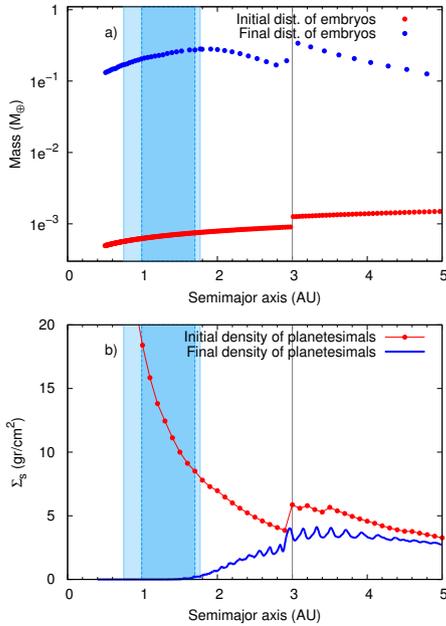


Fig. 2: a) Initial (red points) and final (blue points) distributions of embryos calculated with our semi-analytical model. b) Initial (red line-points) and final (blue line) planetesimal surface densities obtained with our semi-analytical model. In both plots, the clear light-blue zone represents the optimistic HZ (between 0.75 AU and 1.77 AU) while the light-blue zone represents the conservative HZ (between 0.99 AU and 1.7 AU) according to Kopparapu et al. (2013).

tributed primarily to discrepancies associated with the dynamic environment in which planets are formed. Indeed, unlike what happens with the terrestrial planets in the Solar System, the planets in our simulations are formed in the absence of gas giants. These differences naturally lead to distinct dynamical histories for terrestrial planets formed in both systems, so it is expected to obtain differences in the final abundances of chemical elements. Moreover, the abundances of planets formed in our simulations were obtained assuming that collisions are perfectly inelastic. Thus, a more realistic treatment of collisions could provide us with a more accurate calculation of the final abundances.

The abundances of chemical elements of the planets that remain in the optimistic HZ (Figure 4) are also similar to those typical abundances found by Thiabaud et al. (2014) for rocky planets around a solar-type star. However, a comparative analysis between both works should be carried out carefully since the abundances computed for planets in our simulations are obtained after the dissipation of the gas in the system, and Thiabaud et al. (2014) analyzed the formation processes of terrestrial planets until the dissipation of the gaseous component in the disk.

4. Conclusions

Starting from initial conditions obtained with a semi-analytical model, we performed planetary systems with terrestrial planets within the optimistic HZ. After 200

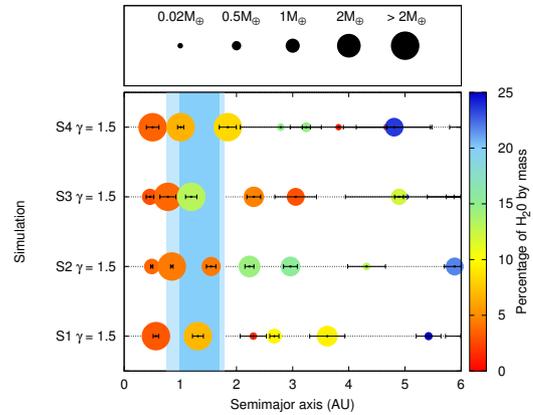


Fig. 3: Final configuration of the 4 N-body simulations. The color scale represents the fraction of water of the planets relative to their masses, the shaded regions, the optimistic and conservative HZ. The eccentricity of each planet is shown over it, by its radial movement over an orbit. All the simulations present planets within the optimistic HZ and their water contents range from 4.29% to 13.19% by mass.

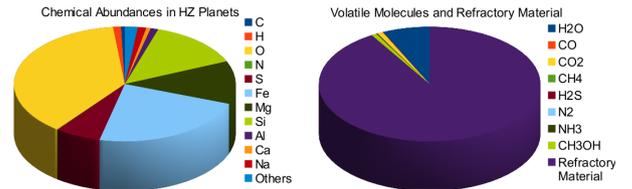


Fig. 4: Average chemical abundances and condensed volatile molecules in the final HZ planets.

Myr of evolution, the final masses and chemical abundances of these planets give similar results to that of the Earth. However, exist differences associated to the dynamical environment in which they are formed. In general, the characteristics of the planets that remain in the HZ, particularly their masses and amounts of water, indicate that they would be potentially habitable planets.

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