ÉCOLE DOCTORALE
SCIENCES DE LA TERRE ET DE L'ENVIRONNEMENT
ET PHYSIQUE DE L'UNIVERS, PARIS

Subject title: **The condensation sequence to the test of silicon isotopes**

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Financing: Doctoral contract with or without teaching assignment

General context

During the formation of the solar system, most chemical elements were introduced in the accretion disk in the form of presolar dust grains, the presolar gaseous phase being made dominantly of a H_2 + CO gas with some other volatiles such as nitrogen or rare gases. The three major components making primitive chondrites (Ca-, Al-rich inclusions or CAIs, chondrules and matrix) formed at various temperatures and times in the accretion disk (e.g. [1]). Their chemistry and mineralogy suggest that their precursors result from condensation of a gas of Solar (or close to Solar) composition made by the evaporation of presolar dust. This process, known as the "condensation sequence" [2, 3], is probably the most important paradigm in cosmochemistry (to compare for instance to plate tectonics in geology). However, the applicability of the theoretical equilibrium condensation sequence [3, 4] to the origin of the components of primitive meteorites remains unclear either (i) because some of these components such as CAIs suffered from very complex post-condensation high-temperature histories strongly modifying their composition e.g. [5], or (ii) because the condensation sequence is very difficult to reproduce by experiments in the laboratory [6]. In addition, recent models describing the formation of the accretion disk during the infall of the parent presolar cloud show that, despite high temperatures develop in the inner disk due to radiative and viscous heating, presolar dust can be either vaporized, thermally processed or preserved, depending whether it is injected in the disk close or far from the forming Sun e.g. [7].

Scientific questions

The goal of this PhD project is to further test the applicability of the condensation sequence to the origin of the precursors of chondritic components. This will be done by developing new proxies to better identify (i) silicates issued from the condensation sequence and (ii) presolar silicates variously preserved or processed, within chondritic components.

Most of the mass of condensable elements is made by O, Mg and Si. Thus, refractory silicates (melilite) and Mg-rich silicates (forsterite and enstatite) predicted to condense sequentially from a Solar gas (between 1625K and 1450K, and below 1450K, respectively, [3]) preserve in their composition a record of most of the condensation sequence. Si isotopes are potentially a very powerful tracer to identify the origin of the precursors of chondritic components because of (i) the large mass-dependent equilibrium isotopic fractionations at high-temperature between SiO gas and silicate (e. g. $\Delta^{30}Si_{enstatite\text{-}gas}$ increasing from ≈1‰ to 2‰ with temperature decreasing from 2000K to 1450K, [8]) and (ii) the large Si isotopic anomalies (10% level) of nucleosynthetic origin carried by presolar SiC grains e.g. [9]. Our latest developments show the feasibility of using Si isotopic compositions to constrain the origin of chondritic components [10]. Yet unpublished results by post-doc Zhengbin Deng and master students Raissa Pimentel and Haoxuan Sun (supervised by Marc Chaussidon and Frédéric Moynier) show for the first time that Si isotopic anomalies can be detected at the level of a few ppm only, opening the possibility to search in the matrix or in chondrules the imprint of presolar silicates. Note that Si isotopes would also be a proxy for the composition of the gas and its fO_2 since thermodynamic calculations show that (i) phases condensing and (ii) temperatures of condensation are very different in dust-enriched systems (oxidized) compared to canonic nebula (reduced) [3, 4].

Obviously, another major aspect of this PhD project will be to assemble a unique set of data allowing to test in an unprecedented way the key question of the existence and origin of the so-called complementarity between chondrules and matrix [11, 12]. "True" complementarity would imply that, for instance, the major silicates in the matrix were condensed from a nebular gaseous reservoir previously fractionated by the condensation of more refractory silicates forming the precursors of chondrules. Si isotopes could be used to track very precisely if the precursors of chondrules and matrix are derived from the same gaseous reservoir, if this reservoir was the same for different chondrites, and if chondrules and matrix are present in complementary amounts (i.e. so that the bulk chondrite has the isotopic composition of their parent gaseous reservoir).

Research schedule

The research schedule of a PhD cannot be defined a priori with great precision, and often new ideas emerge from the first results and this generally makes the PhD project a success. The unavoidable tasks to be done in the PhD are the following:

• selection of several chondritic meteorites for further studies.

This choice will be made easier by [13] giving the "Abundance, major element composition and size of components and matrix in CV, CO and Acfer 094 chondrite". Based on [13], chondrites where either the matrix or the chondrules host the major fraction of Si will be chosen. Other criteria (alteration, availability, previous studies, …) will be used. Separation of the components (e.g. chondrules) by physical means. Sectioning of chondrules, to be able to do, if pertinent, further microbeam techniques (SEM, FIB-TEM, electron microprobe, ion microprobe)

• analytical developments for Si isotopic analysis to reduce the amount of material required, at present 2 mg for a precision of ±0.05‰ 2 s. e. on mass-dependent isotopic variations and of ±3 ppm on non mass-dependent isotopic variations. Efforts will be put on improving both the precision and the sensitivity by using the Nu Instrument Sapphire HR-MCICPMS (installed in spring 2020 at IPGP)

• systematic first order mineralogy and petrology for all samples

• systematic study of the Si isotopic composition of the components (chondrules, isolated olivines, matrix) of at least 4 different chondrites. Because of the variability anticipated from our feasibility study on Allende, a large number of samples will be analysed for each component (e.g. at least 20 samples of matrix, or 20 bulk chondrules in a given chondrite)

• systematic study of chemical composition (major element and selected minor and trace elements)

• systematic mineralogical search for potential presolar Si-bearing phases in samples showing small Si isotopic anomalies in bulk, and further search of large Si isotope anomalies by nanosims

• modeling of the results using classical tools of petrology (e.g. phase diagrams) and of isotopic geochemistry (e.g. mass balance, box models, theory of isotopic fractionation, …) and integration of these results in a thermodynamic model of the condensation sequence (equilibrium, fractionated or not) using for instance the approach developed in [14].

• discussion of all the results (data and modeling) to test the existence of the condensation sequence, to constrain key physico-chemical parameters, to test the presence of matrix/chondrule complementarity and, if present, to find out its origin.

Depending on the results obtained, different other tracks might be explored such as combining Si isotopes with other isotopic systems (e. g. Ti isotopes, O isotopes, …) to bring additional constraints on the fraction or type of presolar components or on the conditions of condensation (or evaporation). Similarly, collaborations or exchanges with Francesco Pignatale (CAGE) might be extremely useful to put all the results in the physical context of the dynamics of the accretion disk.

References

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