INHERITANCE OF METEORITIC ISOTOPIC ANOMALIES FROM A ZONED PROTOSOLAR CLOUD

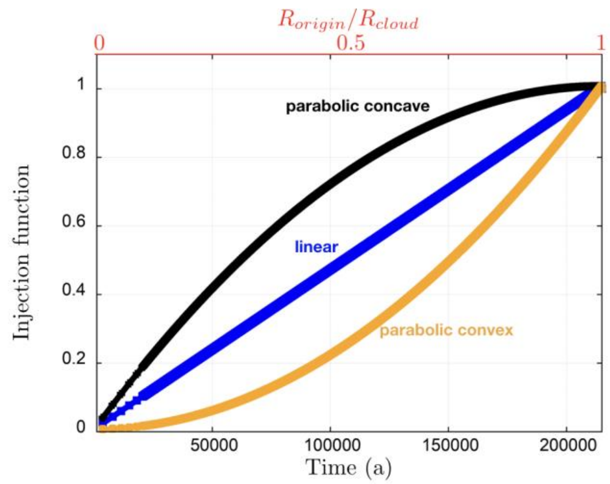
E. Jacquet[1], Francesco C. Pignatale[1,2]. [1]IMPMC, Muséum national d'Histoire naturelle, CP52, 57 rue Cuvier, 75005 Paris, France (Emmanuel.jacquet@mnhn.fr). [2]IPGP, 1 rue Jussieu, 75005 Paris, France.

Introduction: Among the isotopic anomalies shown by bulk meteorites and their macroscopic components such as Calcium-Aluminum-rich Inclusions (CAIs) [1], many can be ultimately traced to variable proportions of presolar grains which carry the isotopic signatures of their parent star's nucleosynthetic processes (whether these grains still survive or have passed on their atoms to Solar System-born solids). It remains to be understood why these proportions varied and thence how this connected with space and time. This would help to rationalize the classification of meteorites, in particular the carbonaceous/non-carbonaceous chondrite (CC/EOR) dichotomy which is especially striking in isotopic space [2], where the CC are systematically enriched in neutron-rich r-process isotopes compared to EOR [1,3].

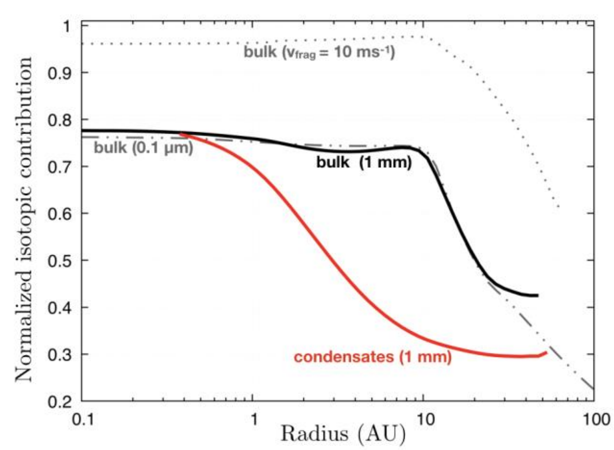
One school of thought is that some "thermal processing" preferentially evaporated some presolar grain populations [4-8], e.g. in the CAI-forming region(s). However, the elements affected by the isotopic anomalies span a wide range of volatilities and presumably of carriers, and it is unclear how the same nucleosynthetic components could have been systematically fractionated that way [9]. It is even uncertain that presolar grains would have been still extant when their host aggregates would have started evaporating, as diffusion would likely have erased micron-scale isotopic heterogeneities.

Another paradigm is suggested by the restriction of the largest nucleosynthetic anomalies to the earliest rocks of the Solar System, in particular CAIs [1]. This indicates an initial heterogeneity which would have been gradually reduced by transport and mixing. Since CAI formation timescales seem commensurate with infall timescales [10, 11], the heterogeneity would date back to the protosolar cloud that collapsed to form the solar protoplanetary disk [1, 12, 13]. We [14] thus set to model this scenario numerically.

Model: We build on our previously developed model of the inside-out collapse of a spherical dense core [11, 15] building a disk evolving due to its "turbulent viscosity". High temperatures suitable for CAI formation can be reached as far as ~1 AU from the proto-Sun (this is consistent with evidence for proton irradiation [16]). The code allows to track different cosmochemical components according to their volatility and their history (e.g. pristine presolar matter or disk condensates). Solid matter is assumed to consist of 1 mm size composite grains. The protosolar cloud is deemed to be chemically uniform (solar), but the refractory component consists of two isotopically distinct endmembers with varying proportions. Specifically, the proportion of the "outer" endmember varies continuously between 0 and 1 from the center to the surface of the cloud, and so does, thus, the composition of the matter infalling onto the disk between the beginning and the end of the infall. We investigated three shapes of the gradient depicted below (but will concentrate on the simple "linear" one):



Results: The black continuous curve in the plot below shows the proportion of the outer endmember (called "normalized isotopic contribution") as a function of heliocentric distance just at the end of infall (the dotted and dash-dotted lines refer to alternative grain growth models and can be ignored here).



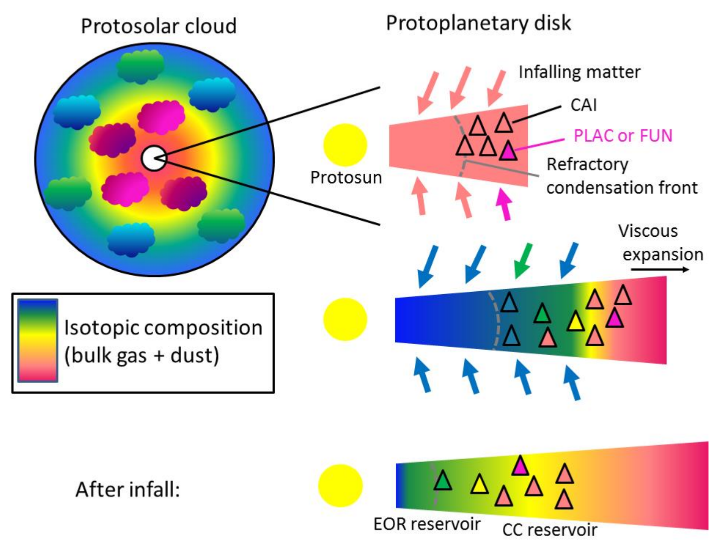
In the inner disk, this proportion is relatively high, that is, close to the composition of the latest infalling batches (most of the earlier matter having been accreted already by the proto-Sun). It tends to decrease (i.e. to be isotopically more "archaic", in term of infall chronology) toward the outer disk. Indeed, although, in our model, the most isotopically archaic material must have landed closer to the Sun (because of lower angular momentum), some has been transported outward following the viscous expansion of the disk, and preferentially survive there. This effectively reverses the isotopic gradient in the protosolar cloud. However, the outer disk contains little material, so the inter-reservoir variability is reduced when weighed by mass.

Since the code individually tracks components according to their history, the plot also shows the isotopic composition of (mean) condensates alone (that is, refractory condensates, as we are considering a generic refractory element). This is the red solid line in the previous plot. It is seen that at a given heliocentric distance, the refractory condensates are systematically more isotopically archaic, on average, than their host reservoir. This is because their production rate was highest during infall, so that the surviving refractory condensates preferentially "fossilize" the isotopic signatures of that era.

Discussion: The greater isotopic variability of CAIs is consistent with model predictions. Later formed solids should record more limited heterogeneities and/or temporal variation, save for intra-reservoir nugget effects (e.g. oversampling of CAIs in chondrule precursors [17, 18]) not modelled by our Eulerian code. Since CAIs appear systematically enriched in r-process isotopes compared to their host chondrites, infall must have evolved from r-process-rich to r-process-poor material. The inversion of the protosolar cloud gradient would then be consistent with CC parent bodies having accreted further from the Sun than EOR's. The viscous expansion may have created an overabundance of CAIs there [11].

PLAty hibonite Crystals (PLACs), which may rank among the very first CAIs, scatter on both sides of the solar composition for Ti or Ca isotopes [19]. This is not consistent with a simple monotonic gradient in the protosolar cloud as modelled here. However, such a gradient could simply be an average trend in the cloud, with superimposed smaller-scale heterogeneities which would be washed out within tens of orbits after landing onto the disk [20]. PLACs would then have had to condense from material freshly added to the disk within that timescale, which (mass-dependent) isotopic evidence for rapid condensation of refractory inclusions allows [21].

Conclusion: The scenario of inheriting nucleosynthetic anomalies from an isotopically heterogeneous protosolar cloud thus appears astrophysically sound. In this framework (sketched below), CAIs would represent time probes of the infall stage.



Sketch of the collapse of an isotopically heterogeneous disk. The varying isotopic compositions are symbolized by different colors, with small cloud symbolizing the smaller-scale heterogeneities mentioned in the previous paragraph. Triangles represent individual CAIs upon condensation and subsequent transport.

References: [1] Dauphas N. & Schauble E. A. (2016). AREPS, 44:709. [2] Warren P. H. (2011). EPSL, 311:93. [3] Budde G. et al. (2016). EPSL, 454:293. [4] Trinquier A. et al. (2009). Science, 324:374. [5] Olsen M. B. et al. (2016). GCA 191:118. [6] Van Kooten et al. (2016). PNAS, 113:2011. [7] Worsham E. A. et al. (2019). EPSL, 521:103. [8] Niemeyer S. (1988), GCA, 52:2941. [9] Nanne J. A. M. et al. (2019). EPSL, 511:44. [10] Yang L. & Ciesla F. J. (2012), M&PS, 47:99. [11] Pignatale F. C. et al. (2018). ApJL, 867 L23. [12] Brennecka G. A. et al. (2020). Science 370:837-840. [13] Huss G. R. & Lewis R. S. (1995). GCA 59:115. [14] Jacquet E. et al. (2019) 884:32. [15] Pignatale F. C. et al. (2019), ApJ, 884:31. [16] Jacquet E. (2019). A&A 624, A131. [17] Jacquet E. & Marrocchi Y. (2017), M&PS, 52:2672. [18] Gerber S. et al. (2017), ApJL 841, L17. [19] Kööp et al. (2018) GCA, 145:206. [20] Boss A. P. (2007), ApJ, 660:1770. [21] Marrocchi Y. et al. (2019). PNAS, 116:23461.