LARGE SCALE NUCLEOSYNTHETIC HETEROGENEITIES ACROSS THE SOLAR SYSTEM IDENTIFIED BY XENON.

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Introduction: The formation of the solar system involved large-scale mixing of material throughout the entire protoplanetary disk. It is thus remarkable that heterogeneities between meteorite groups, but also up to planetary scale, still persist. In the last decade, studies demonstrated the existence of two distinct isotopic reservoirs in the solar system. Carbonaceous chondritic material, thought to originate from the outer regions of the solar system, carries excesses of neutron-rich Cr, Ti, Mo, Ni isotopes compared to non-carbonaceous material [1-3]. The origin of this dichotomy [2,3] and its bearing on the origin and distribution of various nucleosynthetic signatures in solar system material remain debated [4,5]. It is worth noting that, up to now, this dichotomy has been identified mainly for refractory elements [6].

Noble gases are tracers of choice and have been used historically for understanding nucleosynthetic heterogeneities in solar system material [7]. Xenon is a particularly useful element since its nine isotopes ($^{124-136}$Xe) are produced by P-, R- and S-process stellar nucleosynthesis. Studying the relative proportions of Xe isotopes in solar system material (Fig. 1) can thus contribute to put constraints on the different nucleosynthetic environments [8] and to establish their influences on the distribution of nuclides in different regions of the solar system.

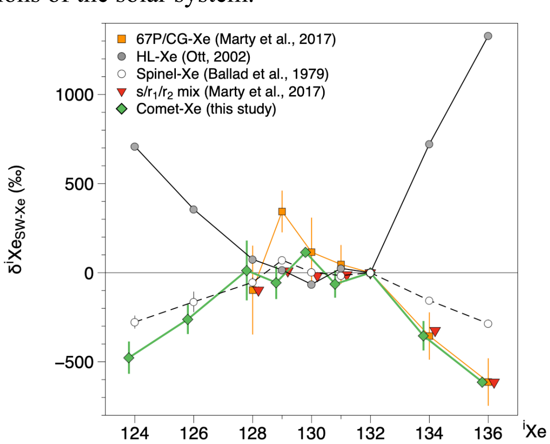

Figure 1: Isotopic composition of cometary xenon extended to $^{124-126}$Xe. The composition computed here is compared to measurements of Xe in the coma of 67P and to the model of [10], to HL-Xe [8] and to Xe in nanospinels of Allende [13]. Errors are 1σ.

Xenon in the Earth's atmosphere presents a mass-dependent fractionation in favor of the heavy isotopes relative to all cosmochemical end-members. After correction for the mass-dependent fractionation, the theoretical ancestor of atmospheric xenon, U-Xe [9], presents depletions in ^{134}Xe and ^{136}Xe isotopes relative to Solar or Chondritic end-members. This deficit of R-process Xe isotopes supports the view that nucleosynthetic heterogeneities persisted during the Solar System formation. Measurements of xenon in the coma of comet 67P/Churyumov-Gerasimenko (67P/CG-Xe hereafter) identified a similar, but more extreme, deficit of cometary gas in these isotopes relative to Solar gas (Fig. 2) [10].

In this study [11], we show that the xenon data from 67P can be re-interpreted with the theoretical framework developed in previous studies of nucleosynthetic anomalies in meteorites [12]. Correlations show that two distinct sources (r and h) contributed R-process Xe isotopes to the solar system and that h-process Xe contributed at least 59% of solar system ^{136}Xe. Results are also used to compute the isotopic composition of the theoretical starting component for Earth's atmospheric xenon. The isotopic composition of this component demonstrates the existence of a temporal or physical separation establishing relative variations of P-process and R-process Xe isotopes across the Solar system.

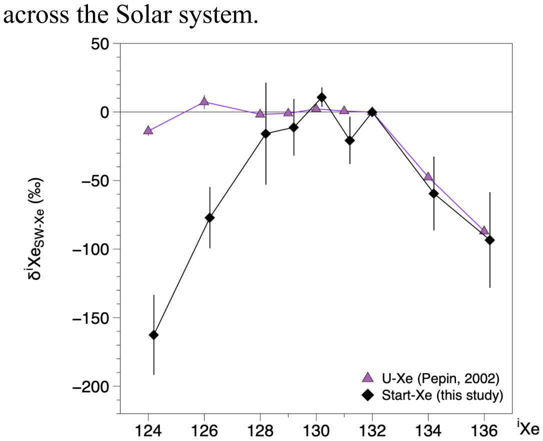

Figure 2: Comparison between U-Xe, the progenitor of atmospheric Xe [9], and Start-Xe computed in this study. Start-Xe is depleted in P-process Xe nuclides. Adding Xe-HL ([8], Fig. 1) cannot compensate for this depletion since it also contains heavy Xe isotopes. Errors are 1σ.

Model: The isotope composition of cometary xenon (Comet-Xe) has been predicted by using the fitted planes presented by [12] and the ^{130}Xe/^{132}Xe and ^{136}Xe/^{132}Xe ratios of 67P/CG-Xe [10]. Errors were propagated by using a Monte Carlo algorithm. 22% of the synthetic cometary component was then mixed with 78% of chondritic xenon (Q-Xe, [14]) following [10] in order to build a theoretical progenitor of Earth's atmospheric Xe labelled Start-Xe.

Results & Interpretations:

Distinct R-process contributions to solar system xenon. Compilation of meteorite data already identified two R-process contributions to solar system xenon labelled r-process and h-process [12]. The fact that 67P/CG-Xe lies on the planes identified by [12] allows to compute a maximum value for r-process ^{136}Xe/^{132}Xe of about 0.19. This result gives a new constraint to correlations identified by [12] and means that the h-process made a significant contribution (>59% of ^{136}Xe) to solar system xenon.

Cometary xenon and the precursor of atmospheric xenon. The isotopic composition of the theoretical cometary Xe determined in this study is matching 67P/CG-Xe for $^{128,130\text{-}136}$Xe. However, it is distinct for ^{129}Xe and presents severe depletions, down to -500 ‰, for ^{124}Xe and ^{126}Xe relative to SW-Xe (Fig. 1). When 22 % of this cometary Xe is mixed with 78 % of Q-Xe [10], the resulting composition, Start-Xe, is distinct from U-Xe for $^{124\text{-}126}$Xe (Fig. 2).

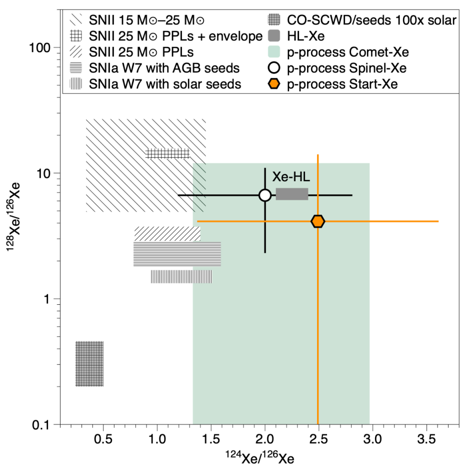

Figure 3: Isotope ratios of the P-process Xe end-member required to compensate for the isotopic depletions identified in this study [11] and in chemical separates from the Allende meteorite [13]. The compositions of Xe-HL [8] and of Xe produced in different theoretical nucleosynthetic environments are also shown for comparison [15]. Errors are 1σ.

Nucleosynthetic heterogeneities across the solar system. While Start-Xe is close to U-Xe for $^{129\text{-}136}$Xe/^{132}Xe ratios, the low $^{124\text{-}128}$Xe/^{132}Xe ratios relative to U-Xe or SW-Xe are incompatible with Start-Xe being the precursor of atmospheric Xe. Mixing with Xe-HL, a nucleosynthetic end-member defined by meteorite studies [16], cannot compensate for the depletion in $^{124\text{-}128}$Xe since it would lead to a departure from U-Xe for heavy isotopes. The most plausible explanation for the depletion in $^{124\text{-}128}$Xe of Start-Xe relative to SW-Xe is the incorporation of a pure P-process Xe to the R/S-process mixture originally considered here.

The P-process isotope ratios required to reach solar ratios for the precursor of atmospheric Xe are 2.15±0.82 and 0-12 for ^{124}Xe/^{126}Xe and ^{128}Xe/^{126}Xe, respectively. These ratios are compared to theoretical ratios derived from existing nucleosynthetic models (Fig. 3, [15]). Two models can be excluded (at 1σ level) but the isotope ratios remain too imprecise to further constrain which type of nucleosynthetic event contributed light Xe isotopes to the inner solar system.

Conclusions: The precursor of atmospheric xenon presents selective depletions in ^{134}Xe and ^{136}Xe isotopes relative to Solar and Chondritic end-members [9]. Such a depletion has been identified in xenon in the coma of comet 67P/Churyumov-Gerasimenko [10] although light Xe isotopes were not detected/measured. By using nucleosynthetic correlations identified in meteorite material [12], we built a theoretical starting composition for the Earth's atmosphere for all Xe isotopes ($^{124\text{-}136}$Xe). This composition presents severe depletions in ^{124}Xe and ^{126}Xe isotopes which cannot be accounted for by adding classical noble gas end-members to the isotopic mixture. These depletions require the incorporation from the interstellar medium of a pure P-process end-member to obtain solar-like isotopes ratios for $^{124\text{-}128}$Xe of the starting composition. Either this P-process incorporation happened before incorporation of R-process nuclides or material in the outer edge of the solar system carries a different mix of presolar sources as in parent bodies of meteorites.

Acknowledgments: The program DIM-ACAV^{+} from Région Ile-de-France is thanked for his financial support to G. Avice. J. D. Gilmour acknowledges STFC (grant number ST/R000751/1). **References:** [1] Warren P. H. (2011) *EPSL, 311,* 93-100. [2] Kruijer T. S. et al. (2017) *PNAS, 312,* 201704461–15. [3] Nanne J. A. M. (2019) *EPSL, 511*, 44-54. [4] Ek et al. (2019) *Nat. Astron.* [5] Jacquet et al. (2019) *ApJ, 884,* 32. [6] Qin & Carlson (2016) *Geochem. Journal, 50*, 43. [7] Reynolds J. H. (1960) *Phys. Rev. Lett., 4,* 351-354. [8] Ott U. (2002) *RiMG, 47,* 71-100. [9] Pepin R. (1991) *Icarus, 92,* 2-79. [10] Marty B. et al. (2017) *Science, 356,* 1069-1072. [11] Avice G. et al. (2019) *ApJ, in press*. [12] Gilmour J. D. & Turner G. (2007) *ApJ, 657,* 600-608. [13] Ballad R. V. (1979) *Nature, 277,* 615-620. [14] Busemann H. et al. (2000) *MAPS, 35,* 949-973. [15] Arnould M. & Goriely S. (2003) *Physics Reports, 384,* 1-84. [16] Huss G. R. & Lewis R. S. (1994) *Meteoritics, 29*, 791-810.