Xenon in the Protoplanetary Disk (PPD-Xe)

K. Marti and K.J. Mathew*
Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, California, USA
*Present address: F/H Area Analytical Labs, Savannah River National Lab, Aiken, SC, 29803 e-mail: kattathu.mathew@srs.gov

Abstract

Relationships among solar system Xe components as observed in the solar wind (SW), in planetary atmospheres and in meteorites are investigated using isotopic correlations. The term PPD-Xe is used for components inferred to have been present in the molecular cloud material that formed the protoplanetary disk (PPD). The evidence of the lack of simple relationships between terrestrial atmospheric Xe and solar or meteoritic components is confirmed. Xe isotopic correlations indicate a heterogeneous PPD composition with variable mixing ratios of the nucleosynthetic component Xe-HL. Solar Xe represents a bulk PPD component, and the isotopic abundances did not change from the time of incorporation into the interior of Mars, through times of regolith implantations to the present.

Introduction

Fifty years ago in a publication termed ‘xenology’ Reynolds (1963) reviewed information available at the time and commented on the potential of the nine-isotope Xe system for solar system research. Concurrently, Signer and Suess (1963) subdivided known solar system gas abundances into ‘solar’ and ‘planetary’ components. This terminology has survived to the present, although it became clear that ‘planetary’ does not apply to planets. The term PPD-Xe (protoplanetary disk) is used here to characterize xenon in the forming solar system. Detailed information on presolar grains and stellar environments is found in Bernatowicz et al. (2006), and the history of research on solar system noble gases is covered in reviews by Wieler (2002), Ott (2002), and Pepin & Porcelli (2002).

The origin of terrestrial and planetary volatiles and processes involved in their evolution to present day compositions are not well understood. Elemental and isotopic abundances of matter in giant planets are generally considered to represent those prevailing in their source reservoirs at the time of formation, and that they represent initial solar system abundances.

Spectroscopic and in-situ measurements of nitrogen isotopic abundances in Jupiter and Saturn (Fletcher et al. 2014; Niemann et al. 1998; Owen et al. 2001) agree with N in the solar wind (SW) (Marty et al. 2011) and therefore agree with this assumption. On the other hand, Saturn's moon Titan has distinct N isotopic abundances (Niemann et al. 2010). The $^{36}Ar/^{38}Ar$ and $^{20}Ne/^{22}Ne$ ratios reported for Jupiter by the Galileo Probe mass spectrometer (Mahaffy et al. 2000) are both consistent with ratios observed in the solar wind (Heber et al. 2009; Meshik et al. 2014).

Noble gases and nitrogen in the atmospheres of Earth and Mars are distinct from SW abundances (Heber et al. 2009) and indicate either different planetary histories or matter from different sources (Bogard et al. 2001). Xe isotopic abundances in the atmospheres of planets Earth and Mars are similar, but strongly fractionated relative to SW Xe (Marti & Mathew 1998), and in planet Mars an interior solar (Chass-S) Xe component was identified (Mathew & Marti 2001).

Accretionary histories of volatiles on terrestrial planets were reviewed by Albarede (2009). It was concluded that volatiles were likely delivered some 100 million years after the formation of the solar system and that the depletion of volatiles on the Earth and other terrestrial planets are not due to loss by outgassing, as the isotopic fractionation of Zn is incompatible with volatilization. Albarede (2009) suggests that these planetary volatiles show contributions of matter from beyond the asteroidal belt. Therefore, comparisons of planetary abundances with cometary isotopic data are important. H and N in comets reveal enrichments in the heavy isotopes (Rousselot et al. 2014). The noble gas atmospheric composition of Jupiter was studied by the Galileo Probe mass spectrometer (Mahaffy et al. 2000). The relative abundances and isotopic compositions of Ar, Kr and Xe were found to be similar to those in SW, but Xe isotopes have large uncertainties. He and Ne abundances relative to H are lower by factors of 0.8 and 0.1, respectively. These abundances show that no single source for planetary volatiles of Earth and Mars is known.

Xe isotopic correlations

Isotopic differences in Xe have long been known to exist in solar, planetary and meteoritic matter (e.g. Reynolds & Turner 1964; Pepin, 1992; Marti & Mathew 1998; Meshik et al. 2014). These isotopic signatures are known to provide clues regarding origin and processes in the PPD (Lavielle & Marti 1992; Huss et al. 1996), and regarding planetary atmospheres (Pepin, 1992; 2000; Marti & Mathew 1998; Crowther & Gilmour 2013; Meshik et al. 2014). SW data from Genesis, from lunar and Pesyanoe isotopic abundances are listed in Table 1, together with meteoritic and planetary Xe components. Abee-Xe data are also included, as enstatite chondritic matter is considered to characterize matter of the inner solar system (Lee et al. 2009; Dauphas et al. 2014).

Xe isotopic correlations are used in Figs. 1 and 2 to study the relationships of PPD-Xe with other components. In Fig. 1, ^{130}Xe is used for normalization, as this isotope is free of interferences from fission components. In literature data corrections for cosmic ray spallation components were applied, based on known spectra and assigning ^{126}Xe excesses to spallation Xe. Fig. 1 shows a ^{136}Xe/^{130}Xe vs. ^{132}Xe/^{130}Xe plot, using data from Table 1. Shifts expected for fission components (^{244}Pu, ^{238}U, and neutron-induced fission of ^{235}U), and for addition of Xe-HL components (Huss & Lewis 1994), as well as those expected from mass fractionation are indicated.

SW Xe data (Genesis, Pesy-S, lunar SW) and Chass-S Xe are clustered, but we note that the ^{136}Xe/^{130}Xe ratio in Genesis Xe (Meshik et al. 2014) plots slightly different from the other data. SW Xe was implanted in the different target materials at different times, while Chass-S Xe represents a Martian interior component.

Fig.1 reveals that trapped meteoritic Xe components are consistent with mixtures of mass-fractionated SW Xe plus HL-Xe, as suggested by Lavielle & Marti (1992). Fig.2 is required to show that fission gases can be excluded. Meteoritic components OC-Xe, Q-Xe and Abee-Xe are consistent, as was concluded for all Xe isotopes (Lee et al. 2009). The data for an Orgueil-residue (Frick & Moniot 1977) plot on a mixing line of a slightly fractionated SW Xe and Xe-HL. The Xe data of planets Earth and Mars allow assessments of fission-free parent reservoirs and evolutionary processes. While Mars atmospheric Xe (Mathew et al. 1998) is consistent with a mass-fractionated SW composition, the terrestrial atmospheric Xe signature is not. In this case, no fission Xe components can produce the observed shift off the mass fractionation line. Therefore, a simple fractionation relationship of terrestrial Xe to either solar or meteoritic Xe, as was suggested (Pujol et al. 2011; Marty, 2012) is not possible. This was pointed out earlier (Pepin 1992; 2000; 2006), and the Genesis data do not change this conclusion.

Fig. 2 helps to clarify fission Xe contributions. The ^{134}Xe/^{136}Xe vs. ^{132}Xe/^{136}Xe for meteoritic Xe data is not consistent with mixtures of SW Xe and fission components. However, the component FVM-Xe (Marti et al. 1989) shows a shift in the direction of ^{235}U(n,f), neutron-induced fission. If trapped meteoritic Xe components are interpreted to represent mixtures of mass fractionated SW Xe and HL-Xe, the data should fall inside the sector determined by these two lines. The isotopic systematics are actually improved in Fig. 2, by replacing SW Genesis Xe by the Sol-Xe composition, where the Sol-Xe, is the average of the four data sets Genesis-Xe, Chass-Xe, Pesy-Xe and lunar SW-Xe.

In Fig.3 Sol-Xe data are used to show and calculate mass-fractionation effects and shifts due to Xe-HL for meteoritic data shown in Fig. 1. Mars atmospheric Xe is consistent with a mass-fractionated Sol-Xe component corresponding to 3.77% / amu (Marti & Mathew 1998). These authors inferred that an additional ^{244}Pu-fission component (2.5% of ^{136}Xe) is required, but Pepin (2000) suggested that a hydrodynamic fractionation option is also consistent with observed abundances. Xe in the Orgueil-residue (Frick & Moniot 1977) requires only the addition of a Xe-HL component, but a better fit is obtained, when the Sol-Xe component is fractionated by 1 permil / amu. Meteoritic Xe components (OC-Xe, Q-Xe and Abee-Xe) are all fitted with Sol-Xe, mass fractionated by 0.9% / amu, and HL-Xe components corresponding to 2.7% of the ^{136}Xe abundance. The Kenna ureilite data show a mass fractionation of 0.6%/amu and a HL-Xe component corresponding to 1.8% of ^{136}Xe.

Xe components in terrestrial well gases were studied by Caffee et al. (1999) and Lee et al. (2009), who observed atmospheric Xe, ^{238}U and ^{244}Pu fission components and a minor component of either solar or Abee-Xe composition. Enstatite chondritic matter is considered to be present in planet Earth and also inner solar system matter (Dauphas et al. 2014).

Other PPD-Xe components

As discussed, solar system components include Sol-Xe and mass-fractionated components thereof, Xe-HL, terrestrial atmospheric Xe and FVM-Xe. Another presolar Xe-G component with excesses of ^{128}Xe and ^{130}Xe was isolated in SiC and graphite of carbonaceous chondrites (Lewis et al. 1994). This PPD component has the signature of products from s-process synthesis that was probably implanted as ions, but its origin is not well understood. The s-process signature does indicate an origin from the He-burning shell of carbon-rich AGB stars (Gallino et al. 1990). Xe-G is a minor component and is not documented in our isotopic correlations, but

Meshik et al. (2014) suggest, that it might account in part for differences between solar and meteoritic components. Zr isotopic variations were recently reported as evidence for the heterogeneous distribution of s-process products in the solar system (Akram et al. 2015).

As noted in Fig 3, the replacement of Genesis Xe by Sol-Xe slightly decreased the heavy isotopes ^{136}Xe and ^{134}Xe relative to ^{130}Xe, while ^{131}Xe is little affected. Similar isotopic shifts are also produced when a few % Xe with terrestrial atmospheric composition is subtracted from Genesis data. Therefore, a look at uncertainties introduced by air blank correction procedures in Genesis data reduction is useful. Genesis blanks were corrected differently in different laboratories. Data used here by Meshik et al. (2014) were corrected for blanks by extrapolating measured ratios to a predetermined solar value of ^{84}Kr/^{132}Xe. Looking at the SW ratio ^{129}Xe/^{132}Xe in Genesis foils as reported by several laboratories, shows that a 3 % atmospheric blank correction increases this ratio only 2 permil. A value of 1.0404 reported by Meshik et al. (2014) compares to values of 1.045 (Crowther and Gilmour, 2013), 1.05 (Heber et al. 2009) and 1.06 (Vogel et al. 2011). As pointed out by Meshik et al. (2014), there is some uncertainty in the solar ratio ^{84}Kr/^{132}Xe, but reported values overlap within uncertainties.

Earth's atmospheric Xe

The Xe isotopic abundances in the Earth's atmosphere (Table 1) show a distinct composition (Fig.1). Several studies attempted to find a precursor reservoir from which terrestrial Xe could have evolved. A parent Xe reservoir, termed U-Xe (Pepin, 2000; 2006) that underwent a postulated hydrodynamic fractionation process in the terrestrial environment, received much attention, but an identification of this reservoir in the solar system is lacking. The U-Xe isotopic composition (Table 1) is, with the exception of the heaviest three isotopes, similar to Sol-Xe or Genesis Xe. As no known fission Xe spectrum matches the excesses in the heavy isotopes, the possible presence of a fractionated fission component was suggested (Igarashi, 1995; Meshik et al. 2015). Here we discuss a possible origin based on PPD Xe components.

Fig. 3 shows that several Xe compositions display variable amounts of Xe-HL. If this component was carried into the PPD by individual nanodiamonds, then only a few in a million diamonds were actually required as carriers. As is well known from numerous isotopic variations in meteorites, including refractory elements (Dauphas et al. 2014; Steele &

Boehnke 2015), the PPD was not totally homogeneous. Since Xe in meteoritic components and minerals contains variable amounts of Xe-HL, PPD matter at different locations must have accumulated varying amounts of nanodiamonds. A location with less nanodiamonds will lack in heavy ^{134}Xe and ^{136}Xe, compared to Sol-Xe. This is what is observed in mass fractionated terrestrial Xe. The U-Xe composition (Pepin, 2000; 2006) and also a primordial Xe composition reported by Takaoka (1972), based on Xe isotopic correlations, both show low ^{134}Xe and ^{136}Xe abundances. The U-Xe reservoir, after hydrodynamic fractionation, requires the addition of ^{244}Pu-fission Xe to match the terrestrial atmospheric reservoir.

We calculate a pathway, starting in a PPD location with less than average nanodiamonds. In this case the Xe-PR (PR for precursor) composition differed from Sol-Xe, lacking some Xe-HL. The deficit used here is 5% at ^{130}Xe, an isotope not affected by fission Xe. This Xe-PR reservoir is then subjected to a mass-fractionation process of 3.77% per amu, as found for the atmospheres of Mars and Earth (Mathew et al. 1998). When comparing the mass-fractionated Xe-PR reservoir to terrestrial atmospheric Xe, we calculate that deficits on the heavy Xe isotopes are consistent with the spectrum of ^{244}Pu fission Xe within uncertainties. The required amount of fission ^{136}Xe to be added is 6.3% of the atmospheric ^{136}Xe abundance, exceeding the amount that can be produced from terrestrial ^{238}U (< 1%). The calculated Xe-PR data are given here, for ease of comparing with U-Xe data:

^{124}Xe:^{126}Xe:^{128}Xe:^{129}Xe:^{130}Xe:^{131}Xe:^{132}Xe:^{134}Xe:^{136}Xe =
0.0283:0.0250:0.5062:6.277:1.00:4.960:6.025:2.120:1.662

The ratio ^{128}Xe/^{130}Xe is not affected by fission components, and differs by 4 permil from U-Xe (the lighter isotopes have larger uncertainties and depend on the Xe-HL composition; a match for ^{136}Xe in U-Xe is obtained by subtracting 5.17% ^{130}Xe-HL from Sol-Xe). Igarashi (1995) reported an approach to determine ‘Primitive Earth Xe’, using the intercept of a mass-fractionated atmospheric Xe with the Xe multi-dimensional isotopic correlations of Xe data from carbonaceous meteorites, and separates thereof. The observed correlations revealed that Xe in carbonaceous chondrites has additional minor components. This ‘Primitive Earth Xe’ data also differed from U-Xe.

Thus, an Earth-Xe precursor can be located in a PPD-Xe environment with variable Xe-HL mixing ratios. Existing data on Martian atmospheric Xe do not indicate a deficit of Xe-HL. No model is currently able to explain the nucleosynthetic origin of Xe-HL, as also the heavy Xe isotopes do not match an r-process Xe component, as observed in solar Xe (Katz et al. 2014). Possibly p- and r-process products were implanted into carriers, into very few, as only one atom of Xe-HL is observed in about one million nanodiamonds. As a result, varying mixing ratios of p- and r- products in molecular clouds or in the PPD are possible, although no variability in excesses of light and heavy Xe isotopes has been documented for Xe-HL. Additional nucleosynthetic Xe products are present in Xe-HL, including an s-process component, and these may have been added in the parent molecular cloud.

As we do not have more information on the fractionation process itself and the timing of acquisitions of inner planet atmospheres, we cannot rule out the possibility that the nebular environment has evolved. The atmospheres of planets Earth and Mars contain ^{244}Pu-fission Xe and radiogenic ^{129}Xe components.

Evolved Compositions

Pujol et al. (2011) reported a so-called fractionated Xe isotopic composition as observed in old quartz samples of the Dresser Formation (Australia), intermediate between modern atmospheric and chondritic OC-Xe. Pepin (2013) offered an alternative interpretation of the Xe data, suggesting an admixture of a U-Xe component from the mantle. It is not clear that an U-Xe component is present in the mantle, but components of either solar Xe (Caffee et al. 1999) or Abee-Xe (Lee et al. 2009) are found in well gases and may produce similar results.

The FVM-Xe component in chondritic metals shown in Fig. 2 is shifted along the neutron-induced ^{235}U-fission line. This component was observed in some temperature steps of chondritic metal separates (Marti et al. 1989), and its carriers may be present in the form of inclusions. If we assume that in these carriers Xe-PR was present instead of Sol-Xe, then an addition of fission components (^{244}Pu and ^{248}Cm) may produce the observed ^{134}Xe/^{136}Xe ratio, instead of an unknown neutron source. The other isotope ratios agree with OC-Xe and Q-Xe within uncertainties. The scatter in Igarashi’s (1995) multi-dimensional correlation plots showed minor components and require, that Xe data of individual meteorites, and in particular separated phases thereof, need detailed assessments for possible spallation, fission and neutron capture contributions.

We have not discussed mechanisms for isotopic fractionation of atmospheric Xe. In addition to the hydrodynamic evolution, processes in dusty plasmas, like low-energy ion implantation, can also produce isotopic fractionations (Bernatowicz & Hagee 1987; Ponganis et al. 1997). The atmospheres of Mars and Earth reveal large fractionations, while meteoritic components show much smaller fractionations, and Xe in the Orgueil residue is only fractionated by < 1%.

The Earth's noble gas elemental abundance ratios with low or 'missing Xe' abundances was addressed in studies of Xe reactions with olivine at depth (Sanloup et al. 2011), in reactions with metal at temperatures and pressure of the Earths core (Zhu et al. 2014), and work on Xe and Ar solubilities in perovskite (Shcheka & Keppler 2012). Further, an ionization model (Hebrard & Marty 2014) was considered in context of a photochemical evolution of the atmosphere, but also in this case there is no indication of a fractionation relationship with Sol-Xe.

Conclusions

The term PPD-Xe is used for components present in precursor molecular cloud material at the time of formation of the solar disk. The discussed components (Table 1), and their isotopic make-up as studied in Figs 1, 2 and 3), include Sol-Xe, Xe-PR, Xe-HL and fission Xe components. Xe-PR is not documented in the figures, but is carried in presolar grains.

The Genesis SW Xe isotopic composition and SW isotopic abundances of implanted Xe (lunar and enstatite achondrite regoliths), as well as Martian interior (Chass-S) Xe agree within errors and determine the average composition Sol-Xe. There are indications that uncertainties in the Sol-Xe data could be reduced, if Genesis data from an extrapolated set of ratios is used, corresponding to a SW ratio ^{84}Kr/^{132}Xe = 9.3.

The isotopic compositions of OC-Xe, Q-Xe and Abee-Xe agree within errors. This composition consists of Sol-Xe, mass fractionated by 0.9% / amu, plus an HL-Xe component of 2.7% of the ^{136}Xe abundance.

Terrestrial Xe is not related to solar or chondritic Xe by a mass-fractionation process, as implied by Pujol et al. (2011) and Marty (2012). Pepin (1992; 2000) inferred a precursor composition U-Xe for the terrestrial reservoir. We calculate that a precursor composition Xe-PR in the PPD source that is lacking 5% ^{130}Xe-HL (relative to Sol-Xe) is similar to U-Xe. Therefore, solar system Xe data suggest that that PPD was heterogeneous and that isotopic abundances were determined by variable mixing ratios with the presolar component Xe-HL.

Acknowledgement
We thank Alex Meshik for discussions regarding Genesis data evaluation.

References

Albarede F., (2009), Natur 461, 1227
Akram W., Schönbächler M., Bisterzo S., & Gallino R., (2015), GeCoA, in press
Bernatowicz T.J., & Hagee B.E. (1987), GeCoA 51,1599
Bernatowicz T.J., Croat T.K., & Daulton T.L. (2006), MESS (Lauretta & McSween, Jr., Eds.)
Bogard D. D., Clayton R. N., Marti K., Owen T., & Turner G., (2001), SSR 96, 425
Caffee M.W., Hudson G.B., Velsko C., Huss G.R., Alexander E.C., & Chivas A.R. (1999), Sci 285, 2115
Crowther S.A., & Gilmour J.D. (2013), GeCoA 123, 17
Dauphas N., Chen J.H., Zhang J., Papanastassiou D. A., Davis A.M., & Travaglio C., (2014), E&PSL 407, 96
Fletcher L.N., Greathouse T.K., Orton G.S., Irwin P.G.J., Mousis O., Sinclair J.A., & Giles R.S., (2014), Icar 238, 170
Frick U., & Moniot R.K., (1977), Proc. LSC 8th, 229
Gallino R., Busso M., Picchio G., Raiteri C.M. (1990), Natur 348, 298
Heber V. S., Wieler R., Baur H., Olinger C., Friedmann T. A. & Burnett D. S., (2009), GeCoA 73,7414
Hebrard E., & Marty B., (2014), E&PSL 385, 40
Huss G. R., & Lewis R. S., (1994), Meteoritics 29, 791
Huss G. R., Lewis R. S., & Hemkin S., (1996), GeCoA 60, 3311
Igarashi G., (1995), Volatiles in the Earth and Solar System, AIP, New York, (K. Farley, ed.) 70
Kratz K.L., Farouqi K., Hallmann O., Pfeiffer B., & Ott U., (2014), Astrophys. Cornell (submitted June 2014)
Lavielle B., & Marti K., (1992), JGR 97, 20,875
Lewis R.S., Amari S., & Anders E., (1994), GeCoA 58,471
Lee J.Y., Marti K., & Wacker J. F., (2009), JGR 114, E04003
Mahaffy P.R., Niemann H.B., Alpert A., Atreya S.K., Demick J., Donahue T. M., Harpold D. N., & Owen T. C., (2000), JGR 105 (E6), 15061
Marti K., Kim J. S., Lavielle B., Pellas P., & Perron C., (1989), Z. Naturforsch. 44a, 963
Marti K., & Mathew K. J., (1998), PIAS (EPS) 107, 425
Marty B., (2012), E&PSL 313, 56
Marty B., Chaussidon M., Wiens R.C., Jurewicz A.J.G., Burnett D.S., (2011), Sci 332, 1533
Mathew K. J., & Marti K., (2001), JGR (Planets) 106, 1401

Mathew K. J., Kim J. S., & Marti K., (1998), M&PS 33, 655
Mathew K. J. & Marti K., (2003), M&PS 38,627
Meshik A., Hohenberg C., Pravdivtseva O., & Burnett D., (2014), GeCoA 127, 326
Meshik A., Pravdivtseva O., Hohenberg C., & Burnett D., (2015), LPSC-46
Niemann H.B. et al. (1998), JGR 103, 22,831
Niemann H.B., Atreya S.K., Demick J.E., Gautier D., Haberman J.A., Harpold D.N., Kasprzak W.T., Lunine J.I., Owen T.C., & Raulin F., (2010), JGR (Planets) 115, 12006
Ott U., (2002), RMG 47, 71 (Porcelli, Ballentine, Wieler, editors)
Owen T., Mahaffy P.R., Niemann H.B., Atreya S., & Wong M., (2001), APJ 553: L77
Pepin R.O., (1992), Ann. Rev. EPS 20, 389
Pepin R.O., (2000), SSR 92, 371
Pepin R.O., (2006), E&PSL 252, 1-14
Pepin R.O., (2013), E&PSL 371, 294
Pepin R.O., & Porcelli D. (2002), RMG 47, 191, (Porcelli, Ballentine, Wieler, editors)
Pepin R. O., Becker R. H., & Rider P. E., (1995), GeCoA 59, 196
Ponganis K.V., Graf T. and Marti K., JGR 102, E8, 19335
Pujol M., Marty B., Burgess R., (2011), E&PSL 308, 298
Reynolds J.H., (1963), JGR 68, 2939
Reynolds J.H., Turner G., (1964), JGR 69, 3263
Rousselot P., Pirali O., Jehin E., Vervloet M., (2014), APJL 780:L17
Sanloup C., Schmidt B.C., Gudfinnsson G., Dewaele A.,Mezouar M., (2011), GeCoA 75, 6271
Signer P., Suess H.E., (1963), ES&M, (Geiss & Goldberg (eds), North Holland, Amsterdam, 241
Shcheka S.S., & Keppler (2012), Natur 490, 531
Steele R.C.J. & Boehnke P., (2015), APJ 802, 80
Takaoka N., (1972), Mass Spectr 20,287
Valkiers S., Aregbe Y., Taylor P.D.P. & De Bievre P., (1998), IJMS 173, 55
Vogel N., Heber V.S., Baur H., Burnett D.S., & Wieler R., (2011), GeCoA 75, 3057
Wieler R., (2002), RMG 47, 21-70, (Porcelli, Ballentine, Wieler, editors)
Wieler R. & Baur H., (1994), Meteoritics 29, 570
Wieler R., Anders E., Baur H., Lewis R.S. & Signer P., (1992), GeCoA 56, 2907
Wilkening L.L. & Marti K., (1976), GeCoA 40, 1465
Zhu L., Liu H., Pickard C.J., Zou G. & Ma Y., (2014), NC 6, 644

Table 1: Isotope abundance ratios in solar system material; spallation corrected literature data (generally using the ^{126}Xe/^{130}Xe ratios) are listed. Sources of the literature data are listed in the footnote.

Comp	^{136}Xe/^{130}Xe	^{134}Xe/^{130}Xe	^{132}Xe/^{130}Xe	^{131}Xe/^{130}Xe	^{129}Xe/^{130}Xe	^{128}Xe/^{130}Xe	^{126}Xe/^{130}Xe	^{124}Xe/^{130}Xe
Genesis	1.8188	2.2370	6.061	5.004	6.306	0.5103	0.02521	0.02976
[1]	±0.0057	±0.0069	±0.015	±0.014	±0.016	±0.0022	±0.00055	±0.00043
Chass-S	1.8012	2.205	6.039	4.978	6.520	0.5112	0.0255	0.0295
[2]	±0.0091	±0.018	±0.027	±0.029	±0.034	±0.0049	±0.0011	±0.0011
Pesy-S	1.8058	2.2325	6.070	4.978	6.337	0.5091	0.0262	0.0295
[3]	±0.0055	±0.0098	±0.028	±0.016	±0.030	±0.0040	±0.0010	±0.0013
SW	1.7971	2.2068	6.020	4.980	6.273	0.5102	0.0255	0.0295
[4,5]	±0.0055	±0.0090	±0.033	±0.017	±0.042	±0.0054	±0.0008	±0.0017
Abee	1.9684	2.3475	6.183	5.045	n.a.	n.a.	0.0267	0.0287
[6]	±0.0020	±0.0098	±0.030	±0.027			±0.0022	±0.0010
OC-Xe	1.963	2.344	6.174	5.060	6.420	0.5110	0.0255	0.0286
[7]	±0.004	±0.005	±0.011	±0.008	±0.011	±0.0020	±0.0002	±0.0003
Plan.	1.942	2.318	6.135	5.038	6.380	0.5100	0.0254	0.0289
[8]	±0.006	±0.007	±0.009	±0.007	±0.012	±0.0020	±0.0002	±0.0003
Q-Xe	1.959	2.342	6.165	5.049	6.387	0.509	0.0252	0.0283
[9]	±0.009	±0.009	±0.023	±0.018	±0.031	±0.002	±0.0003	±0.0004
Kenna-Ur	1.916	2.313	6.136	5.027	6.358	0.508	0.0254	0.0289
[10]	±0.006	±0.006	±0.011	±0.010	±0.015	±0.002	±0.0002	±0.0003
Orgueil	2.391	2.636	6.215	5.144	6.540	0.5265	0.02741	0.03276
[11]	±0.014	±0.012	±0.015	±0.017	±0.026	±0.0027	±0.00017	±0.0003
Mars Atm.	2.269	2.585	6.529	5.180	15.562	0.4728	0.0210	0.0230
[12]	±0.016	±0.011	±0.021	±0.017	±0.041	±0.0069	±0.0011	±0.0011
Earth Atm	2.17569	2.56341	6.60982	5.21551	6.48503	0.46922	0.02186	0.02337
[13]	±0.00112	±0.00046	±0.00064	±0.00050	±0.00271	±0.00019	±0.00005	±0.00008
PPD_Xe	1.8057	2.2202	6.0475	4.9850	6.3590	0.51020	0.02560	0.02957
[this work]	±0.0094	±0.0169	±0.0225	±0.0127	±0.1105	±0.00086	±0.00042	±0.00013
U-Xe	1.657	2.126	6.047	4.996	6.286	0.5083	0.02534	0.02928
[14]	±0.0003	±0.0004	±0.0006	±0.0006	±0.0006	±0.0006	±0.00013	±0.00010

[1] Meshik et al. (2014), [2] Mathew and Marti (2001), [3] Mathew and Marti (2003), [4] Wieler et al. (1994), [5] Pepin et al. (1995), [6] Lee et al. (2009), [7] Lavielle and Marti (1992), [8] Huss et al. (1996) [9] Wieler et al. (1992), [10] Wilkening and Marti (1976), [11] Frick and Moniot (1977), [12] Mathew et al. (1998), [13] Valkiers et al. (1998) [14] Pepin (2000)

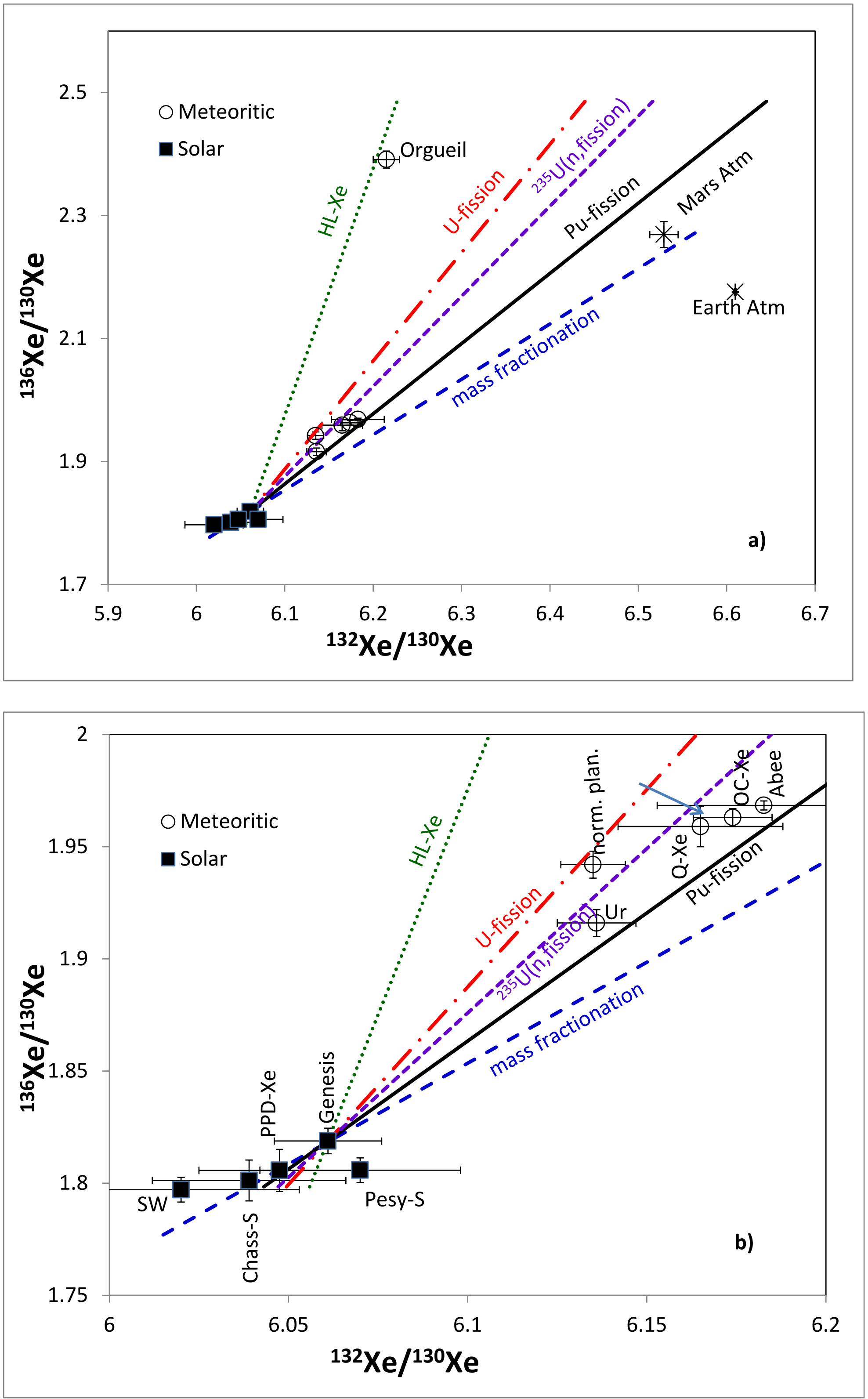

Figure 1: ^{136}Xe/^{130}Xe vs. ^{132}Xe/^{130}Xe in solar system components. Expected shifts due to addition of fission Xe, HL-Xe, and due to mass fractionation process are indicated. Bottom panel expands the region with solar and meteoritic Xe compositions.

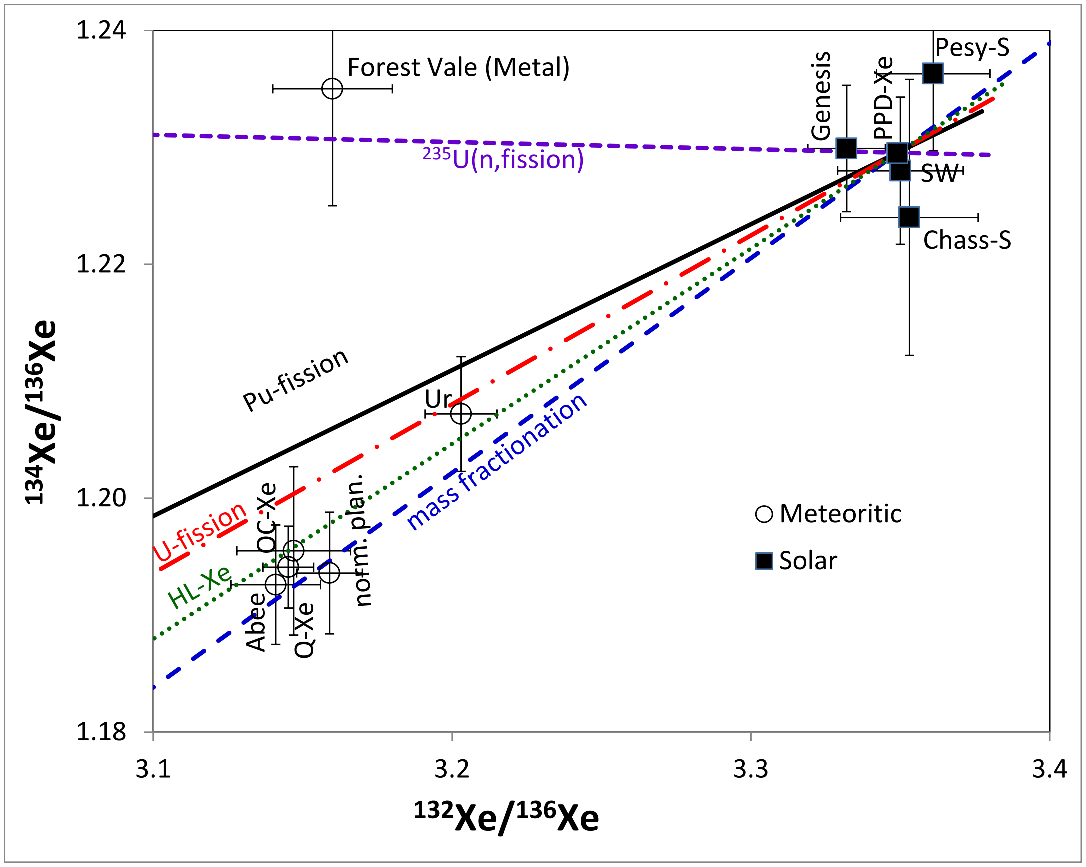

Figure 2: ^{134}Xe/^{136}Xe vs. ^{132}Xe/^{136}Xe in solar system components. Expected shifts due to addition of fission Xe, HL-Xe, and due to mass fractionation process are indicated.

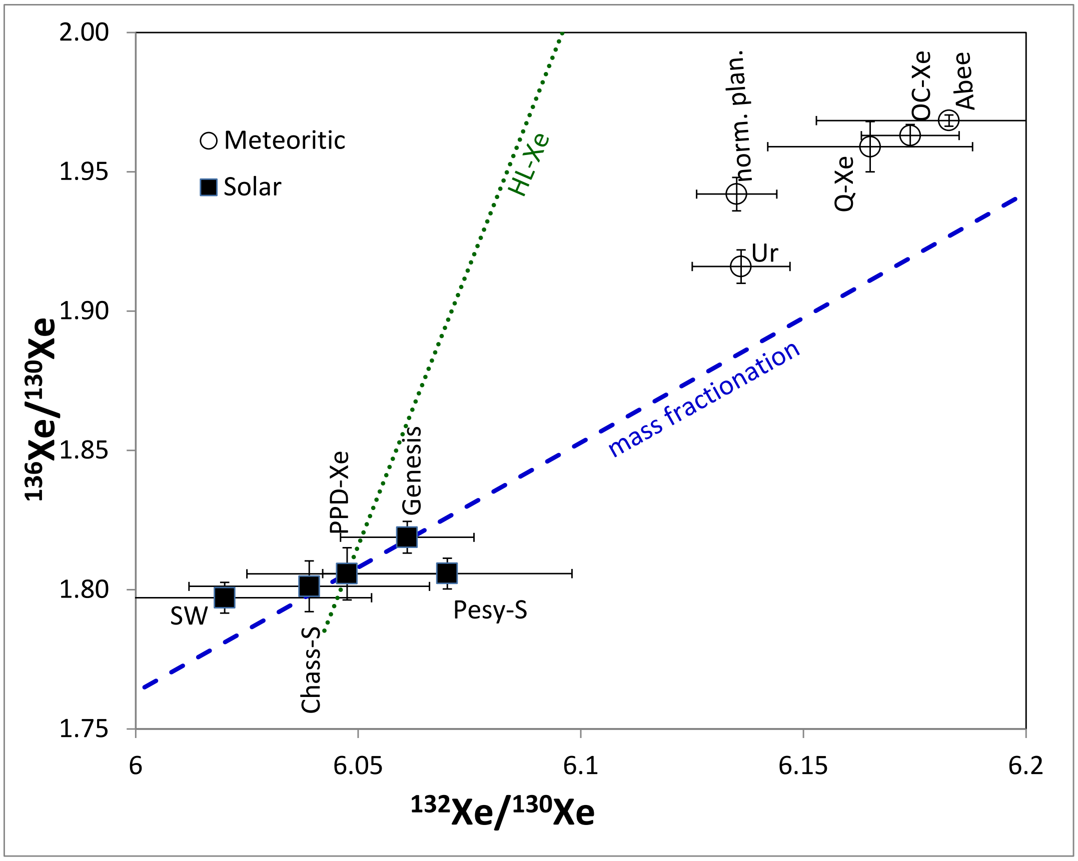

Figure 3: ^{136}Xe/^{130}Xe vs. ^{132}Xe/^{130}Xe in solar system components. Expected shifts due to addition of mass fractionation and due to addition of HL-Xe are indicated.