P-PROCESS SAMARIUM ISOTOPES IN SOLAR SYSTEM MATERIALS: IMPLICATIONS FOR THE ^{146}Sm-^{142}Nd CHRONOMETER. M. C. Ranen[1] and S. B. Jacobsen[1], [1]Dept. of Earth and Planet. Sci., Harvard Univ., 20 Oxford St., Cambridge, MA 02138 (ranen@fas.harvard.edu).

Introduction: The Sm-Nd system is one of the most powerful tools for constraining Solar System processes. Sm has two radioactive isotopes, the long lived ^{147}Sm which decays to ^{143}Nd with a half life of 106 Ga and the now extinct ^{146}Sm which decayed to ^{142}Nd with a half life of 106 Ma. Coupling these two systems can enable the ^{147}Sm-^{143}Nd to give a precise age as well as a tracer for Sm/Nd fractionation while ^{142}Nd/^{144}Nd variations can trace early silicate differentiation. In order to use radioisotope systems to compare fractionation processes in the solar nebula and on planetary bodies it is imperative to know the initial conditions for the object as well as to know bulk reference values. Ideally the initial conditions for all Solar System bodies will be equal. Small variations in initial conditions of either the ^{143}Nd/^{144}Nd ratio or the Sm/Nd ratio will not affect our interpretation of the ^{147}Sm-^{143}Nd system since differences in ^{143}Nd/^{144}Nd are usually large enough (>1ε) that small uncertainties (<50 ppm) in Sm/Nd or initial ^{143}Nd/^{144}Nd are trivial. However, variations seen in the ^{142}Nd/^{144}Nd ratio in terrestrial rocks (the Isua supracrustal belt in Greenland [1]) and differences between different classes of meteorites and the Earth [2] are all less than 50 ppm. In order to interpret the cause of these variations as Sm/Nd fractionation and subsequent decay of ^{146}Sm while it was still alive it is necessary to be certain that the Earth and all planetary bodies had both the same initial ^{142}Nd/^{144}Nd ratios and the same ^{146}Sm/^{144}Sm ratios. Here we examine the initial ^{146}Sm/^{144}Sm ratio of the Solar System, whether this ratio is homogenous throughout the Solar System, how heterogeneities could originate, and finally what these variations in ^{146}Sm/^{144}Sm mean for interpretation of the ^{142}Nd/^{144}Nd ratio.

Nucleosynthetic Components: Most isotopes of heavy elements are made by the s-process (slow neutron capture in an Asymptotic Giant Branch star) or the r-process (rapid neutron capture associated with a supernovae explosion. Another smaller process also associated with a supernova is the p-process which is thought to occur through photo-disintegration reactions. These p-process isotopes are enriched in protons unlike the r- and s-process isotopes. Sm has 7 isotopes, 1 that is p-only (144), 2 s-only (148,150), 1 r-only (154) and 3 having contributions from both the r- and s-process (147,149,152). The now extinct ^{146}Sm was also a p-only isotope. ^{149}Sm and ^{150}Sm both have high neutron capture cross sections and their composition in an object is influenced by the neutron fluence received.

Estimating initial ^{146}Sm/^{144}Sm ratio: ^{146}Sm has been proven to be live during the formation of the Solar System in a number of different meteorites including primitive meteorites such as carbonaceous chondrites as well as in various classes of differentiated meteorites including basaltic meteorites such as the eucrites. Table 1 lists a compilation of coupled ^{146,147}Sm-^{142,143}Nd data for a variety of meteorites [3-9]. The most recent high resolution ^{207}Pb-^{206}Pb ages of CAIs give an age of the Solar System to be 4.567 Ga [10]. All meteorite ^{146}Sm/^{144}Sm ratios were back calculated to an age of 4.567 Ga by using the formula $(^{146}Sm/^{144}Sm)_o = (^{146}Sm/^{144}Sm)_{CHUR,t}e^{\lambda 146t}$. Each sample shows evidence for live ^{146}Sm in the solar system. The only ancient meteorite that had no live ^{146}Sm at the time of closure is D'Orbigny, a relatively newly found angrite [11]. Figure 1 graphically presents these data along with model ^{146}Sm evolution curves for initial Solar System ^{146}Sm/^{144}Sm values of 0.007 – 0.011 at 4.567 Ga. There is wide scatter in these data but it appears that the average ^{146}Sm/^{144}Sm value is at least 0.009 at 4.567 Ga. This is in contrast with [2,12] who both cite a value of 0.008.

P-process heterogeneities: [12] measured all isotopes of Sm in a variety of planetary bodies. in two carbonaceous chondrites studied, Murchison and Allende, they found an average deficit of 118 ppm in the ^{144}Sm/^{154}Sm ratio compared to the terrestrial upper mantle. This will lower the ^{146}Sm/^{144}Sm ratio in carbonaceous chondrites by 1-2% by changing the ^{146}Sm/^{144}Sm production ratio. No deficits in ^{144}Sm were found in an ordinary chondrite and a eucrite studied. This study concluded that r- and s-process isotopes in Sm were homogenously distributed. Somehow the p-process must have become decoupled from the r-process even though both nucleosynthetic processes are believed to take place in a supernova.

Implications for ^{142}Nd/^{144}Nd: [2] found deficits in the ^{142}Nd/^{144}Nd ratio compared to the terrestrial upper mantle in a variety of planetary materials, with the larger differences being seen in carbonaceous chondrites. [13] also noticed this difference and suggested four possible reasons. (i) nuclear variation of initial ^{142}Nd/^{144}Nd; (ii) nuclear variation of (^{146}Sm/^{144}Sm); (iii) variation in Sm/Nd; and (iv) radiogenic evolution of $^{142}Nd/^{144}Nd$ in an Sm/Nd-fractionated "parental" reservoir before ^{146}Sm is extinct. [2] focuses on possibility (iv) concluding that the Earth had a very early silicate differentiation where an early enriched reservoir and an early depleted reservoir were formed prior to the Moon forming impact. [12] shows that the p-process heterogeneities seen in Sm isotopes of carbonaceous chondrites compared to Earth will affect the $^{142}Nd/^{144}Nd$ ratio. Figure 2 presents two scenarios that could explain the differences in $^{142}Nd/^{144}Nd$ seen in the literature. Fig. 2a assumes constant $^{146}Sm/^{144}Nd$ of 0.009 but with a 50 ppm difference in initial $^{142}Nd/^{144}Nd$. Fig. 2b presents $^{142}Nd/^{144}Nd$ evolution assuming that there is a range of initial $^{146}Sm/^{144}Nd$ values from 0.007-0.011. This allows for a difference in $^{142}Nd/^{144}Nd$ of 140 ppm. We know that there is a real variation in $^{142}Nd/^{144}Nd$ of up to 50 ppm. Figure 2 shows that the variation can be explained by either the uncertainties in the initial $^{146}Sm/^{144}Sm$ ratio or by incomplete mixing of ^{142}Nd in the solar nebula. In spite of large possible variations of 20% in ^{146}Sm, it appears to still be the best mixed of all extinct nuclides (more variation is seen in ^{26}Al for ex.). For a precise chronometry to be valid at the 5 ppm level in $^{142}Nd/^{144}Nd$ it is necessary to know $^{146}Sm/^{144}Sm$ to within an uncertainty of 1.4%. Currently there is a 20% spread in this ratio. We need new and better data to help constrain what the initial $^{146}Sm/^{144}Sm$ ratio of the Solar System was and whether or not these p-process nuclides were heterogeneously distributed.

Table 1. Compilation of Meteorite data

meteorite	Age (Ga)	$(^{146}Sm/^{144}Sm)_i$	$^{146}Sm/^{144}Sm$ at 4.567 Ga	Ref.
Divnoe	4.62	0.0116±16	0.0116	[3]
Caddo IAB	4.53	0.0086±21	0.0110	[4]
Acapulco	4.6	0.0067±19	0.0067	[5]
Ibitra	4.46	0.009±10	0.0185	[5]
Morristown	4.47	0.0075±11	0.0144	[5]
ADOR	4.56	0.0118±32	0.0119	[6]
V.M. Pebble 12	4.48	0.0058±15	0.0104	[7]
V.M Pebble 16	4.48	0.0059±4	0.0106	[7]
V.M Pebble 5	4.42	0.0042±17	0.0113	[7]
Mt. Padbury	4.52	0.0056±9	0.0077	[7]
Caldera	4.54	0.0075±10	0.0088	[8]
Moama	4.46	.0041 ± 13	.0084	[6]
LEW	4.553	0.0071 ± 17	.0078	[9]

References: [1] Harper C.L. and Jacobsen S.B. (1992) *Nature, 360*, 728-733. [2] Boyet M. and Carlson R.W. (1995) *Science, 309*, 576-581. [3] Bogdanovski O. and Jagoutz E. (1996) *LPS XXVII*, 129-130. [4] Stewart B. et al. (1996) *EPSL, 143*, 1-12. [5] Prinzhofer A. et al. (1992) *GCA, 56*, 797-815. [6] Jacobsen S.B. and Wasserburg G.J. (1984) *EPSL, 67*, 137-150. [7] Stewart B.W. et al. (1994) *GCA, 58*, 3487-3509. [8] Wadhwa M. and Lugmair G.W. (1995) *MAPS, 30*, 592. [9] Lugmair G.W. and Galer S.J.G. (1992) *GCA, 56*, 1673-1694. [10] Amelin Y. et al. (2002) *Science, 297*, 1678-1683. [11] Tonui E.K. et al. (2003) *LPS XXIV*, Abstract #1812. [12] Andreasen R. and Sharma M. (2006) *Science, 314*, 806-809. [13] Harper C.L. and Jacobsen S.B. (1993) *LPS XXIV*, 607-608.

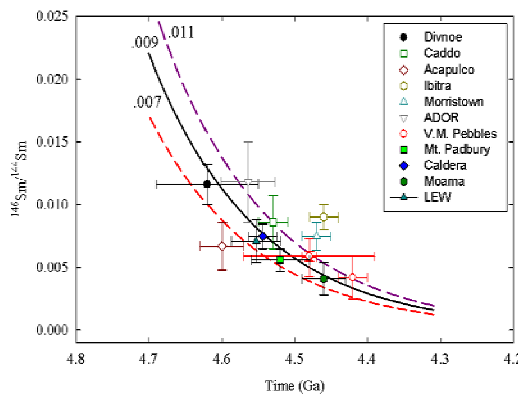

Fig. 1

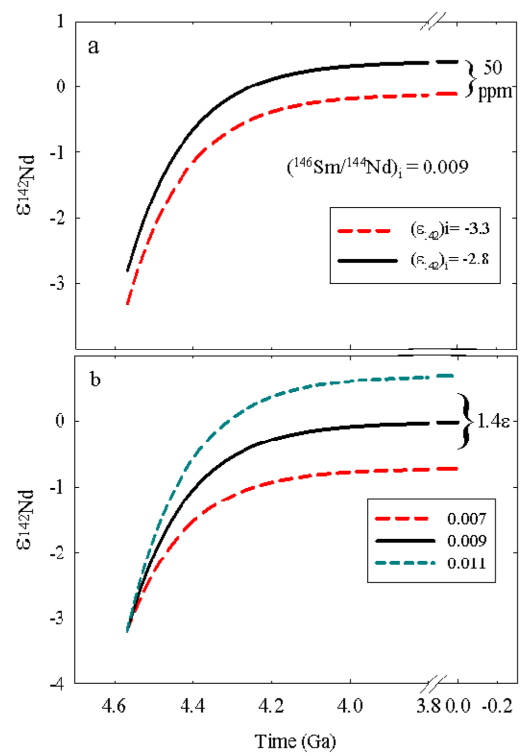

Fig. 2