The Standard Solar Model vs. Experimental Observations

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Abstract. A historical summary of observations since 1960 raises questions about the standard solar model (SSM). The SSM ascribes luminosity to hydrogen fusion in the solar core. It assumes the Sun formed suddenly without mass accretion so its interior had the same composition as its surface. The lightest element, hydrogen, accounts for over 90 percent of the atoms in the Sun's atmosphere. The next lightest element, helium, makes up about 9 percent of it. All 81 heavier elements together make up less than 0.3 percent of the atoms at the solar surface, but almost all those in nearby planets. In contrast to the SSM, measurements since 1960 have revealed evidence of severe mass separation in the Sun and the presence in protoplanetary material of multiple short-lived nuclides and linked chemical and isotopic gradients from nucleosynthesis. By the mid 1970s, measurements suggested that the Sun likely formed on the collapsed core of a supernova and therefore contained few light elements. In the mid-1980s, it was demonstrated that excess light (*l*) isotopes relative to heavier (*h*) ones in the solar wind matched nine stages of mass fractionation, each enriching *l* relative to *h* by $(h/l)^{1/2}$. When the photosphere is corrected for this fractionation, the bulk Sun has the composition of meteorites and nearby planets. In the 1990s, isotope ratios were found to be less fractionated in solar flares as if these flares had by-passed 3.4 stages of fractionation. In the year 2000, heavy elements were reported to be enriched by orders-of-magnitude in an impulsive solar flare. Through nuclear systematics it was shown in 2001 that neutron emission from a collapsed supernova core inside the Sun may initiate a chain of reactions that produce luminosity, neutrinos, and the annual solar wind flux of 3 x 10^{43} H^+ per year. These studies offer another explanation for solar luminosity. They do not corroborate the SSM.

1. Introduction

In 1917 Harkins [1] reported that seven elements - iron (Fe), oxygen (O), nickel (Ni), silicon (Si), magnesium (Mg), sulfur (S), and calcium (Ca) - comprise 99 percent of the material in ordinary meteorites. He noted a link between abundance and nuclear stability, stating that *"all of these elements have even atomic numbers"* (p. 862) and "... *in the evolution of elements much more material has gone into the even-numbered elements than into those which are odd* ..." (p. 869).

In the 1920s [2,3] the Sun's atmosphere was found to consist mostly of an element with an odd atomic number, hydrogen (H). Hoyle [4] notes these results were "... *for atmospheres, however, not the deep interiors of stars* ..." (p. 153). He and others continued to believe the Sun was made mostly of iron "... *until after the Second World War* ..." (p. 153). Then the new idea of a hydrogen Sun gained immediate acceptance by the world, *"We knew it all the time."* (p. 154), perhaps because research during the war [5] had shown that H-fusion could explain solar luminosity if the Sun's interior had the same composition as its atmosphere.

How did the Sun avoid gravitational segregation? The Standard Solar Model simply assumes [6] that an intersteller cloud suddenly formed the Sun as a *"homogeneous"* object with "... *no mass loss or mass accretion* ..." (p. 935). This concept of a homogeneous, H-rich Sun had been widely accepted by the time lunar samples, laden with elements implanted by the solar wind (SW), became available for study in 1969. However, meteorite analyses published as early as 1960 indicated possible problems with the SSM [7,8].

2. Observations from 1960 till 1975

In 1960 the decay product of extinct ^{129}I and an unusual abundance pattern for the other, non-radiogenic xenon isotopes were found in meteorites [7,8]. Noting that ^{129}I exceeded that expected if the solar system formed from an interstellar cloud, Fowler *et al.* [9] suggested that D, Li, Be, B and extinct ^{129}I and ^{107}Pd might have been produced locally, here in the early Solar System.

Evidence of extinct ^{244}Pu, a nuclide that could only be made by rapid neutron-capture in a supernova, was reported in meteorites in 1965 [10]. Subsequently it was found that strange xenon (See Xe-2 in Fig. 1) preserved a record of this rapid neutron-capture at the birth of the Solar System [11], i.e., xenon isotopes made by different nuclear reactions were not evenly mixed in the precursor material that formed meteorites. If the SSM obtains, isotopes would have been uniformly mixed.

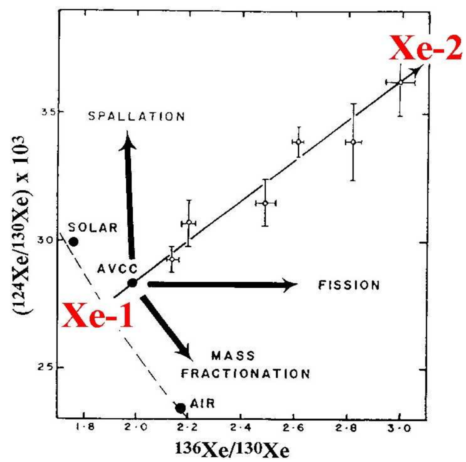

Figure 1. Normal Xe-1 and strange Xe-2

Fig. 1 shows the two major types of xenon identified in meteorites in 1972: Normal xenon (Xe-1) and strange xenon (Xe-2), enriched in the lightest and heaviest xenon isotopes, ^{124}Xe and ^{136}Xe, at the upper right corner [11]. Xe-1 includes the fractionated forms. These lie along the dashed line in the lower left corner. Similar mass-fractionations have been observed in the isotopes of other elements.

In 1975, studies showed that primordial helium accompanied only Xe-2, not Xe-1, at the birth of the Solar System [12,13]. Fig 2 shows this for mineral separates of the Allende meteorite [13]. This link of primordial ^{4}He with Xe-2 is inconsistent with assumptions of the SSM.

3. Results for 1975 to date

The link of primordial helium with Xe-2 at the birth of the Solar System [12-16] suggested an even more drastic form of local element synthesis than that imagined earlier [9]: The Solar System may have formed directly from debris of a single, local supernova (SN). The Sun formed on the collapsed SN core. The inner planets formed in the central, iron-rich region surrounding the SN core where Xe-1 was dominant. The giant Jovian planets formed primarily from elements in the outer SN layers where Xe-2 was dominant [12,14]. This scenario is depicted in Fig. 3.

Fig. 3 raised several questions.

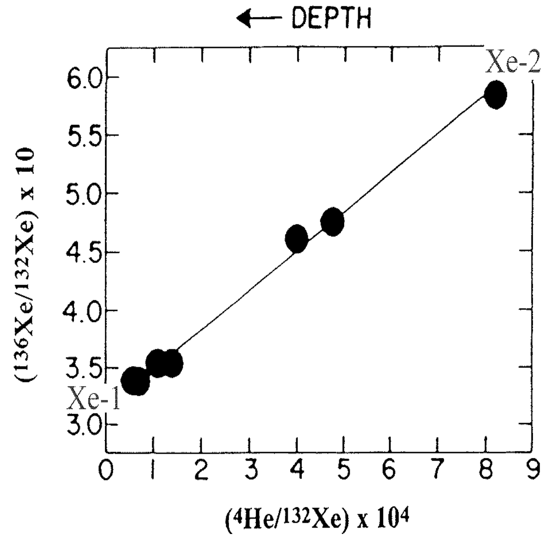

Figure 2. Primordial helium and xenon isotopes in the Allende meteorite

- Is nucleosynthesis the only viable explanation for Xe-2?
- Do other heavy elements trapped with Xe-2 display strange isotope ratios?
- Do the links of Xe-2 with helium and Xe-1 with iron extend across planetary distances?
- Does the Sun's interior contain Xe-1 and abundant iron, with little helium or hydrogen?
- Do meteorites retain a record of mass fraction in the star that produced our elements?
- Does age dating indicate a supernova at the birth of the Solar System?
- Did fusion deplete light elements from the inner part of the Solar System?
- Are luminosity and solar neutrinos compatible with the scenario shown in Fig. 3?

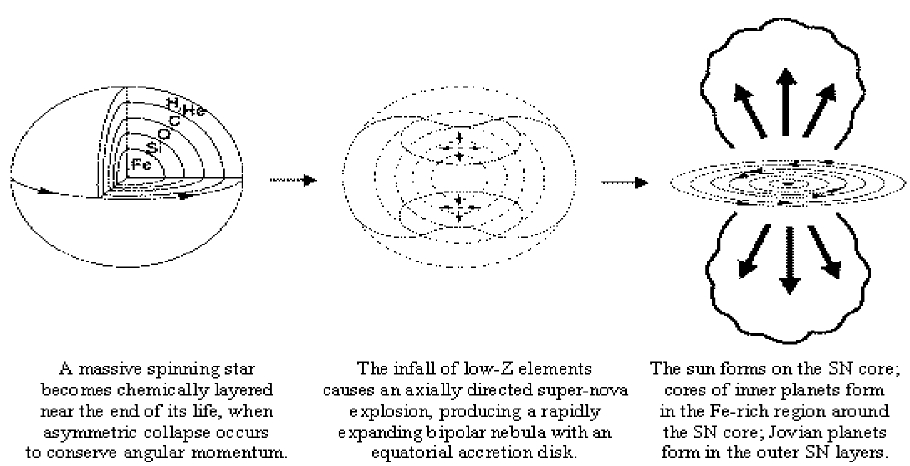

Figure 3. Formation of the Solar System from a supernova [12,14-16]

These have all been answered affirmatively by measurements since 1975.

3.1. The origin of Xe-2

Proponents of the SSM attempted to explain Xe-2 as a fission product of superheavy elememts until 1983 [17]. Then interstellar grains from a supernova were addopted to explain Xe-2 and strange isotope ratios of other elements associated with it [18]. There is no longer any doubt that Xe-2 is nucleogenetic [18]. However, interstellar grains do not explain the link of Xe-2 with primordial helium. Further, this proposal is plagued by the lack of evidence that grains are older than their host meteorites or were irradiated with cosmic rays before being embedded in them.

3.2. Xe-2 linked with other strange elements and helium; Xe-1 linked with iron and sulfur

Fig. 4 shows the strange tellurium isotope ratios found with Xe-2 in the Allende meteorite [19]. Other tellurium analyses [20-22] confirmed strange isotope ratios of tellurium trapped with Xe-2.

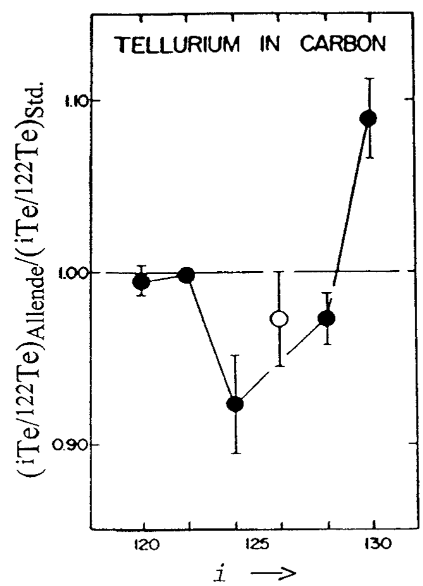

Figure 4. Strange tellurium with Xe-2 in the Allende meteorite [19]

Fig. 5 shows evidence the *Galileo* probe found of Xe-2 on entering Jupiter's He-rich atmosphere in 1996 [23-25]. This confirmed the link of Xe-2 with primordial helium across planetary distances. In Fig. 5, ^{77}Ct is hydrocarbon counts at 77 amu. Counts at 134 and 136 amu are mostly xenon with a trace of hydrocarbon contamination. These increased as the probe descended into Jupiter's atmosphere (left to right). Measurements ceased when the *Galileo* probe was crushed by high atmospheric pressure. Xenon in the solar wind, in Xe-1, and in Xe-2 are shown at (^{136}Xe/^{134}Xe) = 0.80, 0.84, and 1.04, respectively. Therefore, in Jupiter,

$$(^{136}Xe/^{134}Xe) = 1.04 \pm 0.06 \tag{1}$$

Other measurements confirmed that Xe-1 is linked with iron, not only in troilite (FeS) grains of stone and iron meteorites, but also in the planets rich in Fe and S, Earth and Mars [26-30].

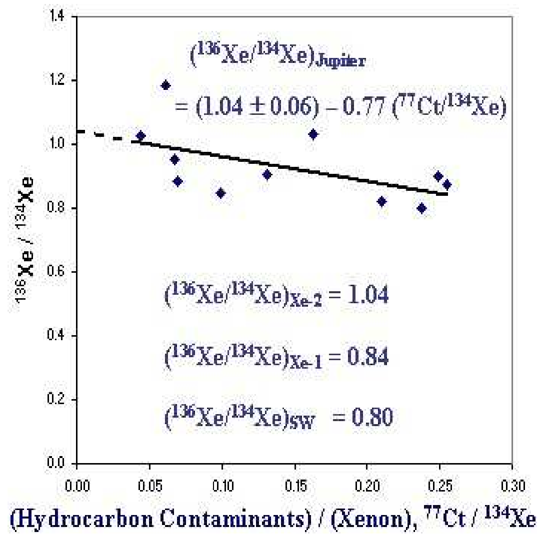

Figure 5. Strange Xe-2 in Jupiter's helium-rich atmosphere

3.3. Xe-1 and iron in the Sun

The solar wind contains Xe-1, as predicted, but its light (*l*) isotopes are enriched relative to the heavy (*h*) ones by about 3.5 percent /amu [31]. As shown in Fig. 6, light isotopes of He, Ne, Ar, Kr and Xe in the solar wind all follow a common mass-dependent fractionation power law, where the fractionation factor, *f*, is

$$f = (h/l)^{4.56} \tag{2}$$

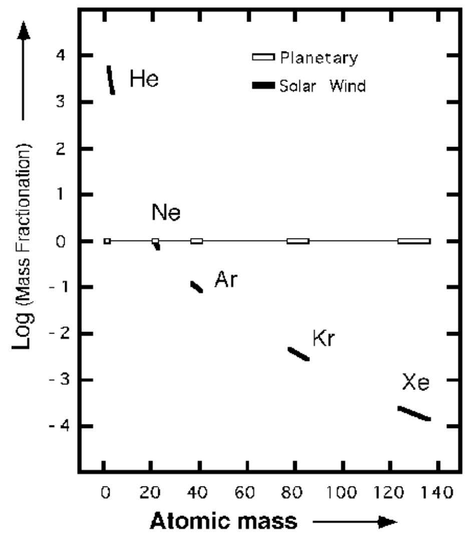

Figure 6. Excess light isotopes in solar wind

Solar flares may also contain Xe-1 but heavy isotopes are more abundant there, as if flares by-pass 3.4 stages of mass fractionation [32]. This is shown in Table 1. The *Wind* spacecraft recently observed large systematic enrichments of heavy elements in material ejected from the Sun's interior by an impulsive solar flare [33].

Table 1. He, Ne, Mg, Ar in solar wind and flares

Isotopic Ratios	Solar Wind	Solar Flares	SW/SF	Expected**
$^{3}He/^{4}He$	0.00041	0.00026	1.58	1.63
$^{20}Ne/^{22}Ne$	13.6	11.6	1.17	1.18
$^{24}Mg/^{26}Mg$	7.0	6.0	1.17	1.15
$^{36}Ar/^{38}Ar$	5.3	4.8	1.10	1.10

Application of Eq (2) to the photosphere further confirmed the Sun's predicted composition: Iron (Fe), nickel (Ni), oxygen (O), silicon (Si), sulfur (S), magnesium (Mg), and calcium (Ca) are the Sun's most abundant elements [31]. These even-numbered elements are made deep inside supernovae. They are the same seven elements Harkins found in 1917 to comprise 99 percent of ordinary meteorites [1].

The probability is very low ($P \leq 2 \times 10^{-33}$) that Eq. (2) by chance selects from the solar atmosphere seven trace elements that a) all have even atomic numbers, b) are made deep in supernovae, and c) are the same elements that comprise 99 percent of ordinary meteorites [1].

Many measurements [34-38] found evidence of severe mass fractionation in lunar and meteorite samples long before this was recognized as a stellar process [31]. For example, the abundance pattern of trace elements in the Sun's photosphere is like that in carbonaceous chondrites that formed far from the Sun [38]. Fractionation plus spallation explains all the alphabetical types of neon reported in meteorites, Ne-A,-B,-C,-D,-E etc. [37]. The dashed fractionation line on the lower left of Fig. 1 and the diagonal line between Xe-1 (lower left) and Xe-2 (upper right) of Fig. 1 forecast [11] the subsequent finding of FUN (Fractionation and Unknown Nuclear) isotopic anomalies [39].

3.4. The supernova at the birth of the Solar System

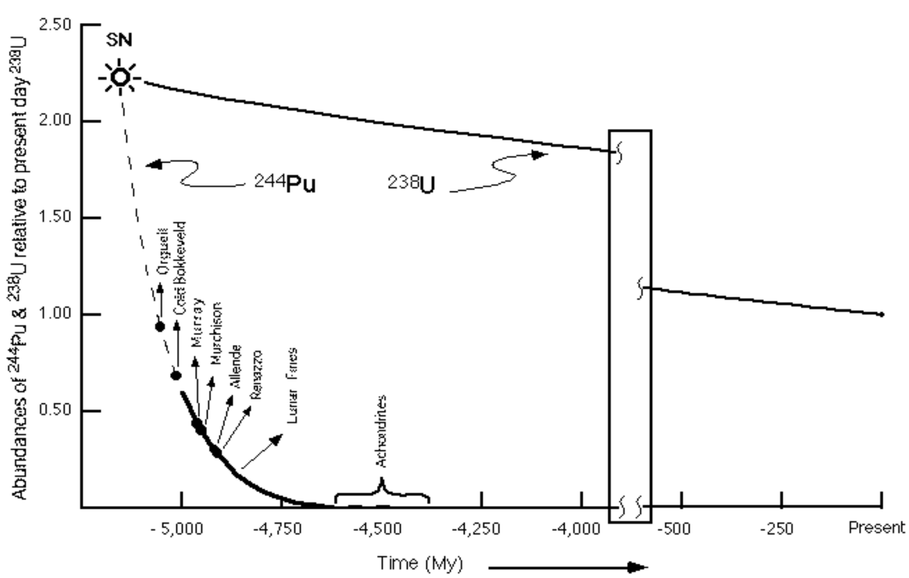

Figure 7. A supernova produced ^{244}Pu about 5 Gy ago and meteorites started to retain its gaseous fission product, ^{136}Xe, about 0.1 Gy later [40,41].

Age dating confirmed a supernova explosion near the birth of the solar system. ^{244}Pu ($t_{1/2}$ = 82 My) is only made by the supernova r-process. It was trapped in meteorites with other actinide elements like uranium and thorium. Kuroda and Myers [40,41] combined ^{244}Pu-^{136}Xe and U,Th-Pb dating to show that the supernova explosion occurred about 5 Gy ago, as illustrated in Fig. 7.

Other laboratories found evidence of a supernova in isotopic anomalies and short-lived nuclides ($t_{1/2}$ = 0.1-100 My) of meteorites. Isotopes of krypton, tellurium and xenon made in the supernova by the r-process underwent chemical separation within 10,000 seconds of the explosion [21,42], before precursor nuclei like ^{83}Br, ^{125}Sb and ^{131}I decayed away. Silicon carbide grains that started to form early in the supernova debris grew larger and trapped higher levels of ^{26}Al ($t_{1/2}$ = 0.74 My). Fallout particles from nuclear weapons also showed this relationship between formation time, grain size and level of trapped readioactivity [43].

There is no proof that fusion depleted light elements from the region where the Sun and the iron-rich planets formed. However, light elements could not exist in stellar regions where fusion produced elements like iron. As shown in Fig. 2, Xe-1 was initially in a primordial noble gas component containing little helium [12,14-16]. Xe-1 was linked with iron across planetary distances [26-31]. Thus, fusion is a viable explanation for the paucity of helium and other light elements in the inner solar system where Xe-1 and iron are dominant.

3.5. The source of luminosity and neutrinos in an iron-rich Sun

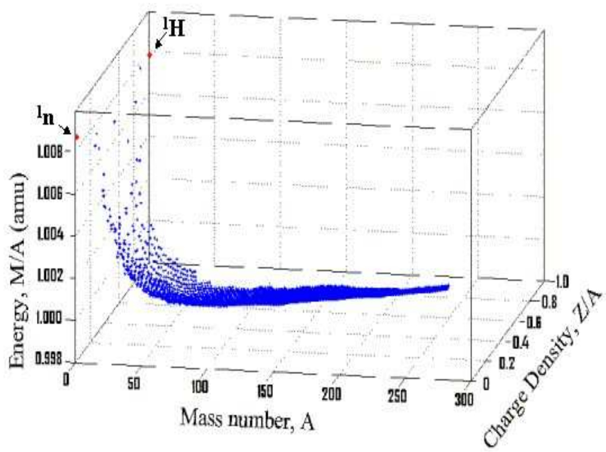

Figure 8. The cradle of the nuclides

Systematic properties of the 2,850 nuclides shown in Fig. 8 reveal an inherent instability in assemblages of neutrons relative to neutron emission that may explain luminosity and neutrinos from an iron Sun [44]. Neutrons emitted by the collapsed SN core at the Sun's center (See Fig. 3) may initiate a chain of reactions that generate luminosity, neutrinos, and a solar wind outpouring of 3 x 10^{43} H^+ per year [44-46]:

(i) Escape of neutrons from the collapsed solar core:

- $<^1_0 n> \rightarrow {}^1_0n + \sim 10 - 22 MeV$

(ii) Neutron decay or capture by other nuclides:

- ${}^1_0n \rightarrow {}^1_1H^+ + e^- + anti - \nu + 0.782MeV$

(iii) Fusion and upward migration of H+:
- $4^1_1H^+ + 2e^- \rightarrow {}^4_2He^{++} + 2\nu + 27MeV$

(iv) Escape of excess H^+ in the solar wind:
- 3 x 10^{43} H^+/year depart in the solar wind

4. Conclusions and future tests

These observations indicate that iron is the most abundant element in the Sun and its overall compostion is like that of ordinary meteorites and terrestial planets. Hydrogen fusion near the solar core generates no more than 38 percent of the Sun's energy. For the SSM, the observed output of solar neutrinos is too low without neutrino oscillations. For the model presented here, there is in fact an excess of solar neutrinos observed. These excess neutrinos likely arise from other reactions, e.g., those that produce excess ^6Li and ^{10}Be in the outer layers of the Sun [47,48] and increased values of the $^{15}N/^{14}N$ ratio in the solar wind over geologic time [49].

These indications of layering and other observations discussed here are, in the author's opinion, consistent with the iron-rich Sun produced in the manner shown in Fig. 3. These observations conflict with basic assumptions of the SSM. The reactions that produced luminosity in an iron-rich Sun also explain the outpouring of protons from its surface. However, these results provide no information of the validity of using the Sun to model other stars.

4.1. Future tests

The following measurements are proposed as additional tests of the iron Sun:

(i) Measure neutrinos from reactions that increased the $^{15}N/^{14}N$ ratio [49] and produced excess ^6Li and ^{10}Be in the outer layers of the Sun [47,48].

(ii) Measure anti-neutrinos (3 x 10^{38} s^{-1}, $E < 0.782$ MeV) from neutron decay at the solar core. Low E targets for inverse β-decay are the Homestake Mine $^{35}Cl \rightarrow {}^{35}S$ reaction [50], the $^{14}N \rightarrow {}^{14}C$ or $^3He \rightarrow {}^3H$ reactions (Time Projection Chambers may be needed [51]).

(iii) Look for background radiation [52] from a supernova (Fig. 3) that exploded here 5 Gy ago (Fig 7).

(iv) Look for evidence of the dense object (about 10 km) at the solar core in exotic magnetic fields, the solar cycle, in effects of irradiation by circular polarized light [53], or quadrupole moments.

(v) Look for enhanced heavy elements in the fast-moving solar wind from the Sun's poles.

(vi) Measure other properties that constrain primary [14,54] or secondry [32,55-59] mass segregation in the Sun and other stars.

5. Acknowledgements

The author acknowledges a deep gratitude to the late Professor Dwarka Das Sabu, who co-authored many of his early papers on the possibility of an iron-rich Sun, to the late Professors Paul K. Kuroda and John H. Reynolds for serving as research mentors, and to Professors Stig E. Friberg, Daniel W. Armstrong and the late Professors Glenn T. Seaborg and Raymond L. Bisplinghoff for encouragement in this 40 year struggle to decipher the Sun. Mr. Jack Koenig and Dr. H. Neal Grannemann provide helpful comments in the preparation of this manuscript.

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