Nuclear Systematics: I. Solar Abundance of the Elements

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Nuclear systematics and the abundance of elements and isotopes in meteorites, in planets, in the solar photosphere, in the solar wind, and in solar flares are used to estimate the abundance of elements in the Sun. The results indicate that ^{56}Fe, the decay product of doubly-magic ^{56}Ni, is the Sun's most abundant nuclide. The next most abundant nuclide is the doubly-magic ^{16}O. The most abundant elements - Fe, Ni, O, Si, S, Mg, and Ca - are the even-Z elements that HARKINS[1] found to comprise ≈ 99% of ordinary meteorites. The least abundant elements have loosely bound nucleons - Li, Be and B - further confirming the proposed link[1] between abundance and nuclear structure, with one conspicuous and important exception. Diffusion enriches light-weight nuclides at the solar surface, hiding the link of abundance to nuclear stability beneath the Sun's H-rich exterior.

Introduction

In 1917, HARKINS[1] determined the abundance of the elements and claimed to have found a relationship between abundance and nuclear structure. Noting that the Earth's crust and the Sun's gaseous envelope may not properly represent the overall composition of these bodies, HARKINS[1] used the results of chemical analyses on 318 iron meteorites and 125 stone meteorites to conclude that the seven more abundant elements all have even atomic numbers, Z, and the most abundant one occurs at Z = 26, iron (Fe).

The Sun contains about 99.8 % of the mass of the solar system. It is now widely believed to be composed mostly of hydrogen (H), an odd-Z element with Z = 1, e.g., ANDERS and GREVESSE[2]. The change in opinions about elemental abundances is often attributed to the 1925 dissertation by PAYNE[3] or to the more widely read 1929 paper by RUSSELL[4]. These workers used lines of different elements in the solar spectrum to show that hydrogen (H) is the most abundant element in the Sun's atmosphere. PAYNE[3] regarded the high value derived for the abundance of H as "*spurious*" (p. 186), and RUSSELL[4] regarded this as a puzzle that remained to be solved. Despite Harkins' earlier warning about using atmospheric abundances and Russell's comment (p. 70) that "*The calculated abundance of hydrogen in the sun's atmosphere is almost incredibly great*", most modern elemental abundance estimates[2] for H, He and other light, volatile elements are based on solar line spectra.

The discovery of energy released in H-fusion and the desire to explain solar luminosity may have played a role in this change of views about elemental abundances. In reviewing the history of the hydrogen-model of the Sun, HOYLE[5] describes a meeting with Sir Arthur Eddington on a spring day in 1940 when, "*We both believed that the Sun was made mostly of iron ....*" (p. 153). He continues,"*The high-iron solution continued to reign supreme .... until after the Second World War ......*" (p. 153). Later, after Hoyle decided that a high-hydrogen model was to be preferred, he reports that the concept was immediately accepted, "*We believed it all the time.*" (p. 154).

The H-model of the Sun may also be attractive because it is consistent with the nebular model for the formation of the solar system[6] and with the Standard Solar Model (SSM)[7]. This assumes that the Sun formed in an instant of time as a fully convective, spherically symmetric, homogeneous body, with no gain or loss of mass. Accordingly, the composition of the bulk Sun is much like that of its atmosphere, mostly hydrogen (H) and helium (He), and its energy comes from the fusion of protons (^{1}H) into the most abundant helium isotope (^{4}He). This reason for solar luminosity remains in vogue, although recent measurements[8] have established increasingly stringent limits on neutrino oscillations to explain the deficiency between the observed and the predicted flux of solar neutrinos[9-11].

An alternative to the SSM model was reported in this journal[12] suggesting that the Sun and its planetary system formed over a very different time scale, from chemically and isotopically heterogeneous supernova (SN) debris[13-14] with abundant Fe but little H or He in the central region where the Sun and the inner planets formed. Additional support for the SN model and an Fe-rich Sun came from the finding of a systematic enrichment of the lighter mass isotopes of elements in the solar wind[15], as if diffusion in the Sun selectively moves lighter isotopes of each element and light weight elements like H to the solar surface.

In this paper, nuclear systematics are used to examine the elemental and isotopic abundances of the SSM[7] and the SN[12] models. In the next paper, nuclear systematics are used to depict the 3-D framework that relates all ground-state nuclides, including those that might be formed under extreme stellar conditions. The source of the Sun's radiant energy is discussed in the third paper.

Nuclear systematics

For the SSM model[7], the most abundant nuclide in the Sun is ^{1}H. For the SN model[12], the Sun's most abundant nuclide is ^{56}Fe. In many respects, the properties of these two nuclides are opposite or quite dissimilar.

^{1}H has an odd atomic number; ^{56}Fe has an even atomic number. Among stable nuclides, ^{1}H has the highest potential energy per nucleon (mass per nucleon) and the highest charge density (charge per nucleon). ^{1}H is widely believed to be the fuel for the fusion reactions that generates light and heat in the Sun and other stars. On the other hand, ^{56}Fe is the stable decay product of doubly magic ^{56}Ni, a nuclide that was recently observed to have been abundantly produced[16] as the ash of violent thermonuclear reactions in supernova 1987A. ^{56}Fe has the lowest mass per nucleon, and an ordinary value for the charge per nucleon of $Z/A = 0.46$. These disparate properties of ^{1}H and ^{56}Fe are shown in Figure 1. Included there are the latest data[17] from the U.S. Department of Energy for all stable and long-lived ($t_{1/2} \geq 7 \text{ x } 10^{8}$ yr) nuclides.

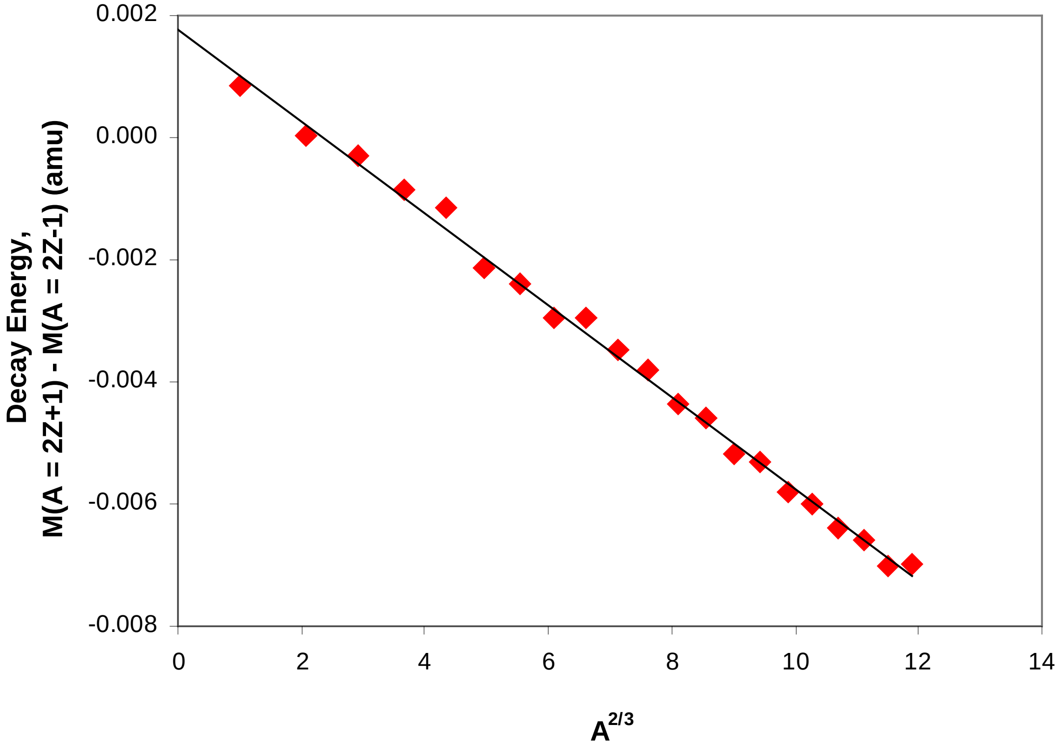

Figure 1

^{1}H is represented by the large symbol in the upper right section of Figure 1. It has the highest potential energy per nucleon of all stable and long-lived nuclides. No other nuclide has a charge density so high as that of ^{1}H with $Z/A = 1$. All other stable and long-lived nuclides have charge densities of $0.4 \geq Z/A \leq$

0.5, except for the very rare isotope of helium, ^{3}He with Z/A = 0.67. This helium isotope and other rare nuclides with high values of M/A are identified in Figure 1 as ^{2}H, ^{3}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B and ^{11}B. Nucleons are loosely bound in these, and their mode of production in stars is poorly understood[18].

^{56}Fe is represented by the other large symbol in the lower central part of Figure 1. All other stable and long-lived nuclides have higher potential energy per nucleon than ^{56}Fe. The roles of ^{1}H and ^{26}Fe, as candidate fuel and ash for thermonuclear fusion reactions in stars, are reflected by their vertical positions as the highest and lowest points in Figure 1. Other nuclides that are easily destroyed by stellar fusion reactions are also identified in Figure 1.

If the SN model[12] is correct and ^{56}Fe is the most abundant nuclide[15], then the data plotted in Figure 1 might suggest that HARKINS[1] was correct to claim a relationship between abundances and nuclear structure. If the SSM[7] is correct and ^{1}H is the most abundant nuclide[2,5], then the data plotted in Figure 1 might suggest that HARKINS[1] was mistaken to advise that "*... the more stable atoms should be more abundantly formed ...*" in the creation of our elements (p. 859). However the wet chemical analyses used by HARKINS[1] and the line spectra used to determine the composition of the solar photosphere[2] indicate elemental abundance rather than the abundance of each nuclide. To further test HARKINS[1] proposed connection between abundances and nuclear stability, we therefore assumed normal isotopic abundances for each element to compute the *average* potential energy per nucleon (M/A) for each element. The results are shown in Figure 2.

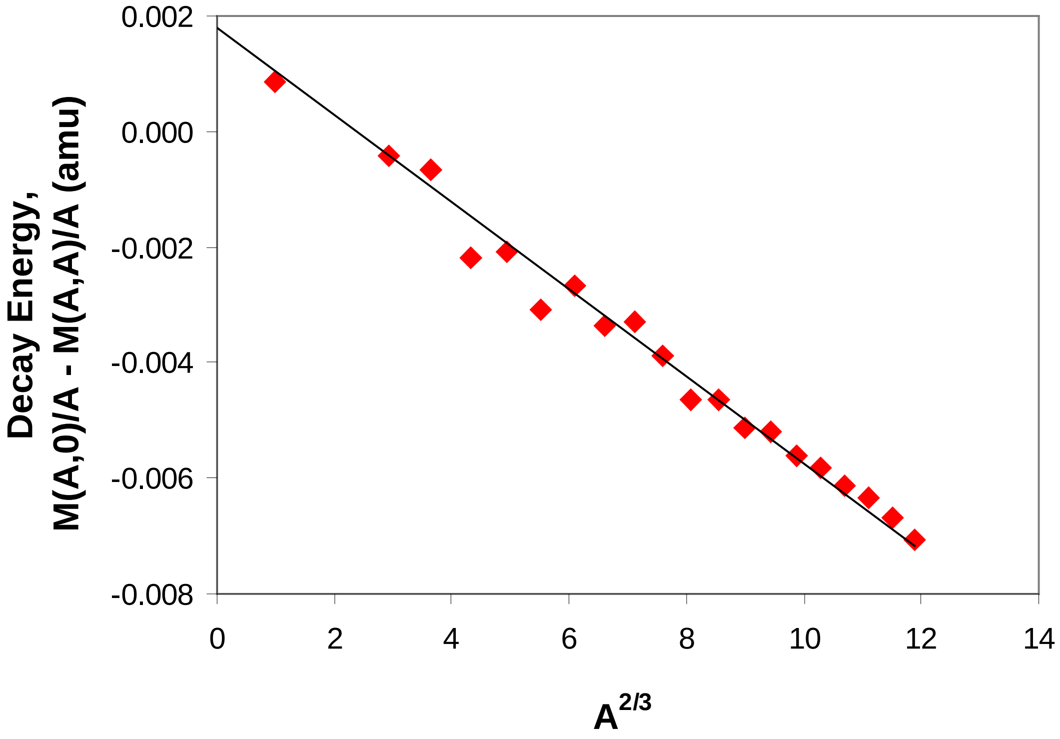

Figure 2

The stable and long lived isotopes of H (^{1}H and ^{2}H) are represented by the large symbol in the upper left section of Figure 2. Those of Fe (^{54}Fe, ^{56}Fe, ^{57}Fe and ^{58}Fe) by the other large symbol. The average potential energy per nucleon is highest for H at Z = 1 and lowest for Fe at Z = 26. Thus the apparent conflict of HARKINS[1] conclusions with the SSM[7] and the H-rich Sun[2,5] and its possible agreement with the SN-model[12] and an Fe-rich Sun[15] is as obvious for elements (Figure 2) as it was for nuclides (Figure 1).

To see if the seeming agreement of the SN-model[12] and an Fe-rich Sun[15] with the conclusions of HARKINS[1] extends beyond the most abundant element, we compare the abundance of each element from MANUEL and HWAUNG[15], normalized to Fe = 10^{12} atoms, with the *average* potential energy per nucleon (M/A) in Figure 3.

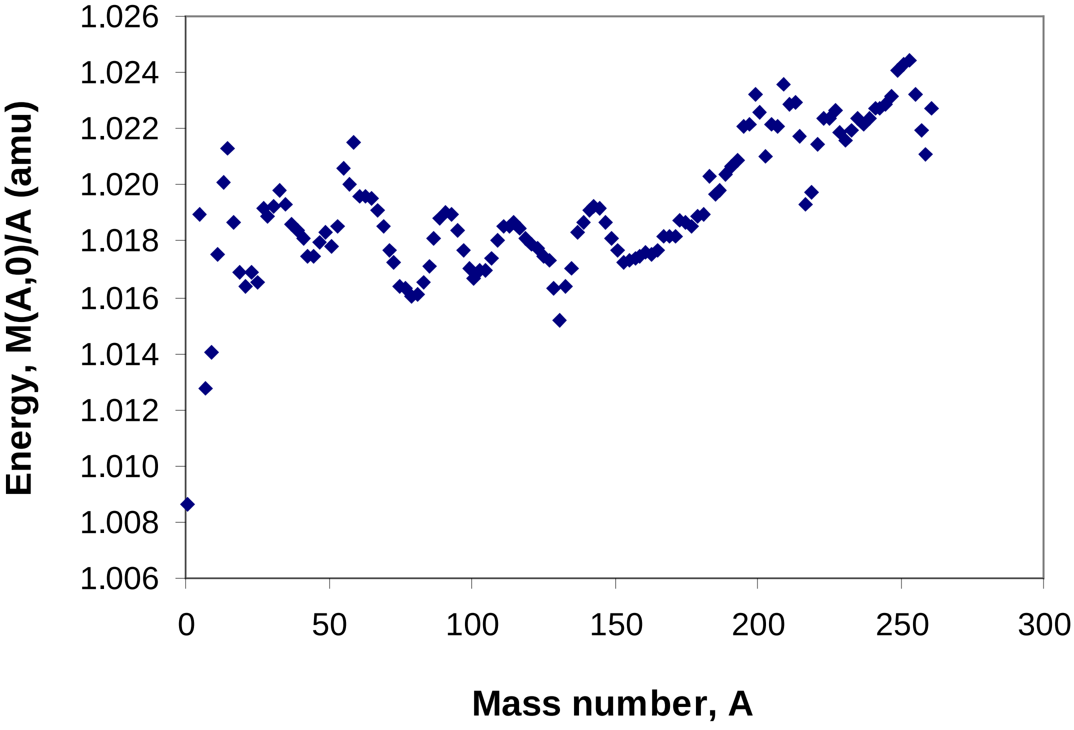

Figure 3

Since the elemental abundances span several orders of magnitude, these are shown as log values on the abscissa. As in Figures 1 and 2, the ordinate (vertical scale) shows the potential energy per nucleon.

The connection between abundances and nuclear stability in Figure 3 seems to extend from the least abundant elements, Li, Be, and B, to the most abundant one, Fe, and all elements except one lie within the area enclosed by the lines in the graph. Variations within this area may indicate that kinetics (reaction path) also influence abundance, but the general trend seems to be consistent with the suggestion of HARKINS[1] that the more stable elements were more abundantly formed.

We suggest that the anomalously high abundance of H provides information about the current dynamics of the Sun. This will be explained further in the third paper in this series.

Elemental and Isotopic Abundances

HARKINS[1] found that the seven most abundant elements - Fe, O, Ni, Si, Mg, S and Ca - all have even atomic numbers. He concluded that the abundances of elements “*... are related to the structure of the nuclei of their atoms*.” (p. 856). Support for this conclusion waned after World War II, when it was decided that the most abundant element in the solar atmosphere[3,4] is also the most abundant element in its interior[5]. Although H has an odd atomic number, Z = 1, the concept of an H-Sun was immediately accepted[5]. More recent analyses of the isotopes of He, Ne, Ar, Kr and Xe implanted in lunar samples by the solar wind showed[15] that the abundances of light-weight isotopes of mass = L are enriched relative to the abundances of heavy isotopes of mass = H by a factor, f, where

$$f = (H/L)^{4.56} \qquad (1)$$

This finding was interpreted as evidence that material at the solar surface has undergone ≈ 9 theoretical stages of mass fractionation from intra-solar diffusion[15], where each stage alters the isotopic abundance by a factor of $\sqrt{H/L}$.

Supporting evidence for intra-solar diffusion came with the finding[19] that the isotopes of He, Ne, Mg and Ar in solar flares show a smaller enrichment of the light mass isotopes, as if solar flares bypass 3.4 of these 9-stages of mass fractionation. Thus, the light-weight isotopes of He, Ne, Mg and Ar in the solar wind are enriched relative to those in solar flares by a factor, f^*, where

$$f^* = (H/L)^{1.7} \qquad (2)$$

Table 1 shows the values of He, Ne, Mg and Ar isotopic ratios in the solar wind and in solar flares and compares the differences with the predictions of Eq. (1).

Insert Table 1

The finding illustrated in Table 1, that isotopic abundances of a refractory element like Mg shared mass fractionation with the isotopes of the highly volatile noble gases, confirmed one of the measurements proposed[15] to test the hypothesis that intra-solar diffusion caused the light isotope enrichments in the solar wind.

However, the most compelling argument for intra-solar diffusion and an Fe-rich Sun comes from a comparison of HARKINS[1] elemental abundance estimate with that found when photospheric abundances are corrected for the mass-fractionation effects given by Eq. (1).

The seven elements that HARKINS[1] found to comprise 99% of the material in ordinary meteorites - Fe, O, Ni, Si, Mg, S and Ca - are all trace elements in the photosphere. When MANUEL and HWAUNG[15] used Eq. (1) to correct elemental abundances in the photosphere for the mass fractionation seen across the isotopes of solar-wind implanted elements, they found that the seven most abundant elements in the bulk Sun were Fe, Ni, O, Si, S, Mg and Ca. The probability that Eq. (1) would select these seven trace elements from the solar photosphere is less than 2 x 10^{-33}. In other words, there is essentially no chance that the fractionation pattern of isotopes in the solar wind[15] and the line spectra of elements in the photosphere[2] would together inexplicably select the same seven elements that HARKINS[1] reported from wet chemical analyses of ordinary meteorites.

Conclusions

The seven most abundant elements in the bulk Sun[15] - Fe, Ni, O, Si, S, Mg, and Ca - are the same even-Z elements that HARKINS[1] found to comprise ≈ 99% of ordinary meteorites. Assuming normal isotopic abundances, the Sun's most abundant nuclide is ^{56}Fe, the decay product of doubly-magic ^{56}Ni, followed by ^{16}O, another doubly-magic nuclide. The three least abundant elements are Li, Be and B. These results confirm HARKINS[1] proposed link between abundance and nuclear structure and are consistent with the SN model for the formation of the solar system[12-15].

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Figure captions

Fig. 1. This plot of potential energy per nucleon versus charge density exhibits the disparate properties of ^{1}H (large symbol in upper right) and ^{56}Fe (large symbol in lower center). These have the highest and lowest potential per nucleon, respectively. Other nuclides with unusually high potential energy are also identified.

Fig. 2. The *average* potential energy per nucleon for all stable and long-lived isotopes of each element displays a maximum value at H (Z =1) and a minimum value at Fe (Z = 26). These are identified by large symbols. Other elements with unusually high potential energy per nucleon are also identified. The suggested link of elemental abundances with nuclear stability[1] would seem to be more consistent with an Fe-rich Sun[15] than with an H-rich Sun[2,5].

Fig. 3. This plot of the *average* potential energy per nucleon for each element versus abundance (log scale) for an Fe-rich Sun[15] shows a general correlation of abundance with nuclear stability[1], with one notable exception. This correlation extends from Fe with the highest abundance and the lowest potential energy per nucleon to Li with the lowest abundance and the second highest potential energy per nucleon. The exceptionally high abundance of H will be discussed in the third paper in this series