

Nuclear systematics:

Part IV. Neutron-capture cross sections and solar abundance

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The abundance pattern of s-process nuclides confirms severe mass separation in the Sun and in the parent star that gave birth to the Solar System. The most abundant elements in the interior of the Sun are Fe, Ni, O, Si and S. These five, even-*Z* elements with high nuclear stability comprise the bulk material of ordinary meteorites and rocky planets close to the Sun. The Sun and other stars operate as giant, magnetic mass-separators that selectively move lightweight elements, and the lighter mass isotopes of each element, to the surface.

Introduction

In 1997 KURODA and MYERS¹ reported that the Solar System started to form about 5 billion years ago, soon after the explosion of a supernova. The following year a paper published in this journal² reviewed evidence that heterogeneous debris from a single supernova produced the entire Solar System, including major chemical and isotopic gradients that exist in our planetary system today.

This is the fourth in a recent series of papers using nuclear systematics to elucidate the Sun's origin, composition, and source of energy. The first paper concluded that the Sun selectively enriches lightweight elements, like H and He, and the lighter isotopes of each element at the solar surface.³ After correcting the solar surface abundances of ROSS and ALLER⁴ for mass separation, the interior of the Sun was shown to consist mostly of Fe, Ni, O, Si, S, Mg and Ca. In 1917 HARKINS⁵ showed that ordinary meteorites consist mostly of these same seven elements. The other two papers in this series used systematic properties of nuclei to elucidate the source of energy coming from the iron-rich Sun.^{6,7}

In a related paper⁸ it was suggested that the Sun's magnetic fields, deep-seated remnants of ancient origin, accelerate H⁺ ions upward. The H⁺ ions act as a carrier gas that maintains mass separation in the Sun, allowing it to operate as a giant magnetic mass separator.⁸

The Sun's magnetic fields are not constant, but change in a regular manner over the 11-year sunspot cycle. This is actually half of the 22-year Hale magnetic cycle, in which the polarity of the magnetic fields reverses twice. There is also evidence of longer cycles in the Sun's magnetic activity. This includes the well-known 70-year hiatus in sunspot activity, from 1645 to 1714, that coincides with the coldest part of the Little Ice Age in Europe and North America. The magnetic

Maunder minimum refers to periods of low sunspot activity for the Sun and other Sun-like stars.^{9,10}

A recently completed survey found a surprisingly high abundance of metals, like iron and nickel, at the surface of other stars thought to be modern examples of the Maunder minimum that our Sun experienced about 300 years ago.^{9,10} This new evidence of a possible link between magnetic activity and the abundance of elements at the surface of Sun-like stars provided additional incentive for another quantitative test of mass separation in the Sun.

Excess lightweight isotopes in the solar wind (SW) provided the first clear indication of mass separation in the Sun.¹¹ The empirical mass fractionation relationship identified seven elements, present only at the part-per-million level in the solar photosphere, as the most abundant elements in the interior of the Sun.¹¹ These same seven, even-*Z* elements comprise ~99% of ordinary meteorites.⁵ The statistical probability³ of this being a meaningless agreement is less than $2 \cdot 10^{-33}$. Such a profound finding merits further investigation.

For example, such mass fractionation should alter the ratio of s-products at the solar surface, $A \approx 25\text{--}210$ atomic mass units (amu), by several orders-of-magnitude. Although nuclear cross sections are not well known, they may be compared with photospheric abundances of s-products as an independent test for the mass fractionation seen in isotope ratios.¹¹

The abundance pattern of s-products

Figure 1 shows the abundance pattern of elements in the solar photosphere from the classical paper by ROSS and ALLER.⁴ Abundance values from CAMERON¹³ are shown for elements not included in the paper by ROSS and ALLER,⁴ or shown only as upper limits. Large diamonds are used in Fig. 1 to represent the five more abundant elements in the solar photosphere: H, He, C, N and O.

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The more abundant elements in Fig. 1 are all lightweight. Three of these, He, C and O, have even values of the atomic number, Z. The other two are odd-Z elements, H and N.

On the other hand, wet chemical analyses of 443 meteorites convinced HARKINS⁵ in 1917 that nature has strong preference for even-Z elements. The analyses revealed that seven even-Z elements comprise 99% of all material in meteorites, Fe, O, Ni, Si, Mg, S and Ca.

Nuclear science was in its infancy in 1917, but HARKINS⁵ noted a possible link between nuclear stability and abundance, “If then, at the stage of evolution represented by the solar system, or by the earth, it is found that the even-numbered elements are more abundant than the odd, as seems to be the case, then it might be assumed that the even-numbered elements are on the whole the more stable.” (p. 859).

HARKINS⁵ also hinted at a possible reason for the discrepancy between the abundance pattern of elements in meteorites and those in the solar photosphere, noting that “...findings are largely influenced by the height in the gaseous envelope of the sun at which the observation is taken.” (p. 860).

However, it was not until 1969, when the Apollo mission returned with samples from the surface of the Moon, that a quantitative explanation could be demonstrated for the discrepancy between the abundance pattern of elements that comprise ordinary meteorites and those at the surface of the Sun.

Analyses revealed that the solar wind (SW) had implanted elements from the Sun into the surfaces of fine-grained lunar soils over billions of years. This added SW-component was most obvious in the highly volatile noble gases, He, Ne, Ar, Kr and Xe. The isotopes of these five elements span a wide mass range, A = 3–136 amu.

Over this entire mass range, the abundance of the lighter isotope of mass L is enriched relative to that of the heavier isotope of mass H by a common fractionation factor, f, which defines this power law:¹¹

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

When the photospheric abundance of elements (Fig. 1) is corrected for the mass separation seen across SW noble gas isotopes¹¹ [Eq. (1)], the internal composition of the bulk Sun is surprisingly like that HARKINS⁵ found in ordinary meteorites. This is shown in Fig. 2, where large diamonds represent the more abundant elements in the bulk Sun – Fe, Ni, O, Si, and S.

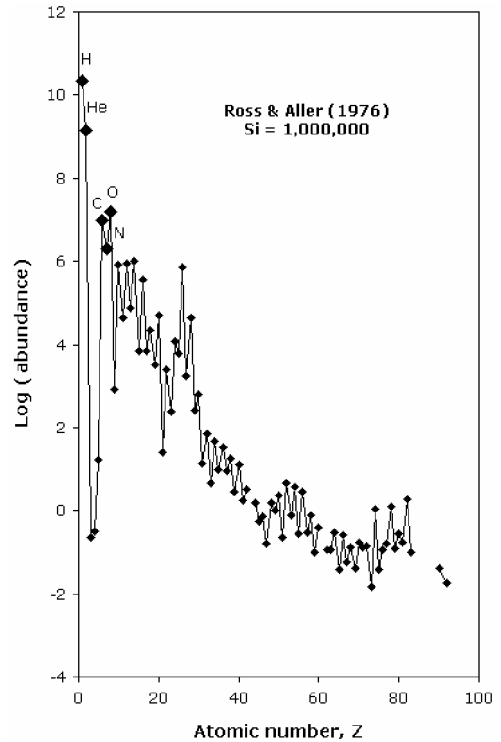


Fig. 1. Chemical composition of the Sun according to ROSS and ALLER.⁴ Large diamonds represent the more abundant elements in the photosphere: H, He, C, N and O

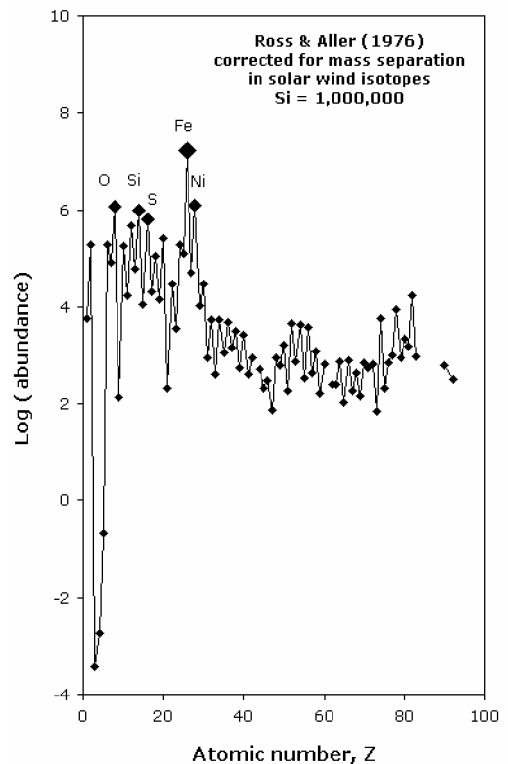


Fig. 2. Chemical composition of the bulk Sun after correcting abundances^{4,13} in the photosphere for the mass separation observed across isotopes of elements in the solar wind. Large diamonds mark the more abundant elements inside the Sun: Fe, Ni, O, Si, and S

BURBIDGE et al.¹² note in their classical paper on the synthesis of elements in stars that the steady-flow abundance, N , of successively heavier mass nuclides made by the s-process (slow neutron capture) will be inversely proportional to their neutron-capture cross sections, σ :

$$\sigma_{(A-1)} N_{(A-1)} = \sigma_{(A)} N_{(A)} = \sigma_{(A+1)} N_{(A+1)} = \text{etc.} = k \quad (2)$$

Steady-flow was apparently established when the s-process made the two, s-only isotopes of samarium, ^{148}Sm and ^{150}Sm . CLAYTON¹⁴ notes that, within error limits, the value of:

$$\sigma(^{148}\text{Sm}) N(^{148}\text{Sm}) = \sigma(^{150}\text{Sm}) N(^{150}\text{Sm})$$

ROLFS and RODNEY¹⁵ report that the abundances and neutron-capture cross sections of the three, s-only isotopes of tellurium, ^{122}Te , ^{123}Te , and ^{124}Te , confirm that the steady-flow s-process also operated across this mass region. However, using abundances of elements at the solar surface, BURBIDGE et al.¹² find that values of the σN product for all s-products decline with increasing A , by about 4–5 orders over the 10-fold mass range of s-products in the Sun. BURBIDGE et al.¹² show values of the σN product versus A before the “iron peak” in Figure VI, 1 on page 584. This only covers a limited mass, $A=24\text{--}48$ amu, but values of the σN product decline as A increases. They show another plot of the σN product versus A after the “iron peak” in Figure VI, 3 on page 586. This covers a wider mass range, $A=60\text{--}210$. Values of the σN product continue to decline as A increases, and like the mass fractionation relationship given by Eq. (1), the decline is steeper in the light mass region and levels off as A becomes larger. The authors include a solid, exponential curve through the data points in Figure VI, 3. However, the caption states that, “*The curve which is drawn is purely schematic.*” (page 586).

Figure 3 shows a plot of all BURBIDGE et al.¹² values of $\log(\sigma N)$ versus mass number, A , for all s-products, over the entire mass range, $A=0\text{--}250$ amu. The exponential, least-squares line through the data defines a new mass-dependent relationship among s-products:

$$\log(\sigma N) = -5.16 \log A + 12.5 \quad (3)$$

The same data¹² are shown in Fig. 4 as a linear plot of $\log(\sigma N)$ versus $\log A$ for all s-products over the entire mass range, $A=0\text{--}250$ amu. The least-squares line through the data yields the same mass-dependent fractionation equation shown in Eq. (3).

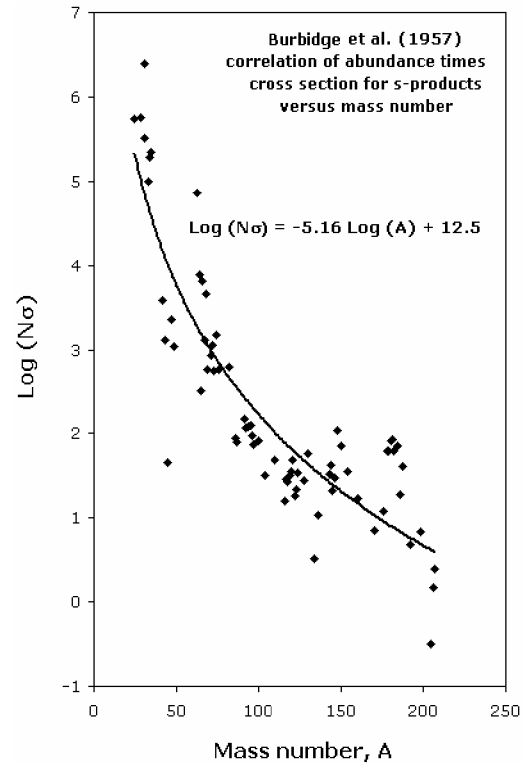


Fig. 3. Values of $\log(\sigma_{(A)}N_{(A)})$ for s-products in the photosphere are not constant, as expected, but decline exponentially as the mass number, A , increases. Data points are all from the Appendix at the end of BURBIDGE, BURBIDGE, FOWLER and HOYLE¹² paper

Application of this equation to the ANDERS and GREVESSE¹⁶ estimate of the abundance of elements in the photosphere and in carbonaceous chondrites is shown in Fig. 5. Large diamonds identify Fe, Ni, O, S, and Si as the more abundant elements in the unfractionated parent source of the solar photosphere and carbonaceous chondrites.

Conclusions

The mass fractionation relationship defined by the anomalous abundance of s-products in the solar photosphere,¹⁶ and the one defined by the anomalous abundance of isotopes in the solar wind,^{3,11} both indicate that Fe, Ni, O, Si and S are the most abundant elements in the interior of the Sun. Isotope ratios are better known than neutron-capture cross sections. Hence, the fractionation relationship given by Eq. (1) is probably more reliable than that defined by neutron-capture cross sections, Eq. (3).

We endorse the idea that mass segregation in the Sun is caused by H^+ ions, produced by neutron decay near the Sun's core and then accelerated upward by solar magnetic fields.⁸ The H^+ ions thus act as the "carrier gas" for mass solar separation. Those H^+ ions that survive the upward journey without being fused into 4He then depart in the solar wind.^{8,17} This also offers a viable explanation for reduced mass separation and increased surface abundances of Fe and Ni, at the surface of other Sun-like stars during periods of low magnetic activity.^{9,10} Violent stellar explosions may be

triggered by the build-up of highly fusile hydrogen during such periods of low magnetic activity.

We endorse the suggestion that a single supernova produced the solar system.² That scenario is illustrated in Fig. 6. If the lightweight elements and carbonaceous material in meteorites came from the outer layers of the supernova, then the similarity in elemental abundances of the solar photosphere and carbonaceous chondrites¹⁶ suggests that mass separation also occurred in the parent star.

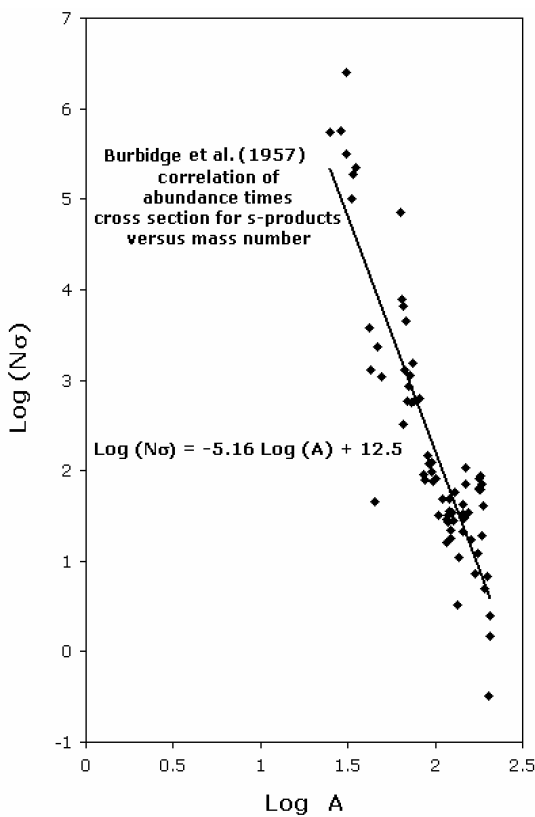


Fig. 4. Values of $\log(\sigma_{(A)}N_{(A)})$ for s-products in the solar photosphere decrease linearly as values of $\log(A)$ increase. Data points are all from the Appendix at the end of the paper by BURBIDGE, BURBIDGE, FOWLER and HOYLE¹²

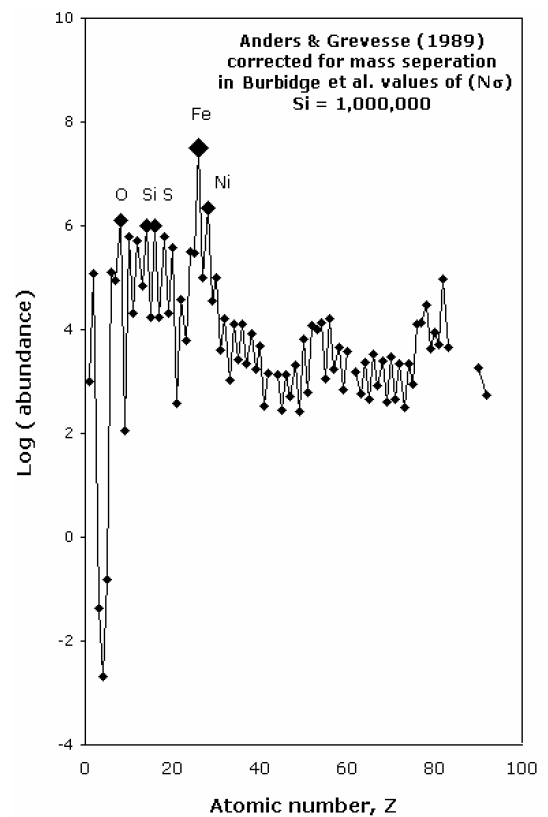


Fig. 5. The abundance pattern of the un-fractionated parent source for elements in the solar photosphere and in carbonaceous chondrites, after correcting measured abundances¹⁶ for the mass separation seen across s-products. The more abundant elements, Fe, Ni, O, S, and Si, are identified by the large diamonds

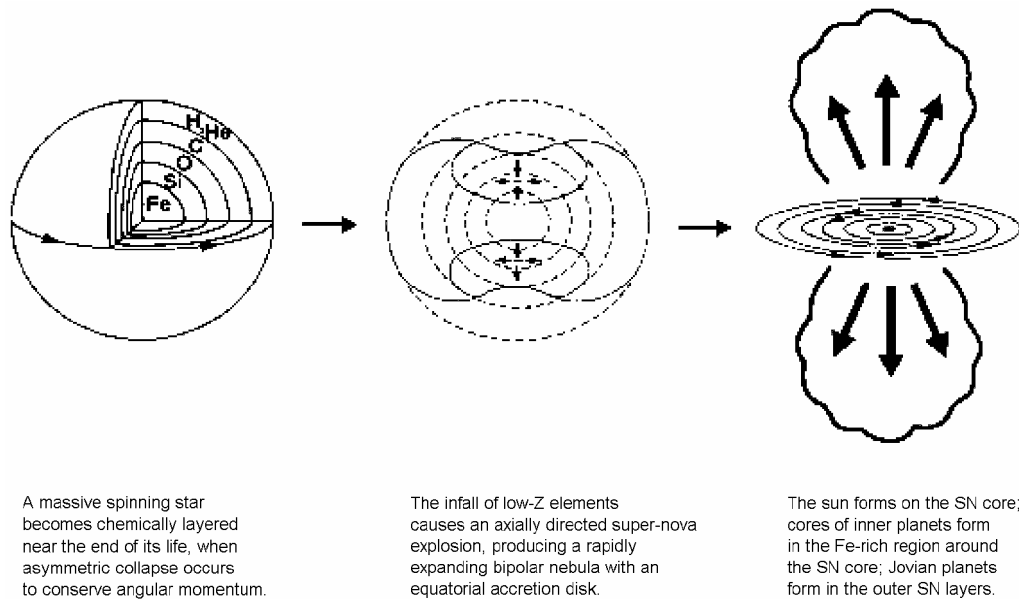


Fig. 6. The solar system formed directly from the heterogeneous debris of a single, spinning supernova that exploded axially to produce a bipolar nebula and an equatorial accretion disk

Finally, if H^+ ions from neutron decay near the solar core is the carrier gas that caused mass separation in the parent star, as well as in the daughter Sun, then the supernova explosion may have simply exposed, rather than generated, the neutron star on which the Sun accreted.

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