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The Oxygen to Carbon Ratio in the Solar Interior: Information from Nuclear Reaction Cross-Sections

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Mass separation in the Sun may explain a serious difficulty that has plagued nuclear astrophysics for decades: Why the oxygen to carbon ratio in the Sun's photosphere is only two, O/C ≈ 2. After correcting for mass fractionation, the ratio of these helium-burning products in the Sun is much larger, O/C ≈ 9-10. The lower value, O/C ≈ 9, is probably more reliable. It is based on measurements of mass separation of stable noble gas isotopes in the solar wind over the mass range of 3-136 amu. The higher value, O/C ≈ 10, is based on a comparison of neutron-capture cross-sections and the abundances of s-products in the photosphere over the mass range of 25-207 amu. Both methods indicate that Fe, Ni, O, Si, and S are the most abundant elements in the Sun. These elements came from the interior of the supernova that formed the solar system.

KEY WORDS: Solar O/C ratio; helium-burning; s-products in the Sun; composition of the Sun.

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I. INTRODUCTION

In the forward to the 1988 nuclear astrophysics textbook, *Caldrons in the Cosmos: Nuclear Astrophysics* [1], William A. Fowler pointed out two serious difficulties in the most basic concepts of nuclear physics:

1. *"On square one the solar neutrino problem is still with us (…), indicating that we do not even understand how our own star really works."*
2. *"On square two we still cannot show in the laboratory and in theoretical calculations why the ratio of oxygen to carbon in the Sun and similar stars is close to two to one (…)"* (page xi).

Analyses of meteorites and lunar samples had already started to unravel both puzzles, but the nuclear astrophysics community had not yet realized the implications of these measurements. For example a 1977 paper on the results of meteorite analyses [2], had concluded that:

1. Essentially all primordial helium in the early solar system was initially associated with "strange" xenon, enriched in isotopes made by r- and p-processes in a supernova [2], and
2. Material from the supernova core likely formed the *"iron cores of the inner planets, iron meteorites, and the core of the Sun"* (p. 209).

A 1983 paper on the analyses of lunar samples had revealed a common, mass-dependent fractionation across the isotopes of He, Ne, Ar, Kr, and Xe implanted in the surfaces of lunar soil samples by the solar wind [3]. The 1983 report [3] had concluded that:

1. Severe mass fractionation occurs in the Sun, and
2. Iron is the most abundant element in the interior of the Sun.

The same mass separation [3] that enriches the lighter isotopes of xenon at the surface of the Sun by 3.5% per mass unit, for example, would increase the C/O ratio at the solar surface by a factor of ≈ 4. In other words, measured mass fractionation across the isotopes of elements predicts that O/C ≈ 8 in the bulk Sun if O/C ≈ 2 at the solar surface.

Helium burning in the red-giant stage of stellar evolution is the likely source of the major isotopes of oxygen and carbon, ^{16}O and ^{12}C [4]. The amounts of oxygen and carbon produced depend on the relative cross-sections for producing ^{16}O by the ^{12}C(α, γ)^{16}O reaction and ^{12}C by the triple-α reaction. The cross-section for the triple-α reaction is relatively well known. An excited state of ^{12}C near 7.6 MeV is produced as a resonance of the (^{8}Be + α) reaction [5].

A recent review of 40-years of progress in understanding the synthesis of elements in stars [6] notes that *"Unfortunately, 40 years after B^{2}FH, the rate of the ^{12}C(α, γ)^{16}O reaction is still not well determined."* (p. 999). Arnett [7] states, *"It is one of the oldest of the vexing problems of experimental nuclear astrophysics."* (p. 225). Abstracts of papers presented at the 2004 Conference on Nuclei in the Cosmos (NIC8) show the continued importance of efforts to determine the cross section of the ^{12}C(α, γ)^{16}O reaction in the nuclear astrophysics community:

1. *"The ^{12}C(α, γ)^{16}O reaction is arguably the most important nuclear reaction yet to be determined on stellar astrophysics."* [8]
2. *"The key reaction ^{12}C(α, γ)^{16}O reaction has been investigated in three different experi-ments at the Stuttgart DYNAMITRON in the course of international collaborations."* [9]
3. *"The fusion of carbon and helium via ^{12}C(α, γ)^{16}O in the helium burning phase of red giant stars is generally accepted to be a key reaction of nuclear astrophysics."* [10]

The problem with O/C ≤ 5 is shown in Figs. 2-4 of the 1964 paper by Denizer and Salpeter [11]. Figs. 2 and 4 [11] show that the value of the O/C ratio after helium-burning depends on the mass of the star. Fig. 3 [11] shows that the final value of the O/C ratio also depends on a multiplication factor in the $^{12}C(\alpha, \gamma)^{16}O$ rate, θ_α^2. Fig. 2 [11] shows that the mole fraction, x_C, of C produced by helium-burning may be as high as $x_C \approx 0.2$ in a star of about 1 M_o (M_o = one solar mass). For stars > 4 M_o, continued helium-burning converts essentially all ^{12}C into ^{16}O.

Denizer and Salpeter show the influence of θ_α^2 in Fig. 3 [11]. Arnett [7] notes that comparable amounts ^{12}C and ^{16}O may remain at the end of helium burning for the 1960's estimated value of $\theta_\alpha^2 = 0.085$. Arnett [7] continues, *"For values of θ_α^2 larger by a factor of four, very little ^{12}C remains. In subsequent years, nuclear experimentalists suggested values that are larger by a factor of ten or more."* (p. 225). This is illustrated by the curve labeled $\theta_\alpha^2 = 1.0$ in Fig. 3 of the paper by Denizer and Salpeter [11]. For $\theta_\alpha^2 = 1.0$, the mole fraction of carbon only reaches a high value of $x_C \approx 0.03$ in a 1 M_o star, and the mole fraction of carbon vanishes in a star > 2 M_o.

In view of evidence that mass separation selectively enriches lightweight elements at the solar surface [3, 12-15], it may be futile to try to fit nuclear reaction cross-sections to the low value of the O/C ratio at the Sun's surface. Cross-sections for helium-burning reactions are not yet known sufficiently well to tell if mass separation has altered ratios of the helium-burning products at the solar surface. However, elements at the solar surface include a wide mass-range of nuclides that were made by slow neutron capture, the s-process [4]. Abundances of these s-products at the solar surface will be used below to test the hypothesis of mass separation in the Sun [3] as the reason for the low value of O/C ≈ 2 [1] in the photosphere.

II. MASS-DEPENDENT SEPARATION OF ELEMENTS IN THE SUN

Fig. 1 shows Anders and Grevesse's [16] widely quoted estimate for the abundance pattern of elements in the Sun and the solar system. The more abundant elements at the solar surface - H, He, C, O, and Ne - are the five lightweight elements represented by large diamonds in Fig. 1.

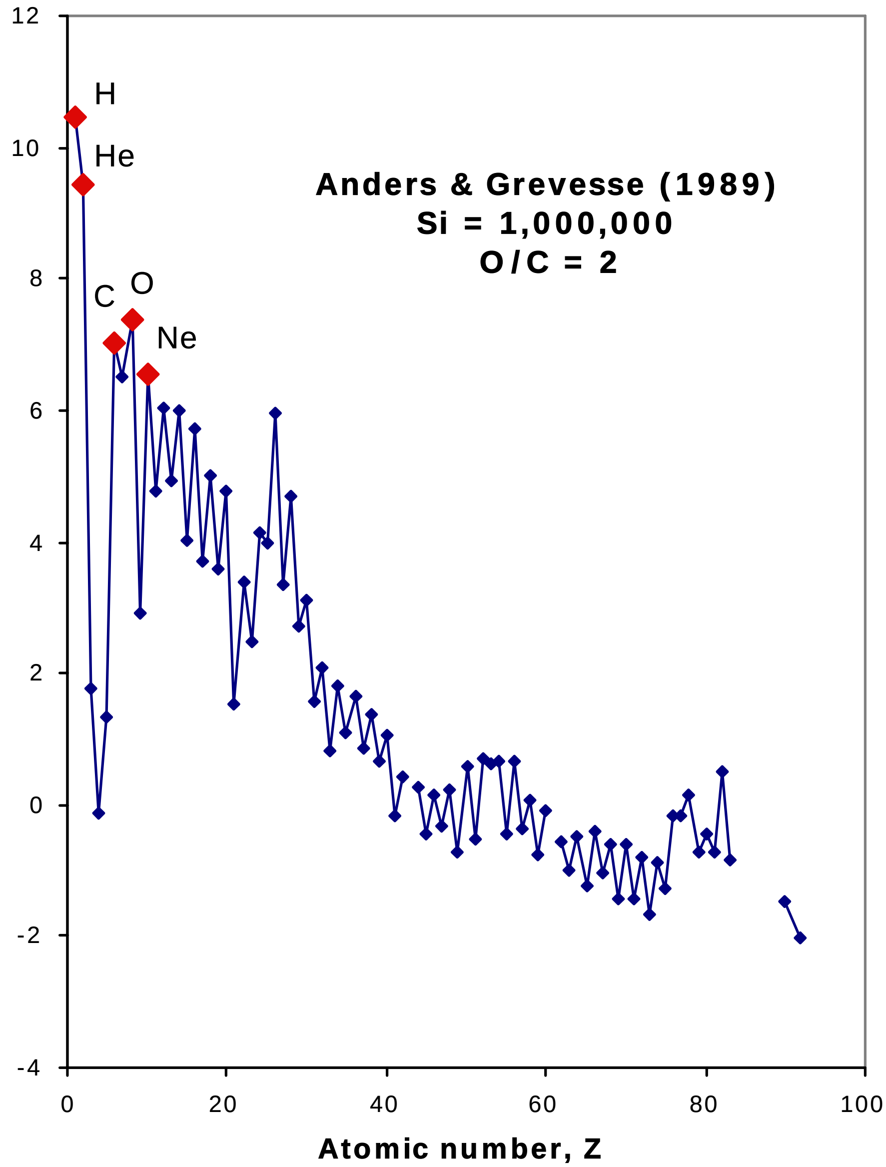

Fig. 1. The abundance pattern of elements in the Sun and in the solar system according to Anders and Grevesse [16]. Large diamonds identify the five more abundant elements, H, He, C, O, and Ne.

However Harkins [17] noted in 1917 that the Sun's gaseous envelope and the Earth's crust are *"mere skin"* (p. 860) that may not reflect the internal compositions of these bodies. He recommended using *"accurate chemical analyses"* on material that *"falls upon the earth's surface from space"* (p. 861) to determine the abundance pattern of elements. Harkins [17] used the results of wet chemical analyses on 443 ordinary meteorites to show that seven elements comprise 99% of the material in meteorites – Fe, O, Ni, Si, Mg, S and Ca.

Noting that these are all even-numbered elements, Harkins [17] concluded *"in the evolution of the elements much more material has gone into the even-numbered elements than into those which are odd."*(p. 869). Anders and Grevesse's [16] report that an odd-numbered element, with atomic number Z = 1, is the most abundant element. According to Anders and Grevesse [16] the lightest element, Hydrogen, comprises ≈ 91% of all atoms in the solar system.

Harkins' was concerned that findings in the sun would be *"largely influenced by the height in the gaseous envelope of the sun at which the observation is taken."* (Page 860). Over half a century later, experimental support for his concern would come from careful isotope analyses of solar-wind (SW) elements embedded in the surfaces of fine-grained lunar samples returned by the Apollo mission to the Moon.

Light (**L**) isotopes of SW-implanted He, Ne, Ar, Kr, and Xe in the surfaces of lunar samples are systematically enriched relative to heavy (**H**) isotopes. The empirical comparison of noble gas isotopes in planetary and solar-wind noble gases follows a mass-dependent power law [3]. This power law defines a common mass-fractionation factor, ***f***, over the entire mass range of stable noble gas isotopes, 3-136 atomic mass units (amu) [3].

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

When the abundance pattern of elements at the solar surface is corrected for the empirical mass fractionation given by eq. (1), it shows that the O/C ratio for the bulk Sun is about four-times the O/C ratio at the solar surface, i.e., the solar system has a value of O/C ≈ 8.

Eq. (1) identifies five elements, present only at the part-per-million level in the photosphere, as the most abundant elements in the bulk Sun. The trace elements in the photosphere that comprise the bulk of the solar interior are Fe, Ni, O, Si, and S [3]. These elements also comprise ≈ 95% of the material in ordinary meteorites, a highly unlikely coincidence [12, 14]!

Nuclides made by slow neutron capture, the s-products [4], span a wide mass range at the solar surface. A comparison of the abundance of s-products in the photosphere with that expected from neutron-capture cross-sections offers *an independent test of mass separation in the Sun*: a) These nuclides are in the photosphere, rather than in the solar wind. b) Very few nuclides used in this test are noble gas isotopes. c) The mass range covered by s-products overlaps that of the Ar, Kr, and Xe isotopes and extends all the way from 25 amu to 207 amu.

The steady-flow abundance, N, of successive nuclides made by the s-process (slow neutron capture) is expected to be [4] inversely proportional to their neutron-capture cross-sections, σ:

$$\sigma_{(A)} N_{(A)} = \sigma_{(A-1)} N_{(A-1)} = \sigma_{(A+1)} N_{(A+1)} \qquad (2)$$

S-products cover a wide mass range, A = 25-207 amu. There are a couple of places near the middle of this mass range where two or more isotopes of the same element were produced only by the s-process. These can be used to check for steady-flow abundance in the s-process.

Steady-flow s-process apparently generated the two, s-only isotopes of samarium, ^{148}Sm and ^{150}Sm. Within error limits, the value of $\sigma(^{148}Sm)\ N(^{148}Sm) = \sigma(^{150}Sm)\ N(^{150}Sm)$ [18].

Rolfs and Rodney [1] note on p. 462 that the abundances and neutron-capture cross-sections of the three, s-only isotopes of tellurium, ^{122}Te, ^{123}Te, and ^{124}Te, demonstrate that the steady-flow s-process also operated in this mass region.

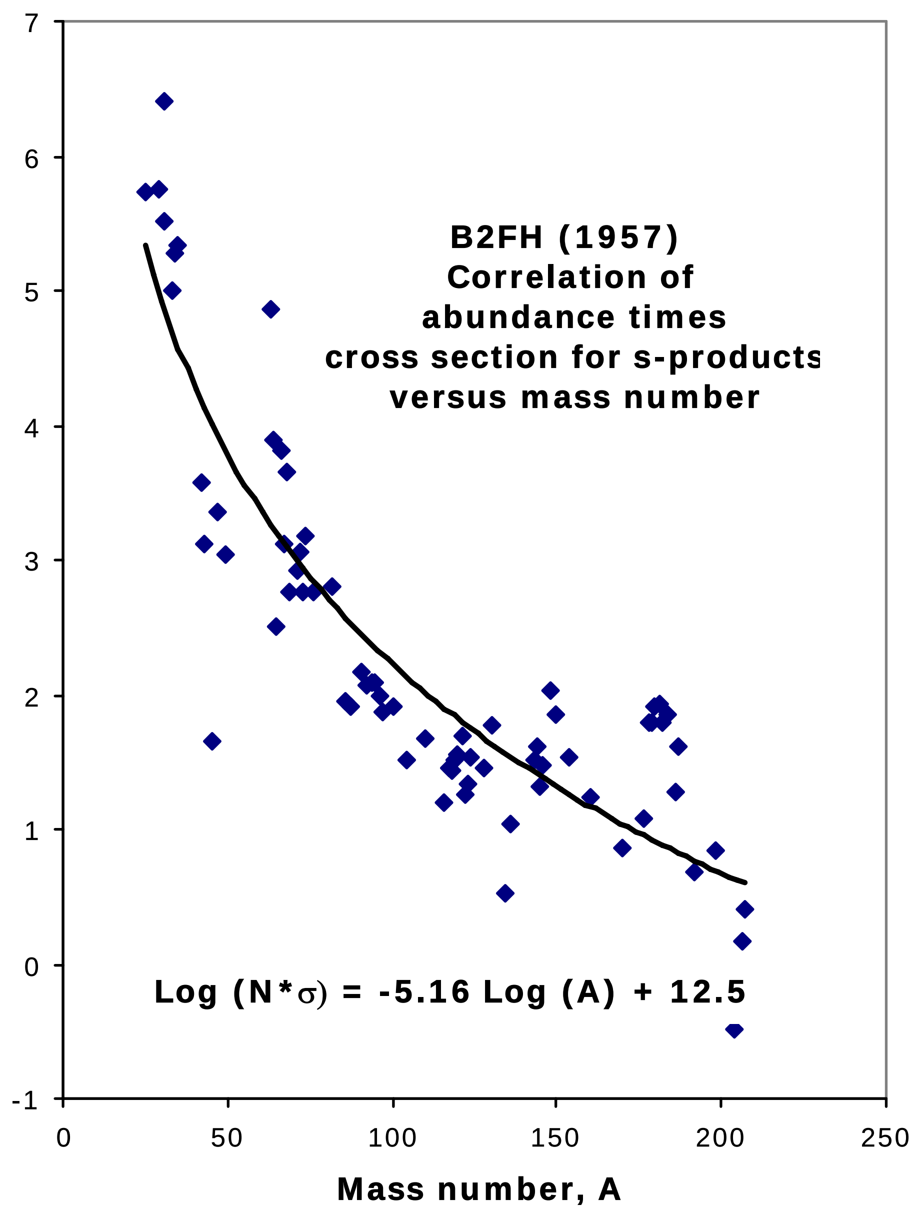

Fig. 2. Values of log (σN) for s-products at the solar surface decline exponentially with increasing mass number, A. The 72 data points [4] cover a mass range of A = 25-207 amu.

However Burbidge, Burbidge, Fowler and Hoyle (B^2FH) [4] show that values of the σN product for s-products at the solar surface tend to steadily decline with increasing A, by about 4-5 orders over the ≈ 10-fold mass range of nuclides made by the s-process. This is shown in Fig. 2.

B^2FH values of log (σN) are shown in Fig. 2 versus mass number, A, for all s-products tabulated in that classical paper [4]. An exponential, least-squares line is shown through the B^2FH data points. Despite the scatter of data points, the overall trend among s-products in the solar photosphere reveals new evidence of mass fractionation in the Sun.

The exponential, least-squares line through the B^2FH data defines a new mass-dependent relationship among s-products in the Sun.

$$\text{Log}(\sigma N) = -5.16 \log(A) + 12.5 \qquad (3)$$

The same B^2FH data are shown in Fig. 3 as a linear plot of log (σN) versus log (A). In this graph the scatter of data is less distracting and the overall trend is perhaps easier to see in Fig. 3 than in Fig. 2. However, the least-squares line through the data yields the same mass-dependent fractionation equation as that shown above in Eq. (3).

Figs. 2 and 3 cover the entire mass range, A = 25-207 amu, of s-products listed by B^2FH [4]. Later papers on the abundance and cross sections of s-products tend to focus only on s-products heavier than elements in the "iron abundance peak". For example Seeger, Fowler and Clayton [19] only report neutron-capture cross-sections and abundances values for A = 63-207 amu.

By limiting the data under consideration to "s-only" products, the mass range is further restricted to the mass range of A = 70-204 amu. However, the scatter of data is much reduced, as shown in Fig. 4 on a plot of log (σN) versus mass number, A, for all "s-only" products [19]. The exponential, least-squares line through the "s-only" data of Seeger, Fowler and Clayton [19], eq. (4), differs little from the mass-dependent relationship defined by B2FH data in eq. (3) above.

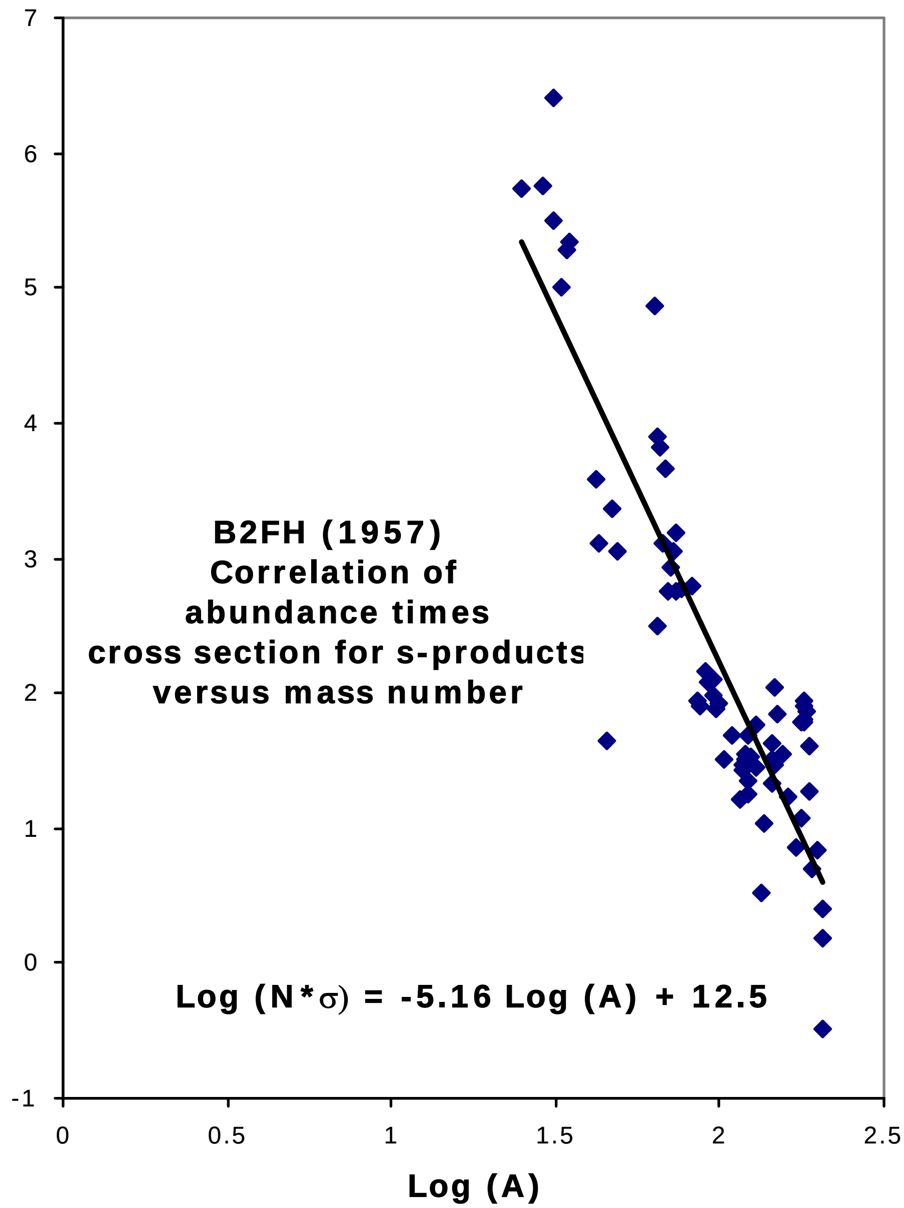

Fig. 3. Values of log (σN) for 72 s-products at the solar surface decline linearly against values of log (A). All data points are from B^2FH [4].

$$\text{Log}\ (\sigma N) = -\ 5.14\ \log\ (A) + 12.2 \qquad (4)$$

The same "s-only" data from Seeger, Fowler and Clayton [19] are shown in Fig. 5 as a linear plot of log (σN) versus log (A). Again, the scatter of data is less distracting and the overall trend is perhaps easier to see in Fig. 5 than in Fig. 4. However, the least-squares line through the data yields the same mass-dependent fractionation equation as that shown above in Eq. (4).

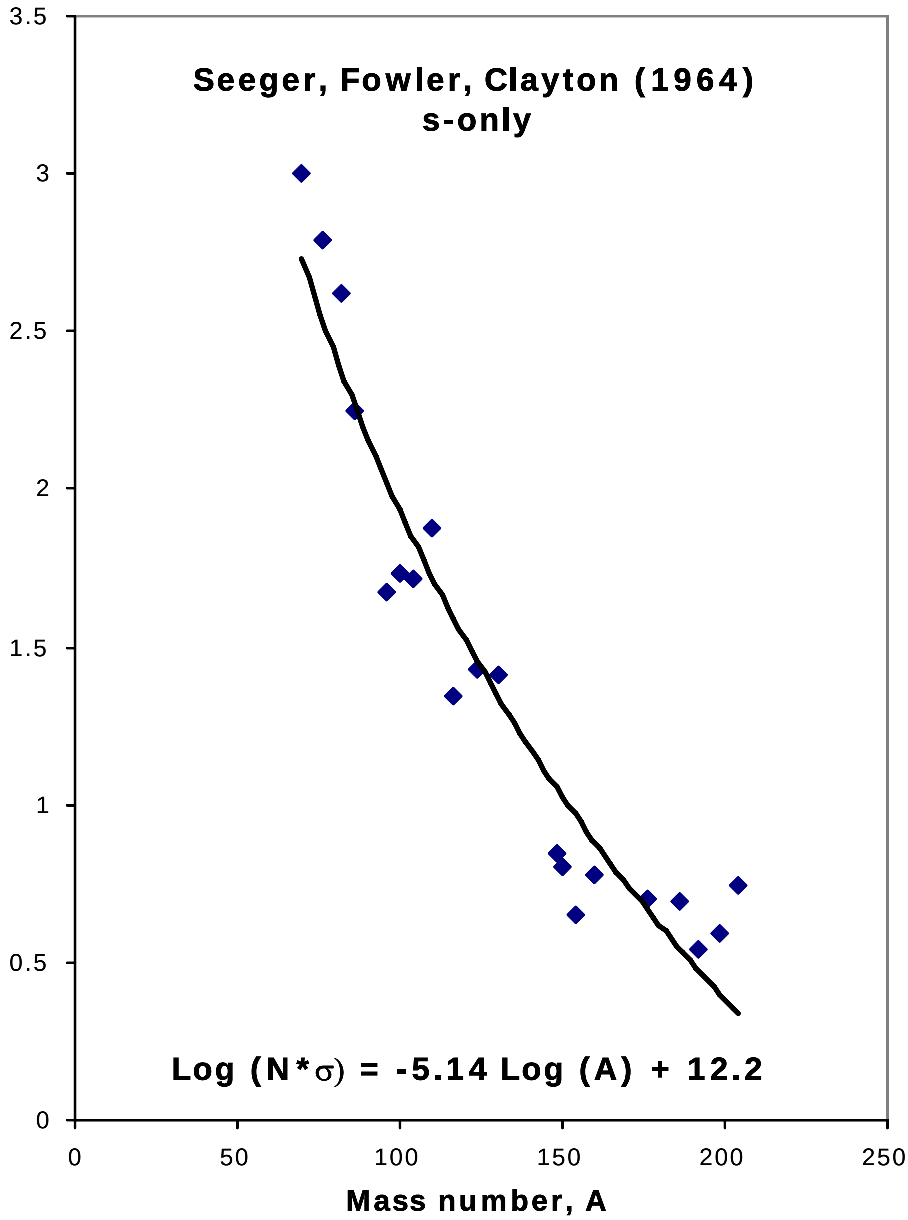

Fig. 4. Values of log (σN) for "s-only" products at the solar surface decline exponentially with increasing mass number, A. The 20 data points [19] cover a mass range of A = 70-204 amu.

In an effort to further reduce experimental uncertainty in the mass separation of s-products in the Sun, the results of Seeger, Fowler and Clayton [19] were further restricted to "s-only" nuclides where the neutron-capture cross-section was measured, not interpolated. This limits the results to five data points covering the mass range of A = 86-204 amu.

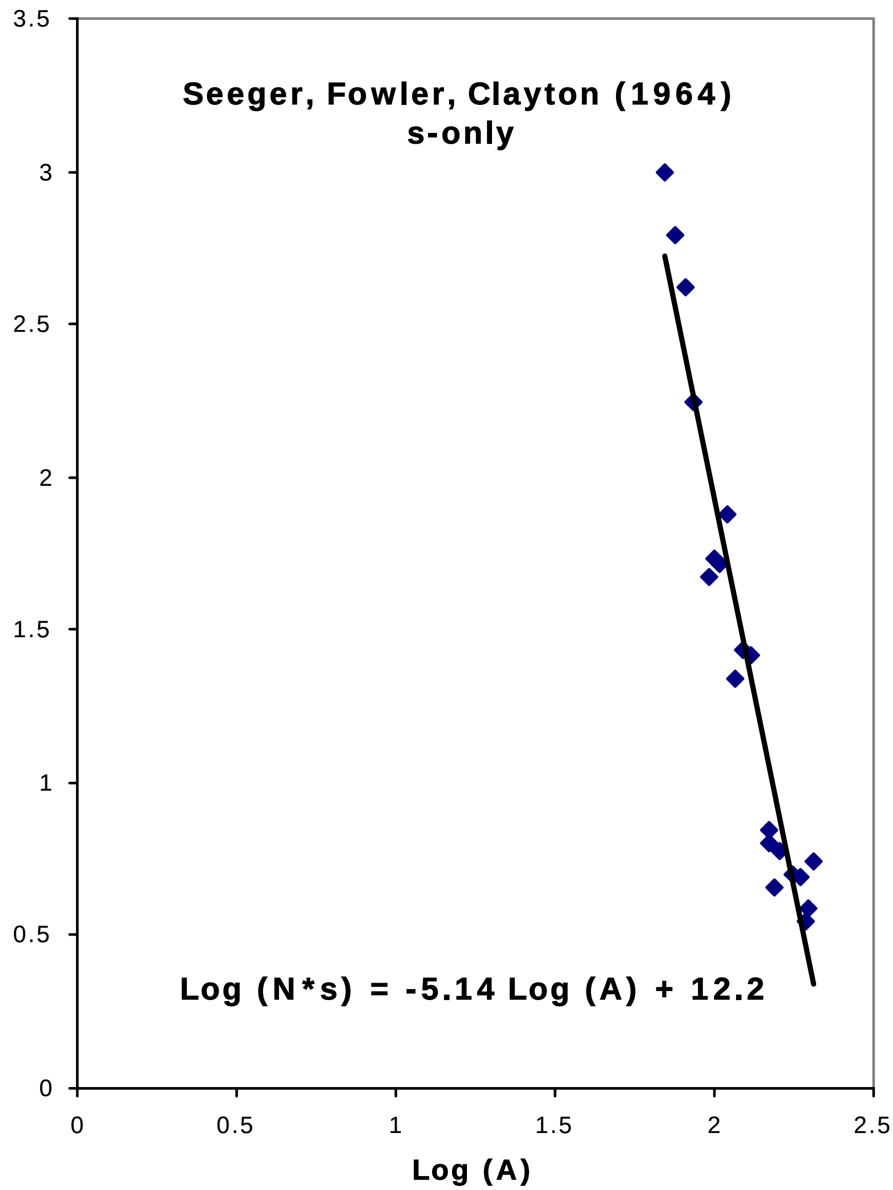

Fig. 5. Values of log (σN) for 20 "s-only" products at the solar surface decline linearly against values of log (A). All data points are from Seeger, Fowler and Clayton [19].

These results are shown in Fig. 6 on a linear plot of plot of log (σN) versus log (A). The least squares line through the "s-only, σ-measured" data of Seeger, Fowler and Clayton [19] yields a less-steep, mass-dependent relationship among s-products in the Sun:

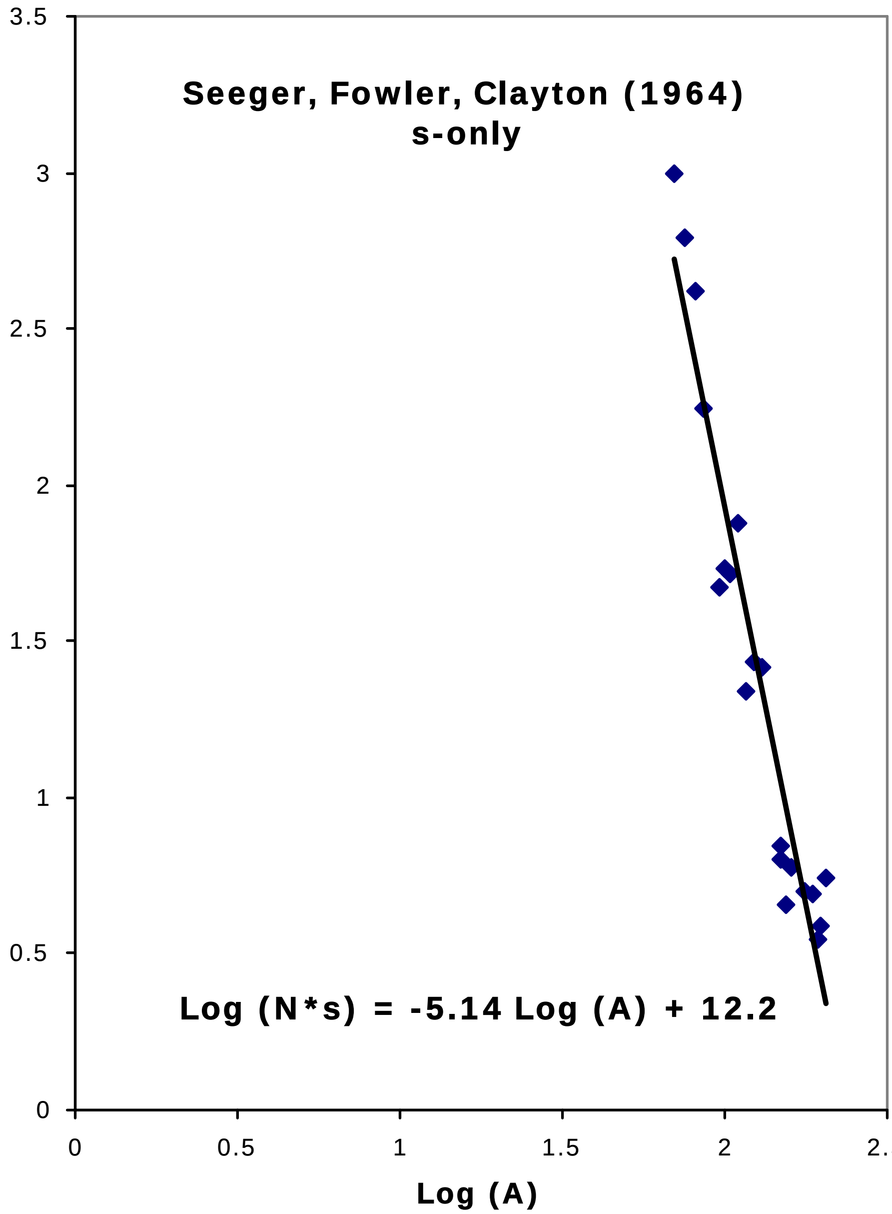

Fig. 6. Values of log (σN) for the "σ-measured, s-only" products at the solar surface decline linearly against values of log (A). The 5 data points [19] span a mass range of A = 86-204 amu.

$$\text{Log}(\sigma N) = - 4.19 \log (A) + 10.2 \qquad (5)$$

Table 1 gives a summary of the above empirical evidence of mass fractionation in the Sun.

Table 1. Experimental Measurements Showing Mass Separation in the Sun

Experimental Basis	Number of Data Points	Mass Range	Fraction Factor, ***f***
Noble gas isotopes in the solar wind	22	A = 3-136 amu	$f = (H/L)^{4.56}$
s-products in the solar photosphere	72	A = 25-207 amu	$f = (H/L)^{5.16}$
s-products in the solar photosphere	20	A = 70-204 amu	$f = (H/L)^{5.14}$
s-products in the solar photosphere	5	A = 86-204 amu	$f = (H/L)^{4.19}$

The last column in Table 1 expresses the mass dependency in the abundance of s-products at the solar surface, shown earlier in eqs. (3-5), in the same way eq. (1) expresses the mass dependency in the abundance of SW noble gas isotopes. The empirical abundance indicates that light (**L**) nuclides are systematically enriched relative to heavy (**H**) ones at the solar surface by a mass-fractionation factor, ***f***. That is the reason why the oxygen to carbon ratio in the Sun's photosphere is only two, O/C ≈ 2 [1].

Fig. 7 shows the solar abundance of elements after the solar photospheric abundance pattern of Anders and Grevesse [16] is corrected for the mass-fractionation observed across s-products. This mass separation is defined by 72 data points from B^2FH [4], covering the mass range of 25-207 amu. It is illustrated in Fig. 2 and Fig. 3 and expressed by the mass-dependency of eq. (3). In this case, the O/C ratio for the bulk Sun is O/C ≈ 10.

Fig. 8 shows the solar abundance of elements when the solar photospheric abundance pattern of Anders and Grevesse [16] is corrected for the mass-fractionation observed across noble gas isotopes in the solar wind [3]. This mass separation is defined by 22 data points covering the mass range of 3-136 amu. It is expressed by the mass-dependency of eq. (1). In this case, the O/C ratio for the bulk Sun is O/C ≈ 9.

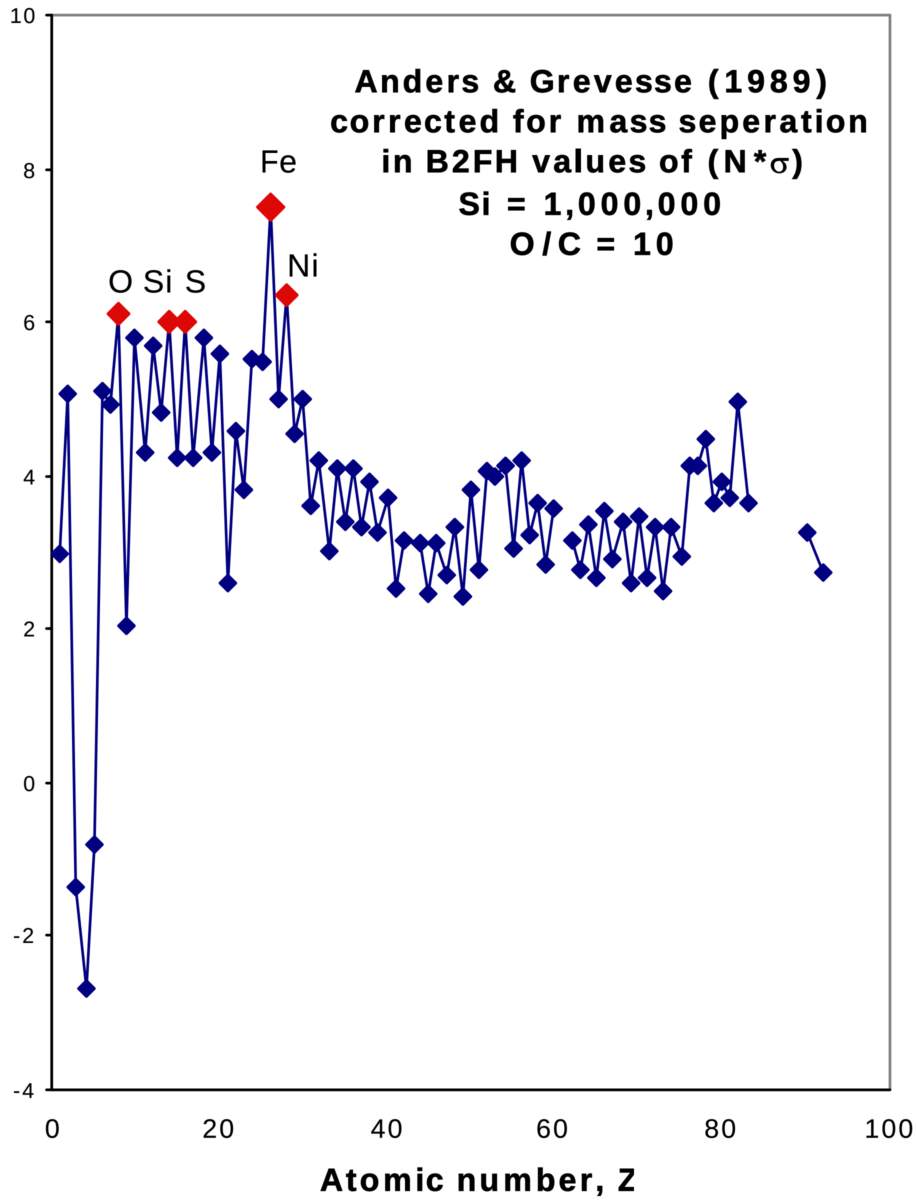

Fig. 7. The abundance pattern of elements in the Sun after correcting solar surface abundances [16] for the mass-separation observed across s-products [4] spanning a mass range of A = 25-207 amu. This predicts a value of O/C ≈ 10 for the bulk Sun.

We prefer the value of O/C ≈ 9 shown in Fig. 8 because:

a. It is based on isotope ratios that are more precisely known than the relative abundances of elements or neutron-capture cross sections, and

b. The data points span the mass range of the stable isotopes of carbon and oxygen .

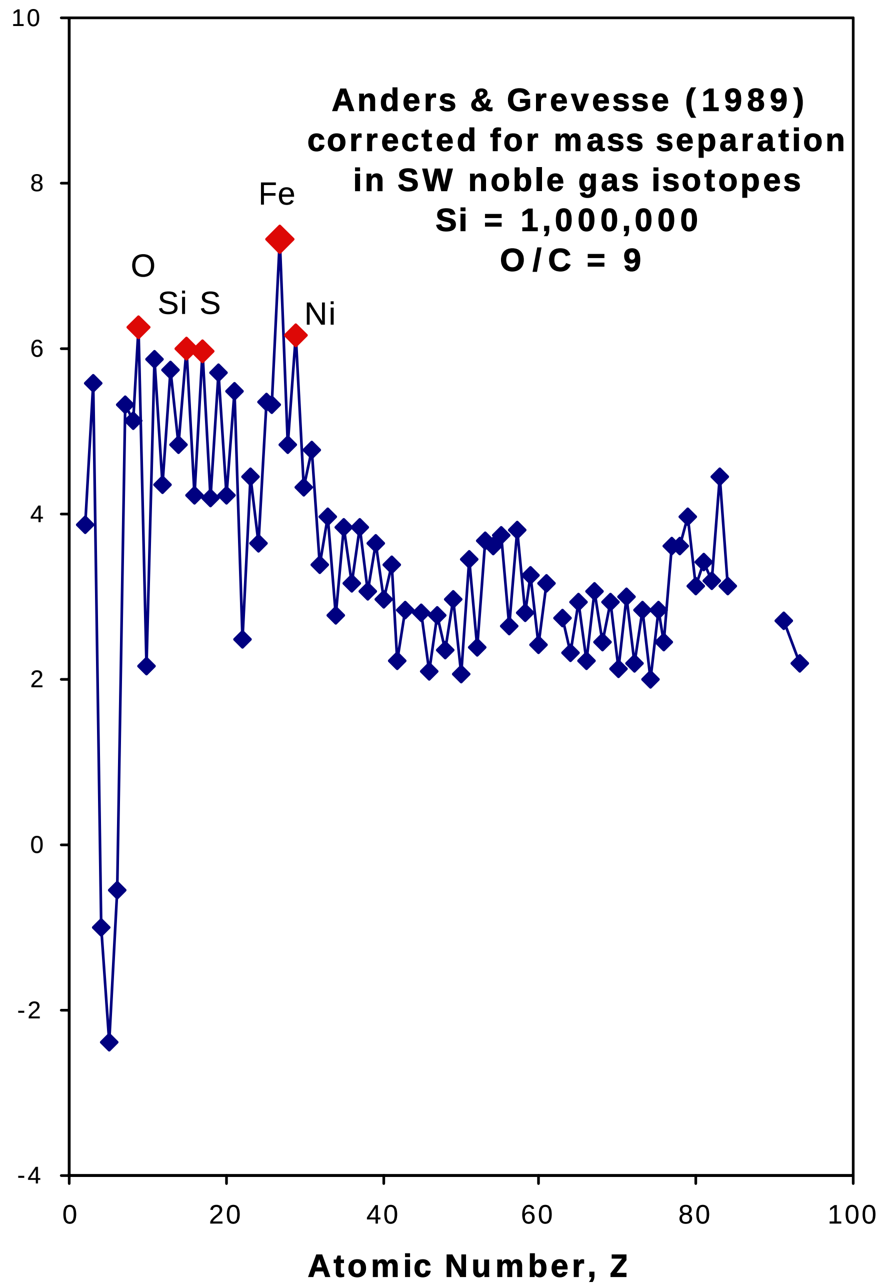

Fig. 8. The abundance pattern of elements in the Sun after correcting solar surface abundances [16] for the mass-separation observed across noble gas isotopes (A = 3-136 amu) in the solar wind [3]. This predicts a value of O/C ≈ 9 for the bulk Sun.

One weakness in our conclusion that O/C ≈ 9 (and Fig. 8 as the composition of the bulk Sun) is that it is based on mass fractionation of isotopes in the solar wind, rather than on material in the Sun itself. Conversely, one argument in favor of O/C ≈ 10 (and Fig. 7 as the composition of the bulk Sun) is that it is based on mass fractionation observed in material in the Sun itself, rather than on material in the solar wind.

III. CONCLUSIONS

The value of the oxygen to carbon ratio in the bulk Sun is O/C ≈ 9-10. For reasons given above, we suspect that the solar value is closer to O/C ≈ 9.

The five most abundant elements in the bulk Sun are Fe, O, Ni, Si, and S. These five elements have high nuclear stability. They are made in the deep interior of massive stars [4], and they comprise about ≈ 95% of the material in ordinary meteorites [17].

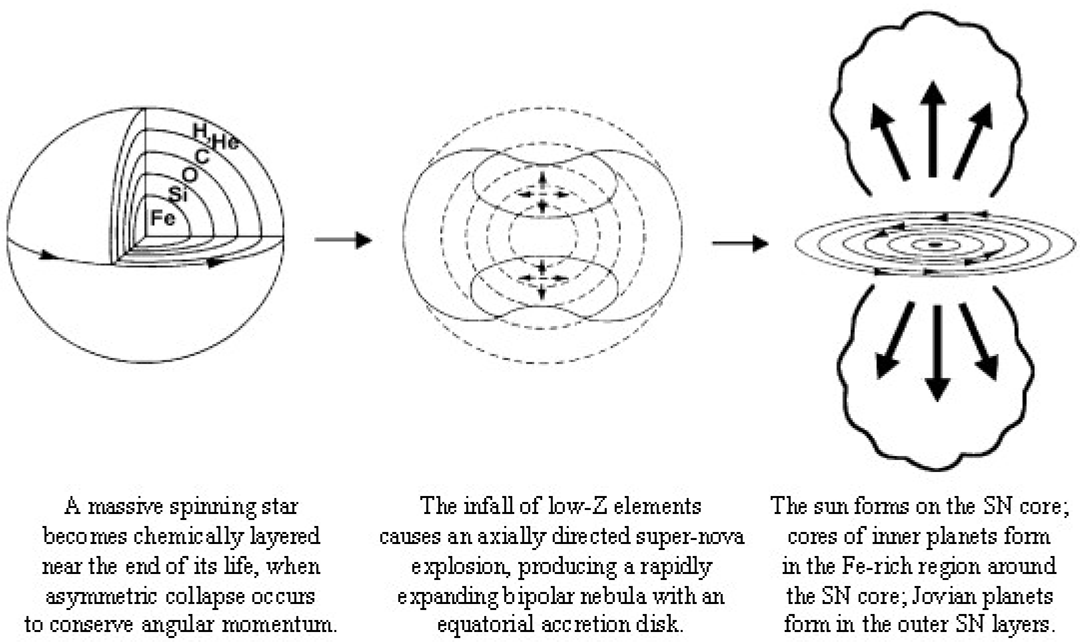

Fig. 9. Formation of the solar system from debris of a single supernova was proposed in 1975 [20] to explain the decay products of short-lived nuclides and inter-linked chemical and isotopic heterogeneities in meteorites and planets. This figure is from ref. [12].

Fig. 9 shows one scenario that has been suggested [12, 20] to explain the formation of the solar system and its iron-rich Sun, beginning with the onion-skin model of a pre-supernova star [ref. 21, pp. 522-523] and following the trail of "fingerprints" that the progenitor star left in stable isotopes [22].

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