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Solar and solar system abundances of the elements

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Abstract

With the recent progress in astrophysical observations, the solar abundances of the elements (elemental composition of the sun) can be profitably compared with the solar system abundances of the elements. In this paper, current solar and solar system abundances of the elements are reviewed and are compared; there seems to be no systematic difference. Solar system abundances of the elements are mostly deduced from the chemical composition of meteorites (mainly C1 chondrites). Compiling and evaluating the data for C2 chondrites, I once inferred that C2 chondrites also were potential candidates for the solar system standard of elemental abundances. The current data show that their abundances correlate with the solar system abundances extremely well. However better data are needed for C2 chondrites in order to acsertain if the correlationis as good as for C1 chondrites. In the near future, the solar wind will be collected by a spacecraft and yield solar abundances with quality comparable to meteorite data.

Introduction

Solar system abundances of the elements are among the most fundamental quantities in earth and planetary sciences. They are measured quantities, not physical constants, and their quality (precision and accuracy) has increased with the advances in analytical techniques. Solar system abundances of the elements are mostly based on the chemical analysis of meteorites. On the other hand, solar abundances of the elements are obtained from spectral observation of the sun. In general, the quality of the solar abundances is much poorer than the solar system abundances, although comparison of the two data sets has become possible with the great improvement in the former values in recent years.

Solar system abundances of the elements have been repeatedly presented. Among the earliest reports, the table compiled by Goldschmidt (1938) is the most famous. To estimate the solar system abundances of the elements, he used both analytical data on meteorites and observational values for the sun. From this table, Suess (1947) later deduced several rules governing the abundances of the elements in the solar system. He found that the elemental abundances were highly dependent on the stability of nuclides, and so his rules were called nuclear systematics. In 1956, Suess & Urey presented their famous table of element abundances in the solar system. They used not only data then available for meteorites and the sun, but also the nuclear systematics postulated by Suess (1947). This table was the basis of the B^2FH model for the nucleosynthesis of the elements (Burbidge *et al.* 1957). During the next two decades, Cameron periodically compiled the elemental abundance data for the solar system (*e.g.* Cameron 1973, 1982). In those days, there were significant developments in analytical techniques (both method and instrument) for meteorites, and so not only the number was increased but also the quality of data were improved. This was a major reason why Cameron revised the abundance table at every opportunity.

In 1982, I had the opportunity of compiling solar system abundances of the elements in collaboration with E Anders (Anders & Ebihara 1982). On that occasion, we used our own analytical data for meteorites (mainly C1 chondrites) in addition to the literature data and compiled an abundance table after critical evaluation of the data. This abundance table was widely accepted by the scientific community and updated in 1989 (Anders & Grevesse 1989). There were few significant changes in solar system abundances of the elements between the two tables, because the analytical data of meteorites reported during that period were limited. In contrast, the solar abundances improved significantly. Reflecting this, Anders & Grevesse (1989) discussed solar and solar system abundances of the elements separately as well as comparatively. Their table, especially for solar system abundances is the current reference for the abundances of elements. As in the past, such compilations need to be revised, although the changes would not be great, especially for elemental abundances of the solar system. In this paper, solar and solar system abundances of the elements are reviewed and some future perspectives are presented.

Solar abundances of the elements

The outer part of the sun consists of the photosphere, chromosphere and corona; the solar photosphere is surrounded by the chromosphere and further enclosed by the corona. The energy released by the present sun is estimated to be 3.83 10^{33} erg sec^{-1} and is believed to be supplied by nuclear fusion reactions. Judging from the current temperature and pressure estimated for the cen-

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tre of the sun, it is inferred that the following reactions (named p-p chains) mainly occur inside the sun;

$$p + p \rightarrow {}^{2}D + e^{+} + \nu \ (99.75\ \%)$$

$$p + e^{-} + p \rightarrow {}^{2}D + \nu \ (0.25\ \%)$$

The deuterium produced reacts with a proton to form ^{3}He as follows:

$${}^{2}D + p \rightarrow {}^{3}He + \gamma$$

From ^{3}He, ^{4}He is produced via three different paths named PP1, PP2 and PP3 as shown below;

[PP1] $^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ (86 %)

[PP2] $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$

$^{7}Li + p \rightarrow 2\ {}^{4}He$ (14 %)

[PP3] $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$

$^{8}Be \rightarrow 2{}^{4}He$ (0.02 %)

The end result is that four protons produce ^{4}He. Under the present conditions, the PP1 reaction is dominant whereas the PP2 and / or PP3 reactions only become significant when temperature reaches 10^{7}K. There is another reaction for producing ^{4}He from protons, called the CNO cycle, in which carbon, nitrogen and oxygen react as catalysts. This reaction becomes important only when the temperature reaches 2 x 10^{7} K. Thus there is the possibility that elemental abundances of hydrogen, helium, lithium and beryllium have changed in the sun.

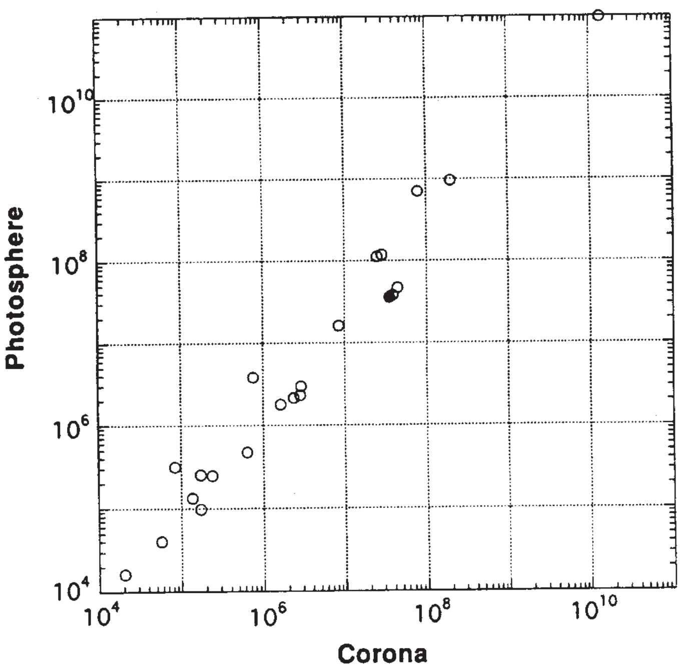

Figure 1. Coronal abundances versus solar photospheric abundances of elements. Elements of first ionization potential (FIP) < 10 eV are not fractionated from Si (= 3.55 10^{7}), which is marked by a solid circle. Elements of higher FIP are depleted in the corona by a constant factor, lying on a line parallel to that defined by the elements including Si. Data from Anders & Grevesse (1989).

How are the abundances for those elements heavier than beryllium affected in the photosphere? ^{8}B could be produced through the PP3 reaction shown above, but it promptly decays to ^{8}Be with a half-life of 0.77 sec. ^{9}B, which is the only stable nuclide of boron (Z=5), could be produced by spallation reactions with heavier nuclides according to nuclear synthesis models.

In order to produce carbon (Z=6), the following reaction must occur:

$${}^{8}Be + {}^{4}He \rightarrow {}^{12}C$$

Since the half-life of ^{8}Be is extremely short (10^{-16} sec), the above reaction can be initiated only at high temperatures (> 10^{8} K) and pressures (high density). Even the center of the present sun does not reach these conditions. Therefore, those elements heavier than Z=4 (beryllium) can be scarcely synthesized in the present sun, suggesting that (except for hydrogen, helium, lithium and beryllium) the elemental abundances of the present sun are essentially the same as those of the ancient sun 4.56 10^{9} y ago.

There are several way in which the solar abundance of the elements can be determined. These are:

(a) photosphere (absorption intensity)

(b) corona (emission intensity)

(c) solar wind (intensity of low energy ion)

(d) solar flare (intensity of high energy ion)

The solar photosphere is the outermost layer of the sun, with an average depth of 400 km. It is generally believed that the photosphere has the representative elemental abundances of the sun, because the surface materials of the sun are not convected and are scarcely mixed with the inner material, which can be affected by the nuclear reactions (more extensively than the photosphere). Although the solar photosphere is thus the most suitable source for the solar abundance of the elements, there are several difficulties in obtaining reliable data. Nevertheless, precision of the solar photospheric data has steadily improved over the last two decades.

The solar abundances of the elements can be also inferred from elemental abundances of the corona, obtained either by observing emission spectra of the corona or by measuring chemical compositions of the cosmic rays it omits. Coronal emission spectra of different regions of the corona have been observed from spacecraft; for instance the corona hole, an active area, a quiet area and a prominence. Although emission spectrometry can potentially yield highly reliable data, the resulting values are not as reproducible as expected and so the solar abundances of the elements deduced from the spectra have relatively large errors (uncertainties). Cosmic rays emitted from the corona are called the solar wind and solar energetic particles (SEP). The solar wind is a current of plasma with high velocity released from the solar corona, and consists mainly of protons and electrons. Although the number of the elements measured in the solar wind is not large (<10), their abundances are in agreement with those obtained from coronal spectrometric observations. The SEP has much higher energy (up to MeV) than solar wind (measured in keV) and is emitted from the corona by several different mechanisms. The elemental abundance data for

SEP are superb in both quality and quantity compared with those for solar wind.

In Figure 1, the elemental abundances of the corona are compared with those from the photosphere. The coronal abundances are averaged values from different sources but are mostly represented by the SEP values. There seems to be a good agreement between these two sources although the coronal abundances are systematically lower than the photospheric data for several elements. These elements have a common characteristics; their first ionization potentials are consistently high (> 11eV). This suggests that there is elemental fractionation between neutral elements (which have relatively high ionization potentials) and ionic elements (which have relatively low ionization potentials) when the elements are transferred from the chromosphere to the corona.

Solar system abundances of the elements

The solar system abundances are mostly determined from the chemical analyses of meteorites. Exceptions are hydrogen, carbon, nitrogen, oxygen and noble gas elements, which are all highly volatile. Among meteorites, C1 (or CI) chondrites have been the most extensively analyzed for this purpose. So far, nine meteorites have been recognized to be C1 or C1-like (Table 1). Of these, four were collected in Antarctica. Antarctic meteorites are susceptible to terrestrial weathering on Antarctica. In fact, Antarctic C1 (or C1-like) meteorites are not always the same as non-Antarctic C1 meteorites in chemical composition, mineralogical texture and/or oxygen isotopic composition, indicating that Antarctic C1's are not suitable specimens for measuring solar system abundances of the elements.

The terminology of "chondrite" is due to the presence of chondrules in the meteorite's texture. If this definition is strictly applied, then C1 chondrites can't be called *chondrites*, because contain no chondrules but consist of 100% matrix materials. This suggests that C1 chondrites are the richest in volatile components among meteorites. Indeed, the water content (measured as H_2O) exceeds 20% (weight %) because the matrix is composed of a large amount of hydrous silicates. Non-Antarctic C1 chondrites are all *falls* (meteorites which were observed to fall and then collected). In contrast, Antarctic C1's are all *finds* (meteorites which were not observed to fall). Among the 4 Antarctic C1's, Y 82162 might be a real C1, but the remaining are between C1 and C2. Among non-Antarctic C1's, Revelstoke and Tonk are too small to be subjected to chemical analysis. Of the remaining three non-Antarctic C1's, Orgueil is the largest and the most frequently analyzed. Thus, solar system abundances of the elements are mostly deduced from the chemical composition of only one meteorite. There are large differences (>10 %) for Hf and Hg between the values of Anders & Ebihara (1982) and Anders & Grevesse (1989). For the rest of the elements, the two sets of values estimated by these authors are within 10 %.

Solar abundance values for hydrogen, nitrogen, oxygen and noble gas elements are deduced from sources other than meteorites. For these elements except noble gases, the solar photospheric data are used. For noble gas elements, each has its own method of estimation. The abundance of helium is calculated using the photospheric value of hydrogen and the He/H ratio for the HII region and/or hot stars (outside the solar system). Solar abundances of neon and argon are also derived from observations of the HII region and other extra-solar regions. However, the values estimated from measurements of prominences, the solar wind and SEP are generally in agreement with those obtained from the spectroscopy of the stars outside our solar system. For argon, an estimated (interpolated) value of ^{36}Ar based on the abundances of ^{28}Si and ^{40}Ca is also consistent with the above values. The abundances of krypton and xenon are determined from the abundances of neighboring elements. For krypton, there are two approaches; either s-process systematics or interpolations based on ^{81}Br and ^{85}Rb for ^{83}Kr, and ^{80}Se and ^{88}Sr for ^{84}Kr. The two values so obtained are similar.

Characteristics of solar and solar system abundances of the elements

Solar versus solar system abundance of the elements

The sun and other members of the solar system must have formed almost simultaneously about 4.56 10^9 y ago.

Table 1

C1 and C1-like chondrites recovered so far.

Meteorite	Year of Recovery	Place of Recovery	Fall or Find	Original Weight
non-Antarctic				
Alais	1806	France	Fall	6 kg
Ivuna	1938	Tanzania	Fall	705 g
Orgueil	1864	France	Fall	>10 kg
Revelstoke	1965	Canada	Fall	1 g
Tonk	1911	India	Fall	7.7 g
Antarctic*				
Belgica 7904	1979	Antarctica	Find	1.23 kg
Yamato 82042	1982	Antarctica	Find	37.1 g
Yamato 82162	1982	Antarctica	Find	39.5 g
Yamato 86720	1986	Antarctica	Find	859 g

*The following C1 properties (shown in parentheses) are confirmed for the Antarctic meteorites; Belgica 7904 (O-isotopes), Yamato 82042 (petrography), Yamato 82162 (O-isotopes, chemistry) and Yamato 86720 (O-isotopes).

The heterogeneity of the source material, proto-solar nebula, has been a subject of discussion for many years. There are several lines of evidence indicating that the solar nebula was heterogeneous in isotopic composition. In contrast, there are no data supporting inhomogeneity of the solar nebula in elemental abundances. The sun represents 99.7 % mass of our solar system, indicating that the elemental abundances of the sun are necessarily those of the solar system. As discussed previously, the elemental abundances of the present sun must be the same as those of the sun of 4.56 10^9 y ago for all the elements except hydrogen, helium, lithium and beryllium. Because solar system abundances of the elements are based on meteorite data, then solar abundances and solar system abundances are essentially identical for these elements except for several light elements and noble gas elements if meteorites, especially C1 chondrites, preserve the elemental abundances of the proto-solar nebula.

In Figure 2, solar and solar system abundances of the elements are compared; elemental abundances (the number of elements) are all normalized to Si = 10^6 atoms. As is readily apparent, elements having relative abundances of more than eight orders of magnitudes form a straight line with a slope of 0.988 (r = 0.977). Whenever either solar abundances or solar system abundances of the elements have been revised, such a graph has been repeatedly drawn and the extent of correlation has increased with the time. Considering that the precision of meteorite data, and especially photospheric data, has greatly improved in recent years and that the agreement between solar abundances and solar system abundances of the elements has been enhanced in recent years, it is clear that elemental abundances of meteorites, especially C1 chondrites, are essentially equal to those of our solar system.

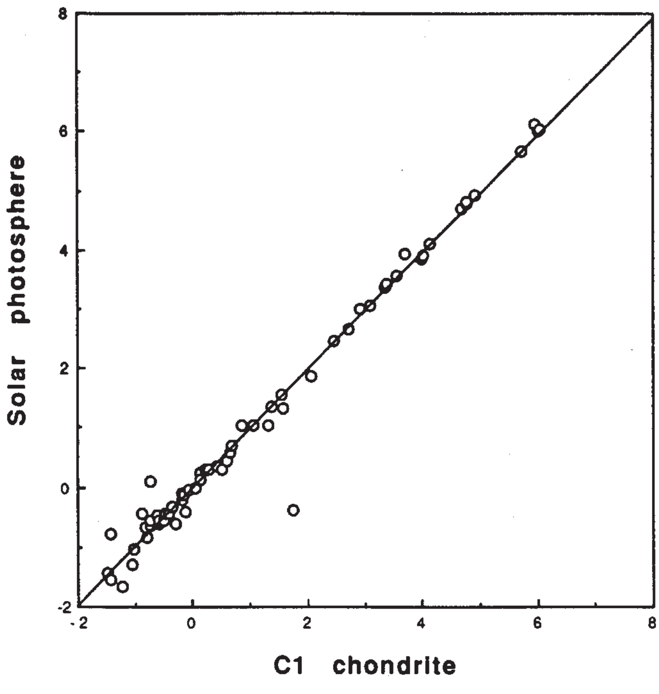

Figure 2. Solar photospheric abundances versus C1 chondrite abundances of elements; abundances are normalized to Si = 10^6. Only Li is located largely apart from the correlation line. From Ebihara (1992). The scale on both axes are logarithm.

Suess' nuclear systematics for solar system abundances of the elements

Suess (1947), evaluating the then available solar system abundances of the elements, found the following systematics for the abundances of the solar system nuclides:

(a) abundances of the nuclides having an odd mass number change smoothly with increasing mass number A for the region of A>50; in this case, abundances of the isobars (nuclides having the same A) are combined;

(b) when A is even, the following variables change smoothly with increasing A;

(i) for the nuclides of A<90, the total abundances of the nuclides having the same I, where I is defined as I = A - 2Z;

(ii) for the nuclides of A>90, the total abundances of the isobaric nuclides;

(c) for isobaric nuclides, the nuclide having a larger I is more abundant than that having a smaller I for the region of A<70; for the region of A>70, the above relation is reversed;

(d) when the numbers of nucleons (proton and neutron) correspond to so-called "magic numbers", some irregularities arise in the relationships mentioned above.

When Suess & Urey (1956) summarized the *cosmic abundances** of the elements, they used the nuclear systematics postulated by Suess (1947). They revised and even infered several values of solar abundances based on these systematics. In later years, these revised or inferred values were replaced with the values measured in meteorites, mainly those of C1. This gave great credit to the Suess' nuclear systematics, even though it is an empirical rule. Thereafter, Suess' nuclear systematics, especially the first rule, has often been used in evaluating solar system abundances of the elements.

Abundances of odd-mass nuclides in C1 chondrites are shown in Figure 3A for A = 59 to 139, and Figure 3B for A = 131 to 209. Elemental abundances of C1 chondrites compiled by Anders & Grevesse (1989) and stable isotope abundances recommended by the International Union of Pure and Applied Chemistry (IUPAC 1991) are used to calculate relative abundances of nuclides having odd A. There appear to be some peaks in Figure 3A. The peaks at A = 89 and A = 117 to 119 correspond to the irregularity due to "magic numbers"; N (neutron number) = 50 for the former and Z = 50 (Sn) for the latter. A peak appearing around 130 can be explained by a relatively high probability of nuclide formation produced by p-process nucleosynthesis. In both Figures 3A and 3B, we see very smooth changes in abundances. In 1982, Anders & Ebihara (1982) identified irregularities at the

*In those days, the term "cosmic abundances of the nuclides" was often used in place of the term "solar system abundances of the elements", possibly with a tacit understanding that there was no significant difference between the two abundances. Strictly speaking, cosmic abundances of the elements cannot be obtained by analysis of any material. However, as our solar system is not special in the astronomical sense, we can assume that the solar system abundances of the elements are representative of the cosmic abundances of the elements, to a first order approximation.

Ag-Cd region and the Nd-Sm-Eu-Gd region. The former irregularity almost disappears in Figure 3A, where new and more accurate values of Ag for C1 chondrites obtained by using mass spectrometric isotope dilution technique (Loss et al. 1984) are used. In contrast, the irregularity at the light lanthanoid region remains unresolved. Anders & Grevesse (1989) concluded that this irregularity suggested the limitation of the Suess' nuclear systematics in evaluating solar system abundances of the elements.

Future perspective for the study on solar and solar system abundances of the elements

Do C1 chondrites yield the solar system abundances of the elements?

C1 chondrites are believed to be the most primitive meteorites and to have experienced no thermal activity since their formation at 4.56 10^9 y ago. This is supported by the observation that C1 chondrites are the richest in volatile compounds (including organic materials) and elements. However, mineralogical observations clearly show that C1 chondrite parent bodies have experienced a near future. Data sources for solar abundances of the elements which can be analyzed with quality comparable with that for meteorites are required.

Solar wind as a promising source of the solar system abundance of the elements

Solar wind is a source of data for solar abundances of the elements which is independent of the solar photosphere. Only a few elements (hydrogen, helium, carbon, nitrogen, oxygen, neon, silicon, argon and iron) have so far been determined in the solar wind. He / H ratios are relatively easily determined by observation from spacecraft. It is well known that the He / H ratio of solar wind varies over minutes to days by a factor of more than 100. With a systematic variation between solar minimum and solar maximum, the mean value for half a year becomes constant, 0.053 to 0.050; this is considerably smaller than the value adopted for the solar system (~0.1). Solar wind abundances of noble gas elements having small Z (helium, neon and argon) were determined by the Apollo mission (Geiss *et al.* 1972) which exposed to solar wind aluminum and platinum foils spread on the surface of the moon for several hours to days. These foils were then returned to earth and analyzed by noble gas mass spectrometry. The results showed that the particle flux changed in the short term, but that the relative abundances of elements and isotopes were essentially constant. Elemental abundances of helium, neon and argon deduced from observation of the HII region are in agreement with those obtained from solar wind and SEP. For carbon, nitrogen, oxygen, silicon and iron, the data obtained by the ISEE-3 satellite are available; the data for oxygen and iron are fairly reliable while those for the remaining elements cannot be regarded as representative of the solar wind.

It seems to be impossible to improve the quality of the data for solar wind using the present techniques and methods. To overcome this, a long-term collection of solar wind and / or a high sensitivity analytical method for chemical and isotopic measurements is needed. For the first alternative, a proposal is the collection of solar wind by spacecraft, similar to the Apollo moon foil experiments. For such measurements a spacecraft is required to stay in space as long as possible, and finally return to the earth. It is highly probable that this will be realized early in the 21st century.

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