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# Isotopes in the Solar Wind: New Results from ACE, SOHO, and WIND

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**Abstract.** Measuring the isotopic composition of the solar wind is interesting because it provides unique information on the isotopic composition of the solar atmosphere, the outer convective zone of the Sun, and the bulk Sun. Comparing the solar isotopic composition with other solar system samples can give clues about the early history of the solar system. If compared with the present-day interstellar medium, e.g. derived from interstellar pick-up ions in the interplanetary medium or from the anomalous cosmic-ray component, the solar isotopic composition yields valuable information on the galactic chemical evolution during the last 4.6 Gy and on the radial migration of the Sun within the galaxy. Solar isotopic abundances of volatile elements (He, Ne) have been used to put constraints on the internal transport of matter during the entire history of the Main-Sequence Sun and on the evolution of planetary atmospheres. More recently, the isotopic composition of refractory elements in different solar wind regimes has been used to infer the importance of fractionation processes operating between the radiative solar core, the outer convective zone, and the solar atmosphere, as well as between the solar atmosphere and the interplanetary plasma. The analysis of the isotopes of Mg, Si, and Ca as observed with the WIND/SMS, the SOHO/CELIAS, and the ACE/SWIMS isotope spectrometers indicate that the variability of isotopic abundance ratios in different solar wind regimes amounts to less than a few percent per mass unit, and that the overall isotopic composition of refractories in the solar wind is within the uncertainties identical to the terrestrial, lunar, and meteoritic composition. From observational evidence and from theoretical models on minor ion heating and acceleration in the corona it seems clear that coronal hole high speed streams provide the most authentic samples of the isotopic composition of the solar photosphere.

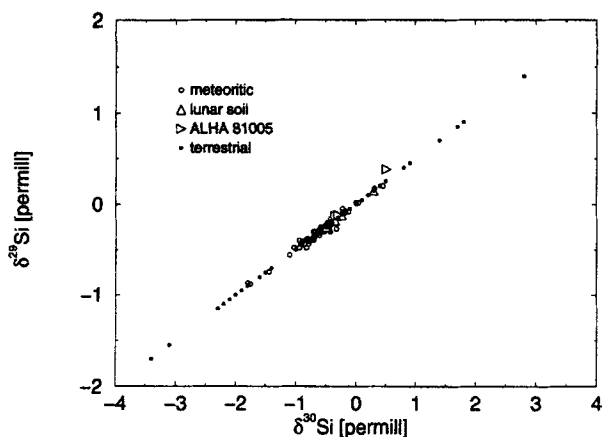
## INTRODUCTION

When the solar system formed from the presolar cloud, it closed itself off from its surrounding interstellar environment and is thus considered a basically unaltered sample of the isotopic composition of the interstellar medium 4.6 Gy ago at about 8 kpc from the galactic center. Some well understood processes, such as radioactive decay of short lived  $^{26}\text{Al}$  into  $^{26}\text{Mg}$ , or of  $^{40}\text{K}$  into  $^{40}\text{Ar}$ , have left their signatures in well preserved samples, and have served and still serve as “clocks” for the understanding of the history and evolution of the solar system.

Refractory elements are well suited to study the variability of isotopic composition because they were not depleted (and thus not fractionated) during the processes leading to the formation of the solar system as we know it today. Silicon, as the second most abundant refractory element is especially well suited for such studies, since none of its three stable isotopes have long-lived radioactive progenitors, as does, e.g.,  $^{26}\text{Mg}$ . In the following, we will briefly discuss the isotopic composition of silicon in the galaxy and show how various processes have re-

sulted in large variations and contrast these observations with the very limited variability present in solar system samples. Under the thus motivated assumption that the Sun has the same isotopic composition of refractory elements as do meteorites, the Earth, and the Moon, we will then continue to investigate the efficacy with which various processes can fractionate isotopes measured in the solar wind.

An immense variability in isotopic composition is contributed from various nucleosynthetic sources to different objects in the galaxy. Refractory or moderately volatile elements which are incorporated into grains at the site of production conserve this variability by preserving the unaltered contributions of many different stars. It can be investigated by analyzing for instance presolar SiC grains which were incorporated into primitive (CI) meteorites at the time of the formation of the solar system (2, 20, 21). Only few other measurements of the isotopic composition of bodies outside the solar system have been possible; they include the interstellar medium (53), and the envelopes of cool stars (33, 24, 45). Across the part of the galaxy accessible to observations, we find variations



**FIGURE 1.** Compilation of the silicon isotopic composition of various sources in the solar system. See (51) for sources and detailed discussion.

in the isotopic composition of silicon by more than a factor of two. See e. g. Wimmer-Schweingruber *et al.* (51) for a discussion.

This large variability of Si isotopic abundances observed in the galaxy is in stark contrast with the variability of isotopic abundances of Si and of other refractory or moderately volatile elements in the solar system. It is well known from studies such as the one of Anders and Grevesse (1) that there is little variation among the abundances of the refractory elements in different materials of the solar system. This homogeneity in elemental compositions of different solar system materials reflects the fact that the early condensates in the inner parts of the solar nebula have not undergone strong chemical fractionation. Consequently, isotopic fractionation - e. g. due to incomplete condensation - was limited to tiny effects (22).

The small variation of solar system isotopic abundances in refractory elements is illustrated in Figure 1 for the case of Si. Plotted is, in the usual  $\delta$ -notation,

$$\delta^{29}\text{Si} \equiv \left[ \frac{(^{29}\text{Si}/^{28}\text{Si})_{\text{meas}}}{(^{29}\text{Si}/^{28}\text{Si})_{\text{std}}} - 1 \right] \cdot 1000,$$

the deviation in the ratio of  $^{29}\text{Si}/^{28}\text{Si}$  from a standard value (3), versus the analogously defined  $\delta^{30}\text{Si}$ . The standard value is, of course, the terrestrial one and, in this notation, lies at (0,0) in this plot. The solar value is very close (51). In this three-isotope diagram a variety of different solar system samples follow a straight line with slope 1/2 which is typical for chemical isotope fractionation. The entire variability is confined to a narrow range of few permills per mass unit, inspite of the large galactic variations just discussed. (The factor of two in variability corresponds to two thousand permill in the  $\delta$ -notation of this diagram.) This clearly reflects the efficient isotopic homogenization of the solar nebula and lends confidence

to the assumption that the bulk Sun and other solar system samples have the same isotopic composition. It is for this reason that Si and Mg are often used as standards for isotopic fractionation in the solar wind (to within few permill per mass unit).

Since meteoritic, lunar, and terrestrial samples can be analyzed in the laboratory, we have very precise measurements of their composition and thus know that of the Sun equally well. As we will discuss further down, it is also safe to assume that the isotopic composition of most elements was not strongly altered in the outer convective zone of the Sun due to gravitational settling (5). Most elements are also not affected by hydrogen burning in the solar core, because their isotopes cannot have been modified by nuclear processes with charged particles due to the high Coulomb barrier of their nuclei. Therefore we may expect the outer convective zone of the Sun to be a largely unaltered sample of the isotopic composition of the early solar nebula, since the mean composition of the solar system is essentially determined by that of the Sun which contains 99.9% of all mass in the solar system.

## FRACTIONATION IN THE SOLAR INTERIOR

Helioseismology has considerably improved the knowledge about the internal structure of the Sun. From observations of solar oscillations it is possible to derive detailed knowledge of the solar interior (see e. g. (19)). Today standard solar models include the effects of element diffusion (see e. g. (10)) which leads to elemental and isotopic segregation. Models including elemental segregation exhibit significantly better agreement with helioseismological data than models which do not take this effect into account. Element and isotopic segregation are due to a competition between two processes. Minor species in the solar interior are influenced by various external forces, for example, gravity, radiation pressure, etc. The particles also collide with each other and scatter randomly. This competition between external forces and random scattering leads to elemental segregation (42). Consistent solar evolution models which include diffusion and radiative acceleration effects (apart from gravitational settling) predict a depletion of the heavy elements at the present day solar surface of the order of 10% (46). To a first approximation, isotopic segregation is no greater than the elemental depletion times the relative mass difference between the isotopes. For the example of silicon we thus arrive at an upper limit for the depletion of the heavier isotopes of about three permill per mass unit. Thus measurements of the isotopic composition of

the solar wind could give constraints on solar evolution models.

## FRACTIONATION IN THE CHROMOSPHERE

The strong fractionation observed for elements in the slow solar wind is mostly due to the FIP effect (First Ionization Potential). Although this effect is of utmost importance for elemental fractionation, it is probably quite unimportant for isotopic fractionation. For instance, the elemental fractionation model of Marsch *et al.* (35) can be understood as a competition between two time scales, diffusion and ionization. The authors derive the following expression for the mass-dependent part of elemental fractionation  $f_{ij}$  between two species  $i$  and  $j$ ,

$$f_{ij} \propto \left( \frac{A_i + 1}{A_i} \frac{A_j}{A_j + 1} \right)^{1/4},$$

where  $A_{i,j}$  is the atomic mass number of species  $i$  and  $j$ . For the example of magnesium this expression yields a depletion of the heavy isotopes of less than half a permil per mass unit. In other words FIP is unimportant for isotopic fractionation according to the Marsch *et al.* model. Note however, that the model of Schwadron *et al.* (43) which invokes resonant ion-cyclotron heating of weakly ionized species to explain the FIP effect could produce significantly stronger isotope effects. This is concluded from analogy with the severe isotope fractionation observed in energetic particles related with impulsive flare events.

## FRACTIONATION IN THE CORONA

The strongest fractionation in the corona is expected to occur around coronal streamers. It is well known that they extend into the heliospheric current sheet (HCS) which exhibits a characteristic depletion of He with respect to hydrogen (9). This finding was originally discussed in the context of a static, gravitationally stratified interior of the streamer, or of a dynamically fractionated flow around the base of the streamer feeding the solar wind. Using measurements of oxygen abundances which is heavier than helium, but has a smaller minimum proton flux factor than helium (16), the first scenario has been ruled out (49, 47). Thus insufficient Coulomb drag may play an important role in fractionating at least part of the slow solar wind and hence it is to be expected that this will also be an effective fractionation process for isotopes.

Under the assumption of an isothermal solar atmosphere and neglecting wave acceleration, one may de-

rive the following expression for fractionation between the two isotopes  $k$  and  $l$  of an element due to inefficient Coulomb drag (6, 7, 8)

$$f_{kl} \propto \frac{2A_k - Q - 1}{2A_l - Q - 1} \sqrt{\frac{A_k + 1}{A_l + 1}}.$$

This expression yields 4% per mass unit for the example of silicon. Thus, for isotopic fractionation, inefficient Coulomb drag can be two orders of magnitude larger than the FIP effect.

Fractionation of isotopes in the solar wind has been found by Kallenbach *et al.* (28). Combining measurements of Ne, Mg, and Si, a depletion of the heavier isotopes has been found to coincide with low He/H abundance ratios. Furthermore, the heavier isotopes are slightly depleted in the slow solar wind, but the isotopic composition of the solar wind is consistent with meteoritic values in high-speed streams (28). This confirms theoretical expectations that isotopic fractionation should be very weak in high-speed streams (5).

Recently, high outflow velocities have been observed in coronal holes (30) which are the source regions of the high-speed streams (31). These observations have been confirmed independently, using the charge-state composition of oxygen (52). Since observations show oxygen outflowing at higher speeds than protons (13), it appears that Coulomb drag plays no role in carrying heavy species in the high-speed solar wind. If indeed wave-particle interaction succeeds to impart the momentum needed to move these species into the coronal hole associated solar wind, as is generally believed, isotope effects are expected to be weak. This is also borne out by the observed constancy of the  $^3\text{He}/^4\text{He}$  isotopic abundance ratio in high-speed streams (7, 18). It is thus to be expected that the isotopic composition of the fast solar wind most accurately resembles that of the reservoir that it is being fed from. Since the well mixed outer convection zone does not know whether it is feeding into the slightly fractionated slow solar wind or into essentially unfractionated high-speed streams, this also means that the observed fractionation in the slow solar wind is entirely due to fractionation in the solar-wind acceleration process. Measurements in high-speed streams should then in turn severely limit the amount of gravitational settling of the heavy isotopes towards the solar core during solar evolution.

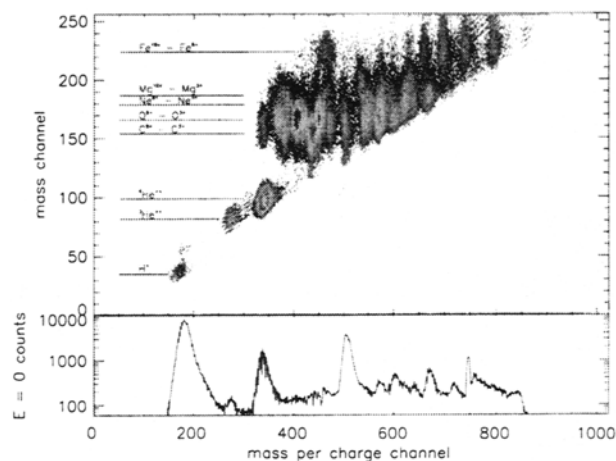
## FRACTIONATION IN TRANSIENT EVENTS

The discussions in the previous sections have made it clear that fractionation of isotopes in the solar wind is rather weak, at most a few percent per mass unit. On

the other hand, laboratory measurements of the content of nitrogen or neon of lunar soils shows some unexpected characteristics. For example, it has been found that the isotopic composition of nitrogen in lunar soils exhibits variations as large as 30 % (29, 4) (see e. g. Geiss and Bochsler (14) for a critical review). While the outermost surfaces of lunar soil grains exhibit normal solar wind isotopic composition for neon, the compositionally distinct more energetic population that has penetrated more deeply into the grains is overabundant by several orders of magnitude (48). That population is enriched in the heavy isotopes of neon. Intriguingly, the energetic population observed in lunar soils seems to be depleted in  $^{15}\text{N}$ , in striking contrast to the neon measurements (37). The origin of these large abundance variations in the nitrogen isotopes or of the overabundance of the energetic population of neon is unknown. However, it has often been speculated that transient events may account for a significant fraction of the material deposited in lunar soils. During such events which might well have been more frequent in the past (due to a more active Sun, more rapid solar rotation), the flux of solar energetic particles (SEPs) increases by several orders of magnitude, setting the stage for much speculation.

Around solar activity maximum, interplanetary space in the ecliptic plane is dominated by transient events. Coronal mass ejections (CMEs) are the most prominent examples. They exhibit tremendous variability in their internal structure and even solar wind composition (39). For example, it seems that the bulk composition of a CME observed on January 6, 1997, is best explained by mass fractionation (54). Elemental enrichment factors of up to  $4.0 \pm 0.6$  for Fe/O relative to a reference (FIP enhanced) interstream solar wind value were found in that CME. Another CME, observed on May 2-3, 1998, exhibited the highly unusual charge-state distribution (17) shown in Figure 2. Such charge-state distributions indicate rapid cooling of the electrons in the ejecta. Such situations occur in extreme non-equilibrium situations when the cooling is much faster than the recombination process (40). Indeed, CMEs have been observed to emit neutral hydrogen lines, indicating the presence of neutral hydrogen atoms (38, 44) at solar distances of up to  $6r_{\odot}$ . Such deficiency of electric charge would of course allow the much weaker gravitational forces to become increasingly important and this might in turn lead to mass dependent fractionation.

In this CME, the  $^3\text{He}$  abundance relative to  $^4\text{He}$  was considerably enhanced over its usual solar wind value and extremely variable in time (17). This can be seen in the panel labelled  $E = 0$  counts in Figure 2. That mass-per-charge histogram has a peak between the proton and alpha-particle peaks which is due to doubly charged  $^3\text{He}$ . Obviously, without need for instrumental correc-



**FIGURE 2.** ACE/SWICS data accumulated during the second half of the May 2-3, 1998 CME. In this mass versus mass-per-charge plot we can easily pick out the charge states of a multitude of ions. This CME exhibited a very unusual charge-state distribution. For example, iron charge states from  $\text{Fe}^{16+}$  coexisted with such low charge states as  $\text{Fe}^{6+}$ . Similar observations can be made for all other ions.

tions,  $^3\text{He}$  is overabundant compared to its solar wind value of  $^3\text{He}/^4\text{He} \sim 1/2450$ . High  $^3\text{He}/^4\text{He}$  ratios in solar energetic particles have recently been observed in some events to coincide with substantial enrichments in the heavy isotopes of heavy elements such as Mg (36, 34). Wimmer-Schweingruber *et al.* (50) investigated whether the enrichment of the heavy isotopes sometimes observed in solar energetic particles was mirrored in the isotopic composition of solar wind Mg and Si. They concentrated on the time period where the unusual mixture of charge states and unusually high  $^3\text{He}/^4\text{He}$  was observed to test for isotopic fractionation in such extreme solar wind conditions. The isotopic composition of Mg and of Si of this specific CME was found to be consistent with meteoritic values, although mass fractionation such as that found in the bulk of the January 6, 1997, CME could not be ruled out due to the large statistical uncertainties (50). However, enrichments by factors  $\sim 2 - 3$  found for SEPs in  $^3\text{He}$ -rich events (36, 34) could be excluded. If such enrichments are observed in the energetic particles for the May 2-3, 1998, event, then this indicates that this enrichment must be mostly due to the acceleration process of these particles, but not of the solar wind. To summarize, we may state that, independent of any model assumptions, the solar plasma in the second half of the May 1998 CME, that experienced very unusual transport through the solar corona (as reflected by the observed unusual charge-state distribution) and had an extremely enriched  $^3\text{He}$  abundance, underwent very little or no isotopic fractionation for Mg or Si.

**Table 1.** Summary of the Isotopic Composition of the Solar Wind

isotope ratio	source*	value	ref.	solar system <sup>†</sup>
<sup>4</sup> He/ <sup>3</sup> He/10 <sup>3</sup>	ASW	2.45 ± .50	(7)	2.05(.2)
<sup>3</sup> He/ <sup>4</sup> He/10 <sup>3</sup>	SSW	2.45 ± .15	(18)	2.05(.2)
<sup>3</sup> He/ <sup>4</sup> He/10 <sup>3</sup>	FSW	3.03 ± .25	(18)	2.05(.2)
<sup>15</sup> N/ <sup>14</sup> N	ASW	200 ± 60	(25)	272
<sup>18</sup> O/ <sup>16</sup> O	SSW	450 ± 130	(11)	498
<sup>20</sup> Ne/ <sup>21</sup> Ne	SSW	440 ± 110	(27)	420(50)
<sup>20</sup> Ne/ <sup>22</sup> Ne	SSW	13.8 ± 0.7	(27)	13.7(3)
<sup>20</sup> Ne/ <sup>22</sup> Ne	SSW	13.64 ± 0.7	(51)	13.7(3)
<sup>25</sup> Mg/ <sup>24</sup> Mg	SSW	(12.8 ± 1.1)%	(5)	12.66 %
<sup>25</sup> Mg/ <sup>24</sup> Mg	FSW	(13.2 ± 1.3)%	(5)	12.66 %
<sup>25</sup> Mg/ <sup>24</sup> Mg	SSW	(13.0 ± 0.7)%	(32)	12.66 %
<sup>25</sup> Mg/ <sup>24</sup> Mg	CME	(11.7 ± 2.1)%	(50)	12.66 %
<sup>26</sup> Mg/ <sup>24</sup> Mg	SSW	(13.8 ± 1.2)%	(5)	13.94 %
<sup>26</sup> Mg/ <sup>24</sup> Mg	FSW	(15.3 ± 1.3)%	(5)	13.94 %
<sup>26</sup> Mg/ <sup>24</sup> Mg	SSW	(13.7 ± 1.0)%	(32)	13.94 %
<sup>26</sup> Mg/ <sup>24</sup> Mg	CME	(14.6 ± 2.4)%	(50)	13.94 %
<sup>29</sup> Si/ <sup>28</sup> Si	SSW	(4.54 ± 0.2)%	(51)	4.63 %
<sup>29</sup> Si/ <sup>28</sup> Si	CME	(5.6 ± 1.6)%	(50)	5.06 %
<sup>30</sup> Si/ <sup>28</sup> Si	SSW	(3.26 ± 0.2)%	(51)	3.10 %
<sup>30</sup> Si/ <sup>28</sup> Si	CME	(3.6 ± 1.5)%	(50)	3.36 %
<sup>40</sup> Ca/ <sup>44</sup> Ca	ASW	50 ± 8	(26)	47.153
<sup>40</sup> Ca/ <sup>42</sup> Ca	ASW	128 ± 47	(26)	151.04
<sup>54</sup> Fe/ <sup>56</sup> Fe	SSW	(8.5 <sup>+0.5</sup> <sub>-2.2</sub> )%	(41)	6.3 %
<sup>57</sup> Fe/ <sup>56</sup> Fe	SSW	< 5%	(41)	2.3 %

\* SSW means slow solar wind, FSW fast solar wind, CME coronal mass ejection, and ASW average solar wind.

<sup>†</sup> Solar system values are those of Anders and Grevesse (1). For noble gases we give solar wind values ((15, 12) for He, and (15) for Ne.) Uncertainties in the last digits are in parenthesis.

## CONCLUSIONS

We have investigated and discussed several possible sites of isotopic fractionation for the solar wind. We found that such fractionation is generally small and, specifically, least important for high-speed solar wind streams which therefore provide the most authentic sample of the isotopic composition of the photosphere. Table 1 gives a summary of all the published values for the isotopic composition of the solar wind. It shows clearly that the isotopic composition of the solar wind is already known for a remarkable number of elements. However, the accuracy is generally only marginally sufficient to test for isotopic fractionation during solar evolution or in the solar atmosphere. Obviously, we need to measure the isotopic composition of the solar wind at cosmochemically relevant accuracy, i. e., to the sub-permill level. It is

the aim of future solar wind composition missions such as Genesis, to perform measurements with the necessary precisions. However, the difficulties in discriminating between different types of solar wind which may well have their specific signatures of isotopic fractionation at these levels, will be exceedingly hard to resolve. It is important to note that since the isotopic composition of the refractory elements is observed to be little fractionated in the solar wind (to within the few percent per mass unit that have been possible to detect so far), this must necessarily also be true for the noble gases. Therefore, such measurements are important, inspite of the difficulties mentioned above, because the solar wind (and especially in high-speed streams) is the only possibility to measure the primordial isotopic composition of the noble gases. Meteoritic and planetary values exhibit large variations due to a multitude of effects. Noble gases serve as important indicators for solar system evolution models and for the development of planetary atmospheres (23), and consequently, the primordial isotopic composition of the noble gases is of utmost interest.

Since the birth of the solar system, the interstellar medium and the galaxy have undergone considerable chemical evolution. Only few direct measurements of the ISM or the envelopes of cool stars have been made so far and they exhibit large variations and uncertainties. Another method to determine the composition of the (very) local interstellar medium is the measurement of interstellar pick-up ions or of the anomalous component of the cosmic rays (ACRs) which consist of pick-up ions accelerated at the termination shock of the heliosphere. Comparing the composition of the solar system and of presolar grains with that of the interstellar medium observed today, it is, in principle, possible to obtain information about the galactic chemical evolution during the last 4.6 billion years and on the radial migration of the solar system within the galaxy.

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