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Sun, solar wind, meteorites and interstellar medium: What are the compositional relations?

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Abstract. Atomic properties of elements determine their chemical behavior, their ionization properties and their interaction with radiation in the solar atmosphere. Whereas the chemical properties influence the condensation process in the primordial solar nebula and, hence, meteoritic abundances, ionization properties seem to provide the most important ordering parameters for producing coronal -, solar wind -, and solar energetic particle abundances from the solar reservoir. Finally, since atomic properties also shape the interaction of solar matter with radiation, understanding these properties determines largely the experimental reliability of photospheric chemical abundances. Isotopic abundances must be derived from *nuclear* properties, which are almost insensitive to atomic processes. The solar spectrum is the result of *atomic* processes in the solar atmosphere. The derivation of isotopic abundances from the solar spectrum is impossible for most species, conversely, the insensitivity to chemical processes makes isotopes the first choice to trace the nucleosynthetic history and the degree of mixing of galactic matter from different astrophysical sources prior to formation of the solar system. The solar wind provides a representative sample of solar isotopes and - to some degree - also a rather trustworthy representation of elements with similar atomic properties, especially volatiles, which are difficult to derive from meteoritic abundances and from optical observations of the solar spectrum.

INTRODUCTION

ACE and SOHO, together with several other space missions have greatly enhanced our current knowledge of the chemical composition of the galaxy and of the Sun. Cosmic rays and heliospheric neutrals and pick-up ions provide information on the present-day local interstellar medium whereas the Sun represents a benchmark for the chemical evolution of the interstellar medium as it existed 4.6 Gy. ago at about 10 kpc from the galactic center. The purpose of this paper is to relate the compositional features between Sun, the solar wind, meteorites and the galactic interstellar medium, and to review mechanisms which could produce compositional variations. The solar wind has the potential of providing the most reliable information on the isotopic composition of the Sun. Heliospheric pick-up ions and anomalous cosmic-ray particles give direct evidence of the composition of the contemporary local interstellar medium surrounding the solar system.

The four topics, Sun, solar wind, meteorites and interstellar medium have a common relation originating in the primordial solar nebula which formed out of the local interstellar medium 4.6 Gy ago. The picture by Shu et al. [1] illustrates the action of the primordial solar wind, redistributing disk material between the accreting central body, the newborn Sun, and the planetary disk, thereby

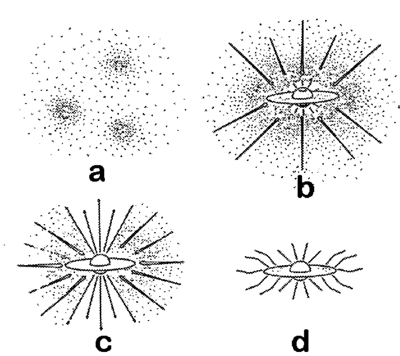

FIGURE 1. Four phases of the evolution of the protosun and protosolar disk according to Shu, Adams and Lizano [1]. Originating from a dense molecular cloud (a) the rapidly rotating Sun emerges (b) together with a circumsolar disk. Differential rotation of the Sun produces strong magnetic fields, which generate a vigorous polar outflow (c) while accretion continues in the equatorial plane. The outflow cone widens and (d) finally, the young, active Sun remains with a thin disk. Reprinted with permission from the Annual Review of Astronomy & Astrophysics, Volume 25 ©1987 by Annual Reviews www.AnnualReviews.org

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fractionating gas and dust from which planetary bodies (including meteoritic parent bodies and comets) began to form. Accretion of the Sun from the protosolar nebula leads to its rapid spin-up. The increasing internal differential rotation of the Sun induces strong polar magnetic fields and a strong polar wind which prohibits further accretion in polar regions while infall of matter at low solar latitudes continues. A fraction of this infalling material, however, does not reach the Sun. Before it reaches the Alfvén point it encounters outflowing solar matter with which it is ejected into higher solar latitudes and falls back to the disk at some remote place. Hence, a fraction of the solar disk is recycled through this process of continuous infall and ejection. As the protosolar system evolves, the wind which originates above the polar regions, increases its aperture cone; magnetic field lines open just as the spokes of an opening umbrella. With each cycle in this turnover process, some material is lost to space and some matter drops to the solar surface. Matter falling back onto the planetary disk will be chemically fractionated; the degree of fractionation will depend on the cycling frequency, i.e., on the cycling time and on the travel distance. The fractionating process is most efficient for frequently cycled matter residing in the innermost parts of the solar system, whereas matter carried over greater distances remains largely unaltered. Hence, mass fractionation in the gas phase is expected to slightly enhance heavier species in the innermost parts of the solar system, whereas the outermost regions and the Sun itself retain their original composition. Experimental evidence about this process is scarce, and from theoretical models it is difficult to estimate even an order of magnitude of its efficiency. In view of the fact that large amounts of disk material have to be recycled within a rather short time, big effects are unlikely to occur.

Carbonaceous meteorites of the class CI are generally assumed to reflect solar composition most closely [2]. Condensation of refractory and moderately volatile elements is considered to be a non-equilibrium process with no isotopic fractionation involved. Volatile elements in planetary materials show generally a large variability in isotopic composition. Part of this variability is ascribed to isotopic fractionation, part must be due to variable mixing of materials from different sources, e.g. grain-gas mixture. In view of the conclusions from the above introductory section, it appears quite reasonable, that meteorites and cometary bodies, which condense farthest out in the solar system, and the Sun, which retained a representative sample of the primordial solar nebula can provide the samples least isotopically fractionated in the solar system. Unfortunately, direct measurements of the solar isotopic composition are impossible, except for a few elements, which form molecules at high temperatures.

FRACTIONATION IN THE PRIMORDIAL SOLAR NEBULA

From the scenario outlined in the introduction some speculations about the large-scale chemical and isotopic evolution of the solar system can be developed. Whereas it appears possible to produce gradients of chemical composition by circulation and redistribution of matter within the accretion disk, isotope effects are probably tiny, i.e., it is no surprise that refractory elements show almost no signs of isotopic fractionation throughout the solar system. In order to noticeably fractionate matter of the solar disk, a significant part of it has to be circulated within the lifetime of the disk. Consider a disk containing one percent of the solar mass. Circulating such an amount of mass during several 10 million years requires typical mass fluences of 10^{13} kg/s. With a typical flow speed of 100 km/s this process will consume only about the equivalent of one permill of the solar luminosity. We further assume that the X-point [1] of the protosolar wind is located at about 100 $R_\odot$. To maintain mass flux and speed as given above, a maximum density on the order of 10^{12} particles per m^3 at the X-point is required, much higher than densities observed at a similar location in the contemporary solar wind. As a consequence, collision frequencies between the dominant species (hydrogen) and minor species are exceedingly large and isotopic effects are small in such an intense wind. A weak mass fractionation in such a bipolar wind can occur through the difference of forces experienced by test particles of different masses. Heavier particles have a tendency to stay behind lighter particles in a drag exerted by a wind of light field particles. Below the critical point, some heavy particles will fall back to the Sun, while their lighter counterparts will be blown out to the solar disk. The effects are tiny and can be estimated from a simple consideration of momentum transfer in a series of elastic collisions from the coronal base at heliocentric distance R to the critical point at r_o with the following simplified expression:

$$f_{ij} = \frac{w_i}{w_j} = \frac{\left[1 - \left(\frac{M_i - m}{M_i + m}\right)^{N(r_o/R)(1-R/r)}\right]}{\left[1 - \left(\frac{M_j - m}{M_j + m}\right)^{N(r_o/R)(1-R/r)}\right]} \qquad (1)$$

In this equation M_i and M_j indicate the masses of two different test particles, m is the mass of the field particles, and $N = n_o \sigma r_o$ a typical collision number on the way of the particles to the critical point, which is of order 3000.

Such a mechanism might naturally lead to the fractionation gradients, e.g. for the $^{52}Cr/^{53}Cr$ isotopic abundance ratio as discussed in the article by Hoppe [3] (see [4] for the original Cr data). Matter launched by a bipolar wind into the disk will generally be depleted in heavier

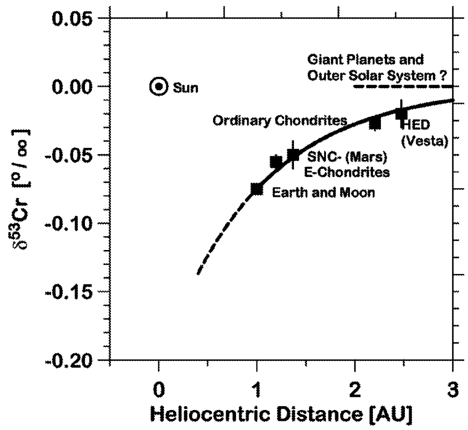

FIGURE 2. Chromium isotope systematics due to fractionated redistribution of matter in the primordial solar nebula

isotopes, whereas the Sun remains at its original composition due to the enormous size of the reservoir. Note, that at this stage the entire Sun is chemically and isotopically homogenized, since the rapidly rotating star is thoroughly mixed through a convective zone which reaches deep into the stellar core. Due to the circulation with the X-wind, the disk tends to undergo a tiny enrichment with light isotopes. The innermost parts of the protoplanetary disk will obtain the strongest enrichment of light isotopes due to the most thorough recycling with short characteristic transfer times, the outer parts will be much less frequently recycled; hence, isotopic effects will level out and the isotopic composition of matter will attain solar values in regions where recycling becomes negligible. Note, however, that these effects should not exceed small fractions of permills, even in the innermost parts of the planetary disk, due to the large densities and the strong coupling of the heavier elements to the bipolar outflow. Furthermore, this mechanism can only work as long as also refractory elements such as chromium are evaporated at the moment of the closest approach to the Sun. Furthermore, although recycling and sorting of dust grains might work in a similar manner in the protosolar disk, it seems highly unlikely that the complicated isotopic pattern of a partly rock-forming and partly volatile element such as oxygen could be explained with this simple idea.

ISOTOPIC FRACTIONATION IN THE CONTEMPORARY SOLAR WIND

It has been emphasized above that recycling of matter through the protoplanetary disk will hardly affect the bulk composition of the Sun. Hence, the Sun is generally considered to represent the most faithful sample of the protosolar nebula with respect to elemental and isotopic composition. Studying the isotopic composition of the solar wind is most interesting in this context, because the solar wind provides the least biased, accessible sample of isotopic solar composition. Nevertheless, it is important to note that the outer convective zone of the Sun has probably undergone some alteration in its elemental and isotopic composition due to the effect of gravitational settling across the boundary between the radiative core and the convective outer zone [5]. The effect amounts to typically a fraction of a percent per atomic mass unit [6].

Apart from fractionation in the source of the solar wind, i.e., matter from the solar atmosphere, which is in constant exchange with matter from the outer convective zone, some isotopic fractionation is also expected in the solar wind feeding and acceleration process. It has been known for a long time that the solar wind undergoes strong variations in its elemental composition, notably its He/H elemental ratio. The issue on the origin of these variations has not been conclusively settled, however, many theories which make an attempt to explain these variations involve the effect of inefficient Coulomb drag in the solar wind acceleration domain (e.g. [7]). The almost permanent depletion of helium relative to hydrogen in the solar wind seems to be a natural consequence of the weak Coulomb drag in the emanating proton flow, because the species $^4He^{++}$ has an exceptionally low drag factor. The three-fluid-models of Bürgi [8], making use of the superradial expansion in magnetic structures, which feed the low-speed solar wind, and which are located at the acceleration site, give a plausible explanation for the sometimes strong depletion of helium near the interplanetary current-sheet as demonstrated by Borrini et al. [9]. Wimmer-Schweingruber [10] found a significant depletion of helium relative to oxygen near sector-boundaries, underlining the strong discrimination of helium due to its weak Coulomb-coupling to hydrogen in coronal regions of strongly diverging magnetic fields. Similarly, Noci *et al.* [11] argued that the sometimes strong enrichment of oxygen relative to hydrogen as observed with SOHO/UVCS at the footpoints of streamers is the consequence of the superradial divergence of flow tubes above those streamers. That collisions play an important role in slow solar wind regimes, overruling the action of waves on particle distributions, has amply been demonstrated under many circumstances [12, 13], most recently by Hefti et al. [14]. In a similar manner Coulomb-collisions could also determine isotopic fractionation effects in the solar wind. Following these lines, Bodmer and Bochsler [15], have investigated the effects of flow geometry in the solar corona and the strength of Coulomb friction on isotopic and elemental fractionation. In their model they found that a significant depletion of helium is always accompanied by a solar wind depletion of the heavier isotopes of the order of a percent per atomic mass unit. According to the predictions of the model of Bodmer and Bochsler, the expected fractionation effect is weaker in the high-speed, coronal-hole associated solar wind. Waves play a much more important role driving minor species in this types of regimes. However, also in this case some Q/M-fractionation will occur. Preliminary estimates indicate that such effects will generally be of the order of a fraction of a percent per mass unit [6]. In fact, the first investigations of the isotopic composition of the refractory element magnesium, which shows only tiny variations in its isotopic composition among different planetary samples, revealed no difference between solar wind and terrestrial Mg [16]. Kallenbach and coworkers [17, 18] have carefully analyzed possible trends of the isotopic ratios $^{24}Mg/^{26}Mg$ and $^{24}Mg/^{25}Mg$ with the solar wind speed and the He/H abundance ratio. They found that the fastest solar wind streams contained magnesium which was depleted by typically 1 percent per mass unit and that there was a general trend of decreasing mass fractionation with increasing wind speed and increasing He/H ratio. In both cases the theoretical predictions are roughly consistent with the observations. However it should be noted that the experimental uncertainties are still substantial. A careful re-analysis of the data collected during five years of operations and a recalibration of the spare sensor of MTOF/CELIAS with terrestrial Mg is pending.

Apart from the fact that helium ions have the least favorable Coulomb drag factors for incorporation into the solar wind, helium is also the element with the highest first ionization potential ("FIP"), and the longest ionization times. The chromosphere looks rather homogeneous on a global scale; chromospheric properties under coronal holes do not differ from those under active regions. The latter are, however, exposed to higher EUV radiation intensities and to radiation spectra which differ from those under the open magnetic field regions. This, in turn, may have some influence on the solar wind feeding process in different chromospheric regimes. If indeed the systematic helium depletion in the solar wind has (partly) to be attributed to the radiation field and not to the inefficient Coulomb drag, the isotopic effects predicted to occur in correlation with the He/H abundance ratio, as discussed above, should rather be taken as upper limits.

ELEMENTAL FRACTIONATION IN THE SOLAR WIND

The elemental composition of the solar wind varies and differs at times significantly from the photospheric composition. It is well known that elements with ionization potentials above 10eV (e.g. He, Ne, Ar, O) are generally depleted compared to the low-FIP elements. Taking oxygen as a reference, this depletion amounts to typically a factor of 3 to 5 in low-speed solar wind whereas it is typically less than a factor of 2 in coronal-hole-associated high speed wind. The same phenomenon is observed in solar energetic particle abundances (see article by Reames [19]) and sometimes much more so in optical observations of active regions. No generally accepted explanation for this effect has been found yet. It is also not understood why the optical observations of Mg/O or Ne/O abundance ratios provide values which vary sometimes by factors of 10 [20], while the particle observations never have shown a clear case with a FIP-fractionation factor of an order of magnitude. We suspect that the solar wind is rather representative for the coronal base whereas optical observations must suffer from strong biases due to large differences in intensity of the different radiating elements of solar surface structures. Even if rather variable abundance ratios exist in different domains of the chromosphere, we believe that the solar wind is fed from much larger reservoirs, to be visualized as a tenuous haze spread above the turbulent dynamic and structured chromosphere.

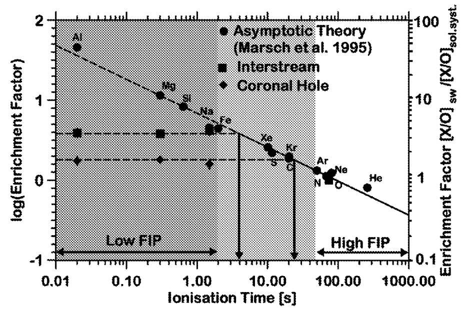

FIGURE 3. Abundances of low-FIP elements in the solar wind. The full line illustrates the result of the simple chromospheric diffusion model of Marsch et al.(1995) [21] which works for high- and intermediate-FIP elements. The preliminary investigations of Na and Al abundances of Ipavich et al. [22] and Bochsler et al. [23] give no evidence of fractionation among low-FIP elements.

Concerning the reliability of the witness samples of the solar atmosphere provided by the solar wind, the important question is whether the feeding process discriminates individually among the low-FIP elements or whether all low-FIP elements are incorporated without discrimination among each other into the solar wind. Of course, it would be most beneficial for abundance studies if the solar wind left low-FIP elements undiscriminated at all times. The next question then is whether the high-FIP elements left behind remain largely undiscriminated among themselves in the solar wind as well. The presently available experimental evidence is limited to results of a few preliminary studies: Aluminum and sodium abundances, two elements which have rather reliably determined photospheric and meteoritic abundances have been measured and compared with the abundance of magnesium in two selected periods of different solar wind regimes [23, 22]. The preliminary result looks promising: The analysis showed no fractionation among the three low-FIP elements Na, Al, and Mg in both types of solar wind although the regular fractionation factors between high/low-FIP elements have verified.

CONTEMPORARY INTERSTELLAR MATTER IN THE INNER HELIOSPHERE

Although the umbilical cord, which connected the interstellar medium and the solar system, has been cut long ago, the heliosphere is still pervaded by contemporary interstellar matter in the form of neutral atomic, molecular and dust particles. The interaction of solar radiation and the solar wind with gas and dust ionizes the gas and evaporates grains in the innermost parts of the heliosphere. Newly ionized interstellar particles are continuously swept to the boundaries of the heliosphere by means of the outward-moving interplanetary magnetic field, i.e., by the so-called pick-up process. Although particles of interstellar origin contribute the far largest fraction of diffuse matter within the boundaries of the heliosphere, their contribution to the solar and planetary reservoirs is minor. They can be distinguished from solar particles due to their different charge state distributions, their isotopic pattern and from their somewhat different energy distributions. Some indications for their presence in the record of the lunar soil and the possible relevance of this record for past encounters of the solar system with dense molecular clouds have been discussed [24, 25]. Pick-up ions from interstellar gas have been identified as the source of the anomalous cosmic rays [26]. Hence, anomalous cosmic rays provide another indirect source of information of the composition of the interstellar medium surrounding the heliosphere.

The inference of elemental abundances in the interstellar gas depends on the so-called "filtration factors". The properties of the interface between the heliosphere and the local interstellar cloud are determined by the interaction of the temporally variable solar wind with the magnetized, structured, partially condensed, and partially ionized interstellar medium. The probability (filtration factor) of a given species to enter the inner heliosphere through this interface depends crucially on the physical properties of this interface. As long as the state of ionization in the local interstellar cloud and the orientation and strength of the magnetic field in the local cloud are not well defined, a straightforward derivation of elemental filtration factors is problematic. Fahr [27], and Geiss and Witte [28] give a detailed account of the difficulties related to the inference of the abundance of volatile species in the local interstellar medium. Obviously, these difficulties become even more significant as soon as moderately volatile and refractory elements are included in such considerations. On the other hand, inferences about *isotopic* abundances of volatile elements are quite straightforward.

The $^{3}He/^{4}He$-isotopic ratio in the local interstellar cloud has been inferred from pick-up ion observations with Ulysses/SWICS [29]. More recently, this ratio has also been successfully been determined directly with the foil collection technique by means of the COLLISA experiment on the Mir space station [30]. Isotopic abundances of other elements can also be inferred in a rather straightforward manner from the Anomalous Component of cosmic rays (see, e.g. [31]).

CONCLUSIONS

Matter involved in almost any astrophysical process will undergo some alteration of its elemental and isotopic composition. This leads to the rich variety of compositional features observed in the galaxy, in the solar system, in meteorites, down to the smallest scales including the tiniest grains or macromolecules that only comprise hundred atoms or less. Cosmochemical and isotopic investigations always deal with a double-faced nature: On one hand one finds interest in studying the physical processes which lead to the compositional variety in order to learn about the history of an object, on the other hand one considers compositional signatures as fixed and uses them as tracers to track the flow and distribution of matter from cosmological scales into galaxies, and stars. Both approaches have been equally successful as has amply been demonstrated in the course of this workshop.

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