INFERENCES FOR ISOTOPIC FRACTIONATION PROCESSES IN THE SOLAR WIND USING THE FULL SOLAR CYCLE RECORD OF ABUNDANCES FROM ULYSSES: ANTICIPATING RESULTS FROM THE GENESIS MISSION

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ABSTRACT

On September 8, 2004, during this conference, the mid-air retrieval of the Genesis mission failed, and the return capsule crashed into the Utah desert sands. Although some important goals of this mission can probably not be achieved, some other issues regarding solar wind composition and the solar wind feeding process can be addressed and possibly solved. The main purpose of the Genesis mission is to obtain information on the isotopic composition of the outer convective zone of the Sun for as many elements as possible. Since it is well known that the solar wind is severely fractionated with respect to the solar atmosphere element-wise, it is essential to gather information on possible isotopic fractionation processes in order to gain maximum information from the Genesis mission. We summarize the observational facts and present some inferences from theoretical models on isotopic and elemental fractionation in the solar wind.

1. INTRODUCTION

The Sun, and particularly its outer convective zone (OCZ), constitutes a practically unaltered reservoir with an isotopic and elemental composition representing accurately the composition of matter from which the solar system formed 4.6 Gy. ago. Theories on the origin of the solar system predict that at most a fraction of the order of 50\% of matter is lost from the protosun, hence, substantial elemental and isotopic fractionation during the formation of the Sun seems unlikely, while of course, volatiles and moderately volatile elements have been severely depleted in the inner planets.

These considerations make the Sun to be the most important reference point for galactic and planetary abundances. It sets an end point to nucleosynthetic evolution of the local interstellar matter 4.6 Gy. ago and, likewise, it sets a benchmark for the initial conditions of the isotopic evolution of the solar system.

The Genesis mission (Burnett et al. 2003) uses the foil collection technique, which was originally developed and successfully applied during the Apollo missions (Geiss et al. 2004). Various targets have been exposed to the solar wind at L1 for a total of 884 days. The main goal of this mission was to capture a sample of the solar wind, which was to be returned to Earth and later analysed in the laboratory. At the moment of writing it is not clear how many of these projects can be realized. Nevertheless, we are confident that at least some studies, e.g. the determination of the isotopic composition of the light noble gases in different streams can be achieved with unprecedented precision. We will discuss in the following how these measurements will not only be of great importance for geochemical and cosmochemical applications, but that they will also provide otherwise unavailable information on fractionation mechanisms in the solar wind feeding process.

2. FRACTIONATION PROCESSES

Chemical and isotopic fractionation of the solar wind begins in its source region, i.e. in the chromosphere or low in the transition region when also species with high ionization potentials become ionized. During the acceleration of the solar wind heavy ions are subjected to the counter action between gravity and the outwards acting combined forces due to wave-particle heating and mirror acceleration from diverging magnetic fields, and Coulomb friction with protons. Whereas the separation of ions from neutrals through first
ionization is a purely atomic effect, and no noticeable isotopic fractionation is expected, inefficient wave particle interaction and Coulomb friction can produce isotopic and elemental fractionation. Fig. 1 illustrates the most important elemental fractionation process for the case of interstream solar wind. The so-called FIP-fractionation produces a systematic depletion of elements with high ionization potentials – by as much as a factor of 3 to 4 in the interstream solar wind and typically a factor of 2 in the coronal hole associated fast solar wind.

As an especially interesting and important case we mention the notoriously depleted He/H ratio, which is under most circumstances systematically below the solar surface by as much as a factor of two. It is interesting because helium has the highest first ionization potential and, hence, is discriminated strongly in the ionization process. Furthermore, $^4\text{He}^{++}$ has the highest Coulomb-drag factor (Geiss et al. 1970), the ion has a rather high mass/charge ratio and it is thus discriminated once more in the heating and acceleration process. The He/H ratio has been routinely measured with virtually all solar wind composition instruments since 40 years, however, it is still difficult to disentangle the various contributions to the overall helium depletion.

3. ESTIMATION OF MAGNITUDE OF ATOMIC EFFECTS

The ionization rate $R_{ik}$ of a species $i$ is calculated from the flux $J(E)$ of ionizing photons of energy $E$ and the ionization cross section, $\sigma(E)$, as a convolution of the two quantities

$$R_{ik} = \int_{E_{thr,i}}^{\infty} \sigma_i(e) J(E) dE. \quad (1)$$

The energy dependence of photoionization cross sections of helium and hydrogen above their respective thresholds is well represented with the following parametrization:

$$\sigma_i = \sigma_{thr,i} \left( \frac{E}{E_{thr,i}} \right)^{-3.5}. \quad (2)$$

Above the hydrogen ionization threshold of the solar spectrum can be approximated by a power law:

$$J(E) = J_0 \left( \frac{E}{E_0} \right)^{-\gamma}, \quad (3)$$

where $E_0$ denotes a lower energy limit above which the spectrum begins to deviate from a Planck distribution and for which the approximation is valid.

The convolution yields the very simple expression:

$$R_{ik} = \frac{\sigma_{thr,i} E_{thr,i}^{1-\gamma} E_0^\gamma}{2.5 + \gamma}. \quad (4)$$

Since we are mainly interested in the ionization ratio of helium and hydrogen we use

$$\frac{R_{ik}}{R_{jk}} = \frac{\sigma_{thr,i}}{\sigma_{thr,j}} \left( \frac{E_{thr,i}}{E_{thr,j}} \right)^{1-\gamma}. \quad (5)$$

This ratio depends only on the cross sections at threshold and the exponent of the power law. It is independent from the absolute flux, $J_0$, which simplifies matters a lot, since the flux varies by as much as an order of magnitude between periods of low and maximum solar activity. To first order, $\gamma$ can be considered as a constant. From the data given in the rather ancient review of Hinteregger (1981) we derive $\gamma = 2.2$ and obtain with $\sigma_{thr,H_0} = 7.4$ Mb and $\sigma_{thr,He_0} = 6.3$ Mb a ratio $R_{He_0,He}/R_{H_0,H} \approx 0.56$. © European Space Agency • Provided by the NASA Astrophysics Data System
close to the typical He/H depletion factor in the corona and the solar wind. To explore the variability and uncertainty of such an estimate we have also carried out a numerical convolution of (1) using the rather coarse UV spectra for different periods of solar activity given in Torr et al. (1979) and the photoionization cross section of Verner et al. (1996) and find $0.33 \leq R_{\text{He}}/R_{\text{H}} \leq 0.74$. Both limits are consistent with observations of He/H depletion factors. Generally, the He/H ionisation ratio increases with increasing solar activity. Two records collected in periods of high solar activity produced ionization ratios near the upper limit, whereas two periods with EUV-fluxes, which were lower by a factor of 4, produced values near the lower limit. Obviously, the ionization process in the solar atmosphere is more complicated than simple photoionization from the ground state of atoms, as is evidenced from the depletion of other high-FIP elements. Nevertheless, the rough estimate indicates that indeed inefficient photoionization of helium in the solar atmosphere could be the main culprit for the notorious and persistent coronal helium depletion.

4. ELEMENTAL FRACTIONATION BY INSUFFICIENT COULOMB DRAG AND INSUFFICIENT WAVE PARTICLE HEATING AND ACCELERATION

Considering fractionation of different isotopic species in the solar wind, one has to assess the magnitude of fractionation effects. Geiss et al. (1970) have investigated the possible effects of inefficient Coulomb drag by protons in the solar wind and defined minimum flux factors, which illustrate the efficiency (or rather the inefficiency) of Coulomb drag.

\[
\Gamma(Z, A) = \frac{2A - Z - 1}{Z^2}.
\]

(7)

$Z$ is the ionic charge and $A$ the mass of the species considered. The higher $\Gamma$, the more difficult it is to accelerate an ion by friction with protons. $^4$He has a particularly unfavorable drag factor among the heavier species. As a consequence, if one has to expect fractionation due to inefficient Coulomb drag, the most significant effect is to be found in the elemental He/H ratio.

Wave-particle interaction plays a major role in the acceleration and heating of minor species in the solar wind. This has been known for a long time, and it has been demonstrated that wave-particle interaction accelerates and heats heavy species in the interplanetary medium between 0.3 and 1 AU (e.g. Marsch et al. 1982, Bochsler et al. 1985). More recently the vigourous action of waves on minor species in the corona has impressively been demonstrated with UVCS measurements (e.g. Cranmer et al. 1999). At least in the case of coronal-hole associated solar wind, wave-particle heating is so efficient, that probably not much discrimination occurs among different species.

A compilation of He/H abundances from Ulysses/SWOOPS (Bame et al. 1992), which covers now a full solar cycle shows that indeed not much variation is observed in coronal hole associated solar wind. Fig. 2 shows a two-dimensional histogram of all SWOOPS measurements. The picture demonstrates that the He/H ratio is remarkably stable, despite the fact that it is below its photospheric value by approximately a factor of two. We interpret this stability at the “wrong” value as evidence for the fractionation to occur at low latitudes in the chromosphere, which looks indistinguishable below coronal holes at higher solar latitudes and equatorial regions, except in regions close to activity centers.

Figure 2: He/H ratios observed with Ulysses/SWOOPS (courtesy of SWRI). The period 1991-1993 is characterized by the maximum of cycle 22 and contains CME ejecta. The high latitude scan of Ulysses begins in 1993 and lasts through 1995. This period is dominated by solar wind from the southern coronal hole. After the ecliptic crossing in 1995, the record is again dominated by coronal hole type solar wind. After 1997 the He/H ratio varies more strongly due to increasing solar activity.

It is worth noting that simultaneously with the variations of the He/H ratio also the Fe/O ratio varies substantially. The latter variability is attributed to the well-known variability of the FIP-effect. Whereas interstream solar wind exhibits a systematic enhancement of the Fe/O ratio of about a factor of 3 to 4 over solar abundances, the enrichment of Fe over O is substantially smaller in coronal hole associated solar wind (e.g. Geiss et al. 1995). (see also Fig.1).
5. ISOTOPIC FRACTIONATION BY INSUFFICIENT COULOMB DRAG AND INSUFFICIENT WAVE PARTICLE HEATING AND ACCELERATION

The best information on the isotopic composition of the solar wind is available from various experiments, which determined the $^3\text{He}/^4\text{He}$ abundance ratio. Because of the large relative mass difference between the two isotopes this ratio is also the most sensitive indicator for isotopic fractionation in the solar wind. The most precise measurements date back to the Apollo Solar Wind Composition Experiment (Geiss et al. 2004).

Routine in situ determinations of the solar wind $^3\text{He}/^4\text{He}$ ratio have been carried out with several instruments (Ogilvie et al. 1980, Bochsler 1984, Gloeckler and Geiss 1998, Bodmer and Bochsler 1998). All investigations yielded results consistent with the Apollo SWC average.

The important question addressed in all these studies was, whether the solar wind showed variations in the isotopic composition of helium, and if yes, to quantify these variations. Bochsler (1984) was unable to give a clear-cut answer because of poor statistics and possible trends in the instrument functions ISEE-3/ICI. Furthermore he found that the variability of his measurements exceeded the variability expected from the Apollo SWC measurements by far, which lead to a very cautious assessment of the solar wind isotopic variability. A typical autocorrelation time scale for variations in elemental (and isotopic) abundance ratios in the solar wind is of the order of 20 hours (Bochsler 1984). We use an exponential description of the temporal evolution of the autocorrelation function

$$K_R(\tau) = \exp(-\lambda |\tau|) \quad (8)$$

(with $1/\lambda$ approximately 20 hours) and denote a typical variance of the logarithm of the flux ratio by Var(r), where $r$ is a point value. From this one obtains a variance of integrated ratios, such as from a long-duration exposure over time $T$ on an Apollo foil

$$\text{Var}<R>_T = \frac{2\text{Var}(r)}{\lambda T} \left[1 + \frac{1}{\lambda T} \left(e^{-\lambda T} - 1\right)\right] \quad (9)$$

(Taubenheim, 1969). The scatter of the $^3\text{He}/^4\text{He}$ ratio found in the Apollo foils was typically 5 to 10%, depending on whether or not one includes the short-time exposure of the Apollo 11 mission. The exposure times varied from 1 to 45 hours. Assuming for simplicity an average exposure of $T=40$ hours one would expect Var(r)$=2\text{Var}<R>$, or, a scatter in single measurements of less than 15%. Considering the fact that the Apollo exposures occurred predominantly during periods of slow solar wind, it appears difficult to reconcile these results with the high variability of $^3\text{He}/^4\text{He}$ reported by Gloeckler and Geiss (1998). On the other hand, Bodmer and Bochsler (1998), using essentially the same dataset from Ulysses/SWICS found no clear evidence for a variability of $^3\text{He}/^4\text{He}$ except due to the counting statistics (Fig. 3).

![Figure 3: (from Bodmer and Bochsler 1998): A comparison of observations with a simulation of the influence of counting statistics assuming a fixed $^3\text{He}/^4\text{He}$ shows no clear difference.](image)

It is illustrative to put these findings in relation to theoretical expectations based on a model using inefficient Coulomb drag to explain the variability of the He/H elemental ratio. Bochsler (2000) used an expression to estimate isotopic effects for a given He/H depletion factor, assuming that the entire elemental fractionation factor, $f_H$, had to be ascribed to inefficient Coulomb drag:

$$f_{ij} = \frac{1-H_i(1-f_{\text{He/H}})/1.4}{1-H_j(1-f_{\text{He/H}})/1.4} \quad (10)$$

with

$$H_i = \frac{2A_i - Z_i - 1}{Z_i^2} \sqrt{\frac{A_i + 1}{A_i}} \quad (11)$$

Using $H_3=0.7$ and $H_4=1.4$ one obtains for the extreme case $f_{\text{He/H}}=0.5$ a fractionation effect of the order $f(3\text{He}/^4\text{He})=40\%$. This would roughly correspond to the difference between fast and slow solar wind reported by Gloeckler and Geiss.
(1998) but it is significantly higher than the intrinsic variability in slow solar wind as derived from the Apollo foils. Hopefully, the Genesis mission, which very recently returned long-time exposed targets from slow and fast solar wind, will shed more light on this issue.

![Graph](image)

**Figure 4**: Mg isotopes have been routinely measured in the solar wind with isochronous mass-spectrometers on WIND, SOHO and ACE since 1994. Mg is particularly interesting because it has three easily detectable stable isotopes, which have presumably identical solar abundances as does terrestrial and meteoritic matter.

Magnesium has three stable isotopes, all of them with relative abundances of more than 10% of the total. It is relatively easy to distinguish the different isotopes from each other in the isochronic time-offlight mass-spectrometers flown on WIND, SOHO, and ACE. From expression (10) one can estimate the Coulomb-drag-related isotopic fractionation effect for a medium mass element such as Mg and finds for a typical ionic charge Z=10 and an extreme value $f_{\text{drag}}=0.5$ a correlated isotopic effect of the order of 5% per mass unit is possible. Such a strong effect can probably be excluded on the basis of existing information (Kallenbach et al. 1998). In fact, these authors conclude that the fractionation amounts to $(1.4 \pm 1.3)\%$ (2σ uncertainty) per amu.

Wave-particle interaction plays apparently a less important role in elemental (and isotopic) fractionation than inefficient Coulomb-drag. If wave action were responsible for fractionation, one would expect a Z/A-dependency in the observable effects. This ratio amounts to 0.5 in the case of the notoriously depleted $^4\text{He}^+$, and it is unfavourably low in the case of Fe$^{10+}$. $Z/A < 0.2$. There is no evidence for a correlated decrease, e.g. of the Fe/Mg ratio with the low He/H ratios observed in interstream solar wind in the Ulysses/SWICS data (von Steiger et al. 2000).

From this, we have no reason to attribute an important contribution of inefficient wave-particle interaction to the observed fractionation effects.

6. **ISOTOPIC FRACTIONATION DUE TO GRAVITATIONAL SETTLING THROUGH THE OUTER CONVECTIVE ZONE/RADIATIVE ZONE BOUNDARY**

A final point needs to be addressed for a conclusive comparison of contemporaneous solar wind with the composition of the protosun 4.6 Gya ago. After the ignition of hydrogen in the solar core, the solar interior became convectively stable. It is generally assumed that the outer convective zone remained practically unaffected in its isotopic composition throughout the solar lifetime, except for a few sensitive nuclei such as D and $^7\text{Li}$. However, it is also known from helioseismological observations that a slow elemental fractionation process occurs between the OCZ and the radiative zone. Helium becomes gradually depleted by gravitational settling through the OCZ/radiative boundary, by typically 10% over the solar lifetime. Such an effect must inevitably also affect the isotopic composition of the OCZ with respect to its original composition. On the basis of models by Turcotte et al. (1998), Bochsler (2000) found an effect of the order of 3% for the $^3\text{He}/^4\text{He}$ ratio and of about 0.5% per mass unit for the oxygen isotopes. Although these effects appear tiny in the view of other fractionation effects, especially comparing fast and slow solar wind, they have to be considered for geochemical applications as the natural spread of oxygen isotopic abundances among different solar system samples varies by the same order of magnitude. Turcotte and Wimmer-Schweingruber (2002) have recently carried out another investigation and came essentially to similar conclusions.

7. **SUMMARY AND CONCLUSIONS**

From the case of He/H variability in the solar wind and from the bias of the average He/H abundance ratio towards a value, which is about a factor of two lower than the generally assumed photospheric value, it is clear that elemental fractionation occurs in the solar wind feeding and acceleration process. We have made an attempt to assess the various contributions to fractionation and their criticality for isotopic fractionation:

- Ionization effects are probably responsible for the continuously observed depletion of helium relative to hydrogen. Since, these effects are atomic in nature, we do not expect that
isotopic abundances are noticeably affected, e.g. in coronal hole associated solar wind, which exhibits a stable bias of He/H.

- Inefficient wave-particle interaction seems equally unimportant for isotopic effects since there is no isotopic signature observed in heavy element abundances.

- Inefficient Coulomb-drag could be responsible for the depletion of He relative to H in interstream solar wind, especially near current sheets. Such an effect would also affect isotopes. From the observations we conclude that this effect amounts to less than 3% per amu for the medium mass elements (O, Ne, Mg, etc.) and to 20% for the \(^3\)He/\(^4\)He ratio.

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