PROCESSES AFFECTING ABUNDANCES IN THE SOLAR WIND*

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Abstract. Data on composition in the solar wind are summarized and compared with best estimates of abundances in the outer convective zone of the Sun. Several mechanisms of element and isotope fractionation are discussed in relation to observed abundances and their variations.

The evidence available so far indicates that in addition to ion fractionation in the corona there is a separation mechanism operating at low solar altitude that affects solar wind composition. It is suggested that the systematic depletion of helium observed in the solar wind is in part caused by ion-neutral separation in the chromosphere-transition zone. Conditions for this mechanism to be effective are discussed. It is shown that ion-neutral separation is much more pronounced than ion-ion separation under these conditions. Therefore, this mechanism should fractionate elements according to the rate at which first ionization occurs. This implies that isotope fractionation by this mechanism is minor.

Ion-neutral separation may be responsible for the general depletion that is observed in the slow interstream solar wind as well as in the fast streams coming out of coronal holes. However, the occurrences of very low He/H ratios are probably caused in the corona.

1. Introduction

Models of solar wind acceleration indicate that Coulomb friction can be adequate to pull helium and heavier elements out of the gravitational field of the Sun (Geiss *et al.*, 1970; Joselyn and Holzer, 1978; Borrini and Noci, 1979; McKenzie *et al.*, 1979). Thus, these models offer an explanation for the main trends in the observation of solar wind composition:

(1) Helium is usually present, but the frequent occurrences of low He/H ratios indicate that coupling between helium and the proton-electron gas is often marginal.

(2) The occurrence of heavier elements (i.e. O, Ne, Si, Ar, and Fe) with roughly solar abundances (Bame *et al.*, 1975; Geiss *et al.*, 1972) can basically be understood in terms of models that include Coulomb friction. In the corona, these elements rapidly attain high ionic charges, giving them a ratio of Coulomb collision cross-section to weight ($\propto Z_i^2/A_i$) that is higher than this ratio is for helium.

The qualitative agreement between some of the general observations and the predictions of models of solar wind acceleration that include Coulomb collisions does not preclude that other factors affect the abundances in the solar wind. One such factor, the energy or rate of first ionization has been mentioned occasionally (Arrhenius and Alfvén, 1971; Geiss, 1972). In this paper, we review solar wind abundances and discuss whether they are different from the abundances in the outer convective zone of the Sun. We show that it is difficult to explain the observed systematic depletion in the He/H ratio by coronal separation processes alone, and we explore whether retardation in the ionization of helium relative to hydrogen contributes to the general depletion of this element in the solar wind.

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2. Abundances of the Helium Isotopes in the Sun and the Solar Wind

In the solar wind, the abundance ratios most extensively investigated are ^{4}He/H and ^{3}He/^{4}He. Neugebauer (1981) has recently published a thorough account of the ^{4}He in the solar wind, its time variation, and the relation of the ^{4}He/H ratio to other solar wind parameters and to observations in the corona. In the low speed solar wind, ^{4}He/H is highly variable with average values of ≤ 0.04 (Robbins *et al.*, 1970; Ogilvie, 1972; Feldman *et al.*, 1977; Neugebauer, 1981a). Since the low speed solar wind probably comes from regions in the lower corona with complicated magnetic field structures, it is very difficult to model the geometric and thermodynamic situation in the source region.

The flux geometry in coronal holes appears to be less complicated. In the high speed wind from these holes, Bame *et al.* (1977) reported

$$(^4\mathrm{He/H})_{\mathrm{SW,\ CH}} = 0.048 \pm 0.005\,. \tag{1}$$

The remarkable constancy in time of the ^{4}He/H ratio and its reproducibility in different coronal holes suggested to Bame *et al.* (1977) that, after all, 0.05 might be the true solar helium/hydrogen abundance ratio.

Estimates of the solar helium abundance, usually giving He/H ~ 0.1, are certainly not precise enough to exclude a ratio of 0.05. However, in recent years, helium abundances have been determined with relatively high precision in a variety of galactic and extragalactic objects. The He/H abundance ratio is found to be remarkably constant, supporting the generally held view that helium is essentially primordial and that the He/H ratio in the interstellar gas of the galaxy has been changed only little by stellar nucleosynthesis. Audouze (1981) has recently reviewed the helium determinations and gives

$$(\mathrm{He/H})_{\mathrm{Primordial}} = 0.076 \pm 0.005\,. \tag{2}$$

Since there is no evidence for a helium/hydrogen fractionation in the formation process of the Sun, we adopt for the outer convective zone (OCZ)

$$\mathrm{He/H}_{\mathrm{OCZ}} = 0.08 \pm 0.01\,. \tag{3}$$

A possible small contribution by stellar production has been included in this value and the error estimate. Comparing (1) and (3), we conclude that ^{4}He is definitely depleted even in the high speed solar wind from coronal holes.

Geiss *et al.* (1972) have obtained for a total collection time of about five days during 1969–1972 an average solar wind ratio

$$(^3\mathrm{He}/^4\mathrm{He})_{\mathrm{SW}} = (4.3 \pm 0.3) \times 10^{-4}\,. \tag{4}$$

More recently, Ogilvie *et al.* (1980) evaluated 4334 mass spectra taken in 1978/79. From a broad distribution of individual ratios, they obtained a remarkably similar average of 4.7×10^{-4}.

Spectrographic estimates of the solar ^{3}He/^{4}He ratio are subject to large uncertainty. Thus, again we have to turn to non-solar observations for obtaining a solar value, bearing in mind that ^{3}He in the outer convective zone of the Sun is the sum of originally present D and ^{3}He (cf. Geiss and Reeves, 1972; Bochsler and Geiss, 1973). D/H has been determined in the dilute interstellar gas through Lyman absorption spectra. The most recent analyses by Laurent *et al.* (1979) and Bruston *et al.* (1981) give

$$(D/H)_{\text{Interstellar}} = (1 \textit{ to } 2.5) \times 10^{-5}\,. \tag{5}$$

If one allows for D destruction between the time of formation of the solar system and now, a somewhat higher ratio than (5) is indicated for the protosolar gas. Thus, we adopt

$$(D/H)_{\text{Protosolar}} = (2 \pm 1) \times 10^{-5}\,. \tag{6}$$

Direct determinations of the ^{3}He/^{4}He ratio in the interstellar gas are subject to large errors (cf. Rood *et al.*, 1979; Audouze, 1981). Thus, one usually resorts to measurements of the ^{3}He/^{4}He ratio in the planetary component of meteoritic helium (Jeffery and Anders, 1970; Frick and Moniot, 1977; Eberhardt, 1978) giving

$$(^3\text{He}/^4\text{He})_{\text{Meteoritic}} = (1.4 \pm 0.2) \times 10^{-4}\,. \tag{7}$$

Combining (2), (6), and (7), we obtain for the outer convective zone

$$(^3\text{He}/^4\text{He})_{\text{OCZ}} = (3.9^{+2.5}_{-1.5}) \times 10^{-4}\,. \tag{8}$$

The larger upper limit allows for a possible admixture of ^{3}He from the solar interior (cf. Schatzman and Maeder, 1981; Geiss and Bochsler, 1981). The derived value for the outer convective zone of the Sun is very close to the ratio (4) measured in the solar wind. The relatively large error of the OCZ estimate precludes any precise conclusion concerning helium isotope fractionation in the solar wind source region. Nevertheless, the similarity of the OCZ and SW ^{3}He/^{4}He ratios indicates that in the solar wind the two He isotopes might often be depleted by a similar factor. Such a similar depletion could hardly be expected to occur at the high temperature prevailing in the SW acceleration region. If, on the other hand, ionization rates affect solar wind abundances, a similar depletion of ^{4}He and ^{3}He would be a natural consequence.

3. Comparison of Elemental Abundances in the Solar Wind and the Outer Convective Zone

The evidence on the abundances in the solar wind of elements heavier than helium is still rather limited. Averages for elemental and isotopic abundances were summarized by Bochsler and Geiss (1976). In the present paper, we discuss primarily element ratios and ^{3}He/^{4}He, and in Table I we give averages for these ratios. For O, Si, and Fe only low speed data have been published so far. The averages given for Ne and Ar represent the results of 5 and 2 foil collection experiments with total collection times of 5 and 3 days respectively. Although the foil collections include some relatively short periods of solar wind at higher velocities, it is difficult to extract from these data information on a possible velocity dependence of the abundances. Thus, determinations of rare ions in high speed streams are still not available.

TABLE I

Comparison of measured solar wind abundances with best estimates of solar abundances

	Solar wind			Refs.	Outer convective zone	Refs.
He/H	0.04 ± 0.01	AV	1962–75	[1]	0.08 ± 0.01	[7]
He/H	0.048 ± 0.005	CH		[2]		
O/H	$(5 \pm 2) \times 10^{-4}$	LS	1969–72	[3]	$(6.9 \pm 2) \times 10^{-4}$	[8]
Si/H	$(7.6 \pm 3) \times 10^{-5}$	LS	1969–72	[3]	$3.9 \times 10^{-5}(1.7)$	[9]
Fe/H	$(5 \pm 3) \times 10^{-5}$	LS	1969–72	[3]	$3.4 \times 10^{-5}(1.7)$	[9]
Ne/He	530 ± 70	AV	1969–72	[4]		
O/Ne					7.5 ± 2	[10]
Ne/H	$(7.5 \pm 2.5) \times 10^{-5}$	AV	1969–72		$1.5 \times 10^{-4}(2)$	
Ne/Ar	41 ± 10	AV	1971–72	[5]		
Ar/H	$1.8 \times 10^{-6}(1.5)$	AV	1971–72		$4.3 \times 10^{-6}(2)$	[11]
$^3He/^4He$	$(4.3 \pm 0.3) \times 10^{-4}$	AV	1969–72	[4]	$\left(3.9 \begin{smallmatrix} +2.5 \\ -1.5 \end{smallmatrix}\right) \times 10^{-4}$	[12]
$^3He/^4He$	$(4.7 \pm 1.2) \times 10^{-4}$	AV	1978–79	[6]		

AV: Average of data, as available during the indicated period.
CH: Average observed in high speed streams from coronal holes.
LS: Low speed (interstream) solar wind data.
Numbers in parenthesis are uncertainty factors.

References:

[1] Neugebauer and Snyder (1966); Robbins *et al.* (1970); Ogilvie and Hirshberg (1974); Neugebauer (1981).
[2] Bame *et al.* (1977).
[3] Bame *et al.* (1975); Grünwaldt (1976).
[4] Geiss *et al.* (1970a, 1972).
[5] Cerutti (1974).
[6] Ogilvie *et al.* (1980).
[7] See text.
[8] Photosphere, Ross and Aller (1976).
[9] Based on abundance in Cl chondrites, Cameron (1980).
[10] H II regions, Meyer (1979).
[11] Interpolated by semi-equilibrium abundance method, Cameron (1980).
[12] See text.

Information on the variability of the abundances of elements heavier than He is still scarce. Geiss *et al.* (1972) found small but significant variations in the Ne/He ratio, Zastenker and Yermolaev (1981) reported large variations, particularly in the Si abundance, and Bame *et al.* (1979) showed that O/He and Fe/He in the interstream wind and in flare-expelled plasma are different. We shall return to these observed variations in Section 6.

For discussing possible differences between solar and solar wind composition, we give in Table I our best estimates of the abundances in the outer convective zone. For this purpose, we had, of course, to disregard determinations in the corona, solar wind or solar cosmic rays – data that are often included in the figures given in abundance compilations.

The elemental abundances and the $^3He/^4He$ ratio are plotted in Figure 1. So far, a significant difference between solar and average solar wind data is only established for the $^4He/H$ ratio.

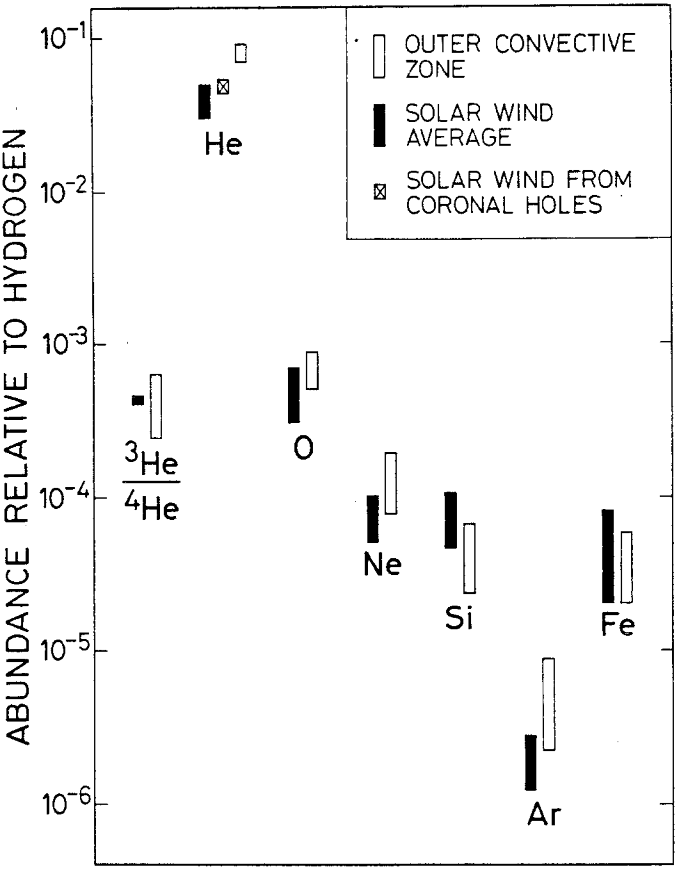

Fig. 1. Elemental abundances and the isotopic ratio ^{3}He/^{4}He as measured in the solar wind are compared to the abundances estimated for the outer convective zone of the Sun. Details on these estimates and references are given in Table I and in the text.

Meyer (1981) and Veck and Parkinson (1981) have derived from X-ray data an inverse relation between ionization potential and coronal abundance and the latter authors suggest that this is due to ambipolar diffusion. There is some indication for a similar trend in the solar wind data (cf. Figure 1), but if one considers the uncertainties in the abundances of *both*, solar wind and outer convective zone, it becomes clear that improved data are needed for firmly establishing such a relation.

Table I shows that, partly for technical reasons, some abundance ratios such as He/Ne, ^{3}He/^{4}He, or Ne/Ar are relatively well determined in the solar wind, whereas the best estimates for the outer convective zone exist for other ratios. An example of the latter is the O/Ne ratio which is remarkably constant in H II regions (Meyer, 1979), and thus apparently quite reliable. Determination of the elemental O/Ne ratio in the solar wind should be feasible by M/Q spectrometers because in a wide range of freezing-in temperatures the dominant fraction of these elements exists in the form of only three ions, O^{6+}, O^{7+}, and Ne^{8+}. These three ions are separable but still similar enough in M/Q and in abundance to allow a good comparison.

4. Difficulty of Ion Separation in the Flow out of Coronal Holes

At the present time, the source region of the low speed solar wind is not well identified, its geometric configuration is unknown, and it is not clear to what extent a steady-state approximation is valid. Thus, a variety of models can be constructed that, by a combination of thermal diffusion and insufficient Coulomb friction, can give any desired ^{4}He/H ratio. A thorough study of the abundances of several ions is probably needed before the low speed solar wind source region can be described with less ambiguity. The situation is better for the extended high speed solar wind streams that originate in coronal holes. Bame *et al.* (1977) have shown that characteristics such as speed, flux and He/H ratio of individual segments of high speed solar wind are identical and remarkably constant over several solar rotations. Moreover, as the authors point out, the flow is 'structure-free' within a high speed stream. Thus, the flow out of coronal holes observed during the 1973/1974 solar minimum appears to be the best example we have of a steady-state solar wind.

From a different point of view, the steady-state nature of the flow is demonstrated by comparing the time integrated flux from a coronal hole with the total plasma content in the corona and transition region of the hole. This comparison, as well as other quantitative estimates in this paper, we base on the coronal hole models of Munro and Jackson (1977) and on the model of the transition region below coronal holes given by Gabriel (1976), bearing in mind, of course, the considerable uncertainties in these models which are due to the scarcity of observational data.

The proton flux in fast streams of 3×10^8 cm^{-2} s^{-1} at 1 AU (Feldman *et al.*, 1976; Bame *et al.*, 1977) corresponds to a fluence of 1.5×10^{15} protons cm^{-2} for a two-month period. Taking the non-radial hole geometry of Munro and Jackson (1977) and Gabriel (1976) into account, we estimate that in a flux tube having a cross section of 1 cm^2 at 1 AU the proton content between the altitudes 3000 km (as given by Gabriel) and $5R_\odot$ is $\sim 1 \times 10^{13}$ protons, i.e. the reservoir between these two altitudes is emptied by the solar wind every 10 h. Thus, in a steady-state outward flow of protons, any pile-up of helium in this reservoir should manifest itself in an increase of the He/H ratio with a time constant of $\sim$ 10 h. Since such an increase is not observed and since inside the fast streams there is very little spatial structure in the speed and in the He/H ratio (cf. Bame *et al.*, 1977), the deficit in helium in the solar wind would have to be compensated by a helium return mechanism that is very smooth in space and time, if the gas supplied to the corona has the solar He/H ratio. These return conditions are difficult to fulfill once the helium is fully ionized: At higher altitudes, any return mechanism would have to overcome the outflow velocity, and it is difficult to see how this could take place without significant structure in space and/or time. At lower altitude (in the low corona and transition zone), thermal diffusion is quite effective in lifting He^{2+} ions upwards, as will be discussed below.

In the transition zone and low corona, the momentum equation can be approximated by the diffusion equation. We shall use here the diffusion equation for minor ions (A_i, Z_i) in a proton-electron plasma (cf. Burgers, 1969)

$$\Delta v_i = D_i \left\{ -\frac{\mathrm{d}\ln c_i}{\mathrm{d}z} + \alpha_i \frac{\mathrm{d}\ln T}{\mathrm{d}z} - A_i' \frac{\Gamma}{kT} + \frac{\Delta F_w}{kT} \right\} . \tag{9}$$

Vertical flow geometry as well as $T_i = T_e$ were assumed for simplicity. Δv_i is the difference between the velocities of the rare ions and the protons, and $c_i = n_i/n_p$ is the ion/proton number density ratio. D_i is the diffusion constant and α_i the thermal diffusion coefficient. $\Gamma = m_0 G M_\odot / r^2$ is the local weight per amu, and $A_i' = A_i - (Z_i + 1)/2$ is the 'effective mass number' which takes into account the weight reduction due to the charge separation E-field. ΔF_w stands for the difference between the forces on the ions and the particles of the main gas by other external fields and waves.

Under the assumption that ion-ion collisions are governed by the Coulomb potential $(1/r)$, the constants D_i and α_i can be derived from the formulae given by Burgers (1969) or Schunk and Walker (1969), giving approximately

$$D_i = \frac{6.6 \times 10^7\, T^{5/2}}{\mu_A{}^{1/2}\, Z_i^2 n_p} , \tag{10}$$

where μ_A is the reduced mass in atomic mass units. For $Z_i \geq 2$, a useful approximation is

$$\alpha_i = \frac{15}{8}(2\mu_A)^{1/2}\left(1 - \frac{1}{A_i}\right) Z_i^2 + \frac{4}{5} Z_i (Z_i - 1) \qquad (Z_i \geq 2) . \tag{11}$$

Both (10) and (11) are valid for rare ions in a p-e gas. However, for low ionic charge and high temperature deviations from the Coulomb potential at close encounters become important. In the temperature range considered here, $T \leq 10^6$ K, we estimate that this effect is small for He^+, He^{2+} and for the charge states $Z \geq 3$ of C, O, and Ne. Our estimates indicate that the Coulomb potential is still a fair approximation for $T \lesssim 7 \times 10^5$ K in the case of doubly charged and for $T \lesssim 2 \times 10^5$ K in the case of singly charged C, O, and Ne.

The diffusion equation (9) can be applied also to neutrals. Below, we shall be concerned with diffusion of helium atoms in a proton-electron gas. Classical collision theory should give a satisfactory approximation in the temperature range $T \leq 5 \times 10^4$ K that we shall consider (Massey, 1982). At long distance He° and H^+ are attracted by the induced dipol potential $(1/r^4)$. However, for energies of a few eV, the deviations from this potential at short range cannot be disregarded. Helbig *et al.* (1970) and Rich *et al.* (1971) give a potential for $\mathrm{He}^\circ\mathrm{H}^+$ which is based on scattering data at 4 eV and on theory. Using this potential, we have numerically calculated momentum transfer cross sections and obtained approximately

$$q_D(\mathrm{cm}^2) \approx 4.2 \times 10^{-16}\, T_4^{-1} \tag{12}$$

(T_4 is the temperature in 10^4 K).

This corresponds to a diffusion constant of

$$D_n = 1.14 \times 10^{21} \frac{T_4^{3/2}}{n_p}. \tag{13}$$

The magnitude of the thermal diffusion coefficient α_n for He° in a p-e gas should be much smaller than α_i for ions (cf. Chapman and Cowling, 1958; Burgers, 1969). We shall disregard here thermal diffusion of He° (cf. Shine *et al.*, 1975). However, for the steepest temperature gradients, this effect is probably not completely negligible.

For obtaining an explicit solution of the motion and concentration of a nuclear species, the diffusion equations (9) of its charge states have to be completed by a set of continuity equations. Since we want to discuss possibilities for element and isotope fractionation in a general way, we shall not aim at deriving solutions for particular models. Instead, we shall discuss types of separation processes which follow from the properties of Equation (9).

Equation (9) is applicable not only to a particular charge state of a nuclear species, but also to the sum of all its charge states, provided ionization and recombination are fast in relation to the rates of change in T and n_e experienced by the moving ions, i.e. provided there is local charge state equilibrium. Δv_i is then the bulk speed of the species, and D_i, α_i, and A_i' are suitable averages that are functions of the altitude z.

As has been shown by Delache (1965, 1967), Jokipii (1965), and Nakada (1969), steady-state solutions of Equation (9) with $\Delta F_w = 0$ lead to strong enrichment of heavier elements in the corona for the estimated steep temperature gradient in the transition zone of the quiet Sun (cf. Dupree, 1972). It has to be noted, however, that the temperature gradient in the transition zone below coronal holes is smaller than the quiet-Sun gradient (cf. Gabriel, 1976).

Abundance observations strongly suggest that diffusive equilibrium normally is not reached. This is not surprising since irregular motions appear to be faster than diffusion velocities. Still, a downward directed diffusion velocity of an element would lead to its depletion in the corona by a degree that would depend on the relative magnitude of diffusive and convective motions (cf. Nakada, 1969). Since a condition for such a net downward motion of a rare ion is $\Delta v_i < 0$ for $\mathrm{d} \ln c_i/\mathrm{d}z = 0$, we consider in the following the equation

$$\Delta v_i = D_i \left\{ \alpha_i \frac{\mathrm{d} \ln T}{\mathrm{d}z} - A_i' \frac{\Gamma}{kT} \right\} \tag{14}$$

which gives the drift velocity under the influence of temperature gradient and gravitation only. If the gas composition is initially homogenous ($c_i = \text{const}$), Equation (14) gives the *initial diffusion velocity*. Thus, it gives the direction of diffusive flow, showing whether the gas will move downward or upward relative to hydrogen.

The condition $\Delta v_i < 0$ in Equation (14) defines a 'critical temperature gradient'

$$T' < T_c' = \frac{A_i'}{\alpha_i} \frac{\Gamma}{k}. \tag{15}$$

TABLE II

The thermal diffusion coefficient α_i and the critical temperature gradient T'_c (Equation 15) at $r = R_\odot$ for ions considered in this paper. α_i was calculated after Schunk and Walker (1969).

Ion	α_i	T'_c (K km^{-1})	Ion	α_i	T'_c (K km^{-1})
$^3He^+$	1.4	47.0	O^+	2.4	206.0
$^3He^{2+}$	7.8	6.3	O^{2+}	11.2	43.0
$^4He^+$	1.7	58.0	O^{3+}	26.5	17.0
$^4He^{2+}$	8.7	9.5	O^{4+}	48.2	9.2
C^+	2.3	158.0	Ne^+	2.4	261.0
C^{2+}	10.9	32.0	Ne^{2+}	11.4	54.0
C^{3+}	25.8	13.0	Ne^{3+}	26.9	22.0
C^{4+}	47.0	6.7	Ne^{4+}	49.0	12.0
			Ne^{5+}	77.5	7.2

In Table II, we give α_i (Coulomb potential approximation) and the critical temperature gradient for ions of several elements (at $r = R_\odot$). According to Gabriel's (1976) model, the temperature gradient varies from >250 to 10 K km^{-1} in the transition region ($z \leq 30\,000$ km) of coronal holes, i.e. it is everywhere higher than the critical value given by (15) for $^4He^{2+}$. Thus, $^4He^{2+}$ tends to move upwards relative to hydrogen throughout this transition region. If we assume that the 'effective temperature' profiles given by Munro and Jackson (1977) in their Figure 7b correspond to ion temperatures, we obtain positive Δv_i for $^4He^{2+}$, even in the case of their lowest profile. We think that these examples indicate how difficult it is to construct a steady-state model which preferentially returns He^{2+} to the Sun.

In Figure 2 we have plotted the Δv_i for various ions as a function of altitude in Gabriel's (1976) transition zone model for coronal holes. Figure 2 allows two important observations which are rather independent of the details of Gabriel's (1976) model: (1) Δv_i is positive for He^{2+} over the whole altitude range considered. He^+ moves downward above 6000 km. However, for $z > 6000$ km, the ionization time for He^+ with Gabriel's (1976) T and n_e coronal hole parameters is less than 1 s. Thus, helium and for the same reason C, O, and Ne are not preferentially returned to the Sun by bulk downward motion in the temperature-density profile above 4000 km given by Gabriel (1976) for coronal holes. (2) For any temperature profile, O and Ne must be doubly charged to move with He^+, and they must be four times charged to behave like He^{2+}.

5. Incomplete Ionization, a Possible Cause for Element Depletion in the Solar Wind

It is likely that mass to the transition zone and corona is supplied inhomogenously, spicules and/or macrospicules being prime candidates (cf. Pneuman and Kopp, 1977). In Table III, we give some typical characteristics of spicules and macro-spicules as they have been summarized by Beckers (1972), Bohlin *et al.* (1975), Bohlin (1977) and Withbroe (1981).

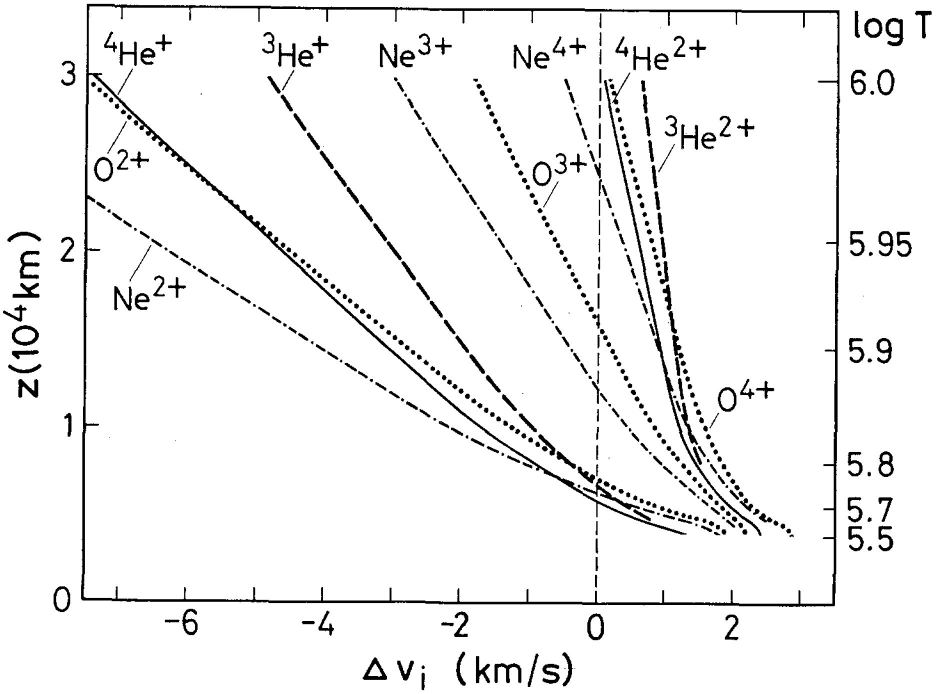

Fig. 2. Diffusion velocities of various ions relative to the main component H^+ in the transition zone below coronal holes (upward velocities are positive). The temperature and density profiles were taken from Gabriel's (1976) model.

TABLE III

Typical characteristics of spicules and macrospicules (cf. Beckers, 1972; Bohlin *et al.*, 1975; Bohlin, 1977)

	Spicules	Macrospicules
Length (km)	10000	20000
Width (km)	1000	7000
Number density (cm^{-3})	$10^{10} - 10^{11}$	
Apparent velocity ($km\ s^{-1}$)	25	$\lesssim 90$
Lifetime (s)	400	800
Time of free fall from top (s)	300	400

In the following, we shall discuss a general mechanism of helium depletion in the corona, using the picture of mass supply by spicules whenever specifics are required: The gas moving upwards from the solar surface is dense and cold relative to the surrounding plasma (cf. the spicule models of Beckers, 1972), and at the outset it will be mainly in the neutral state. The degree of ionization of this gas is gradually increased due to UV irradiation from the surrounding and overlying plasma (cf. Beckers, 1972; Zirin, 1975), and due to collisions with the warming electron gas. In both processes, helium will be more slowly ionized than hydrogen. Later, e.g. when the spicule collapses at the end of its lifetime, remaining gas returns to the Sun whereas at least a fraction of the ionized gas is supplied to the transition zone and corona. This ionized gas will have a reduced He/H ratio because the returned neutral gas is enriched in helium. It is clear that this mechanism requires return of some material at a fairly low temperature, i.e. at $T \lesssim 3 \times 10^4$ K.

The models of physical conditions in spicules given by Beckers (1972) that include ionization by UV and electrons give He^+/H^+ ratios of $\lesssim 60\%$ of the element ratio, as long as the temperature remains $\lesssim 20\,000$ K. Beckers' (1972) models are equilibrium models, but since the lifetimes of spicules are only $< 10^3$ s and conditions are changing rapidly, we should also consider ionization rates. In Table IV, we give rates of ionization by UV for zero optical depth. We have adopted the figures given by Banks and Kockarts (1973) for H, He, O, and O^+ for quiet solar conditions at 1 AU. The rates for Ne were calculated from cross section data (Marr and West, 1976) and the quiet solar UV flux spectrum of Banks and Kockarts (1973). Quiet-Sun rates near the solar surface were calculated by multiplying the 1 AU rates with $(r/R_\odot)^2$. In coronal holes, X-ray and UV fluxes are reduced and the spectrum is modified in comparison to quiet Sun conditions (Huber *et al.*, 1974; Reeves, 1976; Bohlin, 1977; Withbroe, 1981). Coronal lines from ions that exist at temperatures $\gtrsim 10^6$ K are strongly suppressed, whereas the intensity of chromospheric and transition zone lines are reduced by only 25–30%, with the exception of the He II emission which is decreased by about 50% (cf. Bohlin, 1977; Withbroe, 1981). We have used the available information for adapting the ionization rates at $1R_\odot$ to the UV spectrum in coronal holes. The results are given in the third line of Table IV, the corresponding ionization times in the last line.

TABLE IV

UV ionization rates for zero optical depth. The last line gives ionization times for coronal hole conditions at $1R_\odot$

Condition	Distance	Units	H	He	O	O^+	Ne
Quiet Sun	1 AU	$10^{-8}\,s^{-1}$	5.5	4.2	17	8.5	13
Quiet Sun	$1R_\odot$	$10^{-3}\,s^{-1}$	2.5	1.9	7.9	3.9	6.0
Coronal Hole	$1R_\odot$	$10^{-3}\,s^{-1}$	2.1	1.1	5.3	1.8	3.2
Ionization time		s	480	910	190	560	310

Beckers (1972) has reasoned that UV radiation below 504 Å, the ionization limit of He, can penetrate to the center of spicules. But for longer wave lengths, we cannot exclude appreciable attenuation. However, in the material near the sides and the top of the spicules, the rates for zero optical depth may still serve as a guide to relative ionization rates, especially when species with similar ionization potential are compared.

Table III and IV allow us to make the following observations: (1) Ionization by UV may well be significant (cf. Zirin, 1975): the number of photons capable of ionizing helium that are leaving coronal holes is $\sim 10^2$ times larger than the number of leaving helium ions. (2) Ionization by UV of spicular material should be significant because UV ionization times are comparable to spicule lifetimes (Table III). (3) Among all the elements, helium is most slowly ionized by UV (for zero optical depth). At any depth, ionization by UV of He is slower than of Ne, and ionization by UV of O is faster than of H. (4) UV is insignificant for producing He^{2+} and Ne^{2+}. Production of O^{2+} by UV could only be significant (cf. Table IV) if the gas is maintained for some time at $(1-2) \times 10^4$ K.

If the UV radiation field is negligible, and if collisional ionization and recombination are in equilibrium, H and He are ionized at ~ 15000 and ~ 25000 K, respectively, i.e. there is a relatively small temperature difference. However, the appropriate parameter to consider here is the enthalpy, i.e. the heat that must be supplied (at constant pressure) to get partial ionization of an element. If we assume equilibrium between collisional ionization and recombination, the enthalpy per atom of a gas of solar composition with an initial temperature of 5000 K must be increased by 3.5 eV for 10% of H to be ionized, and by 22 eV for obtaining 10% ionization of He. Thus, when the gas is heated up, there is a large interval in which hydrogen is partly ionized but the He^+/H^+ ratio remains low.

We still need to discuss whether there are processes that can sufficiently separate neutrals from ions. Several authors have recognized the potential importance of diffusion on EUV line intensities (Tworkowski, 1975; Shine *et al.*, 1975; Meyer and Nussbaumer, 1979; Roussel-Dupré, 1980). Shine *et al.* (1975) have studied helium diffusion in the quiet-Sun transition zone by solving the time dependent one-dimensional diffusion equation with collisional ionization and recombination as source and sink terms. They find appreciable abundance changes at altitudes of a few hundred km after only 100 s. However, outflow is not considered in their work.

We shall discuss here the problem of separation between neutrals and ions in a general way, and try to derive some relations that are not restricted in their applicability to a particular configuration. A significant fraction of helium will remain neutral only for $T \lesssim 3 \times 10^4$ K. At such low temperatures, ion diffusion velocities are small even for large temperature gradients. If we consider the extreme case in which diffusion is essentially driven by the thermal gradient, we observe (cf. Equation (9)) that in a proton-electron gas the Δv_i's for all heavier ions ($A \geq 3$) are the same within a factor of about 2:

$$\Delta v_i \approx 1.5 \times 10^{-2} \frac{T^{5/2}}{n_p} \frac{\mathrm{d} \ln T}{\mathrm{d}s} \tag{16}$$

(Δv_i in km s^{-1}, ds in km, n_p in cm^{-3}).

This results from the fact that the diffusion constant is proportional to $1/Z_i^2$ and the thermal diffusion coefficient roughly proportional to Z_i^2 (cf. Equation (10) and (11)). The similarities of Δv_i's are also apparent at the lowest altitudes in Figure 2.

For the downward drift velocity of neutral helium, under the influence of gravity, we obtain from (9) and (13)

$$\Delta v_n(\text{km s}^{-1}) \approx 1.5 \times 10^9 \frac{T_4^{1/2}}{n_p(\text{cm}^{-3})}. \tag{17}$$

In order to compare the magnitudes of the downward velocity of He° with the diffusion velocities of the ions in the direction of the positive temperature gradient, we take $T \lesssim 3 \times 10^4$ K and assume that the scale height of T is not smaller than 50 km. Then we obtain from Equation (16)

$$\Delta v_i(\text{km s}^{-1}) \lesssim \frac{5 \times 10^7}{n_p(\text{cm}^{-3})}. \tag{18}$$

Equations (17) and (18) allow some general inferences: (1) Parallel to **B**, the separation velocity between neutral helium and the plasma is nearly two orders of magnitude larger than the relative velocities between ions of different mass and/or charge. Thus, ion-neutral separation will dominate over ion-ion separation under the circumstances discussed here. Perpendicular to **B**, the dominance of neutral over ion diffusion is even more pronounced. (2) If the time available for separation is of the order of the lifetime of spicules (~ 500 s), we obtain for $T_4 = 3$ a neutral-ion displacement s (km) = $130 \times 10^{10}/n$ (cm^{-3}). Parallel to **B**, a displacement of a few hundred km is probably needed for having a significant separation of ions and neutrals. Thus, if we have diffusive separation only under the influence of gravity and the thermal gradient, the proton number density should be $< 10^{10}$ cm^{-3}. Perpendicular to **B**, diffusion of neutrals over shorter distances could lead to an effective separation, i.e. the limit on the density would be higher. (3) Separation could be helped by fields and waves that act on the charged particles and not on the neutrals. However, for making a significant contribution, and thus for increasing the upper limit on the density, such additional forces need to impart an acceleration to the plasma that is at least of the order of magnitude of the gravitational acceleration (cf. Equation (9)). In this case, neutral-ion separation will be much stronger again than the separation between different ions, because even parallel to **B**, the diffusion constant at $T \lesssim 3 \times 10^4$ K for He° is larger than for all ions by a factor of $> 10^2$ (cf. Equations (10) and (13)).

6. Conclusions

Observations of differences between the composition in the Sun and the solar wind, and of time variations of solar wind abundances indicate that element and isotope fractionation is not the result of one process, but that probably several mechanisms have to be distinguished.

6.1. QUASI-STEADY-STATE FRACTIONATION IN THE CORONA

The strong variability of He/H in the low speed solar wind, and the observation that average element depletion does not seem to be a function of atomic mass (cf. Figure 1), can be explained by models in which coupling between the ions is accomplished by Coulomb interaction. Geiss *et al.* (1970) have concluded that the relevant coupling parameter in the solar wind acceleration region is Z_i^2/A_i'. Furthermore, they showed that this parameter has to be modified when thermal diffusion (again a Coulomb collision effect) is taken into account; and that this effect, however, is not very significant in the flat temperature profiles that are inferred for the solar wind acceleration region.

If for an ion species Coulomb friction is insufficient, it will accumulate in the lower part of the acceleration region. Such a *dynamic accumulation* should be most pronounced for ^{4}He, because among the ions of the elements He to Fe existing at $T > 10^6$ K, $^4\mathrm{He}^{2+}$ has the lowest Z_i^2/A_i'.

We may consider *dynamic accumulation* and *static stratification* as limiting cases of ion separation mechanisms in the corona. *Static stratification* obtains when the local bulk speed is low enough for diffusive equilibrium to be reached. If the temperature gradient is smaller than the critical gradient T_c' (Equation (15)), ions are stratified with concentration scale heights proportional $1/A_i'$ (from Equation (9) with $\Delta v_i = 0$), i.e. protons are enriched at high altitudes relative to all other elements. The small negative temperature gradient that exists above the temperature maximum in the corona tends to accentuate the proton enrichment.

Recently, Borrini *et al.* (1981) have demonstrated that minimal He/H ratios coincide with sector boundaries. They suggest that these low helium abundances could be caused if the velocities of H and He in streamers begin to be *relatively* similar only at rather high altitude, i.e. if solar wind acceleration in streamers effectively starts from the upper levels of a stratified corona. If this is *static stratification* in the sense described above, we would expect an *overabundance of H* relative to the other elements in the escaping gas.

6.2. NON-STEADY-STATE EFFECTS

Occasionally, solar wind plasmas with very high helium abundances (He/H $\gtrsim 0.15$) are observed (Robbins *et al.*, 1970; Hirshberg *et al.*, 1970; Bame *et al.*, 1979). The latter authors have identified some of these solar wind samples as flare expelled plasma. The anomalously high helium abundance can be explained (Hirshberg *et al.*, 1970; Hundhausen, 1972) by the high local He/H density ratio that resulted from *dynamic accumulation* or *static stratification* prior to the flare. Bame *et al.* (1979) found that O and Fe are much less enriched than He in the flare-expelled plasma, relative to the interstream solar wind. This may indicate that the high He abundance in this plasma is – at least partly – due to *dynamic accumulation.*

6.3. ANOMALOUS ^{3}He ENHANCEMENTS

Bame *et al.* (1968) and Grünwaldt (1976) observed some occurrences of high ^{3}He abundance with $^3\mathrm{He}/^4\mathrm{He}$ ratios of $\sim 2 \times 10^{-3}$, i.e. a 5-fold increase above the average (cf. Table I). Ogilvie *et al.* (1980) have confirmed these observations with a mass spectrometer and found among their evaluated spectra 6% with $^4\mathrm{He}/^3\mathrm{He} \leq 600$. The event studied by Grünwaldt (1976) is particularly relevant. For a period of two days, $^3\mathrm{He}/^4\mathrm{He}$ was $\sim 2 \times 10^{-3}$ while H : He : O was quite normal. Obviously it is hard to explain these observations with a steady-state Coulomb friction model, even if one includes thermal diffusion. On the other hand, in view of its duration, this event cannot be dismissed as a strange transient. Possibly, ^{3}He enhancements in the solar wind are caused by a mechanism which is similar to the one causing the ^{3}He enhancements in flares (cf. Fisk, 1978), only that the solar wind mechanism is much weaker.

6.4. INCOMPLETE IONIZATION

There are three observations that point towards ion-neutral separation as a possible mechanism affecting solar wind composition: (a) Studies of Meyer (1981) and Veck and Parkinson (1981) indicate that corona abundances are related to the first ionization potential ϕ_I. They suggest that elements with $\phi_I \gtrsim 9$ eV have low abundances relative to hydrogen. (b) The steady, systematic helium depletion in the solar wind from coronal holes is difficult to explain by ion separation in the acceleration region (Section 4). (c) The average ^{3}He/^{4}He ratio in the solar wind is very close to the ratio inferred for the outer convective zone; the latter is, however, subject to a rather large uncertainty (cf. Table I and Figure 1). A similar reduction of ^{3}He and ^{4}He is not expected from separation processes in the corona, but it would naturally result from separation processes that depend on incomplete ionization.

In Section 4, we have discussed the circumstances under which ion-neutral separation could take place. We give limits on temperature and density above which the separation mechanism becomes ineffective. These limits are valid for various geometries in which the mechanism might operate, e.g. in or around spicule-like features or in a flat surface. We have shown that ion-neutral separation is more effective than ion-ion separation at temperatures low enough for the partial survival of neutral atoms. Thus, this mechanism would primarily separate according to the fraction of the species that is ionized at moderate temperature. Separation of ions with different mass or charge states would be less important. Of all the elements, helium would be most affected in this process, whether ionization is primarily by electron collision or by UV. Other elements might also be depleted in relation to the rate at which they become ionized. If ionization is primarily by electron collisions, depletion would most likely occur for He, Ne, and Ar. Abundance *enhancements* relative to hydrogen could result for elements with low ionization potential, e.g. Mg, Si, Fe; and also C, if ionization is by electron collisions. Isotopic fractionation as a result of this process should be small.

The ion-neutral separation mechanism could operate inside and outside coronal holes, and it is difficult to estimate where He/H separation would be more effective. We suggest, however, that the occurrences of very low He/H ratios in the solar wind are not primarily due to this mechanism, but that they are caused in the corona.

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