ABUNDANCES OF CARBON, OXYGEN, AND NEON IN THE
SOLAR WIND DURING THE PERIOD FROM AUGUST 1978 TO
JUNE 1982

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(Received 2 July, 1985)

Abstract. From four years of data provided by the Ion Composition Instrument on ISEE-3, we have derived
flux ratios of minor elements in the solar wind and found He/O = 75 ± 20 and Ne/O = 0.17 ± 0.02. These
results are compared with recent solar energetic particle composition data and photospheric values, and
they are discussed in the light of theoretical models of ionization and acceleration of heavy ions in the solar
chromosphere and corona.

1. Introduction

The understanding of physical mechanisms shaping the abundance pattern of elements
in the solar wind is strongly linked to the availability of continuous records of
abundances of some elements. A continuous record of helium abundances exists for
nearly two solar cycles (Robbins et al., 1970; Neugebauer, 1981a, b), and as a con-
sequence this has led to remarkable progress in the interpretation of phenomena
occurring in the corona and in interplanetary space (e.g., Gosling et al., 1981; Borrrini
et al., 1981, 1982, 1983). More recently, a continuous record of 3He/4He ratios has
become available (Coplan et al., 1983, 1984), and from this it was possible to statistically
deduce several long-time properties of this ratio in the solar wind such as persistence
times and to investigate long-time correlations of this ratio with relevant physical
parameters in the solar wind.

In the past, the number of determinations of fluxes of elements heavier than helium
has been limited and restricted to periods of slow and cool solar wind as is for instance
typical for the driver gas following interplanetary shocks (Bame et al., 1970, 1975;
Fenimore, 1980). A few precise measurements of helium, neon, and argon abundances
in the solar wind have been obtained by means of the foil collection technique during
the Apollo missions (Geiss et al., 1972; Cerutti, 1974). More recently, it has been
demonstrated that rather reliable oxygen abundances can be derived from the M/Q
spectra provided by the Ion Composition Instrument on ISEE-3 (K. W. Ogilvie,
Principal Investigator) under most conditions in the solar wind (Kunz et al., 1983;
Bochsler, 1984). For a few cases, neon abundances have also been reported with this
instrument (Kunz et al., 1983). In addition, a fairly large set of iron-abundance determi-
nations exists for high speed solar wind (v > 600 km s⁻¹) during the period from 1972
to 1976 (Mitchell et al., 1983).

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The relatively few previously published measurements of O/H ratios in the solar wind (Bame et al., 1970, 1975; Kunz et al., 1983) have shown that the oxygen abundances are not very far from photospheric values (within a factor of 3). Although it is not clear whether detected differences within the set of measured O/H ratios are significant, it has been demonstrated quite clearly that Fe and Si abundances vary significantly even under quiet conditions, and it appears that Fe/H and Si/H are correlated with each other (Bame et al., 1975). The observation of a significant decrease of the Fe/H ratio in high speed streams, correlated with the He/H decrease during the decline of solar cycle 20 reported by Mitchell et al. (1983), corroborates the reality of variations of heavy element abundances in the solar wind.

From a small number of mass spectra, Kunz et al. (1983) obtained neon/oxygen ratios consistent with the values of the local galactic medium (Meyer, 1979). Variations in this ratio could not be detected because of relatively large instrumental uncertainties.

Clear evidence for variations in the He/Ne ratio has been obtained from the Apollo foil experiments. There is a variability of the order of 20% in this ratio, and although only five independent data points are available, a statistically significant correlation between the Ne/He and the $^{3}$He/$^{4}$He ratio has been found (Geiss et al., 1972). For two reasons, we expect that larger fluctuations occur in the solar wind than the 20% mentioned above. Since the Apollo values are time integrals over periods ranging from one hour to two days and with the typical persistence times of flux ratios of the order of a day (Coplan et al., 1984; Bochsler, 1984), it is expected that larger short time variations exist. Secondly, the Apollo foils were all exposed in the relatively short interval from 1969 to 1972 around the maximum of solar cycle 20. From the available data, it appears that the solar wind speed never exceeded 400 km s$^{-1}$ during the foil exposures and, hence, the flux ratios and their variations are typical for quiet solar wind flows. Therefore, it remains possible that these ratios change substantially under more extreme conditions.

As pointed out above, the ISEE-3 Ion Composition Instrument provides the opportunity and the resolving power to determine oxygen abundances under virtually all solar wind conditions. Moreover, when the instrument is operating in a high resolution mode, Ne/O ratios can also be determined in many cases. During the four years of operation of ISEE-3 near the libration point 1.5 million km upwind from the Earth, we have been able to obtain almost 50000 data points on the oxygen/helium ratio. In addition, in the interval from 3 January to 24 April, 1980, near the maximum of solar cycle 21, when the instrument was in its high resolution mode, we have derived approximately a thousand values for the Ne/O ratio. The purpose of this paper is to present these new data and to discuss them with special emphasis on long term properties of heavy element abundances. Furthermore, we compare averages with photospheric and coronal values, and we investigate correlations of the He/Ne and Ne/O ratios with other parameters in the solar wind.
2. Data Acquisition, Data Reduction, and Selection Criteria

2.1. Data Acquisition

The Ion Composition Instrument on board ISEE-3 has been described in detail elsewhere (Coplan et al., 1978; Kunz et al., 1983). The ion optic part consists of a stigmatic Wien filter and a hemispherical energy analyzer. The combined information on velocity and energy per charge can be used to produce mass per charge spectra. The resolution of the mass/charge ratio \( M/Q \) (full width half maximum) depends on the kinetic temperature of the solar wind; it is 30 under normal conditions. In order to optimize the time during which the instrument is collecting ions, in each measurement cycle a search is made for helium ions. In the mass channel near \( M/Q = 2 \) (\(^4\)He\(^{++}\)), the instrument searches in the velocity range from 301 to 621 km s\(^{-1}\) for the velocity at which the maximum count rate is observed. In the next step, the instrument scans in a given range centered about the velocity found in the search mode and in a given \( M/Q \) range for solar wind ions. Data described and interpreted here have been obtained in two ways somewhat differing from each other. In the period from 3 January through 24 April, 1980, a high-resolution mode with a step width \( \Delta(M/Q)/M/Q \) of 1.35\% was applied operating in the range from \( M/Q = 2 \) to 3 covered by 31 logarithmically spaced steps. Most of the time the instrument was in the low-resolution mode with a step width of 3.6\% in the range from \( M/Q = 1.4 \) to 5.8.

Figure 1 shows in the upper part a spectrum which was acquired in the high-resolution mode. It is apparent that C\(^5+\) can be resolved from O\(^7+\) and that even the contribution of Ne\(^8+\) is visible on the left side of the O\(^6+\) peak.

In the lower part of Figure 1, we show the same spectrum as it would appear in the low-resolution mode (which covers a wider mass range and has a better time-resolution). Now C\(^5+\) only appears in a characteristic shoulder on the right side of the O\(^7+\) peak.

2.2. Data reduction

A least-square scheme was used in order to determine abundances of ions as functions of measured count rates CTS. Here, we write the flux of an ion \( \phi_i \) as a product of the bulk flux \( \phi \), the fractional abundance of the respective element \( A_{EL} \), and the fraction of this element in the ionization state 'ION', \( X_{ION,EL}(T) \) which is a function of the equilibrium freezing-in temperature \( T \) in the solar corona (Hundhausen et al., 1968; Bame et al., 1974; Kunz et al., 1983):

\[
\phi_i = \phi A_{EL} X_{ION,EL}(T). \tag{1}
\]

Our instrument has a response function for each ion species described by the function \( S_{ION}(m, n, u, T_k) \) which depends on the setting of the instrument (mass channel \( m \), velocity channel \( n \)) and the properties of the ion (essentially on the mass per charge ratio \( M/Q \) of the ion), its bulk speed \( u \) and the kinetic temperature \( T_k \). The count rate produced by the ion 'ION' of the chemical element 'EL' will thus be

\[
C = \phi A_{EL} X_{ION,EL}(T) S_{ION}(m, n, u, T_k). \tag{2}
\]
Fig. 1. Mass spectrum observed on 13 February, 1980. (a) The full line shows the spectrum as it was observed in the high-resolution mode, the dashed lines give the contributions from single ion species as computed with our evaluation procedure for high resolution spectra. (b) shows for comparison how the above spectrum would appear in the low-resolution mode.
The sum of these count rates at a given instrument setting \( m, n \) has to be compared with the observed count rate \( CTS(m, n) \).

The summation of residuals is performed over the matrix of \( m \) and \( n \) settings delimited by \( m_1, m_2 \) and \( n_1, n_2 \):

\[
F = \sum_{m = m_1}^{m_2} \sum_{n = n_1}^{n_2} \frac{(CTS(m, n) - \phi \sum_{EL} A_{EL} \sum_{ION} X_{ION, EL}(T) S_{ION}(m, n, u, T_k))^2}{(DCTS(m, n))^2} = \min.
\]

(3)

\( DCTS(m, n) \) is the estimated uncertainty of the observed count rate at the position \( m, n \). This uncertainty includes statistical fluctuations arising from a Poisson process producing a count rate with constant mean, and if significant, fluctuations of this mean due to variations of solar wind parameters with time.

The free parameters for the minimization of \( F \) are the abundances of the chemical elements \( A_{EL} \) and the equilibrium freezing-in temperature \( T \), which determines the fractional ionic abundances \( X \). Practically, the kinetic temperature \( T_k \) and the bulk speed \( u \) are derived separately from helium measurements as will be discussed in the following.

For a given value \( T \), the functions \( X_{ION, EL}(T) \) can be determined from a compilation such as the one by Shull and van Steenberg (1982), and the only remaining unknowns are the values \( A_{EL} \). Since in this case the unknowns are linearly related to the observed count rates \( CTS(m, n) \), the minimization problem (3) can be solved in a straightforward manner:

\[
\frac{\partial F}{\partial A_{EL}} = 0 \quad (EL = C, N, O, Ne, \ldots).
\]

(4)

This is a system of linear equations (one for each unknown \( A_{EL} \)); it can be solved with standard procedures. The solution of (4), however, can lead to negative abundances and, hence, constraints have to be imposed on the solution, e.g.

\[
A_{EL} \geq 0.
\]

(5)

We obtain an extraordinarily simple case if we assume the same freezing-in temperature \( T \) for all elements in a limited region of a spectrum and determine the flux of one dominating element only. Such an element is oxygen with \( O^6^+ \) and \( O^7^+ \) yielding at normal freezing-in temperatures of the order of 70\% of all ions in the \( M/Q \) range from 2.2 to 2.75. To a good approximation, there is not much \( O^8^+ \) or \( O^5^+ \) to be considered, and the assumption on \( T \) does not strongly influence the result.

An example is shown in the upper left panel of Figure 2. The lines connect points of equal height in the surface \( F \) which has been calculated for varying parameters \( T \) and oxygen density and the observed spectrum shown in Figure 1. The equidistance between two neighbouring lines is 33. There is an elongated minimum near \( T = 1.6 \times 10^6 \) K with a range of \( \pm 2 \times 10^5 \) K. The oxygen density does not depend on the choice of \( T \) in the investigated range.

Under normal conditions, it is thus possible to obtain reasonably good oxygen abundances simply by minimizing \( F \) in Equation (3) with respect to \( \phi \), keeping the
Fig. 2. For the high-resolution spectrum in Figure 1, the dependence of the function $F$ (Equation (3)) on various parameters is shown: (a) Oxygen density and freezing-in temperature, assuming a fixed chemical composition. (b) Carbon/oxygen ratio and freezing-in temperature. (c) C/O ratio and Mg/O ratio. (d) Ne/O ratio and freezing-in temperature.

abundances of elements different from oxygen in fixed ratios relative to oxygen. An erroneous assumption on the abundance of a minor element, say of carbon, of the order of 100% will cause a 15% error on the abundance of oxygen only. The obvious advantage of minimizing $F$ only with respect to one parameter $\phi$ is that $\phi$ can be calculated directly by deriving

$$\frac{\partial F}{\partial \phi} = 0,$$

$$\phi = \frac{\sum_{m=m_1}^{m_2} \sum_{n=n_1}^{n_2} CTS(m,n) \left( \sum_{EL} A_{EL} \sum_{ION} X_{EL,ION}(T) S_{ION}(m,n,u,T_k) \right)}{(DCTS(m,n))^2},$$

$$\sum_{m=m_1}^{m_2} \sum_{n=n_1}^{n_2} \left( \sum_{EL} A_{EL} \sum_{ION} X_{EL,ION}(T) S_{ION}(m,n,u,T_k) \right)^2 \frac{1}{(DCTS(m,n))^2},$$

a scheme which takes little computing time.
$^4\text{He}^{++}$ fluxes have been determined by fitting parabolae to the logarithmic velocity profiles at the mass channel corresponding to $M/Q = 2$. This simple procedure is justified because $^4\text{He}^{++}$ is by far the most abundant ion at $M/Q = 2$. Moreover, under normal circumstances $^4\text{He}^{++}$ is virtually the only occurring helium ion. From the fit taking the instrument function into account, flux, speed, and kinetic temperature of $^4\text{He}^{++}$ were obtained simultaneously.

We thus deal with three different data reduction procedures:
(a) Gaussian fit to velocity profiles at $M/Q = 2$ for $\phi(\text{He})$, $u(\text{He})$, and $T_k(\text{He})$.
(b) Searching for a minimum of a sum of squares $F$ (expression (3)) using a search algorithm (e.g., Gill et al., 1981) with several free parameters such as freezing-in temperature, oxygen and carbon abundances. This procedure was applied to approximately 6000 high resolution spectra (upper spectrum in Figure 1) using the counts from the central velocity channel only.
(c) Determination of the bulk oxygen flux (expression (6)) with all other parameters fixed. This method has been applied to approximately 50 000 spectra – most of them in the low resolution mode – using the available (normally seven) velocity channels $n$ of the scan cycle.

In the rest of this section, we shall discuss some specific features of the the last two evaluation procedures.

2.2.1. Evaluation of Bulk Oxygen Fluxes (Procedure (c))

Procedure (c) was applied to all available spectra using a fixed freezing-in temperature $T = 1.7 \times 10^6$ K. Since all available velocity channels were involved and since usually seven mass channels have been included in the evaluation, the value $\phi$ was derived from approximately 50 observed count rates. The errors caused by statistical fluctuations of count rates were mostly negligible. On the other hand, rather large errors in $\phi$ could emerge if the observed distribution CTS$(m, n)$ did not correspond to the simulated distribution which is the sum of all computed contributions $C$ (expression (2)). This happened in cases when large fluctuations in the solar wind speed occurred during one data acquisition cycle, or when the particle distribution in the real solar wind differed drastically from the simulated distribution which is based on the assumption of a drifting spherical Maxwellian. Drastic deviations produce large $F$-values in expression (3), and these are directly related to the error of $\phi$. An estimate of the error of $\phi$ is obtained from

$$\Delta \phi = \frac{2F}{\sqrt{\partial^2 F / \partial \phi^2}}.$$ 

Equation (6) requires information about the fractional abundances of elements $A_{el}$ other than oxygen. For the determination of oxygen fluxes from low resolution spectra, we have used the solar abundances as given in Table I. This does not imply that the solar wind has a constant chemical composition (see, e.g., Bame et al., 1975). However, since oxygen is the most important contributor in the $M/Q$ range considered, changes in the abundances of the other elements do not strongly influence the oxygen fluxes and O/He ratios obtained.
TABLE I
Solar elemental abundances in the range C to S used for the oxygen determination

<table>
<thead>
<tr>
<th>Element</th>
<th>Adopted for this work</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>C</td>
<td>63</td>
<td>60</td>
</tr>
<tr>
<td>N</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Ne</td>
<td>15*</td>
<td>19</td>
</tr>
<tr>
<td>Si</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Mg</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>S</td>
<td>1.9</td>
<td>2</td>
</tr>
</tbody>
</table>

* See Section 3.5 of this paper.

In expressions (2), (3), and (6), the response function $S$ depends on the kinetic temperature of the ions considered. It has been shown (Schmidt et al., 1980; Ogilvie et al., 1980; Bochsler et al., 1985) that in general, for heavy ions the kinetic temperature $T_k(i)$ describing the velocity distribution of the ion of the species $i$ is proportional to the mass of species $i$, $m(i)$:

$$T_k(i) \sim m(i).$$

(7)

Kunz et al. (1983) have used a generalized form of this rule introducing the parameter $\kappa$:

$$T_k(i) \sim m(i)^\kappa.$$ 

(8)

We have shown elsewhere (Bochsler et al., 1985) that for the data evaluated in this paper, the following linear relation holds:

$$\log T_k(\text{O}^6+) - \langle \log T_k(\text{O}^6+) \rangle =$$

$$= (0.904 \pm 0.003) [\log T_k(^4\text{He}^{++}) - \langle \log T_k(^4\text{He}^{++}) \rangle],$$ 

(9)

with the averages

$$\langle \log T_k(^4\text{He}^{++}) \rangle = 5.363, \quad \langle \log T_k(\text{O}^6+) \rangle = 5.978,$$

yielding an average $T_k(\text{O})/T_k(\text{He})$ ratio of 4.12. The correlation coefficient for the linear relation (9) is 0.84. For normal wave heated regimes, Equation (7) holds and $\kappa = 1$. On the other hand, there is also a number of cases (Schmidt et al., 1980; Bochsler et al., 1985) where solar wind plasma is in a collision dominated regime out to one astronomical unit ($0 \leq \kappa < 1$). The results of the evaluation procedure (c) discussed here are not very sensitive to changes of $T_k$ since all velocity channels are included in the evaluation thus covering a large fraction of the velocity distribution.

Expression (6) also contains the ion bulk speed $u$ as a parameter. We have assumed that heavy ions travel at the same speed as $^4\text{He}^{++}$ for which we have independent...
velocity determinations (procedure (a)). There is ample evidence that this assumption is correct under normal conditions (Ogilvie et al., 1982), and considering the wide range of velocities covered in procedure (c), the results are insensitive to small deviations from the above assumption.

In the case of the low-resolution spectra, a special procedure was used to correct for possible contamination of the O$^{7+}$ peak with 4He$^{++}$ which can become significant in periods of high kinetic temperatures. An extrapolation of the He peak by means of a parabolic fit was made. Whenever this extrapolation did not vanish in the channels of the O$^{7+}$ peak, a correction was applied to this peak. The error of this correction was assumed to be 100, probably a conservative estimate. Large errors in the O$^{7+}$ region will give less weight to this ion in the determination of the oxygen abundance relative to O$^{6+}$, and the large error will ultimately propagate into the error estimate of the final result.

2.2.2. Determination of Several Parameters by Minimization of a Sum of Squares (Procedure (b))

As has been mentioned in the listing of procedures, this data reduction scheme has only been applied to high resolution spectra (cf. Figure 1(a)) which contain sufficient information to derive several parameters. However, although in some cases the derivation of independent parameters is possible (e.g., freezing-in temperature $T$ and $n(O)$ as in Figure 2(a)), in other cases it is not (Kunz et al., 1983).

In the following, we discuss some specific features of solutions to such minimization procedures.

Figure 2(b) shows a contour plot of the surface defined by $F$ which has been evaluated for the spectrum from Figure 1 for a case of two free parameters, here the carbon/oxygen ratio and the oxygen freezing-in temperature. An unambiguous minimum is located near C/O = 1.1 and $T_e = 1.62 \times 10^6$ K. It is evident that acceptable C/O ratios exist only in the range of 0.5 to 1.5, whereas the range of possible freezing-in temperatures is from 1.5 to $1.8 \times 10^6$ K. Large C/O ratios combined with low freezing-in temperatures are strongly excluded as indicated by the steep slope to the upper left corner of the figure. There is a weak interdependence of possible solutions in $T$ and C/O.

A different case is shown in Figure 2(c). Here, C/O and (Mg + Si)/O ratios have been varied for the same spectrum. Since C$^{5+}$ is the only contributor of carbon in the investigated $M/Q$ range, and there is no way to distinguish C$^{5+}$ from Mg$^{10+}$, carbon can be substituted entirely by Mg$^{10+}$ which is the dominant magnesium ion (a constant Mg/Si ratio of 1.06 was assumed). Contour lines in this panel show the strong anticorrelation between Mg and C abundances which results from the possibility of substitution of C by Mg. Thus, additional information is required in order to determine a unique C/O ratio. In our evolution procedure, this ambiguity has been eliminated by relating the magnesium abundance to the abundance of oxygen, i.e., Mg/O was kept constant at 0.0576.

Figure 2(d) shows that for the same spectrum there is virtually no correlation between Ne/O ratios and freezing-in temperatures. This is, of course, due to the fact that in the
investigated temperature range neon is virtually completely in the form of Ne$^{8+}$ with a stable helium-like electron configuration. Moreover, for reasonably resolved spectra, Ne$^{8+}$ is practically the only possible contributor at $M/Q = 2.5$; hence, the appearance and detection of neon is independent of the freezing-in temperature. Therefore, it is possible to obtain neon abundances from the high-resolution spectra for a rather large variety of solar wind conditions.

If more than one abundance value has to be determined and especially if freezing-in temperatures are among the free parameters, in principle more than one solution to the minimization problem (3) can exist; i.e., $F$ has more than one minimum. In practice and under normal conditions, we have never observed more than one minimum of $F$.

2.2.2.1. Selection effects of procedure (b) on high resolution spectra. For spectra observed when high kinetic temperatures prevailed, it was sometimes difficult or impossible to resolve the $^4\text{He}^{++}$ peak from O$^{7+}$ (at $M/Q = 2.29$). In these cases, no freezing-in temperatures and no abundances of elements other than oxygen have been determined. For the determination of more parameters than the oxygen abundance only, we required that an extrapolation of a fit to the helium peak contributed less than 1% to the O$^{7+}$ peak. This requirement led to a substantial reduction in the number of spectra evaluated. Essentially, spectra of ions at high kinetic temperatures have been eliminated by this procedure, and since there is a strong correlation between speed and kinetic temperature.

Fig. 3. Contour plot of $^4\text{He}$ kinetic temperature $T_k$ versus speed for all spectra. The full lines show the distribution for those spectra which have been successfully evaluated with method (b). This comparison illustrates the effect of selecting spectra with well resolved $^4\text{He}^{++}$ and O$^{7+}$ peaks. Method (c) has no significant selection effect.
(Burlaga and Ogilvie, 1970), spectra with large bulk speeds were also preferentially excluded. This is illustrated in Figure 3 which shows a contour plot (dashed lines) of the frequency of occurrence of helium kinetic temperatures and speeds for the high resolution spectra and for which freezing-in temperatures and neon and C$^+5$ abundances were determined. Full lines in this figure show the frequencies of occurrence of the same parameters for the ultimately evaluated set of high-resolution spectra. The requirement of low helium background on the O$^+7$ peak is the only criterion which produced such a bias towards low temperature and low speed conditions. Other criteria which required that the speed did not move by more than one velocity channel or that spectra were complete, i.e., count rates were available in all mass channels of a spectrum, affected nearly all solar wind conditions equally. The same holds for spectra which were excluded for reasons of slow convergence of the chi-square minimization procedure. It is clear that the impact of rejection criteria and the loss of generality caused by the evaluation procedure (b) must be kept in mind when discussing these results.

It has been shown (Ogilvie, 1985) that a previously reported result of Ogilvie and Vogt (1980) concerning the variation of freezing-in temperatures of oxygen with bulk speed was in fact largely due to contamination of O$^+7$ by $^4$He$^++$ in the way described here.

It should be noted here that in our evaluation procedure (c) which consisted only in determining oxygen abundances for assumed freezing-in temperatures and fixed abundances of elements other than oxygen, no noticeable selection effects with respect to solar wind conditions resulted.

2.2.2.2. Choice of kinetic temperature values for high-resolution spectra. For the evaluation of high-resolution spectra which included only one velocity channel, the choice of the correct kinetic temperature is more important than for those cases involving all velocity channels. This is especially true for flux ratios involving elements with large differences in mass such as the He/O flux ratio. If we assume too low a temperature for the heavier species oxygen (choosing $\kappa$ too low in expression (8)), we will obtain too low a flux of the heavier element and, hence, too low an elemental ratio He/O. For low Mach numbers, i.e., low temperatures $T_k(\text{He}) \leq 10^5$ K, for which the angular acceptance of the instrument out of the ecliptic plane is not a limiting factor, the flux ratio of the elements with masses $m_1$ and $m_2$ will depend on the registered count rates for the two elements $C_1$ and $C_2$:

$$\frac{\phi_1}{\phi_2} = \frac{C_1}{C_2} \left(\frac{m_2}{m_1}\right)^{(1-\kappa)/2}.$$  \hspace{1cm} (10)

For our evaluation procedures, we have not determined $\kappa$ individually for each spectrum. For the evaluation of the oxygen data with procedure (c), we have assumed $\kappa = 1$. This assumption is justified since for the vast majority of data kinetic temperatures $T_k$ and number densities are in the range where the mass proportionality of $T_k$ is observed (Bochsler et al., 1985).
For the high-resolution data, due to the restrictive selection criteria, a strong bias towards low kinetic temperatures (Figure 3) and large fluxes resulted. Such conditions prevail in collision dominated regimes, and it is not surprising that the selected spectra have a characteristic collision time-scale \( \tau_c \sim T_k^{3/2}/n_p \) (Spitzer, 1962; Feldman et al., 1974) which is in general shorter by a factor of 2 to 5 compared to normal solar wind conditions in the same period. It should be noted that collision times tend to be shorter for heavier ions due to the \( M/Q^2 \) dependence of Coulomb interaction which can cause thermalization of the plasma in interplanetary space (Spitzer, 1962). Correspondingly, the ratio of kinetic temperatures \( T_k(O^{6+})/T_k(He^{+}) \) for the selected spectra, are in general smaller than for average solar wind conditions. The median value of \( T_k(O^{6+})/T_k(He^{+}) \) for the entire data set is 4.0, whereas for the selected spectra it is near 2.3. This is not surprising since the selection criterion favours low kinetic temperatures and thus short collision times. Furthermore, it is difficult to determine such low temperatures from the data because of the wide spacing of the velocity channels and the velocity resolution of the instrument. The result is an overestimate of \( \kappa \) for the selected spectra, and we conclude that the best estimate for \( \kappa \) lies somewhere between 0 and 0.5. For practical purposes, we have evaluated all high resolution spectra with the assumption \( \kappa = 0 \). For the He/O ratio, according to expression (10), this could result in a systematic overestimate of the order of 20%. Correspondingly, no noticeable systematic deviation is expected for ratios such as Ne/O or C/O. We have investigated the dependence of our He/O determinations with respect to the \( T_k(O^{6+})/T_k(He^{+}) \) temperature ratio. If our assumption \( \kappa = 0 \) would severely differ from the real \( \kappa \)-value, we would have to expect a dependence of the flux ratio on the temperature ratio. We found no such dependence and we, therefore, believe that in reality, variations of \( \kappa \) are not causing a serious bias even for flux ratios involving helium.

2.3. SUMMARY OF DATA ACQUISITION MODES AND EVALUATION PROCEDURES

In Sections 2.1 and 2.2, we have described two data acquisition modes and three data reduction procedures:

- High-resolution spectra in the range from \( M/Q = 2 \) to \( M/Q = 3 \), with logarithmic \( M/Q \) stepwidth 1.35%.
- Low-resolution spectra in the range from \( M/Q = 1.4 \) to \( M/Q = 5.8 \), with logarithmic \( M/Q \) stepwidth 3.64%.
- Procedure (a) (required in each mode) is a simple gaussian fit to the observed velocity profile at \( M/Q \). From this fit flux, speed, and kinetic temperature of helium are obtained.
- Procedure (b) is a search for a minimum of summed squares using \( M/Q \) profiles at one velocity channel. It has been applied to determine He, O, C, and Ne fluxes and freezing-in temperatures under the assumption that the kinetic temperature is the same for all ions (\( \kappa = 0 \)).
- Procedure (c) derives bulk oxygen fluxes using a full range of \( M/Q \) and all (seven) velocity channels. We assume the kinetic temperature for an ion to be proportional to its mass (\( \kappa = 1 \)).
3. Results

3.1. Characterization of period selected for this evaluation

The investigated data cover a period of nearly four years from the launch of ISEE-3 in August 1978 until the removal of ISEE-3 from the collinear Lagrangian point in June 1982. This period corresponds to the last two years of ascent to the maximum of solar cycle 21 and the first two years of decline following the maximum.

Approximately five months of data have been acquired and evaluated in the high-resolution mode lasting through the months of solar maximum. Three short periods have been evaluated and discussed in a previous paper (Kunz et al., 1983).

Several authors have demonstrated that solar wind parameters change significantly during the solar cycle. Such changes have been registered for the average bulk speed, the kinetic temperatures, and, most impressively, for the He/H flux ratio (e.g., Feldman et al., 1978; Borrini et al., 1983; Crooker, 1983). We believe that the averages given in this paper should be representative for the maximum part of the solar cycle, but as we shall show in the following, can also serve to a good approximation for flux ratios during a full solar cycle.

3.2. Freezing-in temperatures

As has been pointed out by Kunz et al. (1983), the freezing-in temperature derived from $M/Q$ spectra in the range $2.0 < M/Q < 3.0$ is largely determined by the state of ionization of oxygen, i.e., on the flux ratio $O^{7+}/O^{6+}$. We have used the method of Kunz et al. (1983) for deriving freezing-in temperatures based on the compilation of ionization and recombination rates of Shull and van Steenberg (1982). For a reliable determination of this temperature, $O^{7+}$ has to be distinguished unambiguously from $^4\text{He}^{++}$ and, hence, only the selected high-resolution spectra are suitable for such measurements. For the 951 selected spectra near solar maximum, we find an average of $1.76 \times 10^6$ K with a standard deviation of single measurements of $2.8 \times 10^5$ K. Our average is compatible with values determined by other groups and other instruments (Bame et al., 1974; Galvin et al., 1984) and with previous observations by Ogilvie and Vogt (1980) at low speeds. There is a weak correlation between the freezing-in temperatures and the $K_p$-index. Our correlation coefficient for daily averages $r_{cor}$ is 0.35. There is no correlation of freezing-in temperatures with speed nor with kinetic temperatures for the high-resolution spectra, although it should be noted that the selected spectra are only representative for low speed and moderately cool solar wind.

As an exploratory procedure, we have also derived freezing-in temperatures for low-resolution spectra using an approach with two free parameters, i.e., freezing-in temperature and bulk oxygen flux. For low-speed spectra, an average of $1.65 \times 10^6$ K was obtained. For the full evaluation of oxygen abundances from low-resolution spectra with fixed freezing-in temperatures, we have used a value of $T = 1.7 \times 10^6$ K. The selection of $T$ for such an evaluation is not very critical as has been illustrated in a special case in Figure 2(a) where the calculated oxygen abundance varies only weakly within a wide range of $T$ (1.4 to $1.9 \times 10^6$ K).
3.3. He/O ratios from low-resolution spectra

We have evaluated 49000 low-resolution spectra and determined oxygen fluxes and helium fluxes. Figure 4 shows histograms of the measured helium and oxygen fluxes and also of the helium/oxygen ratio. Two different weighting procedures were used for the helium/oxygen ratio histogram. The full line histogram weights all spectra equally. Because there are large differences in the magnitude of the estimated error of individual cases, we have also weighted the data according to the inverse square of the error (broken line).

![Histograms of observed helium fluxes, oxygen fluxes and helium/oxygen ratios (single determinations).](image)

Fig. 4. Histograms of observed helium fluxes, oxygen fluxes and helium/oxygen ratios (single determinations). The dashed line shows the He/O histogram weighted with the inverse squares of the estimated uncertainties. The difference of the two He/O histograms indicates that extreme flux ratios are associated with large uncertainties.

The average flux ratio is

\[ \langle \text{He/O} \rangle = 80, \]

the observed standard deviation of single measurements is approximately a factor of 2 \((+100\%, -50\%)\). From the weighted distribution, we estimate the true variance of this ratio to be a factor 1.5 \((+50\%, -30\%)\).

It is evident from the width of the distributions in Figure 4 that helium fluxes and
ABUNDANCES OF C, O, Ne IN THE SOLAR WIND

Fig. 5. Correlogram of oxygen and helium fluxes. The dashed lines are for equal He/O ratios. The ridge defined by the most frequent occurrences runs along a line with He/O = 70.

Oxygen fluxes must be strongly correlated. This is also shown in Figure 5 which is a contour plot with contour lines connecting fields of equal case densities. The dashed lines are lines of constant He/O ratios in this plot. The maximum of the distribution lies at about He/O = 70. The 'center of gravity' of the distribution is at a somewhat higher value: 83, probably caused by larger errors for low oxygen fluxes. The correlation coefficient between log(He) and log(O) is 0.755.

For a comparison with other flux ratio determinations in the solar wind, it is useful to give the ratio of He and O flux averages which is not necessarily the same as the average of measured individual ratios.

We obtain

$$\frac{\langle \text{He} \rangle}{\langle \text{O} \rangle} = 75 \pm 20$$

for this ratio. The error given above includes the estimated error of the instrument calibration, possible deviations due to incorrect assumptions on $\kappa$ in expression (6), the freezing-in temperature, and deviations from the assumed standard composition (Table I). This value is representative for a wide range of solar wind conditions since there is no obvious correlation of the measured He/O ratios with kinetic temperatures and only a weak correlation with speed as is illustrated in Figure 6.
There is a weak correlation of monthly averages of He/O with monthly sunspot numbers $R_Z$ ($r_{cor} = 0.30$). We find

$$\log(\text{He/O}) = 1.062 \times 10^{-3} \times R_Z + 1.696.$$  \hspace{1cm} (11)

For a quiet month with $R_Z = 50$, this relation predicts an average He/O = 56, and for an active month with $R_Z = 200$, it predicts He/O = 81.

The marginally significant decrease of the He/O ratio with increasing bulk speed amounts to approximately 50% over the full available range from 300 to 600 km s$^{-1}$. A causal link for this observation can be established via solar activity which appears to be anticorrelated with the solar wind speed as indicated by the results of Feldman \textit{et al.} (1978).

We have performed an autocorrelation analysis of helium fluxes, of oxygen fluxes, and of He/O ratios. For short time lags of the order of one day, our autocorrelation curves can be approximated by simple exponential functions. Typical persistence times for which the autocorrelation function has decayed to 1/e are 14 hr for the helium flux and 16 hr for the oxygen flux and the He/O ratio. This is somewhat shorter than the value of 20 hr found for $^3$He fluxes (Coplan \textit{et al.}, 1984). There is a small but significant peak.
in the autocorrelation curve near 27 days indicating a tendency of recurrence of He/O ratios after one solar rotation.

The autocorrelation times for large He/O ratios are shorter, whereas the autocorrelation times for low He/O ratios appear to be larger than 16 hr. However, one has to consider that large ratios are in general related with large uncertainties producing shorter persistence times.

Figure 7 illustrates a weak but significant correlation between O/He ratios and the isotopic ratio $^{3}\text{He}/^{4}\text{He}$ in the solar wind. We will discuss this observation in more detail in the next section. The relation implies that variations in the He/O ratio are partly linked to effects which are due to mass fractionation only and not caused by differences in the atomic structures between the two elements He and O.

3.4. He/O RATIO S FROM HIGH-RESOLUTION SPECTRA

For the subset of the 951 high-resolution spectra covering the period from January through April 1984, we find an average of 74 for the $\langle \text{He} \rangle/\langle \text{O} \rangle$ flux ratios and a value of 81 for the average of $\langle \text{He}/\text{O} \rangle$ fluxes. A relative uncertainty of approximately 20% has to be assigned to these values for the uncertainty in $\kappa$ as given in expression (10). There is no significant correlation or anticorrelation of this ratio with the freezing-in temperature determined for each spectrum. This underlines the good resolution achieved in the selected spectra and shows that the assumption of a constant freezing-in temperature in the previous section introduces no bias. The agreement between the averages for low- and high-resolution spectra is satisfactory. The difference of 81 relative
to 75 for the entire data set is marginally significant. We expect a difference of about 5% using relation (11) considering the increased solar activity during the relevant period early in 1980.

The variance of the observed He/O ratios is smaller for the high-resolution data than for the low-resolution value. The observed standard deviation of single ratios is $\pm 50\%$ which comes close to our estimate of the fluctuation from low resolution spectra based on the analysis of weighted histograms.

3.5. Ne/O Ratios from High-Resolution Spectra

The evaluation of neon fluxes from high-resolution spectra yields an average ratio of neon to oxygen fluxes of 0.16 with a relative standard deviation of a factor 1.8. The ratio of average fluxes is 0.18 and our best estimate for this elemental ratio in the (quiet) solar wind is

$$\frac{\text{Ne}}{\text{O}} = 0.17 \pm 0.02.$$  

This value is computed from the $^{20}\text{Ne}/\text{O}$ ratio including a contribution of 7% from $^{22}\text{Ne}$ (Geiss et al., 1972). The relative error given above is smaller than the corresponding error for the He/O ratio since the mass difference between Ne and O is only 25% and, hence, the uncertainty in $\kappa$ has no detectable influence. Moreover, Ne$^{8+}$, on which the neon determination is based, has an $M/Q$ value in between O$^{6+}$ and O$^{7+}$ and, therefore, uncertainties in the variation of the response function of the instrument with $M/Q$ are strongly reduced and have little impact on the final results.

The correlation coefficient between oxygen fluxes and neon fluxes is 0.75 $\pm$ 0.02. The correlation coefficient between He/O and Ne/O ratios is only marginally different from zero (0.11 $\pm$ 0.06). This indicates that a large fraction of the observed fluctuation in the Ne/O ratio is probably not real but caused by random uncertainties in the evaluation procedure. The evaluation of a set of simulated spectra with typical properties and count rates but with a fixed Ne/O ratio of 0.15 gave a standard deviation of evaluated Ne/O ratio of 0.045 compared to the observed standard variation obtained from the real spectra of 0.10.

3.6. He/Ne Ratio from High-Resolution Spectra

Of course, this elemental ratio depends on the previously discussed ratios He/O and Ne/O. However, it is useful for the purpose of intercomparison with other experiments to give some additional information, especially on the correlation of He and Ne fluxes and the corresponding variance of the He/Ne ratio. The average of He/Ne ratio is 540, whereas the ratio of average fluxes is 470. Single measurements of the ratios vary by a factor of 2 about this ratio. Figure 8 shows a contour plot of the distribution of measured He and Ne fluxes, with contour lines connecting the points of equal case densities. Also included in this figure are the individual determinations obtained with the Apollo foil experiments. The averages of the He/Ne flux ratio determined with the foil experiments is 530 (Geiss et al., 1972) in good agreement with the above given value of 470. From Figure 8, it is evident that the variance of our measurements is larger than
the variance observed with the foil experiments. For a direct comparison of the variances obtained by these different methods, one has to take into account that the foil exposures lasted typically a day and, hence, some of the real variations have been averaged out by this method. The variance of such averages of ratios \( R \) over selected periods \( \tau \), \( \text{Var}(\langle R \rangle_\tau) \), can be estimated from the variance of the instantaneous measurements \( \text{Var}(R) \) from

\[
\text{Var}(\langle R \rangle_\tau) = \frac{2 \times \text{Var}(R)}{\lambda \tau} \left[ 1 + \frac{1}{\lambda \tau} (e^{-\lambda \tau} - 1) \right]
\]  

(cf. Taubenheim, 1969). This expression holds for first-order Markov processes with normalized autocorrelation functions of the form

\[
K_R(\tau) = \exp(-\lambda |\tau|).
\]

\( \lambda \) is the inverse of the persistence time which we assume to be 16 hr for He/Ne ratios. For \( \tau = 24 \) hr, the variance of averages will be 64% of the variance of single measurements, correspondingly standard deviations will only be reduced to 80%. It is thus clear that the major part of the scatter from the dashed line in Figure 8 is caused by measurement errors, mainly from neon determinations. Single neon flux determinations have a typical short-time fluctuation of a factor of 2.6 which is considerably larger than for oxygen determinations. This is most likely not real.

The correlation between helium and neon fluxes is 0.66. This relatively weak correlation underlines that although no systematic bias or instrumental effects influence our long time averages, single measurements are affected by rather large uncertainties.
The correlation between Ne and O fluxes is 0.77, the Ne/O ratio is thus less variable than ratios involving helium. We find a weak correlation ($r_{cor} = 0.52$) between Ne/He and O/He.

3.7. C/O Ratios from High-Resolution Spectra

The determination of carbon abundances in high-resolution spectra is entirely based on the appearance of C$^5^+$ as a peak or shoulder at $M/Q = 2.40$ which is close to O$^7^+$ ($M/Q = 2.28$). The difficulties of determining carbon with an $M/Q$ analyzer have been described elsewhere (Kunz et al., 1983). Mg$^{10^+}$ – which is the most abundant ion of Mg in a wide temperature range because of its helium-like electron shell – appears at the same location as C$^5^+$. As we shall discuss in the following, the Mg/C ratio in the solar wind is not necessarily constant and is not easily estimated from solar abundances. With the assumption that the charge state of carbon freezes in at the same temperature as the charge state of oxygen, we would obtain an average C/O ratio of 1.1. Carbon fluxes are correlated with oxygen fluxes with a correlation coefficient $r_{cor} = 0.61$. Single determinations of carbon fluxes vary typically by a factor of 3 which is partly caused by measurement uncertainties. The above C/O ratio of 1.1 would be approximately a factor 2 above the best solar estimate of 0.6 (Anders and Ebihara, 1982).

We have to consider the fact that the charge state distribution of carbon is frozen-in at temperatures $2 \times 10^5$ K below the freezing-in temperature of oxygen (Bochsler, 1983; Bürgi, 1984). Under these circumstances we obtain a C/O ratio of 0.70 which is in agreement with the solar value. However, that does not mean that the flux ratio is always compatible with the average. It has been shown (Kunz et al., 1983) that considerable deviations from this average exist in the sense of larger C$^5^+$ (or Mg$^{10^+}$) abundances. Since large C$^5^+$ abundances can be determined with a higher degree of confidence than abundances below the average, a discrepancy remains for many cases although the average appears to be compatible with photospheric values. Bochsler (1983) and Kunz et al. (1983) have discussed possible reasons for such deviations. Geiss and Bochsler (1984) have pointed out that in a manner analogous to observations of solar energetic particles (e.g., Cook et al., 1984) Mg might be enriched over oxygen by a factor 3 as a rule in the solar wind. Consequently, the C/O ratio given above should be reduced by another 20% to a value C/O = 0.55 in order to account for the enhanced Mg$^{10^+}$ abundance. Despite the fact that we have calculated freezing-in temperatures for each spectrum individually, we observe a tendency of rising C/O ratios with rising freezing-in temperatures. Since we do not expect an intrinsic dependence of the C/O ratio with the freezing-in temperature, this observation comes somewhat unexpectedly. We will attempt an explanation of this puzzle in the next section.

4. Discussion

Table II is a compilation of our elemental ratios as determined in the previous section. For comparison, we also give abundance ratios observed in Solar Energetic Particle populations and the best estimates for the solar ratios.
TABLE II
Elemental ratios in the solar wind

<table>
<thead>
<tr>
<th></th>
<th>Solar wind</th>
<th>Ref.</th>
<th>Solar energetic particles (Cook et al., 1984)</th>
<th>Photosphere (Anders and Ebihara, 1982; and citations therein)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He/O</td>
<td>75 ± 20</td>
<td>(1)</td>
<td>72 ± 6</td>
<td>108</td>
</tr>
<tr>
<td>Ne/O</td>
<td>0.17 ± 0.02</td>
<td>(1)</td>
<td>0.167 ± 0.015</td>
<td>0.187</td>
</tr>
<tr>
<td>He/Ne</td>
<td>470 ± 150</td>
<td>(1)</td>
<td>429 ± 37</td>
<td>580</td>
</tr>
<tr>
<td></td>
<td>530 ± 70</td>
<td>(2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C/O</td>
<td>0.70\textsuperscript{a}</td>
<td>(1)</td>
<td>0.47 ± 0.04</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>0.55\textsuperscript{a}</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} With the assumption that the ionization state of C freezes in at a temperature 2 \times 10^5 K below the oxygen freezing-in temperature. The first value is derived with a solar Mg/O ratio. For the second value, we assume an enrichment by a factor of 3 of the Mg/O ratio in the solar wind.

(1) This work.
(2) Geiss et al. (1972).

We have been able to determine oxygen fluxes and He/O ratios under nearly all solar wind flow conditions which have been encountered during the investigated period from August 1978 through June 1982. Our results indicate that the He/O ratio increases with solar activity less than the He/H ratio. Neugebauer (1981b) has demonstrated that the relative helium abundance increased by 80\% as the solar activity increased from a smoothed sunspot number of 10 to 110 during solar cycle 20. Using our relation (11), we estimate an increase of merely 25\% for the He/O ratio under the same conditions.

Neugebauer (1981b) notes a similarly strong increase of more than factor of 2 of the average He/H ratio associated with the change of the proton speed from 300 to 600 km s\textsuperscript{-1}, whereas from our data there appears to be a decrease of the order of 50\% of the He/O ratio over the same velocity range (cf. Figure 6). The oxygen abundance in the solar wind thus seems to be more strongly related to the helium flux than the proton flux. Oxygen differs in many ways from helium and also from hydrogen. It is more readily ionized than helium (e.g., Geiss, 1982; Geiss and Bochsler, 1984) and, hence, it is not surprising to find a positive correlation of the He/O ratio with solar activity. On the other hand, \textsuperscript{3}He and O have larger \(Q^2/M\) ratios than \textsuperscript{4}He (and H), and the correlation of \textsuperscript{3}He/He with O/He can be attributed to an influence of the proton drag factor. From a different view, this correlation might also be explained by different observed variances of the fluxes of the different ions. The observed variances increase only slightly from \textsuperscript{4}He to O to \textsuperscript{3}He (cf. Figure 4) and Coplan et al. (1984; their Figure 4). However, considering that the \textsuperscript{4}He fluxes have much smaller errors than the O and \textsuperscript{3}He measurements, then it is possible that in reality the variations of the \textsuperscript{4}He flux are the largest of the three ions.

We note in this connection that the acceleration of \textsuperscript{4}He in the corona ought to be particularly sluggish (Geiss et al., 1970; Isenberg and Hollweg, 1983) and that in the process of atom-ion separation \textsuperscript{4}He depletions are particularly likely (Geiss, 1982; Geiss and Bochsler, 1984).
A detailed investigation shows that the average flux ratio $^4\text{He}/^3\text{He}$ increases significantly with increasing He/O ratios which is consistent with results shown in Figure 7. For cases with $40 < \text{He/O} < 60$, we find an average $^4\text{He}/^3\text{He}$ flux ratio of 1800, whereas for the interval $100 < \text{He/O} < 140$ it is 2170. Both increases are mainly caused by increases in the average $^4\text{He}$ flux with $^3\text{He}$ and O remaining essentially unchanged. Comparing histograms of $^4\text{He}/^3\text{He}$ ratios for the two He/O ranges discussed above, we find that the most frequent $^4\text{He}/^3\text{He}$ values are the same in both cases. However, the tails of the $^4\text{He}/^3\text{He}$ histograms differ markedly. The low $^4\text{He}/^3\text{He}$ ratios are more populated (17.7% with $^4\text{He}/^3\text{He} < 1000$) for low He/O cases than for high He/O cases (10.6% with $^4\text{He}/^3\text{He} < 1000$). On the other hand, $^4\text{He}/^3\text{He}$ ratios $> 4000$ are considerably more frequent for large He/O ratios.

$^4\text{He}$ appears to be variable on a particularly short time-scale. The characteristic persistence time for $\log(^4\text{He}$ flux) is 14 hr, 20 hr for the $^3\text{He}$ flux, and 22 hr for protons. Hence, also from this viewpoint, oxygen seems to behave as an ion ‘in between’ helium and hydrogen.

Our average He/O ratio of 75 compares well with the ratio of 72 determined by Cook et al. (1984) for four solar energetic particle events, it is lower by 40% than the solar system value given by Anders and Ebihara (1982). From the relatively small changes of the He/O ratio with changing solar wind conditions, we conclude that other elemental ratios (except those relating to hydrogen) do not change strongly either. Therefore, elemental ratios which are found in typically slow and quiet solar wind conditions are valid as averages to a fairly high degree of approximation, i.e., about $\pm 50\%$, for other solar wind conditions. Our He/Ne ratio is consistent with the value obtained from the Apollo foil experiments (Geiss et al., 1972) although the apparent variance of our measurements is considerably larger due to large uncertainties and the smoothing introduced by the foil exposure method. From the five Apollo foil experiments, a correlation coefficient of the $^3\text{He}/^4\text{He}$ ratios with the Ne/He ratios of 0.931 $(+ 0.061/ - 0.44)$ is derived. Although there is a relatively large uncertainty involved with this correlation coefficient due to the small number of determinations, it is larger than 0.5 at a confidence level of 95%. It is, therefore, not surprising that we also find a correlation between $^3\text{He}/^4\text{He}$ and the O/He ratio in our data. We have pointed out before that this correlation can be explained as being largely due to the comparably strong fluctuations of the He flux. We find it noteworthy that this is also the case for the Apollo foils. The variances of the $^3\text{He}$ and Ne fluxes are somewhat smaller than the variance of the $^4\text{He}$ flux despite the larger measurement uncertainties of $^3\text{He}$ and Ne. Neon, oxygen, and hydrogen are comparable with respect to the rate of ionization in the solar atmosphere, whereas this rate is much smaller for helium (Geiss and Bochsler, 1984). The observation that the variance of helium fluxes is larger than the variance of proton fluxes has been interpreted in terms of changing coupling efficiency in the solar corona (see, e.g., Neugebauer (1981b) for a thorough discussion). We interpret our result in a similar way. Oxygen and neon are less sensitive to the varying fractionation processes and, hence, the net fluctuations (corrected for measurement uncertainties) of oxygen and neon fluxes are smaller than those of helium. In the same context, we have
pointed out that fluctuations of helium occur on a shorter time-scale than those of oxygen and protons.

Kunz et al. (1983) have discussed the difficulties of determining the carbon abundance from a sometimes marginal peak at $M/Q = 2.40$. Based on the assumption that the elemental ratio Mg/C is 0.09, as given by the best estimates in the solar photosphere and assuming that C (and Mg) freeze in their states of ionization as does oxygen, these authors found in three short periods an overabundance of C over O ranging from a few tens of percents to a factor of 3. It seems now more likely that the C/O ratio in the solar wind is compatible with the values found for solar energetic particles or the solar photosphere, whereas a systematic overabundance of Mg and thus of Mg$^{10+}$ of typically a factor of 3 as observed in solar energetic particles might contribute to the apparent overpopulation at $M/Q = 2.40$ (Geiss and Bochsler, 1984). Moreover, it is more likely that carbon freezes its ionization state at temperatures typically $2 \times 10^5$ K below the oxygen freezing-in temperatures than at the same temperature (Bürgi, 1984). From this, we conclude that if carbon abundances in the solar wind have to be estimated from $M/Q$ spectra only and the peak or shoulder in the spectra near $M/Q = 2.4$ has to be used for this purpose, one should apply a first-order correction for Mg overabundance and differences in freezing-in temperatures rather than to use uncorrected values.

Bürgi (1984) finds in his coronal expansion models that the thermal gradient in the corona is steeper and the difference in freezing-in temperatures between C and O is larger for those models which generate larger observed freezing-in temperatures at 1 AU. This might yield the explanation for an observed apparent correlation of C/O ratios with the oxygen freezing-in temperature: for large freezing-in temperatures we tend to overestimate the fraction of carbon hidden in the form of C$^{6+}$ more severely than for lower freezing-in temperatures.

5. Summary

Our results for He/O in the solar wind show that this ratio is in general less variable than the He/H ratio which has been the only elemental ratio for which continuous determinations existed so far. Our average He/O value is marginally compatible with the solar surface value, but it leaves open the possibility that oxygen is depleted in the solar wind relative to hydrogen by approximately 40%. Our He/O ratio agrees with the value found for solar energetic particles (Cook et al., 1984).

The He/Ne ratio derived in this work is in good agreement with earlier single determinations by means of the foil technique. Since we observe no strong variations of the He/O ratio with changing solar wind conditions, we consider our He/Ne ratio to be representative for the solar wind despite the fact that we have good observations only for slow and quiet solar wind.

Our results provide evidence for recent theoretical considerations and models (Geiss, 1982; Geiss and Bochsler, 1984; Meyer, 1985) about the operation and efficiency of fractionation mechanisms in the upper chromosphere as well as in the solar corona.
Acknowledgements

This work is the result of our ICI-ISEE-3 cooperation with Drs K. W. Ogilvie (Principal Investigator) and M. A. Coplan who contributed with many suggestions. The authors are indebted to A. Bürgi, M. A. Coplan, R. Joos, K. W. Ogilvie, and J. Schmid for discussions. We thank Mrs G. Troxler for preparing the manuscript and R. Wright for drawing the figures. This work is supported by the Swiss National Science Foundation.

References