

ELEMENTAL AND ISOTOPIC ABUNDANCES IN THE SOLAR WIND *Johannes Geiss*
An invited review

The use of collecting foils and lunar material to assay the isotopic composition of the solar wind is reviewed. Arguments are given to show that lunar surface correlated gases are likely to be most useful in studying the history of the solar wind, though the isotopic abundances are thought to give a good approximation to the solar wind composition. The results of the analysis of Surveyor material are also given. The conditions leading to a significant component of the interstellar gas entering the inner solar system are reviewed and suggestions made for experimental searches for this fraction. A critical discussion is given of the different ways in which the basic solar composition could be modified by fractionation taking place between the sun's surface and points of observation such as on the Moon or in interplanetary space. An extended review is made of the relation of isotopic and elemental composition of the interplanetary gas to the dynamic behavior of the solar corona, especially processes leading to fractionation. Lastly, connection is made between the subject of composition, nucleosynthesis and the convective zone of the sun, and processes leading to modification of initial accretion of certain gases on the Earth and Moon.

ABSTRACT

INTRODUCTION

During the last few years, the compositional aspect of the solar wind has been given increasing attention. While it had been established for quite some time [Snyder and Neugebauer, 1964; Wolfe et al., 1966; Hundhausen et al., 1967a; Ogilvie et al., 1968] that a rather variable proportion of He⁴ is present in the solar wind, other ions have been found only recently. By means of high-resolution electrostatic analyzers, Bame et al. [1968] measured oxygen and also detected He³ during periods of low solar wind ion temperature, and Bame et al. [1970] showed that multiply charged Si and Fe are present during such periods. Geiss et al. [1970c] gave the abundances of the helium and neon isotopes during the Apollo 11 and 12 lunar landings, using a foil collection technique.

The He/H ratio in the solar wind is highly variable, values between 0.01 and 0.25 having been observed

[Hundhausen et al., 1967a] with an average of about 0.04 [Neugebauer and Snyder, 1966; Ogilvie and Wilkerson, 1969; Robbins et al., 1970]. Bame et al. [1968] reported variations in the O/Ne and He⁴/He³ ratios, and Geiss et al. [1970c] in the He⁴/He³ and He⁴/Ne²⁰ ratios, but there is yet very little statistical information for an assessment of the variability in the abundance of the rare ions.

The reasons for the generally observed variations of the He/H ratio in the solar wind are not clear. It is unknown so far whether heavier ions such as neon, argon, and iron show similar or even larger variations in their abundances or whether their abundances tend to be rather constant, relative to either hydrogen or helium. A comprehensive study of abundances and abundance variations in the solar wind that include several ion species should give much and unique information on processes taking place near the sun. The relative abundances of ions in the solar wind are not likely to be as much affected in interplanetary space as are other solar wind parameters such as the temperatures of ions and

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electrons [Sturrock and Hartle, 1966; Forslund, 1970] and their anisotropy [Wolfe et al., 1966; Hundhausen et al., 1967b]. The abundances and abundance variations of a number of solar wind ions have to be measured if the mechanisms causing the variations are to be understood. The various mechanisms are expected to deplete or enrich different ion species in quite different ways. The charge/mass ratio of the ion (Z/A) would enter into separation processes caused by quasistatic electromagnetic fields. Simple gravitational escape would depend primarily on the mass. Diffusion processes in the photosphere-corona boundary region depend strongly on the degree of ionization [Delache, 1965, 1967; Jokipii, 1965, 1966a; Nakada, 1969]. If dynamical friction is significant in the solar wind acceleration region, a factor similar to Z^2/A is important [Geiss et al., 1970a]. Separation effects depending primarily on the ionization energy as suggested by Lehnert [1970] and Arrhenius and Alfvén [1971] should give large variations in element abundances, but would have relatively small effects on isotopic abundances. On the other hand, wave-particle interactions could lead to mass fractionation, including isotopic fractionation. Abundance correlation studies in the solar wind of the noble gas isotopes and of O, Si, and Fe with their wide range in Z and A should eventually enable us to distinguish between the various processes if these ions can be sampled often enough.

Only when the fractionation processes discussed above are sufficiently well understood can we begin to draw conclusions about solar abundances from solar wind abundance measurements. This is true not only for the relations between elements but also for isotopic ratios. A long time average of abundance ratios does not necessarily give the true solar abundance because the fractionation processes might well introduce a systematic bias.

HELIUM AND NEON ISOTOPES

During the Apollo 11, 12, and 14 landings an aluminum foil was exposed at the lunar surface to collect solar wind particles for subsequent analysis in the laboratory. The concept of this Solar Wind Composition (SWC) experiment and experimental techniques were given by Signer et al. [1965], Bühler et al. [1966], Meister [1969], and Geiss et al. [1969]. For collection times of the order of a few days, the method is virtually restricted to noble gases, but it yields precise results not only for elemental abundances but also for isotopic compositions. Noble gas measurements in the solar wind are of particular importance because (1) their abundances in the sun are difficult to determine spectroscopically; (2) a contribution from infalling meteorites

can be definitely excluded; and (3) by comparative measurements in telluric and meteoritic matter the most interesting and puzzling isotope anomalies have been found in the noble gases.

Results on the fluxes of the He and Ne isotopes in the solar wind obtained from the Apollo 11 and Apollo 12 SWC experiments have been published by Bühler et al. [1969] and Geiss et al. [1970b, c]. They are summarized in table 1. Geiss et al. [1970c] have concluded that the relative abundances obtained from these experiments were not seriously affected by near-lunar perturbations, and that in particular the differences in the observed He^4/He^3 and $\text{He}^4/\text{Ne}^{20}$ ratios correspond to real variations in the abundances of the undisturbed solar wind. This conclusion was based on the observed distribution of the angles of incidence of He^4 (fig. 1), the correlation between the He^4/He^3 and $\text{He}^4/\text{Ne}^{20}$ ratios [Geiss et al., 1970c], and the undisturbed nature of the proton flow observed in near lunar space [Siscoe et al., 1969; Freeman et al., 1970; Clay et al., 1971].

In table 1, the proton flux as observed by Bame and Hundhausen [1970] during the Apollo 12 foil exposure period is used to derive the He/H ratio. Note that the He/H ratio calculated from the results of these two different experiments is close to the established long-time average of about 0.04.

Table 1. Fluxes and ion abundance ratios determined for the Apollo 11 and Apollo 12 foil exposure periods (July 21, 1969, 03:35 – 04:52 GMT, and November 19, 1969, 12:35 GMT – Nov. 20, 1969, 07:17 GMT)

[The He/H ratio has been calculated by combining the Apollo 12 SWC He and the Vela proton data which were obtained simultaneously [Bame and Hundhausen, 1970]. Fluxes are given in $\text{cm}^{-2} \text{sec}^{-1}$.]

| | Apollo 11 | Apollo 12 |
|---------------------------------|---|-----------------------------|
| | (Fluxes in $\text{cm}^{-2} \text{sec}^{-1}$) | |
| He^4 – Flux | $(6.2 \pm 1.2) \times 10^6$ | $(8.1 \pm 1.0) \times 10^6$ |
| He^3 – Flux | $(3.3 \pm 0.7) \times 10^3$ | $(3.3 \pm 0.4) \times 10^3$ |
| Ne^{20} – Flux | $(14 \pm 4) \times 10^3$ | $(13 \pm 2) \times 10^3$ |
| He^4/H^1 | --- | 0.043 |
| He^4/He^3 | 1860 ± 140 | 2450 ± 100 |
| $\text{He}^4/\text{Ne}^{20}$ | 430 ± 90 | 620 ± 70 |
| $\text{Be}^{20}/\text{Ne}^{22}$ | 13.5 ± 1.0 | 13.1 ± 0.6 |
| $\text{Ne}^{22}/\text{Ne}^{21}$ | --- | 26 ± 12 |

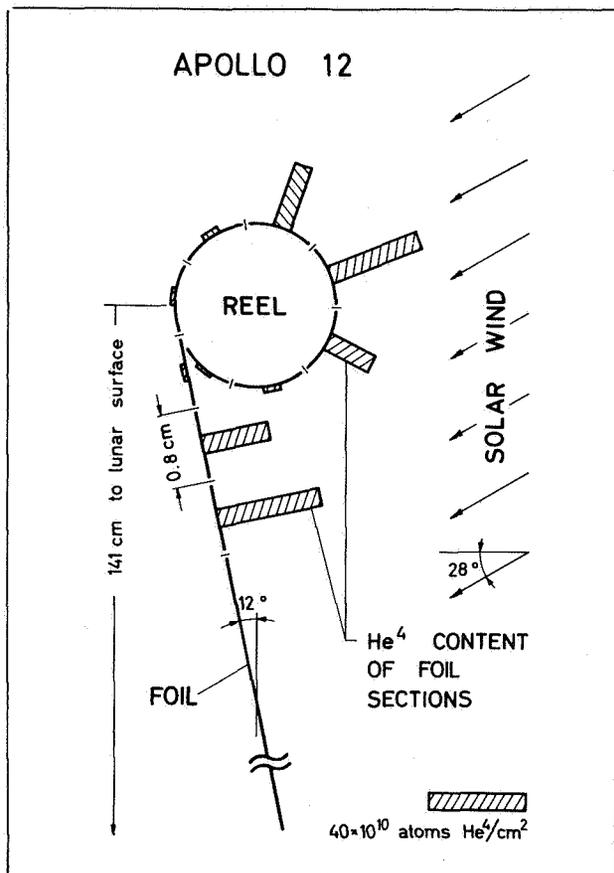


Figure 1. The upper part of the Apollo 12 SWC foil as it was exposed at the lunar surface. The uppermost part of the foil remained rolled around the reel, allowing a determination of the distribution of the angles of incidence of He⁴. The shaded bars represent the measured areal concentrations of He⁴ in the foil pieces. The observed distribution corresponds to a distinctly directional flow and is compatible with a helium temperature below 10⁶ °K. After Geiss et al., 1970b.

OXYGEN, SILICON, AND IRON

During periods of low solar wind ion temperature, O⁶⁺ and O⁷⁺, Si⁷⁺ to Si⁹⁺, and Fe⁸⁺ to Fe¹²⁺ have been identified by the Los Alamos group using the high-resolution solar wind energy/charge spectrometers on board the Vela satellites [Bame et al., 1968, 1970]. The abundances and abundance variations of these ions and their charge distributions are discussed and given in detail in the preceding paper. The elemental abundances

relative to oxygen derived by [Bame et al., 1968, 1970] are listed in table 2.

Table 2. He, O, Si, and Fe abundances in the solar wind obtained from the Vela 3 and 5 experiments [after Bame et al., 1968, 1970]

| Spacecraft | Time | H | He | O | Si | Fe |
|------------|---|------|-----|---|------|------|
| Vela 3 | Average of four spectra Oct. 8, 1965 to March 23, 1966 | --- | 55 | 1 | --- | --- |
| Vela 5 | July 6, 1969 2222 - 2251 UT | 5000 | 150 | 1 | 0.21 | 0.17 |

SOLAR WIND PARTICLES EMBEDDED IN FINE MATERIAL AT THE LUNAR SURFACE

There is very striking evidence that the fine material and many breccias found at the lunar surface are loaded with solar wind particles. In particular, the embedded hydrogen and noble gases can be recognized as being of solar origin because of their very low abundance in lunar surface rocks. From the low D/H ratios obtained, it can be concluded that most of the hydrogen found in the lunar fine material is in fact of solar wind origin [Epstein and Taylor, 1970; Friedman et al., 1970; Hintenberger et al., 1970]. The lowest D/H ratio reported so far is 9 times lower than the ratio in ocean water [Epstein and Taylor, 1970].

The relatively large amounts of noble gases found in breccias and lunar dust are concentrated in the outer layers of the individual grains. By means of etching experiments, Eberhardt et al. [1970] have shown that in the mineral ilmenite the noble gases from helium to xenon are essentially contained in the outermost 0.2 μ of the individual crystals (fig. 2). The range of solar wind particles in materials like ilmenite is estimated to be 0.03 to 0.15 μ.

The lunar dust contains solar wind particles down to a depth of at least 45 cm. As the lunar surface is gardened by impacts of all sizes and probably by other mechanisms, successive layers of grains come to the surface and are exposed to the solar wind.

Although there is a great quantity of solar wind matter at the lunar surface suitable for extensive studies, experimental data cannot easily be translated into solar wind abundances. From the observations it is obvious that the light noble gases have been depleted relative to the heavy ones by temperature diffusion and perhaps also by saturation effects (cf. table 8). Helium released

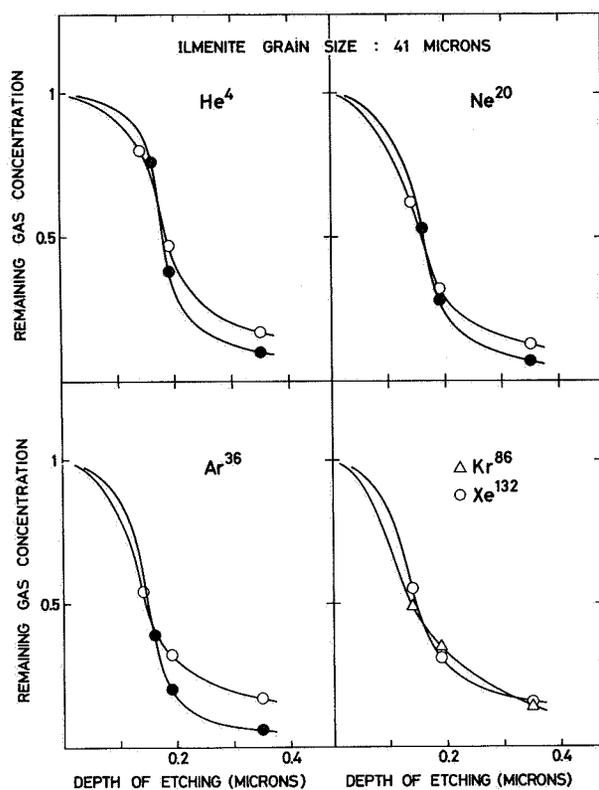


Figure 2. Noble gas concentrations (per gm) measured in a 41 μ ilmenite grain size fraction separated from Apollo 11 fine material (No. 10084) after removal of a thin surface layer by etching with HF. The horizontal axis is equivalent to the thickness of the layer removed from the surface of the individual grains. The vertical axis gives the concentration in the unetched ilmenite. The two curves for He⁴, Ne²⁰ and Ar³⁶ represent the two independent sets of etching experiments performed [after Eberhardt et al., 1970].

Table 3. Solar wind isotopic compositions inferred from trapped gases in lunar surface fine material

[For literature and origin of these data see text.]

| | |
|------------------------------------|------------------------|
| He ⁴ /He ³ | 2700±100 |
| Ne ²⁰ /Ne ²² | 12.85±0.1 |
| Ne ²⁰ /Ne ²¹ | 400±11 |
| Ar ³⁶ /Ar ³⁸ | 5.32±0.08 |
| Ar ⁴⁰ /Ar ³⁶ | <0.15 |
| Kr | Similar to terrestrial |
| Xe | See figure 4 |

to the lunar atmosphere will mostly escape before it becomes ionized. Heavier gases cannot escape gravitationally. They will be ionized within a few weeks and then accelerated by the electromagnetic field of the solar wind [Michel, 1964]. In this way, most of these gases escape, but a fraction is re-embedded in the lunar soil. The relatively high abundance of Ar⁴⁰ is thought to be the result of such re trapping [Heymann et al., 1970; Eberhardt et al., 1970; Heymann and Yaniv, 1970; Manka and Michel, 1970]. In a similar way other constituents of a steady-state or transient lunar atmosphere, such as old solar wind particles, products of outgassing of the lunar interior, or gases of cometary origin, may have been embedded in the surface layers of the grains of the lunar fine material. It would be difficult to distinguish them from the directly implanted solar wind particles. Such considerations have led Podosek et al. [1971] to speak of "surface-correlated" (SUCOR) rather than solar wind noble gases. Another possible source for surface correlated gases is the interstellar gas, which is discussed in a later section.

From all these arguments it is seen that the surface-correlated gases should not be considered as an *a priori* source of information on solar wind composition. In the long run, their value will probably lie in giving information on the history of the solar wind and its composition. Nevertheless, all evidence so far points to a solar wind origin of the bulk of the surface-correlated gases, and isotopic—not elemental—abundances are considered to give a good approximation to solar wind abundances.

Since the noble gases in the mineral ilmenite have apparently suffered least from diffusive losses, the isotopic ratios found for the surface-correlated gases in this mineral can be considered the best approximation to solar wind abundances. The results for the He and Ne isotopes and for Ar³⁶/Ar³⁸ as obtained by Eberhardt et al. [1970] are given in table 3; these are discussed in a later section. Because of the re trapping of released lunar radiogenic Ar⁴⁰ mentioned above, one can give only an upper limit for the solar wind Ar⁴⁰/Ar³⁶ ratio. The value obtained by Bloch et al. [1971] is given. The Kr isotopic composition found in the surface-correlated gas of lunar fine material is similar to that in terrestrial Kr [Eberhardt et al., 1970; Pepin et al., 1970; Hohenberg et al., 1970].

The isotopic composition of surface-correlated xenon is not easily assessed because for the lighter isotopes of this element there is a relatively high spallation component produced by cosmic rays and solar flare particles. However, a large difference from the isotopic composition of air xenon is well established [Hohenberg et al., 1970; Pepin et al., 1970; Marti et al., 1970; Eberhardt et

al., 1970; Podosek et al., 1971]. This is evident from the Xe^{128}/Xe^{130} versus Xe^{126}/Xe^{130} correlation diagram of figure 3, where data points represent measured isotopic ratios from samples of ilmenite of different grain size. If the measured gas samples are composed in

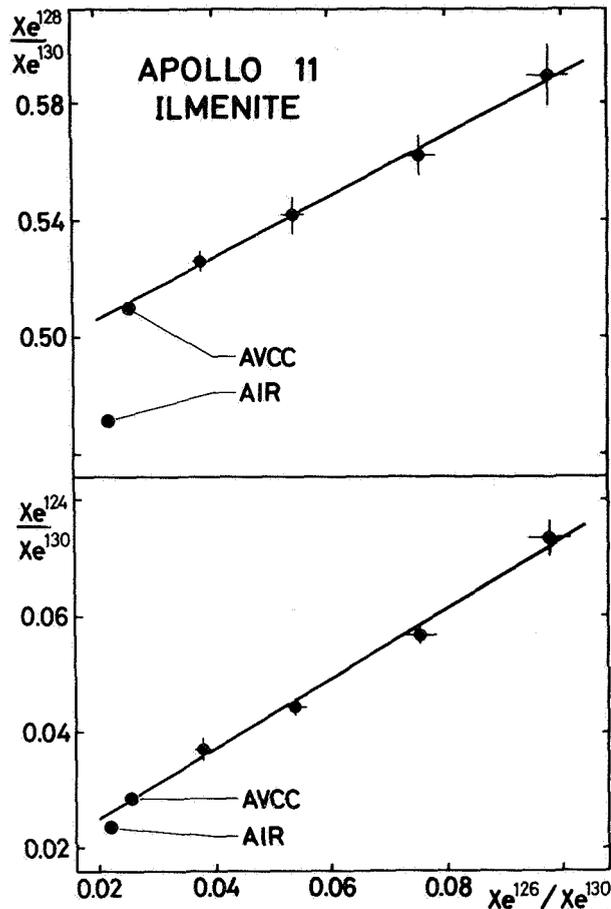


Figure 3. Xenon isotope diagram with isotopic ratios obtained in four grain size fractions of ilmenite (22, 41, 65 and 105 microns) separated from Apollo 11 fine material [Eberhardt et al., 1970]. Xenon is a mixture of a spallation component produced in the lunar material by high energy particles, and a trapped component which is thought to be of solar wind origin. Since the latter component is surface correlated, its concentration per gram increases with decreasing grain size, while the spallation component is relatively independent of grain size. It is seen that the trapped xenon cannot have the isotopic composition of air xenon. The figure suggests that the relative abundances of Xe^{126} , Xe^{128} and Xe^{130} are similar to those found in carbonaceous chondrites (AVCC = average in carbonaceous chondrites).

varying proportions of two isotopically different components, the data should fall on a straight line. It is seen that this is the case, but the straight line does not pass through the air xenon composition point. The surface-correlated xenon in the ilmenite therefore must be different from air xenon. Figure 3 shows that it can be—but does not have to be—identical to the xenon found in carbonaceous chondrites, a meteorite class thought to represent rather primitive solar system material. By making assumptions on the abundance of the spallation component, Eberhardt et al. [1970] and Podosek et al. [1971] have extrapolated their data to the isotopic composition of surface-correlated xenon in lunar fine material. The results of Podosek et al. [1971] are given in figure 4. The errors are an indication of the precision of the measurements and do not include the uncertainties inherent in the extrapolation process. Again a large and yet unexplained difference between surface-correlated and air xenon is obtained, whereas there appears to be agreement with carbonaceous chondrite xenon for the lighter isotopes. The difference in the heavy isotope abundances of AVCC xenon and surface-correlated xenon in lunar dust could be due to a fission component in the carbonaceous chondrites [Reynolds and Turner, 1964]. Dakowski [1969] and Anders and Heymann [1969] have suggested that the origin of this fission component could be due to spontaneous fission of extinct super heavy elements ($Z \sim 112$). Recently, Alexander et al. [1971] have shown that the spontaneous fission of Pu^{244} gives quite a different xenon isotope spectrum, and therefore fission of a super heavy element seems to be the most likely source of this Xe component.

SOLAR WIND GASES TRAPPED IN SURVEYOR 3 MATERIAL

The Surveyor 3 material returned by the Apollo 12 astronauts had been exposed at the lunar surface from April 20, 1967, to November 20, 1969. Bühler et al. [1971] performed a preliminary investigation on a small piece of an aluminum tube that was brought back, and they observed the solar wind He and Ne isotopes trapped in this material. The results are shown in table 4. The He/Ne ratio is low in comparison with the Apollo 11 and 12 SWC results, and it is likely that some helium was lost as a result of the repeated severe heating during lunar noon. Also, the possibility that a residual dust contamination on the aluminum has somewhat affected the neon results cannot be excluded. Helium loss by temperature diffusion could also have changed the He^4/He^3 isotopic ratio, but Bühler et al. [1971] estimate that such a change should not amount to more than 5 to 10 percent.

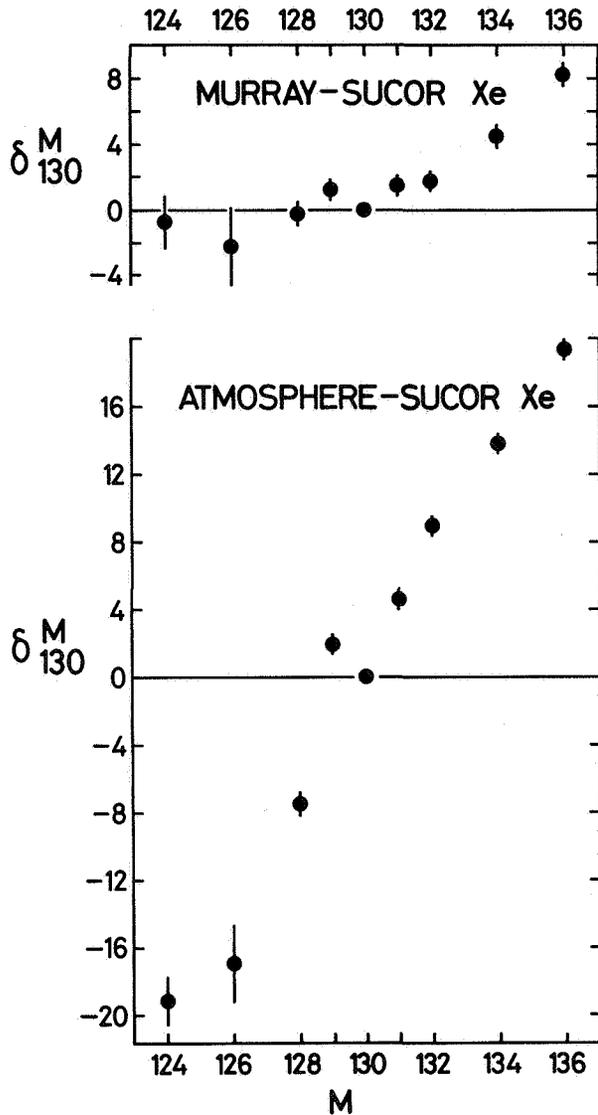


Figure 4. Comparison of isotopic composition of atmospheric xenon, xenon extracted from the carbonaceous chondrite "Murray" and surface correlated xenon "SUCOR" in lunar fine material [after Podosek et al., 1971]. The latter is interpreted as consisting essentially of trapped solar wind particles. The isotopic ratios are normalized to Xe^{130} . Plotted are the relative deviations in percent of atmospheric xenon and Murray xenon respectively from "SUCOR" xenon.

INTERSTELLAR GAS

If neutral, the interstellar gas surrounding the solar system can penetrate into the region of the inner planets. The dynamics has been studied in detail by Fahr [1969] and Blum and Fahr [1970]. These authors have published maps for the expected density of neutral

Table 4. Trapped solar wind He and Ne isotopes measured in returned Surveyor 3 aluminum tube [Bühler et al., 1971]

[The significance of these data and the limits of possible abundance falsifications are discussed in the text. The errors given are the analytical errors only.]

| | |
|-------------------|----------------|
| He^4/He^3 | 2770 ± 120 |
| He^4/Ne^{20} | 295 ± 15 |
| Ne^{20}/Ne^{22} | 13.3 ± 0.4 |
| Ne^{22}/Ne^{21} | 31 ± 5 |

hydrogen around the sun taking into account losses due to ionization by solar EUV and by the solar wind. Holzer and Axford [1970b] have evaluated and discussed the penetration of interstellar He into the solar system. Recently, Bertaux and Blamont [1971] and Thomas and Krassa [1971] have published contour maps of the observed Lyman- α background radiation. These authors conclude that the interstellar gas moves toward the solar system not from the direction of the solar apex, but from a direction close to the ecliptic plane at about 270° ecliptic longitude. The number density of interstellar hydrogen in the vicinity of the sun but outside its sphere of influence is estimated to be 0.05 to 0.10 cm^{-3} [Blamont, 1971]. We shall adopt here the value 0.08 cm^{-3} .

From the magnitude of the peculiar motion of the sun, the velocity of the gas v_o is assumed to be of the order of 20 km/sec. The flux of the interstellar gas is focused by the gravitational field of the sun to an extent determined by $GM_o/v_o^2 r$. For noble gases the radiation pressure effect ought to be small and therefore is not considered here. During the summer months, the earth is in the upstream position with respect to the interstellar gas flow, and it can readily be shown that in this case the flux is given by

$$F = n_o v_o \left\{ \frac{1}{2} \left[1 + \sqrt{1 + (V_\oplus/V_o)^2} \right] \right\}^2 S \quad (1)$$

where $v_\oplus = 42.1 \text{ km/sec}$ is the escape velocity from the solar gravitational field at 1 AU. With $v_o = 20 \text{ km/sec}$ we obtain $F = 2.8 \times n_o v_o S$.

The survival factor S takes into account the losses due to ionization by solar EUV and solar wind. Since the fluxes of these radiations are known to fall off with r^{-2} , the loss equation for particles directly approaching the sun can be integrated to give

$$S = \exp \left[-2K \frac{r_{\oplus}}{v_{\oplus}} (\langle \sigma_{f_{\oplus}} \rangle_{\text{EUV}} + \langle \sigma_{f_{\oplus}} \rangle_{\text{SW}}) \right] \quad (2)$$

with

$$K = \sqrt{1 + (V_o/V_{\oplus})^2} - V_o/V_{\oplus}$$

For $v_o = 20$ km/sec, one obtains $K = 0.63$. Terms of the form $\langle \sigma_{f_{\oplus}} \rangle$ are the loss rates due to EUV and solar wind at 1 AU. Numerical values are listed in table 5. The EUV flux and spectrum are taken from *Hinteregger et al.* [1965] and *Hall and Hinteregger* [1970] for wavelengths below and above 270 Å, respectively. The EUV ionization cross sections are given by *Lee and Weissler* [1955]. $\langle \sigma_{f_{\oplus}} \rangle_{\text{SW}}$ has been calculated with the charge exchange and ionization cross sections for 800 eV protons given by *Green and McNeal* [1971], assuming a proton flux of $2 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$ at 1 AU. We have adopted the abundances in gaseous nebulae [*Aller*, 1961] for the interstellar gas and obtain the neutral fluxes arriving in the upstream (southern) region of the earth orbit as given in table 5. The result for He compares well with the density given by *Holzer and Axford* [1970b], when scaled to the same interstellar density.

Most of these neutral atoms become ionized when further approaching the sun, and are swept back outward by the interplanetary magnetic field, leading to an ionized flux similar in magnitude to the incoming neutral flux. These ions are singly charged, and *Holzer and Axford* [1970a] have suggested that the He^+ ions sometimes reported in the solar wind are of interstellar origin. *Geiss et al.* [1970a] have pointed out that these ions will have a smaller radial velocity than the solar wind ions and a non-radial velocity component. *Holzer and Axford* [1970b] have noted that He^+ originating in this way has a very high apparent temperature. Since this He^+ amounts to only about 1 percent of the solar wind He^{++} flux, it appears rather unlikely that it can actually be seen with an electrostatic analyzer unless, as *Holzer and Axford* [1970b] have postulated, He^+ is sometimes

cooled by interactions with magnetic field irregularities.

A possible way of directly detecting neutral interstellar noble gas atoms at 1 AU is to capture them in a foil flown in near-earth orbit, as on a sky-lab or space station. When the earth is in the upstream position (summer months) the velocity of the incoming neutral atoms relative to a near earth satellite moving in the west-east direction is about 60 km/sec, corresponding to the kinetic energies given in the last column of table 5. At these energies, neon and argon can be captured in an aluminum foil [*Meister*, 1969], although only with relatively low efficiency. A surface composed of lighter elements, such as a beryllium foil, theoretically would give a higher capture probability. At an altitude of 400 to 500 km, absorption, ionization, and charge exchange with the atmosphere are small during the night—when the interstellar atoms should arrive. If the inclination of the satellite orbit is not too high, the flux of trapped or precipitating ions ought to be negligible under quiet conditions. With the flux given in table 5, enough neon for detection and isotopic analysis could be collected with foil exposure times of 1 to 2 months. The survival factor S for argon depends very strongly on the EUV flux, and to a lesser degree also on the solar wind velocity. Thus, during a quiet solar period S for argon may be appreciably larger than 14 percent so that argon could become detectable after 1 or 2 months of collection time.

If the interstellar gas in our vicinity has indeed a number density of only 0.1 cm^{-3} , the primary (neutral) and secondary (ionized) fluxes of interstellar gases are two orders of magnitude lower than the solar wind flux (*cf.* tables 1 and 5) and therefore should hardly affect the solar wind abundances obtained from the Vela and Apollo SWC experiments. However, number densities larger than 1 cm^{-3} occur in interstellar space, and therefore we cannot exclude the possibility that at certain times in the past the interstellar gas may have

Table 5. Estimated fluxes of interstellar neutral atoms at the orbit of the earth when the earth is in the upstream position (during summer)

[The $\langle \sigma_{f_{\oplus}} \rangle$ are the respective loss rates at 1 AU under relatively quiet solar conditions. Also given are impact energies of the atoms on an earth satellite.]

| Element | Abundance relative to hydrogen | $\langle \sigma_{f_{\oplus}} \rangle_{\text{EUV}}$, 10^{-6} sec^{-1} | $\langle \sigma_{f_{\oplus}} \rangle_{\text{SW}}$, 10^{-6} sec^{-1} | Survival factor S , percent | Flux at 1 AU (upstream), $\text{cm}^{-2} \text{ sec}^{-1}$ | Impact energy on satellite, eV |
|---------|--------------------------------|--|---|-------------------------------|--|--------------------------------|
| He | 0.19 | 0.048 | 0.003 | 81 | 7×10^4 | 75 |
| Ne | 1.1×10^{-4} | 0.14 | 0.005 | 59 | 30 | 375 |
| Ar | 8×10^{-6} | 0.24 | 0.2 | 14 | 0.5 | 675 |

contributed appreciably to the influx of particles at the lunar surface. These interstellar gases might be detectable on the moon in certain layers of the fine material or in breccias.

THEORETICAL TREATMENT OF ION MOTION IN CORONA AND SOLAR WIND

Here we review and discuss the question of solar wind abundances and their relationship to solar abundances from the theoretical point of view. *Delache* [1965, 1967], *Jokipii* [1965, 1966a], and more recently *Nakada* [1969] have applied the molecular diffusion equation as given by *Chapman and Cowling* [1958] to the motion of matter from the solar surface into the lower corona. For ions, the thermal diffusion factor α_T is large and negative [*Chapman*, 1958] and therefore the authors find a tendency for strong enrichment of the heavier ions in the corona relative to the photosphere. However, this effect may be partially obliterated by turbulent mixing or inhibited by magnetic fields. *Nakada* [1969] has estimated the degree of mixing and has concluded that it should not be sufficient to extinguish completely the enrichments resulting from molecular diffusion.

The diffusion equation is not applicable in regions of strong acceleration and when the differences between bulk velocities of different ion species become large. Therefore, its validity is restricted to the lower corona. Other methods must be used in the actual acceleration region of the solar wind.

The general equation of motion derived from the Boltzmann equation has been applied to this problem by *Geiss et al.* [1970a]. They assumed a radial magnetic field direction and stationary, spherically symmetric radial motion. On the basis of *Parker's* [1958, 1963] polytropic expansion model *Geiss et al.* [1970a] discussed the general properties of the equation of motion of a rare ion species in a plasma essentially composed of protons and electrons, and gave numerical solutions.

Nakada [1970] has used a more general equation, not assuming $n_I \ll n_p$, and has treated the isothermal case. *Allouche* [1970] has numerically integrated the equation of ion motion for isothermal expansion and also on the basis of the *Sturrock and Hartle* [1966] two-fluid model for $r \leq 7 R_\odot$. With the density and temperature parameters chosen by *Sturrock and Hartle*, the solar wind reaches sonic velocity only at $r \approx 9 R_\odot$. Thus *Allouche's* [1970] results refer to the subsonic region only. In this region, his results are comparable to those of *Geiss et al.* [1970a] if an appropriate value for the polytropic index ($\alpha \approx 1.2$) is chosen. To keep the problem tractable, all the authors assumed Maxwellian velocity distributions. This latter assumption constitutes

the introduction of a hydrodynamic approximation. Such an approximation is applicable only if there are a sufficient number of collisions to maintain a semblance of an equilibrium.

In a proton-electron gas, the mean free path λ_p [*Spitzer*, 1962] for the protons is given by

$$\frac{\lambda_p}{R_\odot} = 0.11 \frac{T^2}{n_p} \quad (3)$$

where T is in 10^6 °K, n_p is in 10^6 cm $^{-3}$, and R_\odot is the solar radius. If in the proton-electron gas there is a small population of heavier ions with charge Ze and mass Am_p , their mean free path $\lambda(Z, A)$ is

$$\frac{\lambda(Z, A)}{R_\odot} = 0.09 \frac{T^2}{n_p} \frac{A^{1/2}}{Z^2} \quad (4)$$

Thus for $^{20}\text{Ne}^{8+}$ the mean free path is 17 times smaller than for protons. The corresponding collision times, t_D are [*Spitzer*, 1962]

$$t_D(\text{Protons}) = 520 \frac{T^{3/2}}{n_p} \text{ sec} \quad (5)$$

and

$$t_D(Z, A) = 410 \frac{T^{3/2}}{n_p} \frac{A}{Z} \text{ sec} \quad (6)$$

(T always in 10^6 °K and n_p in 10^6 cm $^{-3}$). The mean free paths and collision times given in table 6 are based on the densities and proton temperatures obtained from the two-fluid model of *Sturrock and Hartle* [1966]. In evaluating the importance of collisions, one must consider the distance that the ion travels with the local solar wind velocity between two collisions [*Hundhausen*, 1968]. Thus, the number of collisions occurring while the solar wind travels $1 R_\odot$ is also given in table 6. Note that the number of collisions is four times larger for $^{20}\text{Ne}^{8+}$ than for protons, and that collisions for neon are quite effective up to a solar distance of $\sim 10 R_\odot$ —beyond the “sonic point” of the solar wind. Since in the model of *Geiss et al.* [1970a] the physically important region is $\leq 10 R_\odot$, the predictions obtained using that model should have physical significance.

Ion Acceleration by Coulomb Collisions

In discussing the ion motion in the corona and the solar wind, we follow essentially the treatment given by *Geiss et al.* [1970a] and use the same notation. However, we treat certain aspects more generally and add to the discussion of the physical significance and limits of the model. For treatment of the ion transport in the solar wind acceleration region the following approximations are made:

1. The bulk motions of electrons, protons, and heavier ions are radial and spherically symmetric.

2. Forces due to the magnetic field are neglected.
3. Compared to protons, all other ions have negligible abundances, specifically $Z^2 n_I \ll n_p = n_e = n$.
4. The velocity distribution of each particle species is maxwellian around an individual bulk velocity.
5. The local temperatures of protons and electrons are equal $T_p = T_e$. As *Sturrock and Hartle* [1966] have shown, this assumption is probably invalid in the outer corona. However, the electron temperature does not affect the motion of heavier ions very strongly, since collisions with electrons are negligible. In fact, T_e enters into the equations of ion motion only through the electrical field term, and this term does not dominate the acceleration of heavier ions.

Table 16. Mean free paths and collision times. Solar wind parameters after *Sturrock and Hartle* [1966]

| r | $\lambda (^{20}\text{Ne}^{8+})$ | $t_D (^{20}\text{Ne}^{8+})$, sec | Collisions while solar wind travels $1 R_\odot$ | |
|--------------|---------------------------------|--------------------------------------|---|-----------------------|
| | | | Protons | $^{20}\text{Ne}^{8+}$ |
| $1 R_\odot$ | $0.001 R_\odot$ | 12 | --- | --- |
| $2 R_\odot$ | $0.006 R_\odot$ | 130 | 45 | 180 |
| $5 R_\odot$ | $0.010 R_\odot$ | 320 | 6 | 24 |
| $10 R_\odot$ | $0.014 R_\odot$ | 750 | 1.5 | 6 |
| $20 R_\odot$ | $0.008 R_\odot$ | 720 | 1.5 | 6 |

In this approximation the equations for stationary motion of a particular ion species are

$$n_I V r^s = \text{const} \quad (7)$$

$$v \frac{dv}{dr} + \frac{1}{Am_p n_I} \frac{d}{dr} (n_I k T_I) + \frac{GM_\odot}{r^2} - \frac{ZeE}{Am_p} - C = 0 \quad (8)$$

with the collision term

$$C = \frac{4\pi e^4 \ln \Lambda}{m_p} \frac{n}{kT} \frac{Z^2 A + 1}{A A + \vartheta} G \left[\left(\frac{A m_p}{A + \vartheta 2kT} \right)^{1/2} (V - v) \right] \quad (9)$$

and the expression for the electrical field

$$\frac{eE}{m_p} = \frac{1}{2} \left(\frac{GM_\odot}{r^2} + V \frac{dV}{dr} \right) \quad (10)$$

where v is the bulk velocity, n_I the number density, Am_p the mass, Ze the charge, and T_I the local

temperature of the ions; In Λ is approximately 22 [*Parker, 1963*]; V , n , and T are the corresponding values for the protons; $T_I/T = \vartheta$ is assumed to be constant but is allowed to be different from unity. For radial flow $s = 2$ while $s > 2$ corresponds to a flow diverging more rapidly. *Spitzer* [1962] has tabulated $G(x)$, which is defined as

$$G(x) = [\phi(x) - x\phi'(x)] / 2x^2 \quad (11)$$

where $\phi(x)$ is the error function. The asymptotic behavior

$$\left. \begin{aligned} G(x) &= 0.37x & \text{for } x \ll 1 \\ G(x) &= \frac{1}{2x^2} & \text{for } x \gg 1 \end{aligned} \right\} \quad (12)$$

shows that momentum transfer by collisions is strongly nonlinear. Another important feature of C is that it is approximately proportional to Z^2/A . This means that momentum transfer by collisions with protons is very effective for medium and heavy elements.

We complete the system of equations (7) through (10) by using *Parker's* [1963] polytropic expansion model:

$$\frac{dT_I}{T_I} = (\alpha - 1) \frac{dn_I}{n_I} \quad (13)$$

Now eliminate n and normalize the velocities, temperatures, and radius vector to the respective values at the critical ("sonic") point of the expanding proton-electron gas

$$\left. \begin{aligned} r &= r_c \xi \\ V(r) &= V_c W(\xi) \\ v(r) &= V_c w(\xi) \\ T(r) &= T_c \tau(\xi) \end{aligned} \right\} \quad (14)$$

with

$$\left. \begin{aligned} V_c &= \left(\frac{GM_\odot}{sr_c} \right)^{1/2} \\ T_c &= \frac{GM_\odot m_p}{2s\alpha k r_c} \end{aligned} \right\} \quad (15)$$

In terms of these dimensionless variables the equation of ion motion is written

$$\begin{aligned} \frac{dw}{d\xi} \left(2w - \frac{\vartheta\tau}{\alpha A w} \right) &= \frac{\vartheta}{\alpha A} \left(\frac{s\tau}{\xi} - \frac{d\tau}{d\xi} \right) \\ &+ \frac{Z}{A} W \frac{dW}{d\xi} - \frac{2A - Z}{A} \frac{s}{\xi^2} \\ &+ \frac{Z^2}{A} \frac{A + 1}{A + \vartheta} \frac{f}{W\tau\xi^s} G(\Delta w) \end{aligned} \quad (16)$$

with

$$\Delta w = [\alpha A / (A + \vartheta) \tau]^{1/2} (W - w) \quad (17)$$

The dimensionless quantity f denotes the reduced flux

$$f = \frac{\phi_{\oplus}}{\phi_{\odot}} \alpha \left(\frac{s}{2} \right)^{5/2} \left(\frac{r_c}{r_{\oplus}} \right)^{7/2 - s} \quad (18)$$

with the flux unit [cf. Geiss et al., 1970a]

$$\phi_{\odot} = 1.3 \times 10^5 \text{ cm}^{-2} \text{ sec}^{-1}$$

Geiss et al. [1970a] have given a general discussion of equation (16) for $T_I = T$ and have shown that ions heavier than protons are accelerated to solar wind velocity only if two conditions are fulfilled:

1. The proton flux has to be above a certain critical value f_{min} .
2. The effective polytropic index α for the protons has to increase with solar distance and reach a value of at least 1.33. In the model of Sturrock and Hartle [1966], α actually surpasses 1.33 at $r = 10.7 R_{\odot}$.

The magnitude of f_{min} is model dependent and thus not easily specified. However, a simple relation between the critical proton fluxes for different ion species is approximately independent of the expansion model and is given by ($T_I = T$):

$$f_{min} \propto \Gamma^{(1)}(A, Z) \equiv \frac{2A - Z - 1}{Z^2} \quad (19)$$

If thermal diffusion due to nonmaxwellian velocity distributions is taken into account, equation (19) can be modified to give as an approximation

$$f_{min} \propto \Gamma^{(2)}(A, Z) \equiv \frac{2A - Z - 1}{Z^2} + \frac{\alpha - 1}{\alpha} \frac{15}{8} \left(\frac{2A}{A + 1} \right)^{1/2} \left(1 - \frac{1}{A} \right)$$

$$Z > 1$$

$$(20)$$

Minimum flux factors $\Gamma^{(1)}$ and $\Gamma^{(2)}$ for a number of ion species are listed in table 7. For the degree of ionization of O, Si, and Fe we take the most probable charges observed by Bame et al. [1970]. We have obtained the charges of Ne and Ar that correspond to the same ionization conditions from the ionization potentials given by Lotz [1967]. The striking result in table 7 is that the minimum proton flux for ${}^4\text{He}^{2+}$ is higher than for all other ions listed. This means that in this idealized stationary model of the quiet solar wind heavier ions including Fe^{12+} are carried along in the solar wind as long as ${}^4\text{He}^{2+}$ is.

Table 7. Minimum proton flux factors for different ion species

[The flux factors Γ are defined in equations (7.17), (7.18), and (7.19), and their significance is discussed in the text.]

| Ion | $\Gamma^{(1)}$ | $\Gamma^{(3)}$ | $\Gamma^{(2)}$ |
|--------------------------|---------------------------|-------------------------------|-------------------------------|
| | Without thermal diffusion | | With thermal diffusion |
| | $T_I = T_p$ | $T_I = \frac{1}{2}(A + 1)T_p$ | $T_I = T_p$ $\alpha = 1.1$ |
| ${}^1\text{H}^+$ | 0 | 0 | 0 |
| ${}^3\text{He}^{2+}$ | .75 | .62 | .89 |
| ${}^4\text{He}^{2+}$ | 1.25 | 1.14 | 1.41 |
| ${}^{16}\text{O}^{6+}$ | .69 | .70 | .91 |
| ${}^{20}\text{Ne}^{8+}$ | .48 | .49 | .70 |
| ${}^{22}\text{Ne}^{8+}$ | .55 | .56 | .77 |
| ${}^{28}\text{Si}^{9+}$ | .57 | .59 | .80 |
| ${}^{36}\text{Ar}^{8+}$ | .98 | 1.05 | 1.22 |
| ${}^{56}\text{Fe}^{12+}$ | .69 | .74 | .92 |

The existence of a minimum proton flux for an ion species is a result of the nonlinear behavior of the collision term C in equation (16). Figure 5 is a schematic picture of the solutions of the equations of ion motion (16). The eight figures represent the families of solutions for different proton fluxes f , with f rising from figure 5(a) to (h). Physically acceptable solutions have to agree with the boundary conditions (1) low velocity for small solar distance, and (2) vanishing particle pressure for solar distance $\xi \rightarrow \infty$. The latter condition is equivalent to $v \neq 0$ for $\xi \rightarrow \infty$ [cf. Geiss et al., 1970a]. There is never more than one solution fulfilling these conditions, and this particular solution has to pass through the critical point for ions, one of the singular points of the differential equation (16). For small fluxes f , as in figure 5(a), the collision term has little influence and the ion velocity w remains much below the proton velocity W . With increasing flux two additional singular points appear (figs. 5(b) and (c)), but the physically acceptable solution still passes through the singularity with the highest ξ . When a certain flux value is reached (fig. 5(d)), there is a discontinuity in the physical solution $w(\xi)$, as the critical point switches from the singularity on the right to the one on the left. If the proton flux is increased further, the ion velocity w more and more approaches the proton velocity W , and the two singularities on the right begin to disappear.

The picture presented in figure 5 is borne out by the numerical solutions of equation (16). Figure 6 gives the position of the singular points as a function of the flux value f for $\alpha = 1.4$. Note that generally there is a range of

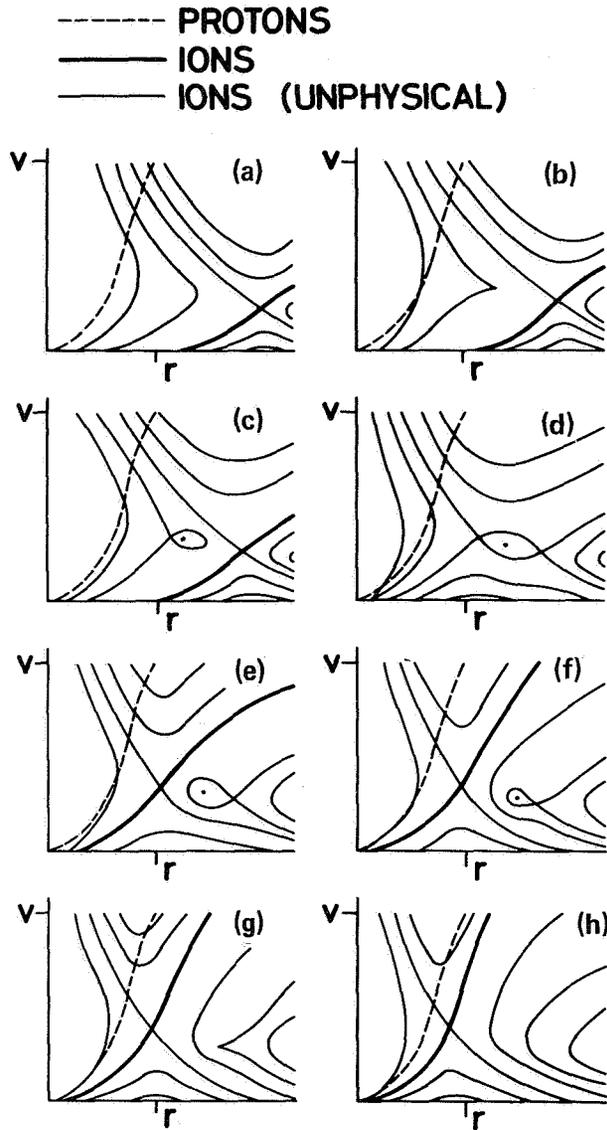


Figure 5. Schematic representation of the solutions (velocity versus solar distance) of the equation of ion motion (16). The eight figures represent the families of solutions for different proton fluxes f , with f rising from figures 5(a) to 5(h). The physically acceptable solution (heavy line) is determined by the boundary conditions.

flux values f with three singularities corresponding to the topologies shown in figure 5(c) through (f). The calculations show that only for lower α and lower masses, such as ${}^4\text{He}^{2+}$ for $\alpha = 1.2$, the three singular points do not develop. The numerical integrations show that the transition from topology 5(c) to (e) occurs for fluxes very near to the relative minimum in the $f(\xi_c)$ plot. Thus, at a critical flux value f_{\min} we have for a small change in flux a very significant change in the physical situation of the heavier ions, which for $\alpha = 1.4$ is

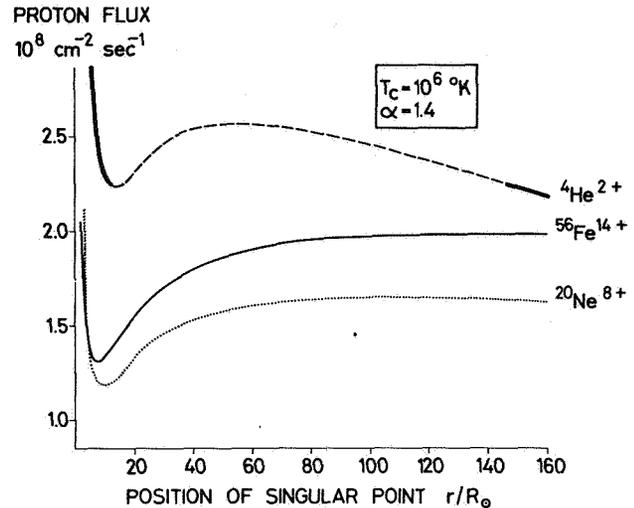


Figure 6. Position of the singular points of equation (16) (both sides in the equation vanish simultaneously) as a function of proton flux [after Geiss et al., 1970a]. A polytropic index $\alpha = 1.4$, and a temperature of 10^6 °K at the “sonic” point of the proton-electron gas are chosen. The dependence of the critical point for ${}^4\text{He}^{2+}$ on the proton flux is shown by the heavy solid line. For low fluxes the critical point is far away from the sun. At a proton flux of about $2.25 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$ the critical point jumps from about $145 R_{\odot}$ to $11 R_{\odot}$, and with further increasing flux it moves continuously closer to the sun. For ${}^{20}\text{Ne}^{8+}$ and ${}^{56}\text{Fe}^{14+}$ this discontinuity in the position of the critical point is even more pronounced.

demonstrated in figure 7. We can describe this change as follows:

For $f = 0$ the ion density distribution is similar to the one in the static atmosphere described by Parker [1961]. The scale height is somewhat larger in our case because of the $V(dV/dr)$ term in the E-field equation (10), which does not exist in the static atmosphere. With increasing proton fluxes the scale height increases—that is, the ion atmosphere is lifted. Still there is no appreciable acceleration of the ions (cf. fig. 7). At some solar distance, equation (16) must become meaningless, since the forces included (gravitation, E field, and drag) fall off rapidly with increasing solar distance, and magnetic field disturbances and instabilities will become the dominating factors for maintaining a fluid-like behavior of the solar wind [Parker, 1958; Scarf, 1966]. At this distance the relative number density of the heavy ions has decreased to a very low value, and consequently their abundance in the solar wind will be low even if the disturbances mentioned can effectively carry them from here on out.

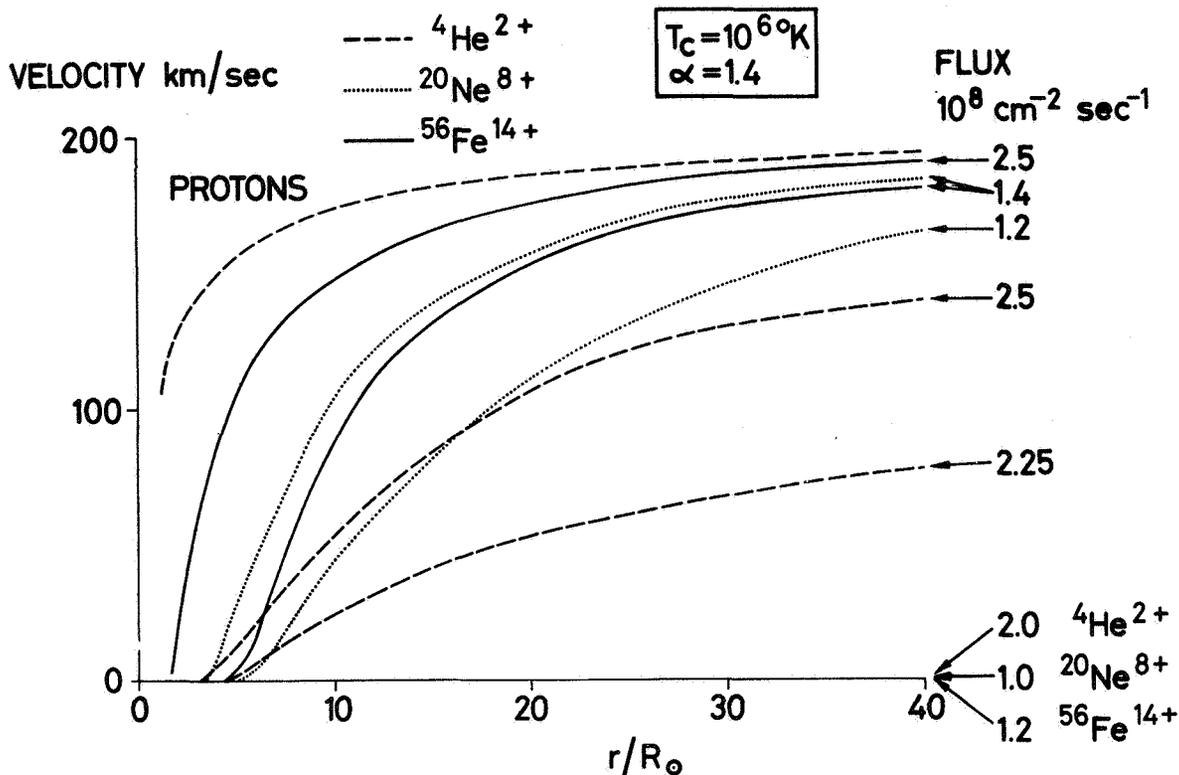


Figure 7. Ion velocities as a function of solar distance and proton flux, obtained by numerical integration of equation (16). $T_I = T$, $\alpha = 1.4$ and $T_C = 10^6$ °K were chosen. ${}^4\text{He}^{2+}$ and ${}^{56}\text{Fe}^{14+}$ after Geiss et al. [1970a]. For ${}^{20}\text{Ne}^{8+}$ and ${}^{56}\text{Fe}^{14+}$ the locking-in of the ion velocity with the proton velocity at the minimum flux is clearly demonstrated. The minimum flux for ${}^4\text{He}^{2+}$ is larger than for the other two ion species.

When f surpasses the critical value f_{\min} , the heavy ions are “locked-in” with the proton motion. In the example given in figure 7, this happens for ${}^{56}\text{Fe}^{14+}$ at a 1 AU proton flux of about $1.3 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$, and for ${}^{20}\text{Ne}^{8+}$ at about $1.1 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$. Since the masses and charges of helium and protons are not so very different, the “lock-in” effect for helium is not as marked. The critical proton flux f_{\min} for ${}^4\text{He}^{2+}$ is around $2.4 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$. Thus the relation between the minimum fluxes of ${}^4\text{He}^{2+}$, ${}^{20}\text{Ne}^{8+}$ and ${}^{56}\text{Fe}^{14+}$ approximately corresponds to the $\Gamma^{(1)}$ values given in table 7, which were derived from an analytical approximation (eq. 16).

The existence of different proton minimum fluxes for different ion species has been demonstrated in figure 7 on the basis of the polytropic expansion model with $\alpha = 1.4$. Under quiet conditions such a high α value is expected in the outer corona (cf. α_p in the Sturrock and Hartle two-fluid model), which is the critical region for ion acceleration. However, $\alpha = 1.4$ is unrealistic in the inner regions of the corona, and therefore leads to solar

wind velocities that are too low; $\alpha = 1.1$ is probably a good approximation for the lower and middle corona. Numerical solutions are given in figure 8. Note that the heavier ions move more slowly in this region than the protons, and this leads to enhanced local abundances of the heavier ions. This will be further discussed in the next section.

So far, our discussion has been based on the assumption that $T_I = T_p$, or $\vartheta = 1$ in the corona and solar wind acceleration region. Such an assumption appears to be justified since the energy equipartition times between protons and ions are similar to the mean collision times given in equation (6). However, it is possible that through heat dissipation by waves and turbulence the temperature of heavier ions is increased above the proton temperature. Ions might also get heated if their bulk velocity lags appreciably behind the proton bulk velocity. Since in the corona the measured electron and ion temperatures generally agree within a factor of about 2 [cf. Billings, 1966], T_I is not expected to be much larger than T , but we should discuss here the influence

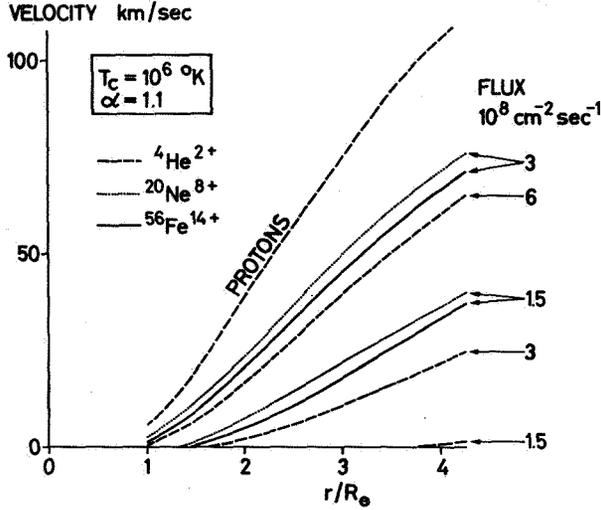


Figure 8. Ion velocities for different proton fluxes and $T_I = T$. $\alpha = 1.1$ is a good approximation for solar distances of a few R_\odot [cf. Sturrock and Hartle, 1966]. It is seen that in this region ions move slower than protons. This leads to enhanced local ion abundances.

of a possible deviation of T_I from T . As can be seen from equation (16), $\vartheta = T_I/T$ does not have a very strong influence on the collision term, and therefore one would not expect the minimum fluxes to change very much for $\vartheta \neq 1$. A minimum flux factor $\Gamma^{(3)}$ can be derived from equation (16) that takes into account possible differences between the local ion and proton temperatures:

$$f_{\min} \propto \Gamma^{(3)} \equiv \frac{2A - Z - \vartheta}{Z^2} \frac{A + \vartheta}{A + 1} \quad (21)$$

This relation becomes unreliable for the limiting case $T_I = AT$ ($\vartheta = A$), where ions and protons have the same velocity dispersion. However, as mentioned before, such a high excess temperature of heavier ions is ruled out by observation. For $\vartheta = (A+1)/2$ —that is, $T_I = 1/2(A+1)T$ —equation (21) is still valid, and numbers for this case have been included in table 7. It is seen that the relation between the minimum fluxes of different ion species remains essentially unchanged, even for drastically increased ion temperatures in the solar wind acceleration region. In all three approximations ${}^4\text{He}^{2+}$ needs a larger proton flux to be carried in the solar wind than all the other ions listed. This result implies that the largest abundance variability in the quiet, quasi-stationary solar wind should occur for He^4 , if collisional momentum transfer is the dominant factor responsible for solar wind abundances and their variations.

Ion Acceleration by Field Irregularities and Waves

We have seen that momentum transfer by Coulomb collisions appears to be a sufficient cause for accelerating heavier ions to solar wind velocities. Momentum transfer from waves or traveling magnetic irregularities will be in competition with Coulomb collisions as regards ion acceleration. The question is which of these processes is dominant at a certain time. In the absence of direct observational evidence on the degree of disorder of the magnetic field and on wave amplitudes in the solar wind acceleration region, this question can be answered best by investigating discrimination with respect to the mass and the charge of the ions.

Wave particle interactions have so far not been studied in the context of ion acceleration in the corona. In order to simplify the situation we shall assume here an average field B_0 in the radial direction on which irregularities or waves are superimposed. It is assumed that the waves travel in the radial direction with a velocity V_w ; B_0 and V_w are constants in space and time. Ions of mass $A \cdot m_p$ and charge Ze are assumed to have initially a velocity distribution characterized by the temperature T_i centered around $v = 0$.

A longitudinal (ion-acoustic) wave can accelerate ions in the radial direction by way of Landau's [1946] trapping process [cf. Spitzer, 1962; Stix, 1962]. Ions to be trapped need a minimum radial velocity v_r , which is given by the relation [cf. Spitzer, 1962]

$$v_r > V_w - \left(\frac{2eU_0}{m_p} \frac{Z}{A} \right)^{1/2} \quad (22)$$

where U_0 is the amplitude of the electric potential in the wave. If ion temperatures are essentially independent of mass, then the acceleration by trapping in longitudinal waves will strongly discriminate against (1) ions of large mass (small thermal velocity) and (2) ions with small Z/A .

Next we study the effects of magnetic disturbances traveling in the radial direction with a velocity V_w . We consider the problem in a frame of reference moving with the wave velocity V_w , which in our case is the Alfvén velocity. In this frame of reference we can consider the wave as a time-independent magnetic field variation. The ions to be accelerated initially have a thermal velocity distribution centered around a radial velocity $-V_w$. For heavier ions the average thermal velocity v_{th} will be much smaller than V_w —that is, the ions move backward with a narrow pitch angle distribution. Pitch angle scattering then results in an acceleration of the ions in the radial direction. The problem of pitch angle scattering by irregularities in a magnetic field has been treated by Jokipii [1966b], Hasselmann and

Wibberenz [1968], and others. Jokipii [1966a] has shown that pitch angle scattering is due to the transverse component of B having a frequency (as seen by the particle) near the gyrofrequency ω_o . In our example, a particle in resonance with a circularly polarized wave will be accelerated according to

$$\frac{dv_{\perp}}{dt} = \omega_o V_w \frac{B_{\perp}}{B_o} \quad \omega_o = \frac{Z}{A} \frac{eB_o}{m_p} \quad (23)$$

With the assumption $v_{\perp} \ll v_{\parallel} \approx V_w$, it follows that

$$\frac{\langle (\Delta v_{\perp})^2 \rangle}{\Delta t} \propto \omega_o^2 V_w^2 \frac{B_{\perp}^2(\omega_o)}{B_o^2} \quad (24)$$

where $B_{\perp}^2(\omega_o)$ is the square of the wave amplitude per unit frequency at the frequency ω_o . Using conservation of energy, we obtain

$$\frac{dv_{\parallel}}{dt} = C_{\text{magn}} \propto \omega_o^2 V_w \frac{B_{\perp}^2(\omega_o)}{B_o^2} \quad (25)$$

Thus in this approximation the "magnetic collision term" C_{magn} is a function of ω_o —that is, a function of Z/A alone. In analogy to observations in interplanetary space [Coleman, 1966; Sari and Ness, 1969; Coleman et al., 1969], we may assume $B_{\perp}^2 \propto \omega^{-\alpha}$, α having values between 1 and 2. From (25) we obtain $C_{\text{magn}} \propto Z/A$ for $\alpha = 1$. C_{magn} becomes independent of Z/A for $\alpha = 2$.

It is seen that accelerations from waves or field disturbances and from Coulomb collisions differ very much in their dependence on ion mass and charge. The former tend to discriminate against the heavy ions, whereas the latter favor them because of the Z^2/A factor in the collision term (eq. (9)).

Ion Separation by Diffusion in the Lower Corona

The diffusion equation can be derived from the momentum equation (8) by neglecting velocity terms of quadratic and higher order. Since thermal diffusion is an effect of nonmaxwellian velocity distributions and thus not contained in equations (8) and (9), the appropriate thermal diffusion term given by Chapman and Cowling [1958] has to be added. Assuming a radial magnetic field and radial motion, one obtains:

$$V - v = D \left[\frac{d}{dr} \ln \left(\frac{n_I}{n} \right) + (2A - Z - 1) \frac{m_p GM_{\odot}}{2kTr^2} + \alpha_T \frac{d}{dr} \ln T \right] \quad (26)$$

with

$$D = \frac{3}{4} \frac{1}{\sqrt{2\pi}} \frac{(kT)^{5/2}}{e^4 m_p^{1/2} \ln \Lambda} \frac{1}{n} \left(\frac{A+1}{A} \right)^{1/2} \frac{1}{Z^2} \quad (27)$$

In first approximation, α_T is given by [Chapman, 1958; Geiss et al., 1970a]

$$\alpha_T = -\frac{15}{8} Z^2 \left(\frac{2A}{A+1} \right)^{1/2} \left(1 - \frac{1}{A} \right) \quad Z > 1 \quad (28)$$

Equation (26) has been discussed and solved by Delache [1965, 1967], Jokipii [1965, 1966a], and Nakada [1969] for the photosphere-corona transition and the lower corona. These authors obtained large enrichments of ions heavier than protons in the corona.

We shall discuss equation (26) by assuming an initially homogenous composition—that is, $d \ln(n_I/n)/dr = 0$. In the lower corona $d \ln T/dr$ is negative, and thus $V > v$. This velocity difference produces the density enhancement of heavy ions in the corona [Jokipii, 1965], which was discussed in connection with figure 8. Across the photosphere-corona boundary a flux enhancement of the positive ions relative to photospheric abundances is possible. Here the continuity equation is not applicable because the source reservoir is virtually unlimited. With a temperature gradient above the photosphere corresponding to $d \ln T/dr \sim 10^{-4} \text{ km}^{-1}$ [cf. Billings, 1966], the thermal diffusion term can in fact be larger than the second term in equation (26) and lead to an enhanced flux of heavier ions. As stressed above and as we shall see in the next section, so far there is no observational evidence that would indicate that this flux enhancement is not virtually obliterated by mixing or impeded by a loop structure in the magnetic field.

DISCUSSION

In figure 9 we compare relative abundances of elements in different materials of solar origin. For hydrogen $\log N$ is normalized to 12.00.

Photospheric abundances for oxygen ($\log N = 8.8$) were taken from Müller et al. [1968] and Lambert [1968], and for silicon (7.55) from Lambert and Warner [1968]. In the past, the iron abundance in the photosphere has been subject to much discussion, since the reported Fe/Si ratio in the photosphere was much lower than Fe/Si in chondritic meteorites. Recently, Garz et al. [1969] and Baschek et al. [1970] have made new determinations of f values for Fe I and Fe II. These new determinations give good agreement for photospheric iron abundances derived from the Fe I and Fe II spectra (7.60 and 7.63, respectively). An average of $\log N = 7.62$ is adopted here.

The coronal abundances are taken from the work of Pottasch [1968]. They were derived from UV spectra obtained at the base of the corona, 10,000 to 30,000 km above the photosphere. Pottasch's [1968] analyses of the forbidden lines in the corona give comparable

results. These latter abundances refer to an altitude of about 75,000 km above the photosphere.

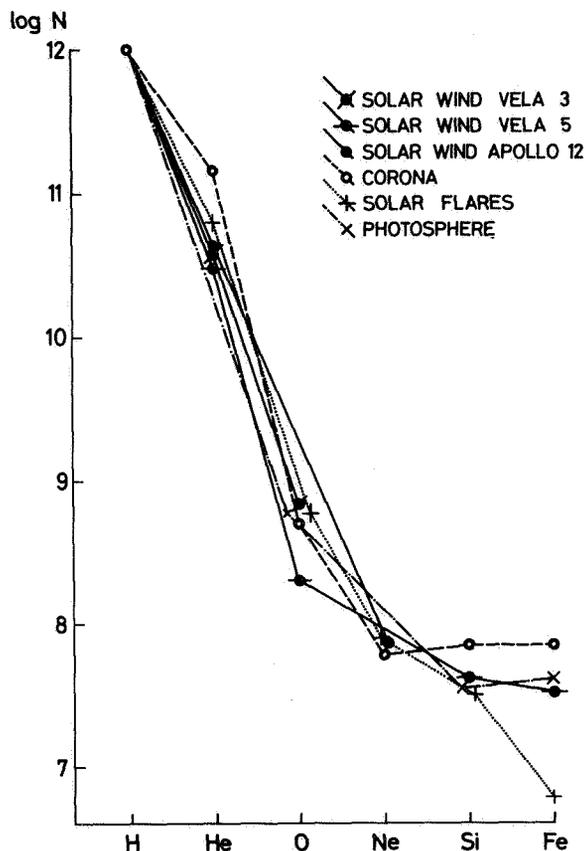


Figure 9. Abundances of elements in different materials of solar origin.

The solar flare particle abundances are taken from *Fichtel's* [1970] presentation. Since for these particles the abundance of hydrogen relative to the heavier ions cannot be determined with certainty, oxygen has been normalized to the photospheric value. Abundances of Si and Fe have been obtained after correcting for the less abundant elements in the elemental groups given by *Fichtel* [1970]. For the solar wind three sets of abundance data are presented in figure 9. The average He/O ratio obtained by *Bame et al.* [1968] from the Vela 3 data has been included by combining it with the average He/H ratio of 0.037 reported by *Robbins et al.* [1970]. The SWC Apollo 12 results [*Geiss et al.*, 1970c] have been chosen for helium and neon since they can be connected to hydrogen by simultaneous observations [*Bame and Hundhausen*, 1970]; compare table 1 of this paper.

If one considers the limitations of all these data, the general agreement is surprisingly good. The intrinsic

uncertainties in the photospheric and coronal abundances combined with the fact that solar wind and corona have only been sampled over limited periods lead us to conclude that the abundances of O, Ne, and Si relative to H agree within the limits of error in all these samples of solar matter. This means that normally the thermal diffusion enrichment process across the photosphere-corona boundary cannot be very effective and is largely obliterated by mixing or quenched by magnetic fields. The abundance enhancement of heavier ions in the corona as predicted from the calculations of *Geiss et al.* [1970a] and *Alloucherie* [1970] are not observed. This is not surprising since the corona data refer to $r < 1.1 R_{\odot}$. At these low altitudes, solar wind expansion models [cf. *Sturrock and Hartle*, 1966] give flow velocities below 10 km/sec, and thus effects arising from differences in flow velocities of a few km/sec can easily be annihilated by turbulent mixing. Thus, we expect that the local enrichment of heavier ions is real only at altitudes of a few hundred thousand km and more above the solar surface.

Figure 9 indicates a large deficit of the iron group in the solar flare particles. As *Fichtel* [1970] has pointed out the measurement by *Bertsch et al.* [1969] refers to relatively high energies (≥ 24.5 MeV/nucleon), and no energy spectra are available. The mass/charge ratio for fully ionized iron is 2.15, slightly higher than the value of 2 for helium and medium nuclei. *Bertsch et al.* [1969] have estimated that this difference can lead to a low abundance of iron, but the effect should not be larger than 30 percent. A possible explanation would be that iron is not fully ionized during a substantial part of the acceleration process.

There are no direct measurements of the helium abundance in the photosphere. In prominences, *Unsöld* [1955] has derived at He/H ratio of 0.16, corresponding to $\log N = 11.2$ for helium. This value is rather uncertain since theory concerning the helium lines in prominences is not completely clear [*Unsöld*, 1969]. *Lambert* [1967] and more recently *Fichtel* [1970] have combined the He/O ratio in solar flare particles with the H/O ratio in the photosphere and obtained $\text{He}/\text{H} = 0.063 \pm 0.008$. This ratio appears to be well founded, since the oxygen abundance in the photosphere is well determined and agreed on by several authors, and since fractionation between helium and oxygen in the solar flare particle population is excluded by substantial observational evidence [*Fichtel*, 1970]. All the helium abundances estimated for the photosphere and the corona are higher than the average solar wind abundance—that is, there is a strong indication that helium is systematically depleted in the solar wind. This

assertion is further supported by the fact that during one full solar rotation the He/H ratio in the solar wind was 0.064 [Robbins *et al.*, 1970]. Also the indicated correlation between general solar activity and He/H ratio [Robbins *et al.*, 1970; Hundhausen, 1970] points in this direction.

If He is indeed systematically suppressed in the solar wind by 30 to 50 percent, it is remarkable that the suppression is not progressively larger for the heavy elements O, Ne, Si, and Fe (fig. 9). This observation is readily explained, of course, if we assume that collisions are the main agent for acceleration of heavy ions during quiet solar conditions.

The time variations of the abundance in the solar wind and in particular the high He/H ratios observed to occur with a delay of the order to 10 hr after an interplanetary shock [Hirshberg *et al.*, 1970; Ogilvie and Wilkerson, 1969] are discussed in the preceding paper. Hirshberg *et al.* [1970] have suggested that these high helium contents may result from the sudden ejection of the helium-rich region in the corona which during the quiet preshock situation results from the retarded acceleration of helium (fig. 8).

The He^4/He^3 ratios obtained from the SWC experiments appear to be systematically lower than the ratio found in the Surveyor 3 material (table 8). Bühler *et al.* [1971] have argued that a He^4 excess of terrestrial origin in the magnetic tail of the earth could not account for this difference and that one might here observe a solar cycle effect. In fact, the Surveyor 3 exposure period coincides with the maximum of the solar cycle, and the average A_p number was 25γ . During the Apollo 11 and 12 foil exposures the A_p numbers were approximately 6γ and 12γ , respectively. Again it is indicated that during solar maximum He^4 is carried along in the solar wind more effectively than during the rest of the solar cycle. He^3 would be less affected, in accordance with the theoretical considerations discussed in the preceding section.

During quiet and quasi-stationary conditions, one would expect on the basis of the Geiss *et al.* [1970a] model a positive correlation between solar wind proton flux and helium abundance. Such a correlation is not observed [Robbins *et al.*, 1970]. It could be that the flux at 1 AU is not a good measure of the flux in the source region. If the coronal structure is dominated by streamers, we have to consider $s > 2$. Variations in s strongly influence the minimum fluxes derived in the preceding section 7, if expressed in absolute fluxes at 1 AU (*cf.* equation (18)). On the other hand, it is possible that collisions often are not quite sufficient for

accelerating $^4\text{He}^{2+}$, and the $^4\text{He}^{2+}$ abundance is strongly influenced by wave-particle interactions in the solar wind acceleration region, even under relatively quiet conditions. In this case, the heavy ions could still get their main acceleration from collisions. Argon has the highest flux factor Γ among those ions listed in table 7 that are heavier than helium. Therefore, larger abundance depletions and variations are expected for Ar than for O, Ne, Si, and Fe.

Ion separation effects in the boundary region between a plasma and a neutral gas [Lehnert, 1970] would depend on the first ionization energy. If such a process is operative at the base of the corona, then the abundances of He and Ne should be correlated, whereas O and Ar should be correlated to H.

As discussed earlier, the isotopic composition in the solar wind and in our atmosphere is nearly the same for Ar and Kr, and is quite different for Ne and Xe. The question is whether these differences are a result of isotopic fractionation or whether different nucleosynthetic sources have contributed to these noble gases. The difficulty with the first hypothesis is that the lightest gas (Ne) and the heaviest would have to be enriched, leaving the other two essentially unchanged. The second hypothesis has to explain the fact that differences of this kind in isotopic composition have not been observed for other elements.

The investigations on solar wind xenon trapped at the lunar surface have confirmed the suspicion derived from meteoritic data that solar Xe is very different from atmospheric Xe [Reynolds, 1963; Marti, 1969]. The nature of this difference has been discussed for many years, but so far it has been impossible to decide whether most of this difference is due to mass fractionation or whether we deal here with products of different nucleosynthetic origin. $\text{Ne}^{20}/\text{Ne}^{22}$ ratios as low as and even lower than the atmospheric ratio have been found in the trapped neon of some meteorites [Pepin, 1967]. However, the difference between solar neon and atmospheric neon is probably due to mass fractionation in the earth atmosphere, since the variation in the $\text{Ne}^{20}/\text{Ne}^{21}/\text{Ne}^{22}$ ratios is compatible with isotopic fractionation [Eberhardt *et al.*, 1970].

Table 8 gives a comparison of isotopic abundances of helium and neon in the solar wind, in lunar surface material, and in auritic meteorites. Where necessary, the abundances have been corrected for the "nucleogenic component" (spallation, radioactive decay). The low $\text{He}^4/\text{Ne}^{20}$ ratios in the lunar material clearly show gas losses by temperature diffusion and/or other processes. Also, in the Surveyor 3 material this ratio is

Table 8. Comparison of relative ion abundances from the Apollo SWC experiments with measured relative concentrations of solar wind particles implanted in lunar fine material, Surveyor 3 material and aubritic meteorites

| | SWC Apollo 11 (a) | SWC Apollo 12 (a) | Surveyor 3 material (b) | Lunar dust (Apollo 11) bulk (c) | Lunar dust ilmenite (c) | Lunar breccia bulk (d) | Aubritic meteorites (e) | Earth's atmosphere |
|---------------------------------|----------------------------|----------------------------|----------------------------------|--|-------------------------------|---------------------------------|-------------------------------|-----------------------|
| He^4/He^3 | 1860 ± 140 | 2450 ± 100 | 2770 ± 120 | 2550 ± 250 | 2720 ± 90 | 2720 ± 100 | 4000 ± 300 | --- |
| $\text{He}^4/\text{Ne}^{20}$ | 430 ± 90 | 620 ± 70 | 295 ± 15 | 90 ± 20 | 217 ± 10 | 55 ± 20 | 380 ± 70 | --- |
| $\text{Ne}^{20}/\text{Ne}^{22}$ | 13.5 ± 1.0 | 13.1 ± 0.6 | 13.3 ± 0.4 | 12.65 ± 0.2 | 12.85 ± 0.1 | 12.6 ± 0.1 | 12.2 ± 0.5 | 9.8 |
| $\text{Ne}^{22}/\text{Ne}^{21}$ | --- | 26 ± 12 | 31 ± 5 | 31.0 ± 1.2 | 31.1 ± 0.8 | --- | --- | 34.5 |

^aGeiss et al. [1970b]

^bBühler et al. [1971]

^cEberhardt et al. [1970]

^dHintenberger et al. [1970]; Pepin et al. [1970]

^eZähringer [1962a, 1962b]; Eberhardt et al. [1965a, 1966]; Marti [1969]

probably lowered. There is a large difference between the He^4/He^3 ratios in aubritic meteorites and in the other sources. It should be mentioned that other meteorite classes, in particular many chondrites, have varying trapped He^4/He^3 ratios, which can be as low as or even lower than those in the fine lunar material [Anders et al., 1970; Black, 1970]. We have chosen here the aubritic values, because it has been shown [Eberhardt et al., 1965a, b] that the trapped noble gases are contained at the surfaces of the individual grains of the meteorite, very similar to the solar wind gases in lunar fine material. Also the He/Ne ratio for this meteorite class is high, indicating that these meteorites have experienced relatively little diffusive losses.

There is an indication for a systematic variation in the He^4/He^3 ratio, if one compares SWC and Surveyor 3 data with the helium embedded in lunar material. Judging from the cosmic ray exposure age, the solar wind particles found in the Apollo 11 lunar fine material were probably embedded during the last few hundred million years. The breccias have collected their solar wind particles before consolidating, i.e., probably earlier than the fine material. Thus there appears to be a correlation between observed He^4/He^3 ratio and time.

However, more detailed investigations are necessary before we can eliminate the possibility that this apparent trend may be the result of secondary effects in the lunar material.

There are several possibilities to explain the differences in the He^4/He^3 ratios:

1. The He^4/He^3 ratio in the outer convective zone of the sun is constant at about 4000; He^4 is systematically depressed in the solar wind relative to He^3 . In an early phase, when the sun was more active, there was less discrimination in the solar wind and He trapped in aubrites represents this ancient solar wind.
2. There is a secular increase of the He^3 content in the outer convective zone of the sun and as a consequence the He^4/He^3 ratio in the solar wind has decreased from an early value of about 4000 to values below 3000 in recent times. Aubritic He would represent a solar wind sample from the early part of the solar history. The cause for such a secular increase in the He^3 content of the outer convective zone could be due to either nuclear reactions at the solar surface or a small degree of mixing between the outer convective zone and the core of the sun, as was suggested by Schatzman [1970].

The number of He^3 atoms produced per cm^2 at the solar surface by nuclear reactions during the lifetime of the sun can be estimated from the following relation:

$$\text{He}^3 = \frac{1-\eta}{\eta} f_{\oplus} \left(\frac{r_{\oplus}}{R_{\odot}} \right)^2 \frac{n_{\text{He}}}{n_{\text{H}}} L \sigma T_s \quad (29)$$

where f_{\oplus} is the flux of solar protons at 1 AU. Multiplication by $(r_{\oplus}/R_{\odot})^2$ gives the flux leaving the solar surface; this actually is an upper limit, since the diffusive character of the particle flow gives a radial decrease less than r^{-2} . The term η is the fraction of the accelerated particles leaving the sun, $1-\eta$ the fraction returning into the sun. L is the range of the energetic protons in number of atoms/ cm^2 , $n_{\text{He}}/n_{\text{H}}$ the abundance ratio in the sun, and T_s the age of the sun. The flux of solar protons averaged over the last 1 million years is estimated at $100 \text{ cm}^{-2} \text{ sec}^{-1}$ above 10 MeV [Finkel et al., 1971]. This corresponds to a flux of about $50 \text{ cm}^{-2} \text{ sec}^{-1}$ above 23 MeV, the threshold for He^3 production in reactions of fast protons with He^4 . The combined cross sections for all the $p\text{-He}^4$ reactions leading to He^3 or H^3 for proton energies above 23 MeV is approximately 60 mb [cf. Audouze et al., 1967]. With an estimated $n_{\text{He}}/n_{\text{H}} = 0.1$, we obtain

$$\text{He}^3 = \frac{1-\eta}{\eta} 10^{21} \text{ atoms/cm}^2$$

The production of He^3 by fast α particles on hydrogen can be neglected in this order of magnitude estimate.

The outer convective zone of the sun contains about $10^{28} \text{ He}^3 \text{ atoms/cm}^2$. Thus η , the fraction of the accelerated particles escaping from the sun, would have to be of the order of 10^{-7} . Such a low value is contrary to present ideas about flares [cf. Lingenfelter and Ramaty, 1967], and is also in disagreement with the upper limits obtained from solar neutron fluxes [Daniel et al., 1969]. A similar conclusion is reached by using the upper limit on the He^3 abundance in flare particles given by Hsieh and Simpson [1970].

3. The He^4/He^3 ratio in the solar nebula was ~ 4000 . In the sun He^3 was increased in the process of deuterium burning to give a lower He^4/He^3 ratio [Ezer and Cameron, 1965]. This ratio was then essentially constant in the outer convective zone since the sun arrived on the main sequence. In this case the aubritic meteorites obtained their trapped helium from the solar nebula.

To distinguish between these possibilities, we need a better knowledge of the present day He^4/He^3 average, we need to clarify through more observations and through theoretical work whether in the solar wind He^4 is systematically depleted, and we need to establish the long-time change—if it exists—of the He^4/He^3 ratio in the solar wind from detailed investigations of lunar surface material.

The He^4/He^3 problem is just one question of fundamental astrophysical importance that has emerged from solar wind abundance studies. Progress during the last years has been rapid, and further studies in this general field should contribute to our understanding of solar and interplanetary physics and to our knowledge of the history of the solar system.

ACKNOWLEDGMENTS

The author wishes to thank H. Leutwyler for valuable suggestions and discussions on the motion of neutral and ionized particles, and H. Chivers for critically reading the manuscript. He acknowledges discussions on various topics of this paper with J. Hirshberg, F. Bühler, H. Debrunner, P. Eberhardt, H. J. Fahr, and G. Wibberenz.

This work was supported in part by the Swiss National Science Foundation.

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C. P. Sonett Could I ask you to comment further on the $^4\text{He}/^3\text{He}$ where you showed the aubrites and the lunar case, i.e., Apollo 11 and 12. I think it is the 4000 ratio. I wonder if there is a possibility that instead of the 4000 for a fossil or primordial ratio, whether perhaps some different effect is taking place.

J. Geiss I should say first that there is other fossil helium in other meteorites, where ratios such as 2000, 3000, and 4000 exist. I selected these 4000 for the aubrites not only because it shows a difference but we have evidence of surface implantation. The aubrites are perhaps not as primordial as, for instance, the carbonaceous chondrites but I think, the matrix in the aubrites is rather original material, at least in terms of chemical composition. And one reason why I think this is an $^4\text{He}/^3\text{He}$ ratio, which should be taken seriously, is that the He/Ne is so high. When the first data from the lunar surface became available, there was some evidence that the isotopic concentration of helium varied with successively older solar winds. In the consolidated dust, ratios such as 3400 were being obtained by the lunar receiving lab, but later others have measured the same stones and don't find these ratios. A year ago or so I was much more in favor of the idea that there is a gradual change in $^4\text{He}/^3\text{He}$. Now we just don't know and we have just this old—this 4000 ratio to worry about. We don't know enough about the modern $^4\text{He}/^3\text{He}$ ratio yet, but by having a few more falls and by looking into the Surveyor material we should be able to establish some kind of average ratio. We have data on the Surveyor material and there the value is about 2700.

Unidentified Speaker Could you comment further about making the separations of ^4He and H?

J. Geiss Well, there are two ways. I'm sure there are more ways, but I've tried to discuss two. One is that there is a separation between the photosphere and base of the corona by diffusion, as was first discussed by Jokipii and DeLache. There is, of course, an effect of thermal diffusion. Gravitational settling is offset by thermal diffusion because the temperature gradient is so high and the thermal diffusion for ions is very large; I think it was pointed out very early by Chapman and by Seaton that this might cause an enrichment of the corona by heavy elements. The argument was that the corona seemed to be more abundant; for instance, in iron, but this is now not so difficult to explain.

The other is that, as I have shown, if you have a very quiet situation and radial magnetic field, a certain flux is needed to drive the helium outward and this flux is higher than even for iron. There should then be correlation between flux and helium abundance, but this does not exist. It is possible, however, that such a correlation is obliterated, for instance, by the streamers, because we refer to the flux at 1 AU; and to extrapolate this backwards to the Sun very large errors may accrue if anything like streamers exist. Then we come to the very enhanced helium abundances. I want to mention that Hundhausen has suggested that once we had a source of enhanced helium abundance and other heavy

DISCUSSION

NOTE: For the reader unacquainted with the terminology of meteoritics, the aubrites are a class of achondritic (stony and lacking chondrules) meteorites commonly called enstatite achondrites. Enstatite is a pyroxine mineral which is relatively iron-free. The name aubrite comes from the location of the first recorded fall of this class, Aubres. ED.

element abundance in the middle corona where the speeds of the heavier ions should be somewhat smaller than the speed of the protons (I think almost any model would suffice). If you suddenly drive out this gas, then you have enhanced abundance of the heavier ions. But this should also be then true for elements such as iron and oxygen.

Unidentified Speaker (Possibly Cowling): In the absence of Chapman perhaps I might make a comment about thermal diffusion. First of all, the thermal diffusion is affected very considerably by a magnetic field, but I don't think that is particularly important because one can rely fairly considerably on thermal diffusion along the magnetic field. On the other hand, one is inclined to overstress the importance of thermal diffusion. Thermal diffusion assists in separating out material to some extent, just because it is cut down less by the large size of the electrostatic forces than ordinary diffusion is, so that you would get a very considerable separation if you have no mixing. But the degree of upset by a moderate amount of mixing would be just as bad whether you have a large thermal diffusion or not.

C. P. Sonett Would you care at all to comment on where the deuterium and the ^3He come from?

J. Geiss You mean, after God or after nuclear synthesis?

C. P. Sonett Isn't it correct that there is even a question involving nuclear synthesis?

J. Geiss The general idea always has been that something like spallation will contribute to the origin of these isotopes. Schatzman has worried very much about this. He has connected it with the lithium abundance and the three elements, lithium, beryllium, and boron. Now, if you make a detailed theory there are always some problems because we know too much about the exact isotopic composition of lithium (i.e., too many measured parameters). So one has to have many theoretical parameters. But it cannot be gotten out of stellar interiors and a high energy nonequilibrium mechanism. I should say that in the solar wind as we see it on the Moon we have no evidence for deuterium.

C. P. Sonett What about ^3He ?

J. Geiss ^3He is present as we see it in the foils, but ^3He could be present on the solar surface because ^3He does not burn in the outer convective zone, I am told; there, one is rather sure that deuterium burns and I think ^6Li also burns in the outer convective zone. It may be that ^3He is marginally stable in the outer convective zone.

E. C. Roelof With regard to the ratio of protons to helium in solar flares I would like to comment that recent observations at low energies, namely, about 1 MeV per nucleon, show that the ratio H/He is quite highly variable as opposed to the case of higher energy, perhaps two magnitudes higher in energy per nucleon, whereas one gets a ratio of something like 60 rather repeatedly at those energies. At low energies during an event the ratio can change by easily a factor of 3, and in quasi-stationary corotating events even the ratio is quite variable. The most interesting ordering aspects of this is that the ratio in the low energy seems to vary in accordance with the spectral steepness of the proton or helium spectrum is a way suggested by Professor Schatzman several years ago. So, in summary, the ratio is variable to low energies and it does seem to vary as the spectral steepness of the particle spectrum varies during an event and at almost any time one observes them.

J. Geiss Do you mean this whole effect is a result of the large difference in rigidity?

E. C. Roelof No, I don't believe that it's completely that, because one finds that the C and O to helium ratios at the same velocity and hence at the same rigidity, if they are fully ionized, will also vary during events. So there are a number of possible explanations, but the possible point is that no single number can be attached to the ratio C and O to helium, helium to proton, for solar flare at these low energies.

D. Heymann May I return for a moment to the question of the $^1\text{H}/^2\text{H}$ ratio. The number is less than 50 parts in a million; but one can also look at it with some comfort because it's clear that if the spallation produced ^3He and ^{21}Ne is considered in these

samples, practically all the deuterium can be accounted for by spallation. Roughly, it depends on what is assumed for the relative yields for deuterium to the ^3He . But it says that if the galactic cosmic ray flux relative to the solar wind had been ten times higher, a deuterium concentration similar to the one you can see on earth in these lunar samples would be present. This may not be the explanation for what exists on earth, but this number of about 50 parts in a million can be viewed in different ways. You can look at it with a long face and say it shouldn't be there. You can also say this is produced by galactic cosmic rays.

J. Geiss And solar flare particles?

D. Heymann And solar flare particles.

Unidentified Speaker I would like to point out that it is not impossible that you would get changes—and if it does decelerate you would expect the heavier matter to settle out. So the flare ejecta should be expected to have the heavier material in a thin shell on the outer face. Another point I would also like to make is I think a lot of the atmospheric escape evaporation work that has been done in the past should perhaps be taken with a large grain of salt, because you have assumed temperatures for the atmosphere which are very dubious, and if there are local hot spots in the atmosphere, as now seems to be possible according to some recent results, the escape base may be much faster than we have believed in the past; hence it is not possible that the neon isotopic ratios that you showed could be explained just on that basis alone.

J. Geiss I think that's quite right.

D. Heymann Of course it is true that one has to take the 4000 number for the ^3He and aubrites seriously because you've shown that it is probably not affected by any fractionation since the helium to neon ratio is as high or similar to what you find in soils. If I adopt that argument, then I say you also have to take that ratio into combination with meteorites seriously because there, too, the ratio of 40:20 is quite high. You cannot reject one number on the basis of a certain argument and say the other one is valid.

J. Geiss I would say that is not valid, but that could be solar wind more recently.

Unidentified Speaker I can use that argument just as well to apply to a carbonaceous meteorite and say we have to accept these values.

J. Geiss Yes, but you can't say there was at one spot in the solar system a ratio of 4000, and the question is how important this was.

M. Dryer When particles strike the moon is it possible that some of them bounce off or perhaps knock other particles off?

J. Geiss Yes. The first slide I showed indicated the impacting of helium on the very well defined aluminum surface and even there the helium bounces off. Now, this very likely comes off as neutral, because there is enough time to attach all the electrons the nucleus requires for neutralization. On the lunar surface, there is a finite probability of a rapid escape at relatively high energy if the direction is right. The other possibility is that you have escape or release of these gases just by heating.