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Solar and Heliospheric Processes from Solar Wind Composition Measurements

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Phil. Trans. R. Soc. Lond. A 1994 **349**, 213-226
doi: 10.1098/rsta.1994.0126

Solar and heliospheric processes from solar wind composition measurements

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Composition measurements in the solar wind provide important information for solar system science and astrophysics. We show in this report how ion composition data are used to investigate chromospheric and coronal processes. Isotopic abundances in the Sun can best be derived from solar wind measurements. $^3He/^4He$ is an isotopic ratio with far-reaching implications. It allows us to determine the deuterium abundance in the proto-solar nebula, which in turn leads to an estimate of deuterium production in the early universe. The interstellar gas is the second most important source of heliospheric ions. Atomic abundances in the local interstellar gas are derived from ion composition measurements, and processes in the solar wind termination region and beyond are studied.

1. Introduction

Ion composition measurements in the solar wind (SW) can be used to study a large variety of processes in the solar system, ranging from the interior of the Sun to the heliospheric boundary. Furthermore, the SW elemental and isotopic composition carries unique information on the origin of planetary atmospheres, the history of the Sun and the evolution of nuclear species in the universe. We report here on some examples demonstrating the far-reaching conclusions which can be drawn from SW composition data.

The earliest composition studies, using energy/charge separation, revealed that aside from protons, alpha particles are regularly present in the solar wind (Neugebauer & Snyder 1966). However, the He/H ratio was found to be systematically lower than the solar abundance ratio. Also certain heavier elements, including oxygen, silicon and iron, have been investigated by energy/charge measurements at times of quiet, low-temperature SW conditions (Bame *et al.* 1975).

A totally different method was introduced with the Apollo SWC experiments. Specially prepared, calibrated foils were exposed at the lunar surface by the Apollo crews to capture SW particles. After the foils were returned to Earth, the particles captured in the foils were analysed by laboratory mass spectrometry, from which the abundances of the isotopes of helium, neon and argon in the solar wind were obtained with high precision (Geiss *et al.* 1970*b*, 1972).

Phil. Trans. R. Soc. Lond. A (1994) **349**, 213–226
Printed in Great Britain

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With magnetic mass spectrometers the mass/charge ratio of ions can be determined, independently of the kinetic properties of the solar wind. Such an instrument, ICE on board ISEE-3, was used to determine the abundances, charge state distributions, velocities and temperatures of He, O, Si and Fe, as well as the $^3He/^4He$ ratio under various solar wind conditions (Coplan *et al.* 1984; Bochsler *et al.* 1986 ; Ogilvie *et al.* 1992).

The recent introduction of the time-of-flight technique to solar wind studies (Gloeckler 1990) has greatly widened the scope of solar wind composition measurements. SWICS-Ulysses is such an instrument (Gloeckler *et al.* 1992). It combines energy/charge separation, acceleration by 20–30 kV, time-of-flight measurement and total energy determination, allowing simultaneous measurements of speed, mass/charge (M/Q) and mass (M) of the ion. Thus, as shown in figure 1, SWICS distinguishes ions with identical M/Q ratios, such as He^{2+} and C^{6+}, C^{5+} and Mg^{10+}, or Si^{8+} and Fe^{16+}. The separation of these pairs of ions allowed one for the first time to determine the abundances of C, Mg, Si and Fe under all solar wind conditions. The low background results from the coincidence method employed by SWICS. The events plotted in figure 1 correspond to 'triple coincidence events' (two time-of-flight and one energy detector signal). Ions that do not cause a response in the energy detector, i.e., singly charged species, produce a 'double coincidence' (the start and stop signal of the time-of-flight measurement), and thus the background is also low for these 'doubles', which is important for investigating pick-up ions of interstellar origin.

2. Origin of the solar wind

(a) *Solar wind acceleration in the corona*

The ions in the solar wind are highly charged, the distribution of charge states reflecting the temperature in the region of origin in the corona (cf. Hundhausen 1972). The correspondence between charge state distributions and coronal temperature is neatly demonstrated in figure 1, where the ion populations in the low-speed 'interstream' solar wind and the fast stream coming out of the south polar coronal hole are compared. The decrease in ionic charge in the fast coronal hole stream relative to the interstream solar wind is clearly visible in figure 1 for iron, oxygen and carbon. The shift in the charge state distributions corresponds to a difference of about 4×10^5 K in the coronal temperature.

The distribution of charge states observed in the solar wind provides constraints on theories of coronal expansion. Model calculations by various authors have lead to the following conclusion. The thermal energy of the heavy elements in the corona is not sufficient to lift them out of the corona. To account for their persistent occurrence in the solar wind momentum transfer from the light ions by Coulomb collisions (Geiss *et al.* 1970a) and from plasma waves (Hollweg 1974) is needed. Coulomb collisions are important in the subsonic regime for lifting the heavy elements up towards the critical point. Waves contribute significantly to accelerating the solar wind to hypersonic velocities, particularly in the coronal holes (Hollweg 1974; McKenzie *et al.* 1979; Bürgi & Geiss 1986). Typical coronal 'scale heights' can be brought into agreement with the maximum coronal temperature only by three-fluid models, i.e., by taking the finite abundance of helium into account (Noci & Porri 1983; Bürgi & Geiss 1986). Model calculations show

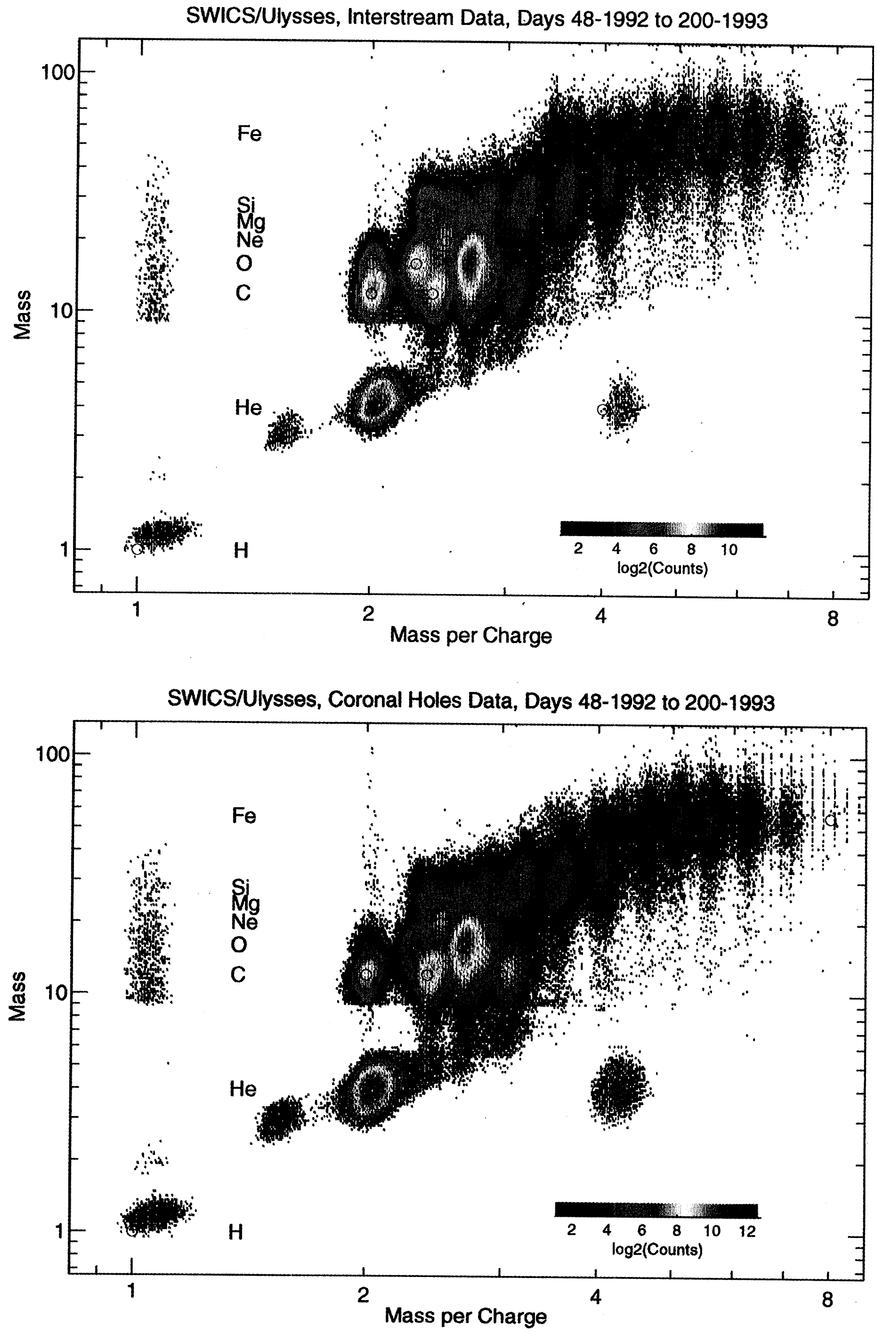

Figure 1. Mass (M) versus mass/charge (M/Q) plot of the solar wind ions measured with SWICS-Ulysses shown separately for slow SW ($V_{SW} < 600$ km s^{-1}) and high-speed stream ($V_{SW} > 600$ km s^{-1}) conditions. Plotted are the raw, directly transmitted events, giving ions with $M > 8.5$ higher priority. The background is mainly due to pile-up and accidental coincidences and can be readily eliminated by proper data processing. SWICS separates ions with identical M/Q but different M, essential for determining abundances of important elements such as C or Mg. In the fast stream coming out of the south polar coronal hole (lower panel) ions have systematically lower charges and elements with low first ionization potential are relatively more abundant than in the slow solar wind (upper panel).

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consistently that the heavy ions, including helium, are slower in the subsonic regime than the protons, leading to increased local helium abundances of 20 to 30% (Geiss *et al.* 1970*a*; Hundhausen 1972; Bürgi & Geiss 1986), thus decreasing the scale height. At the same time momentum transfer to heavy ions from protons and alpha particles becomes comparable, because the Coulomb collision cross-section is proportional to the square of the charge.

The geometry of coronal expansion is thought to be relatively simple in the large polar coronal holes. Ulysses will spend as much as a year in the southern high-speed stream. Thus we hope that detailed comparison between SW data provided by Ulysses with the information on the south polar corona provided by in-ecliptic observations (from space and from the ground), and with model calculations, will lead to a quantitative theory for the origin of the high-speed streams.

(*b*) *Element fractionation in the chromosphere: the FIP effect*

Remote observations of the corona and measurements of abundances in the solar wind and in flare particle populations give a consistent picture of an overabundance of elements with low first ionization potential (FIP), cf. Meyer (1992). Although there are some significant variations to this FIP effect, a basic pattern is recognizable in the low-speed solar wind and in large flares: elements with FIP roughly below 10 eV are overabundant by a factor of about 4 relative to the elements with FIP between 10 eV and 24 eV (cf. Garrard & Stone 1993; Bochsler & Geiss 1989). On the other hand, helium is underabundant (by a factor of 2) relative to these elements (Geiss 1982; Reames 1993). It was first recognized by observations in the magnetosheath that the FIP effect is strongly reduced in fast solar wind streams (Gloeckler *et al.* 1989; von Steiger *et al.* 1992). This has been fully confirmed by the SWICS-Ulysses measurements, as can be recognized in figure 1: the abundances of the sum of the Fe or Mg ions relative to the sum of the O ions is higher in the upper panel than in the lower panel. In table 1 we present average element abundances in the interstream solar wind and in the high-speed stream coming out of the south polar coronal hole. The latter data are preliminary, since Ulysses has yet to pass the larger part of its trajectory over the polar region The data in table 1 are evaluated and discussed by von Steiger & Geiss (1994). The relatively large differences between solar abundance and average interstream abundance are mainly due to the FIP effect. Temporal SW abundance variations are caused in the corona (well documented for the He/H ratio, Hirshberg *et al.* 1972; Borrini et al. 1981; Neugebauer 1982), but systematic fractionations are less pronounced than those caused by the FIP effect which operates in the chromosphere (see below). Since the FIP effect is much reduced in the high-speed stream from the south polar coronal hole, the abundances there are relatively close to the solar abundances (cf. table 1).

Many hypotheses have been advanced for explaining the FIP effect (cf. the recent review by Meyer 1992). Lemaire's (1990) proposal that it is caused by cometary or asteroidal debris evaporating in the corona was disproved by Geiss *et al.* (1992) who argued that solids evaporating in the corona would abundantly add low-charge ions to the SW which are not found. We have subsequently searched for low-charge SW ions over much longer periods of time with the same negative result, cf. Geiss *et al.* (1994*a*). Thus we conclude that the FIP effect is not caused by contamination of the corona, but by a process separating atoms and ions of

Table 1.

	FIP	solar wind in ecliptic	solar wind from coronal holes	SEP-based corona	photo-sphere
H	13.60	1900 ± 400 [a]	824 ± 80 [d,1]	1170 ± 89 [m]	1175 [o]
He	24.59	75 ± 20 [b]	48.5 ± 5 [d,1]	55 ± 3 [m]	115 [o]
C	11.26	0.72 ± 0.10 [c]	0.70 ± 0.10 [c]	0.428 ± 0.043 [n]	0.468 [p]
N	14.53	0.129 ± 0.008 [d,1]	0.145 ± 0.011 [d,1]	0.123 ± 0.009 [n]	0.117 [q]
O	13.62	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$
Ne	21.56	0.17 ± 0.02 [b] 0.14 ± 0.02 [e,2]	0.136 ± 0.011 [d,1]	0.142 ± 0.014 [n]	0.138 [o]
Mg	7.65	0.16 ± 0.03 [c]	0.083 ± 0.02 [c]	0.193 ± 0.011 [n]	0.0447 [o]
Si	8.15	0.19 ± 0.04 [f] 0.18 ± 0.02 [g]	0.054 ± 0.009 [d,1]	0.164 ± 0.0099 [n]	0.0417 [o]
S	10.36	0.038 ± 0.009 [d,1] 0.05 ± 0.02 [h,2]	0.019 ± 0.003 [d,1] 0.022 ± 0.008 [h,2]	0.0377 ± 0.0016 [n]	0.0191 [o]
Ar	15.76	0.004 ± 0.001 [i,2]		0.0037 ± 0.0006 [n]	0.00447 [o]
Fe	7.87	$0.19 \pm^{0.10}_{0.07}$ [j,2] 0.12 ± 0.03 [k]	0.057 ± 0.007 [d,1]	0.172 ± 0.023 [n]	0.0355 [r]
Kr [3]	14.00	3.4 ± 0.4 [l,2]			1.89 [o]
Xe [3]	12.13	0.88 ± 0.12 [l,2]			0.197 [o]

[1] Values determined in the Earth's magnetosheath
[2] Original values not referred to O
[3] Values $\times 10^6$

[a] Bame *et al.* 1975
[b] Bochsler *et al.* 1986
[c] this work
[d] Gloeckler *et al.* 1989
[e] Geiss *et al.* 1970*b*
[f] Bochsler 1989
[g] Galvin *et al.* 1993
[h] Shafer *et al.* 1993
[i] Cerutti 1974
[j] Schmid *et al.* 1988
[k] Ipavich *et al.* 1992
[l] Wieler *et al.* 1993
[m] Reames 1994
[n] Garrard & Stone 1993
[o] Anders & Grevesse 1989
[p] Grevesse *et al.* 1992
[q] Grevesse 1991
[r] Hannaford *et al.* 1992

solar origin. This process must operate at a level in the solar atmosphere where the solar gas is only partly ionized and the density is low enough to allow for separation, conditions that are met in the chromosphere (Geiss 1982).

When proposing a FIP mechanism, the modes of both ionization and separation must be specified. The circumstances of ionization are much more element specific than the process of separation. Geiss & Bochsler (1985) assumed the ionization to proceed in an optically thin medium at the solar surface and calculated the ionization as a function of time of nine important elements, taking into account excitation and ionization by photons and electrons as well as radiative recom-

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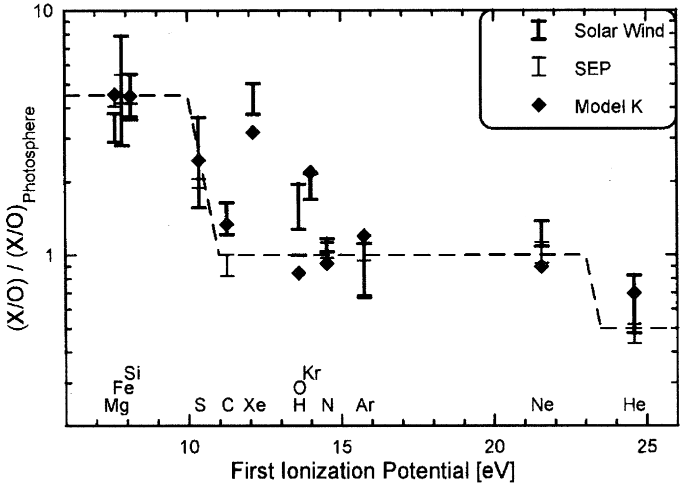

Figure 2. Abundances of elements (cf. table 1) in the interstream (slow) solar wind and solar flare particle populations are plotted as a function of the first ionization potential (FIP). The abundances are normalized to the standard solar abundances and to oxygen. The theoretical results (Model K) obtained with the ion–atom separation mechanism developed by von Steiger & Geiss (1989) are included for comparison.

bination. This mode of ionization was used in the mechanisms of von Steiger & Geiss (1989) and of Marsch *et al.* (1994). The former authors assume separation of atoms from ions across the field lines of very thin magnetic structures, the latter assume a flat geometry with diffusive ion–atom separation proceeding perpendicular to the solar surface and parallel to the $\boldsymbol{B}$-field. The FIP fractionation predicted by the first mechanism is compared in figure 2 with the abundances observed in the interstream solar wind. The agreement is reasonably good. The difference between the predictions of the two mechanisms is not very pronounced, which is not surprising, since they employ the same mode of ionization. For solar wind abundances of Kr and Xe derived from studies of the gases trapped at the lunar surface (Wieler *et al.* 1993), the mechanism of von Steiger & Geiss (1989) gives a somewhat better agreement. A comparison of figures 2 and 3 shows that not FIP, but the ionization time-scale (relative to some transport time-scale) is more directly related to the observed fractionation (cf. Geiss & Bochsler 1986). Competition between these two time-scales is of course the underlying principle of the mechanisms developed by von Steiger & Geiss (1989) and Marsch *et al.* (1994). Aluminium has a very short ionization time under solar surface conditions (figure 3), and thus this element is best suited to check on mechanisms which predict a continued abundance increase with decreasing time of ionization.

3. ^{3}He and deuterium in the proto-solar nebula

Aside from the FIP effect and some temporary fluctuations, SW abundances are remarkably close to the abundances in its source, the outer convective zone (OCZ) of the Sun. In particular, mass fractionation is small in the solar wind and thus isotopic ratios in the OCZ can be deduced with relatively little uncertainty from the corresponding ratios in the SW. With SWC-Apollo the ^{3}He/^{4}He ratio was

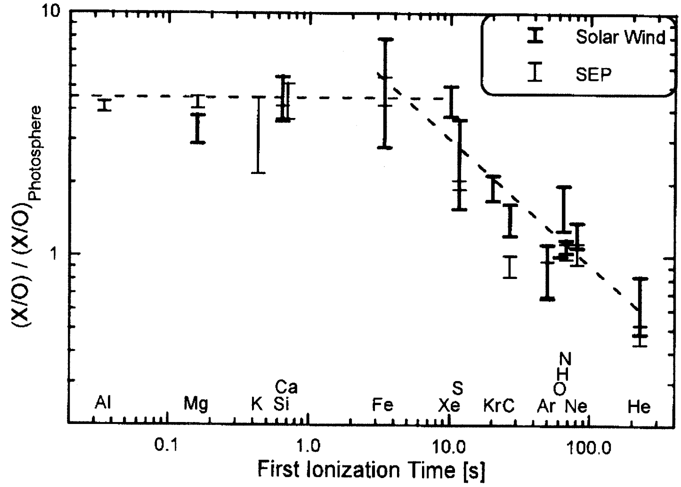

Figure 3. Abundances of elements (cf. table 1) in the interstream (slow) solar wind and solar flare particle populations are plotted as a function of time of ionization in an optically thin environment at the solar surface (cf. Geiss & Bochsler 1986).

determined in five samples taken in 1969–1972. The resulting average is listed in table 2. The Apollo data were confirmed to within 10% by the results obtained in 1978–1982 with ICE-ISEE-3 (table 2).

In the early Sun, deuterium was converted into ^{3}He which has not been further processed in the material which composes the present OCZ (Geiss & Reeves 1972). Still, the ^{3}He/^{4}He ratio in the solar wind cannot be equated with the (D+ ^{3}He)/^{4}He ratio in the proto-solar nebula without considering the potential effects of the following processes: (1) mass fractionation in chromosphere and corona, (2) diffusion of helium out of the OCZ under the influence of gravity (Michaud & Richter 1992), (3) secular transport into the OCZ of ^{3}He produced by the p–p reaction at greater depth (Bochsler *et al.* 1990; Vauclair 1992). Considering the results of composition measurements in the present and past solar wind (the latter recorded in lunar surface material), Geiss (1992) concluded that the combined effect of the three processes amounts to an increase in the solar wind ^{3}He/^{4}He ratio by a factor of only 1.1 ± 0.2, leading to the proto-solar (D+ ^{3}He)/^{4}He) ratio given in table 2. By subtracting from this the proto-solar ^{3}He/^{4}He ratio, derived from meteorite data, the proto-solar D/H ratio of $(2.6 \pm 1.0) \times 10^{-5}$ is obtained (table 2), which is very close to the value Geiss & Reeves derived in 1972 from the SWC-Apollo data. Both are by a factor of $\sim$ 6 lower than the average D abundances on Earth and in meteorites. This large factor is explained by chemical fractionation at low temperature, which most likely occurred in the dense molecular cloud from which the solar system formed (Geiss & Reeves 1972, 1981; Kolodny *et al.* 1981). The proto-solar nebula represents interstellar material of 4.6 Gy ago. In the present-day interstellar gas the D/H ratio is similar to the proto-solar gas (Vidal-Madjar 1991; Linsky *et al.* 1993), probably even somewhat lower. The low universal deuterium abundance, first derived from solar wind ^{3}He, implies an average cosmic baryon density of 4×10^{-31} g cm^{-3} which by itself is too low to close the universe (Geiss & Reeves 1972; Black 1972; cf. Walker *et al.* 1991; Geiss 1992).

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Table 2. $^3He/^4He$ *in the solar wind and the proto-solar* D *and* ^3He *abundances*

description	ratio	value	reference
solar wind			
Apollo	$^3He/^4He$	$(4.25 \pm 0.21) \times 10^{-4}$	a
ISEE-3	$^3He/^4He$	$(4.88 \pm 0.48) \times 10^{-4}$	b
ISEE-3	$^3He/^4He$	4.37×10^{-4}	c
proto-solar	$(D+ {}^3He)/^4He$	$(4.09 \pm 0.87) \times 10^{-4}$	d
	$^4He/H$	$0.10 \pm 0.01)$	e
	$(D+ {}^3He)/H$	$(4.1 \pm 1.0) \times 10^{-5}$	
	$^3He/^4He$	$(1.5 \pm 0.30) \times 10^{-4}$	f
	$D/^4He$	$(2.59 \pm 0.89) \times 10^{-4}$	
	D/H	$(2.6 \pm 1.00) \times 10^{-5}$	
interstellar	D/H	$(1.5^{+0.07}_{-0.18}) \times 10^{-5}$	g
seawater	D/H	16×10^{-5}	

[a] Geiss *et al.* 1970*b*, 1972
[b] Average flux ratio; Coplan *et al.* 1984; Bochsler 1984
[c] Average of ratios; Bochsler 1984
[d] See text
[e] Turck-Chièze *et al.* 1988
[f] Based on 'planetary component' in meteorites; Eberhardt 1974
[g] Lyman absorption towards Capella; Linsky *et al.* 1993

4. Pick-up ions of interstellar origin

The Sun moves through the local interstellar medium (LISM) with a velocity of about 25 km s^{-1}. The neutral gas penetrates into the heliosphere, and some components even reach the region of the terrestrial planets. As they approach the Sun, these interstellar atoms are gradually ionized, and the nascent interstellar ions are picked up by the solar wind plasma (cf. figure 4). In a coordinate system moving with the solar wind, the ions initially have ring-like velocity distributions which are converted into spherically symmetric distributions by wave–particle interaction (e.g., Vasyliunas & Siscoe 1976; Moebius *et al.* 1985; Gloeckler *et al.* 1993). They can be distinguished from the much more abundant solar wind ions in two ways: (1) they are singly charged in contrast to helium and heavier elements in the solar wind which are multiply charged, and (2) they have a broad velocity distribution ranging from 0 to $2V_{SW}$ (in the spacecraft frame) which contrasts with the narrow supersonic velocity distribution of the proper solar wind ions. These differences between the two particle populations are demonstrated in figure 5. Interstellar pick-up He^+ ions were discovered by Moebius *et al.* (1985). With SWICS-Ulysses we have detected, in addition to He^+, interstellar H^+ (Gloeckler *et al.* 1993), N^+, O^+ and Ne^+ (Geiss *et al.* 1994*a*) and derived the composition of the neutral interstellar gas that passes through the boundary region of the heliosphere and penetrates into its interior. The results are given in table 3 and

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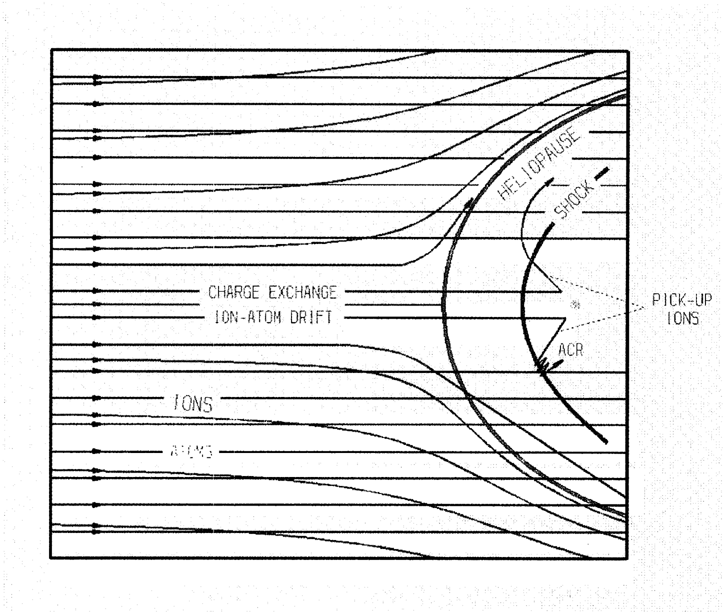

Figure 4. The subsonic case of the interaction of the local interstellar medium (LISM) with the solar wind. Shown are stream lines for incompressible flow (Parker 1963). The heliopause is estimated to occur at a few hundred AU. The stream of interstellar atoms approaching the heliosphere is partially coupled to the diverging proton stream by charge exchange, and thinned out. The interior of the heliosphere is not drawn to scale. Near the Sun, atoms are ionized by solar EUV and SW interaction, forming singly charged ions that are picked up by the solar wind plasma. When reaching the SW termination shock, these pick-up ions can be accelerated to form the anomalous cosmic rays (ACRs).

compared with the standard solar abundances (Anders & Grevesse 1989). Among the heavier elements, the only clear difference is found in the oxygen abundance (relative to helium), which is a factor of two lower in the interstellar component than in the Sun. There are potentially two reasons for this oxygen deficiency. The first is that a fraction of the oxygen in the LISM is bound in grains or is ionized, and in fact, typical O/H ratios in the dilute interstellar gas seem to be 50% lower than the solar system ratio (Jenkins 1987). This leaves not too much room for the second potential cause: oxygen loss due to charge exchange with protons in the LISM-SW interaction region.

The flow geometry of the interstellar ions around the heliosphere has been derived by Parker (1963) and Axford (1972) for the subsonic case and by Baranov *et al.* (1979) for the supersonic case. First, we discuss here the subsonic case, the geometry and flow lines of which are shown in figure 4. The neutrals would continue to proceed straight into the heliosphere if ion–atom interactions were negligible. However, as Ripken & Fahr (1983), Wallis (1984), Moebius (1990) and others have shown, charge exchange between interstellar H atoms and protons causes a partial coupling of the neutrals to the diverging proton flow which leads to a thinning-out of the atomic beam directed at the heliosphere. By solving the appropriate Boltzmann equation, Ripken & Fahr (1983) and Fahr (1991) derived that, depending on the degree of ionization in the interstellar gas, H could be depleted relative to He by a factor of 2 and even more in the neutral gas entering the heliosphere.

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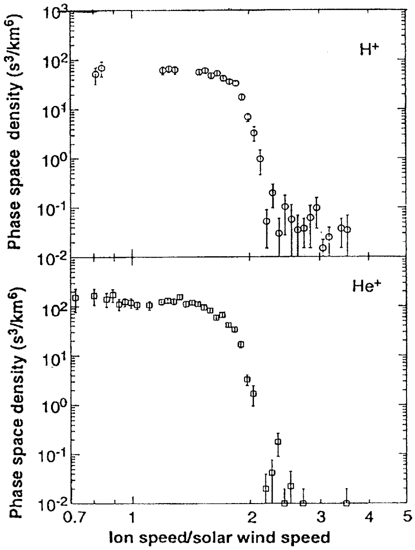

Figure 5. Mass/charge spectrum of heavy ions measured at heliocentric distances from 4.56–5.40 AU (139 days). Both double and triple coincidences are included. MQ^* is the M/Q scale valid for the multiply charged solar wind ions. The exact M/Q ratios for the singly charged interstellar ions, differing from the MQ^* scale, are marked by arrows. Since only ions with $V/V_{SW} > 1.3$ are included the background is very low. N^+, O^+ and Ne^+ were unambiguously identified (Geiss *et al.* 1994*a*).

Table 3. *Atomic abundances in the interstellar gas penetrating into the heliosphere*

	intruding interstellar gas	solar system
H/He	5.9 ± 1.2	10.2
O/He	$(3.5^{+1.8}_{-1.4}) \times 10^{-3}$	8.8×10^{-3}
He/O	290^{+190}_{-100}	114.0
N/O	$0.13^{+0.06}_{-0.06}$	0.13
Ne/O	$(0.20^{+0.12}_{-0.09}$	0.14
C/O	$\leqslant 0.15$	0.42

The depletion of O and H in the beam directed at the central region of the heliosphere can be related by comparing the corresponding reaction equations

$$H + H^+ \rightarrow H^+ + H \tag{4.1}$$
$$O + H^+ \rightarrow O^+ + H \tag{4.2}$$
$$H^+ + H \rightarrow H + H^+ \tag{4.3}$$
$$O^+ + H \rightarrow O + H^+. \tag{4.4}$$

Fahr & Ripken (1984) assumed the re-neutralization reaction (4.4) to be negligible and obtained a much stronger depletion for oxygen than for hydrogen. Fahr (1991) has made an estimate of the influence of (4.4) and concluded that this reaction is significant for LISM proton densities above 10^{-2} cm^{-3}, but that the depletion would still be much stronger for O than for H. We come to a different conclusion: the cross-sections of the reactions (4.1) to (4.4) are related as follows: $\sigma_{(1)} = \sigma_{(3)}$ and $\sigma_{(2)} = (8/9)\sigma_{(4)}$ (cf. Banks & Kockarts 1973). If charge exchange equilibrium prevails in the LISM, the degrees of ionization of oxygen and hydrogen are related by

$$O^+/O = (8/9)H^+/H. \tag{4.5}$$

As the ions are diverted around the heliosphere, the equilibrium (4.5) is disturbed, but charge exchange reactions tend to restore it. The situation is symmetric for O and H, the reaction partners being H and H^+ in both cases, and basically, (4.4) is as important for O as (4.3) is for H. However, the cross-sections and perhaps the velocity distributions are different in the two cases: the cross-sections $\sigma_{(1)}$ and $\sigma_{(3)}$ are about 3 times larger than $\sigma_{(2)}$ and $\sigma_{(4)}$, implying more intense charge exchange activity and more severe loss of H than of O. On the other hand, oxygen would have a narrower velocity distribution than hydrogen, if the two have the same temperature in the interstellar gas. Does this imply that re-neutralization is much less effective in restoring O to the neutral beam directed at the Sun than it is for H? We argue this to be unlikely, because the ions are directed around the heliosphere by electromagnetic forces, which tend to widen the velocity distributions of H^+ and O^+ similarly. Thus we conclude that – relative to helium (not much affected by charge exchange) – oxygen should not be more depleted than hydrogen in the interstellar gas entering the heliosphere. This is consistent with our experimental results for H/He and O/He given in table 3. The depletion of other species such as nitrogen should also not be stronger than that of hydrogen. The supersonic case gives generally weaker extinctions than the subsonic case (cf. Ripken & Fahr 1983), but our argument concerning the relative magnitudes of the extinction of different elements should also hold for supersonic flow.

The results in table 3 indicate that the hydrogen depletion in the interstellar gas entering the heliosphere is of the order of 40%. According to our interpretation, depletion of other atomic species is no more severe. Thus interstellar abundances, particularly those of isotopes, can be derived from observations and measurements in the inner heliosphere with relatively modest corrections.

So far we have discussed the interaction of LISM material with the heliosphere under the tacit assumption that gas and dust can be considered separately. Relatively large interstellar grains were recently discovered by Grün *et al.* (1994) at 4.5–5.4 AU, and the question arises whether evaporation from these interstellar grains could significantly augment the interstellar gas component in the innermost part of the heliosphere and whether such a component could be identified by pick-up ion measurements. We shall discussed this question in a separate paper.

Our results on pick-up ions support the view that the 'anomalous cosmic rays' (ACRs) are derived from the gaseous component in the LISM (Fisk 1976) for the following reasons. First, the ACR abundances (Cummings & Stone 1990) are in reasonable agreement with the abundances of the total ion population produced in the inner heliosphere. Oxygen, the most critical element in this respect, is

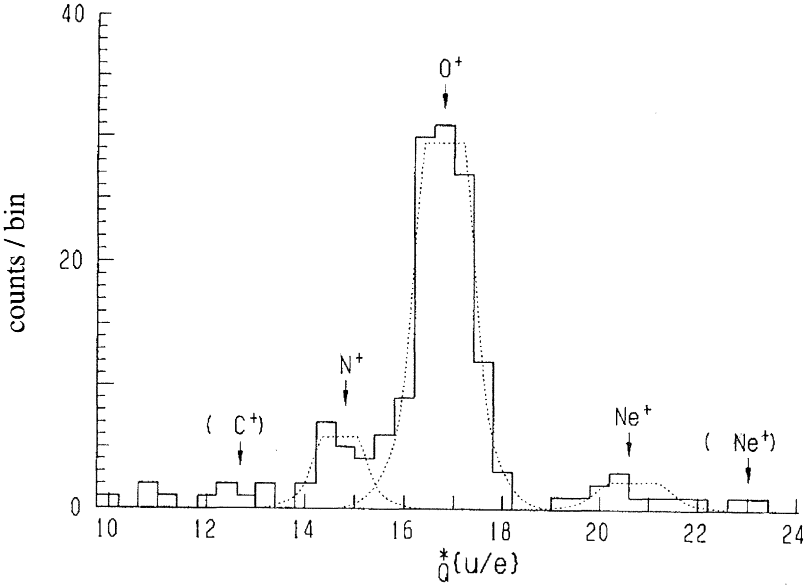

Figure 6. Velocity distributions $f(w)$ of H^+, He^+ and He^{++} as a function of w, the ion speed in the solar wind frame of reference divided by the solar wind bulk speed, observed during a one-day period (Oct 19, 1991) at the leading edge of a corotating interaction region (CIR). The spectra of He^+ and He^{++} have been normalized to that of H^+ at $w = 1$ and $w = 0$ respectively. Clear evidence for the preferential acceleration of the non-thermal pick-up He^+ is the presence of the power law tail, $f(w) = f_0 w^{-4}$, at speeds beyond $w = 1$ where interstellar He^+ is about ten times more abundant than the suprathermal tail of solar wind He^{++}, although the latter has a much higher local density.

neither strongly depleted by charge exchange in front of the heliopause, nor is it significantly augmented by O from the Jovian system (Geiss *et al.* 1994*b*). Second, interstellar pick-up ions are much favoured over SW ions in the acceleration by shocks. Figure 6 gives clear evidence for the preferential acceleration of non-thermal He^+ pick-up ions: in the energy region of accelerated particles this ion is about ten times more abundant than He^{++}, although the local density ratios of H^+:He^{++}:He^+ are about 100 : 2.5 : 0.01. The fact that H^+ and He^+ have the same spectral shape beyond $w = 1$, and He^{++} does not, indicates that a large fraction of accelerated ($w > 1$) protons are of interstellar origin.

We thank H. Balsiger, H. Fechtig, E. Grün and K. Runcorn for discussions, J. Fischer for his support and S. Wenger for help in preparing the manuscript. This work was supported by a Grant from the Swiss National Science Foundation and by NASA/JPL Contract 955460.

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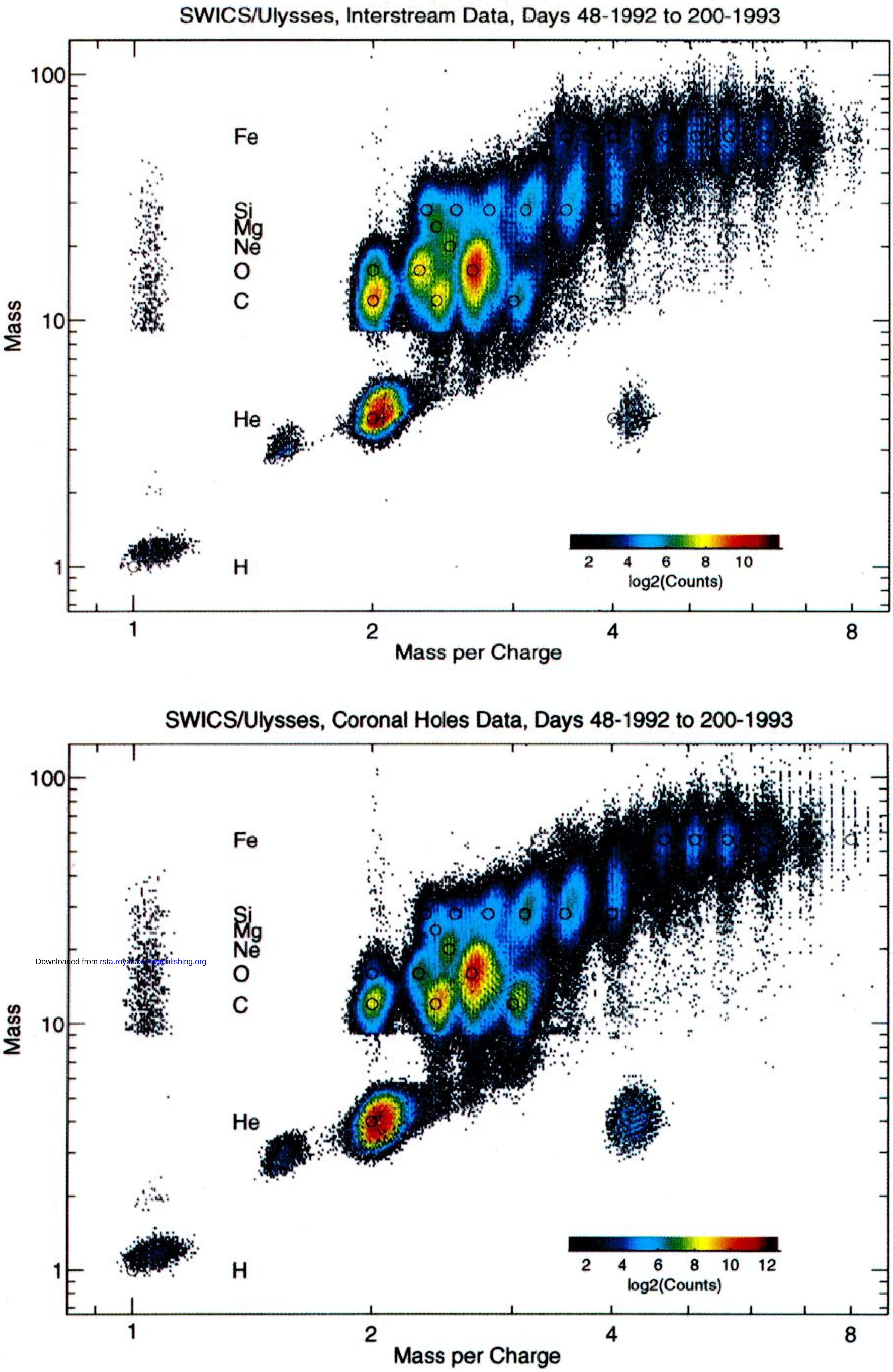
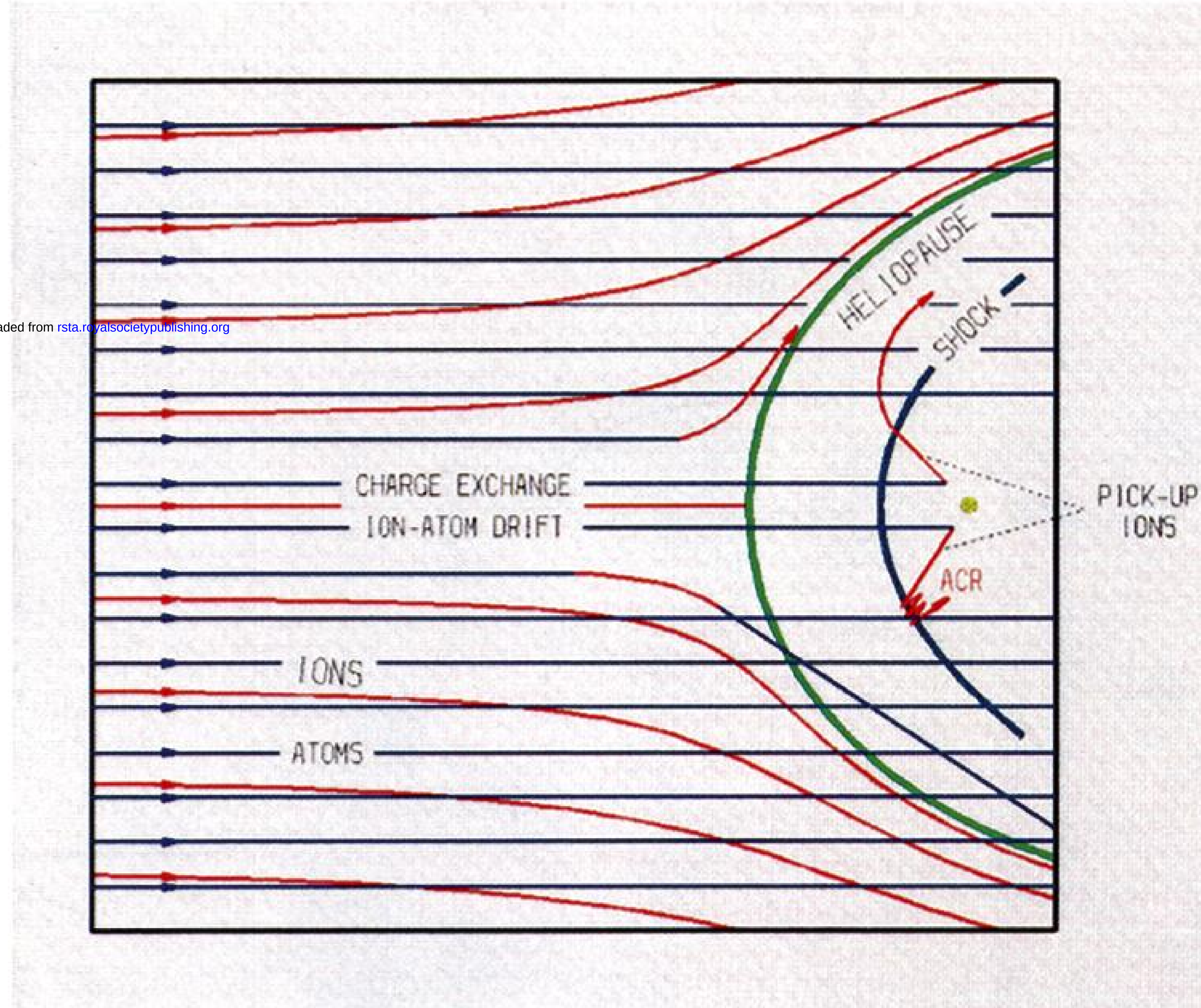


igure 1. Mass (M) versus mass/charge (M/Q) plot of the solar wind ions measured with WICS-Ulysses shown separately for slow sw ($V_{SW} < 600$ km s^{-1}) and high-speed stream $V_{SW} > 600$ km s^{-1}) conditions. Plotted are the raw, directly transmitted events, giving ions ith $M > 8.5$ higher priority. The background is mainly due to pile-up and accidental coin-dences and can be readily eliminated by proper data processing. SWICS separates ions with entical M/Q but different M, essential for determining abundances of important elements such C or Mg. In the fast stream coming out of the south polar coronal hole (lower panel) ions ave systematically lower charges and elements with low first ionization potential are relatively ore abundant than in the slow solar wind (upper panel).



igure 4. The subsonic case of the interaction of the local interstellar medium (LISM) with the lar wind. Shown are stream lines for incompressible flow (Parker 1963). The heliopause is timated to occur at a few hundred AU. The stream of interstellar atoms approaching the eliosphere is partially coupled to the diverging proton stream by charge exchange, and thinned ut. The interior of the heliosphere is not drawn to scale. Near the Sun, atoms are ionized by lar EUV and SW interaction, forming singly charged ions that are picked up by the solar wind asma. When reaching the SW termination shock, these pick-up ions can be accelerated to form e anomalous cosmic rays (ACRs).