ORIGIN OF C^+ IONS IN THE HELIOSPHERE

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Abstract. C^+ pickup ions were investigated with the SWICS instrument along the trajectory of Ulysses, covering a broad range of solar latitude and distance. Whereas nearly all the observed H^+, He^+, N^+, O^+ and Ne^+ pickup ions are created from the interstellar gas penetrating deep into the heliosphere, C^+ comes primarily from an "inner source" which is located at a solar distance below a few AU and extends over all heliospheric latitudes investigated up to now. We present evidence that the C^+ originates from carbon compounds evaporating from interstellar grains. This inner source also produces some O^+ and N^+ with estimated relative abundances of $C^+/O^+ \sim 1$ and $N^+/O^+ \sim 0.2$. However, the total amount of O^+ and N^+ produced by this inner source is only of the order of 10^{-3} as compared to the total production of O^+ and N^+ from the interstellar gas in the heliosphere, respectively. Thus the inner source does not significantly contribute to oxygen or nitrogen in the anomalous cosmic rays (ACR) but its contribution to ACR-carbon may not be negligible.

1. Introduction

Interplanetary space is filled with two types of ions which, under undisturbed conditions, can be readily distinguished by their velocity distribution functions: (1) Dominant are the regular solar wind ions observed in a characteristically narrow Mach angle that corresponds to Mach numbers of typically 10 to 20. These ions are of solar origin. (2) Next in abundance are the pickup ions which have broad "suprathermal" distribution functions that in the undisturbed solar wind show a sharp upper velocity limit at twice the solar wind speed (Möbius *et al.*, 1985; Gloeckler *et al.*, 1993). In free interplanetary space at solar distances of a few to several AU, their number densities are of the order of 10^{-3} relative to the number densities of the solar wind ions. All pickup ions identified up to now are of non-solar origin.

For presenting and discussing pickup ion results, it has become customary to relate $\mathbf{v}$, the velocity of an incoming ion to $\mathbf{v}_{SW}$, the solar wind velocity measured at that time. We thus introduce

$$\mathbf{W} = \frac{\mathbf{v}}{v_{SW}}, \tag{1}$$

the relative speed in the reference frame of the spacecraft, and

$$\mathbf{w} = \frac{\mathbf{v} - \mathbf{v}_{SW}}{v_{SW}}, \tag{2}$$

the relative velocity in the reference frame of the solar wind.

For identifying the sources of individual pickup ion species, three criteria are available:

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(1) *The velocity distribution:* Pickup ions are created from slowly moving neutrals ($W \ll 1$ or $\mathbf{w} \cong -\mathbf{v}_{SW}/v_{SW}$) by some combination of solar UV ionisation and charge exchange with solar wind ions. Prominent among the neutrals in interplanetary space are interstellar gas atoms, cometary constituents or molecules and atoms liberated from grains by evaporation or sputtering. The newly formed ions are immediately picked up by the electromagnetic field of the solar wind, and subsequent pitch-angle scattering would eventually give them a spherically symmetric, shell-like distribution in $\mathbf{w}$. When the average direction of the magnetic field $\mathbf{B}$ is nearly perpendicular to $\mathbf{v}_{SW}$, i.e. for $r > 1$ AU and low heliocentric latitude, approximately spherically symmetric distributions may indeed be achieved (Gloeckler *et al.*, 1993; Gloeckler, 1996). On the other hand, at high latitudes where the $\mathbf{B}$ field is more radially oriented, the $\mathbf{w}$ distribution remains biased in the sunward direction, i.e. ions in the neighbourhood of $W = 2$ remain underrepresented (Gloeckler *et al.*, 1995; Gloeckler, 1996). In either case, the pickup ions are adiabatically cooled in the expanding solar wind. Thus when moving away from their source region, the w distribution of these ions is shrinking. For r^{-2} expansion and an adiabatic coefficient of 5/3, $\langle w^2 \rangle \sim r^{-4/3}$ is obtained.

(2) *The charge states:* Solar wind ions of heavy elements have high charge states resulting from the coronal temperature of $\sim 10^6$ K. On the other hand, the solar EUV spectrum and the cross sections for ionisation or charge exchange with solar wind particles are such that most of the pickup ions are produced with one charge only. In interplanetary space they are removed quickly from the regions of high EUV or solar wind flux, and therefore the overwhelming majority of pickup ions produced from neutral atoms or molecules outside magnetospheres remains singly charged. The only interstellar pickup ion with two or more charges identified sofar is He^{2+}, with a low relative abundance of $He^{2+}/He^{+} \sim 2 \times 10^{-4}$ (Gloeckler and Geiss, 1994; Gloeckler, 1996). Inside magnetospheres, where lifetimes are long and electron energies are high, ions produced from neutral atmospheres may carry two or more charges (Young *et al.*, 1977; Gloeckler *et al.*, 1985; McNutt *et al.*, 1981; Geiss *et al.*, 1992), and therefore, in the wake of planets, multiply charged ions of planetary origin may be found in the solar wind.

(3) *The spatial distribution in the heliosphere:* Ions produced from the interstellar gas have a very characteristic distribution in space, which is governed by the direction of the solar apex (cf. Rucinski and Bzowski, 1996), and the solar distance of maximum abundance is roughly proportional to the ionisation rate. On the other hand, the density of ions of local origin (e.g. comets, Jupiter) decrease with distance from the source (cf. Neugebauer *et al.*, 1987; Geiss *et al.*, 1994b; Ogilvie *et al.*, 1995).

Using the three criteria given above, the interstellar origin of several pickup ions has been established: H^+ (Gloeckler *et al.*, 1993), He^+ (Möbius *et al.*, 1985; Gloeckler *et al.*, 1993); He^{2+} (Gloeckler and Geiss, 1994; Gloeckler, 1996), N^+, O^+ and Ne^+ (Geiss *et al.*, 1994a). All these ions are produced from the neutral interstellar gas flowing through the heliosphere. Recently, Geiss *et al.* (1995) have presented evidence for interstellar grains as a source of pickup ions, in particular the C^+ ions that were found at all solar latitudes and all solar distances visited by Ulysses. In this paper we present further evidence for pickup ions produced from grains in interplanetary space and discuss the origin of these grains.

2. Experimental Results

The trajectory of Ulysses combined with the high mass/charge resolution and the extremely low background of the time-of-flight mass spectrometer SWICS (Gloeckler *et al.*, 1992) on board this ESA/NASA spacecraft is providing a unique global and three dimensional

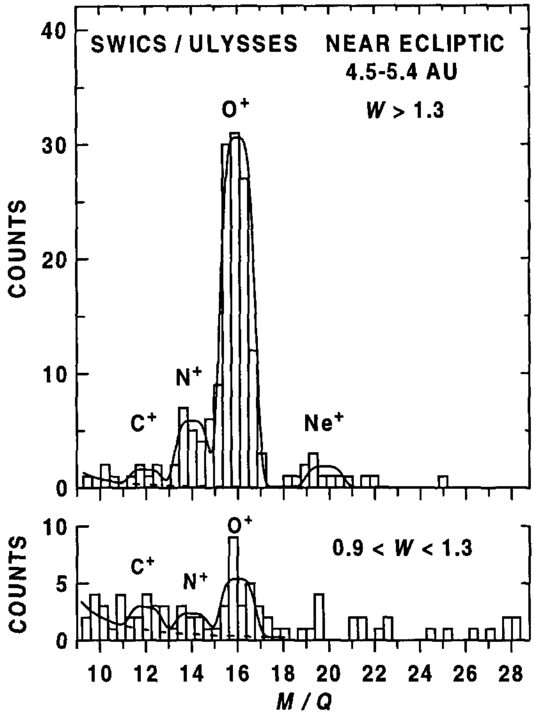

Figure 1. Mass/charge spectra in the slow solar wind near the ecliptic plane at 4.5 – 5.4 AU (139 days of data). The upper panel is for $W > 1.3$ and all azimuth directions, the lower panel is for $0.9 < W < 1.3$. Note that the upper velocity range covers more phase space than the lower one. In order to reduce residual counts from solar wind ions, one eighth of the spin period was omitted in the lower panel. No other background correction was made. Solid lines are fits to the peaks with widths proportional to M/Q. Background estimates are indicated by dashed lines. There is much less C^+ than O^+ at this solar distance, especially in the upper velocity range.

picture of densities and velocity distribution functions of the various pickup ion species. Figures 1, 4, and 6 show mass/charge (M/Q) spectra giving an overview of the occurrence of pickup ions in the M/Q range $\sim$ 9 to 30. During the time interval covered in Figure 1 Ulysses was in the slow solar wind. Since SWICS has an upper E/Q limit of 60 keV/e, corresponding to speed limits of 990 km/s and 860 km/s for C^+ and O^+, respectively, the entire velocity range of C^+ up to the limit $W = 2$ is covered in the slow solar wind most of the time, and for O^+ the velocity coverage is sufficient to allow a good extrapolation to $W = 2$ (cf. Geiss *et al.*, 1994a). O^+ can be readily recognized in both panels of Figure 1. The high abundance of O^+ in the velocity range $W > 1.3$ is in agreement with the copious production expected from ionisation of interstellar O in the vicinity of 5 AU (Geiss *et al.*, 1994a). C^+ is much less abundant at this solar distance. For $W > 1.3$ (upper panel) it cannot be clearly identified, and at lower velocity (lower panel) it can just be distinguished from the background. Geiss *et al.* (1995) have estimated total pickup ion number densities as a function of solar distance in the slow solar wind near the ecliptic plane (cf. Figure 2). From these densities we have calculated source strengths $q(r)$ for C^+ and O^+, using

$$q(r) = \frac{1}{r^2}\frac{\partial(r^2\phi)}{\partial r}, \tag{3}$$

where $\phi(r)$ (= number density times solar wind speed) is the bulk flux of the pickup ion species. The result for $q(r)$ is shown in Figure 3. Although differentiating data points with relatively large statistical errors leads to even larger uncertainties, several conclusions may be drawn from Figure 3: (a) the source locations of C^+ and O^+ are very different, (b) within the uncertainties, all C^+ ions come from an inner source which has its maximum inside 3 AU, (c) there is also an inner source of O^+ with a strength similar to that of C^+, (d) for $r > 4$ AU, O^+ is dominantly interstellar, and (e) the interstellar O^+/He^+ ratio

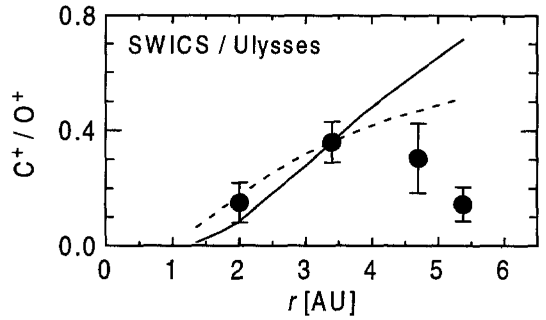

Figure 2. Ratio of the number densities of C^+ and O^+ measured near the ecliptic plane (solid circles), after Geiss *et al.* (1995). The theoretical curves show the radial dependency that would result if interstellar atomic C and O were the source of these ions. These curves were calculated for the Ulysses trajectory, using the following ionisation rates (in units of 10^{-7} s^{-1} at 1 AU): 6 for O^+ and for C^+ (dashed line), and 6 for O^+ and 12 for C^+ (solid line). The decrease of the C^+/O^+ ratio above $\sim$ 4 AU is incompatible with an interstellar gas source for C^+ and implies an inner source for this species.

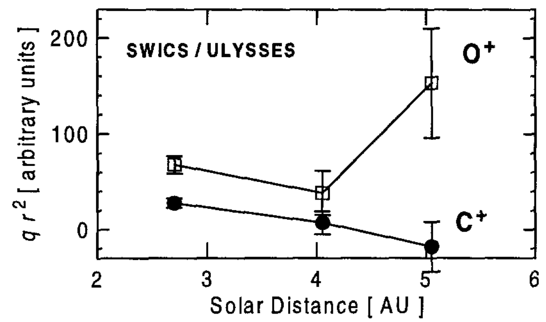

Figure 3. Location of the sources for O^+ and C^+. Given is qr^2 which was calculated from Eq. (3). Whereas $q(r)$ is compatible with the expected production of O^+ from interstellar atomic oxygen, C^+ comes from an inner source which has its maximum at $r < 3$ AU.

derived by Geiss *et al.* (1994a) is unaffected by this inner source because it was essentially based on $W > 1.3$ data taken at > 4.5 AU.

Figure 4 shows the pickup ion M/Q spectra in the high speed streams coming out of the southern and northern coronal holes, giving very similar relative abundances. The typical solar wind speed in these streams was $\sim$ 750 km/s, which corresponds to W limits of 1.33 and 1.15 for C^+ and O^+, respectively. Thus in these high speed streams, coverage of the pickup velocity spectrum is limited, and the comparison between two major W ranges that we show for the slow solar wind (Figure 1) cannot be made. Still, the observations of pickup C^+ and O^+, so clearly identifiable in Figure 4, are very important for characterising the source of C^+. This ion species is found at all the solar latitudes visited by Ulysses, showing that it is produced from an inner non-local source.

3. Discussion

The evidence presented in Figures 1 to 4 demonstrates that the observed C^+ ions are not derived from the interstellar gas, but from a source located inside of 3 AU. The persistence of C^+ over four years of observation and its occurrence at all latitudes is not compatible with one or a small number of local sources such as comets. The abundant occurrence of C^+ far away from the ecliptic plane speaks also against the asteroidal belt as the main source. Instead, the distribution in space and time of the C^+ ions points either to a relatively

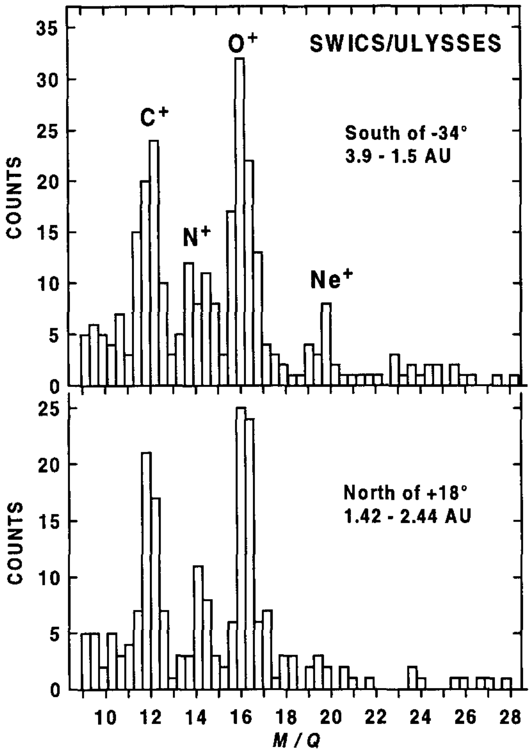

Figure 4. Mass/charge spectra of pickup ions with $W > 0.8$ in the high speed solar wind streams ($v_{SW} > 600$ km/s) originating in the polar coronal holes of the sun. Upper panel: southern high speed stream, 3.9 – 1.5 AU south of -34° (days 93.344 to 94.017). Lower panel: northern high speed stream, 1.42–2.44 AU, north of 18° (days 95.088.5–95.273.6). In order to reduce solar wind related background (e.g. accidental coincidences), ions with $W < 0.8$ were excluded. For the same reason, ions detected during the 12.5% of the spin period when the SWICS aperture included the solar direction were omitted. No further background corrections were made. The M/Q spectra are very similar, an indication that O^+, N^+ and C^+ are derived from extended sources.

large number of small comets ("mini-comets", cf. Brandt *et al.*, 1996) or to dust grains as the primary source. With their dust detector on Ulysses, Grün *et al.* (1993) and Baguhl *et al.* (1995, 1996) have measured the fluxes and arrival directions of dust grains as a function of solar latitude and distance, and they concluded that at solar distances > 3 AU and/or away from the ecliptic plane most of the grains with masses > $2.5.10^{-14}$ g are of interstellar origin, for which they estimate a flux of 3×10^{-17} g m^{-2}s^{-1}. Carbon compounds evaporating from these grains seem to provide a good explanation for our C^+ observations. A few AU is a reasonable distance for loss of carbon compounds from which C^+ is then produced by dissociation/ionisation.

The calculation of partial and total densities from the observed counts involves uncertainties that are not small. They cancel, however, to a large extent, if abundance ratios are considered and if conclusions are drawn from radial trends. Thus we consider the radial trends presented in Figures 2 and 3 as convincing evidence for an inner gas source from which C^+ is produced from carbon compounds or atoms by solar UV and solar wind charge exchange.

In an attempt to distinguish between a finite number of local sources such as mini-comets and a truly distributed source such as free grains, we have studied the distribution of time intervals between individual pickup ion registrations. The result, shown in Figure 5, is that the events, both for all pickup ions with $M/Q > 10$ and for C^+ are compatible with an exponential distribution, i.e. the counts are Poisson distributed. Thus, within the statistical uncertainties we have no indication of a contribution of C^+ ions from point sources, or else we should observe deviations from the exponential distribution. Even if statistically superior data would be available, the case for mini-comets is difficult to falsify,

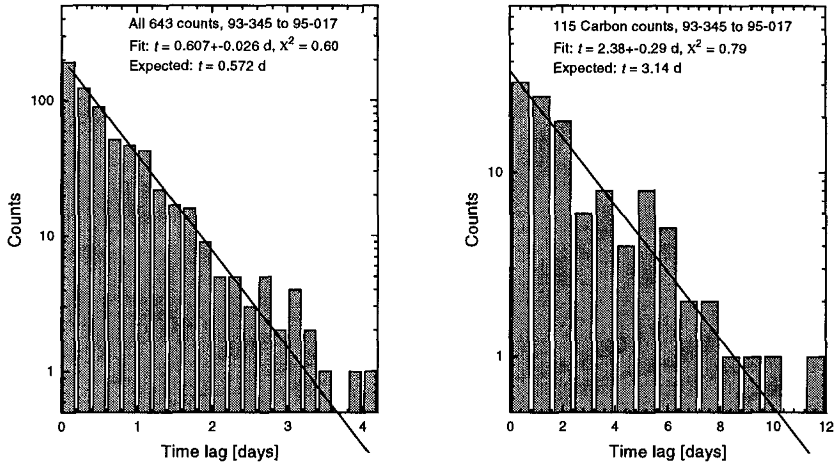

Figure 5. Distribution of time intervals between two adjacent pickup ions detected by SWICS (All ions with $M/Q > 10$ on the left, C^+ ions on the right). For both ion populations, the exponentials are shown that would result for Poisson distributed events, assuming constant a priori probabilities. Within the statistical uncertainties the distributions of events are in agreement with the Poisson distribution. Thus no evidence for one or a few local sources was found.

because of its largely hypothetical nature. We therefore conclude that the best and most consistent explanation of our results is that the C^+ ions observed outside the ecliptic plane are produced from interstellar grains.

For discussing the relative strengths of heliospheric ion sources, Geiss *et al.* (1995) introduced a solar ionisation cross section, for both the interstellar gas and grain sources. If grains are the source, evaporation of a volatile component, followed by dissociation and ionisation give an effective solar distance of ion formation, $R_{\rm eff}$, which defines a geometric cross section

$$\sigma_{\rm ion} = \pi R_{\rm eff}^2 (1 + 2R_f/R_{\rm eff}). \tag{4}$$

The term $(1 + 2R_f/R_{\rm eff})$ allows for gravitational focussing. R_f, a characteristic "focussing distance" is given by $R_f = G(1-\mu)M_{\rm Sun}/v_0^2$ (v_0 is the grain speed in the distant heliosphere). The factor $1-\mu$ allows for a reduction of focussing due to radiation pressure which is important for small grains. With $v_0 = 25$ km/s and neglecting radiation pressure, we have $R_f = 1.44$ AU.

From Figures 3 and 4, we can estimate only an upper limit for the solar distance of maximum C^+ production. Adopting $R_{\rm eff} \cong 2.0$ gives $\sigma_{\rm ion} \cong 30$ AU^2 for the inner C^+ source we have identified here.

Assuming $R_{\rm eff} = 3$ AU and disregarding gravitational focussing, Geiss *et al.* (1995) estimated the C^+ flux at $R_{\rm eff}$ and obtained $\phi_{C+}(R_{\rm eff}) \sim 1 \times 10^{-18}$ g m^{-2}s^{-1}. Using their procedure we get the same value for $\phi_{C+}(R_{\rm eff})$, using $R_{\rm eff} = 2$ and including gravitational focussing. A C^+ flux of 1×10^{-18} g m^{-2}s^{-1} corresponds to a few percent of the interstellar grain flux of 3×10^{-17} g m^{-2}s^{-1} (Grün *et al.*, 1993; Baguhl *et al.*, 1995, 1996). This is a reasonable percentage if a significant fraction of the carbon in the grains is lost at a few AU.

Figures 2, 3, and 4, indicate that inner sources also supply some O^+ and a small amount of N^+. In fact, comparison of our data with the predictions for the production of O^+ and N^+ from the interstellar gas confirms that we have an excess of these ions for

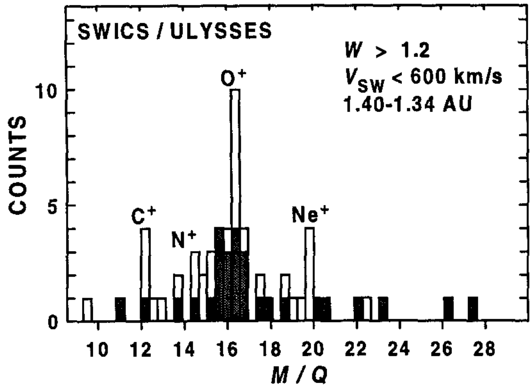

Figure 6. M/Q spectra of ions with $W > 1.2$ in the slow solar wind ($v_{SW} < 600$ km/s) during Ulysses' crossing of the ecliptic plane in the spring of 1995. The data were taken during 49 days when Ulysses travelled from $-22°$ to $+18°$ solar latitude (1.34 – 1.4 AU). The shaded areas represent ions observed near the solar equator, ($-8°$ to $+8°$ solar latitude). The O^+/C^+ ratio is increased in this equatorial region relative to higher latitudes.

solar distances below ~ 3 AU. We can only give here a rough estimate of the relative abundances of C^+, N^+ and O^+ supplied by inner sources, because at high latitude, in the fast streams, SWICS covers only a limited part of the velocity distribution, and near the ecliptic plane in the slow solar wind, where the coverage is more complete, we have a somewhat higher background in the E/Q ranges where these pickup ions occur. Assuming that the radial source distributions for C^+ N^+ and O^+ are similar, we estimate $C^+/O^+ \cong 1$ and $N^+/O^+ \cong 0.2$ at high latitude. Near the ecliptic plane the O^+/C^+ ratio appears to be higher (cf. Figure 3). This is confirmed by the data of Figure 6 which gives the pickup ion counts obtained during Ulysses' crossing through the region of low heliographic latitude at 1.34 AU in the spring of 1995. In particular, the region from $-8°$ to $+8°$ gives a low C^+/O^+ ratio, an indication that near the ecliptic plane and inside ~ 3 AU, grains of solar system origin might contribute to the production of O^+. (assuming that such grains produce a higher C^+/O^+ ratio than interstellar grains). In fact, Grün (1996) did find an increase in the number density of grains by a factor of ~ 3 during Ulysses' ecliptic crossing in 1995 which may be due to grains of solar system origin.

4. Conclusions

The solar ionisation cross section for the interstellar gas source may be written as

$$\sigma_{\text{ion}} = \int \beta\, n\, r^2\, dr\, d\Omega / f_0. \tag{5}$$

$\beta(r) = \beta_e(R_e/r)^2$ is the local ionisation rate, β_e is this rate at 1 AU (R_e), n is the local number density of the neutral species, and $f_0 = n_0 v_0$ is the neutral flux at large distance. Assuming a spherical shape of the termination shock, Geiss *et al.* (1995) have evaluated this integral and obtained for the ion production cross section in the supersonic part of the heliosphere

$$\sigma_i = 4\pi R_{\text{ion}}\{R_{\text{sh}} - \kappa R_{\text{ion}}\}, \tag{6}$$

where R_{sh} is the distance to the termination shock, $R_{\text{ion}} = \beta_e R_e^2/v_0$ is a characteristic ionisation distance, and κ is a slowly varying function of $R_{\text{sh}}/R_{\text{ion}}$ that is obtained numerically. Equation (6) is valid for $R_{\text{sh}} > R_{\text{ion}} > R_f$ and thus applicable for C, N and O.

The cross section for the production of interstellar ion species, σ_{ion} (Eq. 6) increases linearly with R_{sh}, which explains the dominance of the interstellar gas as the source of

Table I

Estimates of total production, in tons per second, of C and O ions from major sources in the heliosphere (1 ton = 1000 kg).

	C [tons/s]	O [tons/s]
Solar wind ($C^{4+,5+,6+}$, $O^{6+,7+,8+}$)	1×10^4	2×10^4
Interstellar gas (from O^+ pickup ions)[a]		2×10^3
Interstellar grains, inner source (C^+, O^+)[b]	2	2
Interstellar gas (from ACR)[c]	10	2×10^3
Halley, outbound at 0.9 AU (C^+, O^+)[d]	2	15
Io-Torus, fast atoms (O^+)[e]		< 0.3
Mars, total O^+ release[f]		10^{-3}

References for data and theoretical work on which these estimates are based:

[a] Geiss *et al.* (1994a)

[b] this work

[c] Cummings and Stone (1990, 1995, 1996)

[d] Krankowsky *et al.* (1986), Eberhardt *et al.* (1987), Jessberger and Kissel (1991), Geiss (1987), Altwegg *et al.* (1993)

[e] Cheng (1986), Luhmann (1994), Geiss *et al.* (1994b), Ogilvie *et al.* (1995)

[f] Lundin *et al.* (1990)

heliospheric ions and of the anomalous cosmic rays (Fisk *et al.*, 1974; Cummings and Stone, 1990). Assuming $R_{\rm sh} = 80$ AU (Cummings *et al.*, 1993; Gurnett, 1995) and $R_{\rm ion} = 3.6$ AU (corresponding to $\beta_e = 6 \times 10^{-7}$ s^{-1}) numerical integration yields $\kappa = 5.8$, leading to $\sigma_{\rm ion} = 2700$ AU^2 for the production of O^+ from interstellar atomic O, which is nearly two orders of magnitude larger than the cross section (Eq. 4) we have estimated for the inner source.

The cross sections given in Eqs. (4) and (6) allow us to compare the strengths of the interstellar gas source with grain sources and local sources. Estimates for some relevant sources are given in Table I. The production of C^+ and O^+ by Halley's comet was calculated assuming 100% of C and O in the gas and 80% of C and 50% of O in the grains were eventually transformed into C^+ and O^+ by evaporation, dissociation and ionisation. The ion production from the interstellar gas derived from ACR measurements were normalized to the O^+ production derived from the pickup ion measurements. With the exception of the O^+ loss from Mars, we have not included here ions leaking out of magnetospheres of planets. Their occurrence in space is essentially limited to the wake region of the planet, which can be avoided when studying ions from extended sources.

Table I indicates that the interstellar gas is the main source of O^+ ions in the heliosphere. The same ought to be true for H^+, He^+, N^+ and Ne^+, because these elements are strongly depleted in asteroids, comets and small planets. In the case of H^+ ions the separation from solar wind protons is obtained from the velocity distribution (Gloeckler *et al.*, 1993; Gloeckler, 1996).

Thus the measurements of the chemical composition, charge states and spatial distribution of pickup ions confirm that the source of hydrogen, helium, nitrogen, oxygen and neon in the anomalous cosmic rays is the interstellar gas (Fisk *et al.*, 1974). The situation with carbon is more complex. Atomic carbon (CI) is observed in the diffuse interstellar medium (Jenkins, 1987). Thus the gas in the local interstellar cloud (LIC) is probably an important source for ACR carbon. However, the abundance of C in the ACR is very low (Cummings and Stone, 1990, 1995, 1996), so that other sources, such as interstellar grains, may be significant (cf. the estimates for C sources from the ACR and from the inner source in Table I). Our measurements imply that a measurable fraction of the carbon in the local interstellar cloud is contained in grains. Thus the carbon in the LIC occurs in three forms: in grains, in the neutral gas, and in ionized form, and none of these forms seems to be negligible. This makes a determination of the degree of ionisation of the carbon in the gas phase of the LIC difficult.

The inner source of pickup ions located at a solar distance of a few AU could significantly contribute to the particles accelerated in corotating interaction regions (Geiss *et al.*, 1995). The C/O ratio of these particles is higher than the solar ratio (Gloeckler *et al.*, 1979; Fränz *et al.*, 1995). Since pickup ions are much more efficiently accelerated by shocks than solar wins ions (Gloeckler *et al.*, 1994) the relatively high abundance of pickup C^+ produced by the inner source could increase the C/O ratio of the CIR particles that are accelerated between 1 and a few AU.

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