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Elemental composition of the inner source pickup ions

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Abstract. Observations of the composition of inner source pickup ions in the solar wind, from the Solar Wind Ion Composition Spectrometer on Ulysses, are presented. The composition is similar to that of the solar wind and, in particular, contains volatile elements such as neon. These observations suggest strongly, and perhaps conclusively, that inner source pickup ions result from solar wind particles that are embedded in dust grains and then released. Our observations also suggest that inner source pickup ions may be an important source for particles accelerated at shocks surrounding corotating interaction regions since the resulting composition will resemble that of the solar wind, as is observed. Mechanisms are described whereby inner source pickup ions can be preferentially injected into the shock acceleration mechanism.

1. Introduction

Geiss et al. [1995] presented observations from Ulysses that demonstrated that there is an additional source for pickup ions in the inner heliosphere from the release of slow moving neutrals from dust grains. Such grains orbit the Sun and release neutrals from the impact of solar ultraviolet radiation. The resulting neutral particles also undergo photoionization and charge exchange and become pickup ions. Unlike interstellar neutral gas, the composition of the dust grains is not limited to particles that are neutral in the interstellar medium. Indeed, *Geiss et al.* [1995] identified the inner source through the observation of pickup C^+.

We present here a more detailed analysis and discussion of the composition of inner source pickup ions as measured by the Solar Wind Ion Composition Spectrometer (SWICS) instrument on Ulysses at < 2 AU from the Sun, at low to middle heliographic latitudes. The observations reveal that the composition of the inner source is, in general, similar to that of the solar wind. Two conclusions are immediately evident. First, the likely source for the inner source pickup ions is the solar wind itself, which has become embedded in the dust grains and then released as slow moving neutral particles. For example, the inner source contains Ne, which is a component of the solar wind but an unlikely component of dust grains. Second, the inner source ions are a possible source for particles that are accelerated in corotating interaction regions (CIRs) at low latitudes. As we discuss, these particles may have some advantages in being preferentially injected into shock acceleration mechanisms, and unlike heavy interstellar pickup ions, the inner source pickup ions will yield the observed composition for the accelerated particles.

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2. Observations

SWICS on Ulysses provides unique identification of the solar wind and pickup ions [*Gloeckler et al.*, 1992]. SWICS uses the techniques of energy per charge analysis, followed by post acceleration of ions by 23 kV, and a time-of-flight and energy measurement to identify ions and sample their distribution functions once every 12 min. Because of the double and triple coincidence techniques used, the background levels are exceedingly low and allow measurements of the very low flux levels of pickup ions. It is necessary, however, in order to determine the composition of minor ions in the inner source, to integrate over extended periods of time. The results present here are thus representative of the average composition of the inner source pickup ion population.

Shown in Figure 1 are the velocity distribution functions of the inner source O^+, C^+, and Ne^+ pickup ions observed with SWICS from November 21, 1994, to May 30, 1995, at low and middle latitudes (< 60°) during the fast latitude scan of Ulysses. The average heliocentric distance and latitude of Ulysses were 1.49 AU and -5.9°, respectively. The distributions are plotted versus the speed of the ions relative to the solar wind speed W in a stationary reference frame relative to the spacecraft. The distribution functions have certain characteristics: (1) they peak at or below the solar wind peak at W=1, and (2) they are relatively cold, in that their effective thermal speed would be small compared to the solar wind speed.

The distribution functions for the inner source pickup ions in Figure 1 are in clear contrast with the usual interstellar pickup ion distributions [*Gloeckler and Geiss*, 1998]. The interstellar pickup ion distribution is quite broad and extends with nearly equal phase space density up to $W \approx 2$, after which there is a sharp cutoff. Interstellar pickup ions gyrate about the magnetic field in the solar wind immediately following their ionization. Although initially they will propagate inward in the frame of the solar wind, upon scattering they can reverse direction, in which case they can acquire speeds (in the spacecraft reference frame) up to the sum of twice the solar wind speed and the initial speed of the slow moving (compared to the solar wind) neutrals; that is, $W \approx 2$. The same process should occur for the inner source pickup ions. However, in the case of the inner source ions the particles result from the absorption of solar wind ions by heliospheric grains and the reemission of neutrals. N. A. Schwadron et al. (Inner source dis-

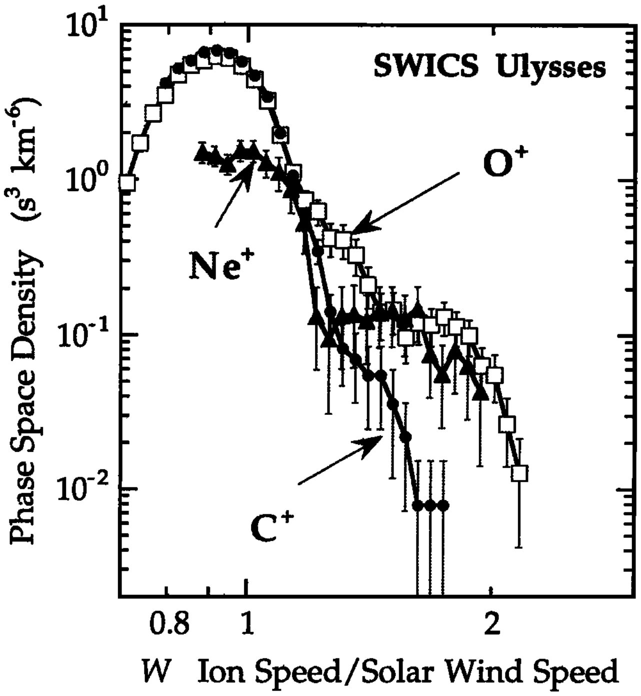

Figure 1. Velocity distribution functions of C^+, O^+ and Ne^+ averaged over the period from November 21, 1994, to May 30, 1995. The large densities of the inner source are clearly evident below $W = \sim 1.2$ not only for C^+ and O^+ but also for Ne^+. Weak contribution of the interstellar distributions are seen for O^+ and Ne^+ above $W \approx 1.2$, but not for C^+.

tributions: Theoretical interpretation, implications, and evidence for inner source protons, submitted to *Journal of Geophysical Research*, 1999a, hereinafter referred to as Schwadron et al., submitted manuscript, 1999a) have shown that the absorption, reemission, and ionization processes that produce the observed inner source pickup ion distributions occur near the Sun, and thus the inner source pickup ions suffer substantial adiabatic cooling. The distribution functions in Figure 1 are clearly weighted toward speeds $W < 1$. The particles thus suffer relatively little scattering and retain their inward motion in the frame of the solar wind. The expansion of the solar wind, however, will tend to reduce the particle speeds perpendicular to the magnetic field and substantially cool the distributions. Modeling of the expected propagation of the inner source pickup ions and the radial profiles for the ionization are presented by Schwadron et al. (submitted manuscript, 1999a).

In Figure 2 the mass histogram of the inner source singly charged heavy pickup ions at low to middle latitudes is displayed. The SWICS observations were made during the same time period as those used in Figure 1. To exclude contributions from interstellar pickup ions [e.g., *Gloeckler and Geiss*, 1998] and to reduce background from multiply charged solar wind ions, we selected ions with W between 0.8 and 1.2. In addition to peaks at masses 12, 16, and 14 amu (C^+, O^+, and N^+), peaks at masses 20, 24, and 28 (Ne^+, Mg^+, and Si^+) are also observed, indicating the presence of these elements in the inner source ions. We note that our detection of Ne in the inner source pickup ion population argues strongly that the solar wind is the source for this volatile element.

In Figure 3 we compare the distribution function of Mg^+ to that of Ne^+ shown in Figure 1. The spectral shape of Mg^+ is similar to that of the other inner source pickup ions shown in Figure 1. The phase space density peaks below $W = 1$. No contributions from interstellar Mg^+ are evident as is expected.

In Table 1 the composition of the inner source pickup ions is compared to average solar wind abundances and the average composition of energetic particles accelerated in CIRs. The abundances of the inner source pickup ions were derived from the respective distribution functions of the individual ions (such as those shown in Figures 1 and 3) in the usual manner [e.g., *Gloeckler and Geiss*, 1998]. The inner source data were averaged for the same time period as in Figure 1, and the ratios are relative to Ne^+, the inner source pickup ion that most likely is recycled solar wind neon. Note that we have not presented data for inner source He^+. Interstellar neutral He penetrates to within ~1 AU or less of the Sun and creates a strong pickup ion population even at the heliocentric distances of Ulysses. In the presence of this strong component, inner source He^+ cannot be distinguished; however, a relative abundance of inner source He^+ not unlike that in the solar wind cannot be ruled out. The abundance of inner source H^+ was obtained from the pickup proton spectrum taken when Ulysses was in the ecliptic plane at 1.35 AU during the time period from February 13 to March 24, 1995, using the technique described by *Gloeckler and Geiss* [1998] and Schwadron et al. (submitted manuscript, 1999a).

We note that the abundance ratios of most of the inner source pickup ions are similar to within a factor ~2 or less to those of both the solar wind and energetic particles accelerated in CIRs. The exceptions are the H^+/Ne^+ and O^+/Ne^+ ratios, which are smaller by factors of ~2 – ~4 for inner source pickup ions compared to CIR, and solar wind ratios.

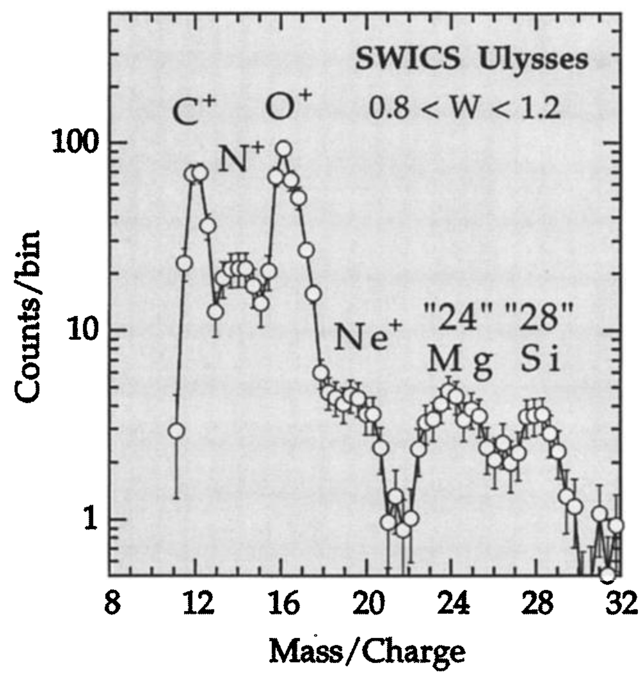

Figure 2. Mass per charge distributions of heavy pickup ions in the inner source. These data were taken over the same time period as in Figure 1. A five-point running average of counts in mass/charge bins > 17 was used to smooth the data. Peaks at mass/charge 24 and 28 are clearly visible, indicating the presence of singly charged Mg and Si (as well as C, N, O, and Ne) in the inner source.

3. Interpretations and Implications

There are several interesting implications for the comparison between the composition of inner source pickup ions and that of the two other constituents given in Table 1:

3.1. Origin of the Inner Source

If we compare, element by element, the composition of the inner source and the composition of the average solar wind, there are interesting similarities and differences. To begin with, all the elements in the solar wind are present in the inner source, with, in a general sense, similar abundances (with the exception of inner source He, which we cannot determine). To within the error bars the N/Ne, the Mg/Ne, and the Si/Ne ratios are the same for inner source pickup ions and the solar wind. The C/Ne ratio is lower by a factor of ~2 in the inner source compared to the solar wind. The principal differences, however, among the various constituents are in the H/Ne and O/Ne ratios. In the inner source pickup ion population these ratios are substantially lower than they are in the solar wind.

The first and most compelling conclusion is that the similarities between the inner source pickup ion composition and that of the solar wind are sufficiently strong so that a solar wind origin for the inner source ions is likely. This is a particularly strong argument because of the Ne abundance in the inner source pickup ion population. Ne is a volatile element and is unlikely to be present in the ambient composition of either interstellar or interplanetary dust grains [*Anders and Grevesse*, 1989]. Presumably then, the dust grains near the Sun [*Leinert et al.*, 1981, 1983; *Leinert and Grün*, 1990] act as reservoirs in which solar wind particles become embedded, as discussed some time ago by *Banks* [1971]. This solar wind material is then released from the dust grain primarily as a neutral particle [*Fahr et al.*, 1981; *Johnson*, 1990] and becomes ionized by photoionization and charge exchange in the solar wind to form much of the inner source pickup ion population we observe. The dust grains, particularly at low and middle latitudes, are concentrated fairly close to the Sun and in some instances are in relatively stable orbits [e.g., *Leinert and Grün*, 1990]. On the basis of their analysis of inner source pickup ion distribution functions, Schwadron et al. (submitted manuscript, 1999a) find that dust releasing the neutrals that become the inner source pickup ions is concentrated at ~10 – ~50 solar radii. At these distances these dust grains are bathed by strong solar wind fluxes, and the surface of the grains should become saturated with solar wind particles. The physics of these various complicated processes has been discussed in detail by *Gruntman* [1996] and *Fahr et al.* [1981].

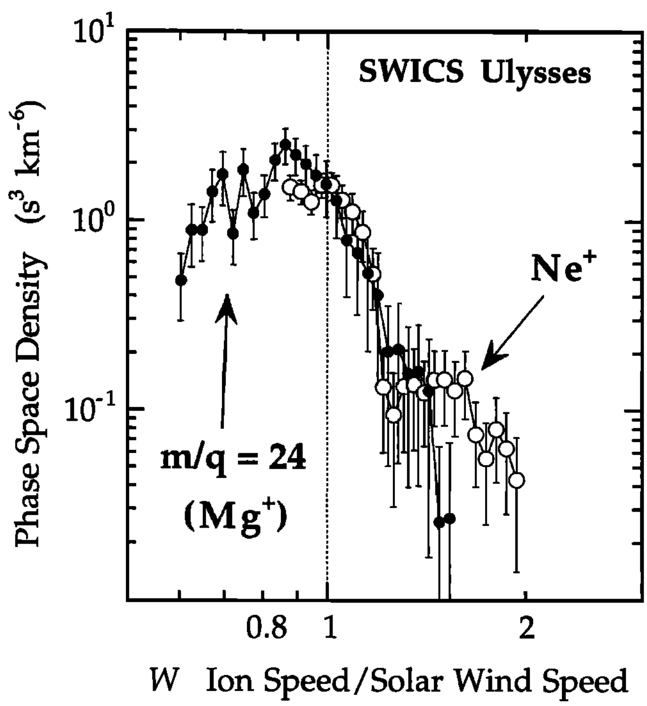

Figure 3. Velocity distribution functions of Ne^+ and Mg^+ pickup ions observed with the Solar Wind Composition Spectrometer during the same time period as in Figure 1. The large densities of the inner source are clearly evident for $W < 1.2$ for both Ne^+ and Mg^+. Contributions of the interstellar Ne^+ are apparent above $W \approx 1.2$. No interstellar features (flat spectrum with a cutoff at $W = 2$) are seen for Mg^+. Ne^+ below $W \approx 0.85$ could not be measured because of spillover contributions from the more abundant neighboring O^+.

Table 1. Element Abundance Ratios (Relative to Ne) of the Inner Source Pickup Ions, the Low Solar Wind, and Energetic Particles Accelerated in CIRs

Element	Inner Source[a]	Solar Wind[b]	CIR Particles[c]
H	7710±1560[d]	12000±5100	33100±10500
He	---------	900±260	1000±88
C	4.57±0.38	8.1±1.1	4.88±0.25
N	1.24±0.16	1.5±0.2	0.91±0.12
O	3.13±0.18	11.4±0.9	6.25±0.31
Ne	1.00±0.17	1.00±0.10	1.00±0.13
Mg	1.52±0.19	1.40±0.28	0.70±0.09
Si	0.99±0.18	1.30±0.17	0.70±0.19

[a]Pickup ions from the low and middle latitude (< 60°) extended inner source (present work).
[b]Average of the fast and slow solar wind abundances compiled by *von Steiger et al.* [1997]. The solar wind Ne abundance we derived from SWICS data using a sophisticated composition analysis developed by N. A. Schwadron et al. (Techniques for analysis of data from time-of-flight instruments, submitted to *Journal of Geophysical Research*, 1999b).
[c]Compiled by *Keppler* [1998].
[d]Errors are due to statistical uncertainties only.

The differences in the composition of the inner source pickup ions and the solar wind may be equally interesting. There appears to be a systematic under abundance in inner source H^+/Ne^+, C^+/Ne^+, and O^+/Ne^+. Hydrogen, as well as neon, should be under abundant in the ambient composition of interplanetary and interstellar grains. Indeed, the presence in the inner source of these elements, particularly Ne, provides strong evidence that the release of the ambient grain material is not the main source of inner source pickup ions. In the case of Ne this element will not form molecules. In contrast, H, C, and O could bind into, for example, H_2 and CO and be released in this form as neutrals, ionized molecules, or perhaps, even negatively charged molecules. Subsequent release of molecules may involve a number of branches [e.g., *Gruntman*, 1996; N. A. Schwadron and J. Geiss, On the processing and transport of inner source hydrogen, submitted to *Journal of Geophysical Research*, 1999]. A portion of the neutral molecules will become ionized molecules and would be picked up. If the lifetimes of the ionized molecules are sufficiently large, they would reach SWICS as ionized molecules and could escape detection. This effect would lead to a systematic under abundance of H, C, and O relative to Ne in the observed inner source pickup ions as is indeed observed.

3.2. Inner Source as an Origin for Particles Accelerated in CIRs

It is well established that energetic particles are accelerated in the vicinity of CIRs, where high- and low-speed solar wind flows interact. *Barnes and Simpson* [1976], *McDonald et al.* [1976], and numerous subsequent observations have shown that particles with energies of a few MeV per nucleon are accelerated at the forward and reverse shocks that surround CIRs. There is also evidence for statistical acceleration of very low energy particles in the regions interior to the CIRs [*Schwadron et al.* 1996].

To understand fully the acceleration at CIRs it is important to be able to trace the particles from the source from which they are injected through to their final accelerated energies. A possible source for particles accelerated in CIRs is interstellar pickup ions. The pickup ions are intrinsically hotter than solar wind ions and could be readily, and perhaps preferentially injected into any heliospheric acceleration process. In fact, there is clear evidence that interstellar He^+ and also H^+ are the primary sources of energetic He and H accelerated in CIRs [*Gloeckler and Geiss*, 1998; *Gloeckler*, 2000]. Interstellar pickup ions, however, have a distinct composition, namely, the composition of particles that are neutral in the local interstellar medium. They are enhanced in H, He, N, and O and should be effectively devoid of C, Mg, and Si [e.g., *Cummings and Stone*, 1996]. In contrast, as is shown in Table 1, particles that are observed to be accelerated in CIRs have a heavy particle composition that resembles that of the solar wind [*Keppler*, 1998].

Gloeckler [2000] has shown that the dominant source of energetic He and H accelerated in CIRs is interstellar pickup ions. Solar wind ions could, of course, experience sufficient heating in the vicinity of the forward and reverse shocks that surround CIRs, in which case they can also be injected into the acceleration process and yield accelerated particles with a heavy ion composition that resembles that of the solar wind [*Gloeckler*, 2000]. An additional source of CIR accelerated particles may be the inner source, which, as can be seen from Table 1, has a composition that in general terms, is similar to that of particles accelerated in CIRs. For this to be an important component the inner source must occupy a preferential status in the injection process.

To be injected into a shock acceleration mechanism, one of two criteria seems to be necessary. The speed of the particle, following its first interaction with the shock, must be sufficient so that it can propagate upstream in the solar wind and return for multiple interactions with the shock. This mechanism is used in standard diffusive shock acceleration, such as described by *Fisk and Lee* [1980]. Alternatively, particles can have a speed small relative to the shock speed, in which case the particles can find themselves trapped between the shock potential and the Lorentz force of the incoming moving magnetic field and drift along the shock front gaining considerable energy. This latter mechanism is known as "shock surfing" and has been described in detail by *Lee et al.* [1996] and *Zank et al.* [1996].

In the case of inner source pickup ions they may have an advantage in a shock surfing injection mechanism. These ions move inward in the frame of the solar wind, and thus a larger fraction of the distribution can satisfy the requirement of having a small speed relative to the shock front. They would thus be preferentially injected at the forward and reverse shocks that surround CIRs. Following some acceleration by shock surfing, the particles would have sufficient energy to propagate back and forth across the shock front and participate in a diffusive shock acceleration mechanism.

An interesting and important prediction of such preferential injection of either the inner source or interstellar pickup ions is that the resulting accelerated particles in CIRs should be primarily singly charged. Clearly, determination of the charge states of the particles accelerated in CIRs should reveal whether they are primarily of pickup ion or of direct solar wind origin.

4. Concluding remarks

We have presented here composition measurements of the inner source pickup ions, which show that the relative abundance has many similarities with that of the solar wind and thus that the inner source is likely to result from solar wind particles that are embedded in and subsequently released from dust grains. In many ways this process of forming the inner source is an interesting addition to the sources of heliospheric particles. The dust grains become a reservoir for solar wind particles, and some form of steady state should be achieved in which the dust grains, while orbiting the Sun, absorb and emit an equal number of solar wind particles. If, as we suggest here, the resulting inner source pickup ions, which appear to suffer little scattering and are cooled and thus are well positioned to participate in a shock surfing mechanisms, are preferentially injected for shock acceleration, then the result is a solar wind population raised to MeV energies in CIRs, as is observed [*McGuire et al.*, 1978; *Gloeckler et al.*, 1979; *Keppler*, 1998].

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