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Inner source distributions: Theoretical interpretation, implications, and evidence for inner source protons

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Abstract. A new and important source of pickup ions has been recently observed for the first time, the so-called inner source. We examine properties of inner source ions at high heliographic latitudes through analysis of data from the Solar Wind Ion Composition Spectrometer on the Ulysses satellite for a period extending through the year of 1994 while Ulysses achieved its southernmost latitudes. As demonstrated by *Gloeckler et al.* [this issue], the relative abundances of inner source ions resemble those of the solar wind, which implies that the dominant production mechanism for the inner source ions involves the absorption and reemission of solar wind ions from interplanetary dust grains. A simple transport model is devised that compares favorably to observed distribution functions and provides an important consistency check for the previously mentioned production mechanism. The model comparison also allows for constraints to be placed on the total dust geometric cross section. The observed distribution function of protons reveals a significant contribution from the inner source, but the abundance of inner source protons relative to oxygen falls significantly below the universal abundance. We postulate causes of this low relative abundance. We also find that inner source protons have a sizable pressure and may constitute an important energetic population in the solar wind, particularly near the their source.

1. Introduction

Neutral particles in the heliosphere may become ionized because of photoionization, electron impact ionization, or charge exchange. Subsequently, such ions are readily picked up by the solar wind as they gyrate about the frozen-in magnetic field lines. Pickup ions can be produced from many sources: interstellar neutrals, comets, planets, and interstellar or interplanetary grains.

Recently, pickup ions were identified that had been picked up close to the Sun [*Geiss et al.*, 1995; *Gloeckler and Geiss*, 1998] and were most probably produced because of the interaction between heliospheric grains and the solar wind. The existence of the inner source for pickup ions was hypothesized initially by *Banks* [1971] for H^+ and He^+. Subsequently, *Fahr et al.* [1981], *Gruntman* [1996], and others treated many of the details and consequences of the interaction between solar wind plasma and heliospheric grains. The inner source was not directly observed, however, until quite recently [*Geiss et al.*, 1995; *Gloeckler and Geiss*, 1998].

The composition of these inner source ions is similar to that of the solar wind, with C^+, N^+, O^+, and Ne^+ all having been identified as components of the inner source [*Geiss et al.*, 1995; *Gloeckler and Geiss*, 1998; *Gloeckler et al.*, this issue]. The fact that these ions are singly charged immediately suggests that they do not originate from the Sun. Solar wind heavy ions such as C, N, and O are typically highly charged if not fully stripped of their electrons. Note in particular the presence of Ne^+ among inner source ions. Small dust grains in the heliosphere are not expected to contain volatile elements such as Ne [see, e.g., *Anders and Grevesse*, 1989]. Hence the presence of Ne^+ among inner source ions provides strong and perhaps conclusive evidence that inner source ions are produced, in large part, through the absorption of solar wind ions and subsequent reemission of neutrals (presumably in molecular form) from dust grains in the heliosphere.

It should be noted that atomic Ne as well as N and O are also found among interstellar neutrals, which are a well-known source of pickup ions in the heliosphere [*Geiss et al.*, 1994]. It is therefore important to distin-

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guish clearly between interstellar and inner source contributions to pickup ion populations in the solar wind. One clear difference between the populations concerns their spatial origin: interstellar pickup ions are born from interstellar neutrals that stream in from beyond the heliosphere and are extinguished because of ionization at radial distances $r \sim 0.5$ - 4 AU [e.g., *Thomas*, 1978]; inner source pickup ions, on the other hand, are produced for the most part close to the Sun because of processes involving dust grains.

The specific spatial distribution of inner source ion production is an important clue as to their origin. Dust grains have a density profile that essentially scales as $\sim 1/r$ as a result of the radial drift velocity, which also scales as $\sim 1/r$, introduced by the Poynting-Robertson effect [e.g., *Leinert and Grün*, 1990]. The solar wind plasma also exerts a drag on the grains, causing the gradient to steepen slightly beyond $1/r$ [*Banaszkiewicz et al.*, 1994]. It should be noted, however, that dust has many sources (e.g., asteroids, comets, and planets). Close to a dust source, the density profile may deviate from this typical $1/r$ spatial distribution. In particular, many of the larger bodies that are dust sources are confined to near the ecliptic plane. Hence the spatial distribution of inner source pickup ion production may be much smoother at high heliographic latitudes as compared to near-ecliptic latitudes. Careful analysis of observed pickup ion distribution functions and comparison to models [e.g., *Gloeckler et al.*, 1993; *Gloeckler and Geiss*, 1998; *Schwadron*, 1998] allow the spatial distribution of pickup ion production to be constrained.

The purpose of this paper may be outlined as follow. (1) Devise a transport model for the inner source ions and compare it to observed distribution functions at high heliographic latitudes; (2) constrain the total geometric cross section through these model comparisons; (3) establish the presence and energetic importance of inner source protons; and (4) explore the implications of the abundance of inner source protons, which appears low in comparison to universal abundances.

2. Observations

The pickup ion data presented here were obtained with the Solar Wind Ion Composition Spectrometer (SWICS) on the Ulysses satellite [*Gloeckler et al.*, 1992]. The observed distribution functions of H^+ (open triangles), C^+ (solid triangles), and O^+ (open circles) are shown in Figure 1 for all of 1994. The observed distribution function $\tilde{f}(v')$ can be related to the distribution function in the solar wind frame, $f(\mathbf{v})$, through an angular integration over the instrument acceptance angles:

$$\tilde{f}(v') = \frac{1}{2\pi} \int_0^{2\pi} d\phi \int_{\text{inst}} d\Omega' f(\mathbf{v} = v'\hat{\mathbf{e}}' - \mathbf{u}) \quad (1)$$

Here v' is the speed in the spacecraft reference frame, $\mathbf{v}$ is the ion velocity in the solar wind reference frame, $\mathbf{u}$ is the solar wind velocity, and $\hat{\mathbf{e}}'$ is a unit vector in a direction at which the instrument accepts ions. The

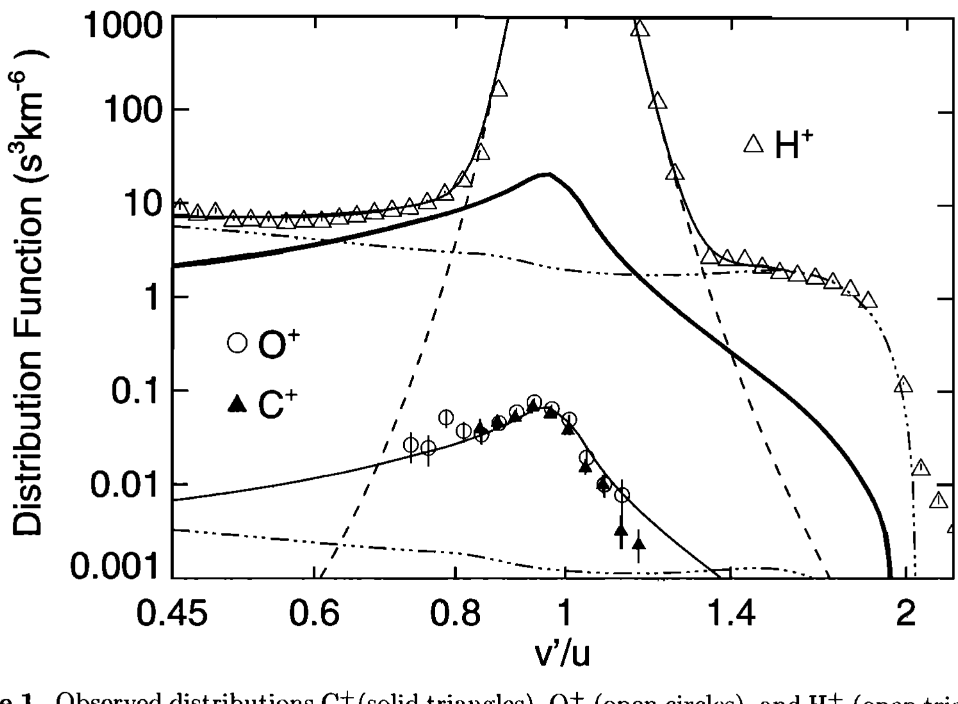

Figure 1. Observed distributions C^+ (solid triangles), O^+ (open circles), and H^+ (open triangles) measured by Ulysses Solar Wind Ion Composition Spectrometer (SWICS) and compared with simulated distributions of solar wind H^+ (dashed curve), interstellar H^+ (upper dash-dotted curve), inner source H^+ (upper thick line), inner source C^+, O^+ (lower line), and interstellar O^+ (lower dash-dotted curve). See sections 2 and 3 for detailed descriptions.

angular integral $\int_{\text{inst}} d\Omega' \ldots$ integrates $\hat{\mathbf{e}}'$ over the instrument angles at a given spin azimuth ϕ. The Ulysses spacecraft spins about an axis directed at Earth. We therefore use the spacecraft spin azimuthal angle ϕ that varies from 0 to 2π as the spacecraft performs a rotation. The second integral over ϕ averages over the spacecraft spin orientations (for a full discussion of the data reduction, see N. Schwadron et al. (Techniques for analysis of data from time-of-flight instruments, available at http://solar-heliospheric.engin.umich.edu/ publications.html, 2000; hereinafter refer to as Schwadron et al. unpublished document, 2000).

During the observation period used in Figure 1, all of 1994, Ulysses moved from 48° latitude to 80°S and then back to 45°S. Ulysses also traveled from 3.8 to 1.6 AU. The solar wind speed was extremely steady with speed $u \sim 780$ km s^{-1}.

A number of distinct populations are apparent in Figure 1. Consider first the protons: the central peak represents the solar wind protons; the broad flat distribution extending to twice the solar wind speed $v' \sim 2u$ represents the contribution from interstellar pickup protons. A kappa function (dashed curve) has been used to fit the solar wind proton peak, and a transport model [*Schwadron*, 1998] has been used to fit the interstellar pickup ion contribution (dash-dotted curve). These two populations can nearly account for the observed proton spectra, all that is but a small excess in the observed distribution in the range $0.6 < v'/u < 0.8$. It will be argued in section 3 that this excess represents a contribution from inner source protons.

Only one population is apparent in the observed distribution for C^+ and O^+, namely, inner source ions. It is well known that solar wind minor ions for carbon and oxygen are not singly ionized and therefore do not contribute to the observed distributions in Figure 1. As for the interstellar pickup contribution, we note first of all that the shapes of interstellar distributions tend to be rather flat, like the dash-dotted curve used to fit the interstellar pickup protons. The shapes for these C^+ and O^+ distributions are strikingly different. It is important to note, however, that the energy cutoff, 60 keV, for the SWICS instruments prevents the observation of C^+ and O^+ much beyond $v'/u = 1.2$ in the fast wind ($u \sim 780$ km s^{-1}).

Another means of ascertaining the contribution of interstellar pickup O^+ is to use the observed interstellar proton curve as a reference and estimate the relative contribution of interstellar O^+. In order to estimate the relative contributions of different interstellar pickup species we use the approximation that the interstellar neutral density is given by $n_n(r) \sim n_\infty \exp(-\lambda_l/r)$, where $\lambda_l = \beta_l r_1^2/v_0$, β_l is the interstellar neutral loss rate referenced at 1 AU, v_0 is the neutral flow speed relative to the Sun, r_1 denotes 1 AU, and n_∞ is the interstellar density at asymptotically large distances from the Sun. If we then assume that pickup ions have a bulk speed equal to that of the solar wind, the expression for the pickup ion density is

$$n_{\text{int}}(r) = r_1^2/r^2 \int_0^r dr' \beta_l n_\infty/u \cdot \exp(-\lambda_l/r'). \qquad (2)$$

Using interstellar parameters given by *Geiss and Witte* [1996] and *Ruciński et al.* [1996], we obtain the following ratio for the density of interstellar pickup O^+ to H^+ at 2.5 AU: $n_{\text{int}}(O^+)/n_{\text{int}}(H^+) \sim 1/1500$. On the basis of this ratio we find that the interstellar O^+ (bottommost dash-dotted curve) contributes very little to the observed distribution function. The interstellar contribution from C^+ is, of course, several orders of magnitude smaller than that for O^+. Therefore we conclude that these distributions for inner source C^+ and O^+ have little or no contributions from interstellar pickup ions.

3. A Model for the Inner Source

The most likely candidates for inner source ion production involve either the absorption of solar wind ions and reemission of neutrals from grains or evaporation and sputtering from grains. In the case of evaporation and sputtering the production of Ne, H, and, to a lesser extent, N would be inhibited since these species are depleted within grains. Therefore the presence of Ne^+ and N^+ among inner source pickup ions suggests a dominant production mechanism that involves the absorption of solar wind and the reemission of neutrals. Below we will demonstrate the presence of inner source H^+, which also favors this production mechanism. We focus in this section on the derivation of a simple model for the production of inner source ions and their subsequent transport in the solar wind.

On the basis of the compositional evidence discussed above we make the explicit assumption that the rate of solar wind absorption in grains is balanced by the reemission rate of neutrals. This assumption would certainly be violated in the case where sputtering or grain evaporation is the dominant production mechanism; however, compositional signatures of sputtering and grain evaporation contradict observations [*Gloeckler et al.*, this issue].

Consider first the production rate for an element X from grains due to the absorption of solar wind ions and the reemission of neutrals. Let us assume a density profile for the dust given by,

$$n_d(r) = n_d(r_1)\left(\frac{r_1}{r}\right)^\chi \exp\left[-\frac{L}{r_1}\left(\frac{r_1}{r}-1\right)\right]. \qquad (3)$$

Here $n_d(r_1)$ is the total number of grains per unit volume at 1 AU. Beyond ~ 10 - 50 solar radii the dust profile takes the form $n_d \propto 1/r$ [e.g., *Leinert and Grün*, 1990], meaning that $\chi \sim 1$ and $50R_s > L > 10R_s$, where R_s is the solar radius. We also assume a solar wind density given by $n_{\text{sw}}(r) = n(r_1/r)^2$ (n is the solar wind density at 1 AU), a constant solar wind speed u, and a solar wind abundance of element X relative to solar wind protons given by $\Xi_X = [X]/[\mathrm{H}]$. The rate per unit volume then that element X builds up in the grains is given by

$$S_{\mathrm{dust}}(r;X) = \Xi_X u n_{\mathrm{sw}}(r)\frac{n_d(r)}{n_d(r_1)}\Gamma. \quad (4)$$

Here Γ is the total dust geometrical factor or, equivalently, the total cross-sectional area per unit volume at 1 AU. Γ may be related to the dust density $n_d(r_1)$ and the total effective cross section of grains, σ_{eff}: $\Gamma = n_d(r_1)\sigma_{\mathrm{eff}}$.

Presumably, the dust outgasses element X at a rate comparable to the absorption rate of solar wind ions. The outgassed elements are undoubtably in molecular form immediately after they are released from the grain. These molecules, if left neutral, would continue to execute the grain orbit. If they become ionized, however, they are picked up by the solar wind. The eventual decay of the molecular forms into singly ionized atoms is inevitably a complicated process. *Gruntman* [1996], for example, considered the decay of molecular hydrogen into H_2^+ and pickup protons. We will fold these complications into a single factor $\xi_{X+} \lesssim 1$, where $(1-\xi_{X+})$ is the fraction of inner source element X that escapes observation. Depending on the details of the molecular destruction, the factor ξ_{X+} may be a function of heliocentric radial distance. For the sake of simplicity we take ξ_{X+} as a constant and express the source rate per unit volume for inner source pickup ions X^+ as follows:

$$S_{\mathrm{X+}} = \beta_{\mathrm{X+}}\left(\frac{r_1}{r}\right)^2 n_d(r). \quad (5)$$

Here the source rate for inner source pickup ions at 1 AU is given by

$$\beta_{\mathrm{X+}} = \xi_{\mathrm{X+}}\Xi_{\mathrm{X}} u n \Gamma / n_d(r_1). \quad (6)$$

We must next consider the transport of newly picked up inner source ions (X^+). The problem at this point can be handled quite easily by borrowing theoretical techniques developed in the study of interstellar pickup ions. The approach is to obtain a solution for the full phase-space distribution function of inner source ions using a transport equation identical to that used for interstellar pickup ions and a source term consistent with (5).

The transport equation for interstellar pickup ions had to account for large anisotropies observed in the pickup ion distribution functions. This large anisotropy is also apparent for inner source ions, as is evident in Figure 1 for the distribution functions of C^+ and O^+. In this case an isotropic distribution function would yield an observed distribution function $\tilde{f}$, which is symmetric about $v'/u = 1$. This symmetry is strongly violated, revealing a rather large anisotropy.

In the studies of interstellar pickup ions it was found that the large anisotropies were due to ineffective scattering through the 90° pitch angle [*Fisk et al.*, 1997]. Here the pitch angle is the angle between the magnetic field direction and the instantaneous ion velocity. The distributions appeared to be uniform in the two hemispheres separated by a 90° pitch angle. Hence the term "hemispheric" was used to characterize the pickup ion distributions. The approximation that distributions are hemispheric may not be valid when turbulence levels are high [e.g., *Chalov and Fahr*, 1998, 1999], but considering the large observed anisotropies and direct observational support for hemispheric distributions [*Fisk et al.*, 1997], the approximation is well justified. The transport scenario may then be summarized as follows: on magnetic field lines that are not perpendicular to the radial direction, interstellar pickup ions are picked up within the sunward hemisphere and adiabatically cool because of the usual betatron effect as they are carried out with the solar wind; pickup ions scatter efficiently within the sunward hemisphere but have difficulty scattering through the 90° pitch angle and therefore only partially fill the antisunward hemisphere.

The full transport equation for pickup ions under the assumption of hemispheric distributions has been written down and solved by *Isenberg* [1997], *Schwadron* [1998], and *Schwadron and Geiss* [this issue]. The starting point is that distributions are uniform in the sunward hemisphere f_- and in the antisunward hemisphere f_+. Here we simplify the transport equations by neglecting field-aligned streaming and adiabatic focusing, which do not play a significant role at the small speeds of inner source ions. This assumption is somewhat subtle but has been checked throughly by comparing approximate solutions with the results of a numerical model [*Schwadron*, 1998] that solves the full transport equations assuming hemispheric distributions. Under these assumptions then the transport equation may be written as follows:

$$u\frac{\partial f_0}{\partial r} - \frac{2u}{3r}v\frac{\partial f_0}{\partial v} = Q_d(r,v)/2 \quad (7)$$

$$u\frac{\partial \Delta}{\partial r} - \frac{2u}{3r}v\frac{\partial \Delta}{\partial v} = -Q_d(r,v)/2 - \frac{2\Delta}{\tau}. \quad (8)$$

Here $f_0 = (f_+ + f_-)/2$ is the isotropic part of the distribution function and $\Delta = (f_+ - f_-)/2$ is the anisotropic part. The ion speed in the solar wind frame is denoted v, and $\lambda = v\tau$ is the scattering mean free path. The radial distance is denoted r, and $r_1 = 1$ AU. We have assumed that the solar wind executes a standard radial expansion.

The source term in (7) and (8), $Q_d(r,v)$, must be consistent with (5) and must also specify the initial speed distribution of the pickup ions. We make the assumption that pickup ions are initially stationary in a reference frame fixed relative to the Sun since they are predominantly born from slowly moving neutrals. Hence $Q_d(r,v)$ is given by

$$Q_d(r,v) = \beta\left(\frac{r_1}{r}\right)^2 n_d(r)\frac{\delta(v-u)}{2\pi u^2}. \quad (9)$$

Here the production rate for inner source species X^+ at 1 AU is $\beta = \beta_{X^+}$, given in (6).

The assumption that pickup ions are initially at rest with respect to the Sun is not fully valid for ions picked up close to the Sun where dust grains have large orbital speeds. For example, at a radial distance of 10 solar radii a grain attains an orbital speed of ~ 140 km s^{-1}. Hence at these small radial distances, neutrals emitted from grains also have large orbital speeds, and the resulting pickup ions may have sizable initial speeds. At 10 solar radii, given a solar wind speed of 750 km s^{-1}, a pickup ion in the solar wind frame would have an initial speed of $v = 1.19u$, i.e., 19% larger than the initial speed assumed in (9). Ions will still be picked up in the sunward hemisphere. At larger heliocentric distances the effect becomes weaker as orbital grain speeds become smaller. A more detailed model of the ion pickup process may slightly modify the inferred source profile. For the sake of simplicity the effects of dust orbital speeds have been neglected in the model presented here.

Under the variable transformation, $w = v/u$, and $y = (r/r_1)w^{3/2}$, and assuming the scattering mean free path λ is constant, (7) and (8) may be rewritten as follows:

$$\frac{\partial f_0(y,w)}{\partial w} = -\frac{3r_1 y}{4uw^{5/2}} Q_d\left[r_s(y,w), v_s(w)\right] \quad (10)$$

$$\frac{\partial}{\partial w}\left[\exp\left(\frac{6r_1 y}{\lambda\sqrt{w}}\right)\Delta(y,w)\right] = \frac{3r_1 y}{4uw^{5/2}}\exp\left(\frac{6r_1 y}{\lambda\sqrt{w}}\right) Q_d\left[r_s(y,w), v_s(w)\right], \quad (11)$$

where the streaming variables are given by $r_s(y,w) = r_1 y w^{-3/2}$ and $v_s(w) = wu$. The analytic solution then readily follows

$$\begin{aligned} f_0(r,w) &= \frac{3}{8\pi u^4}\beta r_1\left(\frac{r_1}{\tilde{r}(w)}\right) n_d\left[\tilde{r}(w)\right] \\ &= \frac{3}{8\pi u^4}\tilde{r}(w) S\left[\tilde{r}(w)\right] \quad (12) \\ \Delta(r,w) &= -f_0(r,w)\exp\left[-\frac{6r}{\lambda}w(1-\sqrt{w})\right], \quad (13) \end{aligned}$$

where $\tilde{r}(w) = rw^{3/2}$ and $S(r) = S_{X^+}(r)$ as given in (5).

In order to perform comparisons with the observed distributions it is necessary to transform the distribution from the solar wind reference frame to the spacecraft frame and to perform the appropriate phase-space integrations as indicated in (1). We must also perform these transformations at several spacecraft locations during the observation periods. We therefore averaged the set of transformed distributions taken every 50 days during the 1994 observation period.

In Figure 1 the solid curves show results of the modeled distributions. In the lower part of Figure 1 we see a comparison between the inner source model results and the C^+ and O^+ distributions during the 1994 period. The C^+ and O^+ distribution are fit by specifying four parameters: the scattering mean free path λ, the quantity $\beta n_d(r_1)$, and the spatial production profile specified by L and χ, as in (3). The values used for these parameters are specified in Table 1. The quantity $\beta n_d(r_1)$ is listed for inner source protons in the second row, and the abundance of inner source H^+ relative to C^+ and O^+ is given in the final row.

Table 1. Modeling Parameters

Parameter	Value
λ, AU	> 2
$\beta n_d(r_1)$ [H^+], cm^{-3}s^{-1} $\times 10^{-10}$	6.2
L, AU	0.05
χ	1.2
[H^+]/[C^+]	310
[H^+]/[O^+]	

In Figure 2 and the upper part of Figure 1 we show model and observation comparisons for the H^+ distribution function. Several different populations are apparent: 1) the dashed curve shows the solar wind protons, modeled here with a kappa function; 2) the dash-dotted curve extending to twice the solar wind speed represents the interstellar protons; and 3) the thick solid curve represents the inner source ions. For the inner source H^+ distribution we simply multiply the C^+ distribution by the abundance ratio [H^+]/[C^+], which is listed in Table 1. Figure 2 shows definitively that inner source ions are observed in the proton spectra since the proton distribution in the speed range $0.6 < v'/u < 0.85$ could not be accounted for without a third distribution of ions.

4. Conclusions

4.1. Transport Implications

The observed distributions are highly anisotropic, consistent with mean free paths $\lambda > 2$ AU, suggesting that ions are essentially unscattered through the 90° pitch angle. This shows clearly that the large mean free path observed for interstellar pickup ions at $r > 1$ AU is still quite large at the much smaller radial distances ($10R_s < r < 0.5$ AU) at which inner source ions are picked up. Moreover, inner source ions cool adiabatically as they propagate because of the usual betatron effect. Hence the mean free path must remain large, $\lambda > 2$ AU over a wide range of rigidities; $R_0/10 < R < R_0$, where R is the ion rigidity and R_0 is the rigidity of the initially picked up ion ($R_0 \sim 2$ MV).

4.2. Pickup Ion Source

Gloeckler et al. [this issue] observe a composition for inner source pickup ions, C^+, N^+, O^+, and Ne^+, which is similar to that of the solar wind. Additionally, in this paper we have demonstrated the existence of inner source H^+. The presence and abundances of inner source species Ne, H, and, to a lesser extent, N, all of which should be depleted within grains, suggest that

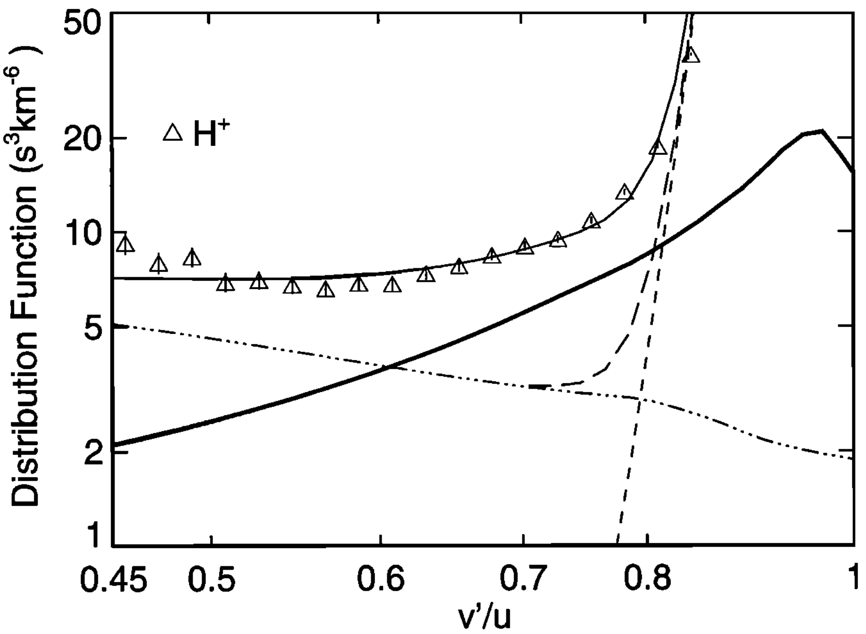

Figure 2. A blown up view of Figure 1 illustrating the necessity of the inner source H^+ (thick line) in addition to the interstellar H^+ (dash-dotted curve) and solar wind H^+ (short-dashed curve). The long-dashed curve shows the sum of solar wind and interstellar distributions, and the thin solid curve shows the sum of inner source, interstellar, and solar wind distributions.

the formation of these inner source components cannot be explained as the result of evaporation or sputtering from grains.

This brings forward a mechanism for ion production in which solar wind ions are absorbed within and reemitted by heliospheric grains. The full details of inner source ion production by this means is necessarily complicated. The reemission process, for example, would involve a number of different molecular forms, and the eventual decay of these molecular forms into singly ionized atoms involves many rates and branching ratios.

We have provided a simple model of the process that assumes that molecules reemitted from the grains dissociate into neutral atoms that are subsequently ionized. The model accounts for the observed distribution functions of C^+ and O^+ with a grain density profile (grain number per cubic volume), which scales as $\sim 1/r$. Since dust profiles are well known to exhibit this $1/r$ dependence [*Leinert and Grün*, 1990], the density profile constrained through model comparisons provides a consistency check for the production mechanism.

The model, however, neglects a number of important details. Consider molecules emitted from grains that become ionized. H_2 may, for example, become charged because of collisions with solar wind protons and subsequent electron capture:

$$H^+ + H_2 \rightarrow H + H_2^+. \quad (14)$$

Clearly, then the charged molecules get picked up by the solar wind before forming singly ionized atoms. It is possible that the inner source atoms are tied up in the form of these charged molecules beyond the point of observation. This would constitute an effective loss process that is neglected by our model.

Among the inner source ions discussed thus far we have not mentioned inner source He^+. Unfortunately, it is quite difficult to say much about He^+ in the speed range $v'/u \sim 1$ with Ulysses/SWICS since time-of-flight events of He^+ are indistinguishable from time-of-flight events from solar wind heavy elements with a mass-per-charge ~ 4. Nonetheless, it is worth mentioning that observations of inner source He^+ could be quite valuable as a means of understanding the inner source. Helium, like neon, is known to be depleted within grains. Therefore its production would necessarily involve the absorption of solar wind ions and reemission of neutrals from grains. Moreover, the universal abundance of helium is rather high, making it easier statistically to observe He^+.

4.3. Implications of a Low [H]/[O] Abundance

The relative abundance of [H]/[O] ~ 310 is strikingly small for inner source ions when compared to the solar wind ($[H]/[O]_{wind} \sim 1550 \pm 140$ from Schwadron et al. (unpublished document, 2000) for [He]/[O] = 68 ± 4 and *Barraclough et al.* [1996], and D. McComas (personal communication, 1999) for [He]/[H] = 0.044 ± 0.003). As usual, however, hydrogen is exceptional because of its low mass and large universal abundance. There may be a number of exceptional processes at work.

Consider first the main reactions involving H_2 [e.g., *Gruntman*, 1996]:

$$\begin{aligned} h\nu + H_2 &\rightarrow H + H \\ H^+ + H_2 &\rightarrow H + H_2^+. \end{aligned}$$

Photodissociation proceeds at a rate $\sim 3 \times 10^{-7}$ s^{-1}, and electron capture proceeds at a somewhat smaller rate $\sim 1.4 \times 10^{-7}$ s^{-1} under typical conditions at 1 AU. As mentioned above, the extent to which the inner source hydrogen is bound up in charged molecular form (H_2^+) constitutes an effective loss of inner source hydrogen. Moreover, the neutral hydrogen formed from photodissociation does not continue on more or less circular grain orbits since it is strongly affected by radiation pressure. Neutral atomic hydrogen would therefore drift outward radially after being dissociated, constituting an effective loss mechanism. A detailed treatment of this process accounts for an $\sim 55\%$ depletion of inner source hydrogen [*Schwadron and Geiss*, this issue].

The transport of picked up inner source protons may also be anomalous, particularly near the Sun. The rigidity of inner source protons is substantially smaller than the rigidity of other inner source ions, meaning that inner source protons sample a much different part of the magnetohydrodynamic turbulence spectrum. Inner source protons may therefore be completely unscattered close to the Sun. Consequently, the shape of the inner source proton distribution may be different than that of other inner source ions, leading to a poor relative abundance estimate from the data illustrated in Figure 1.

4.4. Implications for the Total Cross-Sectional Area of Dust Γ

During the observation period of 1994 the factors $\beta_{\mathrm{H}^+} n_d(r_1) \sim 6.2 \times 10^{-10}$ cm^{-3} s^{-1} and $\beta_{\mathrm{O}^+} n_d(r_1) \sim 2 \times 10^{-12}$ cm^{-3} s^{-1} were constrained through model comparisons. The quantities here are all referenced at $r_1 = 1$ AU. As outlined in section 3, these factors can be directly related to the dust geometric factor: $\beta_{\mathrm{H}^+} n_d(r_1) = \xi_{\mathrm{H}^+} un\Gamma$ and $\beta_{\mathrm{O}^+} n_d(r_1) = \xi_{\mathrm{O}^+} \Xi_{\mathrm{O}} un\Gamma$. Here, again, $1 - \xi_{\mathrm{H}^+}$ and $1 - \xi_{\mathrm{O}^+}$ are fudge factors that represent the fraction of inner source H and inner source O that escape observation (they may, for example, be tied up in ionized molecules). The solar wind flux at 1 AU is given by $un \sim 2.5 \times 10^8$ cm^{-2} s^{-1}, and Γ is the total dust geometric factor or, equivalently, the total cross-sectional area per unit volume. Since inner source hydrogen appears to be strongly depleted, ξ_{H^+} may be a small number. The dust geometric cross-section Γ may be more reliably estimated using inner source oxygen: $\Gamma = \beta_{\mathrm{O}^+} n_d(r_1)/(\xi_{\mathrm{O}^+} \Xi_{\mathrm{O}} un)$. Assuming $\xi_{\mathrm{O}^+} \lesssim 1$ and a relative abundance of oxygen to hydrogen in the fast solar wind $\Xi_{\mathrm{O}} \sim 1/1550$ (from Schwadron et al. (unpublished document, 2000) for [He]/[O] $= 68 \pm 4$ and *Barraclough et al.* [1996], and D. McComas (personal communication, 1999) for [He]/[H] $= 0.044 \pm 0.003$), we obtain the following lower limit for Γ:

$$\Gamma \geq 1.3 \cdot 10^{-17} \mathrm{cm}^{-1}. \tag{15}$$

This value is almost 2 orders of magnitude larger than the value used by *Holzer* [1977], *Fahr et al.* [1981], and *Gruntman* [1996], $\Gamma = 2 \times 10^{-19}$ cm^{-1}, but falls within the large uncertainty range inferred by *Banks* [1971], $\Gamma = 10^{-21}$ - 6.5×10^{-17} cm^{-1}.

We have referenced the dust cross section to 1 AU, as is generally done. We note, however, that our observations are most sensitive to interactions between solar wind and dust close to the Sun, between 10 and 50 R_s. The total geometric grain cross section may indeed become larger at smaller heliocentric ranges, particularly if dust collisions lead to a predominance of small grains close to the Sun.

The reason that zodiacal light observations yield smaller geometric cross sections is not immediately clear. If there is a predominance of submicron sized particles close to the Sun, this would lead to a larger geometric cross section; however, it would also cause zodiacal light to be bluer than the solar spectrum [*Giese et al.*, 1973], while the opposite trend is observed.

An instrument with higher sensitivity for inner source pickup ions may help to resolve some of the questions. To obtain inner source distributions with Ulysses/SWICS, long averaging periods are required, and only the portion of the distribution with the largest amplitude can be accurately determined. Moreover, the highest energy-per-charge steps ($\sim$60 kV) on Ulysses/SWICS cut off an important part of the inner source pickup ion distributions in fast solar wind. Consequently, only knowledge of inner source ions picked up relatively close to the Sun ($<$50 R_s) is gained through the study of inner source pickup ion distributions. With more complete distributions the conclusions presented here may be validated and extrapolated to larger heliocentric ranges. Further observations, potentially with an instrument designed with the study of inner source pickup ions in mind, would help in the interpretation of the inner source.

4.5. Energetic Importance of Inner Source H+

The inner source H^+ density constrained by the fit in Figure 1 is $n_{\mathrm{inner}}(\mathrm{H}^+) \sim 1.7 \times 10^{-4}$ cm^{-3} and is similar to the constrained density of interstellar pickup ions $n_{\mathrm{int}}(\mathrm{H}^+) \sim 1.2 \times 10^{-4}$ cm^{-3} observed in this case at $\sim$ 3 AU. During this 1994 period the solar wind density was a factor $\sim$ 1000 larger than the inner source and interstellar densities. Hence it is plausible that the inner source ions have a large pressure closer to the Sun, particularly if they are more anisotropic near their source.

To quantify the potential energetic importance of this new population, consider the following illustrative calculation. The density of inner source O^+ at $r_{\mathrm{obs}} = 3$ AU was derived from our fit to the distribution function in Figure 1: $n_{\mathrm{inner}}(r = r_{\mathrm{obs}}; \mathrm{O}^+) \sim 5.5 \times 10^{-7}$ cm^{-3}. Consider the density of inner source O^+ at $r_{\mathrm{in}} = 0.3$ AU:

$$\frac{n_{\mathrm{inner}}(r = r_{\mathrm{in}}; \mathrm{O}^+)}{n_{\mathrm{inner}}(r = r_{\mathrm{obs}}; \mathrm{O}^+)} = \left(\frac{r_{\mathrm{obs}}}{r_{\mathrm{in}}}\right)^2 \frac{u - v_O(r_{\mathrm{obs}})}{u - v_O(r_{\mathrm{in}})}. \tag{16}$$

Here $v_O(r)$ is the average speed at which O^+ ions stream against the solar wind in the radial direction. We find that $v_O(r_{obs}) = 80$ km s^{-1}. In the case of a highly anisotropic distribution close to the inner source, $u - v_O(r_{in})$ may be much smaller than the solar wind speed u. In this illustrative example, we take $u - v_O(r_{in}) \sim 10$ km s^{-1}, yielding $n_{inner}(r = r_{in}; O^+) \sim 4 \times 10^{-3}$ cm^{-3}. Factoring in the relative abundance $[H^+]/[O^+] \sim 310$, we find a density of inner source H^+, $n_{inner}(r = r_{in}; H^+) \sim 1.2$ cm^{-3}, and a pressure given by $P_{inner}(r = r_{in}; H^+) \sim m_p n_{inner}(r = r_{in}; H^+) u^2 \sim 1.2 \times 10^{-8}$ erg cm^{-3}. As a comparison, a 4 nT magnetic field at 1 AU has a magnetic pressure given by $B(r = r_{in})^2/(8\pi) \sim 4 \times 10^{-9}$ erg cm^{-3}, and a typical solar thermal pressure at $r = r_{in}$ is given by $P_{sw}(r = r_{in}) \sim 6 \times 10^{-9}$ erg cm^{-3}. In other words, if the inner source ions are highly anisotropic close to the Sun, their pressure $P_{inner}(r = r_{in})$ may exceed both the solar wind's magnetic and thermal pressures.

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