The interstellar hydrogen shadow: Observations of interstellar pickup ions beyond Jupiter

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[1] This study analyzes the first direct, mass-resolved observations of heliospheric pickup ions beyond the orbit of Jupiter. The Cassini Plasma Spectrometer observes H+, He+, He++, and O+ pickup ions of interstellar origin between 6.4 and 8.2 AU. Cassini's trajectory carries it through the downstream direction where we observe enhancements in the pickup He consistent with gravitational focusing by the Sun. We also show the first in situ observations of an "interstellar hydrogen shadow" where pickup H is depleted in the region behind the Sun relative to the local interstellar flow. Most H atoms cannot penetrate into this downstream shadow region both because the outward force due to radiation pressure exceeds gravitational attraction at this time and because H atoms trying to enter the shadow must pass close by the Sun where they have a high probability of being ionized and swept out with the solar wind. *INDEX TERMS:* 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 2144 Interplanetary Physics: Interstellar gas; 2124 Interplanetary Physics: Heliopause and solar wind termination; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2152 Interplanetary Physics: Pickup ions; *KEYWORDS:* interstellar hydrogen shadow, Jupiter, Cassini, pickup ions, heliosphere

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1. Introduction

[2] Heliospheric pickup ions are created in the solar wind when previously neutral atoms are ionized and incorporated into the solar wind flow. These ions begin essentially at rest in the Sun and spacecraft's reference frames. Thus they feel the motional electric field ($-\mathbf{v_{sw}} \times \mathbf{B}$) of the solar wind, which causes them to gyrate around the interplanetary magnetic field (IMF) as it sweeps them outward. As they move outward, pickup ions begin to scatter, forming distributions that are essentially flat for speeds <2 v_{sw} and drop off at speeds above a "knee" at this speed [*Gloeckler et al.*, 1995].

[3] The first interstellar pickup ions discovered [*Möbius et al.*, 1985] were He+ that were created by ionization of interstellar neutral He that had penetrated inside of Earth's orbit (1 AU). Since then, composition and velocity space resolved measurements by the SWICS experiment on Ulysses [*Gloeckler et al.*, 1992] have made it possible to explore heliospheric pickup ions from 1.35–5.4 AU in great detail. The review by *Gloeckler and Geiss* [1998] provides an excellent summary of the SWICS pickup ion observations. These observations include the most common pickup ion, H+, second most common, He+, and several other interstellar pickup ions, N+, O+, and Ne+ [*Geiss et al.*, 1994]. The SWICS team also demonstrated the existence of pickup distributions of He++, which is produced largely by double charge exchange of atomic He with solar wind alpha particles [*Gloeckler et al.*, 1997] and rare ^{3}He+ pickup ions. In addition to the interstellar pickup ions, SWICS distributions showed that the majority of the observed C+ and a fraction of the O+ and N+ are produced by an additional "inner source" of neutral atoms located near the Sun [*Geiss et al.*, 1995]. The inner source velocity space distributions are significantly modified as they cool over the solar wind's transit from their near-Sun source region out to several AU [*Schwadron et al.*, 2000]. Finally, Ulysses/SWICS also observed the ubiquity of pickup ion tails in slow solar wind [*Gloeckler et al.*, 1994; *Schwadron et al.*, 1996; *Gloeckler*, 1999]. These tails do not correlate strongly with the presence of shocks but do correlate with compressive magnetosonic waves, showing that pickup ions are subject to ubiquitous statistical acceleration through transit-time damping of magnetosonic waves in slow solar wind [*Schwadron et al.*, 1996; *Fisk et al.*, 2000]. To the best of our knowledge, the only possible observations of interstellar pickup ions (presumably H+) beyond 5.4 AU were made using a non-mass-resolved (energy/charge) analyzer on Pioneer 10 at ~8.3 AU [*Intriligator et al.*, 1996].

[4] Prior to Ulysses, it was expected that pickup ion distributions should be fairly isotropic due to pitch-angle scattering both from background turbulence and due to self-generated waves [*Lee and Ip*, 1987]. Instead, pickup ion distributions were observed to be highly anisotropic

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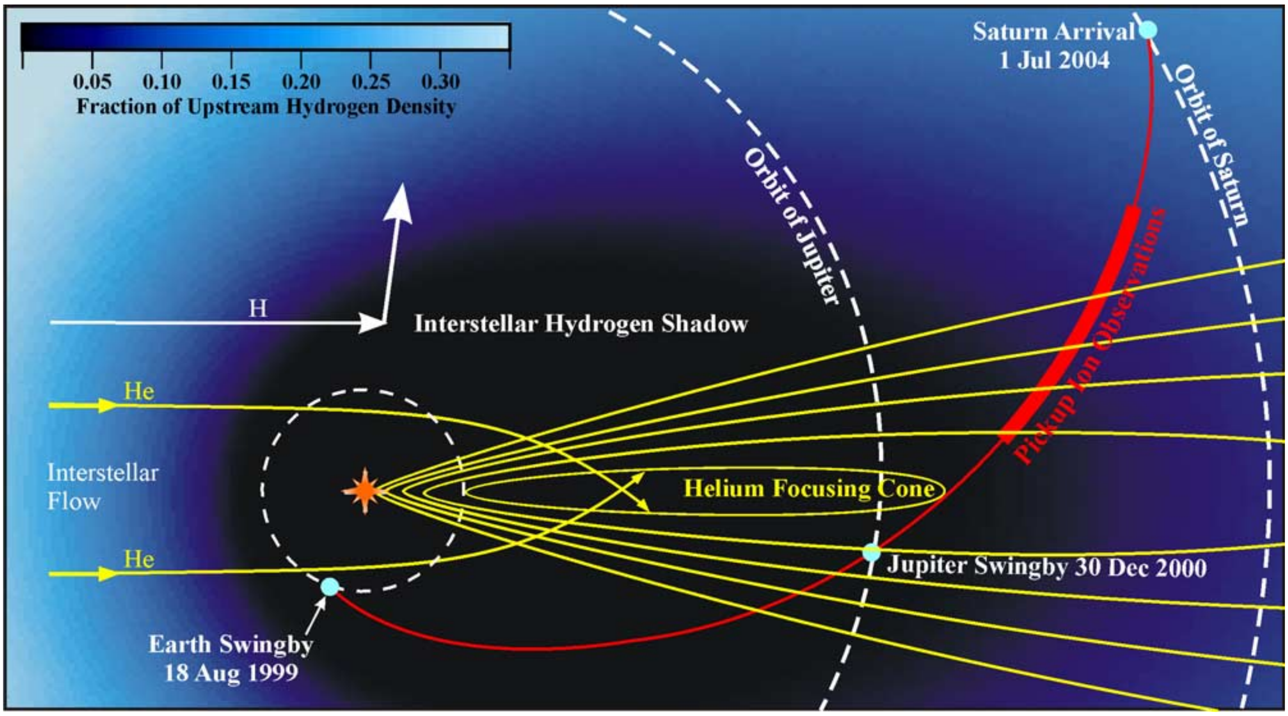

Figure 1. Schematic diagram of Cassini's trajectory between Earth swingby and arrival at Saturn. Pickup ion measurements were made between 6.4 and 8.2 AU (heavy line) as Cassini emerged from the down stream direction. Simulation results show (1) the gravitational focusing of interstellar He in contours of 5/3, 2, 7/3, 8/3, and 3 times the upstream He density and (2) the color-coded H density as a fraction of the interstellar value. The dark region downstream from the Sun is the interstellar hydrogen shadow.

[*Gloeckler et al.*, 1995] with scattering mean free paths of order an AU; the most likely cause is the inhibition of scattering through 90° pitch-angle [*Fisk et al.*, 1997]. Although this lack of scattering is not fully understood, it has been shown that the turbulence of the solar wind has a strong two-dimensional (2-D) component [*Matthaeus et al.*, 1990; *Bieber et al.*, 1996] that is ineffective for pickup ion scattering [*Bieber et al.*, 1994; *Zank et al.*, 1998]. Accurate pickup ion models have been devised to take into account the long scattering mean free path [e.g., *Isenberg*, 1997; *Schwadron*, 1998].

[5] Interstellar pickup ions are generated from neutral atoms that stream into the heliosphere from the interstellar medium. Charge-exchange between interstellar hydrogen and solar wind protons leads to a complex interaction near the nose of the heliosheath, where a so-called hydrogen wall is formed from slowed interstellar hydrogen atoms and charge-exchanged solar wind protons. These interactions also cause the removal, or filtration, of a fraction of the penetrating interstellar hydrogen atoms [e.g., *Baranov and Malama*, 1996]. Additionally, the solar radiation pressure and the rates of photo-ionization and charge-exchange vary both with solar latitude and over the solar cycle. Sophisticated models of interstellar neutral atoms have been developed to take these effects into account [e.g., *Izmodenov et al.*, 1999].

[6] Gravitational focusing of interstellar He [*Thomas*, 1978] was first observed remotely through UV backscatter observations of He I (58.4 nm) [*Weller and Meier*, 1981]. *Möbius et al.* [1985] made the first in situ observations of pickup He+ from the helium focusing cone and has examined numerous details of this focusing since then [e.g., *Möbius*, 1996, and references therein]. Recently, observations from a second SWICS instrument at the Earth-Sun L1 point on the Advanced Composition Explorer has made accurate measurements of the direction of focusing cone and hence interstellar inflow [*Gloeckler and Geiss*, 2001; G. Gloeckler, private communication, 2003]. ACE/SWICS has also observed a significant variation in pickup He+ over the solar cycle attributable to the large variation in the He photoionization rate [*Rucinski et al.*, 2003, and references therein]. Ulysses could not observe the He focusing cone since its orbit is fixed in an inertial frame nearly perpendicular to the upstream direction.

[7] This study examines data from the Cassini Plasma Spectrometer (CAPS) instrument [*Young et al.*, 2004] to show the first direct, mass-resolved observations of interstellar pickup ions outside of Jupiter's orbit. Fortuitously, Cassini's trajectory out to Saturn also carries it downstream from the direction of the Sun's motion through the interstellar medium, allowing the first direct observations of pickup ions in this fascinating region beyond ~5 AU.

2. Observations

[8] Cassini was launched on 15 October 1997 and, after Venus and Earth flybys, headed out toward Saturn where it will provide the first orbital reconnaissance of the Saturnian system. Figure 1 displays the basic geometry of Cassini's orbit. In September of 2001, the CAPS team uploaded

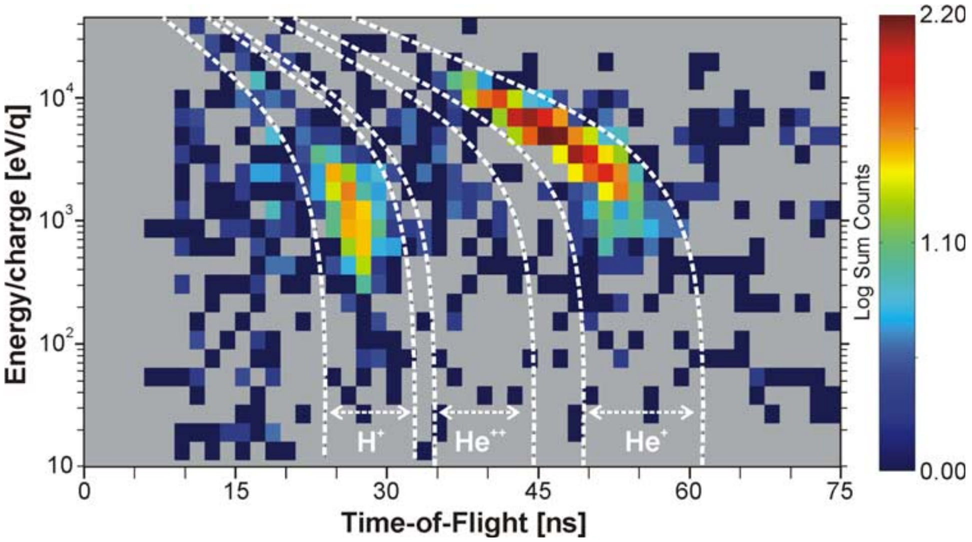

Figure 2. Pickup ion counts as a function of TOF and E/q. Regions of pickup H+, He+, and He++ are identified by the dashed lines.

special software that allowed it to collect and telemeter detections of the relatively rare pickup ions it encounters in transit to Saturn. Beginning in October 2001, CAPS routinely collected pickup ion data until February 2003, when the instrument was temporarily turned off. These observations covered the heliocentric range from ~6.4–8.2 AU (thick portion of trajectory in Figure 1).

[9] The CAPS ion mass spectrometer (IMS) is particularly well suited for measuring heliospheric pickup ions as it combines the very large viewing and geometric factors of an electrostatic top-hat analyzer with an innovative combination of high (m/Δm ~70 FWHM) and medium (~9 FWHM) resolution time-of-flight (TOF) ion mass spectrometer measurements [*McComas et al.*, 1990, 1998; *Young et al.*, 2004]. For this study, we examine the medium resolution TOF data, which have adequate mass resolution and higher sensitivity, appropriate for measuring the rare pickup ions. These data provide count rates summed over look direction as a function of TOF and electrostatic analyzer (ESA) energy/charge (E/q). For the low fluxes of pickup ions, we produce hourly sums of these TOF-spectra. Because the very high solar wind fluxes produce background counts in IMS, we exclude data for times when counts at the solar wind energies indicate the possibility that the instrument may have been viewing the solar wind directly. This process left 2627 one-hour samples distributed over the ~17 months of observations.

[10] Figure 2 displays color-coded start-stop coincidences as a function of TOF and E/q. Pickup H+, He+, and He++ are all clearly present in the figure. A slight enhancement in counts at the TOF-E/q location of O+ is also identifiable when the data are plotted in this format for longer TOFs (not shown). In order to quantitatively analyze the variation in pickup ions over time, we identified regions in the E/q versus TOF space (dashed lines) and summed the ions separately by species at each E/q step. Instrumental effects and differences in efficiency for detecting H+ and He+ in CAPS do not allow us to give a precise value for the ratio of H+/He+ at this time. However, H+ is clearly depleted compared to He+, as expected from gravitational focusing of helium and ionization of hydrogen as predicted in various heliospheric models.

[11] A plot of the integrated one-dimensional phase space density of He+ as a function of E/q is shown in Figure 3. Its shape is that of a classic pickup ion distribution, with a nearly flat top at lower energies and relatively sharp cutoff. For a maximum solar wind speed of 450 km s^{-1}, this cutoff is at 900 km s^{-1} (twice the speed), which for He+ (4 amu) is 1.7×10^4 keV/q. The slight enhancement at energies $\leq$1 keV may be created by a small residual solar wind signal that was not successfully culled out or could simply be showing that the distribution is not fully isotropic [*Gloeckler et al.*, 1995; *Schwadron*, 1998]. Because CAPS

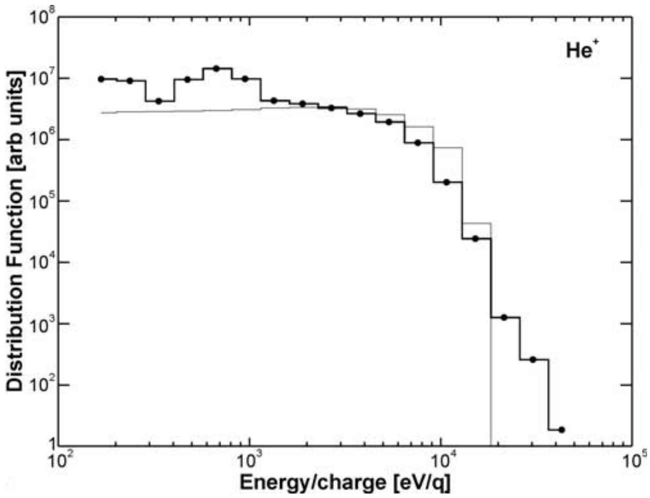

Figure 3. Distribution function ($\propto$ count rate $\times$ E^{-2}) of observed He+ as a function of energy. The shape is characteristic of a pickup distribution with a flat top and cut off at about four times the solar wind energy, and is consistent with the model pickup distribution (thin line, see text).

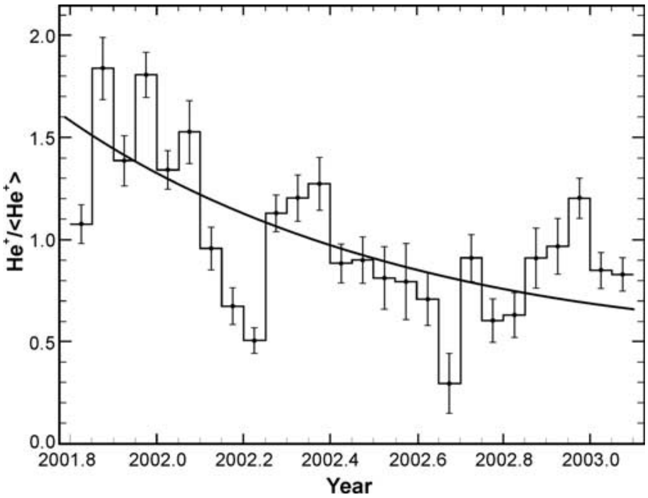

Figure 4. Measured flux of pickup He+ divided by its average value over the 17 months of observation. The observed and modeled (smooth curve, see text) variations show a factor of ∼2 decrease over this period as Cassini moved away from the region downstream from the He focusing cone.

was turned away from the Sun and cannot provide direct solar wind observations for most of the interval examined, we are unable in this study to produce a distribution as a function of measured speed divided by solar wind speed. Thus in Figure 3, the cutoff in the distribution is not as sharp as it might be at least in part because of the mixture of ions picked up at a variety of solar wind speeds. In addition, a long scattering mean free path leads to significant anisotropies that also reduce the sharpness of the cutoff [*Schwadron*, 1998; *Möbius et al.*, 1998]. Superposed on top of the data is the prediction from a simple pickup ion model (described below) that neglects these two effects.

[12] Figure 4 shows the relative variation of the pickup He+ count rates versus time. Pickup ions were summed from 6.3–25 keV/q, which covers the range of pickup He+ around the knee (Figure 3). Error bars represent Poisson statistics on the measured counts in each 0.05 year time bin. Pickup ion fluxes are highly variable, consistent with the large variability seen in our observations. A significant portion of this variability may be due to enhancements that are characteristically observed in solar wind compression regions. *Schwadron et al.* [1999] found a factor of four increase in pickup ion flux even for small compressions driven by relatively modest (∼10%) enhancements in solar wind speed.

[13] Superposed on top of the CAPS data are simple model results generated by integrating a predicted distribution function, taken to be isotropic in the solar wind frame, times velocity over the portion of velocity space observed in the spacecraft frame. The predicted distribution includes convection, adiabatic cooling in the radially expanding flow, and ion pickup [*Vasyliunas and Siscoe*, 1976]. The ion pickup rate at each location is the local ionization rate times the neutral density solved using the "hot" model [*Fahr*, 1971; *Thomas*, 1978; *Wu and Judge*, 1979], which accounts for gravitational focusing by the Sun, ionization loss, and the finite temperature of incoming neutrals. Table 1 lists the

Table 1. Interstellar Parameters and Production Rates Used in the Hot Models of Pickup Ion Populations

Species	N_{TS}, cm^{-3}	T, K	ν_o, km s^{-1}	β_1, s^{-1}	μ
Helium	0.015	6500	26	1.5×10^{-7}	0
Hydrogen	0.1	11000	22	7×10^{-7}	1.5

model parameters taken from *Witte et al.* [2004] and *Gloeckler and Geiss* [2004]: N_{TS} is the interstellar density near the termination shock; T is the neutral temperature; ν_o is the incoming speed of neutrals; β_1 is the ionization rate referenced to 1 AU; and μ is the force of radiation pressure divided by gravity. The model produces strong focusing of He that reproduces the observed factor of ∼2 reduction in the He fluxes over this interval. Other, more complicated models [e.g., *Rucinski et al.*, 2003] show similar strong focusing. Thus the count rate of He+ drops as expected as Cassini moves away from the gravitational focusing cone.

[14] Figure 5 shows the relative variation of H+ in the energy range from ∼1.6–6.3 keV/q as a function of time. This range was chosen since it covers from just above the solar wind energies (and any residual solar wind contamination) through the pickup protons at four times the typical solar wind proton E/q. As Cassini moved further out along its trajectory toward Saturn, it began to emerge from the Sun's interstellar hydrogen shadow, which is caused by both a net repulsion when the radiation pressure is larger than gravitational attraction ($\mu > 1$) and depletion of the incoming neutral H by ionization along trajectories that pass close to the Sun. Over the relatively narrow range of heliocentric angles sampled by CAPS (from 10° to 23° from the downstream direction), the observed H+ ratio increased by a factor of ∼2. Simulation results are again produced using the model described above and values listed in Table 1; again, the hot model reproduces the observed factor of ∼2 variation across this interval, but this time increasing instead of decreasing. The observed and modeled increase in

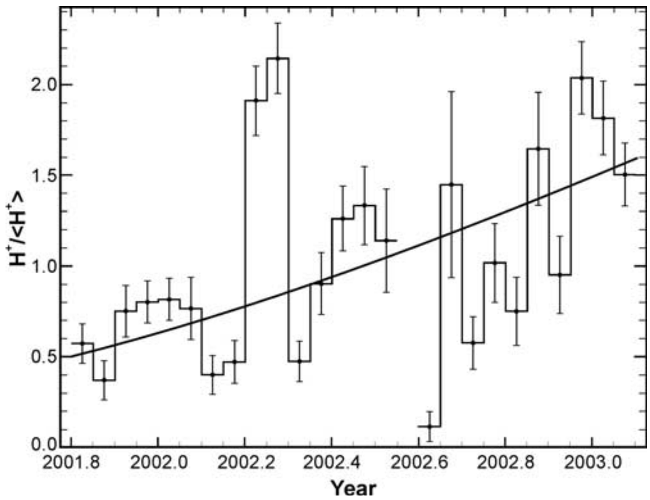

Figure 5. Measured flux of pickup H+ divided by its average value. The missing data point is for a time when no unambiguous pickup H+ data were available. Here, the observed and modeled (smooth curve, see text) values show a factor of ∼2 increase as Cassini moved away from the center of the interstellar hydrogen shadow.

H pickup ions can be best explained by Cassini's motion away from the center of a shadowed region that very few interstellar H atoms can reach.

3. Discussion

[15] This study has (1) reported the first direct, mass-resolved observations of interstellar pickup ions beyond the orbit of Jupiter (6.4–8.2 AU), (2) confirmed the existence of the helium focusing cone at these distances, and (3) made the first direct, in situ, measurements of a large shadow in the interstellar hydrogen population downstream from the Sun's motion through the interstellar medium. While this interstellar hydrogen shadow has never been directly measured before, remote Ly-α observations have shown an asymmetry between maximum column densities in the upwind direction and minimum column densities in the downwind, dating all the way back to *Bertaux and Blamont* [1971].

[16] Figure 1 summarizes the basic geometry of these observations, gravitational focusing, and the shadowing effect. Interstellar neutrals flow into the heliosphere from upstream (the left side in this figure) with finite temperatures. Helium experiences gravitational focusing that enhances the He flux downstream from the Sun (white contours). In contrast, for hydrogen, solar radiation pressure is stronger than the gravitational force ($\mu \sim 1.5$ near solar maximum) and thus the particles are slowed and their trajectories are bent away from the Sun. In addition, because photoionization and the H charge exchange rate increase as R^{-2}, most of the interstellar H is ionized and swept out by the solar wind before it can penetrate to within 2–3 AU of the Sun [e.g., *McComas et al.*, 1999]. In the downstream direction, this leaves a large depletion or interstellar shadow in the neutral hydrogen.

[17] As it completes its trajectory out to Saturn and once in Saturnian orbit (during significant portions of the orbit when it is outside of Saturn's magnetosphere), Cassini will continue to make critical heliospheric pickup ion observations. These continuing observations, along with complementary pickup ion observations that can be made by the Charge Energy Mass Spectrometer (CHEMS) instrument on Cassini, including pickup O and Ne at higher energies [*Mall et al.*, 1996, 1998], will be invaluable for understanding the role of interstellar pickup ions in the heliosphere. As Cassini completes it trajectory out to Saturn, and after it achieves Saturnian orbit, it will be carried ever further away from the Sun's helium focusing cone and interstellar hydrogen shadow.

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