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Interstellar pickup H^+ ions at 8.3 AU: Pioneer 10 plasma and magnetic field analyses

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Abstract. Analysis of Pioneer 10 plasma and magnetic field observations at 8.3 AU in 1975 provides new evidence for the presence of interstellar pickup hydrogen (H^+) ions. Use of plasma sensors that look far from the solar wind direction confirms the spherical shell distribution of the pickup ions in velocity space. Phase space density and flux estimates are closely consistent with those from Ulysses measured under similar conditions. Power spectral analyses of the magnetic field data show a distinct signal a little above the proton gyrofrequency, consistent with the presence of Doppler-shifted ion-cyclotron waves generated by H^+ pickup ions. These results show that the Pioneer data set has the potential for systematic studies of the global properties of interstellar pickup ions.

Interstellar Pickup Ions: Science Tools and Science Puzzles

The *Mobius et al.* [1985] detection of pickup ions of interstellar origin (a.k.a. interstellar pickup ions) has been justly cited as an important milestone in the history of progress toward understanding several scientific problem areas: the local interstellar medium [e.g., *Judge*, 1983], the properties of the outer heliosphere [e.g., *Burlaga et al.*, 1994], and the origin of anomalous cosmic rays [e.g., *Jokipii*, 1986]. It ushered in a data-based era of quantitative development of models and theories pertaining to these phenomena. (For a recent review and an appreciation, see *Isenberg*, [1995].) Using an analyzer which was designed to measure pickup ions on the Active Magnetosphere Particle Tracer Explorer (AMPTE), *Mobius et al.* succeeded in detecting He^+ ions that were formed from neutral interstellar atoms. These 1 AU measurements stood alone until *Gloeckler et al.* [1993] reported that his instrument on Ulysses, also designed for such purposes, had detected interstellar pickup H^+ and He^+ ions at 4.9 AU near the ecliptic. As *Isenberg* [1995] reviews, the Ulysses results revealed that pickup ion fluxes vary more than expected; they exhibit interesting structure that is not fully understood [*Gloeckler et al.*, 1994]. To add to the data base available to advance the project of quantitatively developing our understanding of the interstellar medium, the properties of the outer heliosphere, the origin of anomalous cosmic rays, and the puzzling structure of pickup ion fluxes, we report here a successful detection of interstellar pickup H^+ using the plasma analyzer on Pioneer 10.

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Pioneer's Plasma Analyzers as Detectors of Interstellar Pickup Ions

The plasma analyzers on the Pioneer spacecraft were designed as solar wind measuring instruments and not expressly as pickup ion detectors. Nonetheless, their wide energy range, high sensitivity, and high resolution in velocity space allow them to map the distinctive regions of velocity space where pickup ions reside. They demonstrated their effectiveness in this arena when they detected 0^+ ions from Venus's atmosphere [*Intriligator*, 1982, 1989] and Iogenic ions at Jupiter [*Intriligator and Miller*, 1981]. Interstellar pickup ions are inherently harder to detect, however, since their fluxes are low and, as we now know, irregular. But the *Gloeckler et al.* success showed that, when present, the interstellar pickup ion pattern in velocity space makes a very distinct signal. For our search, the tracking coverage for Pioneer 10 was particularly good. The data segment analyzed here comes from a 10 day interval of good tracking just before a permanent failure of the spacecraft magnetometer. Thus, this interval corresponds to a strategic limit point for the Pioneer 10 data set: best coverage and farthest from sun with magnetometer data. The interval is September 29 through October 8, 1975, when the spacecraft was 8.3 AU from the heliosphere's center, 2.5° south of its equator, and 130° east of its apex. We have seen similar results in other intervals but have not yet made a comprehensive study.

We used a search strategy consistent with the *Gloeckler et al.* result, which confirmed what had been earlier predicted [*Vasyliunas and Siscoe*, 1976], that in velocity space, the interstellar pickup ion distribution approximates a distinctive geometrical figure: a spherical shell centered on the point that marks the solar wind velocity vector; a shell radius equal to the solar wind speed, and a shell thickness that is finite. This result, for the purpose of a search of the Pioneer data, makes the operationally relevant point that in velocity space interstellar ions are well separated from solar wind ions, and they are concentrated in a predictable, well defined region. The search strategy thus becomes one of looking at the shell far from the solar wind direction to minimize background and of integrating for a long time to increase the signal.

The following geometrical aspects of the Pioneer instrument are pertinent to this search strategy. (For other details, see *Intriligator and Miller* [1981], and *Intriligator and Wolfe* [1976].) The instrument views ~ sunward, parallel to the spacecraft spin axis. Particles moving close to the plane formed by the slit axis and the slit normal can enter the slit at all angles up to 54° either side of the slit normal. The entering particles form a 108° wide fan centered on the look direction. This fan of particles runs through an electrostatic analyzer to select those with an energy-to-charge ratio in preset ranges, which are cycled in time. The thus-filtered fan of particles then falls onto the instrument's 26 particle sensors (channeltrons) for counting. Along the fan the channeltrons are more closely spaced near the centerline than near the outer edge. Since the normal to the slit is parallel to the spacecraft spin axis, every half revolution the fan of particles generates a solid-angle cone centered on the look direction with a cone angle of 54°. Thus every half revolution, the instrument can detect all particles in velocity space that lie in this solid-angle cone. Within this cone, the selected energy-per-charge range defines a radial band. As the instrument cycles through its sequence of energy-per-charge ranges, the radial band marches outward along the cone axis, covering it from some inner limit to some outer limit. The spacecraft generates a new cone ~ every 6 seconds, and the energy band sweeps through the cone in 64 steps, thus completing a velocity space measurement.

The Pioneer 10 plasma analyzer has two separate autonomous instruments: Detectors A and B. Detector A works as just described and counts particles and Detector B measures currents and is, thus, less sensitive. Due to its higher sensitivity, Detector A is better suited for use in this search for an interstellar pickup ion signal.

The search strategy calls for looking away from the solar wind as far as possible. This means using Detector A's outer channeltrons (numbers 1 and 26). These have 8° viewing windows spanning angles that range approximately from 46° to 54° away from the spin axis. This window marks the perimeter of the detector's viewing cone in velocity space. It defines a conical shell which intersects the spherical shell of the interstellar pickup ions at a radial "distance" ~ equal to $2V_{sw}$ cos 50° (or 1.27 V_{sw}, more exactly), where V_{sw} is the solar wind speed. These outer channeltrons have larger collecting areas and longer integration periods than the inner ones, the effective sensitivity advantage for the outer channeltrons compared with the inner ones is about 2000. Thus, the velocity space feature for which we are searching is a sharp drop at 1.27 V_{sw} in the phase-space density measured as a function of "radial" distance (i.e., velocity) within this conical shell observed by the outermost channeltrons.

The search strategy also calls for integrating the signal in time. Thus, we "integrated" the signal over the 10 day interval noted earlier by accumulating all of the counts for each measurement cycle in energy bins and dividing by the total accumulation time to arrive at an average count rate for each bin. In the accompanying data presentation figures, these energy bins are plotted at their equivalent velocities. To maintain signal coherence over this 10-day interval, for each measurement cycle we normalized the bins by an energy corresponding to the solar wind speed determined for that cycle. This step insures that the discontinuity stays fixed at the bin that has its normalized, equivalent velocity equal to 1.27.

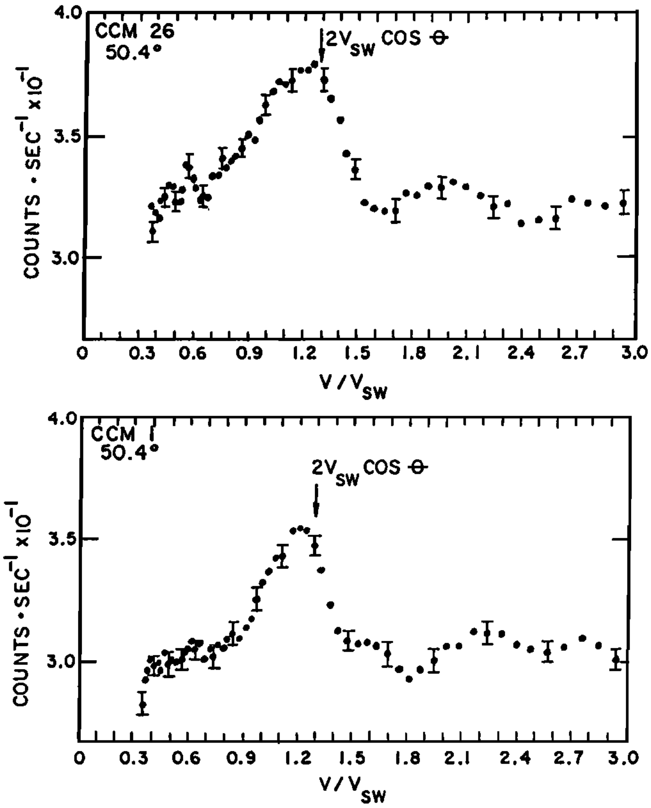

Figure 1. Composite 10 day ion energy per unit charge (E/Q) spectra derived from data measured on channeltrons (ccm) 26 and 1 in Detector A in the solar wind at 8.3 AU by Pioneer 10. The angle (50.4°) that each ccm views with respect to the instrument centerline is indicated. The counts on each of these ccms are integrated over 6 secs. The horizontal axis shows multiples of the solar wind speed, V_{sw}. For this 10 day period, in each instrument cycle the E/Q of each measurement was converted into the corresponding multiple of V_{sw} during that cycle and sums were accumulated in bins centered on 0.01, 0.02, etc. of V_{sw}. The error bars, which are the same for all the points, are shown for every fourth point. The peaks near the energy expected (e.g., $2V_{sw}\cos\theta$ for H^+) for pickup H^+ have been labelled.

The Observed Interstellar Pickup Ion Signal

Figure 1 shows the composite 10-day ion-energy spectrum obtained as just described. The points are three-bin, moving averages of the average count rates. During the 10-day averaging interval the solar wind speed -- against which the energy bins were normalized -- declined slowly from 425 km/s to 380 km/s. As indicated by the confidence bars, the points between V/V_{sw} = 0.8 and 1.4 depart significantly from the nearly constant background level produced by penetrating particles. There is a distinct interstellar ion pickup signal rising as a broad feature centered near V/V_{sw} = 1. It is a relatively weak signature, peaking less than 20% above background. Nonetheless, as evidenced by its size relative to the confidence bars and by its uniqueness in the data field, the signal can be assumed to be real. It is prominent in the plots for both channeltrons. Since these are independent measurements, in effect, one plot confirms the other.

The arrows at V/V_{sw} = 1.27 mark the location in phase space of the discontinuity that is predicted to separate interstellar pickup H^+ ion counts at lower energies from background counts at higher energies. They show that the broad feature has the right position and shape to be a signature of interstellar pickup H^+ ions. The identification becomes more assured when these relatively unprocessed data are converted into phase space densities, after subtracting off the constant background flux. The result for channeltron 26 is shown in Figure 2. Prominent in the figure is the feature most diagnostic of an interstellar pickup ion signature: the precipitous drop near V/V_{sw} = 1.27. The drop actually starts around V/V_{sw} = 1.05, which is 83% of the predicted cutoff ratio (1.27). The difference reflects in part the three-bin smoothing and the effect of the thermal distribution of the

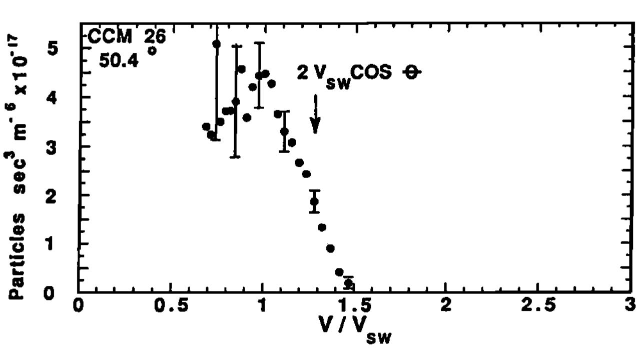

Figure 2. Phase space densities for the composite spectrum from ccm 26 shown in Figure 1. The background of 0.327 is subtracted from the quantities in Fig. 1. These values then are divided by a factor proportional to V^4 to obtain the phase space densities. The predicted sharp cutoff at 2 V_{sw} cos 50° is very evident. The error bars are shown for every fourth point. The evidence for interstellar pickup hydrogen (H^+) ions shown in this figure is very similar to that from Ulysses shown in Fig. 2 of Gloeckler et al. (1993).

incoming neutrals. It also may reflect incomplete pitch angle scattering of the most recently picked up ions. Taking into account the slope broadening effect of the oblique viewing angle of the channeltron, this result agrees well with the beginning of the decline at about 90% of the predicted cutoff ratio seen in the *Gloeckler et al.* result.

Two other forms of evidence are available to support our claim that these detections represent pickup ions: the detection in magnetometer data of characteristic ion cyclotron waves which pickup ions generate; and the correspondence of the phase space density values with expectations based on observations from Ulysses. We consider the waves first.

Associated Ion-Cyclotron Waves

Lee and Ip [1987] predicted that ion-cyclotron waves should accompany the interstellar ion pickup process, as observed in the cometary ion pickup process [as reviewed by *Tsurutani*, 1991]. The waves act to isotropize the pitch angles. Since they are diagnostic of the action of the interstellar ion pickup process, as an indirect check on the interpretation of the feature in Figures 1 and 2 as an interstellar ion pickup signal and as an interesting observation in itself, we analyzed the Pioneer magnetometer data for evidence of such waves. We made auto- and cross-spectra of the components of the magnetic field. During the 30 hour interval from 1800 UT on Day 278 to the end of Day 280, 1975 the field remained constant long enough to attempt to find spectral features in such power spectra. *Lee and Ip* predict that the Doppler shift of the waves will locate their peak in a frequency spectrum just above the local proton gyrofrequency, which was 2.5×10^{-3} Hz during this interval.

Figure 3 shows the results of the spectral analyses in a coordinate system where B_R is the radial component from the sun, B_T is the tangential component defined by the cross product of the solar rotation axis and the radial direction, and B_N is the normal component defined by the cross product of radial and tangential directions. Figures 3a and 3b give autospectra for B_T and B_N and show peaks just above the local proton gyrofrequency, labeled f_p in the figure. The peak stands out more in Figure 3c, which gives the cross spectrum between B_T and B_N. The cross-spectral result is especially convincing since, as seen in Figure 3d, it gives a remarkably high coherence in a fairly narrow band centered a little above f_p. A relatively narrow coherence peak defined by estimates at several adjacent frequencies that is near unity above f_p is too improbable to be an accidental coherence of background fluctuations in the magnetic field. The high coherence implies a fixed phase relationship, and in this case the coherent fluctuations between B_T and B_N are 90° out of phase.

These results are consistent with those of *Murphy et al.* (1995) who found an enhancement in power above the hydrogen gyrofrequency in Ulysses magnetic field data accompanying pickup of interstellar hydrogen ions. The presence of the waves was "a strong function of the angle between the magnetic field and the solar wind direction, with small angles being favored." The Pioneer results agree with this since during the two periods of strongest waves (Day 274 to Day 281) the field was 40°-50° to the solar wind direction.

We conclude that the interstellar ion pickup signal that *Lee and Ip* [1987] discussed is indeed present in the magnetometer data. While this result does not confirm the interstellar-ion-pickup interpretation of the plasma signal seen in Figures 1 and 2, it nonetheless supports it.

Flux and Density Estimates

Additional evidence that these are Pioneer observations of pickup ions comes from a comparison of the phase space density estimates. The peak phase space density in Figure 2 is $4.5 \pm 0.6 \times 10^{-17}$ sec^3/m^6. Figure 2 of *Gloeckler et al.* (1993) shows that from November 24 to December 9, 1991, when under similar solar wind conditions Ulysses was at 4.82 AU from the sun, and $\theta = 99°$, the SWICS instrument

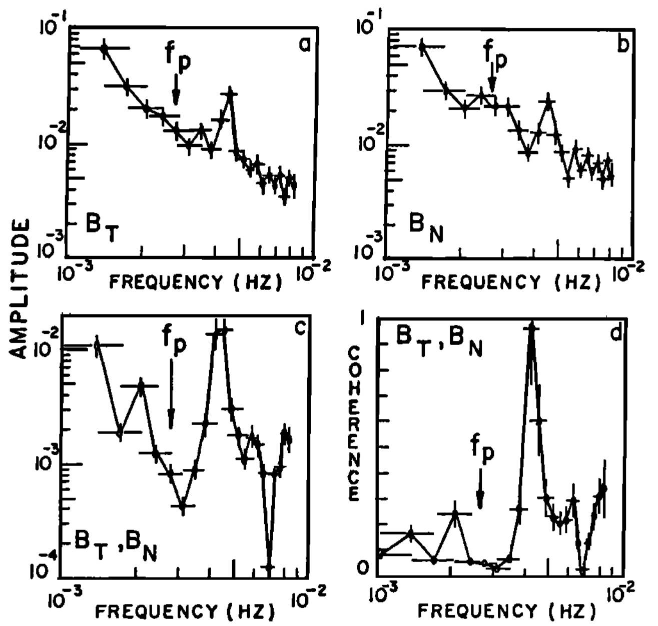

Figure 3. Power spectral analyses of Pioneer 10 magnetometer data recorded between 1800 UT on Day 278 to the end of Day 280, 1975. This period was selected for stability of field magnitude. The autospectra of B_T (Fig. 3a) and B_N (Fig. 3b), and the cross spectrum (Fig. 3c) each show enhancements at a frequency a little above the proton cyclotron frequency ($f_p \sim 2.5 \times 10^{-3}$ Hz) probably due to Doppler shifting. The phase of almost exactly 90° and the high coherence (Fig. 3d) imply a fixed phase relationship.

observed a pickup H^+ phase space density of 3-4 $\times$ 10^{-17} sec^3/m^6. This comparison shows good agreement between the Pioneer and Ulysses results. Since the Pioneer and Ulysses data were recorded at significantly different radial distances, and since the production rate of pickup ions is proportional to the flux of solar wind ions, a better comparison is provided by referring the solar wind fluxes to 1 AU, assuming r^{-2} expansion, and comparing the results to the phase space densities. For Ulysses the flux was 3.8 $\times$ 10^{10} $m^{-2}s^{-1}$ at 4.82 AU or 9 $\times$ 10^{11} $m^{-2}s^{-1}$ at 1 AU. Pioneer 10 had 4 $\times$ 10^{10} $m^{-2}s^{-1}$ at 8.3 AU or 3 $\times$ 10^{12} $m^{-2}s^{-1}$ at 1 AU. Thus a modestly higher phase space density at Pioneer 10 would be expected. Similar phase-space densities at both spacecraft and similar V_{sw} (400 km/s at Pioneer 10 and 458 km/s at Ulysses) imply that the flux values should be similar, with slightly higher values at Pioneer 10 because the spherical shell in velocity space is expected to grow thicker at greater heliocentric distance (V&S Figure 4). Our preliminary estimate of the pickup H^+ flux from the spherical shell model is subject to some uncertainty and so we estimate it at 3-6 $\times$ 10^7 particles m^2/s. Ulysses data estimate the ionization length parameter λ in the range 4-6 AU. Evaluating the V&S model (equation 6) with $\lambda = 4$ and $\lambda = 6$ and using the Pioneer flux estimate range gives an interstellar neutral density N_0 of 0.038 - 0.075 cm^{-3} for $\lambda = 4$ and 0.065 - 0.13 cm^{-3} for $\lambda = 6$. Assuming N_0 has changed little from 1975 to 1991, the Pioneer data seem most consistent with $\lambda \approx 5$, whereas the loss rate of 8 $\times$ $10^{-7}s^{-1}$ (*Gloeckler et al.*) corresponds to $\lambda = 6$. This apparent difference is consistent with solar cycle variations, since 1991 was near a solar maximum while 1975 was close to solar minimum following the large high speed streams of 1973 and 1974.

Conclusions and Implications

The results of this analysis give convincing evidence that Pioneer 10 has detected the signatures of interstellar pickup H^+ ions in both ion measurements and in magnetic field measurements. The result is consistent with the expected spherical shell distribution in velocity space of the pickup ions. The magnetic field fluctuations show evidence of ion cyclotron waves in the expected frequency range and a preliminary estimate of neutral gas density from the Pioneer data is consistent with results from other spacecraft. Since Pioneers 10 and 11 provide a long-term, long-range, apex and anti-apex set of uniform data the present results show that these data are well suited for making relative comparisons of interstellar ion pickup fluxes over broad ranges of heliospheric positions and conditions.

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