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Acceleration of interstellar pickup ions in the disturbed solar wind observed on Ulysses

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Abstract. Acceleration of interstellar pickup H^+ and He^+ as well as of solar wind protons and alpha particles has been observed on Ulysses during the passage of a corotating interaction region (CIR) at ~4.5 AU. Injection efficiencies for both the high thermal speed interstellar pickup ions (H^+ and He^+) and the low thermal speed solar wind ions (H^+ and He^{++}) are derived using velocity distribution functions of protons, pickup He^+ and alpha particles from < 1 to 60 keV/*e* and of ions (principally protons) above ~60 keV. The observed spatial variations of the few keV and the few hundred keV accelerated pickup protons across the forward shock of the CIR indicate a two stage acceleration mechanism. Thermal ions are first accelerated to speeds of 3 to 4 times the solar wind speed inside the CIR, presumably by some statistical mechanism, before reaching higher energies by a shock acceleration process. Our results also indicate that (1) the injection efficiencies for pickup ions are almost 100 times higher than they are for solar wind ions, (2) pickup H^+ and He^+ are the two most abundant suprathermal ion species and they carry a large fraction of the particle thermal pressure, (3) the injection efficiency is highest for protons, lowest for He^+, and intermediate for alpha particles, (4) both H^+ and He^+ have identical spectral shapes above the cutoff speed for pickup ions, and (5) the solar wind frame velocity distribution function of protons has the form $F(w) = F_O w^{-4}$ for $1 < w < \sim 5$, where w is the ion speed divided by the solar wind speed. Above $w \sim$ 5-10 the proton spectrum becomes steeper. These results have important implications concerning acceleration of ions by shocks and CIRs, acceleration of anomalous cosmic rays, and particle dynamics in the outer heliosphere.

1. Introduction

It is now well established that ion acceleration from several hundred keV/nucleon to a few MeV/nucleon occurs in well-developed corotating interaction regions (CIRs) where high- and low-speed solar wind streams merge beyond several astronomical units from the Sun. Such observations were first reported by *McDonald et al.* [1976] and *Barnes and Simpson* [1976] from Pioneer 10 and 11, and later by *Hamilton et al.* [1979] from Voyagers 1 and 2. The forward and reverse shocks that bound the CIR are likely sites for the acceleration, as was shown by *Barnes and Simpson* [1976] and modeled by, for example, *Fisk and Lee* [1980]. However, until recently, instrumentation was not available to measure the energy spectra and compositions of accelerated ions over their full energy range, from solar wind to higher (MeV/nucleon) energies. This information is essential for testing various acceleration models, for determining the source material of the accelerated ions, and for establishing the efficiency with which ions are injected into the acceleration mechanism.

The Ulysses spacecraft, which included instrumentation capable of measuring the energy spectra of various accelerated ion species over the full energy range, encountered many interplanetary traveling shocks as well as CIRs en route to Jupiter as the solar activity was declining [*Burton et al.*, 1992; *Balogh et al.*, 1994]. Acceleration of solar wind ions near such shocks has been observed by *Ogilvie et al.* [1993]. Associated with the CIRs, which are bounded by forward and reverse shocks separated in time by several days, were large increases in the fluxes of pickup H^+ and He^+ that extended to energies well beyond the pickup ion cutoff energy [*Gloeckler and Geiss*, 1994]. These pickup ions are created from interstellar neutral particles that are swept into the heliosphere by the motion of the Sun relative to the interstellar medium. In regions of large solar wind densities resulting from compression in the CIR, the flux of pickup ions (especially of H^+) is enhanced due to increased charge exchange of neutrals with the solar wind [*Gloeckler and Geiss*, 1994].

Using measurements of pickup ions accelerated in a CIR, we can now observe the nascent stages of ion acceleration. What we find is that there are features in the spatial variations and the distribution functions of the accelerated particles, which are not compatible with shock acceleration as the sole acceleration mechanism.

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Upon comparing composition measurements made mostly above several hundred keV/nucleon in corotating regions at one austonomical unit (AU) with inferred coronal (solar wind) abundances, it was argued that the solar wind was the source of all particles accelerated in CIRs beyond several AU [e.g., *Gloeckler et al.*, 1979; *Dietrich and Simpson*, 1985; *Reames et al.*, 1991]. We will present evidence in this paper that will require modification of this conclusion. In particular, we find that interstellar pickup (rather than solar wind) hydrogen and helium are the dominant components of the energetic (a few keV/nucleon to several MeV/nucleon) ion population accelerated in the CIRs.

2. Instrumentation

The results reported here are based on data over a large range of ion speeds obtained with the solar wind ion composition instrument (SWICS) [*Gloeckler et al.*, 1992] and the heliospheric instrument for spectra composition and anisotropy at low energy (HI-SCALE) [*Lanzerotti et al.*, 1992] on board Ulysses. SWICS measures the intensity of solar wind and suprathermal ions as a function of their energy per charge (E), mass (m), and charge state (q), from 0.6 to 60 keV/e in 64 logarithmically spaced steps with $\Delta E/E$ ~0.04. SWICS uses techniques of energy per charge analysis, followed by postacceleration of ions (by 23 kV) and a time-of-flight and energy measurement, to identify ions and sample their distribution functions in its energy range once every 13 min. Because of the double and triple coincidence techniques used, the background levels are exceedingly low, allowing measurements of the very low flux levels of interstellar pickup ions [*Gloeckler et al.,* 1993; *Geiss et al.,* 1994] . The viewing direction of SWICS is such that in one spin-period of Ulysses (~12 s) a π steradian cone, centered approximately in the solar wind direction, is sampled. The LEMS30 telescope (one of five of the HI-SCALE instrument) used in this study measures the total ion flux in several energy intervals from ~60 keV to a few MeV. It has a conical collimator centered at 30° with respect to the spin direction of Ulysses (which points approximately in the solar wind flow direction during the period of these observations). The cone has an opening half angle of 22.5°, so that it also sweeps out a π steradian solid angle that nearly overlaps that of SWICS. A separate telescope, the Wart, determines the ion composition using the dE/dx versus E technique for energies > ~450 keV/nucleon.

It is convenient to organize the data in terms of either W, the ratio of the ion speed in the spacecraft frame of reference divided by the solar wind speed (V_{sw}), or w, the ratio of the ion speed in the solar wind frame divided by V_{sw}. SWICS covers the important velocity range of the thermal and nonthermal solar wind (~0.7 < W < ~1.3), of pickup ions (~0.5 < W < 2) and of accelerated ions (2 < W < ~8), while HI-SCALE allows us to observe the distribution function of accelerated protons from W ~8 to beyond 50.

3. Observations

In this paper we examine in some detail the spatial variations of solar wind, suprathermal and energetic protons during a 3-day period (October 18 to 21, 1991) and the distribution functions of H^+, He^+ and He^{++} observed during a 1-day period (October 19, 0400 to Oct 20, 0400, 1991), behind the forward shock of a CIR on October 19, 1991 at 0440. The sonic Mach number of this shock was 2.53 and the shock parameters were determined to be θ_{BN} = 50° ± 11° and B_2/B_1 = 2.50 ± 0.13 [M. Burton, private communication, 1994; *Balogh et al.*, 1994], where B_1 and B_2 are the magnetic field magnitudes upstream and downstream of the shock respectively. The compression ratio of this shock could not be accurately determined because of insufficient data sampling of the solar wind plasma. Using SWICS measurements of solar wind protons and alpha particles just before the shock and about 13 min behind the shock, we find a compression ratio of about 2.4 ± 0.3. Ulysses was in the ecliptic plane at a distance r of 4.485 AU from the Sun at an angle θ of 101.5° with respect to the flow direction of interstellar neutrals. The average solar wind proton speed and density measured by SWICS during the one day period behind the shock was 393 ± 12 km/s and 1.9 ± 0.6 cm^{-3} respectively.

In Figure 1 we show as a function of W, the phase space density of H^+, He^{++} and He^+ measured by SWICS below W~8, and of ions (mostly protons) and He measured by HI-SCALE above W ~8. All data were averaged over the viewing directions of the instruments and over the spin-period of the spacecraft. In the case of SWICS the normalized ion speeds were computed for each individual 13-min spectrum using the measured solar wind speed, and these spectra were then averaged over the 1-day period of the observation. All of the He^+ are of interstellar origin, He^{++} is predominantly of solar wind origin, and protons have both a solar wind and interstellar origin.

The bulk solar wind protons and alpha particles, not readily visible in this representation, are Maxwellians with thermal speed W_{th} of about 0.05 centered around W = 1 and are part of the first of four types of populations present. Accelerated solar wind H^+ and He^{++} beyond W ~1.1 belong to the second ion population. The spectral shapes of accelerated solar wind particles are power

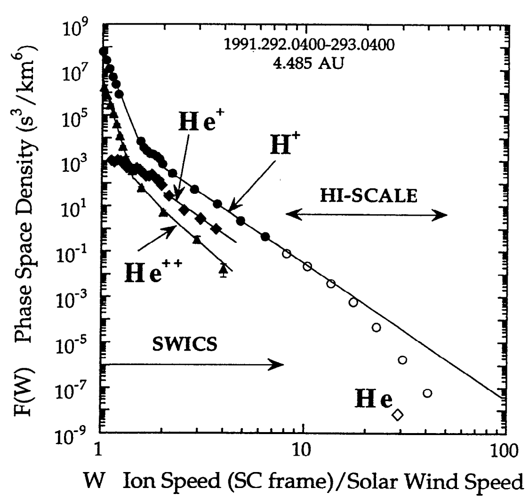

Figure 1. Velocity distribution functions of H^+ (solid circles), He^+ (solid triangles), and He^{++} (solid diamonds) in the spacecraft frame. Data below W ~ 8 (0.6 to 60 keV/e) are obtained with SWICS, while those above W ~8 (open circles for ions, mostly protons, and open diamond for He) are measured with the HI-SCALE instrument. Interstellar pickup H^+ appears as a bump on the spectrum below W = 2. The accelerated solar wind H^+ and He^{++} (1.1 < W < 1.5) have steep power law spectra with respective indices of ~ -22 and ~ -30. Accelerated pickup H^+ and He^+ (W > 2) have identical spectral shapes that are less steep than that of accelerated solar wind He^{++} above W ~1.5, which is a power law of index ~ -8. See text for further discussion.

laws of W with indices of about ~ -22 and ~ -30 for H^+ and He^{++} respectively. The slope of the accelerated solar wind alpha particles changes to ~ -8 above $W = 1.5$. The third population consists of interstellar pickup H^+ and He^+ below $W = 2$ [*Gloeckler et al.*, 1993]. In the case of protons, pickup H^+ dominates over the accelerated solar wind protons for $W > \sim 1.7$, producing a hump in the spectrum. The fourth population, above $W = 2$ includes the accelerated pickup ions. In the case of He^+ they are the sole accelerated ions. In the case of H^+ they are the dominant accelerated ions as will be demonstrated below. The spectrum of the accelerated pickup protons becomes steeper above $W \sim 10$.

Above W ~1.5, corresponding to energies of a few keV/nucleon, the number density of interstellar pickup He^+ is larger than that of the mostly solar wind He^{++}. Furthermore, protons and pickup He^+ have the same spectral shapes between $W = 2$ and ~4, but the He^{++} spectrum appears to be steeper in this W interval. Whether this difference is significant or is simply a result of the spatial variations in the distributions of these particles as discussed below is unclear. A reasonable extrapolation of the He^+ spectrum measured by SWICS, assuming that it steepens similarly to the H^+ spectrum at around W ~10, suggests that the helium flux measured by HI-SCALE at W ~30 most likely includes significant contributions from the accelerated interstellar He^+.

In order to show the spectral features in more detail we replot in Figure 2 (as open symbols) the measured phase space density, $F(w)$, of He^+ (upper panel) and H^+ (lower panel) but now as a function of w, the ion speed in the solar wind frame divided by the solar wind proton speed. We show as the dashed curves the model-based distribution functions of interstellar pickup He^+ and H^+ (integrated over the view directions of SWICS) using standard (zero temperature) analytical expressions for the spatial distribution of interstellar neutrals [e.g., *Thomas*, 1978] and the procedure described by *Vasyliunas and Siscoe* [1976] for obtaining the phase space density of pickup ions (in the solar wind frame) under the assumption of strong pitch angle scattering and adiabatic deceleration. We make the simplifying assumption that the solar wind densities and velocities observed within the CIR are the appropriate ones to use in calculating the pickup ion production rates due to charge exchange. Clearly, within the CIR, parcels of solar wind have crossed the corotating shock at various locations, with the parcels well behind the shock having spent the most time within the CIR. Thus the observed distribution functions will result from a mixture of populations from upstream and downstream of the shock, with the upstream populations modified by compression at the shock front. We used the following values of model parameters tabulated by *Gloeckler et al.* [1993] to obtain the spatial distribution of the neutral densities of hydrogen and helium : $N_O = 0.077$ (0.013) cm^{-3}, $V_O = 20$ (25) km/s, $\beta_{loss} = 7.8 \times 10^{-7}$ (10^{-7}) s^{-1}, and $\mu = 1$ (0), where N_O and V_O are the densities and speeds relative to the Sun of interstellar H and He (values for He are in parenthesis), β_{loss} is the loss rate (normalized to 1 AU) of neutrals due to ionization, and μ is the ratio of radiation to gravitational forces. The production rates, β_{prod} (normalized to 1 AU) of pickup H^+ and He^{++} were taken to be 3.3×10^{-6} s^{-1}, and 1.6×10^{-7} s^{-1} respectively, and were chosen to match the observed spectra at about $w = 1$. We note that while the spatial distribution of interstellar neutrals is determined by the loss rate of neutrals, β_{loss}, which depends on long-term (years) averages of the particle and photon fluxes responsible for the ionization, the locally measured flux of pickup ions is proportional to the production rate, β_{prod}, which depends on the short-term (days) averages of the fluxes causing the ionization [*Gloeckler et al.*, 1993; *Gloeckler and Geiss*, 1994]. In general, $\beta_{prod} \neq \beta_{loss}$. In particular, for the case of pickup H^+ produced within the CIR we find that $\beta_{prod} \sim 4\beta_{loss}$.

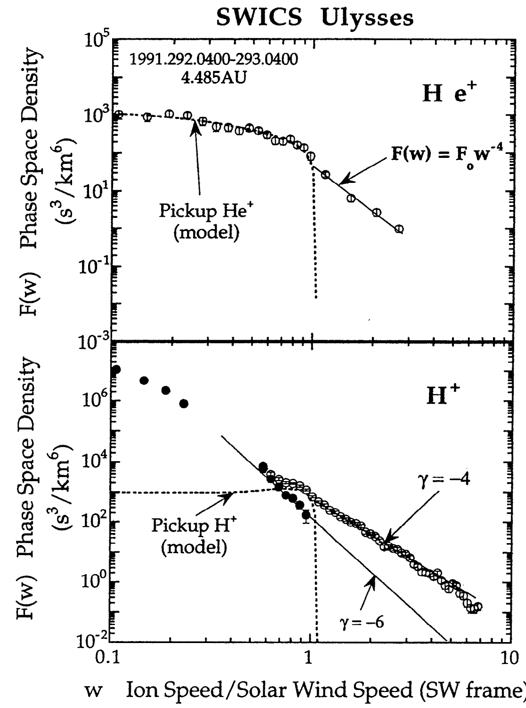

Figure 2. Normalized velocity distribution function (upper) of interstellar pickup He^+, and (lower) of solar wind protons plus interstellar pickup H^+ in the solar wind frame of reference. For w between 1 (the cutoff speed for pickup ions) and ~3 (the upper limit of He^+ observations by SWICS) both species have a power law spectrum with index ~ -4. Below $w = 1$ the He^+ spectrum is well fit by a model pickup He^+ spectrum (see text for details). For protons below $w = 1$ the model pickup spectrum accounts for the observed hump just below $w = 1$. Below $w = \sim 0.6$ are accelerated solar wind protons. To estimate the contribution of accelerated solar wind protons to the phase space density above $w = 1$, we extrapolate the w^{-6} spectrum, determined by the solid circles, beyond $w = 1$. Using this extrapolated spectrum the appropriate moments are computed to obtain the number density and pressure from this portion of the spectrum. See text for additional discussion.

4. Discussion

For He^+ below the pickup ion cutoff speed of $w = 1$ the model velocity distribution function fits the observed spectrum quite well, showing no significant modification of the spectrum due to acceleration. During quiet solar wind conditions, the pickup ion phase space densities are lower than observed here in the CIR, and drop by 3 to 4 orders of magnitude beyond the cutoff speed of $w = 1$ [*Gloeckler et al.*, 1993]. However, in the present case of disturbed solar wind behind the forward shock, the decrease at $w = 1$ is small and the spectra of both protons and He^+ are power laws with exponent of ~ -4 for w between 1 and ~3. The major effect of the CIR on pickup ions below $w = 1$ is to increase their phase space density due to shock compression and increased production from neutrals resulting from increased charge exchange with the high flux solar wind in the CIR.

Unlike in the case for He^+, the proton velocity distribution beyond w ~0.6 (see Figure 2) has nonnegligible contributions from accelerated solar wind protons, interstellar pickup protons (which dominate at w between ~0.7 and 1 producing the bump in the spectrum), and accelerated pickup protons. In order to estimate the contribution of accelerated solar wind protons to the spectrum above $w = 1$, we subtract the model pickup proton distribution function (dashed curve) from the observed spectrum and plot the difference as solid symbols. A reasonable extrapolation of the accelerated solar wind spectrum beyond $w = 1$ is a power law with index of about -6 as shown. Assuming the power law with index 6 ± 2 continues beyond $w = 1$, we estimate that the accelerated solar wind protons contribute about 10% to 40% to the proton number density beyond w ~0.7, with the rest (and most) of the contribution coming from accelerated pickup protons. The spectral shape of the accelerated pickup H^+ remains approximately a power law with index -3.8 ± 0.5.

Using the distribution functions shown in Figures 1 and 2, it is possible to compute the contributions to the number densities and thermal pressures from each of the four types of populations (solar wind, accelerated solar wind, pickup ions and accelerated pickup ions) for each of the three ion species (H^+, He^+, He^{++}). The results of these computations are given in Table 1, where we list the number density in units of cm^{-3} (column 3) and the internal or thermal pressure in units of eV/cm^3 (column 5) for each of the ion species and population types (column 1) in the velocity interval (column 2) where that population type has a measurable contribution. In column 4 is listed the injection efficiency for each of the four accelerated ion populations, where the injection efficiency is defined to be the ratio of the number density of the accelerated component to that of the source plus the accelerated component of that ion population. The fraction of the total pressure in the accelerated populations is given in column 6. The error limits in the absolute values of the number densities and pressures (columns 3 and 5, respectively) are estimated to be about 30% and are due primarily to systematic uncertainties of the instrument response function or uncertainties in model parameters. The error limits in the injection efficiencies and pressure ratios (columns 4 and 6, respectively) are estimated to be about 15% and are due primarily to counting statistics. The error limits in the values for the accelerated pickup H^+ listed in Table 1, columns 3 and 5, are larger due to uncertainties in the amount of contribution from the high-velocity ($w > 1$) tail of accelerated solar wind protons.

Solar wind protons provide by far the largest contribution to the overall number density and internal pressure (1.9 cm^{-3} and 7.1 eV/cm^3, respectively). The second highest contribution to the number density comes from solar wind alphas (0.058 cm^{-3}). However, the second highest contribution to the pressure comes from accelerated pickup protons (1.3 eV/cm^3). The lowest-pressure contribution resides in the accelerated solar wind alpha particles (0.055 eV/cm^3).

Next, we examine the efficiencies of injecting the various ions from their respective source populations (i.e., the solar wind or pickup ions) into the acceleration mechanism. We find that, consistent with the results of *Ogilvie et al.* [1993], only a small

Table 1. Number Densities, Injection Efficiencies, Thermal Pressures, and Pressure Ratios of Ions in each of the four types of Ion Populations Observed Behind the Forward Shock of the Corotating Interaction Region (CIR) from October 19, 0400 to Oct. 20, 0400, 1991

Ion (Source)	Velocity Interval, W	Density, cm^{-3}	Injection Efficiency*	Pressure, eV/cm^3	Pressure Ratio†
H^+(SW)	0.9 - 1.1	1.9‡		7.1‡	
H^+(Acc. SW)	1.1 - 1.6	9.5×10^{-3}	0.005§	0.66	0.085§
H^+(PI)	0 - 2	5.1×10^{-4}		0.21	
H^+(Acc. PI)	2 - 8	$(4\pm1)\times10^{-4}$	0.43±0.08	1.3±0.4	0.85±0.04
He^+(PI)	0 - 2	1.4×10^{-4}		0.14	
He^+(Acc. PI)	2 - 8	2.7×10^{-5}	0.16	0.23	0.61±0.07
He^{++}(SW)	0.9 - 1.1	5.8×10^{-2}		0.78	
He^{++}(Acc. SW)	1.1 - 8	1.7×10^{-4}	0.003	0.055	0.066

*Ratio of the number density of the accelerated component to that of the accelerated plus the source component of that population type.

†Ratio of the internal (thermal) pressure of the accelerated component to that of the accelerated plus the source component of that population type.

‡Error limits in all values in this column are estimated to be about 30%, unless otherwise indicated (see text).

§Error limits in all values in this column are estimated to be about 15%, unless otherwise indicated (see text).

W, ion speed/solar wind speed (in spacecraft frame); SW, solar wind; PI, pickup ions; Acc. SW, accelerated solar wind; Acc. PI, accelerated pickup ions.

fraction of solar wind ions is accelerated, about one-half percent of protons, and only one-third percent of alpha particles. Similarly, less than 10% of the pressure is in the accelerated solar wind. On the other hand, a large percentage of the pickup ions is accelerated (43% of pickup protons and 16% of He^+), and these accelerated pickup ions carry the largest fractions of the pressure (85% for protons and 61% for He^+) of the pickup ion populations. Finally, we note that in the case of both solar wind and pickup ions, protons are more efficiently injected than are He^+ or He^{++}. Thus interstellar pickup H^+ and He^+ ions, and not accelerated solar wind protons and alphas, are the dominant suprathermal (~3 to ~300 keV/nucleon) ion populations in the CIR at ~5 AU.

The fact that the pickup ions are injected far more readily into the acceleration mechanism than solar wind particles is not surprising. The pickup ions have higher thermal speeds and most acceleration mechanisms require a threshold in velocity for particles to be efficiently accelerated. The difference in the rate of injection of hydrogen and helium (for both the solar wind and pickup ions, H is more readily injected than He) suggests that there is a rigidity dependence to the injection, which discriminates against higher rigidity particles.

Our observations place some interesting constraints on acceptable acceleration mechanisms in the CIR. The observed distribution function of accelerated pickup H^+ and He^+ is of the form $F(w) = F_0 w^{-4}$, which is what would be expected in the case of a strong hydrodynamic shock [*Blandford and Ostriker*, 1978]. However, the compression ratio of ~2.4 and Mach number of only 2.5 for the forward shock behind which our observations were made, should have resulted in a steeper spectrum of index just under -5.

More revealing for possible acceleration mechanisms is the spatial distribution of the accelerated particles shown in Figure 3. Plotted here, as a function of time, are the relative changes in the solar wind flux, the accelerated interstellar H^+ (at ~5 keV), and higher-energy H^+ (at ~200 keV). Clearly, the higher-energy particle flux increases approximately exponentially upstream of the shock and peaks at the shock front as would be expected for a CIR where shock acceleration is occurring. However, the accelerated interstellar H^+ at lower energies experiences no noticeable change at the shock front, but rather peaks in intensity well within the CIR, tracking closer to the time profile of the solar wind flux. Furthermore, no measurable fluxes of the ~5 keV protons are observed upstream of the shock.

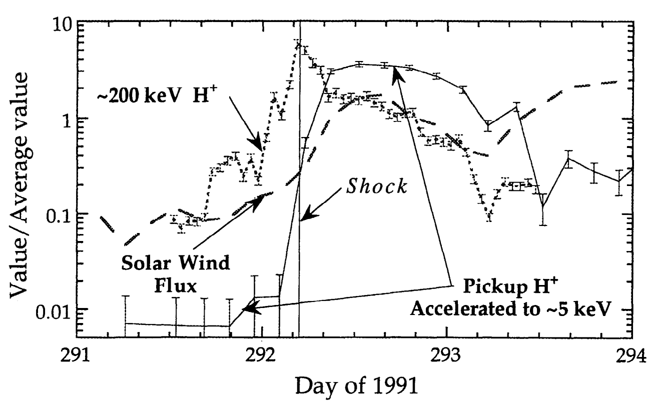

Figure 3. Relative changes in the solar wind proton flux and the fluxes of accelerated pickup H^+ at ~5 and ~200 keV respectively during a three day period starting on October 18, 1991 (day 291). The forward shock of the CIR occurred at 0440 on day 292 as indicated. Consistent with previous observations, the flux of the higher-energy protons rises nearly exponentially ahead of shock and peaks at the shock. The flux of the lower-energy pickup H^+, on the other hand, shows no obvious shock associated increase, reaching a broad maximum well behind the shock. These observations suggest a two-step acceleration process, whereby ions are first accelerated to speeds of several times the solar wind speed within the CIR before reaching higher energies by a more conventional shock acceleration mechanism.

Since the particles seen within a CIR cross the shock at smaller heliocentric distances than Ulysses, we cannot rule out entirely the possibility that the interstellar H^+ was accelerated at a stronger forward shock at smaller radial distances and then convected outward. However, our observations would appear to be more consistent with the interpretation that the lower-energy interstellar H^+ is not accelerated at the shock but rather by some statistical mechanism within the CIR. It is worth noting that the shock normal is observed to be 50° ± 11° and that simulation of the behavior of pickup ions at shocks indicate that a smaller shock angle is required to get sufficient reflection and thus injection of the ions into a shock acceleration mechanism [*Liewer et al.,* 1993]. It is also worth noting that the accelerated spectra shown in Figure 2 appear to be continuous extensions of the $w <$ ~1 pickup ion spectra seen within the CIR. If the pickup ions were being accelerated at a shock remote from Ulysses and then convected to the spacecraft, it would seem that the accelerated spectra would reflect the densities present at this remote shock. Since extensive charge exchange occurs within the CIR and the neutral hydrogen density decreases rapidly with decreasing radial distance [e.g., *Gloeckler and Geiss,* 1994], the densities at the shock at smaller radial distances should be noticeably less for interstellar H^+ than those seen at the location of Ulysses.

Clearly, a complicated picture of acceleration within CIRs is emerging. The pickup ions are the principal particles being accelerated. However, they appear to do so in a two-step process. They are first accelerated to speeds of perhaps several times the solar wind flow velocity within the CIR itself, presumably by some statistical mechanism. They then reach higher energies in a more traditional shock acceleration mechanism at the shocks bounding the CIR.

5. Summary and Conclusions

Our observations of the spatial variations of ~5 and ~200 keV protons and of the distribution functions of H^+, He^+ and He^{++} from 0.6 to 60 keV/charge and H and He up to several MeV/nucleon provide new and previously unavailable information about the initial stages of ion injection and acceleration in a CIR at ~4.5 AU. In particular, we find the following:

1. Interstellar pickup H^+ and He^+ are injected into the acceleration process almost 100 times more efficiently than solar wind protons and alpha particles.

2. As a result of this efficient injection, interstellar pickup H^+ and He^+ are the two most abundant suprathermal (~ few keV/nucleon to approximately several hundred keV/nucleon) ion species in CIRs at (and most likely beyond) ~5AU.

3. Pickup H^+ and He^+ in the CIR at ~5 AU carry about 15% to 20% of the total ion plasma pressure. Most of this pressure is in the accelerated pickup ions.

4. Solar wind protons are injected into the acceleration mechanism more efficiently than He^{++}, and pickup H^+ more

readily than He^+, with the implication that the injection is rigidity dependent.

5. The velocity distribution functions in the solar wind frame, $F(w)$, for H^+ and He^+ are power laws of the form $F(w) = F_0 w^{-4}$ for w between 1 and ~ 3. Beyond w ~ 5-10 the proton phase space density falls off more rapidly with w. This is apparently also true for He^+ (see Figure 1).

6. The spatial distribution of the accelerated interstellar ions suggests that a two-step acceleration process is occurring. The ions are first accelerated to velocities above the solar wind velocity within the CIR, presumably by some statistical mechanism. They then reach higher energies by a shock acceleration mechanism at the shocks bounding the CIR.

These results have important implications concerning ion acceleration by shocks and the influence of pickup ions on the dynamics in the outer heliosphere and the structure of the termination shock.

First, we address the question of the acceleration of ions heavier than helium. Our measurements of injection efficiencies would suggest that for interstellar pickup O^+ and N^+ [*Geiss et al.*, 1994] the high injection efficiency due to their high thermal speed is partially offset by the low efficiency due to their high mass/charge (rigidity). This, plus the low abundance of O^+ and N^+ relative to solar wind O^{6+} and N^{5+} in the inner (< ~5AU) heliosphere probably makes the high charge state solar wind ions the dominant heavy ions accelerated in CIRs in the inner heliosphere, consistent with earlier observations in corotating events [e.g., *Gloeckler et al.*, 1979]. However, in the outer heliosphere (> ~30 to 40 AU), with the solar wind density decreasing as r^{-2} and the pickup O^+ and N^+ density dropping off much more slowly [*Geiss et al.*, 1994] accelerated pickup O^+ and N^+ are likely to become more abundant than accelerated solar wind heavy ions. Another implication of the mass/charge dependence of the injection efficiency is that solar wind C^{6+} is injected more efficiently than O^{6+}. This could explain the somewhat higher carbon to oxygen ratio found in corotating events at 1 AU (C/O ~1) by, for example, *Reames et al.* [1991] and *Gloeckler et al.* [1979] compared to the C/O of ~0.70 in the coronal hole solar wind [*von Steiger and Geiss*, 1994].

Measurements of energetic (0.4 - 0.6 MeV/nucleon) He^+ made by *Hovestadt et al.* [1984] during a ~1.5 year period in 1978/1979 at 1 AU indicated large He^+/He^{++} ratios, with values between 0.3 and 1 not uncommon. These large He^+ abundances were not correlated with the many solar energetic particle events observed during this period, making it difficult to explain these findings in terms of solar origin of energetic He^+. In view of the results reported here, we would suggest that the then puzzling observations of the ubiquitous energetic He^+ at 1 AU [*Hovestadt et al.*, 1984; *Gloeckler*, 1984] are explained quite naturally as accelerated interstellar pickup He^+. Furthermore, the factor of about three larger ratios of H/O and He/O found in corotating events observed at MeV/nucleon energies at 1 AU [*Gloeckler et al.*, 1979; *Reames et al.*, 1991], compared to corresponding coronal hole solar wind abundance ratios [*Gloeckler and Geiss*, 1989], are probably due to the dominance of accelerated pickup hydrogen and He^+ in CIRs as we observe.

Our results also have implications for the acceleration of the anomalous cosmic rays which are now generally accepted to result from the acceleration of the pickup ions somewhere in the outer heliosphere [*Fisk et al.*, 1974], possibly at the termination shock of the solar wind [*Pesses et al.*, 1981]. First, on a global scale, some fraction of the overall interstellar pickup ion population is likely to be already preaccelerated in CIRs and evolving turbulent structures in the outer heliosphere by presumably some statistical mechanism before reaching the termination shock. These preaccelerated pickup ions will probably be more efficiently injected into the acceleration mechanism at the termination shock than the rest of the pickup ion population which is colder.

Finally, it is worth noting that these observations have possible implications for the strength of the termination shock. If we take, as an example, the model pickup ion distribution (as in Figure 2), with the observed solar wind parameters, and assume that the accelerated pickup ions have approximately 6 times the pressure of the pickup ion population, it is possible to extrapolate to the outer heliosphere and find that the pressure in the pickup ions and their accelerated component is about 20% of the solar wind ram pressure at 100 AU, a likely location for the termination shock. If the pressure in the pickup ions is indeed this high, the resulting Mach number of the termination shock is such that the strong shock approximation used in many acceleration models is not appropriate.

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