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He^{2+} Heating at a Quasi-Parallel Shock

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We present the first observations of solar wind He^{2+} heating downstream from the Earth's quasi-parallel shock. These observations show that in conjunction with protons, two different regions are observed. In regions where the proton distribution is cooler, more dense, and similar to that observed downstream from quasi-perpendicular shocks, the He^{2+} distribution is shell-like, also similar to that observed downstream from quasi-perpendicular shocks. In regions where the proton distribution is hotter, less dense, and Maxwellianlike, the He^{2+} distribution is also Maxwellianlike without evidence for a shell. These observations support the interpretation that the nearly isotropic proton and He^{2+} distributions are produced through the strong interaction of a very dense specularly reflected proton beam with the incident solar wind, while the cooler proton distributions and shell-like He^{2+} distributions are produced in a manner similar to that at the quasi-perpendicular bow shock.

INTRODUCTION

The study of collisionless shocks in space plasmas has received considerable attention since the early observations of the Earth's bow shock. Most of this attention has been directed toward the understanding of quasi-perpendicular shocks (shocks whose angle between the shock normal and the magnetic field, ϑ_{Bn}, is greater than 45°). Many of the processes at these shocks, including ion dissipation, are well documented [see *Gosling and Robson*, 1985; *Goodrich*, 1985, and references therein]. While this class of shocks is easier to study than quasi-parallel shocks ($\vartheta_{Bn} < 45°$) both from a theoretical and an observational standpoint, significant advances in the understanding of quasi-parallel shocks have also recently been made. Of particular interest here are observations and computer simulations of quasi-parallel shocks which investigate ion thermalization and suggest that these shocks undergo cyclic reformation [*Burgess*, 1989; *Gosling et al.*, 1989; *Scholer and Terasawa*, 1990; *Thomas et al.*, 1990; *Thomsen et al.*, 1990; *Onsager et al.*, 1990].

Recently, cold beams have been detected just upstream from the Earth's quasi-parallel bow shock [*Gosling et al.*, 1989; *Onsager et al.*, 1990]. These beams have velocity space signatures consistent with near-specular reflection off the nearby shock and are similar to those seen just upstream from the quasi-perpendicular bow shock. Downstream from the quasi-parallel shock, the proton distribution is observed to alternate between a hotter, less dense state and a cooler, more dense state [*Gosling et al.*, 1989; *Thomsen et al.*, 1990] . The hot distributions are Maxwellianlike, while the cooler distributions have a core and shoulder also characteristic of the distributions seen downstream from the quasi-perpendicular bow shock.

From these observations the following model for the quasi-parallel bow shock was developed. This model is supported and strongly influenced by several computer simulations of the quasi-parallel shock [e.g., *Burgess*, 1989; *Scholer and Terasawa*, 1990; *Thomas et al.*, 1990].

Initially, a relatively small fraction (~ few percent) of solar wind H^+ is reflected off the quasi-parallel shock and propagates into the upstream region. These ions generate large- amplitude waves which convect back into the shock. The waves have a profound effect on the shock, causing large fluctuations of the upstream ϑ_{Bn} [*Greenstadt and Mellott*, 1985] which apparently result in the periodic specular reflection of a larger than normal amount of incident solar wind H^+. The large fraction of reflected H^+ propagates into the upstream region and interacts strongly with the solar wind, causing the steepening of the convecting large-amplitude waves and the re-formation of the shock some distance farther upstream.

Downstream from the re-forming quasi-parallel shock, H^+ distributions alternate between a cooler, denser distribution similar to those observed at quasi-perpendicular shocks and a much hotter, less dense, nearly isotropic distribution. The cooler distribution is believed to be formed much the same way that similar distributions are formed at quasi-perpendicular shocks. That is, a relatively small fraction of ions initially specularly reflect off the shock and gyrate into the upstream region. These ions return to the shock because they reflected off the shock when the instantaneous magnetic field-shock normal orientation was quasi-perpendicular or because they couple rapidly to the incident solar wind. In the downstream region they form the observed shoulder on the transmitted solar wind population. The hotter distributions are believed to be generated by the strong interaction between the solar wind and the large fraction of ions that is periodically reflected off the

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shock. The lower densities in these hotter regions may be the result of pressure equalization downstream from the shock.

It has also been suggested that the strongly heated H^+ distributions seen downstream from the quasi-parallel shock and the hot, nearly isotropic distributions seen inside so-called hot diamagnetic cavities or hot flow anomalies (HFAs) are generated by essentially the same strong beam-plasma interaction [*Thomsen et al.*, 1990]. Recent computer simulations of both HFA formation and of the region upstream from the quasi-parallel bow shock suggest that the nonresonant and the resonant ion beam instabilities mediate this strong interaction. For small H^+ beam densities (~ few percent), simulations show that the solar wind and beam interact through the resonant instability and saturation occurs through pitch angle scattering of the beam, with little effect on the solar wind [*Galvez et al.*, 1990]. For the larger H^+ beam densities ($\geq 10\%$) believed to be responsible for strong ion heating at quasi-parallel shocks and in HFAs, simulations show that the interaction between the solar wind and the beam is through the non-resonant instability and both the solar wind and the beam are heated strongly [*Galvez et al.*, 1990]. These simulations used an infinite, uniform plasma and beam. When the dense beam has finite length in the simulation box, the initial interaction is primarily through the nonresonant instability, but the resonant instability eventually dominates [*Onsager et al.*, 1991]. The end result for the ions is the same: strong heating and scattering of both the solar wind and the H^+ beam.

One of the consequences of strong H^+ interaction through the nonresonant instability is strong scattering and heating of the solar wind He^{2+} distribution. Indeed, observations inside HFAs show this strong He^{2+} heating [*Galvez et al.*, 1990]. In this paper we will take the analogy between the HFAs and the quasi-parallel shocks one step further by presenting He^{2+} distributions downstream from a quasi-parallel shock that also show evidence for strong scattering. These observations support the idea that part of the quasi-parallel shock re-formation process entails the reflection of a large fraction of solar wind H^+, which then interacts strongly with the solar wind H^+, producing waves that scatter and heat the solar wind H^+ and He^{2+} distributions.

The He^{2+} observations in this paper were from the Lockheed Plasma Composition Experiment [*Shelley et al.*, 1978]. This set of mass spectrometers measured the velocity distributions of ions from mass/charge (M/Q) = 1 to 150 amu/charge in 64 mass steps and in 32 possible energy steps from near the spacecraft potential to 17.9 keV/e. The spectrometer used here pointed 5° below the spin (ecliptic) plane and had a field of view ranging from a high of about ±20° at low energies to a low of about ±5° at high energies. During the 1978 and 1979 ISEE solar wind seasons this mass spectrometer was programmed to operate in a variety of modes specifically intended for magnetosheath and solar wind studies. In the high bit rate mode of interest for this paper, the He^{2+} spectrum from 10 eV/e to 17.9 keV/e was sampled in 16 energy steps. Each energy step was maintained for slightly more than 1 spin (for 4 s), so that the He^{2+} spectrum with a 7.5° angular resolution in the spacecraft spin plane was completed in 64 s. A new He^{2+} spectrum was obtained approximately every 128 s with intervening time spent measuring other mass/charge ions.

Proton observations in this paper were from the joint Los Alamos /Garching Fast Plasma Experiment (FPE) on ISEE 2 [*Bame et al.*, 1978]. In one 3-s spacecraft spin, this electrostatic analyzer measured the energy-spin angle distribution of the total ion flux from 70 eV/e to 40 keV/e in 16 energy steps at each of 16 azimuths integrated over ±55° of elevation angle relative to the ecliptic. Full two dimensional distributions were repeated every 3 s in high data rate. The FPE moments in this paper were derived under the assumption that all ions were protons.

Magnetic field measurements in this paper are from the University of California, Los Angeles, flux gate magnetometer on ISEE 1 [*Russell*, 1978]. This instrument measured the vector magnetic field 16 times a second in high data rate.

OBSERVATIONS

The bottom two panels of Figure 1 show proton and He^{2+} densities and temperatures downstream from a quasi-parallel bow shock on September 1, 1979. The proton observations for this supercritical shock (fast mode Mach number ~5.5) were discussed in detail by *Gosling et al.* [1989] and *Thomsen et al.* [1990] and serve as an introduction to the new He^{2+} observations in Figure 1. Although ISEE 1 and 2 were downstream from the quasi-parallel bow shock for the entire interval from 1703 to 1709:30 UT, at least two distinct regions can be identified from the proton moments. From 1703:30 to 1704:20 UT and from 1708:40 to 1709:30 UT the proton density was higher and the temperature was much lower than at other times. In these high-density, low-temperature intervals, the proton distribution had characteristics similar to those observed downstream from quasi-perpendicular shocks. In particular, it consisted of a cold core at low energies (less than ~1 keV/e) and a relatively hot shoulder or halo at suprathermal energies (~ few keV/e) [*Gosling et al.*, 1989; *Thomsen et al.*, 1990]. At higher energies ($\geq$10 keV/e), the distribution was different from those observed at quasi-perpendicular shocks because of the presence of the "diffuse" ion population not seen in the quasi-perpendicular geometry. The diffuse ion population is a ubiquitous feature of the regions upstream and downstream from the quasi-parallel shock [e.g., *Thomsen et al.*, 1990]. In the low-density, high-temperature intervals (for example from 1706:30 to 1708:30 UT), the proton distribution was isotropic and Maxwellian-like and did not have the core and halo features seen in the high density, low temperature intervals [*Gosling et al.*, 1989; *Thomsen et al.*, 1990]. However, the hot diffuse ion population was present throughout.

Unlike the proton moments, the He^{2+} moments in the bottom panels of Figure 1 do not exhibit two distinct regions. The He^{2+} temperature was relatively constant throughout the downstream interval, and the He^{2+} density changes did not correlate with those for protons. However, the pitch angle distributions in the upper two panels of Figure 1 clearly show that the He^{2+} distribution was different in the regions of low and high proton temperatures. These distributions were obtained by computing the instantaneous pitch angle distribution in the rest frame of the total proton distribution. The bulk flow velocity from the FPE was used to determine the frame of reference for each spacecraft spin and the instantaneous magnetic field direction for each energy and angle measurement of the He^{2+} distribution was used to determine the instantaneous pitch angle in that frame. Pitch angles not measured by the instrument were interpolated and, in a few cases, extrapolated from measured values. Small dots in the upper panels show the pitch angle and velocity bins used to produce the contour plots, and contours (two per decade) are labeled by the log of the phase space density in cm^{-6} s^3. (Note that the entire energy range for the Plasma Composition Experiment is not displayed in these contour plots.) Although the ISEE 2 proton flow velocities were used for each 3-s spin to determine the frame of reference, no qualitative difference was found by using a bulk flow velocity averaged over the entire ~1 minute required to obtain the He^{2+} distribution.

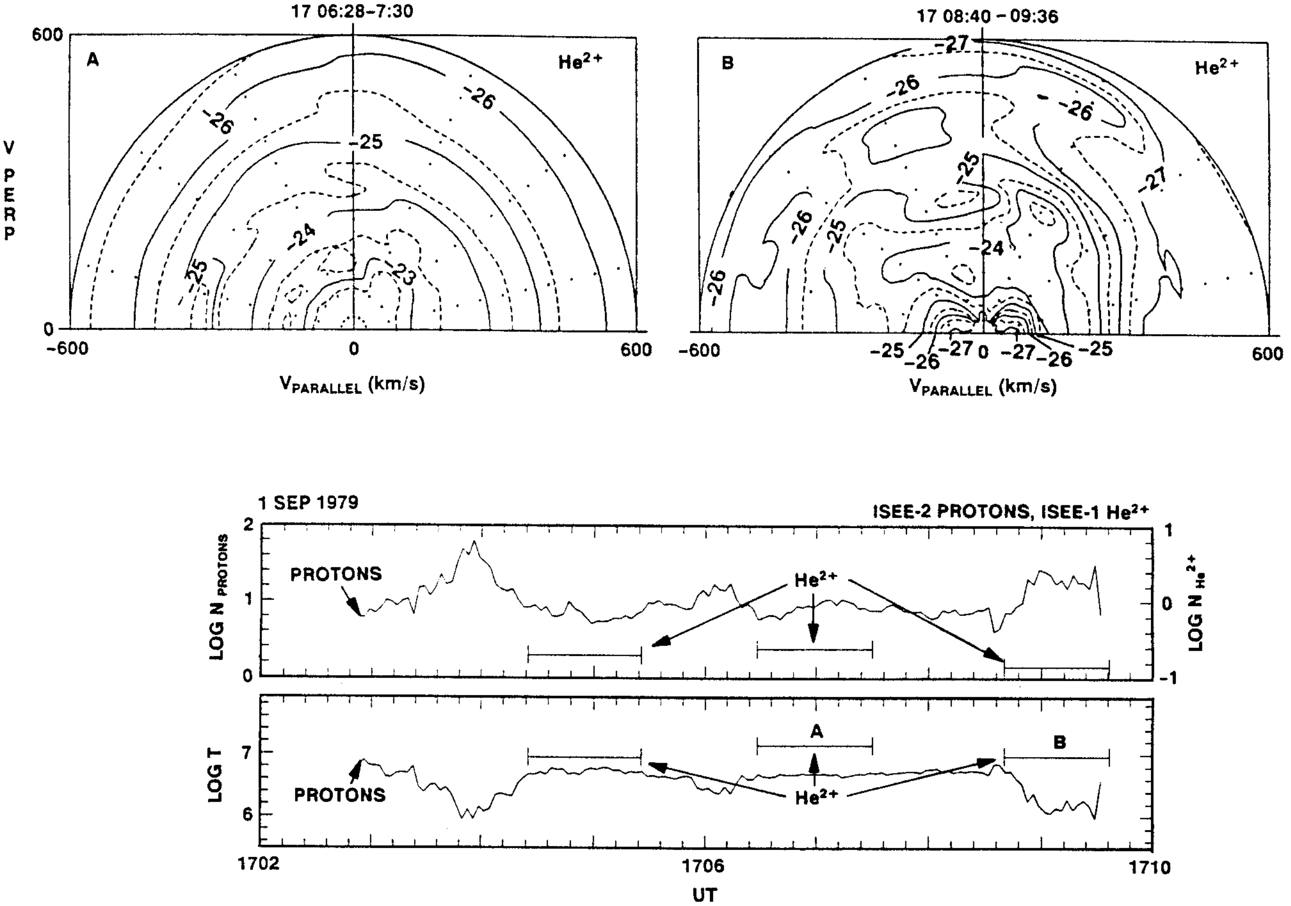

Fig. 1. Proton and He^{2+} moments downstream from a quasi-parallel bow shock on September 1, 1979 (bottom two panels), and He^{2+} pitch angle distributions (in cm^{-6} s^3) in the rest frame of the proton bulk flow (top two panels). The He^{2+} heating downstream from the shock is independent of the proton heating. However, the distributions associated with the high proton temperatures are Maxwellianlike and isotropic (A), and the distributions associated with low proton temperatures are shell-like and anisotropic (B).

Distribution A in Figure 1 was taken during an extended interval when the proton temperature was high. This He^{2+} distribution is nearly isotropic in the proton frame of reference. The other He^{2+} distribution from the high proton temperature interval (from 1704:24 to 1705:24 UT, not shown) was qualitatively similar to distribution A. Distribution B in Figure 1 was taken during a low proton temperature interval. This He^{2+} distribution is in the form of a partially filled shell centered approximately on the proton flow velocity with shell radius ~200 km/s. Note the "hole" in velocity space centered at zero where the phase space density decreases from 10^{-24} to 10^{-27} cm^{-6} s^3. This shell distribution is clearly not isotropic and very different from distribution A.

To emphasize further the differences in these two distributions, Figure 2 shows the phase space density summed over all measured pitch angles versus velocity in the proton rest frame for the same two intervals A and B in Figure 1. This time, however, the full energy range of the Plasma Composition Experiment is shown. Dashed curves in this figure show the one count per sample level. The uniform nature of distribution A extends from near zero velocity to about 800 km/s. The shell structure of distribution B is clearly seen in the right-hand panel by the decrease in phase space density below about 50 km/s. In addition, there is a shoulder on distribution B above about 300 km/s and another break at about 500 km/s, where the suprathermal and more energetic parts of the distribution meet.

Although distributions A and B in Figures 1 and 2 are considerably different from one another, they have nearly the same temperature as evidenced by the moments in the bottom panel of Figure 1. By temperature we mean here the average of the parallel and perpendicular temperatures derived from the second moment of the velocity space distribution. Another way to determine the temperature for the nearly isotropic distribution (A in Figure 2) is to fit the velocity distribution below ~800 km/s with a Maxwellian. This will not produce a meaningful result for the shell-like distribution (B in Figure 2) because it is clearly non-Maxwellian. However, the temperature of this distribution can be approximated by assuming that the thermal speed is the radius of the shell (~200 km/s from Figure 2).

Table 1 shows the He^{2+} temperatures computed from the second moment of the distributions as well as those determined from Maxwellian fits and the radius of the shell. Upstream He^{2+} temperatures were determined by fitting the solar wind distribution along the flow direction with a Maxwellian. The upstream proton temperature in Table 1 is from the Los Alamos Solar Wind Experiment [*Bame et al.*, 1978], while the downstream proton temperatures are from the Los Alamos/Garching FPE. The up-

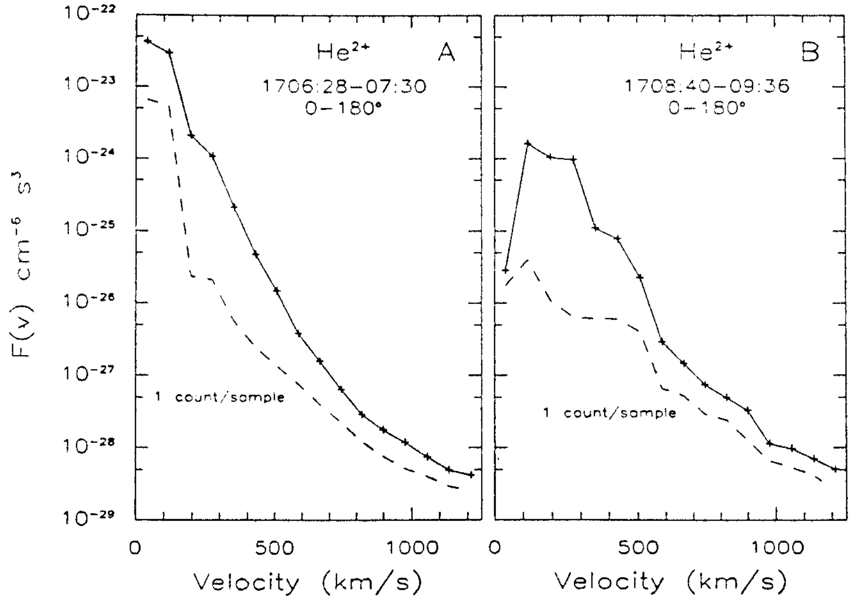

Fig. 2. Velocity distributions for He^{2+} summed over all measured pitch angles for two intervals A and B in Figure 1 downstream from the quasi-parallel shock. Distribution A, associated with high proton temperatures, is Maxwellianlike from near zero to 800 km/s. Distribution B, associated with low proton temperatures, is shell-like with a shell radius of ~200 km/s.

stream temperature ratio in Table 1 is somewhat smaller than the average ratio of 4 in the solar wind [e.g., *Neugebauer,* 1981]. To our knowledge the downstream He^{2+} temperatures and He^{2+} to proton ratios listed in Table 1 are the first reported downstream from the Earth's quasi-parallel shock. For this particular shock the He^{2+} heating appears to be independent of the proton heating. However, the He^{2+} to proton temperature ratio remained roughly constant across the shock if all three measurements are averaged. Table 1 also shows that the moment and fitting methods of determining the He^{2+} temperature produce the same results. This indicates that the hot isotropic distribution A in Figure 1 is well approximated by a Maxwellian from ~0 to ~800 km/s (with correlation coefficient R^2=0.95) and the temperature of the shell distribution B in Figure 1 is essentially determined by the shell radius.

Discussion

In this paper we presented what we believe are the first measurements of the temperature change for He^{2+} across a quasi-parallel bow shock. On average, the He^{2+} distribution and proton distribution maintain their temperature ratio across the quasi-parallel shock.

Although the He^{2+} temperature increase across the shock appears to be roughly constant on average, the He^{2+} distribution observed in the high-density, low-temperature proton region is significantly different from those observed in the low-density, high-temperature proton regions (Figure 1).

In the low-temperature, high-density proton region the He^{2+} distribution (distribution B in Figures 1 and 2) resembles a partially filled shell centered approximately on the proton flow velocity with shell radius ~200 km/s. This shell-like distribution is similar to those observed in the quasi-perpendicular geometry [*Fuselier et al.,* 1988]. In the quasi-perpendicular geometry the formation of a downstream He^{2+} (or other solar wind heavy ion) shell distribution is believed to occur as follows [e.g., *Fuselier et al.,* 1988]: In the solar wind the H^+ and He^{2+} distributions have the same bulk velocity. Across the shock, both distributions are retarded by the same cross-shock electrostatic potential difference. By virtue of its larger M/Q, He^{2+} is decelerated less than H^+ and is initially flowing faster than H^+ in the downstream region. Pitch angle scattering of the He^{2+} distribution by waves in the downstream region eventually produces a shell centered on the H^+ bulk flow velocity with shell radius approximately equal to the initial velocity difference between He^{2+} and H^+ just downstream from the shock.

TABLE 1. Temperatures for September 1, 1979, Quasi-Parallel Shock

Approximate Center Time, UT	T_{He} Moment	T_{He} Fit	T_P Moment	T_{He}/T_P Moment	T_{He}/T_P Fit
1710 (upstream)*	–	2.6×10^5	9.5×10^4	–	2.8
1705 (downstream)	9.0×10^6	9.6×10^6	5.5×10^6	1.6	1.7
1707 (downstream)(A)	1.4×10^7	1.4×10^7	4.8×10^6	2.9	2.9
1709 (downstream)(B)	9.4×10^6	$\sim1\times10^7$†	2.5×10^6	3.8	3.9

*Upstream proton temperatures are from the Los Alamos Solar Wind Experiment on ISEE 1. He^{2+} temperatures are from the Plasma Composition Experiment.

†Converting a shell radius of 200 km/s into a temperature.

Distribution B in Figures 1 and 2 also shows a shoulder above about 300 km/s. In analogy with a similar shoulder seen on proton distributions taken at the same time [see *Gosling et al.*, 1989, Figure 7] the shoulder on the He^{2+} distribution may be evidence for specularly reflected He^{2+} ions that have returned to the downstream region. Recently, specularly reflected He^{2+} was reported in the region just upstream from some quasi-parallel shocks [*Fuselier et al.*, 1990]. Like their proton counterpart, these ions may return to the shock and be transmitted into the downstream region to form the shoulder seen in Figures 1 and 2. A similar shoulder has also been seen on He^{2+} distributions downstream from quasi-perpendicular shocks [*Shelley et al.*, 1976; *Peterson et al.*, 1979; *Fuselier et al.*, 1988].

The only qualitative difference between distribution B in Figure 2 and the distributions seen downstream from quasi-perpendicular shocks is the presence of He^{2+} from ~800 km/s to 1200 km/s, the full range of the instrument. The presence of this hot He^{2+} distribution is consistent with a recent study of the magnetosheath that showed a good correlation between the hot diffuse proton population seen ubiquitously downstream from the quasi-parallel bow shock and a similar hot He^{2+} population [*Fuselier et al.*, 1991]. Evidence for this hot He^{2+} distribution can also be seen in distribution A in Figure 2.

Below the velocity range corresponding to the diffuse ion distribution the He^{2+} distribution in the low-density, high-temperature proton region (A) is significantly different from that in the high-density, low-temperature proton region (B). In distribution A there is neither evidence for a shoulder at about 300 km/s nor evidence for a shell. The distribution in these high-temperature proton regions is nearly isotropic (see Figure 1, distribution A) and Maxwellianlike out to almost 800 km/s.

Nearly isotropic, Maxwellianlike He^{2+} distributions have been seen inside the so-called HFAs [*Galvez et al.*, 1990]. As discussed in the introduction, the distributions seen there are believed to be produced by strong scattering. The waves that mediate this scattering are believed to be produced by the interaction of a dense H^+ beam with the solar wind [*Thomsen et al.*, 1988], through either the nonresonant ion beam instability [*Galvez et al.*, 1990] or some mixture of the nonresonant and resonant instabilities [*Onsager et al.*, 1991]. The end result of this strong interaction is significant scattering of both the solar wind proton and the He^{2+} distributions.

Although the two distributions in Figure 2 are very different, they have the same temperature. In fact, Figure 1 and Table 1 suggest that the He^{2+} temperature increase for this shock is independent of the proton heating. The decoupling of proton and He^{2+} heating at the shock may indicate that the initial velocity difference between the proton and He^{2+} distribution just downstream from the shock determines the final temperature regardless of the level of proton heating. This is probably true for the region of low proton temperature (B in Figures 1 and 2) since the temperature of the He^{2+} distribution is essentially determined by the shell radius (Table 1) which itself is determined by the initial relative drift between the proton and He^{2+} distributions. This might also be the case in the regions of high proton temperature except that the shell is quickly destroyed by strong scattering.

Although we have demonstrated that the He^{2+} distributions are different in the two proton regions downstream from one quasi-parallel shock, we do not have observations downstream from the other shocks recently studied by *Thomsen et al.* [1990]. The main reasons for this are the variety of operating modes of the Plasma Composition Experiment and the time resolution of the instrument. The observations in Figure 1 are a fortuitous occurrence when the Plasma Composition Experiment was in a good mode for He^{2+} observations and the intervals of low and high proton temperatures lasted for ~1 min. Typically, the cyclic variation between low- and high-temperatures occurs ~1 to a few proton gyroperiods (~10 s) [*Thomsen et al.*, 1990], which is much too fast for the ~1 min composition measurements. This relatively rapid variation, coupled with the fact that not all operating modes sampled He^{2+} often enough, makes a survey of quasi-parallel shocks with this composition instrument very difficult.

In summary, we interpret the new He^{2+} observations in this paper as follows. In the cooler, more dense proton regions downstream from the quasi-parallel shock, the core and shoulder proton distributions and the shell-like and shoulder He^{2+} distributions are most likely formed by essentially the same processes that form these distributions at quasi-perpendicular shocks. Namely, the core proton distribution is directly transmitted solar wind protons, the shell He^{2+} distribution arises from a velocity difference between the He^{2+} and proton distributions in the downstream region followed by pitch angle scattering in the proton rest frame, and the shoulders on both the proton and the He^{2+} distributions are initially reflected solar wind ions that have returned to the shock and entered the downstream region. For the hotter, less dense proton regions, either quite different mechanisms must operate than those in the quasi-perpendicular geometry or both protons and He^{2+} must experience strong scattering and energy diffusion. This scattering may result from waves produced through a strong interaction between the incident solar wind and a relatively dense reflected proton beam. The relative constancy of the downstream He^{2+} temperature suggests that a difference in the level of scattering and energy diffusion may indeed be the principal cause of the differences in the observed He^{2+} distributions.

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