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Comment on "MeV magnetosheath ions energized at the bow shock" by S.-W. Chang et al.

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INDEX TERMS: 2154 Interplanetary Physics: Planetary bow shocks; 2716 Magnetospheric Physics: Energetic particles, precipitating; 2728 Magnetospheric Physics: Magnetosheath; 2788 Magnetospheric Physics: Storms and substorms; *KEYWORDS:* cusp, energetic particles, magnetopause boundary layer, magnetosheath, bow shock

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[1] From a study of the 4 May 1998 storm event, *Chang et al.* [2001] (hereinafter referred to as CETAL01) suggested that "ions are accelerated at the quasi-parallel bow shock to energies as high as 1 MeV and subsequently transported into the magnetosheath during this event" and mentioned that "This is confirmed by a comparison of energetic ion fluxes simultaneously measured in the magnetosheath and at the quasi-parallel bow shock when both regions are likely connected by the magnetic field lines" (see their Abstract). After an inspection of the measured energetic ion data, however, one finds that CETAL01 have misplotted the observed ion energy spectrum in the "magnetosheath" (near the cusp) to lower energy which brings it in closer agreement to the flux measured near the quasi-parallel bow shock, making their analysis suspect. In fact, simultaneous measurements at this time indicate that (1) the energetic ion flux near the cusp was about one order of magnitude higher than that near the quasi-parallel bow shock, (2) the energetic ion time signatures were seen first near the cusp then near the bow shock, and (3) the energetic ion flux observed near the bow shock was independent of bow shock geometry. Each of these three facts is sufficient to demonstrate that the quasi-parallel bow shock was not the main source of the energetic ions near the cusp during this event.

[2] CETAL01 stated that "A comparison of Interball and Polar ion spectra can potentially falsify our bow shock source hypothesis and is now the focus of our analysis." In Figure 11 of CETAL01, accordingly, they compared the energetic ion flux measured by Interball near the quasi-parallel bow shock with that measured by Polar near the cusp during the interval 1101–1142 UT on 4 May 1998, where their Polar/CEPPAD energetic ion data (open circles in their Figure 11) were taken only from the ion sensor that was looking 90° from the Polar spin axis. Our Figure 1 replots the Interball data (stars) and the Polar/CEPPAD data (open squares) for the same time interval. Comparing Figure 11 of CETAL01 to our Figure 1, we find that they have misplotted the CEPPAD ion energy spectrum near the cusp to the lower energies which reduces the difference between Interball and Polar ion fluxes. A closer inspection of their Figure 11 suggests that for each energy interval (channel) near the cusp they used the lower energy threshold to represent it without taking into account the effective energy passband [*McKinnon and Fritz*, 1976] of the steep energy spectrum, and the resulting energy spectrum near the cusp shown in their Figure 11 is thus lower than the actually observed spectrum as shown in our Figure 1.

[3] This is not the only case where CETAL01 misplotted the observed ion energy spectrum around the cusp to lower than the actually observed spectrum, for in an earlier paper, *Chang et al.* [1998] (hereinafter referred to as CETAL98) misplotted the MICS (Magnetospheric Ion Composition Sensor) lower energy limit from 1 keV/e to 0.6 keV/e which brought the cusp fluxes into better alignment with "bow shock ion spectra," and in addition, misplotted the HIT (Heavy Ion Telescope) helium data point in the cusp below the actual observed value of 0.22 He^{+2} ions (cm^2-sr-s-keV/e)$^{-1}$ at 0837:40-0845:00 UT on 27 August 1996 [CETAL98, Figure 3]. Based upon such misplotted data, CETAL01 stated in their introduction that CETAL98 "showed that cusp energetic ion spectra (<300 keV e^{-1}) matched very well with a large body of bow shock ion spectra."

[4] Yet even after misplotting the observed CEPPAD ion spectrum near the cusp to below the actual observed one, the Interball ion flux near the bow shock was still lower than the Polar ion flux near the cusp as shown in their Figure 11, so CETAL01 made another spectral adjustment by increasing the measured Interball ion flux near the bow shock by about 300% to match the repositioned Polar ion flux to obtain their Figure 13. They called it a "distance correction" and made it central to their argument stating that "an important piece of evidence for the bow shock source is demonstrated in Figure 13." However, it has been reported [*Lee*, 1982] that the proton flux at 7 R_E from the bow shock is almost the same as that at the bow shock at energies larger than 60 keV; that is, no correction is needed

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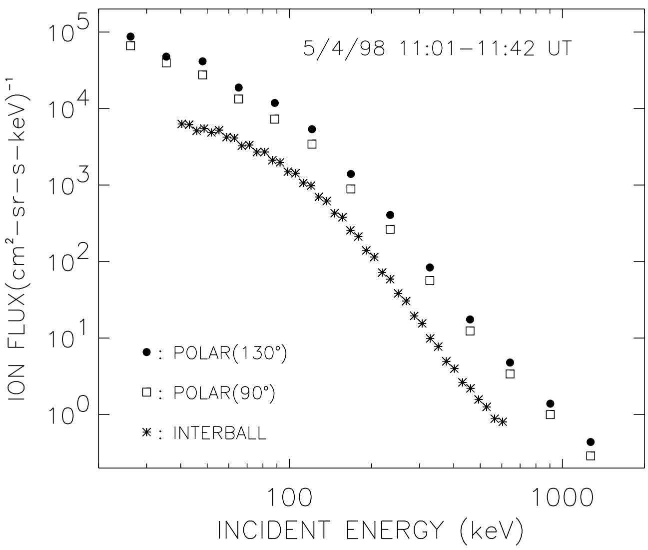

Figure 1. Ion energy spectra observed by Polar with a look-direction of 130° (solid circles) and 90° (open squares) from Polar spin axis and by the Interball (stars) at 1101–1142 UT on 4 May 1998.

to transfer the >60 keV proton flux at 7 R_E to 0 R_E from bow shock [*Lee*, 1982, Figures 1 and 3]. This result was further supported by *Trattner et al.* [1994], who analyzed 382 upstream ion evens and found that there is essentially no correlation between the 67.3 keV proton flux and the distance from the bow shock (the actual correlation coefficient found was about 0.2). They [*Trattner et al.*, 1994] stated that "Therefore the necessary correction of the flux for zero bow shock distance is insignificant" above 67.3 keV/e. The 382 events covers a solar wind velocity with $V_{SW} * cos(BV_{SW})$ from 200 to 700 (km/s). These two papers suggests that when Interball was at a distance of about 4–6 R_E from the bow shock increasing the >60 keV Interball ion flux by about 300% was unjustified.

[5] Additional evidence that CETAL01 mishandled the ion data is shown in their Figure 14. From its left panel, we observe that the oxygen ion (solid circles) flux of solar wind origin is even higher than the total ion flux at about 20 keV, which is obviously impossible. Also from its right panel, the He^{+2}/O^{+6} ratio has a value of about 3 at energies <10 keV/e, which is more than one order of magnitude lower than the known ratio value in the solar wind [e.g., *Möbius et al.*, 1987], suggesting that either the data was misplotted or these ions were not of solar wind origin. Our Figure 2 plots the observed He^{+2} (open triangles), $O^{\geq+3}$ (open sqares), and $O^{\leq+2}$ (solid circles) energy spectra at 1100–1145 UT on 4 May 1998. The $O^{\geq+3}$ was dominated by O^{+6}, and the $O^{\leq+2}$ was dominated by O^{+}. These observations indicate that He^{+2}/O^{+6} ratio has a value of about 100 even at energies <10 keV/e. Our Figure 2 further indicates that energetic (about 100 keV/e) oxygen ions of ionospheric origin were also measured during this period, which is evidence showing that bow shock acceleration is not the main source of these energetic ions. The energetic oxygen ions of ionospheric origin have been observed in the high-altitude dayside cusp [*Chen and Fritz*, 2001].

[6] Another problem in CETAL01 concerns the location of Polar in geospace at 1101–1142 UT on 4 May 1998. CETAL01 stated that "Polar was in the undisturbed magnetosheath according to the plasma and magnetic field data; that is, Polar was located farther into the magnetosheath than that suggested by the model" (shown in their Figure 9). In contrast to CETAL01, during 1101–1142 UT, Polar was in an extremely disturbed magnetic field region with $\Delta B \sim B$ and a field strength peak of about 120 nT [*Chen and Fritz*, 1999]. CETAL01's Figures 1 and 2 imply a D-shaped ion velocity distribution, suggesting that Polar was on open magnetospheric field lines at the time. In other words, these observations suggest that magnetic field lines at the location of Polar were connected with the cusp at this time. Their Figures 1 and 2 further reveal that Polar ion flux was peaked at about 150°–180° pitch angles. Since from 1101 to 1142 UT the Polar spin axis was pointing approximately antiparallel to the local magnetic field direction, the Polar ion sensor looking at a direction of 130° from the spin axis corresponded to a pitch angle also of about 130°, and the 90° look-direction corresponded to a pitch angle approximately around 90° as well. Our Figure 1 shows that the 130° Polar ion flux (solid circles) was higher than that of the 90° Polar ion flux (open squares) and was about one order of magnitude higher than the Interball ion flux (stars) when Interball was near the bow shock. If "Polar is likely to be very well connected to Interball by magnetic field lines," as claimed by CETAL01, then our Figure 1 is sufficient to demonstrate that the quasi-parallel bow shock was not the main source of the energetic ions observed by Polar near the cusp.

[7] Our Figure 3 compares ion fluxes measured by POLAR (solid line) and Interball (dotted line) over three energy ranges (~60–75 keV, 100–140 keV, and 390–545 keV) from 1100 to 1230 UT, where the shaded area indicates the time interval when Interball was magnetically connected to the quasi-perpendicular bow shock and the white areas indicate periods when Interball was magnetically connected to the quasi-parallel bow shock. From 1100 to 1145 UT for each of the energy ranges POLAR measured higher fluxes by about one order of

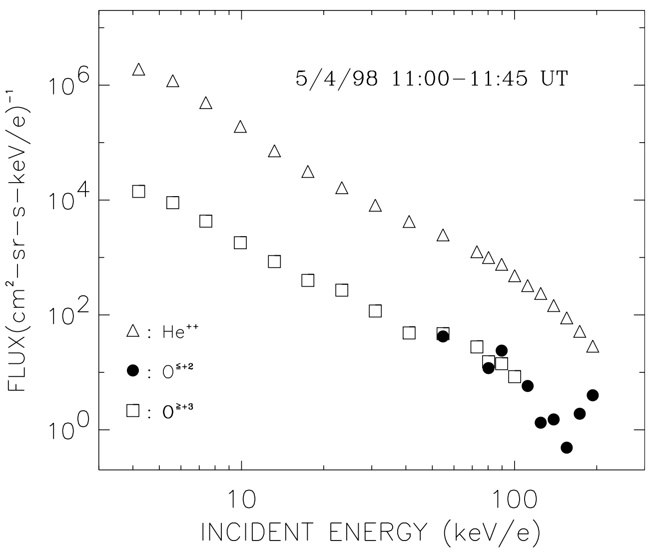

Figure 2. The He^{+2} (open triangles), $O^{\geq+3}$ (open sqares), and $O^{\leq+2}$ (solid circles) energy spectra observed by Polar at 1100–1145 UT on 4 May 1998.

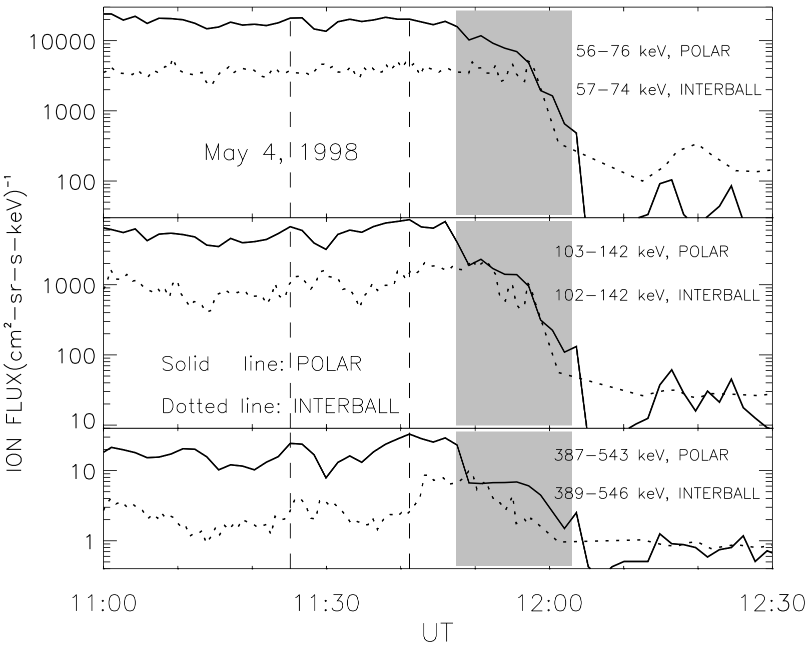

Figure 3. Time profiles of the ion fluxes measured by Polar (solid line) and Interball (dotted line) over three energy intervals (~60–75 keV, top panel; 100–140 keV, middle panel; and 390–545 keV, bottom panel) at 1100–1230 UT on 4 May 1998. The shaded area indicate times when Interball was magnetically connected with the quasi-perpendicular bow shock, and the white areas indicate periods when Interball was magnetically connected with the quasi-parallel bow shock.

magnitude than Interball did. Furthermore, the time profiles of fluxes measured by both POLAR and Interball seem to track fairly closely, and the ion time signatures (peak and valley) were detected first by POLAR near the cusp then by Interball near the bow shock, all of which suggest that POLAR was closer to the energetic ion source region than Interball. The similar temporal variations of the energetic ion fluxes (our Figure 3) and the similar ion energy spectral shapes (our Figure 1), measured by both Interball and Polar, suggest that most of these energetic ions were from the same source. Since Interball was closer to the center of the parallel bow shock (see their Figure 9), the fact that the ion time signatures (peak and valley) were detected first by POLAR near the cusp then by Interball near the bow shock (our Figure 3) is sufficient to demonstrate that the main source for these energetic ions observed by both spacecraft was not the quasi-parallel bow shock.

[8] We note that when the bow shock, which was magnetically connected to Interball, changed at 1147 UT from quasi-parallel to quasi-perpendicular, the 57–74 keV ion flux (top panel of our Figure 3) measured by Interball did not change until 1157 UT. Their Figure 10 indicates that at 1101–1142 UT on 4 May 1998 the Θ_{Bn} for the location of Interball changed between 10 and 40 degrees, while the 57–74 keV ions flux measured by Interball changed by a factor of less than 2. When the Θ_{Bn} for Interball was 10 degrees, indicating that Interball was connected almost to the center of the quasi-parallel bow shock, Interball should see the highest flux if the quasi-parallel bow shock is the dominant source region, but it did not. At 1114 UT when Interball was connected almost to the center of the quasi-parallel bow shock, the 389–546 keV ion flux (bottom panel of our Figure 3) measured by Interball was one order of magnitute less than that at 1149 UT when Interball was connected to the quasi-perpendicular bow shock. Since during 1100–1200 UT, the solar wind pressure (or solar wind density) was almost the same [*Chen and Fritz*, 1999], the above observations reveal that the energetic ion flux observed by Interball near the bow shock was independent of bow shock geometry. Furthermore, the top panel of their Figure 1 indicates that from 1203 to 1220 UT on 4 May 1998, the solar wind ion pressure reduced to the average value (about 3 nPa), and the bow shock position shown in their Figure 9 relaxed sunward even closer to the Interball location. No significant enhancement of energetic ion flux was observed by Interball during this time even though Interball was located almost at the quasi-parallel bow shock. It is interesting to note that at 1203–1220 UT the 389–546 keV ion flux measured by Interball was almost the same as that at 1111–1115 UT even though there was a factor of about 3 difference in the solar wind pressure (or solar wind density) between these two periods. In brief, our Figure 3 and their Figure 10 reveal that the energetic ion flux (~60–550 keV) observed by Interball near the bow shock was independent of bow shock geometry, and only this fact is sufficient to demonstrate that most of these energetic ions were not accelerated at the quasi-parallel bow shock.

[9] CETAL01 also criticized *Chen and Fritz* [1999], saying "... the Geotail and Polar ion flux comparison by *Chen and Fritz* [1999] for this storm event can be wrong." After checking the paper of *Chen and Fritz* [1999], one finds that this paper made no comparison of Geotail and Polar ion fluxes for this storm event.

[10] On the basis of the misplotted ion data, CETAL01 concluded that "The bow shock source of magnetosheath energetic ions for this event strongly supports the bow

shock model of cusp energetic ions [*Chang et al.*, 1998] and is inconsistent with the model of local acceleration in the cusp [*Chen et al.*, 1998].” The observational data shown above demonstrate that the conclusion of CETAL01 is faulty (1) because spectra were consistently lower well away from the magnetopause, with less phase space density, (2) because the ion fluxes temporally followed the changes seen first near the cusp, and (3) because the spacecraft were often not magnetically connected to the quasi-parallel bow shock. Each of these three observational points is sufficient to demonstrate that the bow shock cannot be the source of the observed energetic ions. A local acceleration mechanism, such as that proposed by *Chen and Fritz* [1998], remains the only consistent explanation for these observations; the cusp energetic ions can escape into the upstream and downstream region along open field lines.

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References

Chang, S.-W., et al., Cusp energetic ions: A bow shock source, *Geophys. Res. Lett.*, *25*, 3729–3732, 1998.

Chang, S.-W., J. D. Scudder, K. Kudela, H. E. Spence, J. F. Fennell, R. P. Lepping, R. P. Lin, and C. T. Russell, MeV magnetosheath ions energized at the bow shock, *J. Geophys. Res.*, *106*, 19,101–19,115, 2001.

Chen, J., and T. A. Fritz, Correlation of cusp MeV helium with turbulent ULF power spectra and its implications, *Geophys. Res. Lett.*, *25*, 4113, 1998.

Chen, J., and T. A. Fritz, May 4, 1998 storm: Observations of energetic ion composition by POLAR, *Geophys. Res. Lett.*, *26*, 2921, 1999.

Chen, J., and T. A. Fritz, Energetic oxygen ions of ionospheric origin observed in the cusp, *Geophys. Res. Lett.*, *28*, 1459, 2001.

Chen, J., et al., Cusp energetic particle events: Implications for a major acceleration region of the magnetosphere, *J. Geophys. Res.*, *103*, 69–78, 1998.

Lee, M. A., Coupled hydromagnetic wave excitation and ion acceleration upstream of the Earth’s bow shock, *J. Geophys. Res.*, *87*, 5063, 1982.

McKinnon, J. A., and T. A. Fritz, ATS-6 NOAA solid state proton experiment: Mean energy of a finite energy passband, *Tech. Memo. ERL SEL-45*, Natl. Ocean. and Atmos. Admin., Silver Spring, Md., 1976.

Möbius, E., M. Scholer, N. Sckopke, H. Lühr, G. Paschmann, and D. Hovestadt, The distribution function of diffuse ions and the magnetic field power spectrum upstream of Earth’s bow shock, *Geophys. Res. Lett.*, *14*, 681–684, 1987.

Trattner, K. J., E. Möbius, M. Scholer, B. Klecker, M. Hilchenbach, and H. Lühr, Statistical analysis of diffuse ion events upstream of the Earth’s bow shock, *J. Geophys. Res.*, *99*, 13,389, 1994.

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