8-1-2003

Reply to comment on "MeV magnetosheath ions energized at the bow shock" by J. Chen, TA Fritz, and RB Sheldon

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Recommended Citation

Chang, S.-W., J. D. Scudder, K. Kudela, H. E. Spence, J. F. Fennell, R. P. Lepping R. P. Lin, C. T. Russell, Reply to comment on "MeV magnetosheath ions energized at the bow shock" by J. Chen, T. A. Fritz, and R. B. Sheldon, J. Geophys. Res., 108, A8, 1312, doi:10.1029/2002JA0097242003

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Reply to comment on "MeV magnetosheath ions energized at the bow shock" by J. Chen, T. A. Fritz, and R. B. Sheldon

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Received 4 October 2002; revised 29 April 2003; accepted 8 May 2003; published 5 August 2003.

INDEX TERMS: 2716 Magnetospheric Physics: Energetic particles, precipitating; 2728 Magnetospheric Physics: Magnetosheath; 2788 Magnetospheric Physics: Storms and substorms; 2154 Interplanetary Physics: Planetary bow shocks; *KEYWORDS:* bow shock acceleration, magnetosheath energetic particle, Fermi acceleration

Citation: Chang, S.-W., J. D. Scudder, K. Kudela, H. E. Spence, J. F. Fennell, R. P. Lepping, R. P. Lin, and C. T. Russell, Reply to comment on ''MeV magnetosheath ions energized at the bow shock'' by J. Chen, T. A. Fritz, and R. B. Sheldon, *J. Geophys. Res.*, *108*(A8), 1312, doi:10.1029/2002JA009724, 2003.

[1] The comment [*Chen et al.*, 2003, hereinafter referred to as CFS] attempts to discount a bow shock source of the magnetosheath energetic ions of solar origin observed by the Polar spacecraft during the 4 May 1998 magnetic storm event that is proposed by *Chang et al.* [2001, hereinafter referred to as CETAL01]. CFS further claims that the observed ions are most likely accelerated in the cusp by a still unknown mechanism [*Chen et al.*, 1998]. As shown below, their central arguments are flawed due to apparent confusion over bow shock and magnetopause physics, and the rest of the arguments are irrelevant to the main subject of CETAL01. Nothing presented by CFS challenges a bow shock source nor supports cusp acceleration. On the basis of the large volume of evidence presented by *Chang et al.* [2000, hereinafter referred to as CETAL00] and CETAL01, a follow-up study of CETAL00, Fermi acceleration at the quasi-parallel bow shock remains the most reasonable explanation for this event.

[2] CFS express concerns on (1) IPS spectrum misrepresented in CETAL01, (2) higher flux detected by the 130° IPS sensor, (3) *e*-folding correction at bow shock, (4) shock acceleration, (5) lower energy He^{+2}, $O^{>+2}$, (6) energetic $O^{<+3}$, (7) D-shaped ion distribution, (8) English, (9) comment on [*Chang et al.*, 1998], and (10) typo in CETAL01. Only the first four issues address the main subject of CETAL01. In this reply we first summarize the content of CETAL00 and CETAL01 to provide context for this event and the discussion it has provoked. We then discuss issues raised by CFS and the arguments for and against a bow shock source in the order of their significance and logic flow, as listed from 1 to 10 above.

[3] CETAL00 and CETAL01 examined the origin of energetic H^+, He^{+2}, $O^{>+2}$ ions observed by the Polar CAMMICE and CEPPAD instruments in the magnetosheath, yielding five important results. (1) Ion composition: The presence of energetic heavy ions in the magnetosheath and distinct energetic ion composition and their relative abundance in the sheath and adjacent plasma sheet/low-latitude boundary layer suggest that the observed magnetosheath energetic ions are of solar origin (Plate 1 of CETAL00). (2) Spectral characteristics: Their energy spectra show characteristics of bow shock diffuse ions, namely, exponential or Maxwellian spectra ordered by the energy per charge E/q, not the total energy E, with a common e-folding energy at $\sim$40 keV e^{-1} (Figure 6 of CETAL00, Figures 3 and 4 of CETAL01). (3) Anticorrelation: Their fluxes at energies only above the e-folding energy are strongly anticorrelated with the IMF cone angle (a proxy for θ_{Bn}) as expected for the Fermi process at the shock (Figures 7 and 8 and Plate 2 of CETAL00, Figures 5, 6, 7, and 8 of CETAL01). (4) Anisotropy: They show strong anisotropy toward the magnetopause indicative of a upstream source not the magnetospheric source (Figure 9 of CETAL00). (5) Bow shock spectrum: Bow shock ion spectrum estimated from the foreshock measurements matches very well with the magnetosheath energetic ion spectrum (Figure 13 of CETAL01). The above results strongly suggest that energetic ions above $\sim$40 keV e^{-1} are accelerated at the quasi-parallel bow shock by the Fermi mechanism. Among the five, CFS address only the bow shock spectrum, ignoring other evidence, and make some questionable arguments to discount a bow shock source and jump to the conclusion of cusp acceleration. There is simply no explanation in the cusp acceleration for anticorrelation and anisotropy.

[4] CFS argue that CEPPAD IPS ion spectrum was misrepresented in Figure 11 of CETAL01 (a duplicated spectrum also presented in Figure 13 of CETAL01) and the difference between Interball and Polar ion fluxes should be greater than suggested in CETAL01. (It is wrong to draw

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0148-0227/03/2002JA009724

any conclusion about a bow shock source by a direct comparison of foreshock ion spectrum from Interball and magnetosheath ion spectrum from Polar. We will address this below.) They claimed that "A closer inspection of their Figure 11 suggests... used the lower energy threshold...". (It is particularly distressing that CFS imply their initiative in discovering our use of the threshold energy in displaying IPS spectra. During this comment/reply process, CFS originally applied higher ion energies from a different energy mode to the IPS data, resulting in an incorrect ion flux display and an expanded gap between Interball and Polar fluxes. In our initial response to the editor we identified the above CFS's mistake and stated that "The IPS energies used throughout the study are listed in Figure 7 in paper 1. They are the threshold energies of the energy channels" (in which "paper 1" refers to CETAL01). Since ion fluxes detected by IPS at energy channels above 100 keV fall sharply with increasing energy during this event, statistically most of the ions sampled come from the lowest portion of these energy channels. Thus the threshold energy used in CETAL01 is a good approximation for the most plausible ion energy. Alternatively, one can use the logarithmic midpoint energy to approximate the energy bin for each channel (see Figure 1) as suggested by CFS. The difference between the IPS ion spectra in Figure 13 (or Figure 11) of CETAL01 and Figure 1 is negligible, well within the uncertainty in the data. The actual ion spectrum lies between the two. The bow shock ion spectrum consistently agrees very well with the IPS spectrum as shown in Figure 1. The difference between the bow shock ion flux and the IPS ion flux above 100 keV is smaller than or roughly equal to the difference in the lower energy ion fluxes from the three Polar instruments (CEPPAD, CAMMICE, and Hydra).

[5] CFS include IPS data from the 130° look direction in their Figure 1 to expand the discrepancy between Interball and Polar fluxes to further argue against a bow shock source. CEPPAD IPS sensors have a total number of nine look directions. The reason why CETAL01 selects IPS data from the 90° sensor has already been stated in that paper, "For the purpose of constructing a full energy spectrum for magnetosheath ions, data used in this study are only extracted from the 90° sensor head whose look direction is perpendicular to the Polar's spin axis to match those of CAMMICE and selected Hydra detectors." CFS should know well that the CAMMICE MICS instrument has only one look direction (90° from the spin axis), thus restricting data selection from Hydra and CEPPAD. Furthermore, CETAL01 used these ion data of similar pitch angles to intercalibrate the three instruments to ensure the best quality of the data. Because the magnetic field was highly variable according to the MFE 8-Hz data, the angle between B field and spin axis varied from 30° to 180° but mostly from 120° to 170° so that the 90° IPS sensor covered a broad range of pitch angles ~30°–150° (figure not shown), invalidating CFS's statement about 90° pitch angle for the 90° sensor. Nevertheless, higher fluxes from the IPS 130° sensor still agree quite well with the estimated bow shock ion spectrum presented in Figure 1 or Figure 13 of CETAL01 by taking into account wide energy bandwidth of IPS ($\Delta E/E \sim 30\%$).

[6] Regarding the issue of bow shock spectrum, CFS question the procedure of *e*-folding scaling for the foreshock spectrum in CETAL01. CFS cite theoretical results of

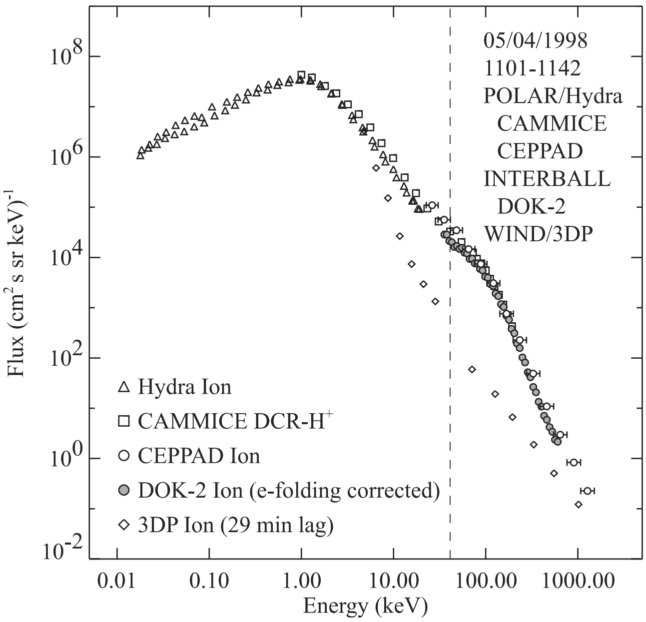

Figure 1. Similar to Figure 13 of CETAL01, with CEPPAD/IPS midpoint energies and energy bandwidths.

Lee [1982] and insist that *e*-folding distance correction is not required for ion energy above 60 keV. This issue has been discussed before (see *Trattner et al.* [1999] and *Fritz and Chen* [1999] who are also two of the authors of CFS). Nothing new has been addressed in CFS. First, it is difficult to understand CFS's logic. It seems unnecessary to argue about whether an *e*-folding correction should be used on observations of bow shock origin particles when CFS discount that origin elsewhere in the Comment. Second, if one scales foreshock ion flux below 60 keV but not above 60 keV for this event, the estimated bow shock spectrum is likely to show an artificial spectral break at ~60 keV in addition to the single spectral break in the bow shock diffuse ion spectrum predicted by *Lee* [1982]. Nor have two breaks been reported. Third, the boundary condition of Lee's calculation matches *Ipavich et al.*'s [1981] upstream diffuse ion events only for average solar wind condition. CETAL01's event occurred during a very intense magnetic storm with an extremely high solar wind velocity (~745 km s^{-1}) and Alfvén Mach number (~7.1). In addition to the upstream solar wind/IMF parameters, loss mechanisms listed in CETAL01 will have significant and different effects on the ion spectrum for normal versus extreme conditions. Thus Lee's theoretical results as well as AMPTE IRM statistical results of *Trattner et al.* [1994] cannot directly apply to this extreme case. For example, the *e*-folding energy in Lee's solution is ~20 keV e^{-1}, different from our ~40 keV e^{-1}. Likewise, the *e*-folding distance is different. By taking into account different boundary conditions, CETAL01 made reasonable assumptions and described detailed procedures to estimate the quasi-parallel bow shock ion spectrum. Finally, commonly known a foreshock ion spectrum is not representative of a bow shock spectrum. It is simply wrong to draw any conclusion about a quasi-parallel bow shock source from a direct comparison of magnetosheath ion flux from Polar and foreshock ion flux from Interball as in Figure 1 of CFS.

[7] CFS state that "the ion time signature (peak and valley) were detected first by Polar near the cusp then by Interball near the bow shock..." to argue against bow shock acceleration for energetic ions observed by both spacecraft. Judging from their Figure 3, Polar fluxes most likely are from CEPPAD IPS, but there is no indication of which sensor(s) are used and whether any interference has been removed from the data as in CETAL01. It is not clear how the Interball's differential number fluxes in their Figure 3 are calculated, since the DOK-2 instrument has a much smaller energy bandwidth ($\Delta E/E \sim 6\%$, also see Figure 1 for DOK-2 energy channels). Both magnetosheath (Polar) and foreshock (Interball) ion fluxes in their Figure 3 show many small-scale variations (or fluctuations) with many more variations in the latter. Without any specific example or analysis, the above CFS's statement about peak and valley is very vague. Relative to each peak and valley on the Polar curves in their Figure 3, there are arguably corresponding peaks and valleys on the Interball curves that are sometimes ahead and sometimes behind those of Polar. There are many factors contributing to these small-scale variations (see details below). Most importantly, CFS fail to recognize the most obvious feature in their Figure 3 which appears to lead to their incorrect conclusions. That is, there was a large flux decrease, by more than one order of magnitude, in the upstream region as Interball was transitioning from a quasi-parallel shock geometry to a quasi-perpendicular shock geometry ($\sim$1147–1203 UT). (We note that Interball fluxes reduced further after $\sim$1159 UT due to a sharp decrease in the solar wind density.) This result is consistent with Fermi acceleration at the quasi-parallel shock, and it also proves CFS is wrong in stating that "In brief... energetic ion flux ($\sim$60–550 keV) observed by Interball near the bow shock was independent of bow shock geometry...". Furthermore, the flux decrease associated with the shock geometry change appeared first at the highest energy and last at the lowest energy in their Figure 3 demonstrating an energy dispersion, similar to the inverse velocity dispersion (but on the diminishing part of the ion flux) and is one of the most important features of bow shock diffuse ions [e.g., *Ipavich et al.*, 1981]. It is strong evidence for Fermi acceleration. CFS compare foreshock 389–546 keV ion fluxes measured at 1114 and 1149 UT. They consider θ_{Bn} but not other important factors such as solar wind parameters, loss mechanisms, prior conditions, and distance to the shock that affect foreshock ion fluxes. Solar wind density and pressure changed rapidly several times from 1114 to 1149 UT. Furthermore, the fluctuation in ion flux at 389–546 keV may not be as large as it appears in their Figure 3 after one takes into account statistical uncertainty in the measurement. This uncertainty may have some effect on the result of fluctuations getting larger as ion energy becomes higher in their Figure 3. Since Interball was transitioning from a quasi-parallel to quasi-perpendicular shock geometry around 1147 UT, by 1149 UT quasi-perpendicular geometry would have lasted for a very short period. CFS's quasi-perpendicular shock at 1149 UT certainly could have been under the influence of the prior state of a quasi-parallel shock geometry or even could remain in the quasi-parallel shock state, since one does not know the exact bow shock location and shape to calculate θ_{Bn} to precisely tell the shock geometry. In summary, CFS oversimplifies a very complex system by only considering θ_{Bn} in comparing ion fluxes measured at two positions and instances separated by a significant interval. Many factors have to be considered for this case, and it becomes very difficult to draw any simple conclusions. It is a lot more reliable to compare ion fluxes measured at adjacent instances or two instances very close to each other so that one need only to focus on one factor to reach a more plausible conclusion as in our case (transition).

[8] Several issues raised by CFS are irrelevant to the main subject of CETAL01, namely, the observed magnetosheath H^+, He^{+2}, $O^{>+2}$ ions above $\sim$40 keV e^{-1} by Polar. Two of them regarding lower energy He^{+2} and $O^{>+2}$ and energetic $O^{<+3}$ appear in their Figure 2 which challenges Figure 14 of CETAL01. Figure 2 reproduces CAMMICE MICS He^{+2} and $O^{>+2}$ ion spectra above 40 keV e^{-1} in their Figure 2 and those in Figure 14 of CETAL01. The ion spectra from both figures for each species are nearly indistinguishable. The only difference between their Figure 2 and Figure 14 of CETAL01 appears in the $O^{>+2}$ ion flux below 40 keV e^{-1}. We speculate that the disagreement is due to different detector efficiencies corresponding to the different mean charge states assumed (O^{+3} in CETAL01 versus O^{+6} in CFS), as MICS $O^{>+2}$ channel integrates over all oxygen charge states greater than or equal to +3 (i.e., +3 to +8). Efficiencies for O^{+3} and O^{+6} above 40 keV e^{-1} are identical so that using O^{+6} efficiency does not change the original result for ion energy above 40 keV e^{-1} as demonstrated in Figure 2. Since the $O^{>+2}$ data below 40 keV e^{-1} in Figure 14 of CETAL01 is not discussed in the paper and the issue of detector efficiency for these data is irrelevant to CETAL01, we will leave it to the PI of the CAMMICE instrument (T. A. Fritz) to address this instrument issue in more detail in a separate paper. In addition, CETAL01 already noted that "...the flatness in the He^{+2} and $O^{>+2}$ spectra below $\sim$5 keV e^{-1} reflects poor efficiency of CAMMICE/MICS for these two species at low-energy channels" so that one should not draw any conclusion from these data. Thus CFS's argument about the He^{+2}/O^{+6} ratio at energies less than 10 keV e^{-1} is moot.

[9] CFS attempt to dismiss bow shock acceleration by presenting energetic $O^{<+3}$ ions in their Figure 2. CETAL01 already noted the existence of energetic ions that were not accelerated at the shock, for example He^+. It is most likely that energetic $O^{<+3}$ ions, presumably of ionospheric origin, are not accelerated at the shock according to Plate 1 of CETAL00. These ions simply cannot prove or disprove CETAL00 and CETAL01's conclusion of bow shock source for energetic ions of solar origin. A separate paper is required to discuss the origin of energetic $O^{<+3}$ ions and many challenges are ahead because the signal-to-noise ratio for the data is very low (cf., Plate 1 of CETAL00).

[10] CFS argue that "CETAL01's Figures 1 and 2 imply a D-shaped ion velocity distribution." Whether there was a D-shaped distribution has nothing to do with a bow shock source for this event. Nevertheless, one should be aware that it requires a two-dimensional (2-D) distribution to determine a D-shaped distribution [e.g., *Cowley*, 1980]. Such a distribution has not been demonstrated by CFS. In fact, as stated in CETAL01 already, the 1-D ion distribution in the magnetosheath presented in Figures 1 and 2 of CETAL01 is a flowing Maxwellian with a suprathermal tail. It is not a

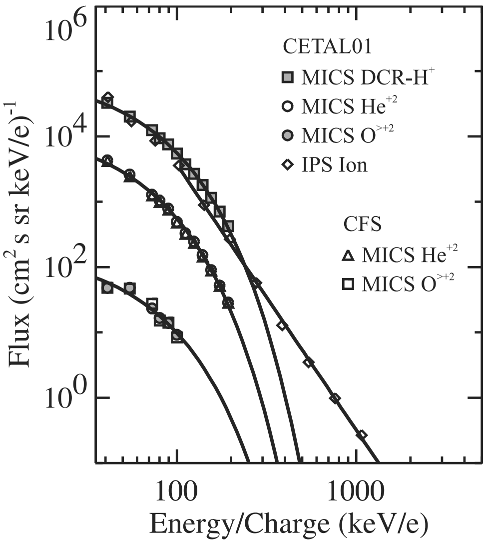

Figure 2. Ion spectra from Figure 2 of CFS and Figure 14 of CETAL01.

D-shaped distribution. CFS's claim that "Polar was on open magnetospheric field lines" is unjustified.

[11] Another irrelevant point from CFS regards "undisturbed magnetosheath" in CETAL01. The meaning of this wording is given in CETAL01 and is also quoted again by CFS. It only means Polar was in the free flow magnetosheath away from the turbulent boundary layer, and it has nothing to do with magnetic field fluctuations. Since CFS does not challenge CETAL01's assessment about Polar's location, their point is irrelevant to the bow shock model.

[12] CFS include comments on another paper [*Chang et al.*, 1998] in the comment. Normally we would not respond to it here, not to mention that their point is completely irrelevant to CETAL01's argument since the conclusion of CETAL01 (a bow shock source) has not been based on the result of *Chang et al.* [1998]. However, we object to CFS's statement that "This is not the only case where CETAL01 misplotted..." so that we address this issue below. First, as stated before, IPS spectrum in CETAL01 was reasonably represented, not misplotted, and it is very similar to the CFS's. Second, the authors of CETAL01 and *Chang et al.* [1998] are not all the same and therefore it is not even possible that CETAL01 have misplotted data in the work of *Chang et al.* [1998]. The issue raised by CFS on MICS energy in the work of *Chang et al.* [1998] has been clarified [*Chang et al.*, 2003]. Cusp energetic ion spectra presented there do indeed agree with a large body of bow shock ion spectra as stated in CETAL01. Nevertheless, CFS have led us to discover a typo in CETAL01. The statement in CETAL01 "Without establishing the link between two regions, the Geotail and Polar... wrong." should read "Without establishing the link between the two regions, the Geotail and Polar ion flux comparison by *Chen et al.* [1999] for this storm event may be wrong." The correct reference is "Chen, J., T. A. Fritz, H. E. Spence, D. L. Matthews, and J. D. Sullivan, May 4, 1998 storm: Multiple spacecraft observations, *Eos Trans. AGU*, *80*(17), Spring Meet. Suppl., S283, 1999." We are grateful to CFS for bringing this to our attention.

[13] In summary, based on apparent confusion over bow shock and magnetopause physics, CFS make flawed arguments and at times use questionable logic to dismiss a bow shock source. Nothing presented by CFS challenges our presented bow shock model, nor does it support cusp acceleration. On the basis of the large volume of evidence presented in CETAL00 and CETAL01, a bow shock source is the most likely explanation for the observed magnetosheath energetic ions of solar origin during this event. Finally, before anyone can make a case for cusp acceleration for this event, they should answer a crucial question first: How can particles originate in the cusp when they are observed in the magnetosheath upstream from the cusp moving toward the magnetopause?

[14] **Acknowledgments.** The work at UAH was supported in part by NASA grant NAG5-12008 and NSF grant ATM-0242427.

[15] Lou-Chuang Lee thanks one reviewer for the assistance in evaluating this paper.

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