Reply

Paulett C. Liewer
Jet Propulsion Laboratory, California Institute of Technology, Pasadena

J. U. Brackbill
Los Alamos National Laboratory, Los Alamos, New Mexico

Introduction

Pauls and Zank [this issue] (hereafter PZ) have expressed several concerns about the two-dimensional fluid-hydrodynamic model of the heliosphere used in our recent Journal of Geophysical Research paper on the hydrodynamic instability of the heliopause [*Liewer et al.*, 1996a] (hereafter Paper 1) and in our Solar Wind 8 paper on the effects of neutrals on the global heliosphere [*Liewer et al.*, 1996b] (hereafter Paper 2). Evidently PZ have confirmed the major result of Paper 1, namely that the heliopause is hydrodynamically unstable due to plasma-neutral charge exchange interactions. However, they raise questions about some of our other results and conclusions. Below, we address their concerns in the order presented in PZ.

1. Equation of State

PZ infer that we have ignored the electron temperature in our hydrodynamic model and included only the proton contribution to the plasma pressure. This incorrect conclusion is, unfortunate y, our fault for not specifying the relationship between plasma pressure P and proton temperature T_{proton} in either Paper 1 or 2. We use the standard [e.g., *Holzer*, 1972] relationship $P = nk_bT$ where n is the plasma density and where $T = T_{proton} + T_{electron}$, that is, the pressure P is the total plasma (proton plus electron) pressure. When we need the proton temperature separately to compute the charge exchange terms, we use T_{proton} = T/2, that is, we assume the protons and electrons have equal temperatures. As stated in Paper 1 and 2, we solve an energy equation where $e = P/(\gamma-1) + 0.5nm_pv^2$, where P is defined above and m_p is the proton mass.

A notational error on our part increased the confusion about our equation of state and led PZ to conclude incorrectly that we neglected the electron temperature. In the description of our model in section 2.1 of Paper 1, we use the symbol T_p to denote the proton temperature (as stated in the text) in the definition of u^*. Unfortunately, in section 2.2 we use the same symbol T_p to denote the *plasma* (proton plus electron) temperature in the definition of the total pressure along the symmetry axis. In section 3, in giving the parameters for the simulations, T_p is the total plasma temperature as indicated.

2. Absence of Hydrogen Wall in Subsonic LISM

PZ are correct that we assumed equal plasma and neutral temperatures in our cases with subsonic interstellar flow. The higher temperature models the effect of an interstellar magnetic field which causes the

VLISM flow speed to be submagnetosonic and eliminates the heliospheric bow shock. We were only interested in the qualitative effect of the lack of a bow shock on the neutral-plasma interaction, particularly with regard to the observed increase in the VLISM plasma ram pressure caused by the charge exchange collisions with the interstellar neutrals in the region just upstream of the nose of heliopause discussed in section 3 below, We agree that the neutral temperature we used here is unphysical and, thus, the neutral density profile in the subsonic case in Paper 2 may well also be unphysical as suggested in PZ. We plan to repeat these calculations with an MHD code in the near future so that the magnet ic field can be properly included.

3. Size of the Heliosphere

We disagree with the comment and conclusions in PZ that the decrease in the solar wind velocity in the inner heliosphere is the sole cause of the decreased size of the heliosphere when neutral-plasma charge exchange interactions are included. We stand by our conclusion in Paper 2, namely, that the charge exchange collisions between the plasma and neutrals beyond the termination shock and heliopause are also important in decreasing the size of the heliosphere. In the region just upstream of the helipause nose, there is a relatively large difference in the neutral and plasma velocities due to the slowing of the VLISM plasma by the bow shock and the diversion of the flow around the heliopause nose. The drag on the VLISM plasma by the neutrals increases the VLISM plasma ram pressure here and contributes to decreasing the size of the heliosphere.

To illustrate this point, Figure 1 plots the plasma density, plasma velocity and normalized plasma x momentum flux $n(k_b T/m_p + v_x^2)$ on the upstream axis – the line from the Sun through the nose of the heliosphere. This is the same case as plotted in Figure 1 of Paper 2, but now with the x momentum flux also shown. When the flow is purely in the x direction, the x momentum is equivalent to the total (thermal plus ram) plasma pressure. The solid curve is the case with neutrals; the dotted line shows the reference run with no neutrals. The locations of the termination shock, heliopause, and bow shock for both cases can be identified with the three jumps in the density curves.

For the case with no neutrals, the x momentum flux is essentially a constant value $P_{vlism}^{tot}(\infty)$ (total VLISM plasma pressure) from the inflow boundary beyond 600 AU to the termination shock location (Figure 1). Note, however, that for the case with neutrals, the x momentum flux rises significantly (by about 60%) between the bow shock and the heliopause. These results can be understood by considering the steady state plasma momentum flux equation:

$$\nabla \cdot (n\vec{v}\vec{v}) + \frac{1}{m_p}\vec{\nabla}P = n n_N \sigma_{cx} u^* \left(\vec{v}_N - \vec{v}\right), \qquad (1)$$

where the term on the right-hand size is the body force on the plasma due to the plasma-neutral charge exchange interaction. Here n_N is the neutral density, σ_{cx} is the velocity-dependent charge-exchange cross section and u^* is an effective velocity defined in Papers 1 and 2 and in the work of *Baranov et al.* [1991]. For the case with no neutrals, the neutral-ion drag force is zero, and, by (1), the momentum flux along a stream line of the flow is constant. Beyond the heliopause, the x axis is a stream line of the VLISM flow and the x momentum flux is observed to be constant. For the case with neutrals, there is a large body force (the neutral-ion charge-exchange drag) directed towards the Sun because of the difference between the plasma and neutral velocities in this region. This drag force causes the observed increase in the VLISM plasma momentum flux (or equivalently the total ram pressure) between the bow shock and the helipause seen in Figure 1 and is responsible for a large part of the observed decrease in the size of the heliosphere.

For the run in Figure 1, the parameters for the interstellar plasma are n = 0.07 cm–3, v = 25 km/s and $T_{plasma} = 10^4$ K, where T_{plasma} is the total plasma pressure; the parameters for the solar wind plasma at Earth are n_E = 7 cm^{-}3, V_{sw} = 450 km/s, and T_{plasma} = 1.5 x 10^5 K. Note that when there is no neutral-ion drag force, the total pressure P^{tot}_{vlism} is constant from the inflow boundary to the termination shock and the location of the termination shock on the upstream axis can be found by balancing the solar wind ram pressure at the shock $m_p n v_x^2$ with the upstream interstellar total pressure $P^{tot}_{vlism}(\infty) = n(k_b T_{plasma} + m_p v_x^2)(= m_p 5 \times 10$ '1 in cgs units). Approximating n(r) = n_E/R^2, where n_E is the density at Earth and R is in astronomical units (AU), this condition becomes

$$\frac{m_p n_E V_{sw}^2}{R^2} = P^{tot}_{vlism}(\infty). \qquad (2)$$

When no neutral-plasma interactions are included, the solar wind velocity V_{sw} is independent of R and we can solve (2) for the expected distance to the termination shock R_s, obtaining $R = \sqrt{n\ m_p V_{sw}^2/P^{tot}_{vlism}}$ = 170 AU in excellent agreement with our simulation results with no neutrals (Paper 2).

When neutrals are included, from Figure 1 it can be seen that the solar wind velocity decreases approximately linearly inside the termination shock, $V_{sw}(R) \approx 470.0 - 0.76R$ km/s, where R is in AU. When neutrals are present, (2) cannot be used to calculate the distance to the shock because the body force invalidates the assumption of constant total pressure (momentum flux) beyond the termination shock. However, PZ have suggested that our observed distance to the termination shock is in agreement with that computed from (2) if the radial dependence of V_{sw} is considered. Proceeding as suggested in PZ, we solve (2) for R_s using the above expression for $V_{sw}(R)$ and $P^{tot}_{vlism}(\infty)$. This gives R_s = 135 AU which does not agree with the values observed in the simulation of $R_s = 115$ AU, contrary to the suggestion in PZ. This is because the increase in the VLISM ram pressure caused by the neutral-ion drag outside the termination shock is also a significant effect in reducing the size of the heliosphere. It may also be that the 1 l% discrepancy in the observed and calculated values in PZ is due to their neglect of the effect of the neutral ion interaction beyond the termination shock.

Thus we conclude that neutral-ion dragon the plasma beyond the termination shock is an important contributor to the decrease in the size of the heliosphere in these calculations. The distance to the termination shock decreased by 32% of which only 14% can be explained by the decreased in solar wind velocity inside the termination shock (Paper 2); the remainder of the decrease is due to the neutral-plasma charge exchange interactions beyond the termination shock and especially beyond the heliopause.

Moreover, we suspect that charge exchange interactions beyond the termination shock are also the dominant cause in the decrease in size observed in the work of *Baranov and Malama* [1993]. Baranov *and Malama* [1993] state that on the upstream axis, the solar wind velocity decreases by 19% from 450 km/s at Earth to approximately 365 km/s at the termination shock at $R_s \approx 110$ AU. A 19% reduction in the velocity would cause only a 19% reduction in the dist ante to the shock if there were no change in P^{tot}_{vlism}. However, from Figure 2 of *Baranov and Malama* [1993] or Figure 3 of *Baranov* and *Zaitsev* [1995] the shock location with no neutrals was about 170 AU (in agreement with our calculation for the same parameters) and thus the distance to the shock has been reduced by about 35%. Thus we suspect that the plasma-neutral charge exchange interactions in the region beyond the termination shock and heliopause also contributed significantly to the observed decrease in the size of the heliosphere in the kinetic ion computations of Baranov and Malama.

4. Effect of Hot Neutrals

We agree that the neglect of energetic neutrals is a limitation (as stated in Paper 1) and inclusion of this effect will act to weaken the hydrodynamic instability (also stated in Paper l). However, PZhave apparently also seen the instability in a more sophisticated model which included energetic neutrals [*Zank et. al.* 1996a, b], thus confirming our primary result. PZ note that the instability is considerably weaker (amplitude of 3 AU), but it is difficult to compare this to our results because no information on grid resolution was given and, in Paper 1 the instability was shown to be very sensitive to grid spacing.

Concluding Remarks

We are pleased that PZ have confirmed our primary result that the heliopause is hydrodynamic unstable with the interaction between the plasma and the interstellar neutrals is included.

Most of the comments in PZ seem to stem from the misunderstanding of the equation of state used in our model, that is, the fact the the plasma pressure is the total (ion plus electron) pressure. The proton temperature, needed to compute the charge exchange cross section was computed from this assuming equal electron and ion temperatures. This was not adequately explained in either Paper 1 or 2 and we apologize for this misunderstanding.

We stand by our conclusion that the interaction of interstellar neutrals beyond the termination shock, and particularly in the region just upstream of the heliopause nose, is also important in determining the size of the heliosphere. Just beyond the nose, the charge exchange interactions between VLISM neutrals and plasma causes an increase in the total VLISM plasma pressure which decreases the size of the heliosphere. This is an additional physical effect that was not noted by previous authors although we suspect it is also important for them.

Acknowledgements. This work was supported in part by NASA Heliospheric Physics and in part by the NSF Center for Research in Parallel Computation under Cooperative Agreement CCR-88809615. A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. The JPL/Caltech CRAY YMP and T3D used in this investigation was supported by NASA.

References

Baranov, V. B., and Y. G. Malama, Model of the Solar Wind Interaction with the Local Interstellar Medium: Numerical Solution of Self-Consistent Problem, *J. Geophys. Res.* 98, 15157, 1993.

Baranov, V. B., and N. A. Zaitsev, On the problem of the Solar Wind Interaction with Magnetized Interstellar Plasma, *Asron. Astrophys. 304, 631, 1993.*

Baranov, V. B., M. G. Lebedev, and Y. G. Malama, The influence of the interfacebetween the heliosphere and the local interstellar medium on the penetration of H atoms to the solar system, *Astrophys. J., 375, 347,* 1991.

Holzer, T. E., Interaction of the Solar Wind with the Neutral Component of the Interstellar Ges, *J. Geophys. Res.* 77, 5407, 1972.

Liewer, P. C., S. R. Karmesin, and J. U. Brackbill, Hydrodynamic instability of the heliopause driven by plasma-neutral charge-exchange interactions, *J. Geophys. Res. 101*, 17,119, 1996a.

Liewer, P. C., S. R. Karmesin, and J. U. Brackbill, The effect of neutrals on the global helioephere and interplanetary shock propagation time to the heliopause, *Proceedings of Solar Wind Eight,* D. Winterhalter, J. Gosling, S. Habbal, W. Kurth, and M. Neugebauer, eds. (AIP, Woodbury, New York), p. 613, 1996b.

Pauls H. L., and G. P. Zank, Comment on 'Hydrodynamic instability of the heliopause driven by plasma-neutral charge-exchange interactions' *J. Geophys. Res.,* this issue, 1997.

Zank, G. P., H. L. Pauls, L. L. Williams, and D. T. Hall, Multi-dimensional modelling of the Solar wind-LISM interaction including neutrals; a Bolzmann Approach, *Proceedings of Solar Wind Eight,* D. Winterhalter, J. Gosling, S. Habbal, W. Kurth, and M. Neugebauer, eds. (AIP, Woodbury, New York), p. 654, 1996a.

Zank, G. P., H. L. Pauls, L. L. Williams, and D. T. Hall, Interaction of the solar wind with the local interstellar medium: A multi-fluid approach, *J. Geophys. Res.*, in press, 1996b.

J. U. Brackbill, Los Alamos National Laboratory T-3, Los Alamos, NM 87545 (e-mail: jub@lanl.gov)

P. C. Liewer, Jet Propulsion Laboratory MS 169-506, Pasadena, CA 91109 (e-mail: pauly@spaceport.jpl.nasa.gov)

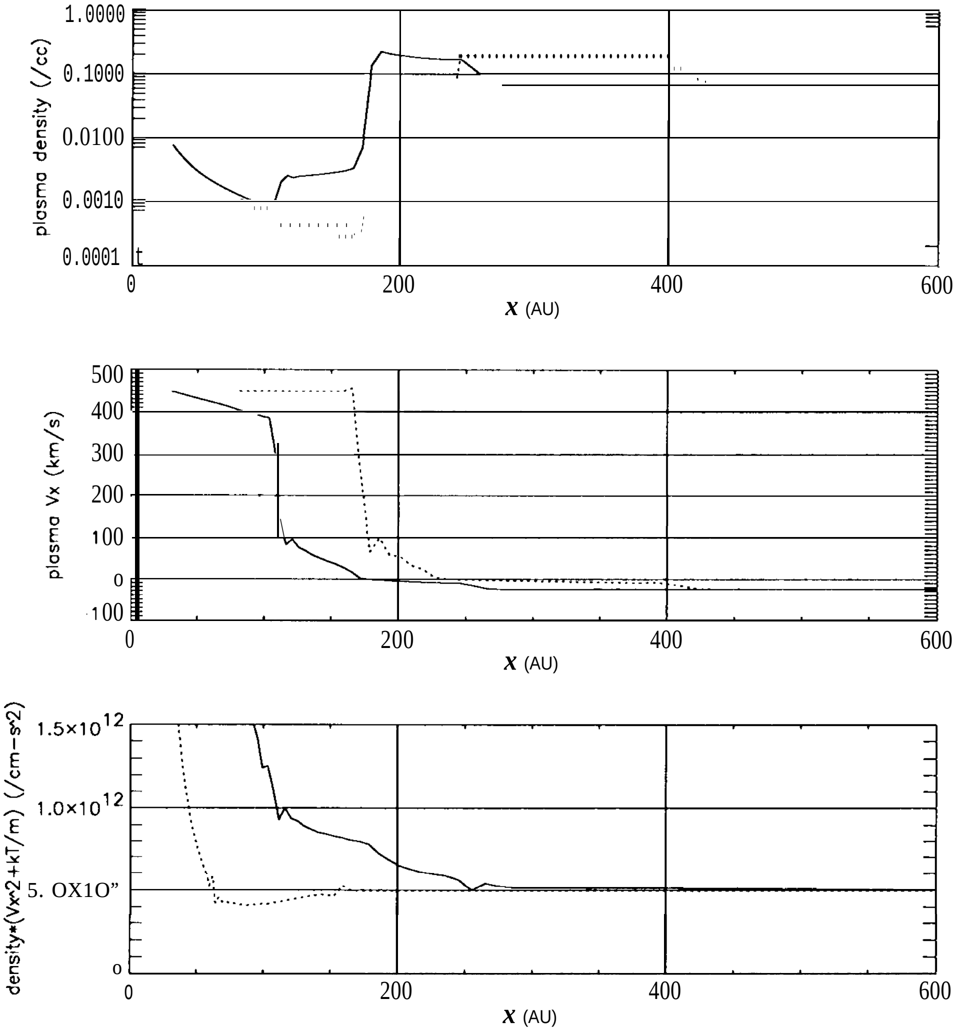
(Received October 15, 1996; revised December 6, 1996; accepted January 16, 1997.)

Paper number 97JA00153.

0148-0227/97/97JA-O0153 $09.00

Figure 1. Simulation results for a case with (solid curve) and without (dashed line) neutrals illustrating the reduction in the size of the heliosphere due to plasma-neutral interactions. Profiles are along a line from the Sun through the nose of the heliosphere, showing (top) density (top), (middle) velocity, and (bottom) normalized x momentum flux. Note the increase in the momentum flux of the interstellar plasma as the flow approaches the nose of the heliopause.

Figure 1. Simulation results for a case with (solid curve) and without (dashed line) neutrals illustrating the reduction in the size of the heliosphere due to plasma-neutral interactions. Profiles are along a line from the Sun through the nose of the heliosphere, showing (top) density (top), (middle) velocity, and (bottom) normalized x momentum flux. Note the increase in the momentum flux of the interstellar plasma as the flow approaches the nose of the heliopause.



plasma density (/cc)
1.0000
0.1000
0.0100
0.0010
0.0001
0
200
400
600
X (AU)
plasma Vx (km/s)
500
400
300
200
100
0
-100
0
200
400
600
X (AU)
density*(Vx^2+kT/m) (/cm-s^2)
1.5x10^12
1.0x10^12
5. OX1O"
0
0
200
400
600
X (AU)

Fig. 1

LIEWER AND BRACKBILL: REPLY TO COMMENT:

LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT:
LIEWER AND BRACKBILL: REPLY TO COMMENT: