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**AN MHD STUDY OF THE INTERACTION BETWEEN THE SOLAR WIND
AND THE INTERSTELLAR MEDIUM**

Submitted by

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SUMMARY

The overall objective of this research program is to obtain a better understanding of the interaction between the solar wind and the interstellar medium through the use of numerical solutions of the time-dependent magnetohydrodynamic (MHD) equations. The simulated results have been compared with observations where possible and with the results from previous analytic and numerical studies. The primary accomplishment of this project has been the development of codes for 2-D models in both spherical and cylindrical coordinates and the application of the codes to the solar wind/interstellar medium interaction. Computations have been carried out for both a relatively simple gas-dynamic interaction and a flow-aligned interstellar magnetic field. The results have been shown to compare favorably with models that use more approximations and to modify and extend the previous results as would be expected. The simulations have also been used along with a data analysis study to provide a quantitative estimate of the distance to the termination and bow shocks. Some of the specific topics that have been studied are : (1) Gasdynamic models of the solar wind/interstellar medium interaction, (2) Termination shock response to large-scale solar wind fluctuations, and (3) Distances to the termination shock and heliopause. The main results from each of these studies are summarized below.

1. Scope of the investigation

The interaction of the solar wind with the interstellar medium has received increased interest recently due to improved observations of the local interstellar medium and to the fact that a deep space probe may soon intersect the shock terminating the supersonic solar wind flow. Previous theoretical and computational efforts at studying the interaction have been hampered by a lack of observational guidance and have not been developed to the level necessary to determine the quantitative effects of some of the important known physical processes on the global interaction. When used in conjunction with present and forthcoming observations, the present models may assist in determining the effects of the relevant physical processes. In addition, they may also indirectly be able to place bounds on the currently unknown or speculative values of physical quantities in the local interstellar medium as well as the location of the termination shock and the heliopause.

Time-dependent, multi-dimensional, gas dynamic and MHD codes have been used to study this interaction through the use of a relaxation technique in which an assumed non-equilibrium initial state approaches a final steady-state equilibrium. Although the codes incorporate numerous physical mechanisms, they can optionally be included in individual studies. The approach is to begin with simple cases, to compare earlier work and build on previous results, and to separately include effects, such as the interstellar and interplanetary magnetic fields, thereby providing a consistent basis from which to quantify the effects of a particular mechanism.

Two separate codes for the 2-D model have been developed. In one the equations are solved in the $r-\theta$ plane of a cylindrical coordinate system in which the axial (z) axis is perpendicular to the interstellar flow direction. For the second the equations are solved in a spherical coordinate system. The two coordinate systems are used in order to allow greater flexibility for the inclusion of a magnetic field within the confines of a 2-D model. A variable grid spacing is incorporated in the radial direction to provide better resolution in the solar wind portion (and near the

termination shock(of the interaction. Each of the three studies carried out are discussed in more detail below. All of these results have been presented in international or national scientific meetings and published in journals.

2. Gasdynamic models of the solar wind/interstellar medium interaction

The first study involves the simulation of representative solar wind/interstellar medium interactions in both spherical and cylindrical coordinates when the interstellar flow is supersonic. As would be expected, both a termination shock and a bow shock are formed. In both coordinate systems the termination shock is noticeably distorted in the downstream direction. These 2-D results have been analyzed and compared with results from more simplified earlier studies (e.g., the gas dynamic study of Baranov, *Space Sci. Rev.*, 52, 89, 1990).

The interaction between the solar wind and the interstellar medium is modeled self-consistently using numerical solutions of the time-dependent gasdynamic equations in spherical and cylindrical coordinates. For the results obtained here it is assumed that the solar wind system moves through the surrounding medium with a supersonic velocity. After an initial (nonequilibrium) state has been specified, the numerical solutions follow the evolution in time until the interaction relaxes to a dynamic equilibrium. As would be expected, the solutions show the formation of a bow shock upstream of the traveling solar system to deflect the interstellar plasma around the cavity created by the solar wind. A termination shock also forms to slow and compress the solar wind plasma. For the simulation in spherical coordinates, the downstream portion of the termination shock reaches equilibrium more than three times further from the sun than the equilibrium distance to the termination shock on the upstream side. The results were published in the paper "Gasdynamic models of the solar wind/interstellar medium interaction" in *Geophysical Research Letters*, Vol. 21, 245-248, 1994.

3. Termination shock response to large-scale solar wind fluctuations

The second study concerns the response of the termination shock to large-scale fluctuations in the solar wind pressure. The analysis of data recorded by the Voyager 2 spacecraft indicates the presence of large-scale fluctuations in the solar wind ram pressure on the time scale of tens of days. The amplitude of the fluctuations is highly variable but often lies within a factor of 5 to 10 change from an average mean value of the ram pressure. Since the spacecraft has presumably not encountered the termination shock yet, these fluctuations should eventually interact with the shock and thereby play a role in determining the shock location.

Numerical solutions of the time-dependent gas equations are used to simulate the response of the termination shock to fluctuations in the solar wind ram pressure comparable to those observed. The primary of this study is that the maximum shock excursion due to fluctuations is of the order of 1 AU, which is smaller than that predicted by other studies. Additional simulations show that the limited movement is due to the fact that the time scale for the termination shock response is substantially larger than the time scale of the fluctuations. It is also shown that the heliopause acts as a barrier for the fluctuations and confines them to the heliosphere. These results were published in the paper "Termination shock response to large-scale solar win fluctuations" in *Journal of Geophysical Research*, Vol. 99, 13,307-13,314, 1994.

4. Study of distances to the termination shock and heliopause

The third study is a collaboration with a data analysis effort by Dr. D. Gurnett of the University of Iowa. We use a numerical gasdynamic simulation of an interplanetary shock, propagating through an equilibrium solution of the solar wind/interstellar medium interaction, to compute the distances to the termination shock and the heliopause that are consistent with the observations.

A new heliospheric radio emission event observed by Voyagers 1 and 2 in mid-1992 have been interpreted by Gurnett et. al. [Science, 1993] as occurring when a strong interplanetary shock interacts with the heliopause. The interplanetary shock can be related to large Forbush decreases recorded by neutron monitors at Earth and by cosmic ray detectors on Pioneer and Voyager spacecraft. The shock is thought to have originated near the Sun during a period of intense solar activity in late-May and early June, 1991. The time delay between the Forbush decrease at the Earth and the radio emission is about 408 days. The shock propagation speed as determined from the Pioneer and Voyager data is estimated to be within the range of 600 and 800 km/sec, with some preference for the higher value.

These observational results have been used as the foundation for a numerical study to simulate the propagation of a solar-generated shock wave through a dynamic equilibrium solution for the solar wind/interstellar medium interaction. A series of parametric studies is used to find the equilibrium solution in which a shock propagating at a selected speed within the observed range (600-800 km/sec) results in a delay (408 days). The solar wind conditions at 1 AU were fixed at $n = 5 \text{ cm}^{-3}$, $T = 10^5 \text{ }^\circ\text{K}$, $v = 400 \text{ km/sec}$, and the interstellar conditions were fixed at $T = 10^4 \text{ }^\circ\text{K}$, $v = 25 \text{ km/sec}$. For a given interplanetary shock speed the interstellar density and magnetic field magnitude were varied until the above time delay was obtained. The termination shock is at a distance of 115 AU, and the heliopause is at 160 AU for an interplanetary shock speed of 800 km/sec. These distances reduce to 92 AU for the termination shock and 128 AU for the heliopause when the shock speed is reduced to 600 km/sec. The results were published in the paper "Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event" in Geophysical Research Letters, Vol. 22, 651-654, 1995.

PUBLICATIONS

Publications and presentations resulting from research supported by this NASA grant are listed below. Copies of the published papers are included in the appendix with this final report.

1. R. S. Steinolfson, A numerical study of the interaction between the solar wind and the interstellar medium, Solar Wind VII, Goslar, Germany, 16-20, 1991.
2. R. S. Steinolfson and T. E. Holzer, A numerical study of the interaction between the solar wind and the interstellar medium. XVII General Assembly of the European Geophysical Society, Edinburgh, Scotland, 6-10 April, 1992.
3. R. S. Steinolfson, V. Pizzo, and T. Holzer, The interaction of the solar wind with the interstellar medium, EOS 73, 445, 1992.
4. R. S. Steinolfson, and V. Pizzo, Gas-dynamic simulations of the two-shock model of the solar wind/interstellar medium interaction, EOS 74, 234, 1993.
5. R. S. Steinolfson, The interaction of the solar wind with the interstellar medium, XXIV General Assembly of the International Union of Radio Science, Kyoto, Japan, 25 August - 2 September, 1993.
6. R. S. Steinolfson, V. Pizzo, and T. Holzer, Gas dynamic models of the solar wind/interstellar medium interaction, Geophys. Res. Lett., 21, 245, 1994.
7. R. S. Steinolfson, Termination shock response to large-scale solar wind fluctuations, J. Geophys. Res., 99, 13,307-13,314, 1994.
8. R. S. Steinolfson and D. A. Gurnett, Termination shock and heliopause distances estimated from coordinated simulations and data analyses, EOS, 74, 487, 1993.
9. R. S. Steinolfson and D. A. Gurnett, Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event, Second Pioneer-Voyager Symposium, Durham, New Hampshire, 31 May - 3 June, 1994.
10. R. S. Steinolfson and D. A. Gurnett, Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event, Geophys. Res., 22, 651-654, 1995.

APPENDICES

R. S. Steinolfson, V. Pizzo, and T. Holzer, Gas dynamic models of the solar wind/interstellar medium interaction, *Geophys. Res. Lett.*, 21, 245, 1994.

R. S. Steinolfson, Termination shock response to large-scale solar wind fluctuations, *J. Geophys. Res.*, 99, 13,307-13,314, 1994.

R. S. Steinolfson and D. A. Gurnett, Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event, *Geophys. Res.*, 22, 651-654, 1995.

Gasdynamic models of the solar wind/interstellar medium interaction

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Abstract. The interaction between the solar wind and the interstellar medium is modeled self-consistently using numerical solutions of the time-dependent gasdynamic equations in spherical and cylindrical coordinates. For the results presented here it is assumed that the solar system moves through the surrounding medium with a supersonic velocity. After an initial (nonequilibrium) state has been specified, the numerical solution follows the evolution in time until the interaction relaxes to a dynamic equilibrium. As would be expected, the solutions show the formation of a bow shock upstream of the traveling solar system to deflect the interstellar plasma around the cavity created by the solar wind. A termination shock also forms to slow and compress the solar wind plasma. For the simulation in spherical coordinates, the downstream portion of the termination shock reaches equilibrium more than three times further from the Sun than the equilibrium distance to the termination shock on the upstream side.

Introduction

The interaction between the solar wind and the local interstellar medium has been an active area of study since at least the early 1960s. Through a combination of theory and the limited observations available, researchers have been able to identify what are believed to be the important physical processes involved in the large-scale, global interaction. The respective level of contribution of the various processes to the overall interaction remains unclear, however, due to a lack of both the necessary data and sufficiently developed models. The current state of understanding based on both theory and observations is summarized in several recent reviews [e.g., Holzer, 1989; Suess, 1990; Baranov, 1990].

Although theoretical studies have not had sufficient observational guidance to support the development of detailed quantitative models consistent with the data, there is indication that some portion of the necessary observations may soon become available. A deep space probe (Pioneer or Voyager) may soon reach the shock that terminates the supersonic solar wind flow [e.g., Suess, 1990]. It may also be possible to detect this termination shock indirectly [Kurth et al., 1987; Lee, 1988] through the detection of radio frequency

waves generated by the shock. Gurnett et al. [1993] have interpreted some radio emission events as having been generated when a strong interplanetary shock interacts with the heliopause. Moreover, there has been an increase in the observational study of the interstellar medium [e.g., Frisch, 1986; Cox and Reynolds, 1987; Davidsen, 1993; Lallement, 1993]. Even with these data sources, it seems clear that our understanding of the physical processes in the interaction and its complete global structure must continue to rely heavily on theoretical and computational models.

We are developing computational models to study the 3-D interaction using magnetohydrodynamic (MHD) theory. Our approach is to begin with the simplest models that contain at least some of the relevant physics and then to build on these models and extend them to a degree of sophistication not previously realized. The models are time-dependent, shock-capturing models so that they allow the capability, once a dynamic equilibrium solution has been computed, of simulating the temporal response of the equilibrium to changes in either solar wind or interstellar properties. We report here on equilibrium solutions obtained from 2-D gasdynamic models in spherical and cylindrical coordinates. Other gasdynamic studies that obtain features similar to those produced in the present simulation have been reported by Shima et al. [1986], Matsuda et al. [1989], and Baranov and Malama [1993]. However, except for the work by Baranov and Malama, these computations were not for the proper parameter regime for the solar wind/interstellar medium interaction.

The interaction between the solar wind and the interstellar medium probably occurs within, and is largely determined by the properties of, the "Very Local InterStellar Medium". The VLISM is that part of the local interstellar medium within about 0.01 parsecs (2000 AU) of the Sun. As the supersonic solar wind flows outward toward the VLISM plasma, it makes a transition to subsonic flow at a termination shock [Parker, 1961]. This shocked solar wind interacts directly with the VLISM plasma at an interface (heliopause) that separates the two plasmas. The region of space dominated by the solar wind is referred to as the heliosphere.

It is believed that the Sun moves through the VLISM at a speed of about 20 km/sec. Since the thermodynamic properties and the magnetic field strength in the VLISM are not well known, it is not clear how this speed compares to wave propagation speeds in the VLISM, although there is some consensus that it is very nearly sonic. If this speed is supersonic, an interstellar bow shock is expected to form to decelerate and deflect the interstellar medium around the heliospheric cavity. No bow shock should form in the subsonic case. We will concentrate here on solutions when the VLISM flow speed relative to the Sun is supersonic, which is often referred to as the two-shock model and has been reviewed by Baranov [1990].

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Solution Procedure

The gasdynamic equations with a ratio of specific heats of 5/3 are solved numerically using an explicit differencing scheme in two spatial directions (the r , θ directions in both spherical and cylindrical coordinates centered at the Sun). The equations and differencing scheme are discussed in more detail by Steinolfson [1994]. Two coordinate systems are considered in order to allow greater flexibility in the later inclusion of the magnetic field within the confines of a 2-D model. In cylindrical coordinates the axis is selected to be perpendicular to the motion of the Sun relative to the local interstellar medium, and all variables are assumed to be independent of distance parallel to the cylinder axis. In spherical coordinates the solution is axisymmetric about a line pointing into the direction of relative motion between the solar system and the surrounding medium. Since the velocity of the Sun relative to the interstellar medium (V_{∞}) is referenced to our Sun-centered coordinate systems, it will be referred to as the interstellar velocity and is assumed to be parallel to the $\theta=0^\circ$ axis.

The simulation box covers an entire hemisphere ($0^\circ \leq \theta \leq 180^\circ$) and extends in radius from 30 to 300 AU. Three of the physical variables (radial flow speed v_r , electron density n_e , and pressure p) are symmetric across the poles while the fourth is antisymmetric (meridional flow speed v_θ). The supersonic solar wind is specified at 1 AU, and an adiabatic atmosphere with constant radial flow speed is used to compute values at the inner radial boundary for the computation at 30 AU. Interstellar plasma conditions and velocity are specified at the outer radial boundary for $0^\circ \leq \theta \leq 90^\circ$, and zero-order extrapolation along the local flow direction is used to obtain values at the outer radial boundary for $90^\circ < \theta \leq 180^\circ$. For fixed physical quantities in the solar wind and interstellar medium, the numerical computation continues until a dynamical equilibrium is obtained.

Numerical Results

Spherical Coordinates. The physical quantities in the solar wind at 1 AU for this simulation are $v_r=300$ km/sec, $v_\theta=0$, $n_e=3$ cm $^{-3}$, and temperature $T=10^4$ °K. The conditions at 1 AU are used to normalize all quantities. The flow speed is

referenced to the sound speed (52.45 km/sec), and the thermodynamic quantities are referenced to their values at 1 AU. The inflow interstellar conditions are $V_{\infty}=24.88$ km/sec, $n_e=0.2$ cm $^{-3}$, and $T=10^4$ °K ($M_{\infty}=1.5$).

The radial grid spacing is fixed at 1 AU, and the angular grid spacing is fixed at 1° , for a grid of 271x181. The initial (nonequilibrium) state for the simulation is constructed by specifying adiabatic solar wind conditions within 30-40 AU, a termination shock at 40 AU, interstellar conditions beyond 80 AU, and a linear fit between the shocked solar wind and interstellar plasmas. The solution continues for 44,000 time cycles, which represents a total physical evolution time of 1.81×10^5 days or 500 years. Based on the sound speed in the interstellar medium (16.59 km/sec), this is the time for a disturbance to cross the 600 AU numerical box more than twice.

The velocity streamlines and contour plots of the thermodynamic quantities in the dynamic equilibrium state are shown in Figure 1. Symmetries, of course, could be used to reflect the solution about the lower boundary. The approximate locations of the bow and termination shocks have been superimposed on the computer-generated plot of the velocity streamlines. In terms of the commonly used nomenclature for shocks in the solar wind, the bow shock is a forward shock, and the termination shock is a reverse shock. The heliopause is easily identified in the figure as the division between interstellar and solar streamlines and has been extended to the pole at 0° by the dashed line.

The spatial structure for several of the physical quantities from the inner boundary out to 200 AU along the radial line at 0° is presented in Figure 2. Although the shocks and heliopause are spread over several grid points (as usual for simulations such as this), the quantities have the expected variation across the discontinuities. The changes in quantities across the shocks agree to within a few percent of the values computed from the Rankine-Hugoniot equations.

Although not shown here, the entropy has been verified to be constant in the regions between the discontinuities in Figure 2. The use of an adiabatic solar wind has the effect of allowing the Mach number to become very large (due to the monotonically decreasing temperature) at large heliocentric distances. Just upstream of the termination shock in Figure 2, the Mach number has a value of about 68, while it is about 58 at the inner computational boundary and 5.7 at 1 AU.

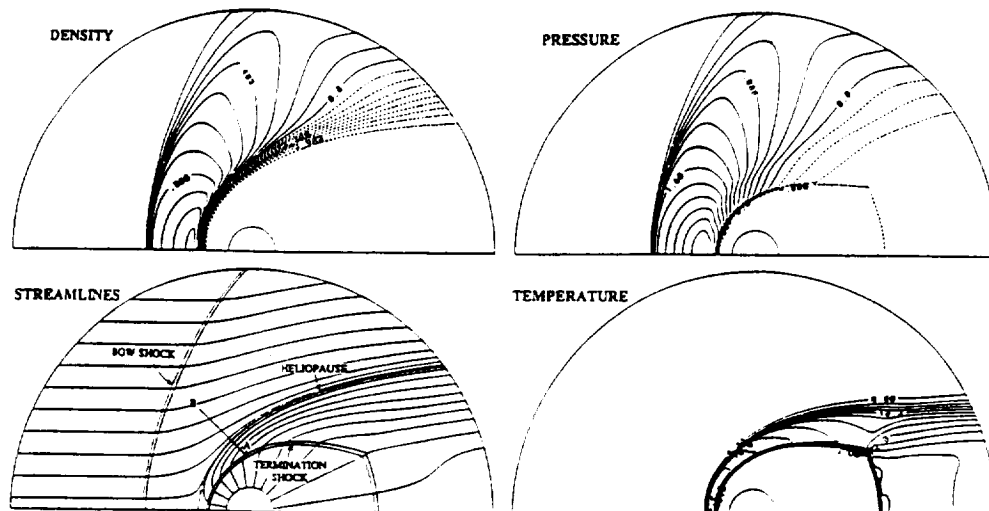


Fig. 1. Thermodynamic quantities and velocity streamlines in the relaxed dynamic equilibrium. The interstellar flow (relative to the solar system) is from left to right. The shock locations drawn on the streamline plot were determined from the contour plots of the thermodynamic variables. For the thermodynamic quantities in the contour plots, the value used to construct the plots is $(Q-Q_{\infty})/Q_{\infty}$, where Q_{∞} represents the interstellar value. A contour level of zero represents the interstellar value, and values greater (smaller) than the interstellar value are represented by solid (dashed) contours. The density contours range from -0.9 to 1.1 in increments of 0.1, pressure from -0.8 to 2.6 in increments of 0.2, and temperature from 8 to 96 in increments of 8.

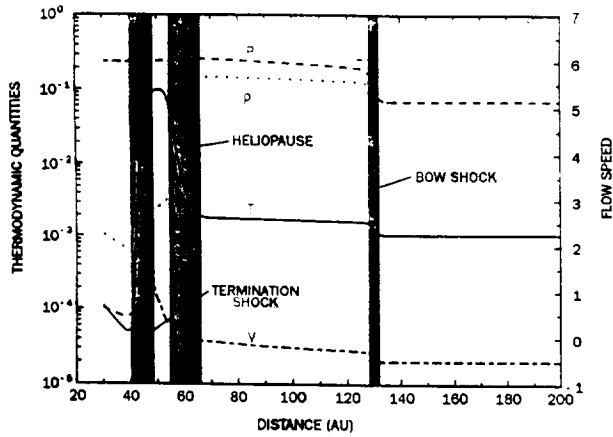


Fig. 2. The variation of physical values along the radial line at 0° in the equilibrium solution. The pressure has been multiplied by 10 and the temperature by 10^{-2} for the indicated scale. Although the "discontinuities" are spread over several grid points, the change in quantities across them agrees with analytic expressions.

As might be anticipated from the results in Figure 1 (particularly the streamlines), a large shear flow develops across the heliopause away from the pole at 0° . This is illustrated in Figure 3, in which the variations of the velocities along the line A-B marked on the plot of the streamlines in Figure 1 are shown. The velocities are the components perpendicular (\perp) and parallel (\parallel) to line A-B defining the normal to the heliopause. The shaded region indicates the approximate numerical width of the heliopause. Despite this large shear, there is no indication of the development of a Kelvin-Helmholtz instability, although this instability has been interpreted as forming at the heliopause in other simulations of the interaction of a stellar wind with the interstellar medium [Matsuda, 1989].

Except for the region near the pole at 180° , the solar wind plasma must turn through a large angle in order to flow out downstream along the heliopause, as indicated by the streamlines in Figure 1. Some part of the turning occurs at the termination shock through a reduction of the flow speed parallel to the shock normal. Note that the flat portion of the termination shock near the 180° pole turns the flow away from the pole. Since the termination shock in this model is a gasdynamic shock, the component of the speed perpendicular to the shock normal must be conserved across the shock. This is no longer required for MHD shocks, so some important differences would be expected when the magnetic field is included. MHD simulations by Washimi [1993] indicate that the magnetic field may produce other significant differences from the gasdynamic results presented here.

Cylindrical Coordinates. The physical quantities in the solar wind at 1 AU for this case are $v_r=60$ km/sec, $n_e=0.25$ cm $^{-3}$, and $T=10^5$ K. As for the above example, the thermodynamic quantities are referenced to their values at 1 AU, and the flow speed is referenced to the sound speed at 1 AU. The interstellar values are $V_\infty=200$ km/sec, $n_e=8 \times 10^{-5}$ cm $^{-3}$, and $T=10^4$ K ($M_\infty=12$). The selected physical values are clearly not physically realistic and have been chosen to obtain a two-shock solution within a few hundred AU of the Sun. Due to the cylindrical geometry, the solar wind density falls off with distance as r^{-1} rather than as r^{-2} as it would for spherical geometry. The inner boundary is at 10 AU, and the outer boundary is at 450 AU. The grid spacings are constant at 3 AU and 3° for a grid of 150×60 .

The pressure is shown in a gray-scale plot in Figure 4 along with representative streamlines. The downstream

portion of the termination shock in this case is ejected out of the numerical box. Preliminary studies indicate that the equilibrium distance of the termination shock from the Sun near the 180° pole increases as the interstellar Mach number increases. The interstellar Mach number for this run is simply so large ($M_\infty=12$) that the equilibrium distance is beyond the outer computational boundary. Other than the different geometry, this solution is qualitatively similar to the previous one. The intention is to use this 2-D cylindrical model as a test-bed for evaluating the effects of magnetic field orientations that would not be possible with the above 2-D model in spherical geometry. Although the absolute values of the magnetic effects may differ from those in spherical geometry, the relative effects should be similar and should provide useful insight into the interpretation of results from eventual 3-D simulations.

Discussion

Two examples of numerical simulations in spherical and cylindrical coordinate systems for the interaction of the solar wind with the interstellar medium (for the case when the solar system is traveling supersonically relative to the surrounding medium) show at least one qualitatively similar result. That is, the distance of the termination shock from the Sun on the downstream side (in the solar system wake) of the moving solar system is substantially larger than the corresponding distance on the upstream side. For the example in spherical coordinates, the distance from the Sun to the termination shock in the direction opposite to that of the relative motion between the solar system and the interstellar medium is more than three times larger than the Sun to termination shock distance in the direction of relative motion. The downstream portion of the termination shock moves out of the computational box for the example in cylindrical coordinates. It should be noted that in simulations for which the solar system moves subsonically with respect to the interstellar medium for the same parametric values as those used here (except for the interstellar wind speed) the distance to the termination shock is only slightly larger downstream than upstream [Steinolfson, 1994].

The solar wind plasma obviously cannot continue to expand outward adiabatically on the downstream side since the thermal pressure would become far too small to maintain lateral force equilibrium with the surrounding interstellar plasma. We suggest that the situation is qualitatively similar to that for supersonic flow in a diverging nozzle exiting into a region with a larger back pressure than the thermal pressure in the flowing plasma [e.g., Shapiro, 1953]. The analogy is

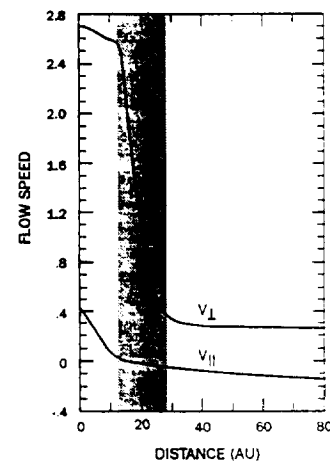


Fig. 3. The variation of the flow speeds with distance along the line A-B indicated on Figure 1 where the distance is referenced to point A on the line. The flow speeds are the values perpendicular and parallel to the line.

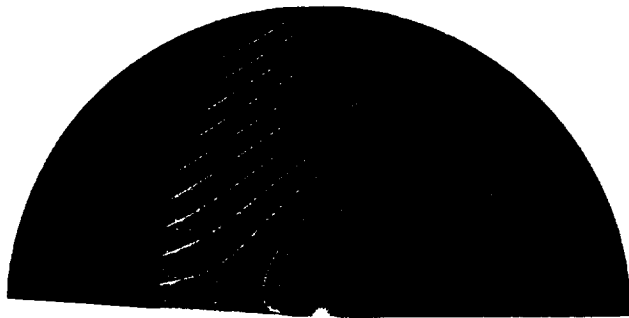


Fig. 4. Streamlines and gray-scale plots of the thermal pressure for the dynamic equilibrium solution in cylindrical coordinates.

only approximate, of course, since the solution on the downstream side must maintain an equilibrium (and must be self-consistent) with the solution on the upstream side. In the case of the supersonic nozzle, the equilibrium position of the shock moves downstream as the back pressure decreases. When the interstellar velocity is subsonic, the back pressure is essentially identical to the interstellar pressure [Steinolfson, 1994]. However, as shown in Figure 1, the back pressure in the present case is considerably less than the interstellar pressure, and, as a result, the termination shock comes to equilibrium further downstream than in the subsonic study. Additional simulations over a wide range of parameter space are needed to establish the generality of this suggested analogy.

The solar wind/interstellar medium interaction computed in the present work and shown in Figure 1 agrees qualitatively with the results obtained by Shima et al. [1986; shown in their Figure 2], although they were considering a more general stellar example and did not use physical values in the proper parametric regime for the solar case. Shima et al. used a similar shock-capturing numerical scheme, but their numerical resolution was substantially coarser than for the simulations presented here. Matsuda et al. [1989] repeated the Shima et al. simulation utilizing much finer numerical resolution and found that the Kelvin-Helmholtz instability developed on the heliopause (see Figure 4 in Matsuda et al.). Since the Shima et al. result did not indicate the formation of the Kelvin-Helmholtz instability, Matsuda et al. naturally attributed its appearance in their simulation to the better numerical resolution. The numerical resolution in the present simulations is even finer than that in the Matsuda et al. study, and yet there is no indication of the formation of any instability on the heliopause (see Figures 1 and 4). It is not clear whether this is due to the different parametric regimes for the two computations, or if it is a result of the numerics in one of the simulations. It does seem curious that the instability in the Matsuda et al. study develops near the pole directed into the interstellar wind ($\theta=0^\circ$), where the velocity shear is very small, and is then convected downstream.

The present results also agree with those obtained in a recent study by Baranov and Malama [1993], which is for parametric values applicable to the solar case although they are somewhat different than those used here. Baranov and Malama used a discontinuity-fitting numerical scheme in which the steady-state equations are solved between the discontinuities, whose locations are adjusted until an equilibrium is reached. The formation of a time-dependent instability, such as the Kelvin-Helmholtz instability, could not be studied with this numerical scheme. Consequently, the results of the present time-dependent simulations support the

use of a discontinuity-fitting scheme, at least for the solar case. The complexity (both numerical and physical) of the interaction of a stellar wind with the interstellar medium dictates that various numerical approaches along with analytical work are necessary in order to establish the physical validity of the model interaction.

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Termination shock response to large-scale solar wind fluctuations

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Abstract. The analysis of data recorded by the Voyager 2 spacecraft indicates the presence of large-scale fluctuations in the solar wind ram pressure on the time scale of tens of days. The amplitude of the fluctuations is highly variable but often lies within a factor of 5 to 10 change from an average or mean value of the ram pressure. Since the spacecraft has presumably not encountered the termination shock yet, these fluctuations should eventually interact with the shock and thereby play a role in determining the shock location. Numerical solutions of the time-dependent gasdynamic equations are used to simulate the response of the termination shock to fluctuations in the solar wind ram pressure comparable to those observed. The primary result of this study is that the maximum shock excursion due to the fluctuations is of the order of 1 AU, which is much smaller than that predicted by other studies. Additional simulations show that the limited movement is due to the fact that the time scale for the termination shock response is substantially larger than the time scale of the fluctuations. It is also shown that the heliopause acts as a barrier for the fluctuations and confines them to the heliosphere.

1. Introduction

As the solar wind plasma flows outward from the Sun, it eventually interacts with the surrounding interstellar plasma, and the two plasmas relax to a dynamic pressure equilibrium. The formation of a cavity in the interstellar medium by the solar wind plasma was initially suggested by *Davis* [1955]. For a pressure equilibrium between the solar and interstellar plasmas to be reached, the solar wind makes a transition from supersonic to subsonic flow at a termination shock [*Parker*, 1961]. The termination shock probably occurs within the range of 50 to 100 astronomical units (AU) from the Sun [e.g., *Suess*, 1990]. At some distance beyond the termination shock, the solar plasma interacts directly with the interstellar plasma at an interface separating the two plasmas. This interface is referred to as the heliopause, and the region containing solar plasma is referred to as the heliosphere.

It is generally believed that the solar system travels through the interstellar medium at a speed of approximately 20 km s^{-1} . The thermodynamic conditions of the interstellar medium are not well known, but if the speed of the solar system through this medium is supersonic, a bow shock forms beyond the heliopause to slow and deflect the interstellar plasma. *Baranov* [1990] has reviewed this two-shock model of the solar wind/interstellar medium interaction. A bow shock would not be expected to form when the speed of the solar system relative to that of the surrounding medium is subsonic.

As summarized in recent reviews on this topic [e.g., *Holzer*, 1989; *Suess*, 1990], the general structure of the interaction of the solar wind with the interstellar medium in terms of the bulk or large-scale properties is fairly well understood in a qualitative sense for steady plasma flows.

There are, of course, several physical processes of a more detailed or localized nature occurring in the two plasmas that are not well understood themselves (e.g., interstellar neutral gas, charge exchange, cosmic rays). Their effect on the overall interaction is also not well understood.

The analysis of data from the plasma science experiment on Voyager 2 as the spacecraft traveled from 1 to 40.4 AU indicates that there are large-scale fluctuations in the solar wind ram pressure occurring on the time scale of tens of days [*Belcher et al.*, 1993]. Data from Pioneers 10 and 11 also show the presence of large variations in the ram pressure [*Barnes*, 1990]. Since the ram pressure plays a major role in controlling the location of the termination shock, it seems logical that large-scale fluctuations in the ram pressure may produce relatively large excursions of the termination shock. *Belcher et al.* [1993] used a kinematic model in which they limited the termination shock speed to 200 km s^{-1} and estimated that the location may vary by as much as 15 AU in response to the observed ram pressure fluctuations. This excursion amplitude is similar to that computed in other one-dimensional analyses [*Barnes*, 1993; *Suess*, 1993]. If there are large-scale movements of the termination shock in response to large-scale fluctuations in the solar wind ram pressure, then a spacecraft that reaches the vicinity of the shock may cross it more than once.

The objective of the present study is to use numerical solutions of the gasdynamic equations to examine the effect that large-scale fluctuations with temporal and spatial scales similar to those observed have on the average or mean behavior of the interaction between the solar wind and interstellar plasmas and particularly on the location of the termination shock. The study is performed for the case of subsonic relative motion between the solar system and the interstellar medium (for reasons discussed in section 3.1). A dynamic equilibrium solution of the interaction is obtained first, and fluctuations in the solar wind ram pressure are then generated to perturb the equilibrium.

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2. Equations and Model

The gasdynamic equations used in this study can be written in the following nondimensional form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1a)$$

$$\rho \frac{d\mathbf{v}}{dt} = -\frac{1}{\gamma} \nabla p, \quad (1b)$$

$$\frac{\partial}{\partial t} \left[\frac{1}{2} \rho v^2 + \frac{p}{\gamma(\gamma-1)} \right] + \nabla \cdot \left\{ \mathbf{v} \left(\frac{1}{2} \rho v^2 + \frac{p}{\gamma-1} \right) \right\} = 0, \quad (1c)$$

where d/dt is the total derivative, and the physical variables ρ , \mathbf{v} , and p are the density, plasma velocity, and thermal pressure, respectively. The density $\rho = n_e/m_p$, where n_e is the electron number density and m_p is the proton mass. All variables have been made dimensionless by normalizing the thermodynamic quantities to the initial values at 1 AU and the velocity to the initial sound speed at 1 AU (a_0). Distance is referenced to 1 AU (r_0), and time is normalized by $t_0 = r_0/a_0$. The only parameter that enters directly into the above equations is the specific heat ratio γ , which we take to be 5/3. Note that the potentially important effects of collisions with neutral species, resonance charge exchange, and cosmic ray pressure have not been included. *Donohue and Zank* [1993] used a gasdynamic model of a localized section of the termination shock to show that acceleration of the anomalous component and/or galactic cosmic rays may significantly influence the nature, structure, and motion of the termination shock. It remains to include the physics of their study into a global model such as that used here. In addition, since this is a gasdynamic model, the magnetic fields of the interstellar medium and of the solar wind are not included. The neglect of the magnetic field in the solar wind should have a minimal effect, since the plasma beta (ratio of thermal pressure to magnetic pressure) is generally large throughout the solar wind. It has been suggested that the magnetic field may provide the largest contribution to the total pressure in the interstellar medium [e.g., *Suess*, 1990], but the physical nature of the interstellar pressure should not significantly affect the present results.

Equations (1a) - (1c) are solved in the r - θ plane of a spherical coordinate system aligned such that the pole of the coordinate system at $\theta=0^\circ$ points into the direction of motion of the solar system relative to that of the interstellar medium. The solution is independent of the azimuthal angle ϕ and thus is axisymmetric about the poles. The coordinate system is centered at the Sun ($r=0$) and remains fixed with respect to the Sun. Consequently, the relative motion between the solar system and the interstellar medium is represented by a velocity of the interstellar medium (V_{is}) in our coordinate system. The simulation box extends from 0° to 180° in θ and from 10 AU to 400 AU. The radial grid spacing is constant at 1.4 AU, and the angular grid spacing is constant at 1° , which gives a grid of 280×181 .

The equations are solved numerically using a two-step Lax-Wendroff differencing scheme similar to that given by *Richtmyer and Morton* [1967], with second-order accuracy. As is usual for such schemes, an additional smoothing must be performed on the values from the Lax-Wendroff step in order to remove high-frequency oscillations and the overshoots and undershoots created near ideal discontinuities such as shocks. A smoothing term suggested by *Lapidus* [1967] was used, as was a flux-corrected-transport term [*Book et al.*, 1975]. The two smoothers produced qualitatively the same results when they both worked. The Lapidus term, though, was considerably more robust in handling the nonuniformities and the substantial range in physical variables in the present problem and was used for the results presented here. The flux-corrected-transport correction required more adjustment of the numerical constants and for some parametric regimes produced questionable results.

An explicit, shock-capturing scheme, as used here, is not necessary for computing the initial dynamic equilibrium solution into which the fluctuations are introduced, although it is essential in order to simulate the proper temporal response to the fluctuations. The initial equilibrium could equally well have been computed using a shock-fitting scheme with either an explicit or an implicit method used to solve for the solution between the discontinuities [e.g., *Baranov and Malama*, 1993]. It might be expected that the addition of a semi-implicit term in the momentum equation would permit the use of a larger time step during the relaxation. However, even with such a term, the time step is still restricted so that plasma cannot be convected farther than a grid spacing in a single time step. With the small grid spacing and the large flow speeds in the solar wind, the time step for a semi-implicit method would be only about 12% larger than that for the explicit method used here. Such a small increase in the time step certainly would not compensate for the additional CPU time necessary to solve the momentum equation implicitly in a semi-implicit method.

Three of the physical variables (radial flow speed v_r , density, and pressure) are symmetric at the angular boundaries, while the fourth is antisymmetric (meridional flow speed v_θ). The supersonic solar wind is specified at 1 AU, and an adiabatic atmosphere with constant radial flow speed is used to compute values at the inner computational boundary at 10 AU. Since this is a supersonic-inflow boundary, all physical quantities can be specified on it. The interstellar density and velocity are held fixed at the outer radial boundary for $0^\circ \leq \theta \leq 90^\circ$, and zero-order extrapolation along the local flow direction is used to update the pressure. Since this portion of the outer boundary is a subsonic-inflow boundary, not all of the physical quantities can be specified there. Zero-order extrapolation along the local flow direction is used to obtain all values at the outer radial (subsonic-outflow) boundary for $90^\circ < \theta \leq 180^\circ$.

The simulation is performed in two separate steps. A dynamic equilibrium is obtained first, and then a fluctuating solar wind flow speed is imposed on this equilibrium at the inner radial boundary. The simulation to compute the dynamic equilibrium is initiated by specifying adiabatic solar wind conditions within 10-40 AU, a termination shock at 40 AU, interstellar conditions beyond 80 AU, and a linear fit between the shocked solar wind and the interstellar plasmas. Starting with this nonequilibrium state, the time-dependent simulation continues until the solution relaxes to a dynamic

equilibrium. The solar wind fluctuations are then generated in the equilibrium solution by temporal oscillations in the solar wind speed at the inner radial boundary. The thermodynamic conditions at the inner boundary remain unchanged during the flow speed oscillations.

3. Numerical Results

3.1. Dynamic Equilibrium Solution

The spatial variation of the thermodynamic quantities and the streamlines after the solution has relaxed to a dynamic equilibrium are shown in Figure 1. The physical quantities in the solar wind at 1 AU for this simulation are $v_r=300 \text{ km s}^{-1}$, $v_\theta=0$, $n_e=3 \text{ cm}^{-3}$, and temperature $T=10^5 \text{ K}$. The reference sound speed is then 52.45 km s^{-1} , and the reference or characteristic time (t_0) is 33.2 days. The fixed, inflow interstellar conditions are $V_{is}=13.28 \text{ km s}^{-1}$ and $n_e=0.2 \text{ cm}^{-3}$. The inflow interstellar temperature is initially set to 10^4 K ($M_{is}=0.8$), but this temperature will change slightly as the pressure adjusts at the inflow boundary. The relaxation required 120,000 time cycles, which represents a total physical evolution time of 4.94×10^5 days, or 1353 years. Based on the sound speed in the interstellar medium (16.59 km s^{-1} or 3.48 AU/yr), this is time for a disturbance to cross the 800 AU numerical box almost six times. This total evolved time should not be regarded as physically relevant; it is simply an indicator of the time required for the solution to adjust to the specified start-up conditions. However,

simulated changes in this equilibrium solution due to changes in the boundary conditions should provide realistic estimates of the actual response time of the solar wind/interstellar medium interaction.

The interstellar flow (in our Sun-centered coordinate system) is from left to right in Figure 1. The locations of the termination shock and the heliopause are indicated on the streamline plot. The rapid changes in variables at the termination shock appear as clustered contours on the pressure and temperature plots. The shock does not appear on the density plot because of the linear scaling used for the contours and the fact that the density at the shock is less than the minimum contour. There is a density jump by about a factor of 4, however, since the termination shock is a strong shock. For this example with subsonic interstellar flow, the termination shock is nearly spherical and does not have the characteristic bullet shape typical of solutions for a supersonic interstellar flow [e.g., *Baranov and Malama, 1993; Steinolfson et al., 1994*]. The formation of a more spherical termination shock is one reason a subsonic interstellar flow solution is used for the initial state. However, since the present study concentrates on examining the fluctuations along the 0° pole, the shape of the downstream portion of the termination shock should have virtually no effect on the results.

3.2. Response to Large-Scale Fluctuations

A sinusoidal temporal variation in the solar wind radial flow speed is now specified at the inner radial boundary in

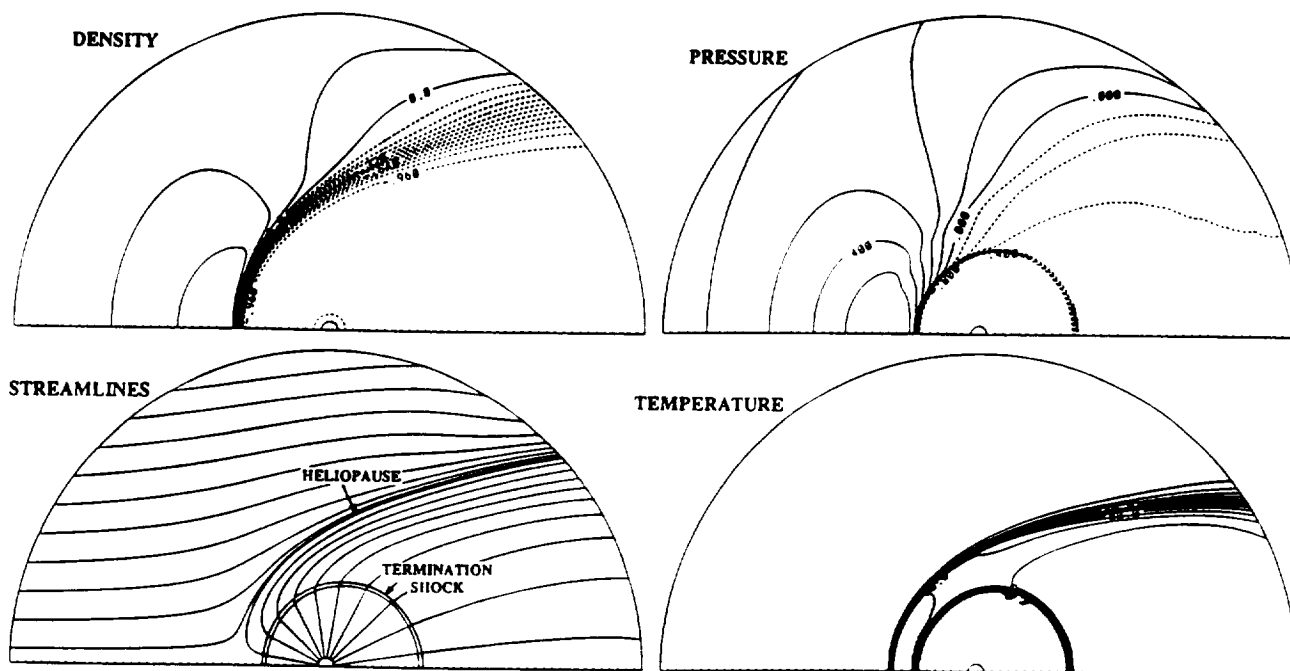


Figure 1. Thermodynamic quantities and velocity streamlines in the relaxed dynamic equilibrium solution. The radial range extends from the inner computation boundary at 10 AU to 400 AU. The interstellar flow (relative to the solar system) is from left to right. The termination shock location drawn on the streamline plot was determined from the contour plots of the thermodynamic variables. For the thermodynamic quantities, the value used to construct the plots is $(Q-Q_{is})/Q_{is}$, where Q_{is} represents the interstellar value. A contour level of zero represents the interstellar value, and values greater (smaller) than the interstellar value are represented by solid (dashed) contours. The density contours range from -0.96 to 0.24 in increments of 0.08, pressure ranges from -0.8 to 0.5 in increments of 0.1, and temperature ranges from 10 to 100 in increments of 10.

order to generate fluctuations in the solar wind ram pressure (ρv^2). The speed oscillation is maintained throughout the numerical computation. Although the change in the boundary conditions occurs only in the flow speed (the thermodynamic quantities are held fixed at the inner boundary), fluctuations in all the physical quantities are generated in the solar wind. The same variation is applied at all angular locations, so the physical situation that is modeled is one in which the flow speed increases and decreases uniformly at all locations on the solar surface. The amplitude of the flow speed oscillation is 100 km s^{-1} , so the speed varies between 200 and 400 km s^{-1} at the boundary. The fluctuation period is taken to be 180 days. This is somewhat larger than the observed large-scale variations in ram pressure occurring on time scales of tens of days reported by *Belcher et al.* [1993], but it will be sufficient to demonstrate the essential physics involved in the response of the interaction to the fluctuations.

The fluctuations in ram pressure at the inner boundary (10 AU) and at two other spatial locations upstream of the termination shock are shown in Figure 2. The ram pressure fluctuations at the inner boundary (10 AU) are due to changes in just the flow speed, but those at the other two locations involve changes in both the flow speed and density. The fluctuations are shown for only the first 2500 days of

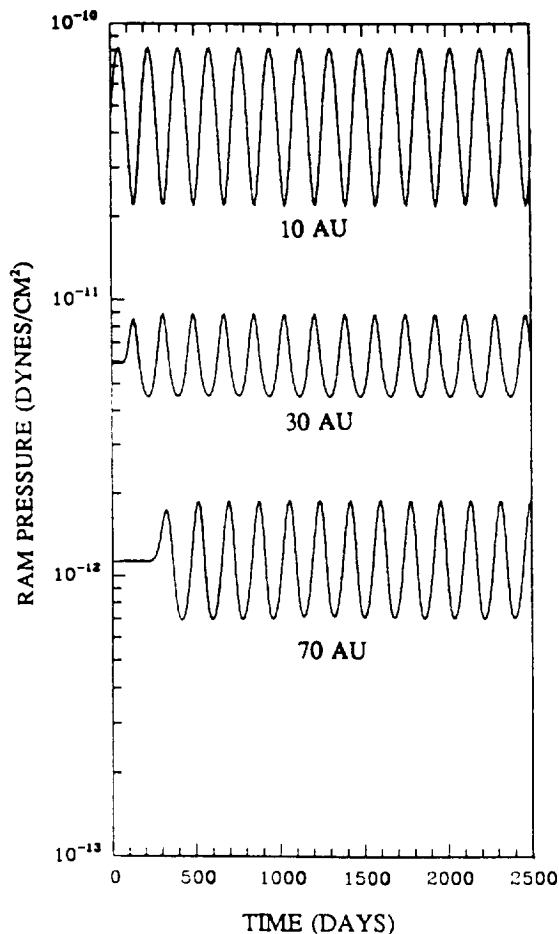


Figure 2. Temporal fluctuations in the solar wind ram pressure at three locations along the pole at $\theta=0^\circ$ upstream of the termination shock. The fluctuations are shown for only the first 2500 days but remain unchanged throughout the remainder of the simulation.

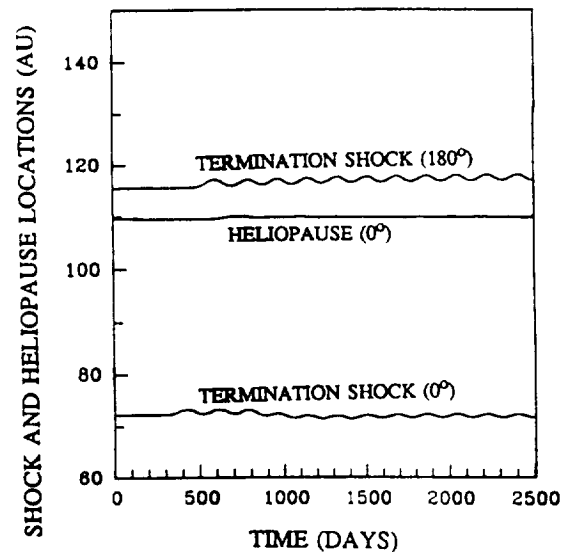


Figure 3. Temporal fluctuations in the locations of the termination shock along the poles at $\theta=0^\circ$ and $\theta=180^\circ$ and of the heliopause along the pole at $\theta=0^\circ$. The fluctuations are shown for only the first 2500 days but remain unchanged throughout the remainder of the simulation.

the simulation, but they remain unchanged for the total computation time of 7800 days. The termination shock in the equilibrium solution is located at about 80 AU; hence the fluctuations at 70 AU are only 10 AU upstream of the shock. The average value of the simulated ram pressure is less than the observed average value in Figure 3 of *Belcher et al.* [1993] owing to the lower-than-observed solar wind speed used in the simulations. This lower speed was used so that the termination shock would be located fairly close to the Sun when reasonable (anticipated) values were used for interstellar conditions. The magnitudes of the simulated ram pressure fluctuations in Figure 2 are at the low end of the observed magnitudes in Figure 3 of *Belcher et al.* [1993] and are similar to those of the fluctuations during solar minimum periods.

The temporal responses of the termination shock at the poles ($\theta=0^\circ, 180^\circ$) and of the heliopause at the 0° pole are shown in Figure 3. The period of the response is the same as that of the applied speed oscillation (180 days). The amplitude of the response represents a total movement of the termination shock of about 1 AU. It should be noted that the amplitude of the response shown here is virtually identical to that when the applied flow speed oscillation amplitude at the inner boundary is either reduced to 75 km s^{-1} or increased to 125 km s^{-1} . This indicates that the amplitude of the termination shock response may have saturated and that it would not increase significantly with further increases in the amplitude of the ram pressure fluctuations. If the flow speed oscillation amplitude is decreased to 50 km/s , there is a noticeable reduction (about 20%) in the oscillation amplitude. The oscillation amplitude at which the termination shock response saturates naturally depends on the oscillation period, but this dependence is not investigated here.

Although the simulated termination shock does not move as much as might be anticipated in response to the ram pressure fluctuations, the amplitudes of the spatial oscillations are significant, as shown in Figure 4. This figure

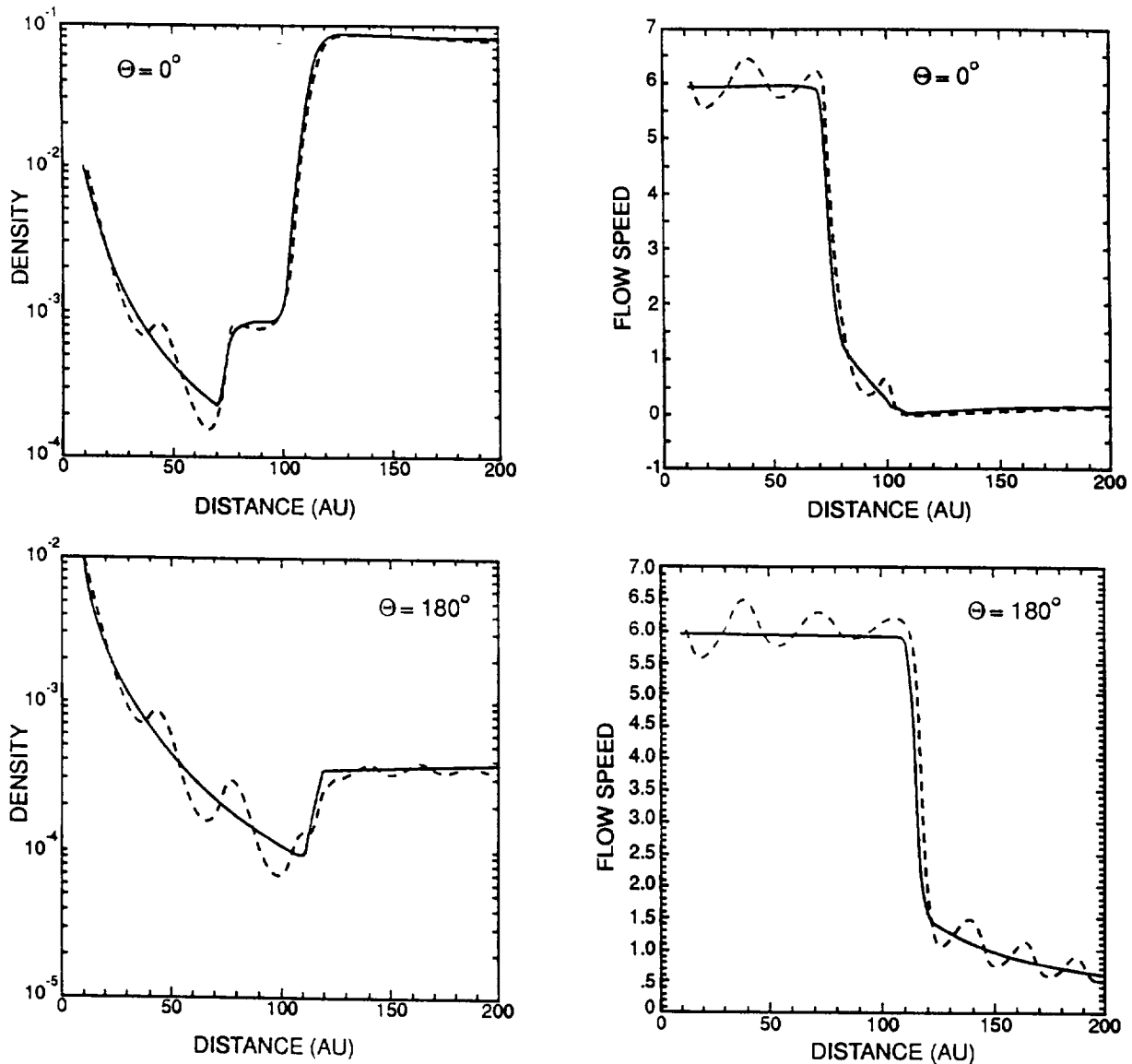


Figure 4. Spatial fluctuations in the density and flow speed along the poles (at $\theta=0^\circ$, 180°) at the end of the simulation (dashed curves) superimposed on the dynamic equilibrium state (solid curves).

compares the spatial structures of the density and radial flow speed along the poles in the dynamic equilibrium solution (solid curves) with the structures after the speed oscillation has been applied for 7800 days (dashed curves). It is evident from this figure that even though only a flow speed oscillation was applied at the inner boundary, large oscillations in both flow speed and density are generated in the solar wind. Notice from the plots along the 0° pole that the fluctuations do not get through the heliopause into the interstellar medium. This is more apparent in Figure 5, in which the contour levels have been tailored to bring out fluctuations in the thermal pressure beyond the termination shock. The heliopause effectively acts as a barrier to confine the oscillations to the solar wind plasma.

The simulated response amplitude is substantially less than the 10 AU (or larger) movement of the termination shock due to ram pressure fluctuations predicted by more approximate theories [Barnes, 1993; Suess, 1993]. It is also less than the shock movement estimated in the study by Belcher

et al. [1993], in which the termination shock location was computed using observed ram pressure fluctuations with a 200 km s^{-1} limit on the shock speed. There are at least two reasons why the results of the studies cited above for the response amplitude of the termination shock differ from the present results.

First, the earlier studies are all one-dimensional and effectively assume that an isolated section of the termination shock responds independently of the rest of the termination shock. This, of course, does not happen in practice, and the entire termination shock responds collectively to solar wind ram pressure fluctuations. In the extreme case, one can envision situations in which one section of the termination shock is being subjected to a maximum in a ram pressure fluctuation while an adjoining section, not too far removed in angular distance from the first but at a different radial distance from the Sun, must respond to a minimum in the fluctuation. The first section will tend to move outward, and the second one will tend to move inward. Although this

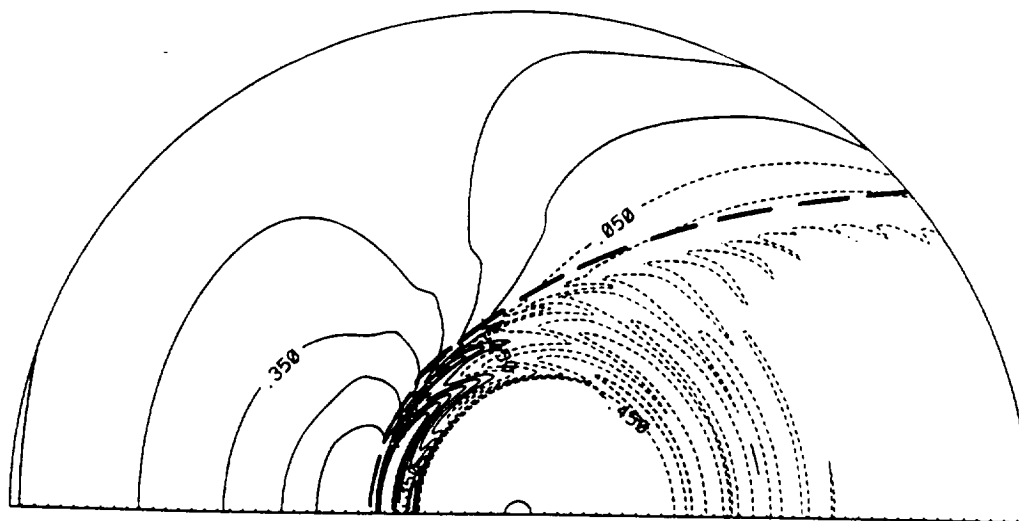


Figure 5. Contour plots of the thermal pressure illustrating confinement of the fluctuations to the heliosphere. The heavy dashed curve marks the location of the heliopause. The fluctuations within the termination shock do not appear in this figure, since the pressure within the termination shock is below the minimum contour level.

effect must be accommodated to a certain extent for all fluctuations, it becomes more important as the period of the fluctuations decreases. A second, much more important reason for the difference between the present results and those in earlier studies probably has to do with the more rapid response times either calculated or assumed in the earlier studies compared to those computed in the present study. This is now discussed in more detail.

3.3. Termination shock response time

As an estimate of the time it takes the termination shock to respond to changes in the solar wind quantities, we rapidly increase the solar wind flow speed at the inner boundary

from 300 km s^{-1} in the equilibrium solution to 400 km s^{-1} , hold the speed constant at 400 km s^{-1} at the inner boundary, and follow the evolution in time until the interaction approaches a new dynamic equilibrium. The flow speed is increased over 45 time cycles, which represent about 90 days, or half the period of the fluctuations used in the above study. The temporal response of the termination shock locations at the poles and of the heliopause at the 0° pole are given in Figure 6. The termination shock and heliopause gradually approach their new equilibrium position.

The termination shock at the 0° pole initially moves outward rapidly (between about 300 and 700 days in Figure 6) when it is first impacted by the solar wind disturbance. The shock at this location then rebounds (between about 700

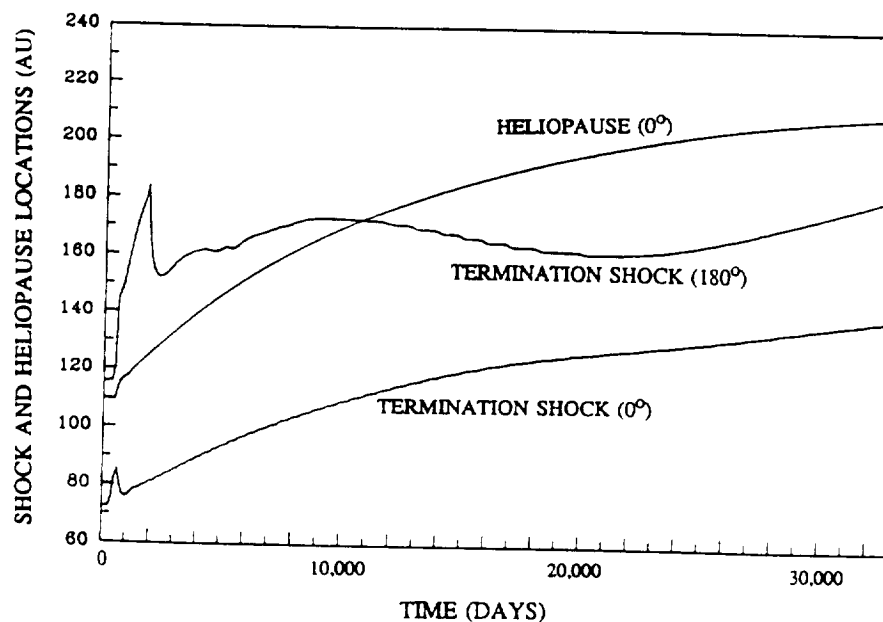


Figure 6. Temporal responses of the termination shock locations at the poles and of the heliopause at the 0° pole as the solar wind speed in the dynamic equilibrium solution in Figure 1 is increased over 90 days from 300 km s^{-1} to 400 km s^{-1} and then at that level.

and 1000 days) and then monotonically approaches an equilibrium position. The average outward speed of the termination shock along the 0° pole during the initial rapid movement, approximately 73 km s^{-1} , is followed by an average outward speed from 1000 to 6000 days of 7.2 km s^{-1} . Both of these speeds are smaller than the maximum shock speed computed or estimated in earlier studies [Belcher *et al.*, 1993; Barnes, 1993; Suess, 1993]. During the 90-day half-period of the fluctuation used above, the termination shock would move 3.8 AU if traveling at 73 km s^{-1} and 0.38 AU if traveling at 7.2 km s^{-1} . These distances are smaller than the excursions predicted in the earlier studies and are, respectively, larger and smaller than the 1 AU movement reported on above (section 3.2). The average speed of the termination shock during the computed 1 AU fluctuations is about 20 km s^{-1} (1 AU in 90 days). This study also shows that if a single increase in ram pressure of infinite duration is input, as Barnes [1993] did, the termination shock would then have time to reach larger speeds.

The termination shock at the 180° pole also experiences an initial overshoot, but the heliopause does not. The motion of the termination shock along the 180° pole following the initial overshoot in Figure 6 illustrates an important feature of the relaxation simulation. Once the downstream (from 90° to 180°) portion of the termination shock reaches the vicinity of its equilibrium position, it oscillates over a very long period. This particular computation was not continued beyond the time shown in Figure 6, so it is not known whether the oscillation amplitude decreases with time. The simulation to determine the initial equilibrium solution (section 3.1) was continued long enough to determine that the oscillation amplitude was slowly decreasing with time. The spatial variation of the physical quantities and the streamlines for a 400 km s^{-1} solar wind speed are not shown here. However, other than the larger distances to the termination shock and the heliopause, there are no qualitative differences between that solution and the solution shown in Figure 1 for a 300 km s^{-1} solar wind speed.

4. Discussion

The response of the termination shock to large-scale fluctuations in the solar wind ram pressure is studied using numerical solutions of the gasdynamic equations. The first step in this study is to compute a dynamic equilibrium solution for the interaction between the solar wind and the interstellar medium by using a numerical relaxation procedure. The ram pressure fluctuations are then generated in the solar wind by temporal flow speed oscillations at the inner radial boundary for the computation. The subsequent solar wind ram pressure fluctuations are comparable in amplitude (near the observed minimum) and time scale (near the observed maximum) to those observed by Voyager 2 [Belcher *et al.*, 1993].

The maximum movement of the termination shock in response to the ram pressure fluctuations is about 1 AU for a 100 km s^{-1} flow speed oscillation at the inner boundary. Although only an oscillation in the flow speed is used as the driving mechanism, the solar wind disturbance consists of fluctuations in all physical quantities, including the density. When the driving flow speed oscillation is reduced to 75 km s^{-1} , the termination shock response is almost identical to that

for the larger-magnitude speed oscillations reported on here (which, in fact, is the same as that for 125 km s^{-1} oscillations), indicating that the response has saturated and would remain the same for even larger amplitude fluctuations. As a result, the fact that the magnitude of the ram pressure fluctuations are near the low end of those observed should not make any significant difference. That is, the termination shock response would be the same as that computed here even if the oscillation amplitude were increased to the maximum observed value. A reduction to 50 km s^{-1} , however, reduces the termination shock movement somewhat. It should also be noted that the time scale for the fluctuations used here (180 days) is somewhat larger than observed. Consequently, the predicted 1-AU excursion should be considered an upper limit which would most likely be reduced for shorter-period fluctuations. One additional caution that should be mentioned is that the ambient or background solar wind flow speed of 300 km s^{-1} used in the study is lower than typical observed values. The effect of a larger ambient speed should be investigated, though one would anticipate that the deviation from the ambient value would have more of a role in determining the amplitude of the termination shock fluctuation.

The magnitude of the termination shock excursion computed here (1 AU) is substantially less than the 10 to 15 AU excursions predicted by other methods [Belcher *et al.*, 1993; Barnes, 1993; Suess, 1993]. These other methods are more approximate in the sense that they are one-dimensional and thus consider only the movement of an isolated section of the termination shock rather than the collective response of the entire termination shock. The previous methods also do not consider the complete interaction region between the solar wind and the interstellar medium. One possible explanation for this difference is that the numerical differencing scheme used here contains inherent dissipation, as does any such numerical scheme, which may act to reduce the termination shock response time. This effect has been minimized in the present study by not adding any additional dissipation. Along the same lines, it should be emphasized that the differencing scheme is explicit, so all relevant time scales are included in the evolution.

The response of the termination shock may also be restricted by the fact that it is spread over several grid points in the simulation. This effect is difficult to quantify, but it should be noted that the spatial scale of the oscillations is considerably larger than the numerical width of the termination shock, which should tend to minimize the effect. A much more likely explanation for at least the major portion of the difference is that the termination shock simply does not respond as rapidly as either assumed or calculated in the earlier studies. The response time was simulated in the present study by computing the time needed for the interaction to reach a new equilibrium following a fixed change in the solar wind properties and was shown to be much larger than that used in the previous studies. However, given the numerical approximations and uncertainties, the actual termination shock response will probably be bounded by the values predicted here and those from the earlier work.

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Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event

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Abstract. A new heliospheric radio emission event observed by Voyagers 1 and 2 in mid-1992 is believed to have been produced by the interaction of an interplanetary shock with the heliopause. The shock is thought to have originated near the Sun during a period of intense solar activity in late-May and early-June, 1991. The observed travel time of the shock to the heliopause is 408 days; the initial speed is estimated to be between 600 and 800 km/s. We use a numerical gasdynamic simulation of an interplanetary shock, propagating through an equilibrium solution of the solar wind/interstellar medium interaction, to compute the distances to the termination shock and the heliopause that are consistent with these observations. For a shock speed of 600 km/s, the termination shock is located at 92 AU, and the heliopause is located at 128 AU. These distances increase to 112 AU and 156 AU when the shock speed is increased to 800 km/s.

Introduction

Pioneers 10 and 11 and Voyagers 1 and 2 are on their way to explore the interaction of the solar wind with the interstellar medium. Pioneers 10 and 11 are currently at heliocentric distances of 58.6 and 39.8 AU (astronomical units), and Voyagers 1 and 2 are at 54.5 and 41.9 AU (all distances are as of January 1, 1994). None have yet crossed the termination shock, where the solar wind is expected to become subsonic, or the heliopause, the boundary between the solar wind and the interstellar plasma. Because of the exploratory nature of these missions, there is considerable interest in obtaining improved estimates of the distances to these boundaries. Most previous estimates have been obtained by assuming a total pressure for the interstellar medium and computing boundary locations from pressure balance considerations. Unfortunately, relatively little is known about the various contributions to the total pressure of the interstellar medium in the vicinity of the Sun. Based on current best estimates, the distance to the termination shock is believed to be between 70 and 100 AU, and the distance to the heliopause between 100 and 150 AU [e.g.: Holzer, 1989; Baranov, 1990; Suess, 1990; Suess and Nerney, 1994]. A strong, new heliospheric radio emission

event was recently detected by the plasma wave instruments on the Voyagers 1 and 2 spacecraft [Gurnett et al., 1993]. In their analysis of this event, Gurnett et al. proposed that the radio emission is produced by the interaction of an interplanetary shock with the heliopause. Making rather simple assumptions about the speed of the shock, Gurnett et al. estimated that the heliocentric radial distance to the heliopause is from 117 to 177 AU. Here we use a numerical simulation to more accurately model the propagation of the interplanetary shock and thereby obtain an improved estimate of the distance to the heliopause (and termination shock). To obtain a solution that agrees with the observations, the total pressure of the interstellar plasma is varied until the travel time of the interplanetary shock through the corresponding equilibrium solution for the solar wind/interstellar medium interaction agrees with the observed travel time. With this approach, the interstellar pressure is a result of our study rather than an assumed quantity. These numerical results depend, of course, on the validity of the interplanetary shock model proposed by Gurnett et al. [1993].

The 1992-93 Heliospheric Radio Emission Event

Beginning in early July 1992, the plasma wave instruments on the Voyagers 1 and 2 spacecraft (located at 49.0 AU and 37.6 AU, respectively) detected strong, new heliospheric radio emission around 2 to 3 kHz [Gurnett et al., 1993]. This event reached peak intensity in early December 1992, and declined to near the receiver noise level by mid-1993. At peak intensity the total power radiated was estimated to be at least 10^{13} Watts. Gurnett et al. [1993] proposed that the radio emission was produced by the interaction of an interplanetary shock with the heliopause. The interplanetary shock is believed to have originated at the Sun during a period of intense solar activity in late-May and early-June, 1991. The coronal mass ejections and associated interplanetary disturbances associated with the late-May/early-June solar events are believed to have merged in the outer heliosphere into a single, quasi-spherical interplanetary shock that was subsequently detected by various instruments on Pioneers 10 and 11 and Voyagers 1 and 2. The propagation speed of the interplanetary shock has been variously estimated to be 820 ± 45 km/s [Van Allen and Fillius, 1992; Van Allen, 1993], 600 to 800 km/s [Webber and Lockwood, 1993], and 550 km/s [Belcher et al., 1993]. The uncertainties are due in part to the difficulty of identifying the exact onset times at the Sun, and in part to the spread in the arrival times at the various spacecraft. Since the shocks may decelerate, their speeds at large distances from the Sun may be overestimated.

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The travel time of the shock from the onset of the period of intense solar activity on day 145, 1991, to the arrival at the heliopause on day 188, 1992, is 408 days, or 1.12 years [Gurnett et al., 1993]. The travel time is also subject to various uncertainties, and in fact, McDonald et al. [1993] have suggested that the interaction may have been triggered by an earlier period of solar activity in March 1991. Because of the uncertainties in the propagation speed and travel time of the interplanetary shock, for the purpose of this paper the original values reported in Gurnett et al. [1993] will be used; i.e., 600 to 800 km/s and 408 days.

Numerical Procedure

The gasdynamic model used here is the same as that used by Steinolfson [1994]. For the present study two separate simulations are required. In the first simulation, a dynamic equilibrium solution is obtained by numerically computing the relaxation from an initial nonequilibrium state with specified solar wind conditions at 1 AU and specified conditions at the interstellar inflow boundary. In the second simulation, an interplanetary shock with a speed of either 600 or 800 km/s is introduced into the equilibrium solution near the Sun and allowed to propagate outward through the solar wind and into the interstellar medium.

For the equilibrium solution, the physical quantities in the solar wind at 1 AU are held fixed at the following values: density $n_E=5 \text{ cm}^{-3}$, temperature $T_E=10^5 \text{ K}$, radial velocity $(v_r)_E=400 \text{ km/s}$, and theta velocity $(v_\theta)_E=0$. The solar wind Mach number at 1 AU is $M_E=7.6$. The quantities in the interstellar plasma that are held fixed are the temperature $T_{is}=10^4 \text{ K}$ and the interstellar flow speed $V_{is}=24.88 \text{ km/s}$. These values give a supersonic interstellar flow with a Mach number of $M_{is}=1.5$. A trial value is selected for the interstellar density n_{is} , and a dynamic equilibrium solution is computed. The final interstellar density is determined iteratively by requiring that an interplanetary shock with a speed of either 600 or 800 km/s propagate from the Sun to the heliopause in 408 days.

Sun-fixed spherical coordinates are used in the simulations. The simulation box extends from 30 AU to 550 AU and from 0° to 180° in θ , with the $\theta=0^\circ$ pole directed into the interstellar flow. The solution is assumed to be axisymmetric about the poles so there is no variation with the azimuthal angle ϕ and the computation becomes two-dimensional. A coordinate transformation allows the radial grid spacing to vary monotonically from a minimum of 0.85 AU at the inner boundary to a maximum of 3.15 AU at the outer boundary. The angular grid spacing is constant at 1° , which gives a grid of 335×181 . The equations are solved numerically using a second-order explicit scheme with a high-frequency filter [Steinolfson, 1994].

Three of the physical variables (v_r , n , and pressure p) are symmetric at the poles while the fourth is antisymmetric (v_θ). An adiabatic solar wind with constant flow speed is used to obtain boundary values at the inner radial boundary at 30 AU from the specified solar wind conditions at 1 AU. Since this is a supersonic-inflow boundary, all physical quantities can be specified on it. The outer radial boundary for $0^\circ \leq \theta \leq 90^\circ$ is also a supersonic-inflow boundary. Zero-order extrapolation along the local flow direction is used to obtain values at the outer radial [outflow] boundary for $90^\circ < \theta \leq 180^\circ$.

After a dynamic equilibrium solution has been computed, an interplanetary shock propagating at a speed of either 600 or 800 km/s in separate simulations is generated at the inner radial boundary. The shock is produced by changing the

boundary conditions at 30 AU to the values given by the shock jump conditions for a shock at the inner boundary traveling at the selected speed. These revised boundary conditions are then maintained for the duration of the simulation.

Numerical Results

The dynamic equilibrium solution in which a shock initiated at the inner boundary with a speed of 600 km/s takes approximately 408 days to travel from the Sun to the heliopause is shown in Figure 1. A constant 600 km/s shock speed from the Sun to the inner computational boundary at 30 AU is assumed. The pressure is referenced to the interstellar value. Due to the linear spacing used for the contours, the spatial variation of the pressure within the termination shock is not shown in this representation. Although not shown here, the entropy has been verified to be constant along the streamlines between the discontinuities. The pressure and other thermodynamic plots have been used as a guide to draw the approximate locations of the shocks and heliopause on the computer-generated streamline plot. The termination shock is elongated in the downstream direction and has the bullet shape characteristic of the equilibrium solution for a supersonic interstellar flow [e.g., Baranov and Malama, 1993; Steinolfson et al., 1994].

The pressure increases from the bow shock to the heliopause near the $\theta=0^\circ$ pole to form a high pressure region just ahead of the heliopause. Since the flow is adiabatic between the bow shock and the heliopause, a density pile-up

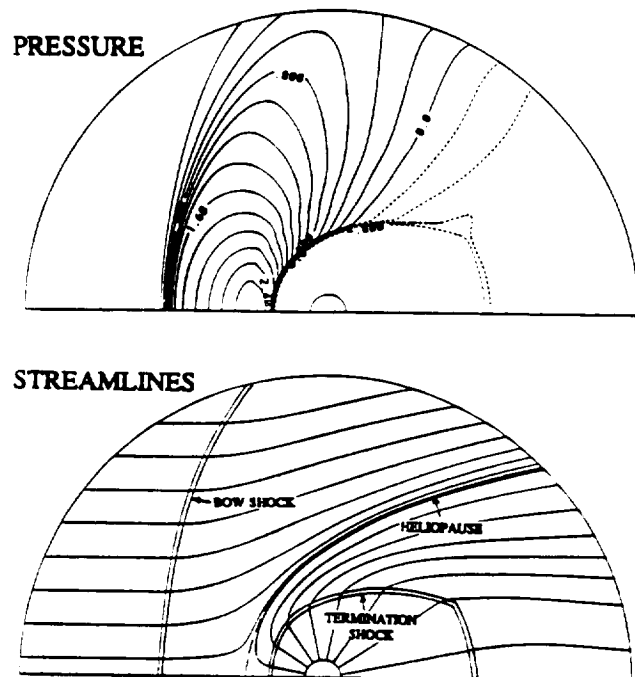


Figure 1. Thermal pressure contours and velocity streamlines in the dynamic equilibrium solution for a solar wind shock speed of 600 km/s. The interstellar flow (relative to the solar system) is from left to right. The shock locations plotted on the streamline plot were determined from the contour plots of the thermodynamic variables. The value used to construct the plots for the pressure is $(Q-Q_{is})/Q_{is}$, where Q_{is} represents the interstellar value. Values greater (smaller) than the interstellar value are indicated by solid (dashed) contours. The pressure contours range from -0.8 to 2.4 in increments of 0.2.

region is also formed ahead of the heliopause. Such a density pile-up has been used by Gurnett et al. [1993] to explain the increase in the radio emission frequency with increasing time as the shock propagates through the region beyond the heliopause.

The spatial variation of the thermodynamic quantities and the flow speed along the radial line at the 0° pole are given in Figure 2. The thermodynamic quantities are normalized to their values at 1 AU, and the flow speed is referenced to the sound speed at 1 AU in this representation. The shaded regions identify the approximate locations of the shocks and the heliopause. Although the shocks and heliopause are spread over several grid points, the changes in physical quantities across them are consistent with the jump conditions across shocks and contact surfaces.

The temporal variations of the radial location (dashed curves) and velocity (solid curves) along the 0° pole of an interplanetary shock propagating through the above equilibrium solution are shown in Figure 3. The velocity is positive when the shock motion is away from the Sun. In this example the initial shock speed (in the laboratory frame) at the inner boundary is 600 km/s, slowing to 540 km/s when the shock reaches and interacts with the termination shock. This interaction results in the generation of an inner shock which is the new (perturbed) termination shock, and an outer shock which is the continuation of the interplanetary shock. The perturbed termination shock initially moves outward at about 190 km/s. It overshoots its final equilibrium position, and after a strongly damped oscillation comes to rest at a distance slightly greater than 107 AU.

During the interaction with the termination shock, the interplanetary shock quickly decelerates from 540 km/s to 450 km/s and then slows by another 40 km/s before reaching the heliopause. At the heliopause the shock again decelerates quickly from 410 km/s, eventually approaching an asymptotic speed of about 40 km/s as it propagates into the interstellar medium. During the time period represented by the light lines, the numerical logic used to track the interplanetary shock does not work well due to the complex shock-shock interactions.

As can be seen in Figure 3, the interaction of the interplanetary shock with the heliopause occurs over several days.

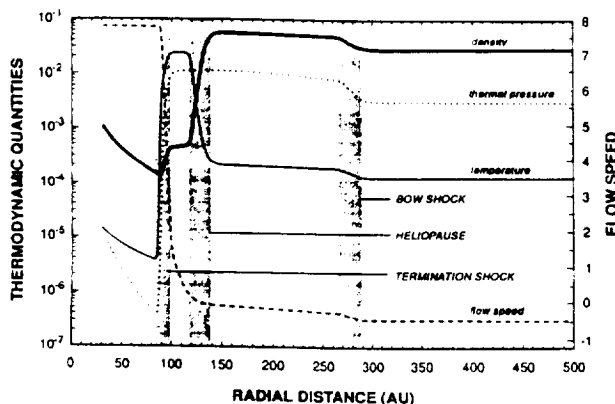


Figure 2. The variation of physical quantities along the radial line at $\theta=0^\circ$ in the equilibrium solution. The pressure has been multiplied by 10 and the temperature by 10^{-3} for the indicated scale. The thermodynamic quantities are referenced to their values at 1 AU using Q/Q_E , where Q_E is the value at 1 AU. The flow speed is divided by the sound speed at 1 AU. Negative values of the flow speed are directed toward the Sun.

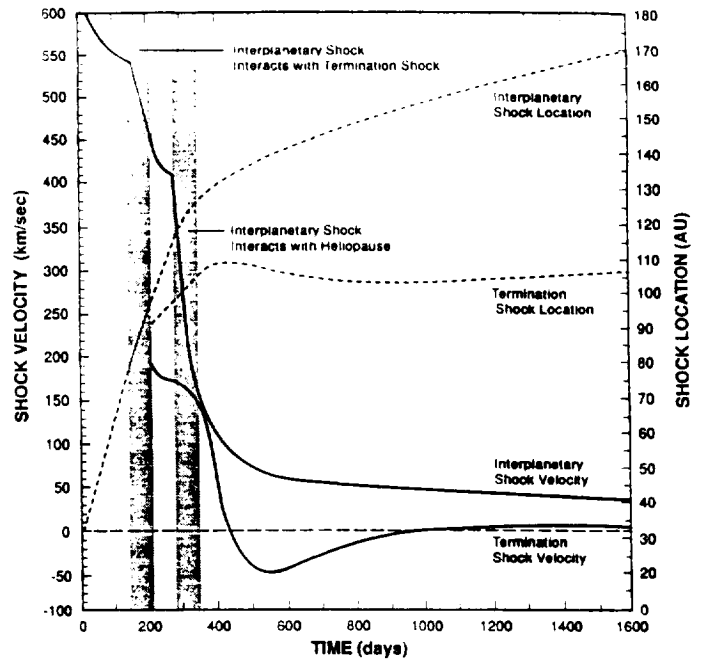


Figure 3. The temporal variation of the velocity (solid curves) and location (dashed curves) along the 0° pole of the interplanetary shock prior to and after its encounter with the termination shock and of the termination shock after it has been set in motion by the interaction with the interplanetary shock. The horizontal dashed line indicates a zero shock velocity.

To compare with the observations, a time toward the end of the interaction is taken as the onset time of the observed radio emission. To obtain the total time delay from the injection of the interplanetary shock near the Sun to the onset of the radio emission, the time necessary for the shock to travel from the Sun to the inner boundary at 30 AU must be added to the time given in Figure 3. For a shock speed of 600 km/s, it takes about 65 days for the shock to traverse 30 AU. Consequently, the total travel time corresponds to the observed value of 408 days. As seen in Figure 2, the termination shock is centered at about 92 AU and the heliopause is at 128 AU along the 0° pole for the dynamic equilibrium solution. The interstellar plasma density has a value of $n_p=0.14 \text{ cm}^{-3}$ for this solution.

A study identical to that described above was also performed using an interplanetary shock speed of 800 km/s. In this case the termination shock is located at 112 AU and the heliopause at 156 AU. Since the interplanetary shock is now traveling faster, the termination shock and the heliopause must be located farther from the Sun to give the observed 408-day propagation time. The interstellar density required to produce this new equilibrium configuration is correspondingly lower, $n_p=0.09 \text{ cm}^{-3}$. Since there is no qualitative difference from the previous 600 km/s solution, illustrations analogous to those shown above are not given for the 800 km/s solution.

The interstellar plasma densities obtained for the above two equilibrium solutions are probably unphysically large due to the omission of the interstellar magnetic field pressure. This omission is not expected to adversely affect the results of the study performed here, especially if the field orientation is such that tension forces on the heliopause are minimal (such as for a flow-aligned magnetic field). Let us

for now assume that only the total interstellar pressure is important in the pressure balance, without regard for how the pressure is obtained. Then, if we further assume that the interstellar magnetic field provides some of the computed total pressure and that the interstellar density has a more physically realistic value, the magnetic field strength necessary to provide this pressure contribution can be easily computed. For our values of T_{is} and V_{is} , the sum of the thermal and dynamic pressures becomes $1.3 \times 10^{-11} n_{is}$ dynes/cm². The magnetic field strength in nT necessary to maintain this total pressure with an interstellar density (in cm⁻³) less than that used in the simulations can be written as

$$B_{is} = 1.814 \sqrt{(n_{is})_{sim} - (n_{is})_{obs}}$$

where $(n_{is})_{sim}$ is the value from the simulation and $(n_{is})_{obs}$ is the value from observations.

For a shock speed of 800 km/s, the density from the simulation is $(n_{is})_{sim} = 0.09$ cm⁻³. If the density in the interstellar medium is $(n_{is})_{obs} = 0.04$ cm⁻³, as suggested by Gurnett et al. [1993], then $B_{is} = 0.41$ nT, whereas if $(n_{is})_{obs} = 0.01$ cm⁻³, $B_{is} = 0.51$ nT. The corresponding values for the 600 km/s shock speed, for which $(n_{is})_{sim} = 0.14$ cm⁻³, are $B_{is} = 0.57$ nT for $(n_{is})_{obs} = 0.04$ cm⁻³ and $B_{is} = 0.65$ nT for $(n_{is})_{obs} = 0.01$ cm⁻³. The difference between the minimum [0.41 nT] and the maximum [0.65 nT] values for the magnetic field strength is quite small.

Discussion

Gurnett et al. [1993] have proposed that the 1992-93 heliospheric radio emission event is caused by the interaction of an interplanetary shock with the heliopause. The numerical simulations presented in this paper demonstrate that for an interplanetary shock speed of 600 km/s the observed travel time of 408 days can be obtained if the interstellar total pressure is such that the termination shock in the equilibrium solution is located at 92 AU and the heliopause is located at 128 AU. If the shock speed is increased to 800 km/s, these distances increase to 112 AU and 156 AU.

If the distances computed in the present numerical study are taken to be realistic estimates, the earliest any spacecraft would encounter the termination shock would be in 2004 by Voyager 1 [based on the spacecraft trajectories in Figure 2(b) from Suess, 1990]. Voyager 2 would reach the termination shock in 2008 and Pioneer 11 in 2014. The above encounter times are based on the estimates using the 600 km/s shock speed. If the results for the 800 km/s shock speed are used, the encounter with the termination shock increases to 2009 for Voyager 1, 2014 for Voyager 2, and 2018 for Pioneer 11. These encounter times are underestimates since the distances to the termination shock found in this study are those along the direction of relative motion between the Sun and the interstellar medium, which, as seen in Figure 1, are the minimum distances. All the spacecraft are traveling at a relatively large angle to this direction and, as a result, would require more time to reach the termination shock.

One factor that might compromise the estimated distances to the termination shock and the heliopause determined from this study is the fact that the interplanetary shock is initiated at 30 AU rather than at the surface of the Sun so any shock deceleration within 30 AU is not modeled self-consistently. In fact, the shock is assumed to have a constant speed from the Sun to 30 AU. This difficulty is mitigated somewhat in that the time the shock spends in traversing 30 AU is about

15% of the total time required for the shock to reach the heliopause. It is certainly conceivable that our initial interplanetary shock speeds at 30 AU may be too large due to shock deceleration. A lower interplanetary shock speed would reduce the distances to the termination shock and the heliopause. The spread of the shocks and heliopause over a few grids also makes it hard to select a time when the interactions between the interplanetary shock and the termination shock and heliopause actually occur. In addition, the interplanetary magnetic field strength, not included in our gasdynamic study, increases from the termination shock to the heliopause. This increases the fast magnetosonic speed and thereby modifies the interplanetary shock speed. Despite these qualifications and others of less importance, the distances estimated here should be accurate to within something less than 10 AU.

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