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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].

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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.

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 $n_E=5$ cm^{-3}, temperature $T_E=10^5$°K, radial velocity $(v_r)_E=400$ 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 $T_{is}=10^4$°K and the interstellar flow speed $V_{is}=24.88$ 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 $\theta=0°$ 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 335x181. 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 $0°\leq\theta\leq90°$ 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 $90°<\theta\leq180°$.

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 $\theta=0°$ 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

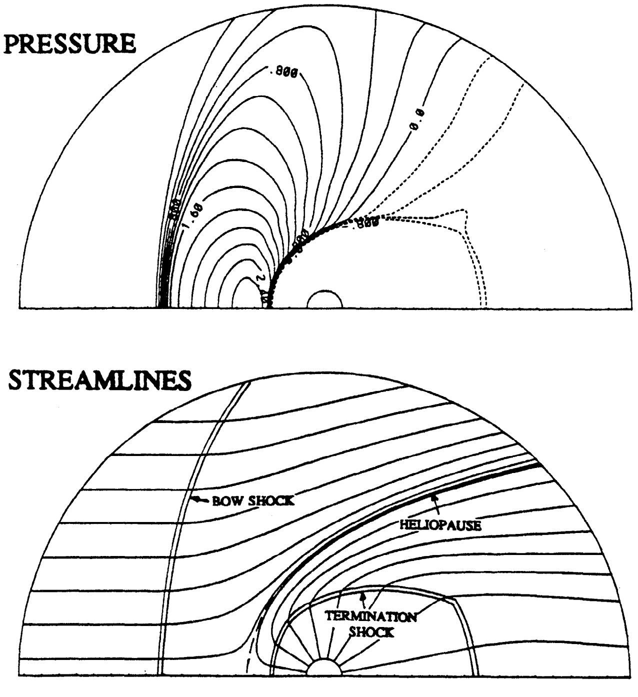

Figure 1. Thermal pressure contours and velocity streamlines in the dynamic equilibrium solution for a solar wind shock speed of 600 km/s. The interstellar flow (relative to the solar system) is from left to right. The shock locations plotted on the streamline plot were determined from the contour plots 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.

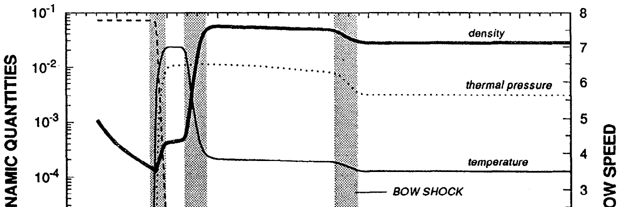

Figure 2. The variation of physical quantities along the radial line at $\theta=0°$ in the equilibrium solution. The pressure has been multiplied by 10 and the temperature by 10^{-3} for the indicated scale. The thermodynamic quantities are referenced to their values at 1 AU using Q/Q_E, where Q_E is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

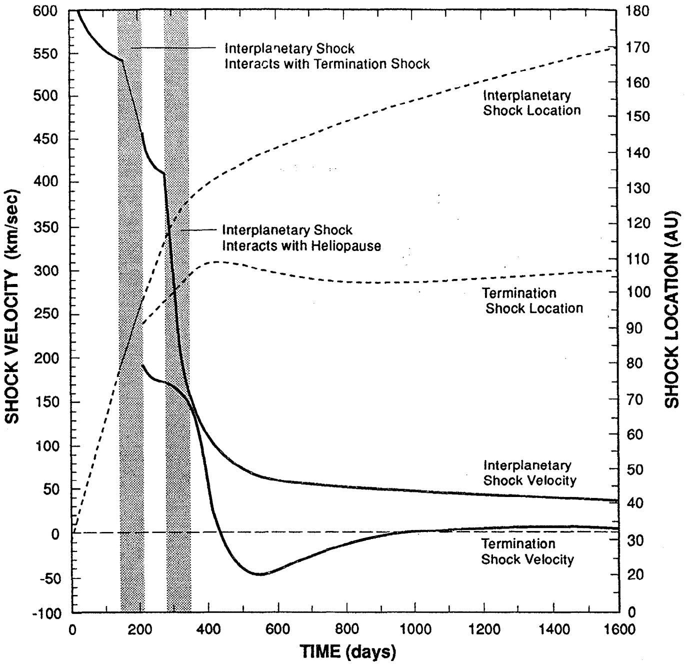

Figure 3. The temporal variation of the velocity (solid curves) and location (dashed curves) along the 0° pole of the interplanetary shock prior to and after its encounter with the termination shock and of the termination shock after it has been set in motion by the interaction with the interplanetary 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 $n_{is}=0.14$ 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, $n_{is}=0.09$ 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 1.3×10^{-11} n_{is} dynes/cm^2. 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

$$B_{is} = 1.814\sqrt{(n_{is})_{sml}-(n_{is})_{obs}} \quad ,$$

where $(n_{is})_{sml}$ 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 $(n_{is})_{sml}=0.09$ 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 $(n_{is})_{sml}=0.14$ 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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