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Transient shocks beyond the heliopause

R. L. Fermo
Department of Space Science and Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899, USA

N. V. Pogorelov
Department of Space Science and Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899, USA

L. F. Burlaga
Goddard Space Flight Center, National Aeronautics and Space Agency, Greenbelt, MD 20771, USA

Abstract.
The heliopause is a rich, dynamic surface affected by the time-dependent solar wind. Stream interactions due to coronal mass ejections (CMEs), corotating interaction regions (CIRs), and other transient phenomena are known to merge producing global merged interaction regions (GMIRs). Numerical simulations of the solar wind interaction with the local interstellar medium (LISM) show that GMIRs, as well other time-dependent structures in the solar wind, may produce compression/rarefaction waves and shocks in the LISM behind the heliopause. These shocks may initiate wave activity observed by the Voyager spacecraft. The magnetometer onboard Voyager 1 indeed observed a few structures that may be interpreted as shocks. We present numerical simulations of such shocks in the year of 2000, when both Voyager spacecraft were in the supersonic solar wind region, and in 2012, when Voyager 1 observed traveling shocks. In the former case, Voyager observations themselves provide time-dependent boundary conditions in the solar wind. In the latter case, we use OMNI data at 1 AU to analyze the plasma and magnetic field behavior after Voyager 1 crossed the heliospheric boundary. Numerical results are compared with spacecraft observations.

The Voyager spacecraft were launched in 1977 and are just now reaching the outer edges of the heliosphere and beyond. The termination shock, where the solar wind becomes subsonic, was passed by Voyager 1 in 2004 at 94 AU and by Voyager 2 in 2007 at 84 AU from the sun [1, 2, 3, 4, 5]. Between 28 July and 25 August 2012, Voyager 1 perceived a two-step increase in the galactic cosmic ray (GCR) flux, as well as intermittent drops and ultimately an exponential decay in the anomalous cosmic ray (ACR) flux [6, 7, 8]. Simultaneous jumps in the magnetic field strength were
not accompanied by a magnetic field rotation, contrary to expectations [6], but the continuous presence of GCRs from that point to the present day suggests that the 2012 crossing likely was the heliopause. Regardless, it is clear now that the heliopause is not a static boundary. A pair of shocks were observed well into the local interstellar medium (LISM) [9, 10]. Solar transients may play a role in the dynamics of the heliopause.

Two examples of such solar transients are coronal mass ejections (CMEs) and corotating interaction regions (CIRs). A coronal mass ejection is a large-scale release of plasma and magnetic field from the solar atmosphere [11, 12, 13]. Usually modeled as a helical flux rope, these structures first form in the corona but are then ejected out into interplanetary space, where they are subsequently called interplanetary coronal mass ejections (ICMEs) [14, 15, 16, 17]. In contrast, corotating interaction regions form out in the solar wind, as CIRs are created when fast solar wind pushes against regions of slow solar wind. Both CMEs and CIRs can generate shocks and act as sources of particle acceleration [18, 19, 20].

As ICMEs and CIRs propagate outwards from the sun, multiple such solar wind transients may collide with one another and form global merged interaction regions (GMIRs) [21, 22, 23, 24, 25, 26]. These are large, global-scale structures often characterized by enhanced magnetic fields and density fluctuations [22, 27, 28, 29]. However, their ultimate destiny as they approach the outer heliosphere is not yet well understood.

Numerical simulations of the propagation of time-dependent perturbations of the solar wind were first performed using a gas dynamics treatment (without magnetic field, for example) [30, 31, 32, 33, 34, 35], although later considerations included the effects of magnetohydrodynamics (MHD) [36, 37, 38, 39, 40, 41, 42, 43, 44]. The effect of GMIR-like perturbations on the magnetic field distributions in the heliosphere and beyond it in the LISM were considered in Pogorelov and Zank (2005) [45] and Pogorelov et al. (2012) [46]. One-dimensional MHD models suggest that these GMIRs and their associated shocks will have observable effects even at distances as far as Voyagers 1 and 2 [47].

In this paper, we will expand upon such one-dimensional models by simulating solar wind transients in fully three-dimensional MHD models. This will have the advantage of including heliospheric structures not present in one-dimensional models, such as the termination shock and heliopause. In Pogorelov and Zank (2005) [45], it was demonstrated in a three-dimensional MHD-neutral model that GMIRs are able to reach the heliosheath. Fig. 1, taken from Pogorelov and Zank (2005) [45], shows their propagation beyond the termination shock. However, the simulations were not executed for sufficiently long periods of time to describe their propagation through the heliopause boundary into the local interstellar medium. In this paper, we present simulations in which GMIRs are in fact able to penetrate into the LISM.

For our simulations, we use the fully three-dimensional code MS-FLUKSS [48]. The partially ionized plasma is modeled as four separate fluids: the hydrogen plasma, neutral interstellar hydrogen, neutral hydrogen from the heliosheath, and neutral hydrogen from the inner heliosphere (created from within the termination shock). The governing equations for the plasma fluid are the standard ideal magnetohydrodynamics (MHD) equations

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]
Figure 1. Variations in the magnetic field strength (µG) in the meridional plane (axes in AU) as a GMIR propagates towards the heliopause. Courtesy of Pogorelov and Zank (2005), Fig. 2 [45].

\[
\begin{align*}
\frac{\partial \rho v}{\partial t} + \nabla \cdot \left( \rho v v - \frac{\mathbf{B} \mathbf{B}}{4\pi} \right) + \nabla p &= H_{\rho-H}^m \\
\frac{\partial e}{\partial t} + \nabla \cdot \left( (e + p) v - \frac{\mathbf{B}(v \cdot \mathbf{B})}{4\pi} \right) &= H_{\rho-H}^e \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (v \mathbf{B} - \mathbf{B} v) &= 0
\end{align*}
\]

which are the conservation laws for mass, momentum, energy, and magnetic flux,
respectively. Likewise, the Euler gas dynamic equations

\[
\frac{\partial \rho_i}{\partial t} + \nabla \cdot \rho_i \mathbf{v}_i = H_{H-p,i}^d
\]

\[
\frac{\partial \mathbf{v}_i}{\partial t} + \nabla \cdot \rho_i \mathbf{v}_i \mathbf{v}_i + \nabla p_i = H_{H-p,i}^f
\]

\[
\frac{\partial e_i}{\partial t} + \nabla \cdot (e_i + p_i) \mathbf{v}_i = H_{H-p,i}^e
\]

govern the evolution of the neutral fluids. Here, \( \rho \) is the density, \( \mathbf{v} \) the flow speed, \( p \) the pressure, \( e \) the total energy density, \( \mathbf{B} \) the magnetic field, and \( t \) the time. The subscripts \( i \) correspond to each individual neutral population. The source terms \( H_{p-H} \) and \( H_{H-p,i} \) regulate the rate of charge exchange between protons and the various neutral hydrogen populations.

The inner boundary conditions are obtained from OMNIweb, which cross compares in situ data from several spacecraft in geocentric or L1 orbits, such as ISEE, Wind, and ACE. The resulting 1-hour averaged plasma and magnetic field data are taken as the inner boundary at 1 AU. The magnetic field strength from OMNI is used in conjunction with the solar tilt angle data from the Wilcox Solar Observatory (WSO) to fit to a Parker spiral solution for the solar wind at 1 AU. The outer boundary conditions at \( r = 1000 \) AU are taken from the parameters of the LISM consistent with McComas et al. (2015) \[49\]: \( n = 0.08 \) cm\(^{-3}\), \( n_1 = 0.175 \) cm\(^{-3}\), \( v = -26.4 \) km/s, \( B = 3.0 \) \( \mu \)G, \( T = 8000 \) K.

Before performing the time-dependent simulation, we set up a steady-state solution from the solar wind conditions in early 2004 and run the code for approximately 3000 solar rotations. This allows the system to self-consistently generate the basic heliospheric structures, most importantly the termination shock and the heliopause. This steady-state solution is used as the initial condition from early 2004.

In our time-dependent run, solar transients such as CMEs and CIRs during our simulation period will be seen as density and magnetic field enhancements at 1 AU, as reflected by the OMNI observational data. These fluctuations will propagate from 1 AU outwards towards the outer heliosphere. Fig. 2 shows the density in the meridional plane at several times. Fig. 2(a) shows the density at the beginning of the simulation. The ripples within the termination shock of Fig. 2(b) are solar transients such as CMEs or CIRs which were observed in the OMNI data and are propagated out from 1 AU. The color scale has been adjusted in Fig. 2(c) to accentuate the ripples in the heliosheath, where the GMIRs slow down and begin to pile up. The color scale has been adjusted once again in Fig. 2(d) to make more visible the fluctuations in the LISM. The attached multimedia file density.mp4 in the online version of this publication shows more clearly the outward propagation of these structures through and beyond the termination shock and heliopause.

Two straight lines in Fig. 2 roughly show the directions of the trajectories of the two Voyager spacecraft projected onto the meridional plane. The ripples in density and magnetic field should therefore be seen in cuts along the Voyager 1 and 2 trajectories. Figs. 3(a) and (b) show the density profiles along the Voyager 1 and 2 trajectories, respectively, on 29 October 2012. Likewise, Fig. 3(c) and (d) show the respective profiles
Figure 2. The plasma density (cm$^{-3}$) in the meridional plane (axes in AU) at various times, including (a) the steady-state solution from which the time-dependent simulation begins on 10 March 2004. Note that the other three plots show the plasma density at different color scales, in order to accentuate the GMIRs (b) within the termination shock on 28 May 2005, (c) in the heliosheath on 16 February 2010, and (d) in the LISM on 29 October 2012.
Figure 3. The plasma density (in cm$^{-3}$) on 29 October 2012 along the trajectories (radial distance in AU) of (a) Voyager 1 and (b) Voyager 2, and the magnetic field strength (in $\mu$G) along the trajectories of (c) Voyager 1 and (d) Voyager 2.

for the magnitude of the magnetic field along the Voyager 1 and 2 trajectories on the same date. As before, the outward propagation of these structures along the Voyager 1 trajectory is best observed in the attached multimedia files $V1$-$logN$.mp4 and $V1$-$logB$.mp4 in the online version of this publication. We see that enhancements in the density and magnetic field which can be associated with GMIRs are able to cross the termination shock, slow down and pile up in the heliosheath, and are even able to cross the heliopause into the local interstellar medium.

We compare these to a pair shocks observed by Voyager 1. In Fig. 4, a figure taken from Burlaga et al. (2014) [10], Voyager 1 crossed a transition region $T$ from the solar
Figure 4. Daily averages from Voyager 1 of the observed (a) magnetic field strength $B$ (nT), (b) azimuthal angle $\lambda$ (°), and (c) elevation angle $\delta$ (°) between 1 January 2012 and 30 May 2014. The current sheet $T$ is now believed to be the heliopause. Two shocks were observed following the heliopause crossing, labeled $FS$ and $. Courtesy of Burlaga et al. (2014), Fig. 1 [10].

wind into the LISM. Following that, the spacecraft encountered two shocks, labelled $FS$ and $. The former was associated with a jump in the magnetic field strength $\Delta B_{FS} = 0.2$ nT, the latter with a slight decrease of $\Delta B_t = -0.031$ nT, although neither was accompanied by a noticeable rotation in the magnetic field, consistent with the $T$. The first shock was observed on 30 November 2012, the second on 8 May 2013, for a separation $\Delta t = 160$ days.

Consider now that, based on the local parameters observed by Voyager 1, one may calculate the local Alfvén speed $v_A = 38$ km/s, the local sound speed $v_s = 17$ km/s, and consequently the magnetosonic speed $v_{ma} \approx \sqrt{v_A^2 + v_s^2} \approx 42$ km/s, which we use as a lower limit for the shock speed $v_{shock} \gtrsim v_{ma}$. Using the Voyager 1 speed $v_{V1} = 3.6$ AU/year, we can subsequently calculate a lower limit for the shock separation distance $\Delta x = (v_{shock} - v_{V1})\Delta t \gtrsim 2.1$ AU.

Table 1 shows a direct comparison between the observed shock parameters calculated here and the same observed in the GMIR fluctuations seen in the simulations. In the latter case, the shock jumps $\Delta B$ and shock separation $\Delta x$ are computed as in the intervals shown in Fig. 3(a) for GMIR fluctuations after they have crossed the heliopause. The range of values provided represents an aggregate of GMIR fluctuations over the course of the simulation along the Voyager 1 and 2 trajectories. The magnetic field jumps $\Delta B$ observed across the shocks are comparable to those seen in the simulations. The observed shock separation distance $\Delta x$ is slightly smaller than those seen in the simulations, although it is quite feasible that this gap can be bridged by increasing the resolution in the simulations. The shock speed in the simulations, calculated roughly
as the distance traversed by the crest of GMIR fluctuations after having crossed the heliopause divided by the transit time, appears to be slower than the calculated lower limit based on the observed magnetosonic speed $v_{ma}$. This could perhaps be attributed to the incorrect distance in the simulation of the heliopause, which has been pushed out to $140-150$ AU, roughly $20-30$ AU farther out than where it was observed by Voyager.

### Table 1. Comparison of shock parameters

| Shock parameter       | Observed by Voyager 1 | MHD simulations |
|-----------------------|-----------------------|-----------------|
| Shock jump $\Delta B$| $0.03 - 0.2$ nT       | $0.01 - 0.12$ nT|
| Shock separation $\Delta x$ | $\gtrsim 2.1$ AU       | $3 - 15$ AU     |
| Shock speed $v_{shock}$ | $\gtrsim 42$ km/s     | $28 - 33$ km/s  |

We therefore present GMIRs as a feasible explanation for the shocks observed by Voyager 1 beyond the heliopause. A fully three-dimensional MHD model of the heliosphere shows that the density and magnetic field enhancements associated with GMIR signatures should have observable effects at the location of Voyager 1, fairly consistent with those seen in reality. Further work is needed, however, with higher resolution simulations and a more realistic heliopause location. This will lessen the effects of heliopause and shock broadening and likely increase the correspondence between the simulations and observed shock parameters. Subsequent simulations should better reflect termination shock and heliopause distances, north-south asymmetries, and shock physics. Furthermore, future simulations will enable timing tests to demonstrate when precisely we would expect to see certain solar transients observed at 1 AU to reach the Voyager 1 spacecraft. This was accomplished by Liu et al. (2014) [47] using a one-dimensional MHD model, but a fully three-dimensional model that incorporates the termination shock, heliosheath, and heliopause at their observed locations will increase the predictive capability. Another important question is the nature of these fluctuations in the magnetic field, whether they represent the GMIRs themselves or if the jumps in magnetic field are in fact foreshocks or reverse shocks related to the GMIRs. Further study of the plasma parameters near these magnetic field jumps at higher resolution will help in identifying these structures.

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