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THE INTERACTION OF AN INTERPLANETARY SHOCK WITH THE EARTH'S BOW SHOCK AND MAGNETOPAUSE

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Abstract. We compare numerical results of a global magnetospheric MHD code with results of a 3-D MHD magnetosheath model for the interaction of an interplanetary shock with the bow shock and magnetopause. We estimate the accuracy of the modeling using the Rankine-Hugoniot conditions. We demonstrate that the numerical solutions are rather accurate, and the errors are caused mainly by a low grid resolution.

1. Introduction

An interplanetary shock (IS) is usually a sharp increase of the solar wind density, velocity and magnetic field magnitude corresponding to a fast shock in the MHD theory. Striking the magnetosphere, the shock results in a sudden impulse or a sudden commencement in ground magnetograms [e.g. *Araki*, 1994]. To study carefully the interaction of IS with the magnetosphere one may consider how the initial IS will evolve:

- After interaction with the bow shock (BS)
- During propagation through the magnetosheath
- After interaction with the magnetopause (MP)
- During propagation inside the magnetosphere (and, in particular, due to interaction with the plasmapause).

Since the BS is a reverse fast shock and the MP usually corresponds to a tangential discontinuity, the interactions IS-BS and IS-MP can be described using the Rankine-Hugoniot (R-H) conditions [*Ivanov,* 1964; *Dryer,* 1973; *Grib et al.,* 1979]. The R-H conditions give a precise solution based on the MHD theory. In a hydrodynamic solution, interaction between two shocks (forward and reverse) results in the modified two shocks and a contact discontinuity between them. The situation is more complicated in the MHD approach where from three to seven MHD discontinuities may result from the interaction IS-BS depending on the orientations of the shock normals and the interplanetary magnetic field (IMF) [*Pushkar et al.,* 1991].

Using numerical MHD models, one gets an approximate solution which may include modeling and discretization errors. However now only MHD models can give a self-consistent three-dimensional (3-D) solution and describe both the interactions IS-BS and IS-MP, and the propagation of IS through the magnetosheath and in the magnetosphere. The problem is to control the accuracy of the numerical models and to understand the limits of their applicability. In this paper, we want to compare predictions of two numerical 3-D MHD models with precise solutions obtained by the R-H conditions for the interactions IS-BS and IS-MP.

2. Interaction between interplanetary shock and the bow shock

Generally magnetospheric MHD codes can be divided into global ones, which include all regions from the supersonic solar wind to the inner magnetosphere, and local ones, which simulate local regions with more or less homogeneous plasma and magnetic field conditions. We will compare results of the global BATS-R-US code [*Powell et al.,* 1999; *Gombosi et al.,* 2003; *De Zeeuw et al.,* 2004], hereafter Model 1, and of the local magnetosheath 3-D MHD model [*Samsonov,* 2006; 2007], hereafter Model 2. We impose variations through the IS in the supersonic solar wind corresponding to a forward fast shock in agreement with the R-H conditions (see first line in Table 1). The angle between the IMF and flow velocity is 45 degrees before the IS, the velocity is directed along the GSM OX axis, and the IMF lies in the XY plane. According to the R-H conditions along the Sun-Earth line [*Grib*, 1982], and numerical results from the 1-D MHD model [*Yan and Lee,* 1996] and from the 3-D MHD model [*Samsonov et al.,* 2006], the interaction IS-BS with such an angle between **B** and **V** results in a forward fast shock (FS), a forward slow expansion wave (SEW), a contact discontinuity (CD), a reversed slow shock (SS), and a modified BS. *Samsonov et al.* [2006] noted that the SEW, CD, and SS propagate with similar velocities through the magnetosheath. Therefore they can not be distinguished in the 3-D simulations and (probably) in the observations. Table 1 shows velocities of the discontinuities and jumps of MHD parameters through the discontinuities obtained from Model 2.

Using these values, we can check the conservation of mass, pulse, energy as well as other R-H conditions through the discontinuities. Comparing upstream and downstream values for the conservative variables (mass, pulse, energy), we find that relative errors (i.e. $|X_u\text{-}X_d|/ X_u$) do not exceed 3-4 percent.

Table 1. Velocities of discontinuities in the Earth's frame V_{sh} and values of MHD parameters upstream and downstream of discontinuities at the Sun-Earth line obtained in the simulations with Model 2. IS is the initial interplanetary fast shock in the solar wind, FS is the modified forward shock after the IS-BS interaction, CD+ is the combination SEW-CD-SS, BS is the modified bow shock.

	V_{sh}, km/s	ρ_u/ρ_d cm^{-3}	$B_{\tau u}/B_{\tau d}$ nT	T_u/T_d 10^6 K	V_{xu}/V_{xd} km/s
IS	594	5/14.2	3.5/10.7	0.24/0.92	400/525
FS	447	18/32	20/33	3.70/5.61	58/221
CD+	245	32/41	28/33	5.71/4.06	245/245
BS	119	14.2/41	11/32	0.96/3.91	524/259

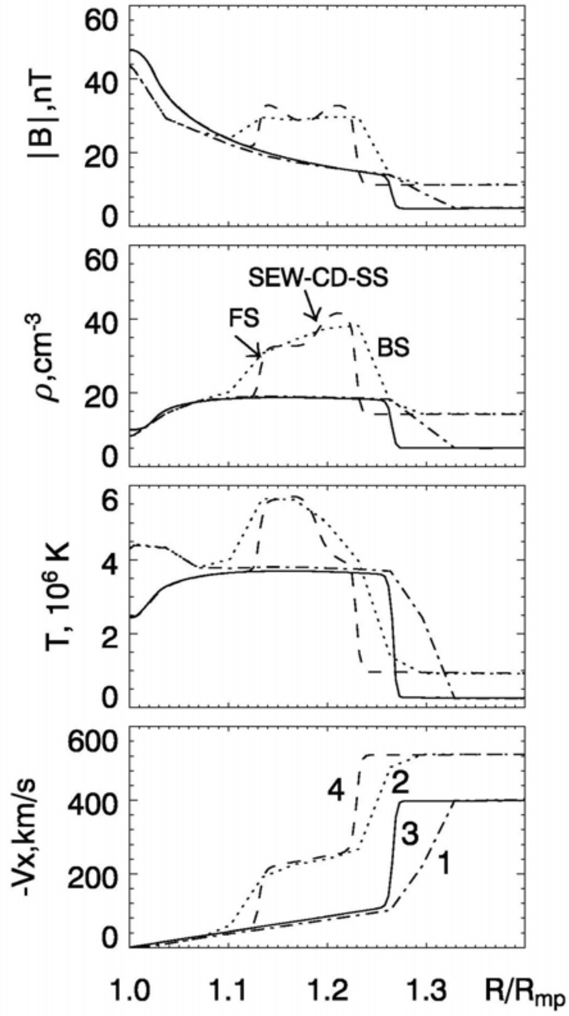

Fig. 1. Numerical results from Model 1 (lines 1, 2) and Model 2 (lines 3, 4) along the Sun-Earth line. Lines 1 and 3 correspond to the initial state before the interaction; lines 2 and 4 show a state after the interaction. The radial distance is normalized to the subsolar magnetopause distance. The forward fast shock FS and the discontinuities SEW-CD-SS move leftward, toward the magnetopause.

For example, $X_u=\rho_u(V_{sh}-V_{xu})$ and $X_d=\rho_d(V_{sh}-V_{xd})$ for the conservation of the mass. Existence of small errors is reasonable, because the limited spatial resolution in the 3-D simulation prevents us from determining the precise upstream and downstream parameters.

Figure 1 allows us to compare the results from Models 1 and 2. The initial state shown by lines 1 and 3 represents quasi steady-state solutions obtained for constant solar wind conditions. Lines 2 and 4 show parameters shortly after the IS-BS interaction. It is clear that the difference of the predictions of Model 1 from the predictions of Model 2 is caused by a lower spatial resolution or equivalently by a larger numerical viscosity in Model 1. However, Model 1 gives nearly the same jumps of parameters through the FS and the BS. The SEW-CD-SS is a relatively weak discontinuity, therefore the corresponding variations in Model 1 are very smooth. Moreover, Model 1 predicts smaller magnetic field strengths and larger temperatures than Model 2 near the magnetopause (on the left side of the Figure), and this may be a consequence of magnetopause magnetic reconnection in Model 1 because the magnetic field rotates 90˚ at the subsolar point.

3. Interaction between interplanetary shock and the magnetopause

Only Model 1 gives a self-consistent description of the FS-MP interaction. We compare predictions of the global MHD model with the results obtained by the R-H conditions below. As usual, the magnetopause is assumed to be a tangential discontinuity (TD). Using the R-H equations for typical conditions in the outer magnetosphere and magnetosheath, *Grib et al.* [1979] found that the interaction FS-TD results in a FS transmitted into the magnetosphere, a modified TD, and a fast expansion wave (FEW) reflected into the magnetosheath. Our analysis confirms this conclusion, but we note that the FEW is usually a weak discontinuity and may barely reach the bow shock moving opposite to the bulk flow (see *Samsonov et al.*, 2006).

Figure 2 shows results of Model 1 at two times: when the FS nearly reaches the MP (solid lines) and then 15 s later when the FS propagates into the magnetosphere (dashed lines). Arrows show motion of the FS, MP, and BS with respect to the Earth. Note that the global model predicts a high density (up to 30 cm^{-3}) and a low temperature (~ 10^6 K) inside the magnetosphere which results in a smaller FS velocity in the magnetosphere than that which occurs in reality. The numerical results obviously show the moving FS and MP, but it is nearly impossible to see the reflected FEW. Solving the R-H equations with the same upstream-downstream conditions, we find that the FEW should indeed be extremely weak in this case. Generally the numerical results agree with the solution of the R-H equations. We determined the discrepancy between the upstream and downstream values for the conservative MHD variables, as in the previous section. The relative errors for the FS in the magnetosphere do not exceed 10 percent. However it is rather difficult to make the same analysis for the MP and FEW, because of the low accuracy in determining the velocity of the discontinuities in the simulation.

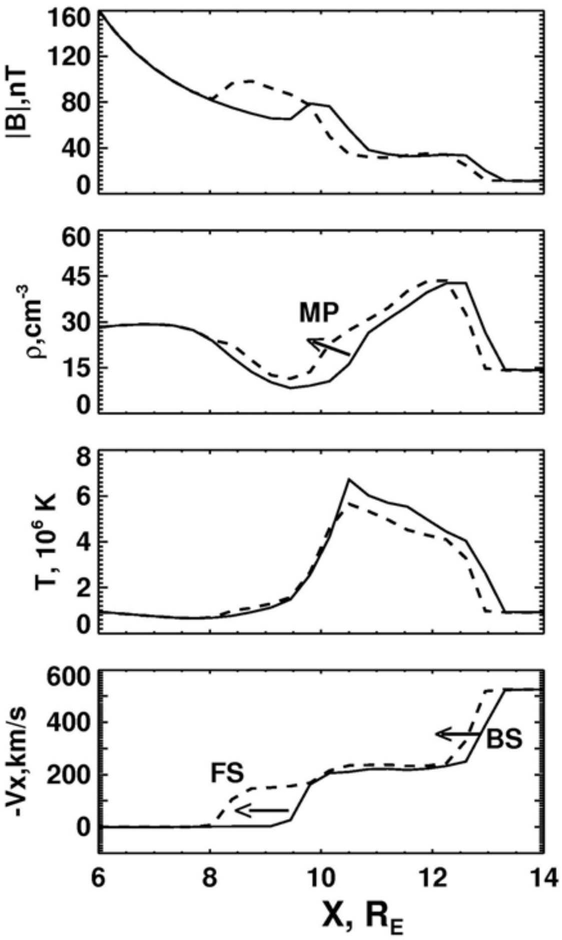

Fig. 2. Numerical results from Model 1 along the Sun-Earth line illustrate the interaction of the FS with the MP. Solid lines correspond to the moment when the FS nearly reaches the MP, dashed lines show conditions 15 s later when the FS propagates into the magnetosphere.

4. Conclusion

Studying the interactions of IS with the BS and MP, we compare the numerical results of the global BATS-R-US model and of the 3-D MHD local magnetosheath model. We control the accuracy of the numerical predictions using the R-H conditions. We find that the numerical results satisfy the conservative equations for mass, pulse and energy. Small errors result from insufficient spatial resolution in the 3-D simulations, since we can not determine accurately all upstream and downstream parameters, and velocity of discontinuities. The errors seem to be fewer in the local magnetosheath model, however this model gives a self-consistent description only for the IS-BS interaction. Although we study a run of the global MHD code with an increased spatial resolution near the Sun-Earth line (the minimal grid spacing is 0.125 R_E), all discontinuities are strongly smoothed in the simulation. While variations through the FS and BS are well determined, the SEW-CD-SS is observed only as a smooth increase of the density and a decrease of the temperature slowly propagating across the magnetosheath. The FEW, which appears after the IS-MP interaction, is too weak to be observed in the simulation.
Finally, we conclude that the global and local MHD codes can be used for modeling the IS – magnetosphere interaction, but one should carefully control the accuracy of numerical predictions.

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