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Stationary slow shocks in the magnetosheath for solar wind conditions with $\beta < 2/\gamma$: Three-dimensional MHD simulations

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Abstract. Magnetohydrodynamic simulation results are presented of three-dimensional bow shock flows around a conducting paraboloid surface. For upstream parameter values for which switch-on shocks occur, a stationary secondary shock of slow type is formed which follows the leading shock front and is attached to it. These results may have direct implications for the structure of the flow in the Earth's magnetosheath. They offer a physically attractive explanation for the possible observation of stationary slow shocks in the magnetosheath and in the distant magnetotail region.

1. Introduction

In supersonic flow of a neutral fluid around a blunt body a bow shock is formed. This bow shock separates the upstream supersonic region from the downstream subsonic region immediately in front of the object. In a similar way a bow shock forms in a superfast magnetohydrodynamic (MHD) flow of a conducting fluid around a blunt body. In the MHD case, however, the leading shock front can, in principle, be followed by secondary shock fronts of slow or intermediate type in the flow region downstream of the leading shock front. This can be understood in terms of the properties of MHD waves and shocks.

The dynamical evolution of a neutral fluid is described by the hydrodynamic equations, which allow for one linear wave mode with isotropic sound speed c. A hydrodynamic shock connects a supersonic state to a subsonic state. A conducting fluid is described by the MHD equations [*Landau and Lifshitz*, 1984], which allow for three linear wave modes. The (positive) wave speeds of the fast, Alfvén, and slow waves are represented by c_f, c_A, and c_s, respectively. MHD waves are anisotropic because the wave speeds strongly depend on the angle between the direction of propagation and the magnetic field $\vec{B}$. For any direction n, it holds that $c_f^{(n)} \geq c_A^{(n)} \geq c_s^{(n)}$. In MHD, there exist three types of shocks: the fast, intermediate, and slow shocks. A fast shock connects a state of superfast flow with a subfast but super-Alfvénic state. A slow shock is a transition from a superslow but sub-Alfvénic state to a subslow state. Intermediate shocks connect a super-Alfvénic state to a sub-Alfvénic state. There exist several different types of intermediate shocks, because the super-Alfvénic upstream state can be superfast or subfast, and the sub-Alfvénic downstream state can be superslow or subslow. Fast shocks refract the magnetic field away from the shock normal in going from the upstream to the downstream state, while the magnetic field strength increases. Slow shocks refract the field towards the normal, while the magnetic field strength decreases. Intermediate shocks flip the magnetic field over the normal, such that the component of the magnetic field tangential to the shock front changes sign. A switch-on shock is a limiting case of a fast shock, for which the upstream magnetic field is normal to the shock surface, while the magnetic field makes a finite angle with the normal in the downstream state. The plasma β is defined as $\beta = 2p/B^2$, where p is the thermal pressure and B is the magnitude of the magnetic field. Switch-on shocks cannot arise when $\beta > 2/\gamma$ [*Kennel et al.*, 1989]. A switch-off shock is a limiting case of a slow shock, for which the downstream magnetic field is normal to the shock surface, while the magnetic field makes a finite angle with the normal in the upstream state. The upstream normal Alfvénic Mach number $M_A^{(n)} = |v^{(n)}|/c_A^{(n)}$ — with n the direction normal to the slow shock front — equals one for a switch-off shock.

In a superfast MHD flow of a conducting fluid around a blunt body a bow shock is formed. The state upstream of this shock is superfast. The downstream flow is subfast, but can still be super-Alfvénic or superslow, such that in theory Alfvén waves or slow waves can steepen into secondary shocks in the region downstream of the leading shock. Downstream of the leading shock

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front, secondary shock fronts of slow or intermediate type can thus in principle be present and stationary secondary shocks may be necessary to channel the flow around the object in some parameter regimes. Such stationary secondary shocks have been found recently in two-dimensional (2-D) MHD bow shock flow simulations for upstream parameter values for which switch-on shocks occur [*De Sterck et al.*, 1998, 1999; *De Sterck and Poedts*, 1999] but have not yet been identified in three-dimensional (3-D) MHD bow shock flows [*Song and Russell*, 1997]. In this brief report we show preliminary simulation results of stationary 3-D MHD bow shock flows. We show that for upstream parameter values for which switch-on shocks occur, a stationary secondary shock of slow type follows the leading shock front and is attached to it.

The problem of superfast MHD flow around an object is relevant for the case of solar wind flow around planets [*Petrinec and Russell*, 1997]. Therefore we present simulations performed in the context of the solar wind flow around the Earth. As sketched in Figure 1, the magnetopause separates the magnetospheric region close to the Earth where the magnetic field is of terrestrial origin, from the region where the magnetic field is of solar wind origin. The region between the bow shock and the magnetopause is called the magnetosheath. The flow of the solar wind around the Earth can most accurately be modeled taking into account the magnetosphere and the ionosphere [see, e.g., *Raeder et al.*, 1998, and references therein], but for our purpose of investigating the flow in the magnetosheath behind the bow shock, we can as a first approximation study the flow around a perfectly conducting paraboloid which models the magnetopause [*Wu*, 1992; *Cable and Lin*, 1998].

The solar wind flow is most of the time almost radial along the Sun-Earth line, so for simplicity, we align the velocity of the incoming plasma with the Sun-Earth

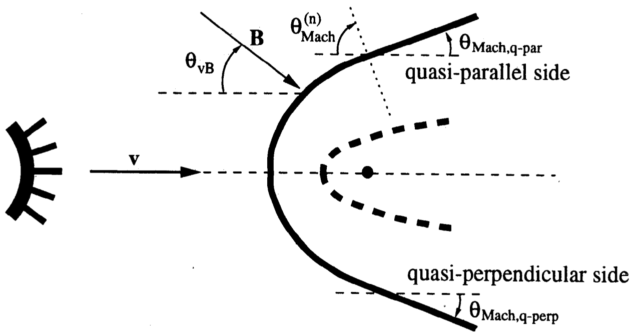

Figure 1. Sketch of the flow of the solar wind around the Earth. We model the magnetopause (thick dashed) as a conducting paraboloid. The bow shock is thick solid. $\theta_{Mach,q-par}$ is the Mach angle on the quasi-parallel side of the bow shock, where the magnetic field is close to parallel to the shock normal. $\theta_{Mach,q-perp}$ is the Mach angle on the quasi-perpendicular side. $\theta^{(n)}_{Mach}$ is the normal Mach angle on the quasi-parallel side.

line and with the symmetry axis of the paraboloid. The magnetic field $\vec{B}$ makes an angle θ_{vB} with the velocity $\vec{v}$ in the uniform upstream flow. For definiteness we think of the magnetic field as lying in the ecliptic plane, but a field rotated out of that plane would simply make the solutions presented below rotate around the Sun-Earth line. This flow problem has three independent free upstream parameters, for which we choose the Mach number $M = v/c$, with c the sound speed, the plasma β, and the angle θ_{vB}. We simulate the 3-D bow shock flows starting from a uniform initial condition and by advancing the time-dependent MHD equations with $\gamma = 5/3$ until a steady state solution is reached. See *De Sterck et al.* [1998] for the ideal MHD equations and for a description of the numerical technique used. The simulations are performed on stretched polar-like structured grids with $30 \times 60 \times 30$ or $60 \times 120 \times 60$ cells. In this brief report, simulation results are presented for a limited choice of inflow parameter values in the switch-on regime, and we make a preliminary assessment of the relevance for observed magnetosheath flows. A more complete analysis will be presented in a forthcoming paper (H. De Sterck and S. Poedts, Slow shocks and space weather: 3-D MHD simulations of the Earth's bow shock and magnetosheath, submitted to the *J. Atmos. Solar-Terr. Phys.*, 1999).

2. Simulation Results

Figure 2 shows simulation results of a 3-D bow shock flow with inflow $\beta = 0.4$ and $M = 2.6$, for $\theta_{vB} = 5°$ and $\theta_{vB} = 15°$. Units are expressed in Earth radii R_E, and the approximate size and location of the Earth is indicated by a circle in the origin of the coordinate system. The distance between the Earth and the magnetopause is taken as $10\,R_E$ along the Sun-Earth line, and $17\,R_E$ in the direction perpendicular to this line. It can clearly be seen that the leading shock front is followed by a secondary shock front, which is attached to the leading front. The secondary shock front is of slow type, as is shown in Figure 3, which represents a cut along the thick line indicated in Figure 2b perpendicular to the secondary shock front. Going from left to right in Figure 3, the density, pressure, and magnetic field strength first increase when the leading fast shock is passed. At the second discontinuity, the density and the pressure rise, whereas the magnetic field strength decreases sharply. This is a clear signature of a slow shock. This diagnosis is confirmed by the normal Mach number plots of Figures 3d-3f. The flow is superslow but sub-Alfvénic upstream from the secondary shock, and subslow downstream. The shock is thus a slow shock. The upstream Alfvénic Mach number is very close to one, however, so the shock is very close to a slow switch-off shock. The magnetic field lines in Figure 2b switch back strongly in the vicinity of the slow shock near the magnetopause. The component of the magnetic field tangential to the shock surface $B^{(t)}$ is almost switched

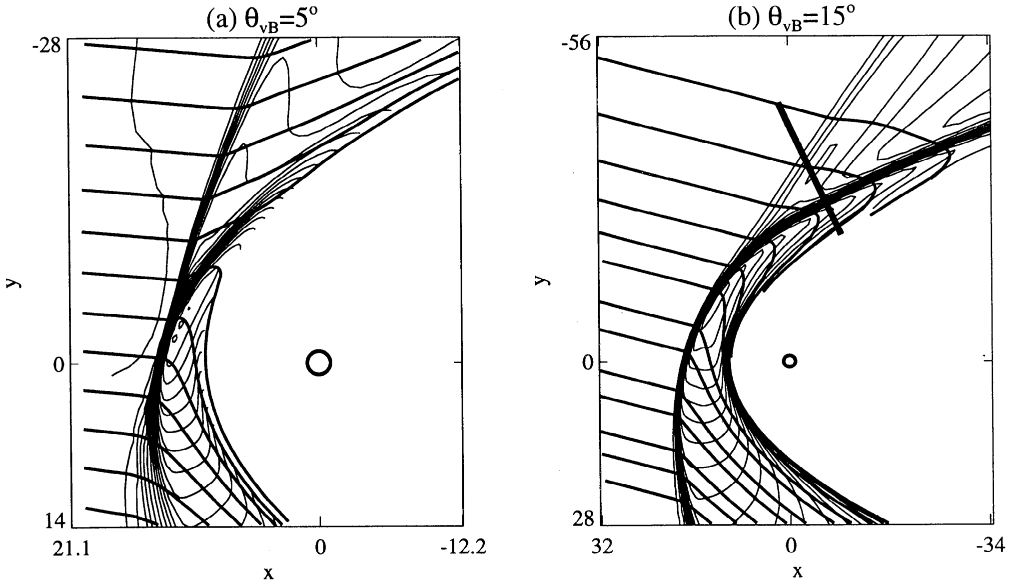

Figure 2. Three-dimensional bow shock flows around a paraboloid surface with inflow $\beta = 0.4$ and $M = 2.6$. Density contours and field lines in the ecliptic plane.

off at the shock itself, such that the field lines become almost parallel to the shock normal downstream of the shock. The shock is followed by a strong rarefaction wave, in which the magnetic field rotates further.

Figure 4 is a 3-D visualization of the flow of Figure 2b and shows how the secondary shock extends away from the ecliptic plane up to $z \sim 15\ R_E$.

3. An Explanation: Switch-On Shocks

For the 3-D flow configuration discussed in Section 2 the condition for the occurrence of switch-on shocks can be written as

$$M_- = \frac{1}{\cos\theta_{vB}}\sqrt{\frac{2}{\gamma\beta}} < M$$

$$< M_+ = \frac{1}{\cos\theta_{vB}}\sqrt{\frac{2}{\gamma\beta}}\sqrt{\frac{\gamma(1-\beta)+1}{\gamma-1}}, \qquad (1)$$

with $M = v/c$ and v the total magnitude of the velocity [*Kennel et al.*, 1989; *De Sterck et al.*, 1998]. Switch-on shocks cannot arise for $\beta > 2/\gamma = 1.2$. In Figure 5 the switch-on parameter regime in the θ_{vB}–M plane is indicated for various values of β. For a given value of θ_{vB}, switch-on shocks can arise for values of M between M_- and M_+ (corresponding to the two solid lines). The Mach number has to be higher than $M_0 = c_f/c$ (dotted line), with c_f the fast MHD speed along the Sun-Earth line, because the inflow along the Sun-Earth line has to be superfast to have a fast bow shock. The limit $M = M_-$ corresponds to $\theta_{vB} = \theta^{(n)}_{Mach}$ (Figure 1).

The reader can verify that the parameter values for the simulation results shown in Section 2 were taken in the switch-on regime, with $M_- < M < M_+$ (Equation (1)). We have performed many more simulations with parameter values in the switch-on regime, and in the resulting flows we have always obtained a secondary slow shock front following the leading front and attached to it. This is analogous to the case of 2-D field-aligned flow [*De Sterck et al.*, 1998, 1999; *De Sterck and Poedts*, 1999], where a secondary slow shock was obtained for

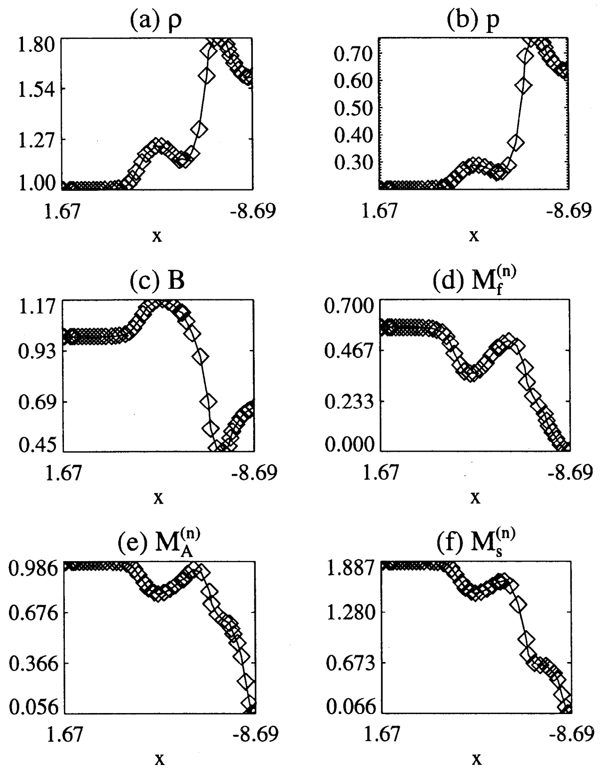

Figure 3. Cut along the thick solid line in Figure 2b, normal to the secondary slow shock front.

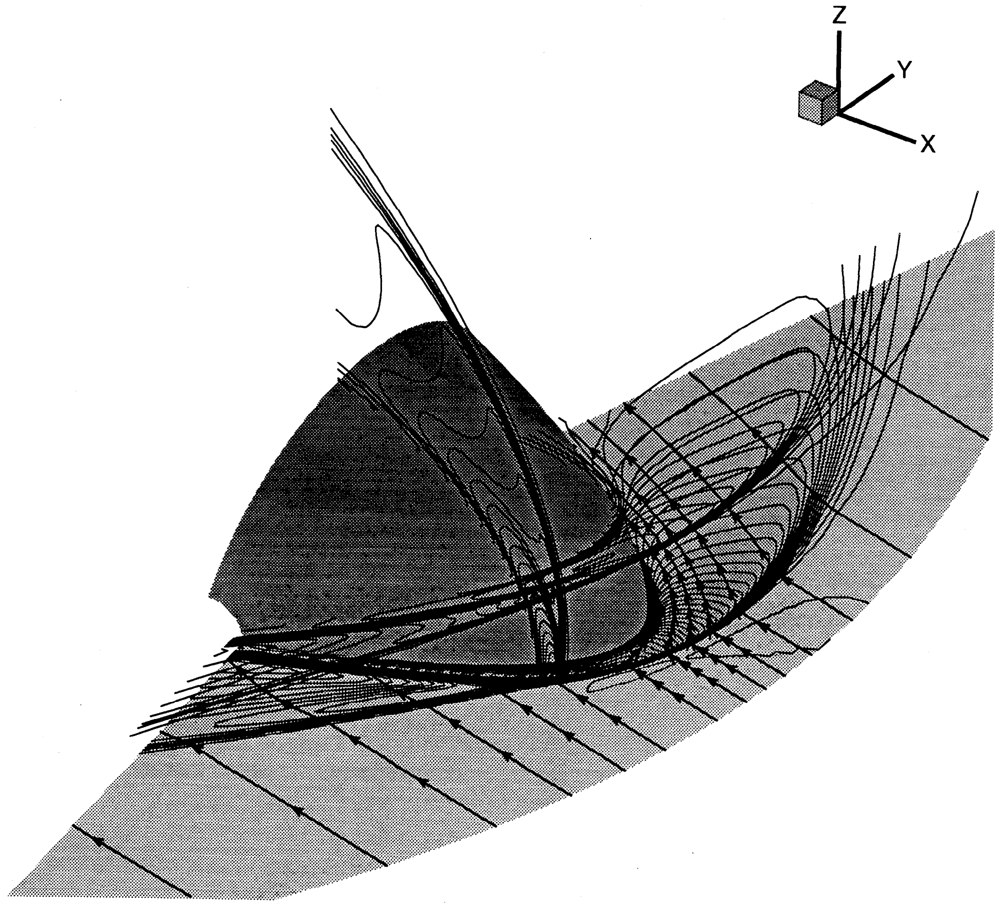

Figure 4. Three-dimensional visualization of the flow of Figure 2b. Density contours and magnetic field lines are shown in the shaded ecliptic plane. Density contours are also drawn in two additional planes. This shows that the secondary slow shock extends well out of the ecliptic plane.

parameter values in the switch-on regime (Equation (1) with $\theta_{vB} = 0$). The secondary slow shock is required because of the geometrical properties of switch-on shocks, as can be deduced from the same reasoning as the one used in the 2-D case [*Steinolfson and Hundhausen*, 1990; *De Sterck et al.*, 1998]. We have shown results here for flows around a paraboloid surface, but we have obtained qualitatively similar conclusions for the flow around a conducting sphere. All these points will be discussed in more detail in a forthcoming paper (H. De Sterck and S. Poedts, Slow shocks and space weather: 3-D MHD simulations of the Earth's bow shock and magnetosheath, submitted to the *J. Atmos. Solar-Terr. Phys.*, 1999).

Another important point is that the leading shock fronts in Figures 2a and 2b contain segments of stationary intermediate shocks. There has been much discussion about the physical existence of intermediate shocks [e.g., *Wu*, 1991; *Freistuehler*, 1998; *Myong and Roe*, 1997; *De Sterck et al.*, 1998]. Our present results seem to be the first confirmation that stationary intermediate MHD shocks can exist in realistic 3-D flows, which is consistent with recent theoretical results on the existence of those shocks. The analysis of this topic is beyond the scope of this paper, however.

4. Discussion

The simulation results presented in Section 2 show that secondary slow shocks exist in 3-D MHD flow around an object for parameter values in the switch-on regime. This is a remarkable result on its own and an extension of the 2-D results obtained by *De Sterck*

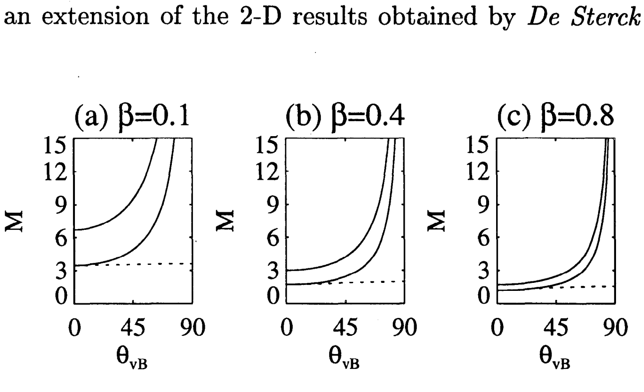

Figure 5. Switch-on parameter regime for various values of β when the field is not aligned to the flow.

et al. [1998, 1999] and *De Sterck and Poedts* [1999]. It may apply to shocks induced by fast solar coronal mass ejections [*De Sterck et al.*, 1998; *Steinolfson and Hundhausen*, 1990]. It may also have direct implications for the structure of the flow in the Earth's magnetosheath under switch-on solar wind conditions. Indeed, the observation of slow shocks has been claimed in the dayside magnetosheath and in the distant magnetotail region. *Song et al.* [1990, 1992] and *Song and Russell* [1997] claim the existence of density enhancements of slow mode type in front of the dayside magnetopause in more than 50% of ISEE1 and ISEE2 passes. The slow mode structures were interpreted as slow shock fronts, and a Rankine-Hugoniot analysis of one example lead to upstream Mach numbers $M_A^{(u)} = 1.17$ and $M_s^{(u)} = 1.38$ and to downstream Mach numbers $M_A^{(d)} = 0.93$ and $M_s^{(d)} = 1.00$ [*Song et al.*, 1992]. Note that these Mach numbers are taken in the direction normal to the slow shock but that we have dropped the superscript (n) here. These values are close to the values of a slow switch-on shock, for which $M_A^{(u)} = 1$ and $M_s^{(u)} > 1$, and $M_A^{(d)} = M_s^{(d)} < 1$. It turns out that the secondary slow shock in Figure 2b has Mach numbers in a similar range: $M_A^{(u)} = 0.99$ and $M_s^{(u)} = 1.6$, and $M_A^{(d)} = 0.65$ and $M_s^{(d)} = 0.65$. This suggests that the slow shocks observed by Song et al. may be of the same type and origin as the slow shock in Figure 2b.

However, this suggestion remains speculative because of several reasons. The solar wind often has a high plasma β, and switch-on shocks do not occur for $\beta > 1.2$. We have made a preliminary analysis of three arbitrarily chosen months of ACE [*Stone et al.*, 1998] solar wind satellite data (July 1998, and January and February 1999) and have found that for each of these months the solar wind averaged over 5-min time intervals was in the switch-on regime (Equation (1)) for $\sim$ 8% of the time. This is clearly not enough to explain slow shocks in front of the dayside magnetosheath in more than 50% of the cases, as reported by *Song et al.* [1990], especially if one realizes that the solar wind is often quite oscillatory and that it may not often reside in the switch-on regime long enough for the slow shock to form. However, we have found that several times per month the solar wind seems to reside in the switch-on regime for 2 hours or more, and estimates of the dynamical response time of the magnetosheath flow indicate that the slow shock could be formed in such a time span. This has to be confirmed in future time-dependent MHD simulations which take into account the rather erratic behavior of the solar wind. Moreover, the solar wind is often low-β for a substantial time when a magnetic cloud hits the Earth's magnetic environment. Indeed, for instance in the magnetic cloud event of January 1997 [*Burlaga et al.*, 1998] the plasma β was approximately equal to 0.1 for $\sim$ 22 hours, with a Mach number $M \sim 12$ and $\theta_{vB} \sim 70°$. We have performed a simulation with these parameter values (not shown owing to space constraints) and have found a secondary slow shock as in Figures 2a and 2b. This indicates that during this event a slow shock may have existed in the magnetosheath in the direction of the magnetotail on the quasi-parallel side.

It has to be noted that the magnetopause flow tends to be disturbed by kinetic waves of various kinds which often complicate a clear interpretation of macroscopic flow structures. For this and other reasons, some skepticism has arisen about the interpretation of the observations by *Song et al.* [1990, 1992] Indeed, the observed slow mode waves may not be stationary but may be transient structures. It has been shown in 2-D MHD simulations [*Yan and Lee*, 1994] that transient slow mode waves and shocks can be generated by the interaction of various solar wind waves with the Earth's bow shock and magnetosphere. This has been confirmed in 2-D hybrid simulations [*Lin et al.*, 1996] and in 3-D MHD simulations [*Cable and Lin*, 1998]. Also, the simulation results of Section 2 show that the point where the secondary shock is attached to the leading shock shifts tailward for increasing θ_{vB}. The secondary shock is then not present in the dayside magnetosheath close to the Sun-Earth line, where the shocks were reported by *Song et al.* [1990]. Slow shocks have, however, also been reported in the distant magnetotail region [*Feldman et al.*, 1984, 1985], and the secondary shocks of Section 2 may be related to these observed slow shocks.

Our simulations do thus not seem to explain in full the observations of *Song et al.* [1990, 1992] and *Song and Russell* [1997]. However, they do offer a physically attractive explanation for the possible observation of stationary slow shocks in the magnetosheath and in the distant magnetotail region and predict the possible existence of secondary slow shocks in the magnetosheath during magnetic cloud events. More analysis of the observational results and more comprehensive simulations are clearly necessary but are beyond the scope of the present brief report.

5. Conclusions

We have shown that for upstream parameter values in the switch-on regime ($M_- < M < M_+$ in Equation (1)) a secondary slow shock is formed in 3-D MHD bow shock flows. The slow shock is attached to the leading shock front. Slow shocks may thus exist in the Earth's magnetosheath. In this brief report we have not shown any simulations for parameter values outside the switch-on regime, but preliminary results show that slow secondary shocks can also be formed when $M_0 < M < M_-$ and when $M_+ < M$ (with $\beta < 2/\gamma$), and even in the case that $\beta > 2/\gamma$. In those cases the formation of the secondary slow shock is not related to the geometrical properties of switch-on shocks but instead may depend more on the shape of the magnetopause and the angle θ_{vB}. In those cases the secondary shock is generally not attached to the leading shock front. This would mean that MHD simulations predict that stationary slow secondary shocks may exist in the magnetosheath for more than the 8% of time that the solar wind is in the switch-on regime. This is a promising thought but clearly needs more investigation.

We want to conclude with two remarks. It is important to note that the results presented in this paper are MHD simulations which do not take into account kinetic effects. Kinetic effects are certainly important for many aspects of the plasma flow in the Earth's magnetic system, and it will be interesting to see if the slow secondary shocks will remain present in 2-D and 3-D hybrid or kinetic simulations with parameter values in the switch-on regime [*Lin et al.*, 1996; *Omidi et al.*, 1998]. Also, the MHD solutions were obtained in the idealized setting of flow around a rigid conducting paraboloid surface. It will be interesting to see how the slow shock structures influence the inner magnetosphere and the ionosphere in Geospace Global Circulation Model simulations [e.g., *Raeder et al.*, 1998]. When slow shocks are present, the magnetic field topology in the magnetosheath may change substantially, which may be important for magnetic reconnection processes at the magnetopause and for storm and substorm mechanisms. The temporary global reconfiguration of the magnetosheath flow during magnetic cloud events may influence the mechanism and timing of magnetic storms.

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