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# Steady state slow shock inside the Earth's magnetosheath: To be or not to be?

## 2. Numerical three-dimensional MHD modeling

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[1] Large-scale structures in the dayside terrestrial magnetosheath are studied in this paper. The question about existence of the steady state slow MHD shock in the inner magnetosheath is one of the principal theoretical and experimental problems which has not been solved yet. In part 1, the original observations have been revisited. In this part, the numerical results of the three-dimensional MHD model are presented and discussed. It is shown that for the given observations the density enhancement identified previously as a slow mode transition region is explained by temporal variations of the magnetic field and density observed in the supersonic solar wind. There are three factors resulting in the density increase in the slow mode transition region: A density increase in the upstreamflow, a decrease of the IMF modulus, and a new IMF orientation which forms a quasi-parallel bow shock in the subsolar region. We show that numerical solutions obtained by non-stationary and stationary MHD models are significantly different for the same solar wind conditions. We discuss how the magnetopause motion may enlarge the observed variations of the magnetosheath density. Also we answer the question why the existed numerical MHD models do not predict the slow shock in the steady state solution and show how the magnetosheath flow may be organized without such shock.

*INDEX TERMS:* 2728 Magnetospheric Physics: Magnetosheath; 2753 Magnetospheric Physics: Numerical modeling; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2752 Magnetospheric Physics: MHD waves and instabilities; *KEYWORDS:* Magnetosheath, numerical modeling, slow MHD shock, solar wind - magnetosphere interactions, solar wind discontinuities

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### 1. Introduction

[2] Numerical modeling of the terrestrial magnetosheath was begun in 60-th years of the last century with pioneer works of John Spreiter [*Spreiter and Jones*, 1963; *Spreiter et al.*, 1966]. The kinematic model developed by Spreiter and his colleagues predicts that the plasma density increases monotonically from the bow shock to the magnetopause having a maximum at the subsolar magnetopause. *Lees* [1964] analyzing MHD flow along the stagnation streamline made an opposite conclusion that the density decreases to zero at the magnetopause subsolar stagnation point. *Zwan and Wolf* [1976] obtained a numerical solution for the magnetosheath taking into account the influence of the magnetic force on plasma flow. Considering plasma motion inside separate magnetic flux tubes, they confirmed the

conclusion about the plasma depletion near the magnetopause. Following analyses of satellite data show that a layer with decreased plasma density and increased magnetic field is really observed in the inner magnetosheath for many events [*Paschmann et al.*, 1978; *Crooker et al.*, 1979; *Paschmann et al.*, 1986]. *Phan et al.* [1994] using statistical analysis of data concluded that the plasma depletion layer (PDL) (in their paper, it is called the magnetosheath transition layer) forms only for a low-shear magnetopause when the angle between the magnetosheath and magnetospheric magnetic fields does not exceed 30 degrees. While *Pudovkin et al.* [1982, 1995, 2001] showed in the numerical results and in observations that the plasma depletion and the magnetic barrier exist for a southward interplanetary magnetic field (IMF) too if one considers the whole magnetosheath profiles, but not a narrow part close to the magnetopause.

[3] The three-dimensional (3-D) isotropic MHD models follow the Zwan and Wolf model [see, e.g., *Wu*, 1985; *Ogino*, 1986; *Erkaev*, 1988]. Later, the numerical anisotropic

MHD models [Samsonov and Pudovkin, 1998; Erkaev et al., 1999; Pudovkin et al., 1999] which take into account the difference between the ion temperatures in direction perpendicular and parallel to the magnetic field correct a little previous numerical results of the isotropic models. Now there is a large number of stationary magnetosheath profiles at the Sun-Earth line and at some distance from this line obtained by the numerical MHD models from different scientific groups. All these results confirm the previous conclusion about the presence of the PDL near the magnetopause, whereas a weak local maximum of the plasma density is formed either in the middle of the magnetosheath [Wu, 1992] or immediately downstream of the bow shock [Farrugia et al., 2000; Samsonov and Pudovkin, 2000]. All the models above show that the density is nearly constant across most part of the magnetosheath, and a comparatively large density gradient in the radial direction exists only in the PDL.

[4] Nevertheless, some observations of the last decade challenged these numerical predictions. Song et al. [1990, 1992] found in ISEE 1 and 2 data that there is a maximum of density in the subsolar magnetosheath rather close to the magnetopause (at distance about  $0.4 R_E$ ) observed on many crossings. Since the density maximum coincides with a local minimum of the modulus of magnetic field, the observed structure was identified as the slow MHD wave. Southwood and Kivelson [1992, 1995] proposed a scenario how to explain these observations. According to their picture, the slow shock forms upstream of the PDL in the stationary plasma flow. They argued that such shock is an essential element of the dayside magnetosheath which needs to divert flow away from the subsolar point and to make possible the following plasma depletion near the magnetopause. It should be noted that the Southwood and Kivelson model gives just a qualitative description of the magnetosheath flow, therefore it seems to be only a possible scenario rather than a theoretical model. We draw another qualitative picture without the slow shock in section 4.

[5] Scientists who develop magnetosheath numerical models have tried to find the slow shock in results of their simulations, and sometimes their efforts were successful. However, the reasonable explanation was connected only with temporal variations in the upstream solar wind flow. Particularly, Yan and Lee [1996] found by a 2-D MHD simulation that the slow mode waves may be generated after interaction between incident interplanetary waves and the bow shock. The propagation speed of these slow MHD waves decreases as they approach the magnetopause. As a result, the slow MHD waves will stay in front of the magnetopause for a comparatively long time, about 15 min, before the wave energy is completely convected tailward. Cable and Lin [1998] considered an interaction between a rotational discontinuity and the bow shock using a 3-D MHD model, and obtained a pressure pulse which convects across the magnetosheath and finally reaches the magnetopause. Samsonov and Pudovkin [1999] got similar numerical results, but instead of the rotational discontinuity they imposed a rotation of the IMF in the YZ GSE plane (without Bx component) on the solar wind boundary. In summary, these models predict that a temporary structure with anticorrelated density and magnetic field variations may be formed inside the magnetosheath after interaction of some solar wind discontinuities with the bow shock.

[6] As we note before the published numerical MHD models do not predict formation of the slow MHD shock in a steady state flow. Some of these numerical results were compared with documented observations in the subsolar region. Thus Farrugia et al. [1998] reproduced a steady magnetosheath crossing measured by AMPTE/IRM on 24 October, 1985. They concluded that the predicted numerical results are in good agreement with the data. Particularly, they noted that there was no slow mode wave transition both in the observations and in the simulation. Later, Samsonov and Pudovkin [2000] and Farrugia et al. [2001] compared results of the 3-D anisotropic MHD models with the AMPTE/IRM and Wind observations and also found no evidence of the slow shock formation.

[7] Interesting numerical results were obtained by De Sterck and Poedts [1999, 2001]. They found stationary 3-D MHD solutions of the magnetosheath flow with a complex double-front shock topology, when the intermediate MHD shock accompanies the usual bow shock structure. This intermediate shock forms for a limited range of the solar wind parameters when the IMF is rather large (upstream  $\beta < 1.2$  for an adiabatic flow). Therefore these results may hardly explain numerous observations of the slow shock obtained by Song et al. [1990, 1992] for different solar wind conditions. Recent 2-D hybrid simulation of pressure evolution and waves in the magnetosheath made by Lin et al. [2001] reveals waves with anticorrelated density and magnetic field modulus in the inner magnetosheath farther away from the bow shock, but the authors suggest that these waves are the mirror mode.

[8] Zhang et al. [1996] investigated the problem of the origin, exogenous (upstream solar wind variations) or endogenous (interaction with the magnetopause), of the structures observed by Song et al. [1990, 1992]. They considered three events and concluded that two of these events are explained by the endogenous origin, while for one event the density enhancement results from a corresponding variation of the solar wind density. Song et al. [1999a, 1999b] used a modification of the Spreiter's model in order to predict variations of the MHD parameters in the magnetosheath. In their approach, temporal variations observed by ISEE 3 in the supersonic solar wind are taken as the boundary conditions for the numerical magnetosheath model. After the simulations, the obtained numerical results compare with the data from ISEE 2 which has crossed the magnetosheath during the corresponding time. They studied four events when the slow mode transition region (SMT) was observed in the inner magnetosheath and found that their numerical model cannot explain the observed density enhancement. It was supposed that the observed structure is the slow MHD wave, whereas the applied numerical model is not an MHD one and, therefore, cannot predict formation of such waves.

[9] Recently Samsonov and Hubert [2002] revisited one event on day 260/1978 which was classified previously [Song et al., 1990, 1992; Zhang et al., 1996] as a typical example of the SMT. Like Song et al. [1999a], they used the data from ISEE spacecraft, but made the simulation with a 3-D MHD model. The observed density increase in the SMT has been reproduced in the numerical simulation as a temporal structure convected across the magnetosheath with a bulk flow. At the same time, it has been found that quasi

steady state magnetosheath profiles in the case of constant solar wind conditions show no evidence of the density increase in front of the magnetopause. Therefore the authors concluded that the observed density enhancement for this event is caused by temporal variations in the solar wind upstream of the bow shock. They argued that variations of the IMF modulus and direction, and the inward magnetopause motion result in a density increase in the magnetosheath as well as a simple convection of a density pulse from the solar wind to the magnetopause.

[10] In this paper, we discuss the question: Does the MHD theory predict the slow MHD shock in the magnetosheath or not? We show results of calculations for two events classified as the SMTs using the numerical non-stationary 3-D MHD model combined with the magnetopause model of *Shue et al.* [1998]. We draw a physical picture of the magnetosheath flow and show that the diversion of the flow around the magnetopause may be organized without the slow shock. The paper is organized as follows: The next section contains a description of our numerical model; in the third section the numerical results are shown; in the fourth section we analyze features of the MHD flow in the magnetosheath near the magnetopause; in the fifth section we discuss some aspects of the magnetosheath modeling which may influence the accuracy of numerical predictions and compare the obtained results with those of *Song et al.* [1999b]; and finally, the conclusions are given.

## 2. Numerical Model

[11] We have modified the numerical model developed by *Samsonov and Pudovkin* [1998, 2000] to use temporal variations of the magnetic field, plasma density and bulk velocity on the inflow solar wind boundary. In this model, interaction of the supersonic plasma flow with a solid spherical body (approximately a hemisphere) is calculated by the following non-stationary 3-D MHD equations:

$$\partial\rho/\partial t = -\nabla \cdot (\rho\mathbf{V}), \quad (1)$$

$$\frac{\partial}{\partial t}(\rho\mathbf{V}) = -\nabla \cdot \left[ \rho\mathbf{V}\mathbf{V} + I \left( p + \frac{B^2}{8\pi} \right) - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right], \quad (2)$$

$$\partial e/\partial t = -\nabla \cdot \mathbf{q}, \quad e = \frac{\rho V^2}{2} + \frac{B^2}{8\pi} + \frac{p}{\gamma - 1},$$

$$\mathbf{q} = \mathbf{V} \left( \frac{\rho V^2}{2} + \frac{\gamma}{\gamma - 1} p \right) + \frac{1}{4\pi} [\mathbf{B} \times (\mathbf{V} \times \mathbf{B})], \quad (3)$$

$$\partial\mathbf{B}/\partial t = \nabla \times [\mathbf{V} \times \mathbf{B}], \quad (4)$$

where all parameters are used in their usual notation, and  $\gamma = 5/3$ .

[12] The MHD equations are solved by using the explicit conservative finite-difference Rusanov shock-capturing scheme of third order of accuracy [*Rusanov*, 1970]. The simulation box is limited by two spheres: The inner sphere is an unpenetrable perfectly conducting obstacle with the boundary conditions  $V_n = 0$  and  $B_n = 0$ , the boundary conditions at the outer sphere correspond to conditions in the solar wind upstream of the bow shock. The radius of the outer sphere is 1.9 times larger than the radius of the inner sphere, while the radius of the inner sphere varies in

dependence on the upstream solar wind conditions. Four outflow boundaries are determined by latitudes and longitudes, both at  $\pm 83$  degrees. The latitude is measured from the equatorial plane, and the longitude is measured from the noon plane. These boundaries contain free boundary conditions. The flow velocity at the outflow boundaries exceeds the magnetosonic speed. The bow shock forms inside the numerical box self-consistently in simulations.

[13] The numerical simulation presented in this paper consists of two stages. At the first stage, by the method of relaxation we calculate a quasi steady state flow with fixed solar wind boundary conditions observed at the beginning moment of the considered event. This solution is the beginning condition for the following calculations. At the second stage, we calculate the MHD parameters in the magnetosheath using variable solar wind boundary conditions according to the observed temporal variations obtained by a solar wind monitor. In every time step of these calculations, we save values of all MHD parameters taken at the grid node which is closest to the current position of a spacecraft in the magnetosheath. In summary, observations in the solar wind are used to make numerical predictions in the magnetosheath and, then, the predictions are compared to magnetosheath observations.

[14] In this model the magnetopause motion in response to the solar wind variations is taken into consideration. *Sibeck and Gosling* [1996] demonstrated that some variations of the MHD parameters observed in the magnetosheath are caused by the magnetopause motion. In magnetosheath crossings with the duration of a few hours, there are many variations of the upstream plasma density, velocity and the IMF Bz component. These variations result in some displacement of the magnetopause and therefore in some change of the relative spacecraft position inside the magnetosheath. Usually, it is supposed that the distance from the Earth to the magnetopause subsolar point ( $R_{sub}$ ) depends on the solar wind dynamic pressure, the value of the IMF Bz [*Roelof and Sibeck*, 1993; *Petrinec and Russell*, 1996; *Shue et al.*, 1998; *Kuznetsov and Suvorova*, 1998] or the value of the magnetosheath magnetic field [*Pudovkin et al.*, 1998]. Here we present the numerical results using only one of these empirical models, namely the model of *Shue et al.* [1998]. The radius of the inner sphere in our simulation varies with the predicted  $R_{sub}$  in response to changes in the solar wind conditions. It is assumed that the magnetopause motion influences only a relative spacecraft position inside the magnetosheath, but does not change a calculated solution inside the numerical box. In other words, only the estimated distance between the spacecraft and the magnetopause varies due to the magnetopause motion. This assumption seems to be simplistic, but, on the whole, this model is more appropriate than the previous models with a fixed magnetopause for events when the solar wind conditions vary in time.

## 3. Simulation of Typical Cases

[15] We analyze two events from the original statistics of *Song et al.* [1990] observed by ISEE 1 and 2 during the magnetosheath crossings in the subsolar region using simultaneously the solar wind data from ISEE 3. The two cases are complementary. First case (day 260/1978) dem-

onstrates that the observations of the SMT follow a variation with small density enhancement, decrease of the IMF modulus and changes of the IMF direction observed upstream of the bow shock by ISEE 3. These are typical features of many cases presented in Table 1 in Part 1. In second case (day 270/1978), the interval of the SMT corresponds to an increase both of the density and of the magnetic field modulus in the solar wind, while the IMF direction changes insignificantly.

### 3.1. Day 17/09/1978

[16] Figure 1 shows the upstream parameters observed by ISEE 3 (six upper panels), the predicted position of the subsolar magnetopause point (7-th panel), the data from ISEE 1 in comparison with numerical results obtained by our MHD model (five lower panels). The magnetopause crossing was observed by ISEE 1 at about 1524 UT at (9.2, -2.3, 4.1)  $R_E$  GSE, the bow shock crossing was three hours later at (12.7, -1.3, 5.2)  $R_E$ . The observed density near the inner magnetosheath boundary is about  $15 \text{ cm}^{-3}$  (two times larger than in the supersonic solar wind), but between 1534 and 1610 UT a structure with increased density and decreased magnetic field was observed both by ISEE 1 and 2. It has been noted that the edges of this structure coincide with two discontinuities in the magnetic field [Song *et al.*, 1992; Hubert, 2001]. Hubert [2001] have shown that these discontinuities observed inside the magnetosheath correspond to the discontinuities observed by ISEE 3 near the Lagrangian point at 1440 and 1507 UT, respectively. Thus the time lag between the solar wind and magnetosheath observations is equal to 54 minutes for the first discontinuity, but it is 9 minutes larger for the second discontinuity. Hubert [2001] analyzed the second discontinuity using the ISEE 3 data and found that the plane of this tangential discontinuity does not tend along the spiral direction. Taking into account that the position of ISEE 3 was at a large distance from the Sun-Earth line (211, -80, 17)  $R_E$  GSE and using simple estimations, he obtained nearly the same time lag as it was observed.

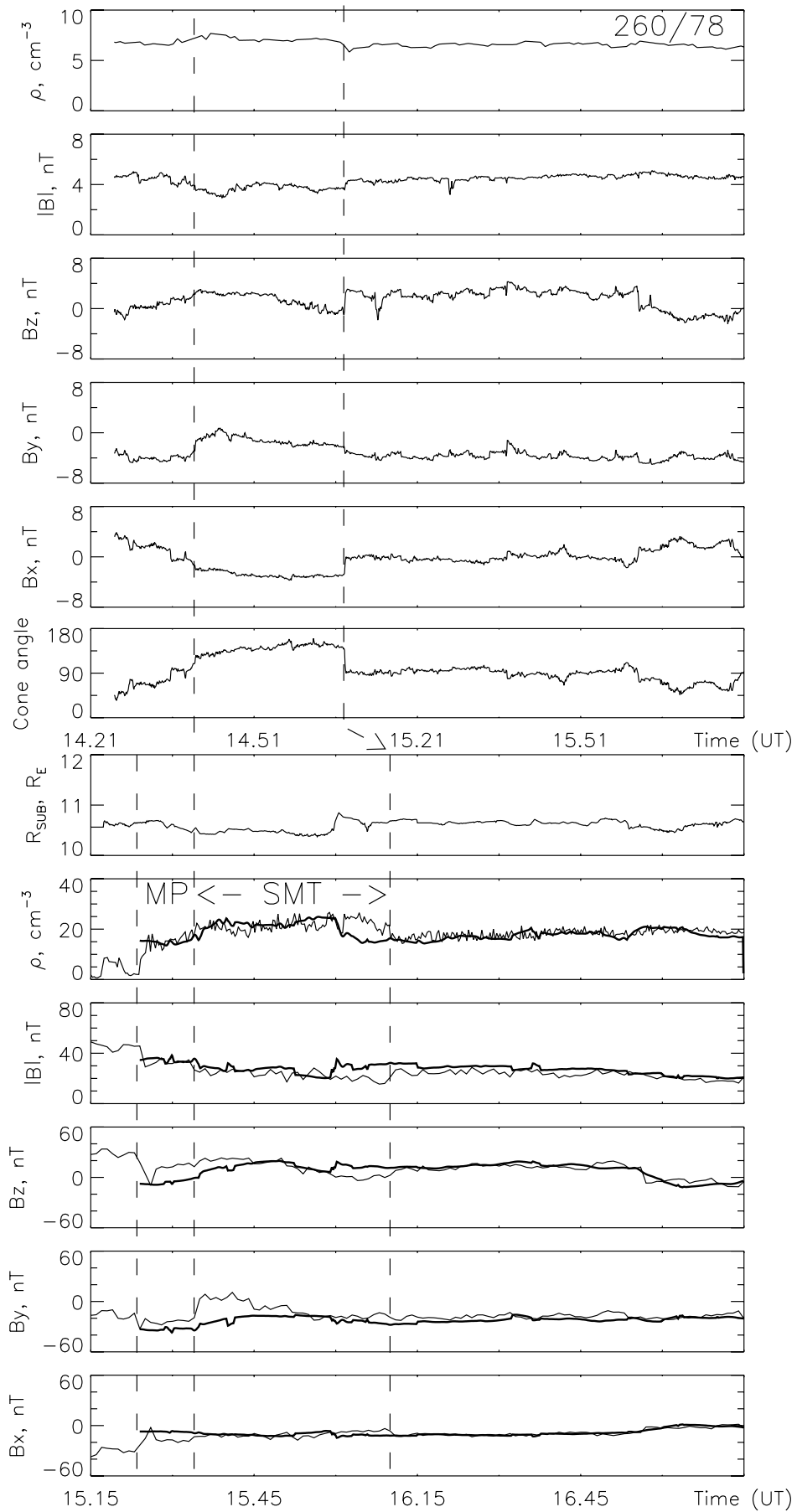
[17] Using the additional time shift equal to 9 min at the outer edge of the SMT, we conclude that the results of our simulation shown in Figure 1 reproduce the observed density increase and the magnetic field decrease. We identify three factors in the supersonic solar wind which result in this density enhancement. First of all, there is a small density increase around 10% observed by ISEE 3. The second factor is a small magnetic field decrease also observed by ISEE 3. Numerical simulations with a stationary model [for example Farrugia *et al.*, 2000] show that for a larger Alfvén-Mach number and the same Mach number the density becomes larger on space profiles along the subsolar line. In other words, when one reduces the mod-

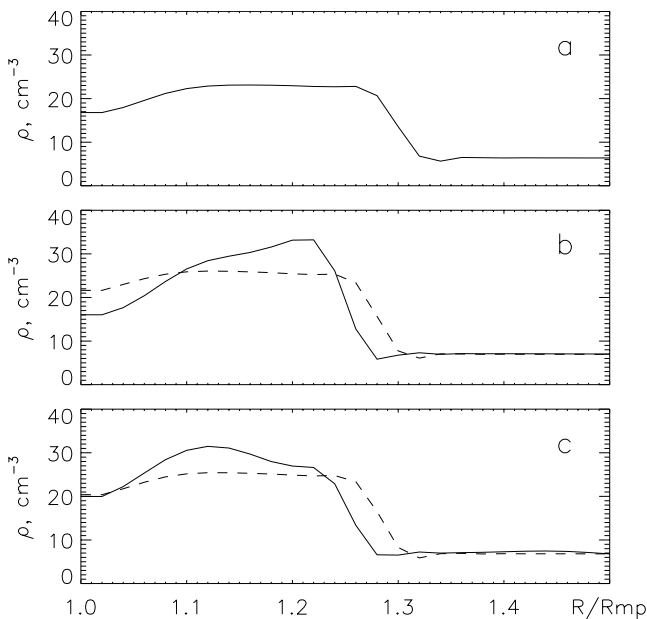
ulus of magnetic field in the upstream solar wind, the magnetosheath density obtained in a stationary MHD solution increases. Thus a variation with decreased IMF and constant solar wind density by itself will produce a variation with increased density after the bow shock crossing. Finally, the third factor is a new orientation of the IMF. The IMF cone angle defined as  $\arccos(B_x/|B|)$  (6-th panel of Figure 1) increases after 1440 UT and suddenly decreases at 1507 UT. Therefore most part of the SMT has been observed in the magnetosheath region downstream of the quasi-parallel bow shock (in the subsolar region, the parallel bow shock corresponds to the cone angle close to 0 or 180 degrees). According to the numerical simulations [Samsonov *et al.*, 2001], the density downstream of the parallel bow shock is a little higher than the density downstream of the perpendicular shock, while the modulus of the magnetic field is less in most part of the magnetosheath. It is explained by the Rankine-Hugoniot relations at the bow shock, since there is no magnetic field increase across the parallel shock.

[18] At the same time, all three factors noted above do not result in a large enough density increase if one will use a stationary model considering evolution of the magnetosheath flow as a number of steady state solutions. Figure 2 shows spatial profiles of the density along the Sun-Earth line at 1509, 1539 and 1540 UT, respectively. The profile on panel a corresponds to a quasi steady state solution at 1509 UT, at the beginning of the event. Solid and dashed curves on panels b and c are results of the non-stationary and stationary models (we find a stationary solution by the method of relaxation) at 1539 and 1540 UT, i.e., near the first observed maximum of the magnetosheath density. The density pulse obtained near the bow shock at 1539 UT moves to the magnetopause going through a half of the magnetosheath in one minute. Although quasi steady state solutions (dashed curves) at 1539 and 1540 UT predict a larger density than the solution at 1509 UT, but sufficiently less than the non-stationary solutions with the same solar wind conditions. In general, all stationary solutions have qualitatively a similar form which depends slightly on the upstream conditions. On contrary, a non-stationary solution varies every minute in response to new variations in the solar wind and also due to propagation of previous variations inside the magnetosheath. Thus a maximum of the plasma density in a non-stationary space profile may be observed in any point inside the magnetosheath in dependence on the time interval after its observation in the solar wind.

[19] During the observation of this SMT, the Earth magnetopause shifts inward according to Shue *et al.*'s model [1998] (see 6-th panel of Figure 1), what may enlarge the predicted variations of the  $\rho$  and  $|B|$ . However, comparison with the previous results [Samsonov and Hubert, 2002]

**Figure 1.** Six upper panels show the temporal variations of the solar wind parameters observed by ISEE 3 between 1421 and 1621 UT on day 17/09/1978. Six down panels show comparison of the numerical MHD results (thick curves) with the outward magnetosheath crossing of ISEE 1 (thin curves) between 1515 and 1715 UT. The upper panels show the solar wind density,  $|B|$ , the IMF components, and the IMF cone angle defined as  $\arccos(B_x/|B|)$ . The down panels show the position of the magnetopause subsolar point calculated by Shue *et al.*'s [1998] model, the density, the magnetic field modulus and components. The left vertical dashed line marks the magnetopause crossing, two other vertical lines separate the region identified as the slow mode transition region while in the solar wind (upper panels) the edges of this region correspond to two magnetic field discontinuities. The numerical results predict the observed density increase, but the duration of this structure is shorter in the simulation than in the observation. The reason of this is discussed in text.





**Figure 2.** The space density profiles along the Sun-Earth line. Figure 2a shows a quasi steady state solution at 1509 UT, i.e., at the beginning of the event. Figures 2b and 2c show numerical results at 1539 and 1540 UT, respectively. The solid lines correspond to solutions obtained by the non-stationary MHD model, the dashed lines correspond to steady state solutions for the same upstream conditions. This figure illustrates the difference between results of non-stationary and stationary models and a propagation of a density pulse in the non-stationary solution.

shows that the behavior of the MHD components stays generally the same as in the simulation with a fixed magnetopause boundary. We note that the numerical predictions about the magnetic field components near the magnetopause are less successful than the predictions of other parameters. Although the  $B_y$  and  $B_z$  components in the simulation have a similar trend as in the data, but the predicted values are different. It may be caused, for example, by magnetopause surface waves or some other variations connected with processes at the magnetopause which are not included in the present numerical model. In contrast with this, the behavior of the MHD components in the outer magnetosheath (the complete crossing shown in Figure 1 of *Samsonov and Hubert, 2002*) reveals better agreement with observations. For example, the magnetic field discontinuity observed by ISEE 2 near 1656 UT is reproduced at the same time in the simulation, but with a more gradual change due to influence of the numerical viscosity.

### 3.2. Day 27/09/1978

[20] Like in the previous event, the position of ISEE 3 was far upstream of the bow shock (213, -98, 13)  $R_E$  GSE while ISEE 1 crossed the dayside magnetosheath from the magnetopause (7.6, -3.8, 3.8)  $R_E$  to the bow shock. The ISEE 1 position before a data gap at 0608 UT was (10.4, -3.7, 4.6)  $R_E$ . The numerical results and the ISEE data for this event are shown in Figure 3 which is organized similar to Figure 1. The SMT region for this event consists of a few

density peaks observed in the inner magnetosheath between 0408 and 0443 UT.

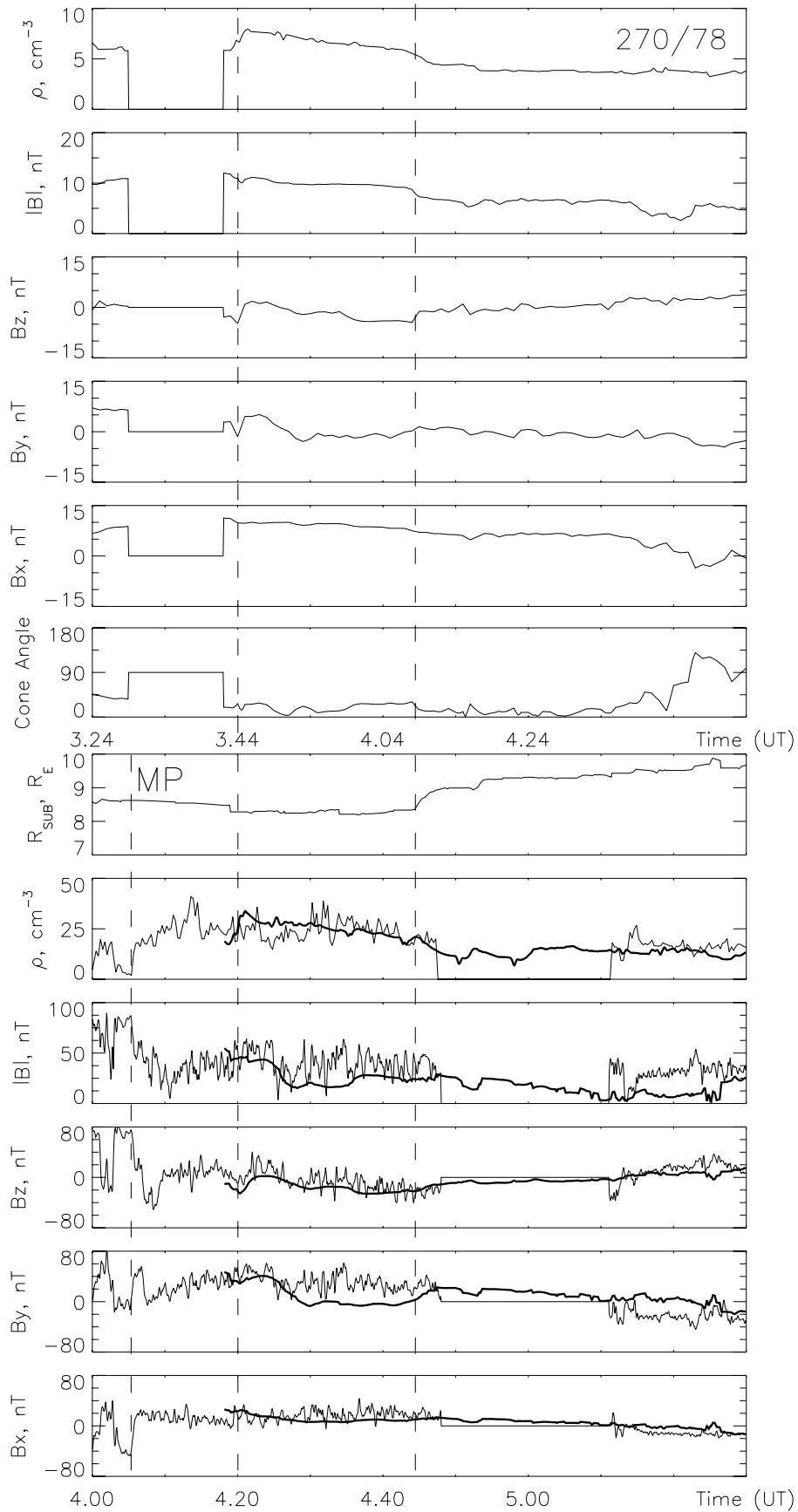
[21] The time shift between the solar wind and magnetosheath observations is estimated to be equal to 36 minutes. In fact, the observed solar wind velocity for this interval is rather high and varies between 600 and 700 km/s. In order to determine precisely the time shift we made a cross correlation analysis for the  $B_y$  and  $B_z$  components and found that such shift (i.e., 36 min.) gives a best correlation for the both field components considering the ISEE 3 observations between 0342 and 0356 UT and the ISEE 1 observations in a wider interval.

[22] Thus we have to conclude that the largest density peak in the magnetosheath at 0414 UT cannot be predicted from the solar wind data because it coincides (after the time shift) with the ISEE 3 data gap between 0329 and 0342 UT. Numerical predictions shown by thick lines in lower panels of Figure 3 are displayed beginning from 0418 UT, although the real simulation of the case has been begun using the solar wind data before the gap (in order to get better initial conditions).

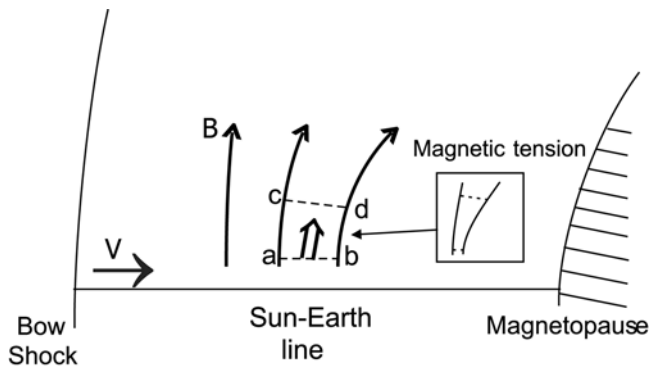
[23] In general, the predictions of magnetosheath density are close to the ISEE 1 data (excluding the ISEE 1 data gap between 0448 and 0511 UT). The solar wind during the interval between two dashed lines at 0344 and 0409 UT is more compressed in comparison with surrounding values, therefore large predicted density in the magnetosheath between 0420 and 0445 corresponds to the large upstream values. It seems that temporal variations of the IMF does not influence the behaviour of the magnetosheath density in this case. Large fluctuations of the observed density around the predicted values may be explained by a few factors below.

[24] Predictions of the magnetosheath  $B_z$  are rather close to the observations during the whole considered interval. This confirms that our choice of the time lag is reasonable. While the numerical results for  $B_y$  coincide with the data between 0418 and 0428 UT, they are lower than the observed values after 0428 UT till the data gap at 0448 UT. Note that the magnetosheath crossing is downstream of the quasi-parallel bow shock what is confirmed by a high level of magnetosheath magnetic field fluctuations and a large IMF  $B_x$  in the upstream data. The IMF cone angle is close to zero during the whole interval which corresponds to the observed SMT. Our numerical experience teaches us that in the case of a quasi-parallel bow shock the magnetosheath magnetic field near the magnetopause becomes very sensitive to small perturbations in the upstream boundary conditions, and, thus, it is sometimes hardly predictable. Moreover, kinetic effects which are not predictable by an MHD model are important downstream of the quasi-parallel bow shock too.

[25] Another factor which may complicate the numerical predictions for this event is the data gap of ISEE 1 between 0329 and 0342 UT. For a non-stationary model, it is important to know the 'history' of the flow (at least during last 10 minutes), because the flow configuration in the magnetosheath in any moment depends on previous variations of the upstream conditions. Lastly, as we discuss below some local variations in the solar wind may exist near the Sun-Earth line, but are not observed by ISEE 3 far, about 100  $R_E$ , from this line (see, for example, *Richardson*



**Figure 3.** The numerical results and data for event on day 27/09/1978. The format is the same as that in Figure 1.



**Figure 4.** This sketch illustrates how the magnetic tension diverts plasma flow along the magnetic field lines around the magnetosphere. The cross section of a magnetic tube near the Sun-Earth line  $ab$  is less than the cross section  $cd$  at some distance from this line. This explains one mechanism of plasma depletion in the MHD model (see details in text).

and Paularena [2001] studies about typical scales of solar wind variations).

#### 4. Diversion of Magnetosheath Flow in MHD Model

[26] Usually, the magnetosheath numerical models calculate interaction between a supersonic flow and a perfectly conducted unpenetrable obstacle. Thus the normal component of the magnetic field on the obstacle is supposed to equal zero. At the same time, both the slow MHD and Alfvén waves cannot propagate in direction strictly perpendicular to the magnetic field. Cable and Lin [1998] demonstrated that the radial component of the flow velocity is larger than the radial velocities of the MHD slow and intermediate waves across the whole magnetosheath in the ecliptic plane for typical solar wind conditions. It means that any disturbance initiated near the magnetopause cannot propagate upstream in the magnetosheath, but will be convected back to the magnetopause immediately.

[27] Southwood and Kivelson [1995] found an inconsistency in the physical explanation of the plasma depletion with the Zwan and Wolf model [1976]. They argued that the depletion of plasma cannot be explained without the slow shock immediately upstream of the PDL. However, the same question may be addressed to any other numerical MHD models, because they predict qualitatively the same density profiles as the Zwan and Wolf model. Below we show how plasma can be removed from the subsolar magnetosheath without any additional shock.

[28] Southwood and Kivelson [1995] criticized the squeezing mechanism which results in the plasma depletion according to Zwan and Wolf [1976]. They stress that the magnetic pressure cannot push plasma along the field lines away from the subsolar region. However, we note that it is true only when the magnetic field lines are parallel. According to the numerical simulations, the magnetic field is most compressed near the Sun-Earth line close to the magnetopause. The effect, like in a magnetic bottle, exists in this case: The gradient of the magnetic pressure pushes plasma away from the subsolar region. Figure 4 illustrates this

process. Planes  $ab$  and  $cd$  cross the same magnetic flux tube, and  $ab$  is closer to the Sun-Earth line. Since the intensity of magnetic field is bigger at the Sun-Earth line, the cross section  $ab$  is less than  $cd$ .

[29] Moreover, the numerical MHD results show that both the density and the gas pressure are bigger at the Sun-Earth line than away from this line at the same magnetic field line. Therefore the gas pressure gradient is the second factor what moves plasma away from the subsolar region along the magnetic field lines. While the magnetic field lines are removed from the subsolar region only with the flow directed perpendicular to the magnetic field, the plasma particles leave the subsolar region both in direction across and along the magnetic field lines. Thus even if the flow velocity perpendicular to the magnetic field is usually bigger than the parallel velocity, the magnetic field will be accumulated in the subsolar region more easily than the density.

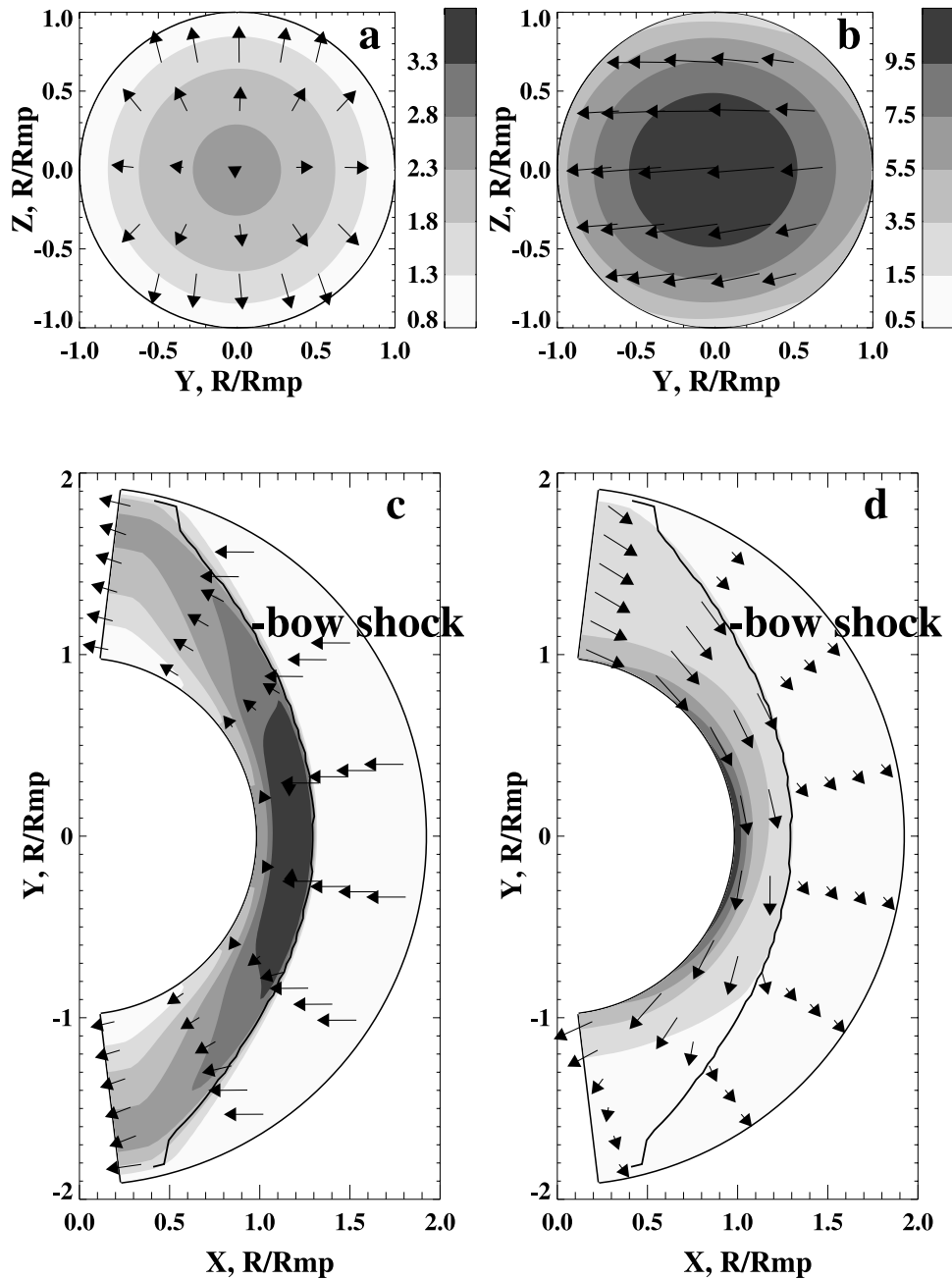
[30] Illustrating these conclusions, we show the contour lines of the plasma density and of the modulus of magnetic field on the magnetopause surface (Figures 5a and 5b) and in the equatorial plane (Figures 5c and 5d) obtained by our simulation for the event on day 17/09/1978. These contours correspond to the steady state solution which is the beginning condition for this event. Arrows show the direction of the velocity and magnetic field vectors, respectively. The IMF at this moment is mainly in the equatorial plane with a large  $x$  component. The contours in the equatorial plane illustrate that the PDL forms near the obstacle, while the contours on the magnetopause surface show that both the magnetic field and the density are larger close to the subsolar point. Although the plasma flow near the magnetopause accelerates better in the direction perpendicular to magnetic field lines (in this case, along  $OZ$  axis), there is a velocity component along the magnetic field ( $OY$  axis) too.

## 5. Discussion

### 5.1. Some Problems of Magnetosheath Modeling

[31] There are a few reasons, why behaviour of the MHD parameters in the magnetosheath cannot be predicted well by a numerical model. Two reasons have been discussed above: Unpredictable variations downstream of the quasi-parallel bow shock and data gaps in the upstream values. In part I [Samsonov and Hubert, 2002], it is noted that magnetopause motion influences the magnetosheath flow too. We take into account this motion with help of the statistical magnetopause model of Shue *et al.* [1998], which used 5-min average solar wind data. It is not quite clear yet how well this statistical model, which predicts an average position of the magnetopause, is appropriate to use in combination with a non-stationary magnetosheath model. In any case, we do not observe a strong influence of the magnetopause motion on the magnetosheath flow with the present model.

[32] Another problem discussed in Part I is connected with correlation of magnetic field and plasma data when two spacecraft (one in the solar wind and another one in the magnetosheath) are separated by a large distance. Ideally, to make simulations of the MHD parameters in the magnetosheath and to compare them accurately with observations, we must have input solar wind data in the right place, namely near the same streamlines which cross the dayside magneto-



**Figure 5.** Figure 5a shows contours of the plasma density and arrows of the velocity projected on the magnetopause surface (the point of view is from the Sun). Figure 5b shows contours and arrows of the magnetic field on the magnetopause surface. Figures 5c and 5d show the same parameters as Figures 5a and 5b, respectively, but projected in the equatorial plane. The density and magnetic field are normalized to the corresponding solar wind values. The distance is normalized to the obstacle (magnetopause) radius. See color version of this figure at back of this issue.

sheath. However, since it is usually impossible, any numerical model may fail in predictions of very localized structures.

[33] Correlating observations obtained from different missions, it is worth to consider also the possibility of multiple time shifts. We note that actual orientations of the IMF discontinuities do not show strong grouping in the spiral direction, but may vary in a wide range of angles (see, for example, *Sergeev et al.* [1998a] or *Weimer et al.* [2002]). Therefore the time shift between observations in the solar wind at some distance from the Sun-Earth line and in the

magnetosheath may vary in some limits during any considered case. Moreover, *Sergeev et al.* [1998b] demonstrated that for one particular event with a very slanted solar wind discontinuity the time difference between observations of this structure by two spacecraft in the magnetosheath was as large as  $\sim 1$  hour. Thus one need not to be surprised about a difference between observed and predicted time shifts around 5–10 minutes or even more during one event which may be found when upstream solar wind data are correlated with magnetosheath observations.

[34] *Hubert and Samsonov* [2004] show that the observed SMTs are closely connected with temporal variations of the upstream parameters. However, in order to give a wider picture we discuss below another possibility when anticorrelated density and magnetic field variations may be initiated directly in the magnetosheath or at the magnetopause. We note the paper of *Omidi and Winske* [1995] where the mirror and slow waves (MIAOW) were identified near the magnetopause in the 1-D hybrid simulations. A little later *Johnson and Cheng* [1997] using combined kinetic-MHD approach found that the mirror mode may have a real phase velocity if inhomogeneities in the background plasma and magnetic field parameters are taken into account. Apparently neither the pure mirror wave nor the MIAOW wave can be obtained in the numerical solution using an MHD model. Observations analyzed by *Balikhin et al.* [2001] show existence of standing waves in the magnetosheath with properties similar to those found by *Omidi and Winske* [1995] for the MIAOW waves and by *Song et al.* [1994] for the slow MHD waves. However, the authors conclude that these waves can be described correctly only with the kinetic theory because their wavelength has the same order of magnitude as the proton gyroradius and their frequency in the plasma frame is higher than the ion gyrofrequency. The kinetic effects are believed to be particularly important downstream of the quasi-parallel bow shock. The above mentioned results show that kinetic and MHD structures in the magnetosheath have similar properties, therefore the problem of identification of magnetosheath waves may be rather complicated. At the same time, we stress again that these results give no evidence to prove existence of the steady state slow MHD shock, and the observations noted above are not connected with those described by *Song et al.* [1990].

## 5.2. Comparison With Previous Numerical Results

[35] Two observed events in the dayside magnetosheath on days 17/09/1978 and 27/09/1978 have been analyzed in this paper using a 3-D MHD model. We find that the observed density enhancement in the inner magnetosheath which was named the SMT by *Song et al.* [1992] is explained completely by the exogenous origins (i.e., upstream variations in the supersonic solar wind), and not the endogenous origins (i.e., an interaction of the magnetosheath flow with the magnetopause) as it was assumed before [*Song et al.*, 1992; *Zhang et al.*, 1996; *Song et al.*, 1999b]. Since the event on day 17/09/1978 has been studied carefully in the papers noted above, we should explain why we obtain the opposite conclusion than the authors of the previous works.

[36] The IMF variations play an important role for this case as well as for many other events with the observed SMTs. Previously, *Song et al.* [1992] and *Zhang et al.* [1996] considered correlation of the plasma density in the magnetosheath SMT and during the corresponding interval in the upstream solar wind. Since the density increase in the magnetosheath for this case does not correlate with upstream data, they concluded that the origin of this structure is endogenous. Later, *Song et al.* [1999b] analyzed this event using the kinematic model. The main problem of the kinematic model is that this model does not take into account influence of the magnetic field on the plasma

parameters (i.e density, velocity) in a proper way. It is not so important in those regions where the plasma beta is high ( $\beta \gg 1$ ). However, the modulus of magnetic field increases from the bow shock to the magnetopause for most observations, therefore the kinematic model is less appropriate for the inner magnetosheath than for the outer magnetosheath. In other words, only MHD models can answer correctly the question: Does the slow MHD waves exist in the magnetosheath or not?

[37] The numerical model used by *Song et al.* [1999b] predicts that the density is nearly constant across the whole magnetosheath crossing for the event on day 17/09/1978, and small variations of the magnetosheath density are only due to small variations of the upstream solar wind density. In contrast with this, the numerical MHD model used in this work predicts that the density increase in the magnetosheath results from temporal variations both of the solar wind density and magnetic field. Moreover, our numerical model is built by the non-stationary equations, while, the model of *Song et al.* [1999b] has used the stationary equations. Therefore the present numerical results show a real evolution of the MHD parameters in the magnetosheath with time, which is different from a simple combination of stationary solutions for variable solar wind conditions. An important thing is that a non-stationary solution ‘remembers’ the history of a flow (i.e., it depends on boundary conditions which were before this moment). Also only a non-stationary solution takes into account properly the interaction between interplanetary discontinuities and the bow shock.

[38] Another important question is how to determine the time shift between observations near the L1 Lagrangian point and inside the magnetosheath. *Song et al.* [1999a, 1999b] supposed that the time shift does not change during a whole magnetosheath crossing. However, before we have noted that the time shift may be variable even during one crossing. Analyzing the orientation of the tangential discontinuity at the end of the SMT for the event on day 17/09/1978, *Hubert* [2001] have found that the time shift for this discontinuity is bigger at 9 minutes than the shift for other structures both before and after the discontinuity. Our analysis of the event on day 27/09/1978 shows that the time shift can be determined more precisely in a short interval if one finds correlation coefficients between the IMF components ( $B_y$  and  $B_z$ ) and the magnetosheath magnetic field. A simple method when the time shift is determined as a result of division of  $\Delta x$  (the distance between two spacecraft along the Sun-Earth line) by a constant solar wind velocity is often least accurate (*Weimer et al.* [2002]).

## 6. Conclusion

[39] Summarizing this work, we want to stress the following:

[40] 1. Steady state solutions in the dayside magnetosheath obtained by different numerical MHD models (and not only by the model presented in this paper) with typical boundary conditions at the magnetopause and in the solar wind do not show formation of the slow MHD shock inside the magnetosheath. Since these models use various numerical approaches, we think that this conclusion does not depend on a numerical method.

[41] 2. In part 1 [Hubert and Samsonov, 2004] it has been shown that all events in the statistics of Song *et al.* [1990] correlate with temporal variations of the magnetic field and/or plasma density in the upstreamflow (when the upstream observations are available). In this part, using the numerical results we show how the real observations of two magnetosheath crossings are reproduced with the MHD model. Three factors are identified which result in the density increase in the magnetosheath: A density increase in the upstreamflow, a decrease of the IMF modulus, and a new IMF orientation which forms a quasi-parallel bow shock in the subsolar region. It has been shown that the numerical results obtained with a non-stationary MHD model are different from the results obtained with a stationary MHD model. In our opinion, only a non-stationary MHD model describes properly the interaction of interplanetary discontinuities with the bow shock and the following propagation of disturbances across the magnetosheath.

[42] 3. Plasma flow in the magnetosheath is diverted around the magnetosphere without the slow MHD shock. We show that large magnetic and plasma pressures in the subsolar region push plasma away in directions both perpendicular and parallel to magnetic field lines.

[43] The detailed analysis of data presented in Part 1 and the results of 3-D MHD modeling discussed in Part 2 confirm that the origin of the magnetosheath SMT's is exogeneous and connected with temporal variations of the IMF and of the solar wind density. Various questions so far asked about the nature of this phenomenon have been answered in these two parts.

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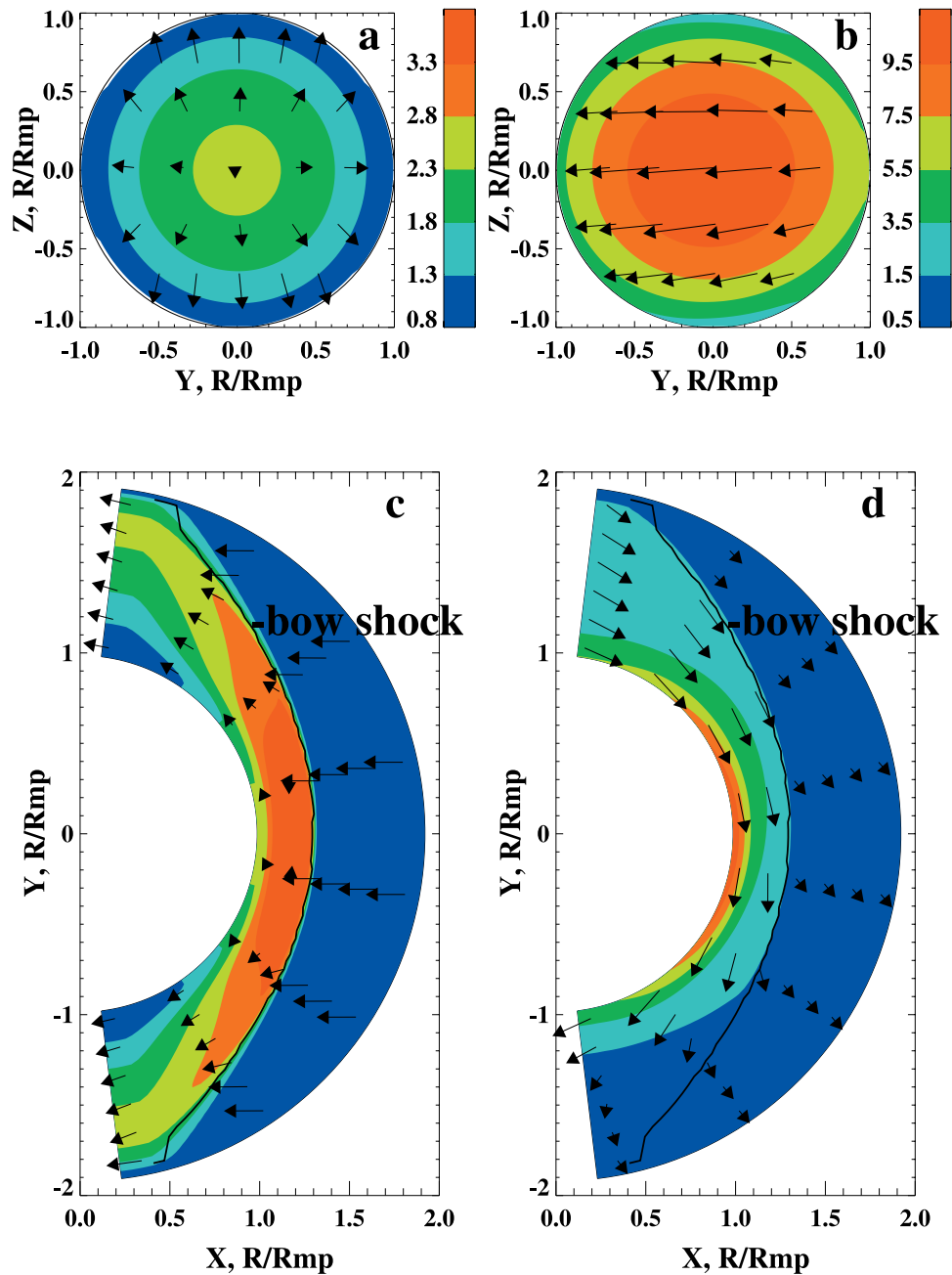
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**Figure 5.** Figure 5a shows contours of the plasma density and arrows of the velocity projected on the magnetopause surface (the point of view is from the Sun). Figure 5b shows contours and arrows of the magnetic field on the magnetopause surface. Figures 5c and 5d show the same parameters as Figures 5a and 5b, respectively, but projected in the equatorial plane. The density and magnetic field are normalized to the corresponding solar wind values. The distance is normalized to the obstacle (magnetopause) radius.