MAGNETOPAUSE CUSP INDENTATION: AN ATTEMPT FOR A NEW MODEL CONSIDERATION

M. Kartalev[1], S. Savin[2], E Amata [3], P. Dobreva[1], G. Zastenker[2], and N.Shevyrev[2]

[1]Institute of Mechanics, Bulgarian Academy of Sciences, Acad. G. Bontchev Str., Block 4, 1113, Sofia, Bulgaria
[2]Space Research Institute, Russian Academem of Sciences, Profsousnaya, 84/32, 117811 Moscow, Russia
[3]Istituto di Fisica dello Spazio Interplanetario C.N.R. Via del fosso del cavaliere 100 00133 ROMA Italy

ABSTRACT

We report an attempt for numerical modeling of the magnetopause indentation, formed by the magnetosheath - cusp interaction. Our attempt is based on a new numerical magnetosheath - magnetosphere model, developed in the Institute of Mechanics, Sofia. The model includes, in a self-consistent modular approach, the models of the magnetosheath and the magnetosphere. The latter is a hybrid between data-based magnetospheric current system and numerically obtained magnetopause shielding current system. A simplified gasdynamic approach is applied for the magnetosheath. The positions and the shapes of the bow shock and the magnetopause are determined self-consistently as a part of the numerical procedure, based on the pressure balance. The substantial difference of the processes, responsible for the pressure formation inside and outside magnetopause indentations over cusps, poses difficulties of the problem solution for the closed magnetosphere. We discuss the considered problem in the light of CLUSTER and Interball-1 data. Both magnetopause normals and plasma decelerations into the over-cusp indentation can be taken into account in the frame of the model, along with the magnetopause shape dependence on the geomagnetic dipole tilt. Our attention addresses the specific challenging problem, arising in determining the magnetopause indentations around the cusp regions.

Key words: magnetopause; magnetosheath; cusp; indentation.

1. INTRODUCTION

The knowledge of the cusp associated magnetopause regions are of great importance for understanding of very basic aspects of the solar wind influence on the Earth's environments. The understanding of such details of these regions as magnetopause structure and its geometry peculiarities could be useful for understanding of important details of the process of energy transfer from solar wind to magnetosphere and polar ionosphere. In this short communication we focus our attention on the problem of the specific cusp associated magnetopause shape.

It is well known that most of the widely used data based magnetopause models besides assuming general simplifications like axial symmetry, also do not take into account so called magnetopause cusp indentations (e.g. (Shue et al., 1997; Roelof and Sibeck, 1993)). Some recently developed data based models (Boardsen et al., 2000; Eastman et al., 2000), making use of very extensive polar orbit measurements of Hawkeye satellite, provide more precise prediction of the high latitude antisunward of the cusp part of the magnetopause,as well of its nose subsolar part, but the authors especially underline that they do not model the cusp indentation itself. Thus, some kind of "asymptotic" behavior of the cusp associated region is estimated nevertheless by this model. The definite determination of the magnetopause cusp indentation however is avoided by this model too.

The situation is quite similar regarding the existing theoretical approaches dealing with magnetopause shape and position. The majority of the used in the literature models, from "classic" numerical magnetosheath models (e.g. Spreiter and Stahara (1994)) to most of the sophisticated $3D$ global MHD models of the solar wind-magnetosphere interaction, are not designed for treatment of the magnetopause cusp indentations.

One of the first attempts for deriving more realistic magnetopause geometry utilizing magnetosheath / magnetosphere pressure balance was done by Mead and Beard (1964), but relying on too simplified approach for the magnetospheric magnetic field. Recently Sotirelis (1996); Sotirelis and Meng (1999) solved analogical problem using more realistic data based Tsyganenko'96 magnetospheric field model (Tsyganenko, 1995). The magnetopause shape obtained by these authors includes cusp indentations. The used there magnetosheath pressure on the magnetopause however is taken by idealized

Proceedings Cluster and Double Star Symposium – 5th Anniversary of Cluster in Space, Noordwijk, The Netherlands, 19 - 23 September 2005 (ESA SP-598, January 2006)

Newton approach, which is quite inadequate in particular especially over the geometric peculiarities of the magnetopause cusp indentations.

In the present work we implement a new magnetosheath/magnetosphere numerical model, in which the magnetopause shape is determined again satisfying pressure balance, but utilizing the real gasdynamic “outside” pressure on magnetosheath. This model is described briefly in Section 2. In Section 3 we implement this model for a comparison with the measurements from two satellite magnetosheath crossings.

2. SHORT DESCRIPTION OF THE IMPLEMENTED MAGNETOSPHERE - MAGNETOSHEATH MODEL

The used here new **model of the system magnetosphere - magnetosheath** (Kartalev et al., 1995, 1996; Dobreva et al., 2004; Kartalev et al., 2005) comprises in a self-consistent way two “sub-models”: a 3D numerical data based model of the magnetosphere with included data based magnetospheric magnetic field systems and arbitrary magnetopause, and a 3D gasdynamic numerical model of the magnetosheath with “flexible” magnetopause. The shapes and positions of the shock wave and of the magnetopause are self - consistently determined as a part of the solution.

The new **3D finite element magnetosphere magnetic field model** is a generalization of the earlier developed 2D (Kartalev et al., 1995) and simplified 3D (Kojtchev et al., 1998) models. The shielding field is obtained numerically solving the Chapman-Ferarro problem in these models. The solution utilizes the dipole field and data based cross-tail, Birkeland and ring currents. In the considered case we make use of the Tsyganenko data based ($T96$ and $T01$) models (Tsyganenko, 1995, 2002a,b) (details in (Dobreva et al., 2004)). The 3D Chapman Ferarro problem is solved for an arbitrary magnetopause, considering the whole magnetospheric field $\mathbf{B}$ as a sum of the sought shielding field $\mathbf{B}_s$, the dipole field $\mathbf{B}_d$, the fields, produced by the cross-tail current system ($\mathbf{B}_t$), the Birkeland currents ($\mathbf{B}_b$), and the ring current ($\mathbf{B}_r$). As usual, it is supposed that $div\ \mathbf{B}_s = 0$, $rot\ \mathbf{B}_s = 0$ and, therefore, a field potential U exists:

$$\nabla U = \mathbf{B}_s; \quad \triangle U = 0$$

Neumann boundary condition is posed on the magnetopause with local normal $\mathbf{n}$ (here we consider only closed magnetosphere):

$$(\mathbf{B}_s, \mathbf{n}) = -\frac{\partial U}{\partial n} = -[(\mathbf{B}_d, \mathbf{n})+(\mathbf{B}_t, \mathbf{n})+(\mathbf{B}_r, \mathbf{n})+(\mathbf{B}_b, \mathbf{n})]$$

It is possible to include here different “internal” fields, taken from different physics based or data based models. In the calculations of the present work we make use of this flexibility of the scheme. It is worth emphasizing that all the ”data based shielding fields” from Tsyganenko model, adjusting that model to some data based, but quite idealized (symmetric in particular) magnetopause, are **omitted** here. Respectively, the data based magnetopause, used in Tsyganenko model, doesn’t participate in our consideration. Our numerically obtained shielding field corresponds to our numerically obtained magnetopause.

The implemented **Gas-dynamic numerical magnetosheath model** utilizes a slightly modified grid - characteristic numerical approach, developed by Magomedov and Holodov (1988) and applied previously in modelling of the magnetosheath problem in axially symmetric approach, as well as in other astrophysical problems (Kartalev et al., 1996, 2002; Keremidarska and Kartalev, 1998, 1999) . Essentially 3D Euler gasdynamic equations are applied in appropriate curvilinear coordinates.

The problem domain is divided into two sub-domains for better description of arbitrary elongated tail region of the magnetosheath. Spherical coordinates $x_1 = \theta, x_2 = r$, $x_3 = \varphi$ are applied for the dayside magnetosheath (standard definition, where φ is the azimuthal direction), and in the tail region the equations are applied in cylindrical coordinates $x_1 = -z, x_2 = r, x_3 = \varphi$ (again standard definition where z is direction to the sun). In these coordinates the equations for the shock wave and for the magnetopause (tangential discontinuity) could be presented as: $x_2 = R_s(t, x_1, x_3)$ and $R_m = R_m(t, x_1, x_3)$, where t is the time. An additional coordinate transformation is applied and practically used in the computational scheme:

$$\xi = x_1, \ \zeta = x_3, \ \eta = \frac{x_2 - R_m}{R_s - R_m},$$

in which the shock wave and the magnetopause are coordinate surfaces. In the implemented time marching scheme, for the points of the boundaries, the Rankine-Hugoniot relations are used at each time forward step. The computed on the magnetopause magnetosphere pressure essentially participates in these steps for the magnetopause points. The algorithm determines the new position of each boundary point of the next time layer.

The leading procedure in the **self-consistent model of the whole system magnetosheath-magnetosphere** is the external (magnetosheath) problem. Current magnetopause shape and position are known at each time step of the procedure. The magnetosphere problem is solved using this current magnetopause geometry. The Neumann problem for this shape is solved then, obtaining somed *inside* pressure distribution on the magnetopause. This current inside pressure distribution is essential in the work of the magnetosheath part of the algorithm, which not only gives the parameter values at the next time step, but also determines new positions of the shock wave and magnetopause, searching better satisfaction of the pressure balance on the magnetopause. Thus we have a new geometry of the magnetosphere and the procedure goes to the next time step. The convergence is reached when the solution and the boundaries become stationary.

The needed input parameters for the whole system modelling are: solar wind plasma and magnetic field parameters (ion density, ion velocity, electron temperature, magnetic field components B_y, B_z); Earth parameters (dipole tilt angle, Dst index, UT).

The output of the model are: magnetopause and shock wave shapes and positions; distribution of the parameters in the magnetosheath (enthalpy, pressure, three components of the velocity, density, temperature, Mach number). Distribution of the magnetic field in the magnetosphere is also a model output. It differs from that of Tsyganenko models because of the different shielding field.

3. COMPARISON OF SOME CLUSTER AND INTERBALL-1 MAGNETOSHEATH MEASUREMENTS WITH MODEL PREDICTIONS

The model is implemented here to the interpretation of the measurements from two real satellite magnetosheath crossings, especially focusing the attention on the magnetopause crossings. In both cases the orbits cross the magnetopause in the cusp region and also in both cases the really obtained crossing point differs from that predicted by usually utilized data based or numerical magnetosheath models.

CASE A: Cluster magnetosheath crossing orbit on 13 February 2001

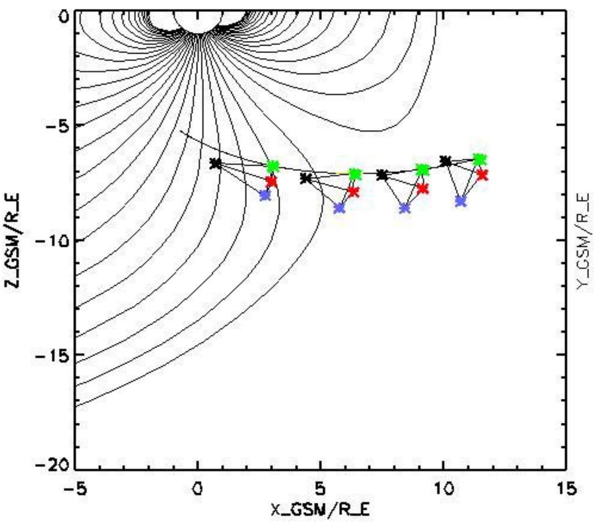

Figure 1. The Cluster orbit between 16:00 and 23:59 UT on 13 February 2001 in the x-z GSM plane (black, red, green and blue for Cluster 1-4 spacecrafts respectively). The magnetic field lines in this figure are drawn using T96 model field (Tsyganenko, 1995). From Cargill et al. (2004).

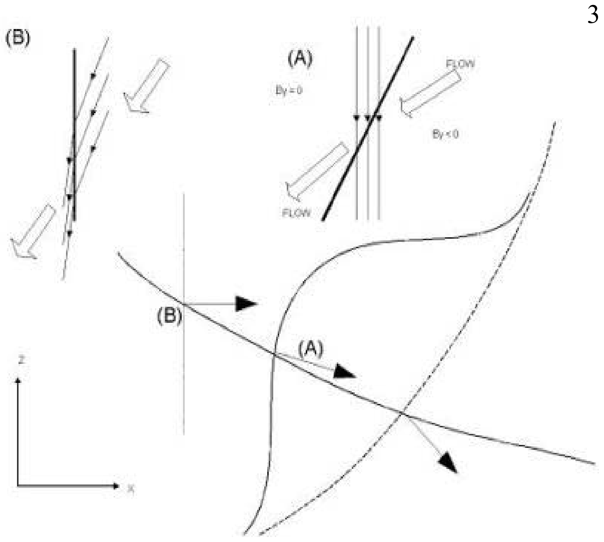

Figure 2. A sketch of the cusp encounter at 20:00 UT on 13 February 2001 (From Cargill et al. (2004)). A conjectured geometry is shown in the lower part. The sketches are not to scale. The solid line running from lower to upper left is the spacecraft trajectory. The outer dashed line is a sketch of a nominal magnetopause. The next (solid) line is a possible magnetopause geometry that gives rise to the measured normal (shown by arrow and labelled A). The upper right and left parts of the sketch show the magnetic field and plasma configuration at the outer and inner boundary, respectively

This case was investigated in details in the literature (Dunlop et al., 2004; Cargill et al., 2004; Amata et al., 2005; Savin et al., 2005). A fragment of the Cluster orbit near the magnetopause crossing is shown in Fig.1. The precise analysis of the simultaneous measurements by all four Cluster spacecrafts made it possible to determine in the cited works, besides of the plasma and fields parameters, also the magnetopause normal spatial variations and - as a consequence - the possible manetopause geometry, including a cusp indentation (see details in Fig.2, taken from Cargill et al. (2004).

CASE B: Interball-1 magnetosheath crossing orbit on 22-23 February 1997

It seems that this orbit, passing through the magnetosheath, is also a typical “candidate” to be an example of a cusp indentation crossing. The existing problem here (arising when using some “nominal” magnetopause shape, like Spreiter (Spreiter and Stahara , 1994) one) is the discrepancy between the identified by real Interball-1 measurements magnetopause crossing and the cross-point of the trajectory with model magnetopause (dashed magnetopause on the Fig.3.

Model implementation

A set of needed for model running input solar wind data were taken from ACE and WIND spacecrafts data archives respectively, “shifting” as usual these data by appropriate time, taking into account the solar wind speed. The needed Dst index was taken from Kyoto data center archine and the dipole tilt angle was computed for the considered time moments. The needed coordinate transformations were performed as to apply GSM coordinates to the model.

The used **input parameters for the CASE A**, corresponding to the magnetopause crossing in 20:00 UT on 13 February 2001 were appropriately shifted by time ASE solar wind plasma and magnetic field data, as follows: density $\rho = 5\ cm^{-3}$, velocity $V_x = 560\ kms^{-1}$, electron temperature $T_e = 150000\ K$; interplanetary magnetic field components: $B_y = 3\ nT$, $B_z = -5\ nT$. Specific heats ratio was taken to be 1.67. Dst index was -20.

The input data for the CASE B: The needed solar wind plasma and magnetic field parameters were obtained shifting appropriately by time data, measured on WIND spacecraft, corresponding to 20:20 UT on 22 February 1997: as follows: density $\rho = 6.7\ cm^{-3}$, velocity $V_x = 380\ kms^{-1}$, electron temperature $T_e = 176000\ K$; interplanetary magnetic field components: $B_y = -7.0\ nT$, $B_z = -1.0\ nT$. Specific heats ratio was taken to be 2 (the reason will be commented elsewhere). Dst index was -23.

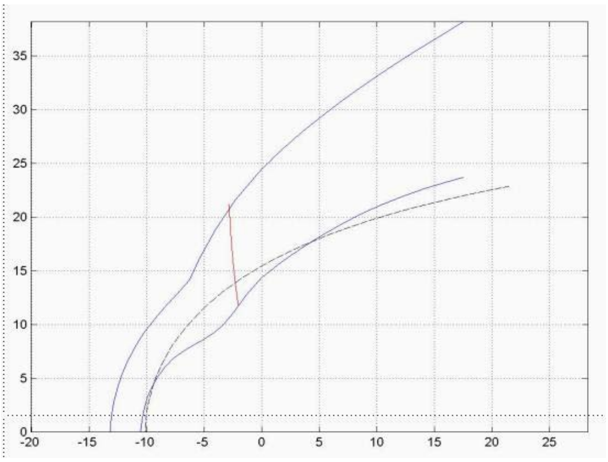

Figure 3. Cross-sections of the obtained magnetopause and shock shapes for the Case B (Interball-1, 22 February 1997, 20:20 UT, corresponding to the moment of the magnetopause crossing). The presented here cross-section is that, containing magnetopause crossing. The magnetopause, predicted for the same conditions by (Shue et al., 1997) model is plotted by dashed line.

It is well known that the precise procedure for comparing measured along the trajectory parameters with the obtained by the modeling values, requires numerous model runs with input data, related to as more as possible trajectory points. There are two basic criteria characterizing the model performance: (i) The coincidence between the measured and predicted positions of the shock wave and magnetopause crossings; (ii) The coincidence among parameter distributions along the trajectory. In this brief paper we consider only the magnetopause crossing and parameters near magnetopause as far as the possible cusp indentation may strongly affect them.

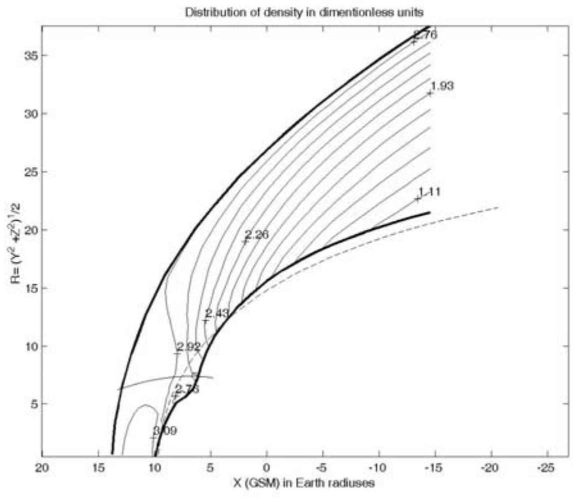

Figure 4. Magnetosheath cross-section containing magnetopause-crossing point of the Cluster 13 February 2001 orbit. This crossing point, obtained directly by data analysis, is labeled by circle on the trajectory line. The iso-lines of the computed by model dimensionless density distribution are plotted. The magnetopause, predicted for the same conditions by (Shue et al., 1997) model is plotted by dashed line.

As a result of the model runs for both cases, we obtain magnetopause shapes with cusp indentations (Fig. 4 and Fig. 5 for the Cluster and Interball-1 cases respectively). The determined directly from the data characteristics magnetopause crossings are labeled by circles on the orbit traces there. It is worth noting that a close look at the magnetosheath density distribution along the magnetopause cusp indentations, shown in Figs. 4, 5, demonstrates an agreement with the expected from gasdynamic (or MHD) point of view and predicted earlier for instance by Cargill (1999); Taylor and Cargill (2002). The predicted there (in idealized consideration) picture contains an extension wave over the indentation coast, which is near to the subsolar point, and a compressional wave (or even shock wave) affecting the other coast of the cusp indentation. The presented numerical results confirm in general similar tendency.

The above mentioned asymmetry on the “magnetosheath side of the cusp indentation corresponds to some asymmetry in the pressure distribution as well. The latter, compared with relatively more symmetric distribution of the “inside” magnetospheric magnetic pressure, could give rise to possible interesting speculations. Thus, the difference between inside and outside pressure on the magnetopause is shown (is some dimensionless parameters) in Fig. 7. It is seen that this pressure difference is essentially different in the labeled points on two coasts of the cusp indentation. It seems that numerical convergence cold

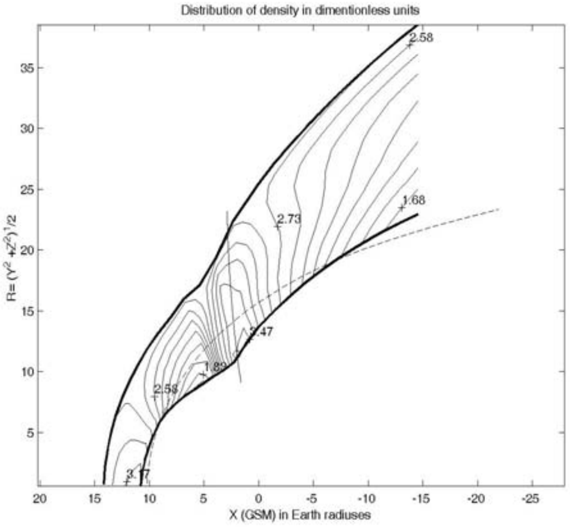

Figure 5. Magnetosheath cross-section containing magnetopause-crossing point of the Interball-1 22-23 February orbit. This crossing point, obtained directly by data analysis, is labeled by circle on the trajectory line. The iso-lines of the computed by model dimensionless density distribution are plotted.

be reached on this magnetopuse section only introducing some reconnection. The obtained by Cluster plasma velocity (30 km/s)normal to the magnetopause boundary (Cargill et al., 2004; Dunlop et al., 2004), in approaching the cusp, could be appropriate argumentation supporting such a possibility. Further investigations are needed to study this interesting aspect of the problem.

4. SUMMARY

Two satellite crossings of the magnetosheath are considered (Cluster orbit on 13 February 2001 and Interball-1 orbit on 22-23 February 1997), characterized by some similarities in magnetopause crossings. In both cases the obtained by measurements magnetopause crossings do not match their positions, predicted by data based or numerical models. In the considered Interball-1 case the magnetopause crossing essentially differs from that predicted by one of the widely used data based models (Shue et al., 1997). The considered here Cluster orbit has been thoroughly investigated in the literature and the replacement of the magnetopause crossing there from the predicted by idealized magnetopause models crossing point was explained in details by the presence of magnetopause cusp indentation.

Our model simulation obtains existence of a cusp indentation in both considered cases. A new numerical model of the system magnetosphere-magnetosheath was implemented in this simulation. It is shown that:

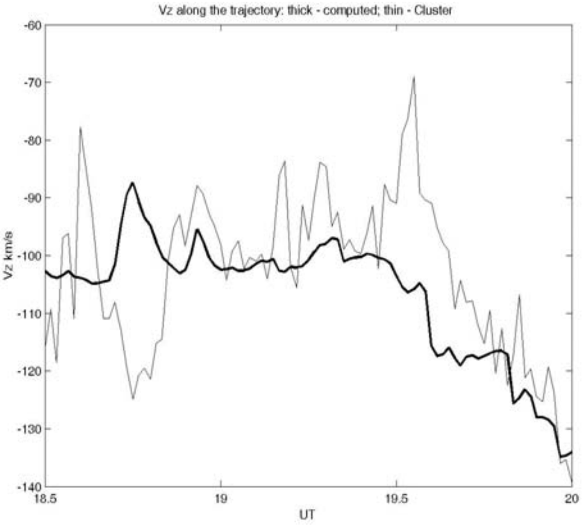

Figure 6. Comparison between the measured by Cluster (Thin line) and predicted by model (thick line)distribution of the Vz velocity component in approaching magnetopause (20:00 UT) through the magnetosheath

- The orbit crossings with the magnetopause in both cases coincides satisfactorily well with the model prediction under the appropriate solar wind and Earth-magnetosphere conditions
- The predicted by the model Cluster orbit for the considered case crosses the cusp indentation through its more distant from the nose coast. This is exactly as it was found by Dunlop et al. (2004) and Cargill et al. (2004) found earlier precisely analyzing Clusters data.
- In the Cluster case the measured V_z plasma velocity component undergos a specific trend, explained in above mentioned papers by the specific indentation geometry. The model predicts quite well this velocity behavior.
- Some questions for further investigations are posed concerning possible effect of reconnection, driven by specific gasdynamic pressure asymmetry caused by the cusp indentation geometry.

ACKNOWLEDGMENTS

This research was partially supported by the Bulgarian National Council "Scientific Research" under Project No NZ-1315/03. The work of M.K. and P.D. was sponsored by Air Force Office of Scientific research, Air Force Material Command, USAF, under grant number FA8655-05-1-3024 The work in Space Research Institute, Moscow was partially supported by RFBR grant No. 04-02-16152. The work of S.S. and E.A. was partially supported by INTAS-03-50-4872.

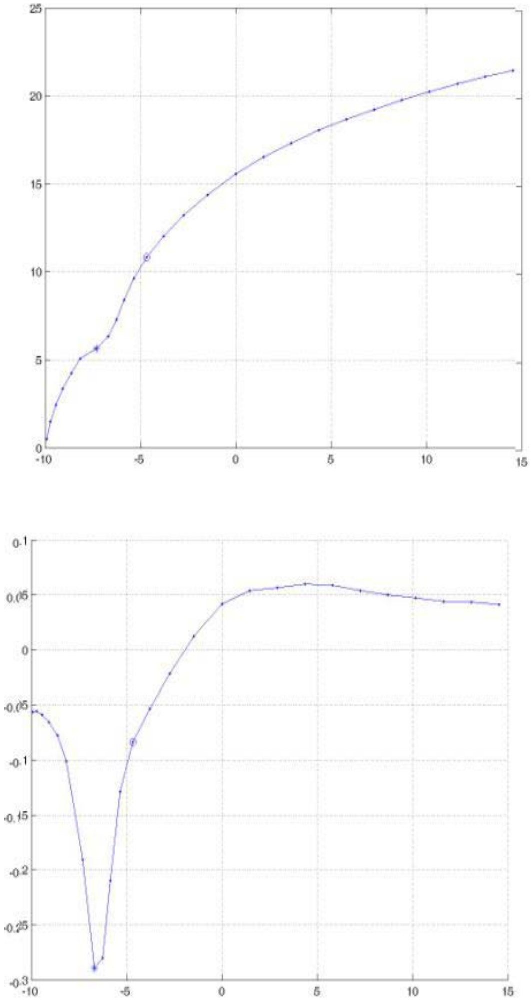

Figure 7. Bottom panel: *Difference between outside and inside pressure (in certain dimensionless parameter) over the magnetopause (shown respectively on the* upper panel*). Resut are from the model run for Cluster case, 13 February, 2001*

REFERENCES

Amata E., Savin S., Marcucci M. F., Cattaneo M. B., Andre M., Dunlop M., Khotyantsev Y., Decreau P. M. E., Rauch J. L., Trotignon J. G., Buechner J., Blecki J., Gough P., Buckley A., Skalsky A., Romanov S., Zelenyi L., Voloshevich A., Reme H., 2005, Subitted.

Boardsen S. A., Eastman T. E., Sotirelis T., and Green J. L., 2000, J. Geophys. Res., **105**, 23,193 - 23,219.

Cargill P. J., 1999, J. Geophys. Res., 2000, **104**, 14,647 - 14,653.

Cargill P. J., Dunlop M. W., Lavraud B., Elphic R.C., Holland D. L., Nykyri K., Baloch A., Dandouras I., and Reme H., 2004, altitude cusp: boundary structure and magbetic field depletions., Ann. Geophys., **22**, 1739- 1754.

Dobreva P. S., Kartalev M. D. , Shevyrev N. N., Zastenker G. N., 2004, Planet. Space Sci., **53**, 117-125.

Dunlop M. W., Lavraud B., Cargill P., Taylor M.G.G.T., Balogh A., Reme H., Glassmeier K. -H., Elphic R.C., Bosqued J. -M. , Fazakerley A. N., Dandouras I., Escoubet C.P., Laakso H., Marchaudon A., 2004, Kluwer Academic Publishers.

Eastman T. E. , Boardsen S. A., Chen S. -H., Fung S. F., and Kessel R., L., 2000, J. Geophys. Res., 2000, **105**, 23,221 - 23,238.

Kartalev, M. D., M. S. Kaschiev and D. K. Kojtchev, 1955, J. Comput. Phys., **119**, 220-230.

Kartalev, M. D., Nikolova V. I., Kamenetsky V. E. and Mastikov I. P., 1996, Planet. Space Sci., **44**, 1195-1208.

Kartalev, M. D., Keremidarska V. I., Grigorov K. G. and Romanov D. K., 2002, *in* ESA Publ. **477**, 555-558.

Kartalev, M. D., P. S. Dobreva, D. K. Kojtchev, V. I. Keremidarska, 2005, Self-consistent model of the system magnetosphere - magnetosheath, in preparation.

Keremidarska V. I. and M. D. Kartalev, 1998, *in* Finite Difference Methods: Theory and Applications, eds A. A. Samarskii et al., Nuava Science, U.S.A., 197-205.

Keremidarska, V. I. and M. D. Kartalev, 1999, J. Theor. Appl. Mech., *No* 1, .

Kojtchev, D. K., M. S. Kaschiev and M. D. Kartalev, 1998, *in* Finite Difference Methods: Theory and Applications, eds. A. A. Samarskii et al., Nuava Science, U.S.A., 126-138, 1998.

Magomedov, K. M., A. S. Holodov, Grid characteristic nomerical method, Nauka, Moscow, 1988.

Mead G.D., Beard D.B., 1964, J. Geophys. Res., **69**, 1169.

Roelof F. C. and Sibeck D. G. , 1994, J. Geophys. Res., **99**, 8787-8788.

Savin S., Amata E., Dunlop M., Khotyantsev Y., Decreau P. M. E., Rauch J. L., Trotignon J. G., Buechner J., Nikutoski, Blecki J., Skalsky A., Romanov S., Zelenyi L., Buckley A., Carozzi T. D., Gough P., Song P., Voloshevich A., Alleyne H., 2005, submitted.

Shue J. -H., Chao J.K., Fu H. C., Russel, Song P., Khurana K.K., and SingernH.J., , 1997, J. Geophys. Res., **102**, 9497-9511.

Sotirelis T., The shape and field of the magnetopause as determined from pressure balance, 1996, J. Geophys. Res., **101**, 15,255-15,264.

Sotirelis T., Meng C. -I., 1999, J. Geophys. Res., **104**, 6889.

Spreiter, J. R., S. S. Stahara, , 1994, Adv. Space Res., **14**, (7)5- (7)19.

Taylor M. G. G. T., Cargill P. J., 2002, J. Geophys. Res., **107**, 10,29/2001JA900159.

Tsyganenko, N. A., 1995, J. Geophys. Res., **100**, 5599-5612.

Tsyganenko, N. A., 2002a, J. Geophys. Res., **107**.

Tsyganenko, N. A., 2002b, J. Geophys. Res., **107**, 2002b.