Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 66, No 2, 2013

EXPLORATIONS COSMIQUES

MODELLING THE MAGNETOSPHERE RESPONSE TO THE PASSAGE OF AN INTERPLANETARY MAGNETIC CLOUD. INTERBALL-1 CROSSINGS

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(*Submitted by Corresponding Member P. Velinov on October 25, 2012*)

Abstract

We utilize the IMECH numerical model of the solar wind interaction with the system magnetosheath-magnetosphere in modelling this system interaction with interplanetary magnetic clouds. The used model integrates self-consistently a 3D numerical magnetosheath model and a modified Tsyganenko magnetosphere model with numerically-computed shielding field, providing in particular a 3D magnetosheath and shock wave geometries and positions. It is demonstrated that the relatively simplified model predicts adequately the magnetosheath structure, and especially – the magnetopause behaviour, as the parameters vary with the passage of a magnetic cloud. Special attention is paid to the magnetic cloud event on 10–11 January 1997 and Interball-1 crossing from the magnetosphere to the magnetosheath.

Key words: magnetic cloud, magnetosheath, magnetosphere, numerical modelling, extreme solar wind events

Introduction. This work considers one of the most interesting phenomena in solar wind observations – the magnetic cloud passage of 10–11 January 1997. A magnetic cloud is a solar wind ejection defined with a strong, slowly rotating magnetic field and low proton temperature [1]. A magnetic cloud, registered at

The work is supported by the Bulgarian National Council "Scientific Research" under Project DMU–03/88.

WIND in the beginning of January 10, passed the Earth and produced a major geomagnetic storm.

The extreme and unusual magnetic cloud event of 10–11 January was widely discussed in literature. The ability of the Shue 97 model [2] to predict Interball-1 and Geotail MP (Magnetopause) crossings for the given period has been tested in [3]. The unusual features of the plasma population in the Earth's magnetosphere, based on Interball-1 measurements, was presented in [4]. The observed Interball-1 MP crossings, much closer to the Earth than usual, were investigated in [5]. The relation between the magnetic cloud and the solar wind events was made in [1]. The impact on the Earth's magnetosphere, according to global MHD simulation, was presented in [6].

The observed strong magnetic cloud on 11 January 1997 possesses the typical characteristics of a magnetic cloud – a strong and slowly rotating magnetic field, low density and temperature between the leading and trailing edges of the cloud [7]. Unusual for this event is the movement of a highly dense region at the trailing edge of the cloud. This high dense region has an unusual composition, including relatively high – up to 10% helium ions proportion [1].

The presence of this condense partition at the rear edge is related to the density and respectively dynamic pressure enhancement. Two abrupt increases in the solar wind dynamic pressure were measured by WIND spacecraft in early January 11, 1997. The first one was at about 01:20 UT (Fig. 1*b*), when the pressure jumped from 10 to about 30 nPa. This enhancement was accompanied with the Interball-1 entry in the magnetosheath region. The second increase from 30 up to 50 nPa 20 min later compressed the dayside magnetopause earthward of geosynchronous orbit. The dynamic pressure decreased suddenly at 02:20 to 14 nPa, resulting in magnetopause expansion, associated also with the Inreball-1 return to the magnetosphere.

Our main purpose is to investigate the magnetospheric response to the magnetic cloud disturbance by comparing results from a physical model and the real crossings of Interball-1 spacecraft. This investigation includes the numerical simulation of the period 00:30 to 01:35 UT on 11 January 1997 and the interpretation of Interball-1 crossings, which includes the Interball-1 movement into the magnetosheath during the first pressure enhancement. The present research presents an opportunity to test the capabilities of the magnetosheath-magnetosphere model to predict the boundary crossings of the satellite under extreme solar wind conditions. A brief description of the implemented model follows.

Model description. Self-consistent model demonstrates the flexibility of the modular approach, combining two different models – those of the magnetosheath and the magnetosphere. The ideal gas dynamics approach is used for the description of the flow between the bow shock and the magnetopause. The flow in the magnetosheath is governed by the Euler's gas-dynamics equations in the 3D case. The applied numerical scheme is a slightly-modified grid-characteristic

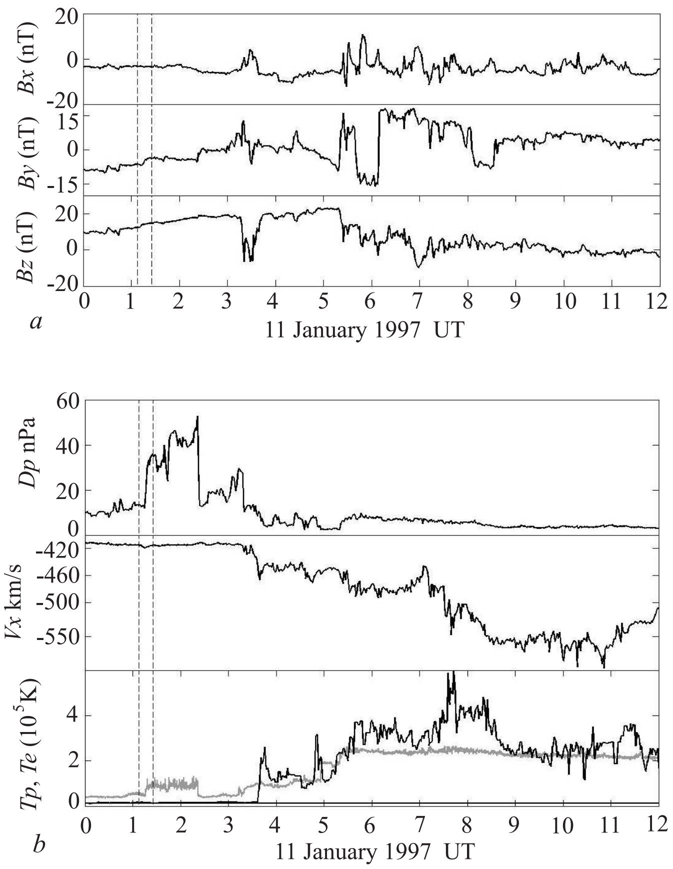


Fig. 1. Input data: *a*) Magnetic field vector components(IMF) for 11 January 1997; *b*) Plasma parameters – dynamic pressure(top), Vx velocity(middle panel), proton (black), and electron (gray) temperatures(bottom). Data are shifted in time

numerical approach developed by [8]. For better description of the day and night parts of the region, different coordinate systems are introduced in each of them – spherical coordinates in the dayside and cylindrical coordinates in the tail. The interaction between different regions takes place through the boundary conditions. Rankine–Hugoniot relations are applied at the points of the bow shock, while boundary conditions at the magnetopause are reduced to the pressure balance equation. As a final result of the magnetosheath task, the new positions of the boundaries are determined.

The present magnetosphere model could be considered as a generalization of the 3D finite element numerical model developed earlier in the Institute of Mechanics, Bulgarian Academy of Sciences [9]. The net magnetic field inside the magnetosphere in the present variant consists of: a) the Earth's dipole field B_d;

b) the field from different extraterrestrial current systems – cross-tail B_t; ring B_r and Birkeland B_b currents, and the field due to the Chapman–Ferraro currents B_{CF}. The field of the extraterrestrial current systems is calculated using the data-based magnetospheric magnetic field model of TSYGANENKO T96 [10] or T01 [11]. The experimental model of Tsyganenko is modified in the way to fit the physical statement of the solved problem. Namely, the data-based magnetopause incorporated in Tsyganenko model is omitted and consequently the shielding field, connected with that boundary form is used no more. The field of the shielding current system is calculated numerically, using the method of the finite elements. The field under determination B_{CF} is by definition curl and divergent-free and therefore, a harmonic scalar function – field potential U exists. Laplace equation is solved for the unknown potential

$$\Delta U = 0, \quad \nabla U = B_{CF}.$$

Neumann boundary condition representing a closed magnetosphere is set at the boundary

$$(B_{CF}, n) = -\partial U/\partial n = -[(B_d, n) + (B_t, n) + (B_r, n) + (B_b, n)],$$

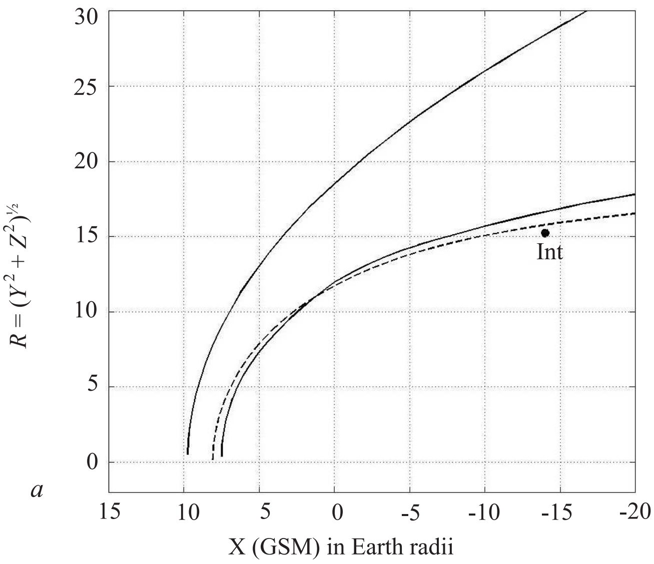
where n is the local normal.

At the beginning, some initial three-dimensional axi-symmetric shapes for the bow shock and magnetopause are posed. Then an iteration algorithm is performed, calling successively the magnetosheath and magnetosphere modules. The cycle continues until reaching convergency, which corresponds to achieving pressure balance on both sides of the magnetopause.

Input data for the self-consistent model are the parameters of the incoming solar wind flow: dynamic pressure Dp, By and Bz components of IMF, temperature $T = Te + Tp$, where Te is electron and Tp – proton temperatures. The polytropic index γ, the dipole tilt inclination and the Dst index of the geomagnetic disturbance are also set at the beginning of the calculation. More detailed description of the model performance can be found in the following papers [12–14].

Input data. As solar wind monitoring, we use the measurements of WIND satellite. The input data are shifted appropriately by the time of the propagation of the solar wind from WIND to the Earth. Taking into account that WIND is situated at about 93 R_E (Earth radii, in GSE) and the solar wind speed is 410 km/s, the calculated time shifting is 23 min. The fluctuation of the magnetic field components (Bx, By, Bz) for January 11, 1997 is presented in Fig. 1*a*. The corresponding solar wind plasma parameters are shown in Fig. 1*b*.

The algorithm used in the present data interpretation is similar to that used by the authors in previous studies [13–18]. The considered time period is divided into intervals with relatively uniform parameters and the calculations are performed for each set of average parameters characterizing the interval. For the



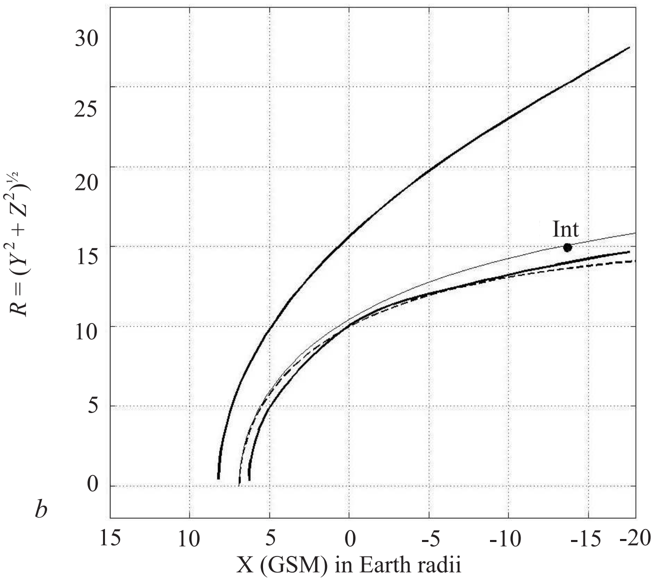


Fig. 2. *a*) Bow shock(outer curve) and magnetopause positions at 01:10 UT on January 11, 1997. The solid curve represents current magnetosheath-magnetosphere model, the dashed curve is the Shue 1998 magnetopause. Input parameters – $Dp = 10.3$ nPa, $Bz = 10$ nT, tilt $= -26°$. Interball-1 location is labeled with Int and marked with a black point. *b*) The same as Fig. 2*a*), but calculated for 1:25 UT with input parameters – $Dp = 30.3$ nPa, $Bz = 12$ nT, tilt $= -27°$. The gray curve is the model of Shue 97

event on 11 January 1997 magnetic cloud, the considered time period is from 00:30–01:35 UT (UT is already shifted). It is divided into two subintervals – [00:30–01:20 UT], [01:20–01:35 UT]. For each subinterval we choose one time and do the calculations with values typical of this time moment. The selected times are 01:10 UT, 01:25 UT respectively (marked with vertical dashed lines). The first time corresponds to the moment before Interball-1 entry in the magnetosheath, the second is connected to the spacecraft passage into the magnetosheath. *Dst* index (taken from Kyoto database) varies from 3 (at 1:00 UT) to 50 nT (at 2:00 UT), dipole tilt – from $-26°$ to $-27°$, and polytropic index γ is set to be 5/3.

Numerical results. The calculations from the model are obtained in dimensionless units. In order to transfer the model output values into their real physical dimensions, we multiply them by the used input values.

Interball-1 is a high-apogee satellite sent to study solar-terrestrial relations [19]. At 1:20 UT on 11 January 1997, Interball-1 moved from the magnetosphere to the magnetosheath, where it stays until 2:10 UT. At 1:20 UT, the satellite was located at a point with GSM coordinates (-14.0, 15.2, -1.0).

The next two figures consist of model results, calculated with input parameters, described in section "Input data". The location of the satellite and the calculations of the magnetopause positions from two models – the current (solid curve) and Shue 98 (dashed line) models, corresponding to the time moment of 01:10 UT are presented in Fig. 2*a*. Both models predict, that Interball-1 is in the magnetosphere, coinciding with the satellite observations. The picture represents a plane passing closest to the satellite location at the given time. Calculations are performed in GSM coordinates.

The pressure jump at 01:20 UT led to the magnetosphere compression and thus Interball-1 crossed into the magnetosheath. This is confirmed by the numerical calculations (Fig. 2*b*). Magnetopause positions, estimated from three models are presented – the present model(solid), Shue 98 [20] (dashed) and Shue 97 (grey). The magnetosheath-magnetosphere and Shue 98 models correctly predict that the spacecraft is in the magnetosheath. Only Shue 97 [2] predicts, that Interball-1 is in the magnetosphere, which is not a good approximation to the observed magnetopause crossings.

Summary and discussion. This is the first published test about the model performance under extreme solar wind conditions. The model adequately predicts the magnetopause compression caused by the dynamic pressure enhancement. This compression causes Interball-1 satellite entry into the magnetosheath, which is in good correlation with the outputs from the present model. The presented results show that the overall model is a reliable tool for describing the impact of the solar wind on the Earth, even in highly-disturbed conditions.

A segment with unusually high density at the trailing edge of the cloud pushed the dayside magnetopause earthward of geosynchronous orbit. Some of the satellites at geosynchronous orbit, like LANL 1994-084 and GSM 4, moved into the magnetosheath. The results from the model, concerning the geosynchronous crossings, will be presented in the accompanying paper "Modelling the magnetosphere response to the passage of an interplanetary magnetic cloud. Geosynchronous crossings".

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