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INTERDISCIPLINARY TOPICS

ION FLUX IN THE MAGNETOSHEATH: RESULTS FROM GAS-DYNAMIC MODELLING AND INTERBALL-1 MEASUREMENTS

Dedicated to Professor Zapryan Zapryanov on the occasion of his 90th anniversary

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ABSTRACT: In this work, the possibilities of the magnetosheath-magnetosphere model for describing the plasma parameters in the magnetosheath are demonstrated. We consider the problem of a flow around a body (the Earth's magnetosphere) with two movable boundaries – the bow shock (BS) and the magnetopause (MP). The grid-characteristic method is applied to describe an ideal gas flow in the transition region (magnetosheath). A theoretical finite element model and the semi-empirical Tsyganenko model are used to describe the magnetic field in the magnetosphere. The model allows a self-consistent determination of the magnetosheath boundaries for a given momentary state of the solar wind. For these input parameters the three-dimensional solution in the transition region is calculated. An analysis of the ion flux was made based on the model and the data measured by the Interball-1 satellite in several cases of magnetosheath crossings. The advantages and limitations of the model for describing the magnetosheath flow are analyzed.

KEY WORDS: magnetosheath; plasma parameters; gas-dynamics; numerical modeling.

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1 Introduction

The magnetosheath is a transition region that is formed in the interaction of the solar wind with the Earth's magnetosphere. It is a highly turbulent region as some of the perturbations are caused by the solar wind conditions and some are inherent to the magnetosheath itself. As a transition region it plays an important role in the transfer of energy from the sun to the magnetopause and, in particular, to the Earth. We need reliable magnetosheath models to understand the mechanism of this energy transfer.

A pioneering work in gas-dynamic modeling of the magnetosheath is the Spreiter and Stahara model [1]. A scheme for comparing the Spreiter model with satellite measurements was proposed by Song [2, 3] and such analysis was done for a number of events. However, the Spreiter model has a number of limitations, such as for example, the axisymmetric shape of the boundaries, which are not self-consistently determined.

The numerical magnetosheath-magnetosphere model provides new possibilities for interpretation of plasma parameters in the magnetosheath. The model was developed by a team at the Institute of Mechanics of the Bulgarian Academy of Sciences. In several cases, the model has already been applied to characterize processes in the Earth's magnetosheath. In the previous articles, various plasma parameters have been considered - comparison with the experiment was done for the density [4, 5], the velocity components [5, 6] and the ion flux [7, 8]. The satellite registered positions of the BS and the MP were compared with the boundary positions, obtained from the model [5–8].

In the present work, an analysis of the ion flux was made on the basis of the model and of the values measured by the Interball-1 satellite in several passes through the magnetosheath. We consider the ion flux variations in four cases – 24 May 1997 (Case 1), 25 February 1997 (Case 2), 01 March 1997 (Case 3) and 16-18 January 1997 (Case 4). Using our model, we investigate the ion flux under various solar wind conditions.

2 Brief Description of the Self-Consistent Magnetosheath-Magnetosphere Model

The description of the magnetosheath-magnetosphere system is based on the so-called modular approach. This approximation allows different models to be incorporated in each of the regions considered.

In our model, a magnetic field model is applied in the magnetosphere and an ideal gas model in the magnetosheath. An iterative algorithm is performed starting from initial shapes of the boundaries and a reasonable initial solution. The forms of the BS and MP are self-consistently determined during the iteration process (Fig. 1). The

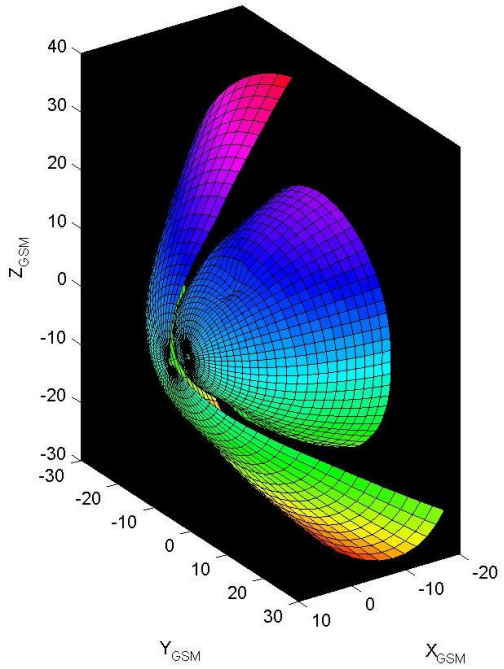

Fig. 1: 3D shapes of the BS and MP, calculated by the grid-characteristic method. Input parameters: dynamic pressure $P_d = 2$ nPa, Mach number $M = 8$.

method is sufficiently flexible to allow various features of the shape of the MP, such as the indentations in the cusp area, the north-south, and east-west asymmetries to be taken into account. In the magnetosheath, a three-dimensional solution is obtained, which includes the density, velocity and temperature. Other parameters such as ion flux and Mach number can be further calculated from the obtained solution.

The model is based on a single-fluid approximation, where the flow velocity is the ion velocity and the temperature is the sum of the ion and electron temperatures.

The flow in the magnetosheath is assumed to be inviscid, non-heat-conducting, compressible gas of infinite electrical conductivity. The solution in the magnetosheath is calculated with the grid-characteristics method [9, 10], while in the magnetosphere the problem of finding the Chapman-Ferraro currents is solved for a given three-dimensional asymmetric shape of the magnetopause by the finite element method. The field in the magnetosphere is calculated as a sum of different sources: the dipole field, the field, produced by the ring, Birkeland, tail currents, and that of the magnetopause currents, which is the subject of determination. The description of the ring and Birkeland currents is based on the Tsyganenko 2001 model [11], while the tail

current is based on the Tsyganenko 1995 model [12], as it provides a more reliable representation of the field in the equatorial tail region.

The magnetosheath-magnetosphere model uses as input parameters the ion density, velocity, temperature (which is a sum of the ion and the electron temperatures), B_y and B_z components of the interplanetary magnetic field (IMF), polytropic index γ. The other input parameters describe the current state of the Earth's magnetosphere. They are the Dst index, provided by Kyoto Dst indices service, and the magnetic dipole inclination (in rad), calculated for the given time moment.

Calculations are performed in 3D space in GSM (Geocentric solar magnetospheric) coordinates. As a rule, the model results are obtained in dimensionless units. The dimensionless values are converted into dimensional ones by multiplying them at each point by the corresponding parameters of the solar wind. Thus, we compare not relative, but real parameters values and real three-dimensional positions of the BS and MP.

3 Brief Description of the Comparison Algorithm and Input Data

The comparison algorithm is the one already proposed in previous articles [7, 8]. For solar wind monitoring we use data from the WIND satellite. The plasma data (velocity, ion number density and electron temperature) were measured by WIND/SWE (Solar Wind Experiment) device [13], the proton temperature - by the WIND/3DP (3D Plasma Analyzer) [14]. We use IMF data from the WIND/MFI(Magnetic Field Investigation) instrument [15]. Input data have a time resolution of 1.5 min for the density and velocity, 1 min for the magnetic field, 12 s for the electron temperature and 3 s for the proton temperature.

Interboll-1 was a high-apogee satellite [16], moving in an elliptic orbit with an apogee of 195000 km and a perigee in the interval 500–10000 km [17]. The main objective of the Interball project was to provide measurements to better understand the nature of the Sun-Earth interaction. The plasma measurements were provided by the VDP (omni-directional plasma sensor) device, containing 4 Faraday cups, one of them oriented along the Sun-Earth line, the other three – perpendicular to that axis [18]. Measurements have a time resolution of 1 s.

Figure 2 presents the satellite positions in the magnetosheath for the considered cases. The trajectory is located in the cusp area in Case 1, close to the terminator plane in Case 2 and Case 3 and at the tail – Case 4. The inner curve is the magnetopause from the Shue model [19], corresponding to solar wind values $P_d = 2$ nPa, IMF $B_z = 0$ nT. The outer curve is the shock wave position, obtained from the current model for the given magnetopause shape.

The incoming solar wind flux, measured by the WIND satellite for event 1 to event 4, is presented in Fig. 3. The moments of satellite crossings of the bow shock and magnetopause are marked with BS and MP respectively (Fig. 3).

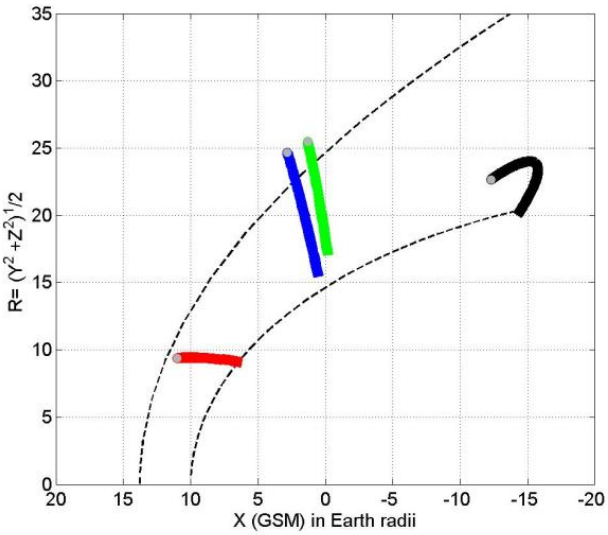

Fig. 2: Plot of Interball-1 magnetosheath orbits for the events under consideration: Case 1 (red), Case 2 (green), Case 3 (blue) and Case 4 (black). A projection in the plane $(X, (Y^2 + Z^2)^{1/2})$ is presented.

On 24 May the satellite was moving from the solar wind to the magnetosphere, crossing the BS at 6:20 UT and the MP at 9:17 UT. The curve (in red), shown in Fig. 2, is the Interball-1 orbit in the magnetosheath. The trajectory was almost in the main meridional GSE (Geocentric solar ecliptic) plane. In this case there is a drop in the solar wind flux of about 2 times (Fig. 3).

The conditions on 25 February were extremely quite with solar wind plasma parameters close to the mean ones (Fig. 3). Several BS crossings were registered at the intervals [3:00–3:20] UT and [4:00–4:36] UT. Since our goal is not to analyze multiple crossings, we will only consider the moment of the satellite's final entry into the magnetosheath, i.e. 4.36 UT. The satellite moved southward in the dusk sector, crossing the BS at 4:36 UT and MP at 19:20 UT. At the moment of the MP crossing the trajectory was close to the equatorial GSM plane.

On 01 March 1997 the spacecraft was at the dusk sector, moving southward (Fig. 2), crossing the BS at 1:15 UT and entering into the magnetosphere at 16:08 UT. At the moment of MP crossing the trajectory was close to the equatorial GSM plane. In this case the input ion flux changes a little during the interval considered (Fig. 3).

There was a significant change of solar wind flux in the last event 16–18 January. The input flux increased about four times, reached the peak at about 20:50 UT on

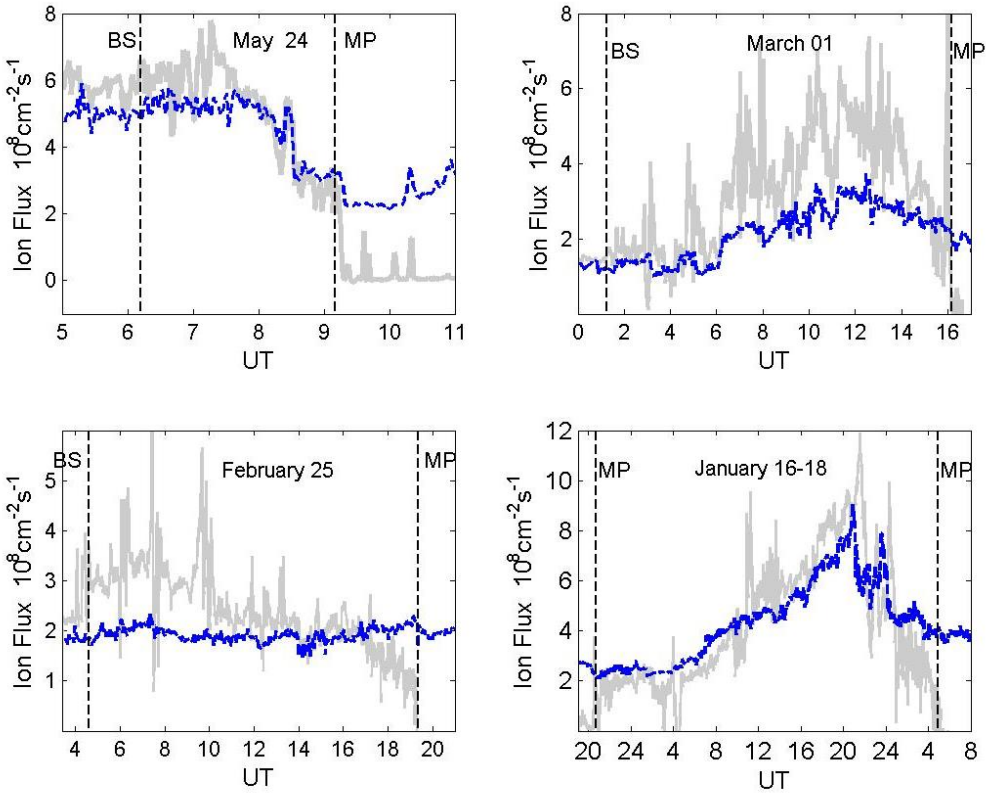

Fig. 3: Input solar wind flux, measured by WIND (blue) for Case 1 to Case 4. Interball-1 flux (gray) in the magnetosheath is given for comparison. WIND data are shifted in time.

17 January, then decreased again (Fig. 3). The satellite was at the tail (Fig. 2) at -13 -15 Re (Earth radii) in the dusk sector, moved from north to south, and in the second half of the interval was close to equatorial GSE plane. The satellite crossed the MP at 20:30 UT on January 16 and entered in the magnetosphere again at 4:53 UT on 18 January.

4 Numerical Results

A comparison between the modeled and satellite-measured ion flux for 24 May is shown in Fig. 4. The modeled flux is along the x-axis since the experimental one is measured along that axis. There is a flux drop after 7:30 UT that is due to a drop of the solar wind flux. It can be seen, that the model reproduces the trend seen in the measurements, with the model values being higher than the experimental ones near

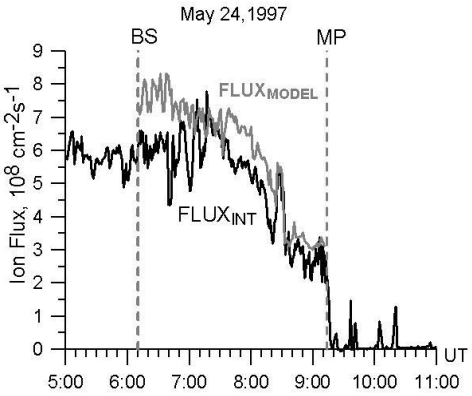

Fig. 4: Comparison of the modeled (grey) and experimental (black) ion flux along the satellite orbit for the Case 1.

the BS (around 6:30 UT).

A comparison of the calculated and measured ion flux for Case 2 is given in Fig. 5. The satellite remains in the magnetosheath about 15 hours (Fig. 3). The calculated values follow the variations of the experimentally measured ones, with the model

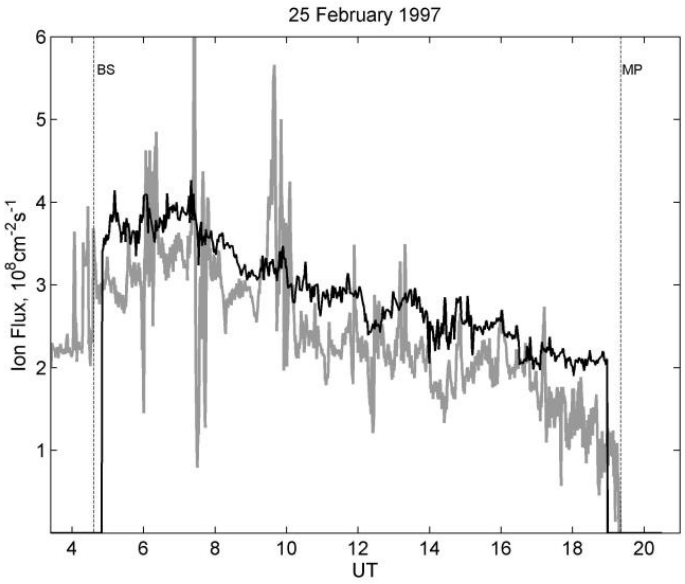

Fig. 5: Comparison of the modeled (black) and experimental (gray) ion flux along the satellite orbit for the Case 2.

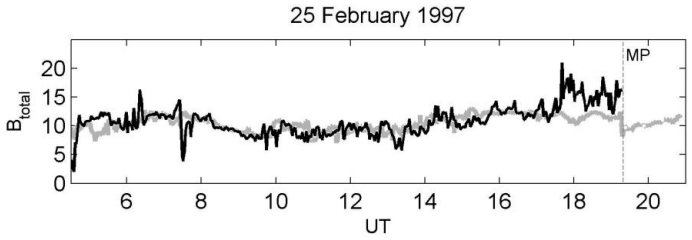

Fig. 6: WIND registered IMF (gray) and Interball-1 registered magnetosheath magnetic field (black) for the Case 2. WIND data are shifted appropriately.

values being higher by about 20% on average. In the interval close to the MP (after 17:00 UT) the measured flux drops and starts to deviate from the model predictions. The decrease is unrelated to the input data as the solar wind remains constant in this interval. This is associated with the satellite passage through a plasma depletion layer (PDL) [20], which is characterized by an increase in the magnetic field and a decrease in the density. Although most often the PDL occurs during northward IMF, the depletion of plasma has also been observed during events with southward IMF [21]. The depletion region (at the interval after 17:30 UT) can be identified in Fig. 6, where the IMF, measured by WIND (multiplied by a factor of 3 [22]) and the magnetosheath magnetic field, measured by the Interball tail probe [23], are plotted. Modeling of such a structure is beyond the scope of gas dynamics, but we can indirectly estimate the thickness of the depletion layer to be 1.5 Re, calculated as the distance from the model magnetopause to the position of the satellite at the time of the flux drop (17:00 UT).

Figure 7 shows a comparison between the model and the experimental ion flux for the case of 01 March, when the satellite crosses near the terminator plane and remains in the magnetosheath about 15 hours. It can be seen that in the interval after 5:00 UT there is an extremely good coincidence between theory and the experiment, the difference being 4%. The discrepancy is obtained in the interval from the BS crossing at 1:15 UT to about 5:00 UT. This is due to the fact that in this interval, the magnetic pressure dominates over the dynamic pressure in the solar wind and the Alfven Mach number is less than the average value of 8. The plot shows an acceptable coincidence between the observed and calculated distribution at the 40 min interval before the MP crossing (unlike the previous case). In this case, the solar wind conditions do not favor the PDL formation, as the IMF is almost aligned with the velocity vector. Moreover, the solar wind flux also drops in this interval (Fig. 7).

On January 16 (Case 4) Interball-1 was situated in the tail magnetosphere. In this event the satellite did not cross the bow shock, it crossed the magnetopause twice

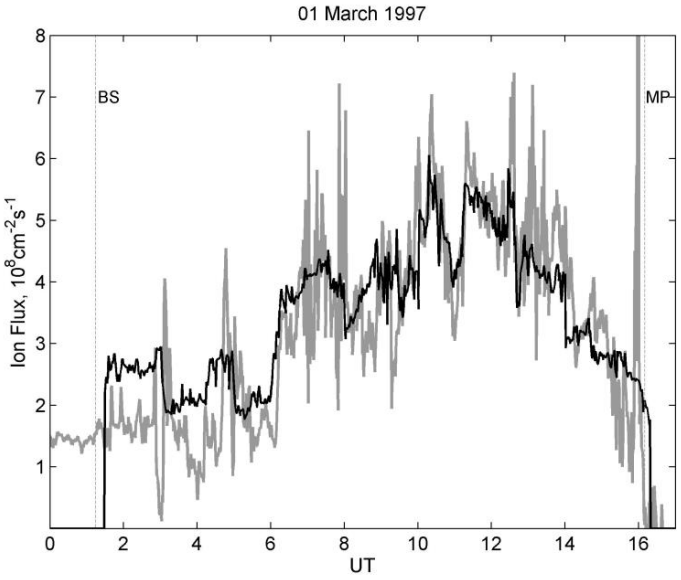

Fig. 7: Comparison of the modeled (black) and experimental (gray) ion flux along the satellite orbit for the Case 3.

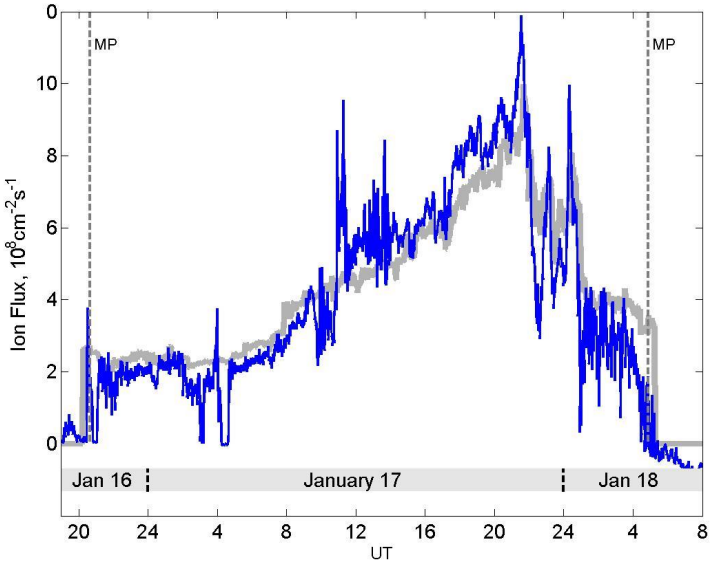

Fig. 8: Comparison of the modeled (gray) and experimental (blue) ion flux along the satellite orbit for the Case 4.

(Fig. 2). The comparison between the measured and calculated flux (Fig. 8) shows that the model values coincide well with the values from the experiment. In this case the increase of the flux in the magnetosheath is due to a change of the solar wind conditions.

5 Summary

The aim of this article is to describe the advantages and limitations of a gas-dynamics model for describing the ion flux in the magnetosheath. An analysis was made of the results of 4 events in which the satellite passed through the magnetosheath. It is shown, that the gas-dynamic model reproduces accurately the plasma variations in the magnetosheath. The electromagnetic terms are neglected in gas dynamics equations and not only this model, but the gas dynamics models in general are limited in describing local structures where the magnetic terms play an important role.

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