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Near-magnetopause magnetosheath in 3D gasdynamic module of the numerical magnetosheath–magnetosphere model

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Abstract

This paper describes an approach to a theoretical interpretation of Interball-1 satellite measurements data in two cases of the satellite's crossings of the magnetosheath. An interpretation is made of both the measured crossings of the magnetosheath boundaries and the behavior of the registered plasma parameters. In our case, it is the value of the ion flux along the spacecraft trajectory. The magnetosheath–magnetosphere model, developed at the Institute of Mechanics, Sofia, Bulgaria, is used as a theoretical basis. It describes the interaction between the solar wind and the Earth's magnetosphere in a simplified gas-dynamic approximation. A characteristic feature of the model is that it allows for the self-consistent description of the magnetosheath boundaries – the bow shock (BS) and the magnetopause (MP). The three-dimensional picture of the magnetosheath fluid flow is also obtained as part of the solution. The magnetosheath characteristics thus obtained are in correspondence with a given momentary state of the interplanetary medium, defined on the basis of WIND satellite data (appropriately shifted by time). The results are discussed in the context of advantages and limitations of using the gas-dynamic model for the interpretation of magnetosheath plasma measurements in the near-magnetopause magnetosheath.

Keywords: Interball-1; Magnetosheath; Plasma parameters; Gas-dynamics; Numerical modeling

1. Introduction

Earth's strong magnetic field serves as a shield by creating around the Earth a protective area – the magnetosphere, in order to protect the planet from the surrounding solar plasma. Since the solar wind is a supersonic flow, a bow shock is also formed. A transitional area, the magnetosheath is formed between the magnetosphere and the BS, whereby the solar wind slows down, heats up and become more compressed. Additionally, in its effort to pass around that obstacle, the solar wind deviates significantly from the Sun–Earth direction. Understanding the processes that take place in the transitional area will advance the explanation of the way in which the Earth's surface is affected by solar wind disturbances.

Some classical models, above all that of Spreiter et al. (1966) and Spreiter and Stahara (1980) have been used for the description of the magnetosheath plasma parameters. The model is based on the gas-dynamic theory describing the interaction between the solar wind flow and the Earth's magnetosphere, and outlines the magnetosheath distribution of the plasma parameters in a two-dimensional approximation. Analysis of the Interball-1 satellite data by means of the Spreiter et al. (1966) model has been the object of numerous publications – Nemecek et al. (2002) and Zastenker et al. (2002), etc. The effect of solar wind on the magnetosheath's characteristics is partly taken into account in the Spreiter et al. (1966) model. The BS position is determined as a function of the Mach

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number and the polytropic index γ. However, the Spreiter et al. (1966) model was developed long ago and shows some deficiencies. The MP shape is strongly axisymmetric and not self-consistent, and it does not take into account, for example, the dependence on the dynamic pressure, the cusp indentations, etc. Therefore, a comparison necessitates the scaling of either the spacecraft trajectory or the boundary position, so that the registered crossing should coincide with the boundary. It is only then that the model calculations and the data analysis are made.

Another model, although working in a magnetohydrodynamic approximation, has also been used for experimental data analysis – Samsonov et al. (2001, 2007). In its initial variant, the model has been developed for description of the subsolar point region – Samsonov et al. (2001). It has been then extended to include the flank region, and comparison with the Cluster data showed some good correspondence – Samsonov et al. (2007). That model, however, is not self-consistent either, since the boundaries are idealized and their description is via rotational surfaces.

The magnetosheath–magnetosphere (MM) model has been so far applied to Interball-1 experimental measurements analysis – Dobreva et al. (2005, 2006) and Zastenker et al. (2008). The analyzed crossings were mainly in the dayside – in either the cusp region or close to the subsolar region. The model has been used for the comparison of plasma parameter values along the spacecraft trajectory – mainly the measured ion flux – Dobreva et al. (2005, 2006). In some cases, other parameters have also been compared, e.g. ion number density and the three magnetosheath flow velocity components – Zastenker et al. (2008). It has been demonstrated that the model recreates well the influence of external parameters on magnetosheath parameters behavior. Additionally, the model recreates the influence of the magnetosheath's own processes on parameters behavior, e.g. during the satellite travel in the cusp region close to the midday–midnight meridional plane.

For the purpose of this study, two cases have been chosen of Interball-1 magnetosheath crossings – 25 February 1997 and 01 March 1997. We used the magnetosheath–magnetosphere model as a theoretical tool to describe the ion flux behavior along the satellite trajectory inside the magnetosheath. In the contest of our model, for the first time we interpret data in the region close to the magnetopause (near-magnetopause magnetosheath). One of the events was related to the passage of the satellite through the plasma depletion layer (PDL) – a layer near the magnetopause with lower plasma density and higher magnetic field, compared to the corresponding upstream magnetosheath parameters – Wang et al. (2003). The obtained results are discussed in the context of the gas-dynamic approximation.

The following is a brief presentation of the model, the input and experimental data used in the interpretation, and analysis of the model–experiment comparison.

2. A short description of the magnetosheath–magnetosphere self-consistent model

We have used the so-called modular approach to describe the system of interconnected regions. This approach allows for the application of different methods and physical models for each region analyzed. In our study, a model of magnetosheath ideal gas and a magnetospheric magnetic field model have been used.

The flow in the magnetosheath region is assumed to be compressible, inviscid, non-heat-conducting gas of infinite electrical conductivity. A specific feature of our formulation is that the shape of the obstacle is also being determined in the process of finding the solution. The algorithm accounts for such shape characteristics as the dawn–dusk asymmetry and the north–south asymmetry (due to the non-zero dipole tilt angle).

The magnetosphere model is based on the classical formulation of the Chapman–Ferraro problem for the determination of the MP currents confining the magnetospheric magnetic field inside a given 3D magnetopause shape. The calculation of the magnetospheric source field (ring and Birkeland currents) is based on the T01 – Tsyganenko (2002) experimental model. T96 variant – Tsyganenko (1995) is used for the tail current calculation, as it enables more accurate representation of that current system.

In our model construction the solar wind interaction with the Earth's magnetosphere is described within the framework of a single-fluid approximation. In our approximation, the velocity of the fluid is the ion gas velocity, while the temperature is the sum of the temperatures of the ion gas and the electron gas: $T = T_p + T_e$ (T_p being the temperature of the protons, T_e – of the electrons). The approach used here is different from the previous version – Dobreva et al. (2005), where the temperature of the fluid was just the electron temperature.

The current version also differs from the previous one in the use of highly refined finite element grid in the magnetosphere. In contrast to the 188 element mesh in Dobreva et al. (2005), an 1504 element approximation is used here. It allows much smoother and more precise description of the magnetopause, especially in the region of the cusp indentation. In order to improve the accuracy we need more computational resources. Optimization compilation techniques were adopted to parallelize considerable portion of the code in order to reduce the computational time – Dobreva (2013).

The features mentioned above are mainly related to the accuracy and the performance of the algorithm execution. The physical framework of the model, used in this work, was previously described in more details in Dobreva et al. (2005, 2008).

3. Data interpretation procedure

3.1. Interball-1 measurements.

Interball-1 was a high-apogee satellite, whose primary objective is to study the Sun–Earth interaction processes