Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 38 (2006) 616–626
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

A new model of Mercury's magnetospheric magnetic field

James Scuffham *, André Balogh

Space and Atmospheric Physics Group, Department of Physics, Imperial College London, SW7 2BW, UK

Received 1 November 2004; received in revised form 5 August 2005; accepted 30 August 2005

Abstract

Two new missions will arrive at Mercury within the next decade. Interest in this enigmatic planet has therefore been revived in the magnetospheric community, and new models of Mercury's magnetic field are demanded. In the past, there have been several attempts to model the magnetosphere of Mercury based on simply scaling models of the Earth's magnetosphere. Although these scaled models have enjoyed many successes, their global magnetic configurations are determined by measurements made at the Earth, not at Mercury. In this paper, we develop a new empirical model of the Hermean field which is constrained wherever possible by the Mariner 10 dataset. We also explore the response of the model to upstream solar wind conditions. Data-based empirical models are an invaluable tool in magnetospheric physics at the Earth, and will doubtless prove to be just as useful at Mercury. The model developed here is generally applicable, and can be used to fit a much larger spacecraft dataset when it becomes available.

Keywords: Mercury; Magnetic Field; Magnetosphere

1. Introduction

Almost 30 years have passed since Mariner 10, man's sole mission to the planet Mercury, transmitted its final data to Earth. The brief glimpse this data offered has greatly enhanced our knowledge of this enigmatic planet, but Mercury is far from being understood. New in situ data is soon expected from Mercury: NASA's MESSENGER and ESA/JAXA's BepiColombo missions will arrive at the planet within the next decade. This has sparked a renewed interest in the planet, and particularly in its magnetic field, since this holds vital clues to the puzzle of Mercury's internal structure and thermal evolution. The interaction of Mercury with the solar wind is also of great interest, because of all the planets we have explored, it most closely resembles that of the Earth. Mercury has a mini-magnetosphere, much smaller than the Earth's both in absolute size and in relation to the radius of the planet. Its magnetosphere is highly dynamic; solar wind driven convection is the dominant plasma transport process. There are no trapped particles, and therefore no permanent ring current can form at Mercury. In addition, field aligned currents may be insignificant due to the lack of a substantial ionosphere.

The imminence of these new missions has revived interest in Mercury, and new numerical models of its magnetosphere have begun to emerge. Data-based empirical models have proved to be an invaluable tool in magnetospheric science; models of this type have been widely used for the Earth (Tsyganenko, 2002), and similar models are being developed for Jupiter and Saturn. Such a tool will doubtless also be required for Mercury as soon as enough data becomes available. This paper describes initial attempts to develop such a model. In this work, we construct a new empirical model of Mercury's magnetosphere. Our objective is to make use of the limited dataset wherever possible, without resorting to scaling arguments. Our ultimate goal is to use the model in the science planning stages of the BepiColombo mission. The foremost requirement of the model is therefore its accuracy. As far as the very limited dataset will allow, the model must accurately represent the real Hermean magnetic field. The model should also be

* Corresponding author. Tel.: +01293428270.
E-mail addresses: james.scuffham@physics.org, phm3js@surrey.ac.uk (J. Scuffham).

0273-1177/$30 © 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2005.08.052

globally applicable, since the two BepiColombo orbiters will explore both the inner magnetosphere and the deeper tail regions. Finally, the model must be simple enough that an ordinary desktop computer is capable of running the code.

The paper first describes the structure of the proposed model, and its parameterisation in terms of upstream solar wind conditions. The response of the model to the interplanetary magnetic field (IMF) and solar wind dynamic pressure are then explored, with some predictions made regarding the frequency of direct solar wind access to the surface.

2. The structure of the model

The proposed model is modular, representing each magnetospheric current system separately. Since no permanently trapped particles are expected to exist at Mercury, we do not include a module representing a ring current. Similarly, no field aligned current module is included, due to the numerous uncertainties regarding their nature, strength and closure path. The remaining modules, representing the internal field, magnetopause currents, magnetotail and reconnection are discussed in turn in the following sections.

2.1. Internal field

There is a great uncertainty surrounding the Hermean internal field. Attempts to describe its character by various methods produce a wide variety of different results. The problem is that the flyby data we have to work with has inherent non-uniqueness; the two Mariner flybys occurred with the same side of the planet facing the spacecraft. Essentially, there is insufficient data to constrain sophisticated models of Mercury's internal field (see Connerney and Ness (1988) for more details). For this reason, we do not attempt to model a complex internal field for Mercury, but limit ourselves to a simple, untilted dipolar field.

The exact choice of the value of the dipole moment to use in the model is somewhat arbitrary, given that all the estimates given in the literature are equivalent. We have therefore chosen to use the mean value of all the available estimates, -228 nT R_{M}^3, as the parameter for our model.

2.2. Magnetopause shape

The dominant factor governing the contribution of the magnetopause currents to the overall field is the geometry of the magnetopause. Some considerable effort was therefore expended in deciding the precise shape and size of the magnetopause that should be used in the model. Previous studies (Russell, 1977; Slavin and Holzer, 1979a) have traditionally considered all four of the crossings locations together, and fitted a conic section to them in the same way as has been done for large numbers of crossings at the Earth. In this work, we have chosen to consider each crossing individually. This will allow us to take account of any change in upstream conditions and magnetospheric state that may have occurred between the crossings. However, a single point in space does not provide us with sufficient information to constrain a three-dimensional model shape. To make the problem tractable, we first assume that the magnetopause is cylindrically symmetric about the planet-Sun axis, and we supplement the crossing location data with the normal vectors provided by minimum variance analysis (MVA). MVA has been carried out on three of the four crossings by Russell and Walker (1985). The outbound crossing of the first flyby was not analysed by Russell and Walker, apparently due to the temporary loss of the appropriate data by NASA. That data has now been made available, and we have performed a minimum variance analysis on the crossing. A normal vector direction of (0.398, −0.836, 0.338) was found, with a intermediate to minimum eigenvalue ratio of 2.54. This direction remains consistent if the crossing is analysed over nested intervals.

The empirical shape we have chosen to use for the model is that of Shue et al. (1998). This choice was made because of that model's success in representing the magnetopause of the Earth. The shape is defined by the parametric equation:

$$r = r_0\left(\frac{2}{1+\cos\theta}\right)^{\alpha}, \tag{1}$$

where r_0 is the standoff distance and α controls the rate of tailward flaring. The model magnetopause surface should satisfy two conditions simultaneously: it should contain the Mariner 10 crossing location, and its normal vector at the crossing location should match the MVA result. We therefore minimise the following quantity

$$M = \cos^{-1}(\hat{\mathbf{n}}\cdot\hat{\mathbf{m}}) + |r_{\mathrm{c}} - r|, \tag{2}$$

where $\hat{\mathbf{n}}$ and $\hat{\mathbf{m}}$ are the model and MVA normal vectors respectively. r_{c} is the observed crossing radius and r is that of the model. This merit function has a minimum when the radii are equal and the angle between the model and MVA normals is zero. Fig. 1 illustrates the results of this fitting procedure for all four crossings, and the numerical results are displayed in Table 1.

The extrapolation of a single point in space into a fully three dimensional shape may obviously be subject to significant error. However, it is the aim of this work to squeeze as much information as possible from a severely limited dataset, so our approach is justified. It is instructive to compare the results with those of previous studies. Of these, the most comprehensive is that of Slavin and Holzer (1979a), who inferred magnetopause standoff distances from both the bow shock and magnetopause crossings of Mariner 10. Our results predict smaller standoff distances than those reported by Slavin and Holzer, although MP2 agrees closely with their bow shock estimate (Table 1). The behavior of the magnetopause during the first flyby appears to be similar in both studies, with the standoff distance increasing from MP1 to MP2. The third flyby,