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Three Dimensional MHD Modeling of Mercury's Magnetosphere During ICMEs

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Introduction

NASA's MESSENGER mission will enter its orbit about Mercury in 2011 and make observations of this magnetosphere during solar maximum when encounters with Interplanetary Coronal Mass Ejections (ICMEs) are most likely. We use the BATS-R-US MHD model, modified to simulate Mercury's magnetosphere, to investigate the response of this small magnetosphere to ICME conditions. Mercury is treated as a sphere with limited conductance, and the spherical simulation grid is set to have an inner boundary just above one R_M. A control case is established consisting of typical quiet time solar wind conditions. The low Alfvén Mach number regime is then systematically explored using series of steady state simulations in which the IMF Bz is steadily decreased. We find that Alfvén wing formation takes place during extreme ICME conditions as predicted by earlier analytic calculations. Finally, we simulate Mercury's interaction with a realistic ICME event whose values are chosen to be consistent with an event measured by Helios 1 on June 20, 1981 at 0.34 AU.

Idealized Cases

The typical quiet time solar wind conditions are chosen as follows: The plasma properties are $n_{sw} = 35\text{cm}^{-3}$ and $v_{sw} = 400\text{km/s}$ [1], and the magnetic field is set according to the Parker spiral with $B_x = -15\text{nT}$, $B_y = 5.45\text{nT}$, and $B_z = 0\text{nT}$. In contrast, during ICMEs, the magnetic field magnitude can increase to more than 100nT leading to extremely low Alfvén Mach numbers (M_A). To study this situation in an idealized manner, we slightly reduce the velocity and lower the magnetic field B_z to strongly negative values.

Figure 1 summarizes some of the results of these idealized cases. On the right hand side of the figure, we show quiet time configuration. The relatively large B_x component introduces a significant a significant asymmetry between the northern and southern lobes. The magnetospheric configuration we calculate is in very good agreement with prior studies [2]. The left hand side of the Figure demonstrates the low M_A configuration of the magnetosphere that may occur when

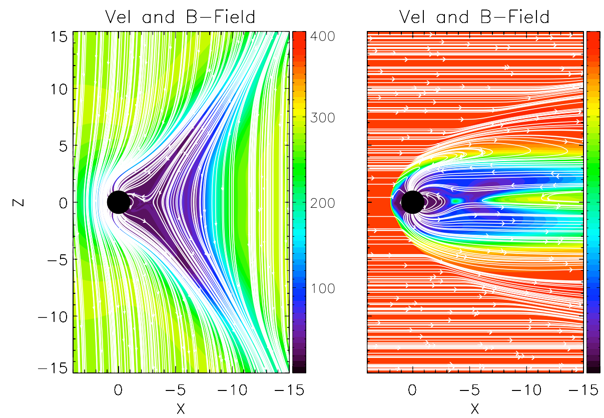

Figure 1: The figure shows the results of MHD simulations of Mercury's magnetosphere. The color represents total velocity, and the white stream lines represent magnetic field. The plot on the left shows a case where the Alfvén Mach number is less than one. The plot on the right shows the result for typical solar wind conditions.

Mercury encounters an ICME. At this time the dayside magnetopause is eroded, and the lobes begin to separate causing significant flaring in the tail.

Figure 1 illustrates two special cases (normal and strongly disturbed), but the entire transition between these cases is also studied. We accomplish this by conducting a sequence of steady state simulation with progressively increasing solar wind M_A from below one until we reach typical conditions. Between an M_A of 1 and 2 the solution appears as a hybrid of the solutions in Figure 1 with separation between the lobes and the flaring in the tail decreasing as the Mach number increases. Once the Mach number exceeds two a well defined bow shock is formed, the lobe separation is minimized, and the magnetosphere appears more similar to the quiet time case. In general, the transition between low solar wind M_A and typical Hermean magnetosphere manifests itself as a superposition of the two cases trending towards the typical case as the M_A increases. Our result is similar to past studies of the Earth's magnetosphere during low M_A solar wind conditions [3, 4].

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Mercury's Interaction With an ICME

The MESSENGER spacecraft will enter orbit during solar maximum and it will likely observe Mercury's magnetosphere as it interacts with ICMEs. In the previous section we discussed idealized simulations that focus on a single aspect of such interactions. During an ICME, however, much more dynamic behavior is expected that can simply not be captured by steady state simulations. We therefore carry out a time-dependent simulation of a realistic ICME impinging on Mercury's magnetosphere.

Figure 2 shows Helios 1 measurements of an ICME at 0.34 AU. We use these data to provide a time-dependent boundary condition to our model. Using 128 processors on the the Pleiades supercomputer, we simulated the entire 14 hour event in approximately 39 hours (about 36% real-time).

We find a number of interesting features in this time-dependent study. During the early part of the event the Alfvén Mach number drops to almost one, leading to a wing-like separation of the lobes. Unlike in the steady state case, the solution has a North-South asymmetry owing to the strong B_X component. Moreover, lobes separate and come together on an extremely short time-scale. Other interesting features include the formation of plasmoids and flux transfer events. Such features were observed in-situ by MESSENGER during the previous fly-by [5]. A particularly interesting time-period is between 9-12 UT, where the IMF B_X rapidly switches between strongly positive and negative values. This rapid switching appears to drive a series of plasmoids in the tail in much the same way that a B_Z southward turning would. Solar wind sector crossings also involve strong B_X changes, and our result suggests that Mercury's encounter with them would be of keen scientific interest.

We finally examine how the solar wind impingment on Mercurys surface during ICMEs changes over time. During periods of particularly strong driving with B_Z south, a larger than normal fraction of the magnetic flux opens allowing for more direct access to the surface. Tracking the time history of the solar wind impingment on Mercury's surface will allow us to assess the variability in the sodium exosphere during an ICME.

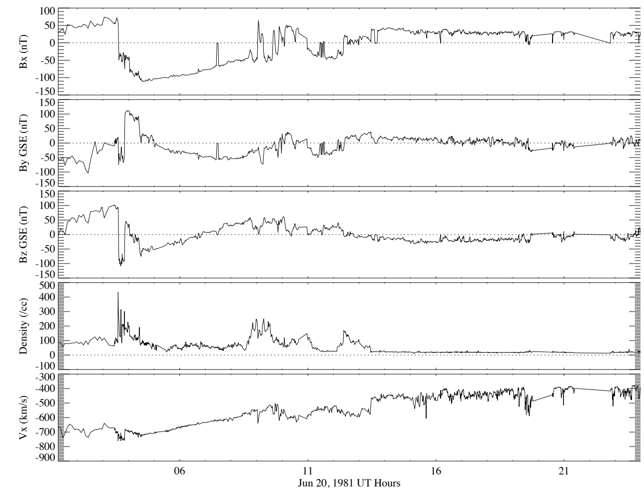

Figure 2: The above plot shows Helios 1 measurements at 0.34 AU [1]. These conditions are used to drive the simulation of Mercury's interaction with a realistic ICME.

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