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# The interplanetary magnetic field environment at Mercury's orbit

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## ABSTRACT

Mercury is exposed to the most dynamic heliospheric space environment of any planet in the solar system. The magnetosphere is particularly sensitive to variations in the interplanetary magnetic field (IMF), which control the intensity and geometry of the magnetospheric current systems that are the dominant source of uncertainty in determinations of the internal planetary magnetic field structure. The Magnetometer on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft has made extensive magnetic field observations in the inner heliosphere over the heliocentric distances of Mercury's orbit, between 0.31 and 0.47 AU. In this paper, Magnetometer data from MESSENGER, obtained at rates of 2 and 20 vector samples per second, are used together with previous observations in the inner heliosphere by Helios and at Earth by the Advanced Composition Explorer, to study the characteristics of IMF variability at Mercury's orbit. Although the average IMF geometry and magnitude depend on heliocentric distance as predicted by Parker, the variability is large, comparable to the total field magnitude. Using models for the external current systems we evaluate the impact of the variability on the field near the planet and find that the large IMF fluctuations should produce variations of the magnetospheric field of up to 30% of the dipole field at 200 km altitude, corresponding to the planned periapsis of MESSENGER's orbit at Mercury. The IMF fluctuations in the frequency range $10^{-4} < f < 10^{-1}$ Hz are consistent with turbulence, whereas evidence for dissipation was observed for $f > 1$ Hz. The transition between the turbulent and dissipative regimes is indicated by a break in the power spectrum, and the frequency of this break point is proportional to the IMF magnitude.

## 1. Introduction

Understanding Mercury's magnetic field depends critically on quantitative specification of external current systems, which are primarily determined by the solar wind and its embedded interplanetary magnetic field (IMF) imposed on the planetary magnetosphere (e.g., Siscoe et al., 2000). The magnetospheric configuration and current systems are particularly sensitive to the IMF and its variability in direction and intensity (Kabin et al., 2000). To predict the dynamic response of Mercury's magnetosphere and to identify time intervals with quiet magnetospheric conditions, those most suitable for establishing the planet's intrinsic magnetic moment and field geometry, it is therefore necessary to determine the characteristic variability of the IMF in the heliocentric distance range of Mercury's orbit. Vector measurements of the IMF in the inner heliosphere have been made by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft during the cruise phase of the mission and allow for detailed studies of the IMF environment in Mercury's orbital zone.

The MESSENGER observations complement IMF measurements in the inner heliosphere by other spacecraft. Observations by the two Helios probes represent the most comprehensive single data set in the inner heliosphere region to date (Mariani and Neubauer, 1990). Helios pioneered the measurements on temporal scales of months to ~ 10 s. Launched on 10 December 1974 and 15 January 1976, respectively, Helios 1 and 2 had an anticipated primary mission duration of 18 months. However, Helios 1 and 2 continued to provide data until 15 March 1986 and 8 January 1981, respectively. The primary science orbits covered heliocentric distances between 0.29 and 1 AU (Marsch, 1990). Helios observations spanned a time interval from decreasing solar activity through solar maximum.

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To zeroth order, Helios data confirmed key properties of the theory of Parker (1958). Consistent with the condition of a divergence-free magnetic field in a radial wind, the radial component of the field, $B_R$, was observed to decrease as $B_R \propto 1/r^2$, where $r$ is the heliocentric radius. Similarly, the data showed a decrease in transverse components of the IMF (Mariani et al., 1978) that follows $1/r$, and a radial dependence of the IMF magnitude that goes as $B \propto 1/r^2$ close to the Sun but asymptotically approaches a $B \propto 1/r$ dependence at greater distances (Musmann et al., 1977; Burlaga, 2001). Verification of Parker's theory was also provided by the combination of observations from Mariner 4, Mariner 5, Pioneer 6, Pioneer 10, and Mariner 10 (Behannon, 1978). Helios also provided insight into IMF variability on many temporal scales. Moreover, the Helios observations showed conclusively that the inner heliosphere had the characteristics of an evolutionary, dynamic, and turbulent medium (e.g., Mariani and Neubauer, 1990; Marsch, 1990, and references therein).

The observations by MESSENGER during the mission cruise phase en route to insertion into orbit about Mercury in March 2011 provide the first extensive inner heliosphere magnetic field observations in nearly 30 years. The MESSENGER data complement the Helios observations because they were made during the extended deep solar minimum preceding solar cycle 24, which was distinguished by extremely low levels of the average magnetic field intensity (Smith and Balogh, 2008) and a very weak solar wind (McComas et al., 2008). Our observations, together with the Helios data, offer an opportunity for comparison of Mercury's IMF environment over a large range of solar activity levels. Furthermore, the higher magnetic field sampling rate of the MESSENGER data provides insight into previously unexplored physical regimes of IMF fluctuations.

This paper is structured as follows. In Section 2 we describe the instrumentation and data used. Our IMF analysis in Sections 3–5 addresses three basic regimes. The large-scale topology of the underlying magnetic field and its consistency with Parker's (1958) seminal paper is examined in Section 3. In Section 4, we then explore the variability of the IMF on timescales from several tenths of a second to about one day. In Section 5, we focus on periods of a few hours, commensurate with MESSENGER's transit time through Mercury's magnetosphere once in orbit about the planet, and we assess the implications of this variability on the dynamics of Mercury's magnetosphere. This last topic is of particular importance for MESSENGER, because during the mission's orbital phase IMF observations will not be made while the spacecraft is in transit through the magnetosphere, and a quantitative understanding of the ambient variability in the IMF conditions imposed on the magnetosphere is necessary to understand the corresponding uncertainties in determinations of Mercury's internal magnetic field. The results may also allow us to identify signatures of IMF variability and quiescence to select the prime data for analysis of the internal field structure. The results are summarized in Section 6.

## 2. Instrumentation and data set

The MESSENGER spacecraft carries a Magnetometer with the three-axis fluxgate sensor mounted at the end of a 3.6-m-long boom (Anderson et al., 2007). The instrument features two measurement ranges: a coarse range ($\pm$51,300 nT) for testing on the ground and a fine range ($\pm$1,530 nT) for nominal operations during the cruise and orbital phases of the mission. The magnetic field observations are digitized using three 20-bit analog-to-digital converters. In the fine range, the one-count level corresponds to 0.047 nT. The spacecraft is magnetically clean to this level. The instrument's digitization rate is 20 $s^{-1}$ internally, and the output data rate is commandable from 0.01 to 20 $s^{-1}$ (Anderson et al., 2007).

With the exception of solar eclipses and trajectory-correction maneuvers, the Magnetometer has operated continuously since 2007 to support in-flight calibration and trending analyses, and the long-duration cruise phase of the MESSENGER mission has produced a database of IMF observations in the inner heliosphere in the radial range $0.3 < r < 0.6$ AU. During the cruise phase, the typical sample rate is 2 $s^{-1}$, and intervals of 20 $s^{-1}$ data lasting typically 1 h per day have been obtained since December 2009. Since August 2007, MESSENGER has spent a total of 268 days at the heliocentric distances of Mercury's orbit, 0.31–0.47 AU.

## 3. Statistics of IMF observations

For the analysis in this section, the Magnetometer observations were transformed into heliospheric radial-tangential-normal (RTN) coordinates and then 1-min averages were calculated. The RTN coordinate system is defined such that $+R$ is in the Sun-to-spacecraft direction, $+T$ is the cross-product of the heliographic polar axis and the $+R$ direction, and $+N$ completes the right-handed system (Fränz and Harper, 2002). The averaging time was chosen to reduce the data volume for statistical analysis while still resolving the characteristic timescale of Mercury's magnetospheric convection, i.e., the Dungey (1961) cycle time. The Dungey cycle time at Mercury is about 2 min (Siscoe et al., 1975; Slavin et al., 2009). The resulting database comprises a total of nearly 400,000 data points.

To illustrate the character of the IMF fluctuations in the inner heliosphere and their difference from those at 1 AU, we show magnetic field data in Fig. 1 from both MESSENGER and the Advanced Composition Explorer (ACE) spacecraft for a representative 10-day period in January 2010. The ACE spacecraft has been monitoring the interplanetary environment at Earth's first Lagrangian L1 point since 1997. Magnetic field data are provided by the magnetometer instrument described by Smith et al. (1998). At the time the data were acquired, the MESSENGER spacecraft was at a heliocentric distance of 0.35 AU and located 80° west of the Earth–Sun line. Both time series are plotted with 1-min time resolution and in the same format showing the three components of the field, field magnitude, and azimuth angle, defined as $\varphi = \arctan(B_T/B_R)$ such that an azimuth of zero is anti-sunward and 90° is in the $+T$-direction.

There are characteristic differences between the MESSENGER and ACE observations that should be expected on the basis of the theories of Parker (1958) and those that followed (Zurbuchen, 2007, and references therein). First, $B_R$ is bimodal in nature, indicative of two magnetic polarities that are separated by a large-scale current sheet (Zurbuchen, 2007). Due to details of the shape of this sheet, and also because of the differences in the relative size of positive and negative sectors, one of these sectors may be observed at a higher probability than the other. From Gauss's law, $\nabla \cdot \mathbf{B} = 0$, $B_R$ is proportional to $1/r^2$, leading to a substantial decrease of $B_R$ from MESSENGER to ACE. $B_T$ is pointed parallel or anti-parallel to the solar rotation direction. Parker (1958) found that $B_T \propto 1/r$ and also depends on the solar wind speed, which is not measured by MESSENGER in the inner heliosphere. Parker (1958) did not include a $B_N$ component, but there are several mechanisms for its origin, such as transport of magnetic field on the solar surface, stream–stream interactions, or turbulent motions (for details, see Zurbuchen, 2007). As the solar wind propagates away from the Sun, high-frequency variations tend to be damped out, e.g., due to stream–stream interactions (Schwenn, 1990). The enhanced variability in the IMF evident in the MESSENGER data is therefore unique to the inner heliosphere.

The radial component measured by MESSENGER exhibits a clear bimodal character, as expected. Before a rather abrupt transition on 10 January 2010 around 04:00 UTC, $B_R$ was mostly negative and afterwards it was largely positive. This change reflects the two-magnetic-sector structure of the IMF with a current-sheet in