Planetary and Space Science 59 (2011) 2004–2015

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

MESSENGER observations of the plasma environment near Mercury

Jim M. Raines [a,*], James A. Slavin [b], Thomas H. Zurbuchen [a], George Gloeckler [a], Brian J. Anderson [c], Daniel N. Baker [d], Haje Korth [c], Stamatios M. Krimigis [c,e], Ralph L. McNutt Jr [c]

[a] Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, 2455 Hayward St., Ann Arbor, MI 48109-2143, USA
[b] Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[c] Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA
[d] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA
[e] Academy of Athens, Athens, Greece

ARTICLE INFO

Article history:
Received 5 August 2010
Received in revised form
27 January 2011
Accepted 7 February 2011
Available online 19 February 2011

Keywords:
Mercury
Magnetosphere
Plasma
MESSENGER

ABSTRACT

The MESSENGER Fast Imaging Plasma Spectrometer (FIPS) measured the bulk plasma characteristics of Mercury's magnetosphere and solar wind environment during the spacecraft's first two flybys of the planet on 14 January 2008 (M1) and 6 October 2008 (M2), producing the first measurements of thermal ions in Mercury's magnetosphere. In this work, we identify major features of the Mercury magnetosphere in the FIPS proton data and describe the data analysis process used for recovery of proton density (n_p) and temperature (T_p) with a forward modeling technique, required because of limitations in measurement geometry. We focus on three regions where the magnetospheric flow speed is likely to be low and meets our criteria for the recovery process: the M1 plasma sheet and the M1 and M2 dayside and nightside boundary-layer regions. Interplanetary magnetic field (IMF) conditions were substantially different between the two flybys, with intense reconnection signatures observed by the Magnetometer during M2 versus a relatively quiet magnetosphere during M1. The recovered ion density and temperature values for the M1 quiet-time plasma sheet yielded $n_p \sim 1$–$10\ \mathrm{cm}^{-3}$, $T_p \sim 2\times10^6$ K, and plasma $\beta \sim 2$. The nightside boundary-layer proton densities during M1 and M2 were similar, at $n_p \sim 4$–$5\ \mathrm{cm}^{-3}$, but the temperature during M1 ($T_p \sim 4$–8×10^6 K) was 50% less than during M2 ($T_p \sim 8\times10^6$ K), presumably due to reconnection in the tail. The dayside boundary layer observed during M1 had a density of $\sim 16\ \mathrm{cm}^{-3}$ and temperature of 2×10^6 K, whereas during M2 this region was less dense and hotter ($n_p \sim 8\ \mathrm{cm}^{-3}$ and $T_p \sim 10\times10^6$ K), again, most likely due to magnetopause reconnection. Overall, the southward interplanetary magnetic field during M2 clearly produced higher T_p in the dayside and nightside magnetosphere, as well as higher plasma β in the nightside boundary, ~ 20 during M2 compared with ~ 2 during M1. The proton plasma pressure accounts for only a fraction (24% for M1 and 64% for M2) of the drop in magnetic pressure upon entry into the dayside boundary layer. This result suggests that heavy ions of planetary origin, not considered in this analysis, may provide the "missing" pressure. If these planetary ions were hot due to "pickup" in the magnetosheath, the required density for pressure balance would be an ion density of $\sim 1\ \mathrm{cm}^{-3}$ for an ion temperature of $\sim 10^8$ K.

1. Introduction

The Fast Imaging Plasma Spectrometer (FIPS) (Zurbuchen et al., 1998; Andrews et al., 2007) is part of the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) instrument payload (Solomon et al., 2007). Its purpose is to determine the plasma properties and abundances of elements in Mercury's space environment, which have important implications for the composition of the planet's surface materials. Planetary ions are thought to be created primarily by the interaction of solar radiation and solar wind ions with Mercury's atmosphere and surface (Zurbuchen et al., 2008). The FIPS investigation has already reported the first measurements of planetary ion composition at Mercury taken during the first flyby of Mercury (M1) by MESSENGER on 14 January 2008 (Zurbuchen et al., 2008). FIPS also obtained on-board energy spectra and directional information for H^+ during the first and the second flybys, the latter of which (M2) took place on 6 October 2008. Detailed analysis of these H^+ energy spectra is complicated by the

* Corresponding author. Tel.: +1 01 7347636223; fax: +1 01 7346159723.
E-mail addresses: jraines@umich.edu (J.M. Raines), james.a.slavin@nasa.govm (J.A. Slavin), thomasz@umich.edu (T.H. Zurbuchen), gglo@umich.edu (G. Gloeckler), Brian.Anderson@jhuapl.edu (B.J. Anderson), daniel.baker@lasp.colorado.edu (D.N. Baker), Haje.Korth@jhuapl.edu (H. Korth), Tom.Krimigis@jhuapl.edu (S.M. Krimigis), Ralph.McNutt@jhuapl.edu (R.L. McNutt Jr).

0032-0633/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2011.02.004

placement of the FIPS sensor relative to other elements of the spacecraft, including a sunshade, that collectively limit the instrument's field of view (FOV) to directions transverse to the Mercury–Sun axis. For this reason the FIPS FOV seldom includes the plasma flow direction as required by standard plasma moment computations. Here we report a new algorithm developed to derive bulk plasma parameters from these H^+ energy spectra, and we discuss their implications for the physical processes that govern Mercury's magnetosphere.

MESSENGER has confirmed and extended the earlier Mariner 10 measurements of Mercury's small, ~250 nT-R_M^3, intrinsic magnetic field, where R_M is Mercury's radius (Anderson et al., 2008, 2010). The resulting magnetosphere is much smaller than Earth's, by about a factor of 8, but qualitatively similar in terms of its overall structure (Russell et al., 1988; Slavin, 2004; Baumjohann et al., 2006; Fujimoto et al., 2007). Mercury's magnetosphere is immersed in the supersonic heliospheric plasma, which is up to ten times stronger and more variable than the solar wind at Earth, mostly due to Mercury's closer distance from the Sun (Marsch et al., 1982). These strong and variable heliospheric flows, coupled with the relatively small size of the magnetosphere, cause some important and unexpected magnetospheric properties compared to their counterparts in Earth's magnetosphere.

In order to place the MESSENGER measurements into a broader context of solar and inner heliospheric conditions, the MESSENGER team has carried out an extensive set of modeling runs with the Wang–Sheeley–Arge (WSA) ENLIL model (Baker et al., 2009, this issue, and references therein). This three-dimensional magnetohydrodynamic code uses the Wang–Sheeley–Arge approximation for the corona and then propagates the solar wind out through the inner heliosphere. It has been used to predict the plasma and interplanetary magnetic field properties near the MESSENGER spacecraft during the Mercury encounters. The forecasted average solar wind proton densities were the same during both M1 and M2, ~60 cm^{-3}. Bulk solar wind speeds were similar, 420 km/s during M1 and 380 km/s during M2, though the predicted temperature during M1, 1.2×10^5 K, was substantially lower than the 2.0×10^5 K forecast for M2 (Baker et al., 2009, this issue).

The first MESSENGER flyby measurements showed that Mercury's magnetosphere is immersed in a cloud of planetary ions that extends beyond the dayside bowshock and revealed the existence of a "boundary layer" of indeterminate origin at the inner edge of the plasma sheet and just inside the dawn magnetopause (Anderson et al., 2008; Slavin et al., 2008; Zurbuchen et al., 2008). The MESSENGER trajectory during both flybys, along with model bowshock and magnetopause positions, is shown in Fig. 1. (The reader is referred to Fig. 1 of Slavin et al. (2008) for a more detailed diagram of Mercury's magnetospheric structure.) This boundary layer was identified on the basis of sudden decreases in the magnetic field that are almost certainly diamagnetic in origin and, therefore, should be associated with commensurate increases in the plasma pressure, needed to maintain stress balance. The second flyby confirmed the existence of this dayside boundary layer as a stable feature of Mercury's magnetosphere (Anderson et al., 2010; Slavin et al., 2009a). Further, the second flyby took place during a period of southward interplanetary magnetic field (IMF), in contrast to the steady northward IMF observed during M1. Consistent with these IMF conditions, M2 observations revealed very intense magnetic reconnection at the dayside magnetopause and in the magnetic tail (Slavin et al., 2009a).

A second region of sudden magnetic field decrease was identified in both flybys, in the inner magnetosphere directly behind the planet (as seen from the Sun) where the magnetic field is strongly northward (Anderson et al., 2008, 2010; Slavin et al., 2008, 2009a). One possible explanation of this nightside diamagnetic depression is that it was due to the presence of a flow-braking region, where flux tubes convecting toward the planet run into the planetary dipole magnetic field and slow to near stagnation. In this scenario, the flow slows (i.e., "brakes") due to the adiabatic compression and heating of the plasma-sheet plasma as the closed magnetic flux tubes decrease in volume during convection toward the planet (Erikson and Wolf, 1980). At Earth, flow braking is typically observed where the magnetic field transitions from tail-like to dipolar in configuration, with an associated average increase in field strength of 6.7 nT (Shiokawa et al., 1997). We refer to this region hereafter as the nightside boundary layer.

To analyze the plasma properties of these regions, we developed a method for deriving H^+ bulk parameters from the FIPS energy spectra that relies on the assumption that the thermal speed (v_{th}) of the H^+ ions is large compared to the bulk flow speed (v_{bulk}). Such an assumption allows the computation of proton density (n_p) and temperature (T_p) from our observations, as long as a general shape of the plasma velocity distributions is assumed. Here, the velocity distribution functions (described below) are assumed to follow a simple convected Maxwellian distribution. We focus on times when the direction of the magnetic field is largely perpendicular to the

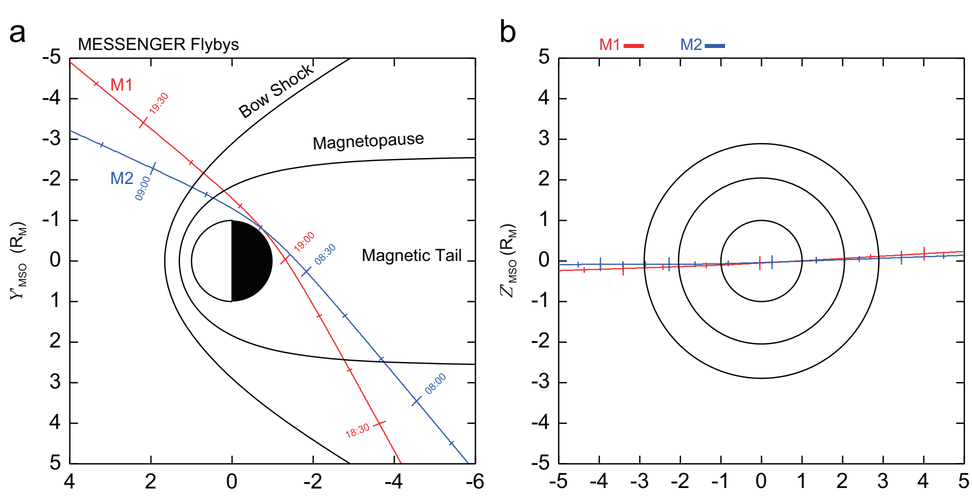

Fig. 1. The MESSENGER trajectories during M1 and M2, as well as model positions of the bowshock and magnetopause. Coordinates shown are aberrated Mercury solar orbital (MSO) coordinates. This system is similar to MSO coordinates (see text) except that the X'_{MSO} and Y'_{MSO} coordinates are rotated clockwise by 7° from the solar direction to account for average aberration of the solar wind vector due to Mercury's orbital velocity. Details of the models can be found in Slavin et al. (2009b).