Hybrid Simulations of Solar Wind Proton Precipitation to the Surface of Mercury

S. Fatemi1,2, A. R. Poppe3, and S. Barabash1

1Swedish Institute of Space Physics, Kiruna, Sweden, 2Department of Physics at Umeå University, Umeå, Sweden, 3Space Sciences Laboratory, University of California, Berkeley, CA, USA

Abstract

We examine the effects of the interplanetary magnetic field (IMF) orientation and solar wind dynamic pressure on the solar wind proton precipitation to the surface of Mercury using a hybrid-kinetic model. We use our model to explain observations of Mercury’s neutral sodium exosphere and compare our results with MESSENGER observations. For the typical solar wind dynamic pressure at Mercury our model shows a high proton flux precipitates through the magnetospheric cusps to the high latitudes on both hemispheres on the dayside, centered near the noon meridian with ~11° latitudinal extent in the north and ~21° latitudinal extent in the south, which is consistent with MESSENGER observations. We show that this two-peak pattern is controlled by the radial component (B_x) of the IMF and not the B_z. Our model suggests that the southward IMF and its associated magnetic reconnection do not play a major role in controlling plasma precipitation to the surface of Mercury through the cusps. We found that the total precipitation rate through both of the cusps remain constant and independent of the IMF orientation. We also show that the solar wind proton incidence rate to the entire surface of Mercury is higher when the IMF has a northward component and nearly half of the incidence flux impacts the low latitudes on the nightside. During extreme solar events (e.g., coronal mass ejections), our model suggests that over 70 nPa solar wind dynamic pressure is required for the entire surface of Mercury to be exposed to the solar wind plasma.

1. Introduction

Mercury holds the weakest global magnetic field of internal origin among the magnetized planets in the solar system (Ness et al., 1974; Anderson et al., 2008). Magnetic field observations from the MESSENGER spacecraft suggested that Mercury’s magnetic field can be modeled as a single dipole with a southward pointing magnetic moment of 195 ± 10 nT·R_M^3 displaced 484 ± 11 km (~0.2R_M) northward from the center of the planet with <3° tilt from Mercury’s rotation axis (e.g., Anderson et al., 2011), where R_M ≈ 2440 km is the average radius of Mercury. This weak magnetic field, however, interacts continuously with the dynamic interplanetary magnetic field (IMF) and solar wind plasma to form a “minimagnetosphere” that is qualitatively similar to the magnetosphere of Earth, although nearly 20 times smaller in size (e.g., Fujimoto et al., 2008; Ogilvie et al., 1974; Slavin et al., 2008, 2009). In general, this interaction forms a bow shock and a magnetopause (Winslow et al., 2013), funnel-shaped magnetospheric cusps over the polar caps (Poh et al., 2016; Raines et al., 2014; Winslow et al., 2012), and an extended magnetotail with a central current sheet (e.g., Poh et al., 2017; Slavin et al., 2012; Sundberg et al., 2012; Sundberg & Slavin, 2015).

Mercury has a very thin, collisionless, and surface-bound gaseous exosphere mainly composed of H, He, Na, Mg, Al, K, Ca, Mn, Fe, and perhaps O. These elements have been observed through measurements of neutrals using Earth-based ground telescopes (e.g., Bida & Killen, 2017; Bida et al., 2000; Doressoundiram et al., 2010; Killen et al., 2005; Leblanc et al., 2008; Leblanc et al., 2009; Mangano et al., 2013, 2015; Potter & Morgan, 1985, 1997; Sprague et al., 1997) and direct in situ measurements by the Mariner 10 and MESSENGER spacecraft (e.g., Broadfoot et al., 1976; Merkel et al., 2017; McClintock et al., 2008, 2009; Vervack et al., 2016). They have also been observed indirectly through MESSENGER observations of planetary ions in Mercury’s magnetosphere (e.g., Raines et al., 2014; Vervack et al., 2010; Zurbuchen et al., 2008, 2011). Similar to the exospheres of other terrestrial bodies, the exosphere of Mercury is generated through various processes including thermal desorption, photon stimulated desorption, solar wind ion sputtering, chemical sputtering, and micrometeorite impact vaporization (e.g., Killen & Ip, 1999; Killen et al., 2001, 2007; Lammer & Bauer, 1997; Lammer et al., 2003; Leblanc & Johnson, 2003; McGrath et al., 1986; Wurz et al., 2010).
Because of the intense solar irradiation at Mercury's surface, which is due to the proximity of Mercury to the Sun, thermal and photon stimulated desorption are suggested to have the largest contribution to the formation of Mercury's neutral exosphere (e.g., Gamborino et al., 2019; Leblanc & Johnson, 2003; McGrath et al., 1986; Mura et al., 2009; Wurz & Lammer, 2003; Wurz et al., 2010). However, the particles released by these two processes have relatively low velocities and thus are more gravitationally bound to the planet, compared to the particles released by micrometeorite impact vaporization and solar wind ion sputtering (e.g., Leblanc & Johnson, 2003; Schmidt et al., 2010, 2012; Schmidt, 2013; Wurz et al., 2010). The sputtering process depends on the momentum and energy of the impacting ions as well as the surface composition and sputtering yield (e.g., Killen et al., 2001; Killen et al., 2004; Lammer & Bauer, 1997; Wurz & Lammer, 2003). For Mercury, the solar wind and magnetospheric ions are the main constituents for ion sputtering and magnetospheric cusps are suggested to be the main channels for the access of the solar wind ions to the surface, especially at high latitudes (e.g., Kallio & Janhunen, 2003; Killen et al., 2001; Lammer et al., 2003; Leblanc & Johnson, 2003; Massetti et al., 2003; Massetti et al., 2007; Potter & Morgan, 1990; Raines et al., 2013, 2014; Winslow et al., 2012). It has been hypothesized that the impact of ions to the surface of Mercury liberates sodium (Na) atoms through chemical sputtering, ion-initiated collision cascades, and ion-enhanced diffusion (e.g., Killen et al., 2007; McGrath et al., 1986; Mura et al., 2009; Sarantos et al., 2008). These processes may directly knock off atoms from the surface and release them to the exosphere and/or may free atoms from the mineral bonds in the crystalline structure. These neutrals are then available as adsorbed atoms on the surface and, thus, facilitate thermal and photon stimulated desorption processes that release the weakly bound particles from the surface and form a neutral exosphere (e.g., Leblanc & Johnson, 2003; Mura et al., 2009; Yakishinisky & Madey, 1999). Therefore, understanding solar wind ion precipitation to the surface of Mercury is a key process in understanding the formation of Mercury's neutral exosphere.

Since sodium (Na) is a volatile element and therefore is released from the surface more easily compared to other elements, it is highly affected by solar radiation pressure, and has strong emission lines. Na has been one of the most observed species in the exosphere of Mercury (Baumgardner et al., 2008; Cassidy et al., 2015, 2016; Doressoundiram et al., 2010; Killen & Ip, 1999; Killen et al., 2001; Killen et al., 2004; Leblanc et al., 2008, 2009; Leblanc & Johnson, 2010; Mangano et al., 2013, 2015; Massetti et al., 2017; McGrath et al., 1986; Mouawad et al., 2011; Orsini et al., 2018; Potter & Morgan, 1985, 1990, 1997; Potter et al., 2006, 2013; Schleicher et al., 2004; Yoshikawa et al., 2008). In contrast to other neutral elements, the Na exosphere possesses noticeable features including high peaks at relatively high latitudes on the dayside (e.g., Leblanc et al., 2008; Mangano et al., 2013, 2015; Massetti et al., 2017; Orsini et al., 2018; Potter et al., 1999), a dawn-dusk asymmetry with a slightly denser exosphere at dawn compared to dusk (e.g., Cassidy et al., 2016; Leblanc & Johnson, 2010; Potter et al., 2006; Sprague et al., 1997; Schleicher et al., 2004), and an extended comet-like tail on the nightside of Mercury (e.g., Baumgardner et al., 2008; Kameda et al., 2008, 2009; McClintock et al., 2008; Potter et al., 2002; Potter & Killean, 2008; Schmidt et al., 2012). The high-latitude Na enhancements, which often appear at both hemispheres and are known as “two peaks” or “double peaks” (e.g., Mangano et al., 2015; Massetti et al., 2017; Orsini et al., 2018; Potter et al., 1999, 2006), are hypothesized to be related to the sputtering of neutral Na induced by the incidence of the solar wind plasma to the surface of Mercury through magnetospheric cusps (e.g., Killen et al., 2001; Killen et al., 2007; Leblanc & Johnson, 2003; Mangano et al., 2013, 2015; Massetti et al., 2007, 2017). On the other hand, the dawn-dusk asymmetry is suggested to be related to the thermal and photon stimulated desorption processes that are more effective at dawn compared to dusk to knock off the neutrals from the surface (e.g., Mura et al., 2009; Potter et al., 2007), and the extended antisunward Na tail is due to the high solar radiation pressure (e.g., Baumgardner et al., 2008; Kameda et al., 2008; Potter et al., 2002; Schmidt, 2013).

Mangano et al. (2015), using ground-based telescope observations, classified Na emission into two major recurrent patterns: a single peak at low latitudes close to the equator and the double peak at high latitudes. They found the double peak emission is the most common pattern (61%) in Mercury’s Na exosphere with distinct emission peaks on both hemispheres at high latitudes. This supports the view on the major role that the cusps play in the solar wind ion precipitation to high latitudes (e.g., Killen et al., 2001; Leblanc et al., 2008, 2009; Mangano et al., 2013, 2015; Massetti et al., 2007; Potter & Morgan, 1990). Combining telescope observations with MESSENGER magnetic field observations, Mangano et al. (2015) also found correlations between the IMF orientation and Na emission in a subset of their observations. They concluded that a southward IMF ($B_z < 0$), which is thought to be a favorable orientation for magnetic reconnection at Mercury (e.g., Slavin et al., 2008, 2009), is usually correlated with the double peak emissions at high latitudes, whereas a
northward IMF ($B_z > 0$) is more often associated with a single peak emission near the equator. Although the southward IMF is thought to be a favorable orientation for dayside magnetic reconnection, MESSENGER magnetic field observations, however, surprisingly showed that there is almost no correlation between magnetic reconnection rate and IMF orientation at Mercury (DiBraccio et al., 2013), which is perhaps a result of the low plasma $\beta$ and low Alfvén Mach number at the orbit of Mercury (DiBraccio et al., 2013; Massetti et al., 2017). This finding by MESSENGER does not support the correlation between the IMF orientation and the dayside Na emission (e.g., Massetti et al., 2017).

In addition to observations, numerical simulations have also suggested that magnetic reconnection, especially for a southward IMF, facilitates the access of the solar wind plasma to the surface of Mercury through magnetospheric cusps (e.g., Benna et al., 2010; Chanteur et al., 2014; Kallio & Janhunen, 2003; Massetti et al., 2007; Trávníček et al., 2010; Varela et al., 2015). Although some of these studies were conducted prior to the MESSENGER observation of the northward offset in Mercury’s magnetic dipole, some models, even without including a dipole offset, predicted a noticeable north-south asymmetry in the solar wind precipitation to the dayside surface of Mercury (e.g., Benna et al., 2010; Burger et al., 2010; Kallio & Janhunen, 2003; Sarantos et al., 2001). Several of these models suggested that this asymmetry arises when the radial component of the IMF ($B_r$) is dominant (e.g., Massetti et al., 2003; Sarantos et al., 2001; Varela et al., 2015), which is a typical feature of the Parker spiral near Mercury’s orbit (James et al., 2017; Korth et al., 2011; Sarantos et al., 2007). After the discovery of Mercury’s dipole offset, it was suggested that the north-south asymmetry in the solar wind plasma precipitation to high latitudes could be an effect of the magnetic dipole offset (e.g., Winslow et al., 2014). However, some simulations showed that even a centered dipole combined with higher magnetic moments (e.g., quadrupole, octupole, and higher terms) has a considerable influence on the north-south asymmetry of the solar wind precipitation to high latitudes (Richer et al., 2012; Varela et al., 2015).

MESSENGER observations have also shown that considerable plasma flux impacts the low latitudes on the nightside close to the equator (e.g., Korth et al., 2014; Winslow et al., 2012, 2014), with a higher flux to the southern hemisphere compared to the north (e.g., Winslow et al., 2012, 2014). While a few global MHD simulations predicted this low-latitude precipitation on the nightside (Benna et al., 2010; Burger et al., 2010; Varela et al., 2015), hybrid-kinetic simulations, prior to the present study, only suggested plasma precipitation to high latitudes, mainly around the open-closed field line boundary on the nightside (Kallio & Janhunen, 2003; Trávníček et al., 2010; Wang et al., 2010).

Here, we use a three-dimensional hybrid-kinetic model of plasma (particle ions and fluid electrons) and present global maps of the solar wind plasma precipitation to the surface of Mercury for various IMF and solar wind dynamic pressure. First, we describe the time-integrated calculation of solar wind precipitation of particles to Mercury, which is necessary given Mercury’s highly dynamic magnetosphere. Then, we explain our simulation results and compare them with observations. Finally, we provide detailed analysis on plasma precipitation to the surface of Mercury under different solar wind plasma dynamic pressures and IMF orientations as well as the cusp dynamics and plasma precipitation through the cusps to explain some of the observed features in Na exosphere. Our global precipitation maps provide a better understanding of the magnetosphere-exosphere-surface coupling at Mercury (Milillo et al., 2005; Orsini et al., 2007) and can be applied in Monte Carlo simulations of Mercury’s exosphere (e.g., Gamborino et al., 2019; Mura et al., 2009; Schmidt, 2013; Wurz & Lammer, 2003), a tool that is required to better interpret observations by the European Space Agency (ESA)’s BepiColombo mission (Benkhoff et al., 2010; Milillo et al., 2010) and future ground-based telescope observations.

2. Model

We use the Amitis simulation code, the first three-dimensional (3-D in both configuration and phase space), time-dependent hybrid model of plasma that runs entirely on Graphics Processing Units for faster and more environmentally friendly parallel computation (Fatemi et al., 2017). In this model, the ions are kinetic charged particles and electrons are a massless, charge-neutralizing fluid. As explained in detail in Fatemi et al. (2017), electric fields are directly calculated in the model from the electron momentum equation for massless electrons (i.e., $m_e = 0$), magnetic fields are computed from Faraday’s law, and the divergence-free condition of the magnetic field is satisfied over the entire simulation domain. Amitis allows the definition
of custom electrical conductivity profiles for the interior of a body from a highly resistive to highly conductive interior with the possibility of defining multiple conductivity layers with and without longitudinal and latitudinal inhomogeneities (Fatemi et al., 2017; Fuqua Haviland et al., 2019). The model self-consistently couples the interior magnetic response to the ambient plasma environment using a semi-implicit method (model details are extensively explained in Fatemi et al., 2017). Amitis has been previously used to study the plasma interaction with the Moon (Fatemi et al., 2017; Fuqua Haviland et al., 2019; Garrick-Bethell et al., 2019; Poppe, 2019), asteroid 16 Psyche (Fatemi & Poppe, 2018), and Mercury (Fatemi et al., 2018) and our simulation results have been previously validated through comparison with analytical theories (Fuqua Haviland et al., 2019) and with ARTEMIS and MESSENGER observations (Fatemi et al., 2017, 2018; Poppe, 2019).

2.1. Coordinate System and Simulation Parameters

We use a Mercury Solar Orbital (MSO) coordinate system centered at Mercury’s center of mass, where the +x axis points to the Sun (i.e., the solar wind flows along the −x axis), the +y axis is opposite to the orbital motion of Mercury around the Sun and points toward dusk, and the +z axis points to geographical north, perpendicular to the xy plane, and completes the right-handed coordinate system. Mercury, in our model, is a spherical object with a radius $R_M = 2,440$ km without an exosphere. We assume Mercury is a uniform resistive body with a resistivity $\eta = 10^7$ $\Omega$ m, and its surface is a perfect plasma absorber; that is, when the ions impact the surface, they are removed from the simulation domain. We place a southward oriented magnetic dipole along the −z axis with a magnetic moment of $195$ nT $R_M^3$, displaced $484$ km northward from the center of Mercury in the MSO coordinate system (Anderson et al., 2010, 2011). For simplicity, we ignore the $\sim 3^\circ$ magnetic dipole tilt from the spin axis of Mercury.

We use a simulation domain of size $−6R_M \leq x \leq +6R_M, −12R_M \leq (y,z) \leq +12R_M$ with a regular-spaced Cartesian grid with cubic cells of size $\Delta L = 175$ km ($\sim 0.07R_M$). At time $t = 0$ s, each grid cell is initially loaded with 16 protons with mass $m_p = 1.0$ amu and with a drifting Maxwellian velocity distribution. The solar wind plasma flows along the −x axis; thus, the particles (i.e., solar wind ions) are continuously injected into the simulation domain from the inflow boundary at $x = +6R_M$ and removed at the outflow boundary at $x = −6R_M$. The four other boundaries, which are perpendicular to the solar wind flow direction, are periodic for particles and electromagnetic fields. For each simulation, the upstream plasma conditions remain constant at the inflow boundary.

We run every simulation for 500 s, which is approximately equivalent to the completion of four Dungey cycles (~2 min at Mercury Slavin et al., 2009) within the magnetosphere of Mercury, over six solar wind convection times through the entire simulation domain, and over 120 gyrations of the solar wind ions (the typical solar wind proton gyroprecession is $\sim 3.5$ s for $20$ nT magnetic field). We advance particle trajectories by using a time step of $\Delta t = 10^{-3}$ s, which is $\sim 3 \times 10^{-4}$ of the proton gyroprecession in the solar wind and is $\sim 10^{-3}$ of a proton gyroprecession near Mercury’s magnetic poles. This small time step assures that the ion gyromotion is fully resolved within our simulations.

As summarized in Table 1, we conducted a series of hybrid simulation runs using the Amitis code for the “typical” solar wind condition near the orbit of Mercury (Runs T1–T6), for the solar wind conditions during the first and the second Mercury flybys by MESSENGER (Runs M1 and M2, respectively), and for extreme solar events (Runs E1–E3). Mercury has the most eccentric orbit around the Sun compared to other planets in the solar system. With eccentricity $e \approx 0.2$, Mercury’s distance from the Sun varies from $\sim 0.31$ AU at perihelion to $\sim 0.46$ AU at aphelion, where 1 AU (astronomical unit) is the distance of the Earth from the Sun. As a consequence, solar wind plasma and IMF conditions change considerably during one revolution of Mercury around the Sun (Sarantos et al., 2007; Korth et al., 2011; James et al., 2017). In this study, we have chosen our solar wind plasma and IMF configurations within the range of the observed values near Mercury. For runs T1 to T6, we set the solar wind parameters close to the median of the most probable values observed at Mercury’s perihelion and aphelion, explained by Sarantos et al. (2007), Korth et al. (2011), and James et al. (2017). For these runs, we set the IMF magnitude $|B| = 18$ nT, solar wind density $n_{sw} = 50$ cm$^{-3}$, solar wind speed $|v_{sw}| = 370$ km/s, and solar wind ion and electron temperatures $T = 12$ eV. In order to study the effects of various IMF angles on the solar wind proton precipitation to the surface of Mercury, we only change the IMF orientation for Runs T1–T6. To investigate the effects of the high solar wind dynamic pressure, we conducted Runs E1–E3, which are similar to Runs T1 and T2, except the solar wind dynamic pressure $P_{dyn} = m_p n_{sw} v_{sw}^2$ is higher.
Finally, for completion of our analyses and in order to compare our results with some of the previous studies of the solar wind plasma interaction with the magnetosphere of Mercury, we also modeled the interaction for MESSENGER’s M1 and M2 flybys (Runs M1 and M2). The MESSENGER spacecraft made the first (M1) and the second (M2) flybys of Mercury on 14 January 2008 and 6 October 2008, respectively, at similar true anomalies of $\sim 290^\circ$ along Mercury’s orbit (e.g., Slavin et al., 2008, 2009; Solomon et al., 2007). As explained in detail in Fatemi et al. (2018), we inferred the solar wind plasma dynamic pressure during those two flybys through comparison between our hybrid simulations and the magnetic field observation by MESSENGER. The parameters listed in Table 1 for M1 and M2 flybys were obtained from the best match between our hybrid simulations and MESSENGER observations (also see section 3.1). For the M1 and M2 flybys, the Keplerian speed of Mercury is compensated by a 50 km/s downward component (along the $+y$ axis) for the solar wind velocity. Realistically, Mercury’s orbital speed varies between $\sim 30$ to $\sim 70$ km/s due to the eccentric orbit of Mercury, which results in $<4\%$ variation in the solar wind dynamic pressure. Since this speed introduces an asymmetry in our simulations, we did not include it to our simulation runs, except for the M1 and M2 flybys. In Table 1, $\beta$ is the ratio of thermal pressure to magnetic pressure and $M_s$ and $M_A$ are the solar wind sonic and Alfvénic Mach numbers, respectively.

### 2.2. Calculating Plasma Precipitation to the Surface of Mercury

Two different approaches are often applied to calculate plasma precipitation to the surface of planetary bodies from numerical simulations: (1) if the simulation is particle based, for example, full particle-in-cell or hybrid-kinetic model, one can take a snapshot of the particles spatial and velocity distribution at a certain time and then calculate the density and flux of precipitating plasma from the impacting particles to the surface of a body (e.g., Herčík et al., 2016; Trávníček et al., 2010), or (2) using test particle simulations by following trajectories of many particles through a background electric and magnetic fields, or any other applied forces (e.g., Fatemi et al., 2012, 2016; Poppe et al., 2018). Here, we already know that the magnetosphere of Mercury is highly dynamic, sensitive, and responsive to the solar wind plasma and IMF variations (e.g., Burlaga, 2001; Slavin et al., 2008, 2009), and the magnetic reconnection rate ($\sim 0.15$) and Dungey cycle ($\sim 2$ min) are relatively high and fast, respectively, compared to those at other magnetized planets (Slavin et al., 2009). We also know that unlike other planetary magnetospheres, the minimagnetosphere of Mercury is almost filled in by the body of the planet itself, which highly affects the dynamics of ions within the magnetosphere (Delcourt & Seki, 2006). Therefore, we propose not to use either of the previously explained methods to calculate plasma precipitation to the surface of Mercury. This is because the former method represents particles distribution at a given time and does not include the overall particle dynamics in the magnetosphere. In addition, it requires an extremely high number of particles per cell to provide a statistically reasonable results. The latter method is not suitable either, because a time snapshot of electric and magnetic fields does not represent the overall dynamics of the Hermean magnetosphere. In addition, storing all particle data from our hybrid simulations at every time step throughout the entire simulation generates extremely large data files, which are not economically efficient to be stored for further analyses.

| Run # | B | $|B|$ | $n_{sw}$ | $|v_{sw}|$ | $P_{dyn}$ | $\beta$ | $M_s$ | $M_A$ |
|-------|---|-----|---------|---------|--------|--------|--------|--------|
| T1    | [0.0, 0.0, +18.0] | 18.0 | 30.0    | 370     | 6.9     | 0.9    | 5.9    | 5.1    |
| T2    | [0.0, 0.0, −18.0] |     |         |         |         |        |        |        |
| T3    | [−17.55, 0.0, +4.0] |     |         |         |         |        |        |        |
| T4    | [−17.55, 0.0, −4.0] |     |         |         |         |        |        |        |
| T5    | [+17.55, 0.0, +4.0] |     |         |         |         |        |        |        |
| T6    | [+17.55, 0.0, −4.0] |     |         |         |         |        |        |        |
| M1    | [−18.0, 0.0, +4.0] | 18.4 | 32.0    | 365     | 7.0     | 0.9    | 5.9    | 5.1    |
| M2    | [−15.2, 0.0, −8.5] | 17.4 | 32.0    | 400     | 8.7     | 1.0    | 6.5    | 6.0    |
| E1    | [0.0, 0.0, +18.0] | 18.0 | 70.0    | 600     | 42.2    | 2.1    | 9.7    | 12.8   |
| E2    | [0.0, 0.0, −18.0] |     |         |         |         |        |        |        |
| E3    | [0.0, 0.0, +18.0] | 18.0 | 120.0   | 600     | 72.3    | 3.6    | 9.7    | 16.7   |
Therefore, in this study, after our simulations reached a state that the Hermean magnetosphere is fully developed (here in our model is 380 s, which is equivalent to the completion of more than three Dungey cycles), we store particle data (i.e., position and velocity) within 50 km altitude (<30% of our grid cell sizes) above the surface of Mercury for every ~0.2 s within a period of 120 s, and we assume that all of those particles impact the surface of Mercury. This approach allows us to consider dynamic effects of the magnetosphere on the overall plasma precipitation to the surface of Mercury. The total duration of our particle storage time (120 s) is long enough for the completion of one Dungey cycle and ~35 gyration of the solar wind ions. For two of our simulations (Runs T1 and T2), we stored particles data for a longer period (300 s) and compared precipitating plasma density and flux to the surface with those obtained from 120 s integration time (not shown here). We did not observe any noticeable differences in our results and thus concluded that 120 s for particle storage is long enough to capture the Hermean magnetospheric dynamics.

2.3. Limitations in Simulations

Here we only included the solar wind protons in our simulations and did not take into account the effects of solar wind alpha particles or planetary ions and their precipitation to the surface of Mercury. Exospheric neutrals are the main sources of planetary ions, which are formed through a combination of different processes including photoionization, charge exchange, and electron impact ionization (e.g., Killen et al., 2007). Depending on the energy and formation altitude of these ions, some may return to the surface and contribute to surface weathering processes. Heavy planetary ions (mainly Na+, O+, and H2O+ groups) have been observed by MESSENGER (Raines et al., 2013; Zurbuchen et al., 2008, 2011) with a substantial density enhancement over the cusps on the dayside and near the equator in the central plasma sheet (Raines et al., 2013). However, the highest observed density for these ions, which belongs to the Na+-group ions, is below ~0.1 cm⁻³ (Raines et al., 2013), which is a few orders of magnitude lower than the typical solar wind plasma density near the orbit of Mercury (~30 cm⁻³). The low density of planetary ions implies that they do not have a significant contribution to the overall structure of the Hermean magnetosphere and cusp dynamics; thus, they are excluded from our simulations here. However, it is worth noting that planetary ion impact into the surface of Mercury may provide a considerable contribution to surface weathering due to their higher mass and momentum transfer to the surface compared to solar wind protons (Delcourt et al., 2003; Delcourt & Seki, 2006). Investigating the effects of planetary ions is outside the scope of this research and left for future studies.

In addition to heavy planetary ions, the solar wind plasma also composed of multiply charged heavy ions (e.g., He⁺², O⁺⁶, O⁺⁷, Si⁺⁸, and Fe⁺⁹) (e.g., Bame et al., 1970, 1975; Bochsler, 2007; Collier et al., 1996; Gloeckler et al., 1992; Von Steiger et al., 2000). Although protons are the dominant solar wind ion species (~90–95%), solar wind heavy ions transfer higher energy and momentum to the surface when impacting Mercury. For example, Wurz et al. (2010) suggested that only 5% of solar wind alphas (He⁺²) may contribute ~30% of the total surface sputtering yield. However, for simplicity, we did not include the solar wind heavy ions in this study.

Due to the similarities between the surface of Mercury and the Moon, Lue et al. (2017) suggested that the flux of scattered protons from the surface of Mercury should be similar to that from the surface of the Moon. At the Moon, <1% of the incident solar wind proton flux is backscattered in charged form from the unmagnetized and/or weakly magnetized regions on the lunar surface (Lue et al., 2014; Saito et al., 2008). Since the fraction of the backscattered protons is very low, we did not include them in our simulations. However, the backscattered protons on Mercury’s closed field lines may return to the other hemisphere and deposit additional energy onto the surface.

MESSENGER observations at low altitudes (<150 km) detected signatures of remanent crustal magnetization at Mercury (Johnson et al., 2015; Hood, 2015). Due to the orbital geometry of MESSENGER, crustal fields have been primarily observed over the north polar region near the Caloris impact basin with a strength of a few nano-Tesla at ~40 km altitude (L. L. Hood, 2015, 2016). At the moment, and before arrival of ESA’s BepiColombo mission to Mercury, we do not know much about Mercury’s crustal magnetic fields, but if they are similar to those on the Moon and/or Mars (e.g., Acuña et al., 1999; Hood et al., 2001), their topology could be very complex and their strength on the surface could reach hundreds or even thousands of nanoteslas, especially if the source magnetization is very strong and close to the surface. If the crustal fields are strong enough, they can affect plasma dynamics and eventually influence plasma precipitation patterns to the surface. However, due to the lack of detailed information about Mercury’s crustal magnetization and
in order to provide a simplified understanding on the global plasma precipitation to the surface, the crustal fields are not included in our simulations.

Because of its close proximity to the Sun, Mercury is exposed to extreme solar events such as CMEs. MESSENGER observations together with simulations have shown that during such extreme events, the dayside magnetopause could collapse to the surface (Exner et al., 2018; Jia et al., 2019; Slavin et al., 2014; Winslow et al., 2019; Winslow et al., 2020). The recent Earth-based radar observations of Mercury's librations and Mercury's gravity field have suggested that Mercury has a large conductive core of radius \( \sim 0.8 \, R_M \) (Hauck et al., 2013; Hiremath, 2012; Smith et al., 2012). During the extreme events, this large conductive core would respond to variations in the magnetopause current and induce an electric current to cancel out magnetic field variations inside the core (Glassmeier et al., 2007; Grosser et al., 2004; Heyner et al., 2011; Jia et al., 2015). Jia et al. (2015) using a global MHD simulation showed that increasing the solar wind dynamic pressure from \( \sim 11 \) to \( \sim 66 \) nPa induces \( \sim 200 \) nT fields on the surface of Mercury that moves the magnetopause to \( \sim 0.1 \, R_M \) further upstream compared to the conditions when the conductive core is not taken into account. We did not include a conductive core in our simulations presented here. For simplicity, we assumed Mercury is a resistive body with a uniform resistivity \( 10^7 \) Ohm \( \cdot \) m. Since in our model the solar wind plasma and IMF remain constant upstream of all of our simulations, therefore a conductive core effect would not be influential.

### 3. Simulation Results and Comparison With Observations

#### 3.1. Solar Wind Proton Precipitation to the Surface of Mercury

Here we present our hybrid simulation results for the solar wind plasma interaction with the magnetosphere and surface of Mercury for various IMF and solar wind plasma conditions listed in Table 1.

Figure 1 shows a snapshot of our hybrid simulation results at time \( t = 500 \) s for Run T1, a perfectly northward IMF (Figure 1, top panels) and Run T2, a perfectly southward IMF (Figure 1, bottom panels). Regardless of the IMF direction, this figure shows that for typical solar wind plasma conditions at Mercury's orbit (i.e., \( P_{\text{dyn}} \approx 7–8 \) nPa and plasma \( \beta \approx 1.0 \)), the interaction between the solar wind and the weak intrinsic magnetic field of Mercury forms an Earth-like magnetosphere with distinct magnetospheric boundaries including a collisionless bow shock, magnetopause, funnel-shaped magnetospheric cusps, and an elongated magneto-tail, all of which are consistent with the global structure of the Hermean magnetosphere observed by Mariner 10 and MESSENGER (e.g., DiBraccio et al., 2013; Ogilvie et al., 1974; Slavin et al., 2008, 2009; Winslow et al., 2012, 2013). A bow shock is evident upstream with a large jump in the magnetic field strength and direction shown in Figures 1a and 1b, a large plasma density enhancement evident in Figures 1e and 1f, and plasma flow deceleration shown in Figures 1g and 1h. Figures 1c and 1d show that the bow shock-associated electric current forms a boundary between the Hermean magnetosphere and the incident solar wind. We have calculated electric current density, \( J \), using the general Ampère's law, \( J = \mu_0^{-1} \nabla \times B \), where \( B \) is the magnetic flux density obtained from our hybrid simulations and \( \mu_0 = 4 \pi \times 10^{-7} \) H/m is the vacuum permeability. However, we only show the \( J_y \) component of the electric current in Figures 1c and 1d. The magnetopause is also evident as the innermost intense current near the dayside of Mercury. The funnel-shaped polar cusps that enable direct access of the solar wind plasma into the surface of Mercury can be seen at high latitudes close to the surface on the dayside in Figures 1e and 1f. The magnetosheath, the region of space located between the magnetopause and the bow shock where the solar wind is decelerated and its dynamic pressure is converted into thermal and magnetic pressure, is also present and can be seen in Figures 1g and 1h.

Despite similarities in our simulation results between the northward and southward IMF, there are several fundamental differences in the structure of the Hermean magnetosphere between the two runs. For instance, comparing Figure 1c with Figure 1d shows that both the bow shock and the magnetopause stand closer to the planet for the southward IMF (Run T2) compared to the northward IMF (Run T1), which is suggested to be an effect of the magnetic reconnection for the southward IMF that erodes the dayside magnetopause (Jp & Kopp, 2002; Slavin et al., 2008; Slavin & Holzer, 1979; Trávníček et al., 2010). In particular, the simulations show that the bow shock for the northward IMF forms at \( x \approx +2.23 \, R_M \) near the magnetic equator, while for the southward IMF stands at \( x \approx +1.92 \, R_M \). We also see that the subsolar standoff distance of the magnetopause for the northward and southward IMF is \( x \approx +1.46 \, R_M \) and \( x \approx +1.39 \, R_M \), respectively. These results are in agreement with the average distance of the bow shock (~1.96 \( R_M \)) and standoff distance of the magnetopause (~1.45 \( R_M \)) observed by MESSENGER (Winslow et al., 2013). Figure 1c shows that the magnetopause current density for the northward IMF, that is, \( \sim 135 \) nA/m\(^2\), is ~3.5 times weaker than that
Figure 1. Hybrid simulation results presented in MSO coordinate system for (top panels) Run T1, the perfectly northward IMF, and (bottom panels) Run T2, the perfectly southward IMF, as listed in Table 1. (a, b) Background color shows the magnitude of the magnetic field in logarithmic scale, and the streamlines show magnetic field line tracing. (c, d) Electric current density flowing normal to the presented planes along the along the $y$ axis. We calculated electric field from the general Ampère's law, $J = \mu_0^{-1} \nabla \times B$. (e, f) Plasma density normalized to the upstream solar wind density, $n_{sw} = 30$ cm$^{-3}$. (g, h) Solar wind plasma speed normalized to the upstream solar wind speed, $|u_{sw}| = 370$ km/s. Our simulation results are three-dimensional (3-D in both velocity and space), but we only present two-dimensional cuts in the midnight meridian plane ($xz$ plane at $y = 0$), viewed from the orbital motion of Mercury (i.e., the $-y$ axis). Mercury is shown by a circle, centered at the origin of the MSO coordinate system. The bow shock and magnetopause currents are labeled in panel c and the direction of the solar wind (SW) and the IMF are shown by black and green arrows, respectively, in panels (c) and (d).

for the southward IMF, which is $\sim 490$ nA/m$^2$ and is outside the color bar range for better visualization of the electric currents. Another noticeable difference is in the topology of the magnetic field lines in the magnetotail. Figure 1a demonstrates that the magnetic field structure at the nightside close to the planet is nearly dipolar for the northward IMF, while Figure 1b shows that the closed field lines are at very low latitudes close to the equator for the southward IMF.

Figure 2 shows global maps of the solar wind proton precipitation to the surface of Mercury obtained from our hybrid simulations for the perfectly northward IMF in Run T1 (Figures 2a and 2b), and for the perfectly southward IMF in Run T2 (Figures 2c and 2d). The maps are generated through the time-integration method explained in section 2.2. The top panels in Figure 2 show the relative solar wind proton density, $n/n_{sw}$, and the bottom panels show the relative proton flux, $F/F_{sw}$, that impact the surface of Mercury, all normalized to the solar wind upstream values presented in Table 1 (i.e., $n_{sw}$ and $F_{sw} = n_{sw}|u_{sw}|$). We estimated the boundary of the open-closed magnetic field lines from magnetic field line tracing of our simulations presented in Figures 1a and 1b (i.e., at a fixed time $t = 500$ s) and showed the boundaries by dashed black lines on each panel in Figure 2. The local time (LT) is also shown at latitude $0^\circ$ in Figures 2a and 2c, and the dayside hemisphere is located between 6 and 18 LT, and the subsolar point is at latitude $0^\circ$ and 12 LT.

Regardless of the IMF direction, Figures 2b and 2d show a high proton flux impacts the surface of Mercury at high latitudes on the dayside (two peaks). These protons are just outside of the closed magnetic field line region, and they access the surface of Mercury through the magnetospheric cusps (cusp precipitation). While the density of the cusp precipitating protons is nearly 2-4 times higher than the upstream solar wind density, their flux is comparable or slightly lower than the upstream solar wind flux, suggesting that the impacting protons have lower energies compared to the upstream solar wind energy. By comparing the left panels with the right panels in Figure 2, we see that the IMF orientation controls fundamental differences in proton precipitation patterns to the surface. For example, we see that the open-closed magnetic field line boundaries move closer to the magnetic equator for the southward IMF, compared to those for the northward IMF. This is in agreement with the response of the Hermean magnetosphere to the IMF orientation predicted by simulations (e.g., Massetti et al., 2007; Trávníček et al., 2010; Varela et al., 2015) and observed
Figure 2. The global maps of solar wind proton precipitation to the surface of Mercury from hybrid simulations, (a, b) for the perfectly northward IMF in Run T1, and (c, d) for the perfectly southward IMF in Run T2, presented in Table 1. (a, c) The density of precipitating protons normalized to the upstream solar wind density \( n_{sw} = 30 \text{ cm}^{-3} \) and (b, d) the flux of precipitating protons normalized to the upstream solar wind flux \( F_{sw} = 1.1 \times 10^{13} \text{ m}^{-2} \text{ s}^{-1} \). Mercury’s local time is labeled at latitude 0° on panels (a) and (c). The subsolar point is at the center of each panel at latitude 0° and longitude 12 hr. The open-closed magnetic field line boundaries calculated from magnetic field results of our hybrid simulations are shown by dashed black lines in each panel. The closed magnetic field lines encompass between the drawn solid lines in the northern and southern hemisphere of Mercury. All the color bars are in logarithmic scales. The maps are generated through the time-integration method explained in section 2.2.

by MESSENGER (e.g., Winslow et al., 2012). We see that the equatorward motion of the field line boundary for the southward IMF on the nightside of Mercury is more significant compared to those on the dayside. By comparing Figure 2b with Figure 2d, we see that a larger area on Mercury’s dayside surface is protected by the closed magnetic field lines against the impact of the solar wind protons for the northward IMF compared to the southward IMF.

Another noticeable difference between the two simulation runs is a considerable incidence of solar wind protons to the nightside surface of Mercury for the northward IMF. Figure 2a shows the density of the impacting protons to the nightside surface is comparable to the upstream solar wind proton density. However, Figure 2b shows that the flux of these protons is relatively low, that is, \( 10^{-2} < F/F_{sw} < 10^{-1} \). Our simulations suggest (not shown here) that the incidence energy of those protons for the northward IMF is close to or lower than 1% of the upstream solar wind energy, whereas the incidence energy of particles to the nightside for the southward IMF is close to or comparable to the solar wind energy, even though the overall flux is lower in this case. Figure 2b also shows an asymmetry in the incidence of protons to low latitudes on the nightside. While the low latitudes between 0 and 6 LT are more protected against the impact of the solar wind protons, the low latitudes at 18–24 LT, however, are exposed to a higher flux of solar wind protons. The incidence of the solar wind protons to the nightside is partly associated with the planetward flow of plasma from the magnetotail reconnection and partly due to the quasi-trapped protons in the nightside magnetosphere, evident in Figure 1e close to Mercury, that could not complete their drift motion around the planet and come back to the dayside. Such quasi-trapped particles for the northward IMF have been previously observed by MESSENGER (Herčík et al., 2016; Schriver et al., 2011).

Figure 3 shows the global structure of the Hermean magnetosphere for hybrid simulation Runs T3 (top panels) and T4 (bottom panels). The IMF component parallel to the solar wind flow \( (B_x) \) is the most dominant component in these simulations, which is consistent with magnetic field observations near the orbit of Mercury (e.g., James et al., 2017; Korth et al., 2011; Sarantos et al., 2007). One of the most noticeable differences between the simulations presented in Figure 3 and those shown in Figure 1 is the magnetospheric foreshock region, evident in Figure 3. The foreshock is a region upstream of the bow shock that is magnetically connected to the shock and filled with backstreaming particles from the shock (e.g., Eastwood et al., 2005, and references therein). We see the foreshock and its associated magnetic field perturbations upstream of
Figure 3. Hybrid simulation results presented in MSO coordinate system for (a, c, e, and g) Run T3 and (b, d, f, and h) Run T4 listed in Table 1. The figure format is the same as that shown in Figure 1.

the quasi-parallel shock in Figures 3a and 3b, where the IMF is connected to the planetary bow shock. We also see electric current perturbations associated with the foreshock upstream of Mercury in Figures 3c and 3d and the ion foreshock region in Figures 3e–3h. A time series of our hybrid simulations (not shown here) suggests that the Hermean foreshock is a dynamical system even though the upstream solar wind parameters remain constant during our simulations. MESSENGER had previously observed foreshock-associated ultralow frequency waves upstream of the Hermean bow shock (Le et al., 2013), but only recently were direct observations of Mercury’s foreshock plasma reported by MESSENGER’s Fast Imaging Plasma Spectrometer instrument (Glass et al., 2019). Recently, Jarvinen et al. (2020) using a global hybrid model of plasma provided a detailed analysis on the structure of the ion foreshock of Mercury and its associated ultralow frequency waves. Investigating the properties of the Hermean foreshock is beyond the scope of the presented research here and left for future studies.

Figure 4 shows the solar wind proton precipitation to the surface of Mercury for simulation Runs T3 (left panels) and T4 (right panels) when the IMF is antisunward (i.e., planetward, \( B_x < 0 \)). There are some fundamental differences between the results from these runs and those presented in Figure 2, which show the effects of the \( B_z \) component of the IMF on the solar wind proton precipitation to the surface of Mercury. For example, comparing Figure 4b with Figure 4d shows that the dayside surface of Mercury is less protected against the solar wind plasma when the planetward IMF has a small northward component. This is opposite to the results presented in Figure 2 for purely \( \pm B_z \) fields. Figures 4b and 4d show a large plasma flux impacts the surface of Mercury at high latitudes on the dayside (two peaks) through magnetospheric cusps (cusp precipitation). Unlike the results presented in Figure 2, the flux of precipitating plasma through the northern cusp is higher than that through the southern cusp when the IMF has a northward component. In addition, we see from Figures 4b and 4d that the incidence plasma flux to the nightside surface of Mercury is considerably higher compared to those presented earlier in Figure 2. The precipitating plasma to the nightside has a high density and flux near the open-closed filed line boundary at the nightside as well as lower latitudes close to the equator.

Figure 5 shows the solar wind proton precipitation for hybrid simulation Runs T5 (left panels) and T6 (right panels) when the IMF is sunward (i.e., \( B_x > 0 \)). The only difference between the upstream solar wind plasma parameters for these simulations and those presented in Figure 4 is the \( B_z \) orientation of the IMF. Figure 5 shows that when the IMF is sunward, the southern hemisphere of Mercury is more exposed to the solar wind protons, while the northern hemisphere is more protected against the solar wind plasma compared to the conditions that the IMF points away from the Sun (Figure 4). These results are consistent with some of
Figure 4. The global maps of the solar wind proton precipitation to the surface of Mercury from hybrid simulations for planetward IMF, (a, b) for Run T3, and (c, d) Run T4, presented in Table 1. The figure format is the same as that shown in Figure 2.

the previous models on the solar wind plasma precipitation to the surface of Mercury (Mangano et al., 2013; Massetti et al., 2007) and telescope observations of Na exosphere (Leblanc et al., 2009).

As listed in Table 1, we investigate plasma precipitation to the surface of Mercury for the first two MESSENGER flybys known as the M1 (14 January 2008) and M2 (6 October 2008) flybys. For both of these flybys, MESSENGER almost passed through the equatorial plane of Mercury where the IMF was planetward and northward during the M1 and planetward and southward during the M2 flyby (Slavin et al., 2008, Slavin et al., 2009). As explained previously by Fatemi et al. (2018), we used Amitis to infer solar wind plasma parameters upstream when MESSENGER is passing through the magnetosphere of Mercury during the M1 and M2 flybys. Our model (not shown here but explained in detail in Fatemi et al., 2018) suggests that the solar wind dynamic pressure during the M1 and M2 flybys was 7.0 and 8.7 nPa, respectively. Figure 6 compares our hybrid simulation results (red lines) with MESSENGER magnetic field observations (black lines) for the M1 (Figures 6a–6d) and M2 (Figures 6e–6h) flybys. The location of different magnetospheric boundary

Figure 5. The global maps of the solar wind proton precipitation to the surface of Mercury from hybrid simulations for sunward IMF, (a, b) for Run T5, and (c, d) Run T6, presented in Table 1. The figure format is the same as that shown in Figure 2.
Figure 6. Comparison between our hybrid simulation results (red lines), undisturbed intrinsic magnetic dipole of Mercury (blue dashed lines) and MESSENGER magnetic field observations (black lines) along the trajectory of MESSENGER for (a–d) the M1 flyby on 14 January 2008, and (e–h) the M2 flyby on 6 October 2008. The midpoint location of the bow shock (BS) and magnetopause (MP) boundaries estimated by Slavin et al. (2008) and Slavin et al. (2009) as well as the closest approach (CA) to the planet are shown by the vertical black lines.

crossings, that is, the bow shock (BS) and magnetopause (MP), are shown by solid vertical lines on each panel. Figures 6a–6d show that there is a very good agreement between our hybrid simulations and MESSENGER magnetic field observations during the M1 flyby. We see that our model almost perfectly captures different magnetospheric boundaries and processes during the M1 flyby including the inbound bow shock (BS) crossing at 18:08, inbound magnetopause (MP) crossing at 18:43, double magnetopause layers at 19:14 (see Anderson et al., 2011; Müller et al., 2012, for more details), and outbound bow shock (BS) crossing at ∼19:19 (MESSENGER boundary crossings are obtained from Slavin et al., 2008).

Figures 6e–6h show that there is also a good agreement between our hybrid simulations and MESSENGER magnetic field observations for the M2 flyby, except a large discrepancy between our simulations and observations in the $B_x$ component (Figure 6e) after MESSENGER passed the inbound magnetopause and moved into the plasma sheet close to the planet at nightside (between ∼08:10 and ∼08:40). In this period, the $B_x$ component of our hybrid simulation is very close to the undisturbed planetary dipole field shown by dashed blue lines. This is because in this period, a plasma void (vacuum) region forms in our simulations on the nightside close to Mercury due to plasma absorption on the planetary dayside. An example of a nightside vacuum region can be seen in Figure 1f where plasma density is almost zero in the nightside magnetotail. Moreover, the difference between our hybrid simulations and MESSENGER magnetic field observations could be associated with time variability of the upstream IMF, which is not included in our simulations.

Figure 7 shows the solar wind proton precipitation to the surface of Mercury for the M1 (left panels) and M2 (right panels) flybys. Since the IMF orientation and strength during these two flybys are similar to those presented in Runs T3 and T4, our results presented in Figure 7 are similar to those presented in Figure 4. Some minor differences between the results in Figures 4 and 7 are associated with the 50 km/s solar wind flow speed along the +y axis we have considered only for the M1 and M2 flybys (see section 2.1). Our hybrid simulations presented in Figure 7 are qualitatively similar to MHD simulations presented by Benna et al. (2010) and Burger et al. (2010). Both of these studies, similar to our results presented in Figure 7, predicted
Figure 7. The global maps of the solar wind proton precipitation to the surface of Mercury from hybrid simulations, (a, b) for the M1 flyby, and (c, d) for the M2 flyby, presented in Table 1. The figure format is the same as that shown in Figure 2.

a high proton density and flux impacting the dayside magnetosphere through the cusps as well as plasma precipitation to the nightside at low latitudes only for the M1 flyby (i.e., northward IMF), also evident in our simulation results presented in Figures 7a and 7b. This is in contrast to previous hybrid simulations of plasma precipitation to the surface of Mercury during the M1 and M2 flybys did not predict the low-latitude nightside precipitation and only predicted plasma impact to the high latitudes at the boundary of open-closed field lines (Trávníček et al., 2010; Wang et al., 2010).

In addition to the IMF direction, we examined the effects of the solar wind dynamic pressure on the solar wind proton precipitation to the surface of Mercury. Figure 8 shows our hybrid simulation results for Run E1, a perfectly northward IMF (left panels), and Run E2, a perfectly southward IMF (middle panels), where the solar wind dynamic pressure for both of these runs is 6 times higher (42.2 nPa) than those presented in Figure 2. The right panels in Figure 8 show the simulations results for Run E3, a perfectly northward IMF where the solar wind dynamic pressure is an order of magnitude higher (72.3 nPa) than those presented in Figure 2. From all the different panels in Figure 8 we see that the southern hemisphere of Mercury’s dayside is highly exposed to the solar wind plasma for high dynamic pressures. Similar to the results presented in Figure 2, the incidence flux to the southern hemisphere of Mercury is slightly higher for a perfectly southward IMF (Figure 8d) compared to that for a perfectly northward IMF (Figure 8b). For example, the median incidence flux to the southern hemisphere for Runs E1 and E2 are ∼31% and ∼42% of the solar wind upstream flux, respectively. In addition, Figure 8b shows that for the perfectly northward IMF a significant fraction of the solar wind flux (over 25%) impacts the low latitudes on the nightside surface of Mercury. Results from Run E3, Figures 8e and 8f show that almost the entire dayside surface of Mercury is unprotected against the incidence solar wind for very high dynamic pressures (72 nPa here), although some regions on the northern hemisphere remain partially protected against the solar wind. Our magnetic field line tracing could not always determine the open-closed field line boundary on the southern hemisphere on the dayside for the simulations presented in Figure 8, especially for Run E3, as the dayside magnetopause partially collapsed to the surface or stands right above the surface. Therefore, we do not show the field line boundaries on the dayside for simulation Run E3 on the southern hemisphere.

3.2. Precipitation Flux to the Surface of Mercury

Using our simulation results presented in section 3.1, we calculated the solar wind proton precipitation rate ($Q_t$) to the surface of Mercury (i.e., the integral of the incidence flux over the entire surface), and the results are summarized in Figure 9. Figure 9a shows the total proton incidence rate to the entire surface of Mercury for each simulation run. Figure 9b shows the percentage of the incidence rate separated into four different quadrants on the surface including the northern hemisphere on the dayside (i.e., 0–90°N and 6–18 LT, shown by blue bars), the southern hemisphere on the dayside (i.e., 0–90°S and 6–18 LT, shown by green
Figure 8. Contour maps of the solar wind proton precipitation to the surface of Mercury from hybrid simulations, (a, b) Run E1, (c, d) Run E2, and (e, f) Run E3, presented in Table 1. For Runs E1 and E2, the solar wind proton density \( n_{\text{sw}} = 70 \text{ cm}^{-3} \), the solar wind flow speed \( |v_{\text{sw}}| = 600 \text{ km/s} \), and the solar wind dynamic pressure \( P_{\text{dyn}} = 42.2 \text{ nPa} \). For Run E3, the solar wind proton density \( n_{\text{sw}} = 120 \text{ cm}^{-3} \), the solar wind flow speed \( |v_{\text{sw}}| = 600 \text{ km/s} \), and the solar wind dynamic pressure \( P_{\text{dyn}} = 72.3 \text{ nPa} \). We could not trace the open-closed magnetic field line boundaries on the dayside southern hemisphere for Run E3 due to the disappearance of the southern cusp. The figure format is the same as that shown in Figure 2.

bars), the nightside (i.e., 90°S to 90°N) between 0 and 6 LT (orange bars), and the nightside between 18 and 24 LT (magenta bars). The percentage of the incidence rate to the entire dayside and nightside hemispheres are also labeled on the top left and top right of the bar charts for each simulation run, respectively.

Figure 9a shows that for the typical solar wind condition near the orbit of Mercury (i.e., Runs T1–T6, M1, and M2) the total incidence rate is \((1.1–4.8) \times 10^{25} \) protons per second, while for the extreme events (i.e., Runs E1–E3) the incidence rate increases to \((2.2–9.8) \times 10^{26} \) protons per second, which is one to two orders of magnitude higher compared to the runs for typical solar wind conditions. Figure 9a also shows that for the

Figure 9. (a) The total solar wind proton incidence rate to the entire surface of Mercury for the typical solar wind condition at the orbit of Mercury (i.e., Runs T1–T6, M1, and M2) and for extreme events (i.e., Runs E1–E3). The northward (N) or southward (S) oriented IMF as well as the planetward or sunward pointing IMF are labeled at the top of this panel; (b) the percentage of the total incidence rate into four different quadrants on the surface including the northern dayside quadrant covering an area between 0–90°N and 6 to 18 local time (blue bars), the southern dayside quadrant covering an area between 0–90°S and 6 to 18 local time (green bars), the area covered between 90°S to 90°N and 0 to 6 local time (orange bars), and the area covered between 90°S to 90°N and 18 to 24 local time (magenta bars). The percentage of the precipitation rate to the entire dayside and nightside hemispheres are labeled on the top left and top right of the bar charts for each simulation run.
typical solar wind condition the total incidence rate is higher when the IMF has a northward component compared to that when the IMF has a southward component. As shown previously in Figures 2, 4, and 5, and also evident from Figure 9b, most of the precipitating particles impact the nightside surface of Mercury when the IMF is northward. For example, as labeled in Figure 9b, 52% of the total incidence protons impact the nightside surface of Mercury for Run T1. Moreover, we see from Figure 9b that, in general, for typical solar wind conditions, \( \geq 50\% \) of the precipitating protons impact the nightside hemisphere, except when the IMF is southward and has an angle larger than the typical Parker spiral angle (\( \sim 16-30^\circ \), depending on Mercury’s distance from the Sun James et al., 2017) at the orbit of Mercury (i.e., Runs T2 and M2).

Furthermore, Figure 9b shows that, regardless of the IMF direction, the southern quadrant on the dayside (green bars) is more exposed to the solar wind protons compared to the northern quadrant (blue bars), which is due to the northward displacement of the planetary magnetic field. This asymmetry is increasingly evident when the IMF has a dominant sunward component (i.e., Runs T5 and T6) or when the \( B_y \) component is zero (i.e., Runs T1 and T2). When the IMF is sunward, the incidence rate to the southern quadrant is nearly an order of magnitude higher than that to the northern quadrant. On the contrary, when the IMF is planetward, our simulations suggest that the northern quadrant on the dayside becomes more open to the solar wind protons compared to the other IMF orientations. For example, the incidence rate to the dayside Northern Hemisphere for Run T3 is \( \sim 0.49 \times 10^{25} \) protons per second, while for Run T5 is \( \sim 0.23 \times 10^{25} \) protons per second. Our simulations also show that there is an asymmetry in the solar wind proton precipitation on the nightside. When the IMF is northward and \( B_y \neq 0 \) (i.e., Runs T3, T5, and M1), most of the incident particles to the nightside impact the area covered between 18–24 LT (purple bar). On the contrary, when the IMF has a southward component (i.e., runs T4, T6, and M2), the incidence rate to the area covered between 0–6 LT is dominant (orange bars). When the solar wind dynamic pressure is extremely high (i.e., Runs E1–E3), most of the precipitating solar wind protons impact the southern quadrant on the dayside (Runs E1 and E2), unless the dynamic pressure is exceptionally high (e.g., Run E3) such that the entire dayside magnetosphere collapses to the surface and differences between the northern and southern hemispheres are muted.

### 3.3. Proton Precipitation Through Magnetospheric Cusps

We also estimated the geographical extent for precipitation patterns through magnetospheric cusps to the surface of Mercury for each of our simulations except for Run E3. Since the entire dayside magnetosphere has collapsed to the surface for that run, there is basically no cusp for that simulation, and is thus not included in our analyses here. Figure 10a shows the latitudinal extent of the cusp precipitation. Regardless of the IMF direction, we see that, in general, the solar wind protons precipitate to higher latitudes on the northern hemisphere, compared to those impacting the surface on the southern hemisphere, which is due to the northward offset in Mercury’s dipole magnetic field. For the typical solar wind condition at the orbit of Mercury (i.e., Runs T1–T6, M1, and M2), the northern and southern cusps are centered at \( \sim 70^\circ \)N and \( \sim 53^\circ \)S, respectively, on average. The solar wind proton precipitation through the northern cusp extends between \( 67^\circ \)N and \( 78^\circ \)N with an average latitudinal extent of \( \sim 11^\circ \) for the simulation conditions modeled here. The precipitation through the southern cusp has a broader extent compared to the northern cusp and is located between \( 46^\circ \)S and \( 66^\circ \)S with an average latitudinal extent of \( \sim 21^\circ \). For high solar wind dynamic pressures (i.e., Runs E1 and E2), we see that the northern cusp does not extend as much as the southern cusp does. This is again due to the northward offset of Mercury’s internal fields that makes the magnetic fields much stronger in the northern hemisphere compared to the southern hemisphere, especially at high latitudes. For simulation Run E1, the southern cusp precipitation extends between \( 79^\circ \)S and \( 3^\circ \)S, and for Run E2 it extends between \( 73^\circ \)S and \( 17^\circ \)N. Figure 10b shows the center of longitudinal extent in LT. The center of the cusp precipitation in the northern hemisphere is close to 13 LT and in the southern hemisphere is near 12:30 LT.

The limits of the northern cusp extent from our simulations shown in Figures 10a and 10b are in good agreement with MESSENGER observations. Winslow et al. (2012) from the first six months of MESSENGER observations of the magnetic pressure deficit in the northern cusp found the limits for the cusp are 55.8°N and 83.6°N with the mean extent of \( \sim 11^\circ \) latitude, and extends for 7.2–15.9 hours in LT, centered near noon. Later, Winslow et al. (2014) used proton reflection and observation of proton loss cones to show that the northern cusp is centered at \( 76.4^\circ \)N on local noon extending \( 15.6^\circ \) in latitude and 7.5 hr in LT. Due to the orbital geometry of MESSENGER, the spacecraft was located outside of the magnetosphere and the southern cusp could not be mapped to the surface (Winslow et al., 2014); thus, no observation is available to be compared with our model results in the southern cusp.
Figure 10. (a) Latitudinal extent for the solar wind proton precipitation through northern and southern magnetospheric cusps for different hybrid simulation runs listed in Table 1, (b) The center of the longitudinal extent in the northern (blue line) and southern (orange line) cusp precipitation area shown in local time. (c) The incidence area of the solar wind proton precipitation through the northern (blue line) and southern (orange line) magnetospheric cusps to the surface of Mercury. The sum of the covered area by the northern and southern cusp precipitations is shown by the black line. (d) The incidence rate of the solar wind proton precipitation through the magnetospheric cusps in the same format presented in panel c.

We also calculated the incidence area and the incidence rate of the solar wind protons precipitating through the magnetospheric cusps, and the results are shown in Figures 10c and 10d, respectively. We see that in general, the cusp precipitation area and the incidence rate through the southern cusp is higher than that through the northern cusp. For typical solar wind conditions, the cusp precipitation area on the northern hemisphere is between $1.8 \times 10^{11}$ and $1.2 \times 10^{12}$ m$^2$ and on the southern hemisphere is between $7.7 \times 10^{11}$ and $3.7 \times 10^{12}$ m$^2$. As shown in Figures 10c and 10d, our simulations suggest that there is an anticorrelation between the northern and southern cusp precipitation area and the incidence rate, such that the total incidence area and the incidence rate over both cusps (shown by black lines in Figures 10c and 10d) remain relatively constant for different IMF orientations ($\sim 2.5 \times 10^{12}$ m$^2$ and $7.7 \times 10^{24}$ protons per second, respectively, on average). This shows that the total proton impact rate and the incidence area through magnetospheric cusps are not strongly controlled by the IMF orientation. However, as shown in Figures 10c and 10d, the increase of the solar wind dynamic pressure considerably enhances the incidence area and the incidence rate of protons, especially through the southern cusp.

Winslow et al. (2012) also estimated the northern cusp area and the solar wind proton precipitation through that area using MESSENGER observations. They found that $(1.1 \pm 0.6) \times 10^{25}$ protons per second impact the surface over an area of $(5.2 \pm 1.6) \times 10^{11}$ m$^2$ near the northern cusp. These results are in agreement with our simulation results presented in Figures 10c and 10d. Winslow et al. (2012) also found that the plasma pressure in the northern cusp is $\sim 40\%$ higher when the IMF is planetward than when it is sunward. Our simulations also suggest that nearly an order of magnitude higher number of protons impact the surface through the northern cusp (blue line in Figure 10d) when the IMF is planetward (Runs T3 and T4) compared to when the IMF is sunward (Runs T5 and T6). Winslow et al. (2012) also predicted that the particle flux impacting the surface near the southern cusp should be about 4 times higher than in the north. Our simulations suggest that when the IMF is planetward (Runs T3 and T4), there is little difference between the precipitation rate through the northern and southern cusps, whereas for the sunward IMF (Runs T5 and T6), this difference becomes considerable with nearly an order of magnitude higher incidence rate to the southern hemisphere (orange line) compared to the northern hemisphere (blue line). Some of these differences between MESSENGER observations and our simulations could be associated with the different method we have taken in estimating the cusp and the method applied by Winslow et al. (2012). While Winslow et al. (2012) obtained
their results by detection of magnetic field depression through the assumption of pressure balance between magnetic field and plasma at the orbit of MESSENGER (∼400–700 km above the surface), we have directly calculated the cusp precipitating area from our hybrid simulations on the surface of Mercury.

4. Discussion

One of the frequent patterns observed for Na exosphere is the double peak emission at high latitudes on the dayside, which is suggested to be correlated with plasma precipitation through magnetospheric cusps (e.g., Killen et al., 2001; Leblanc et al., 2008; Mangano et al., 2013, 2015). Recently, Mangano et al. (2015) using ground-based telescope observations of Na emission combined with MESSENGER magnetic field observations showed a relatively strong correlation between the double peak emission and southward IMF conditions. A southward IMF is a favorable orientation for magnetic reconnection, a process that is thought to play a major role in the entry of the solar wind plasma into the magnetosphere of Mercury (e.g., Raines et al., 2015; Slavin et al., 2008, 2009). In addition to observations, numerical simulations have also suggested that the magnetic reconnection during southward IMF results in higher access of the solar wind plasma to the surface of Mercury (e.g., Chanteur et al., 2014; Ip & Kopp, 2002; Kabin et al., 2000; Kallio & Janhunen, 2003; Massetti et al., 2007; Trávníček et al., 2007; Trávníček et al., 2010; Varela et al., 2015). However, when the radial component of the IMF is dominant, which is a typical feature of the Parker spiral near the orbit of Mercury (James et al., 2017; Korth et al., 2011; Sarantos et al., 2007), our simulation results (Figures 4 and 5) and analyses (Figure 10) do not show any strong dependence between the $B_z$ component of the IMF and plasma precipitation to high latitudes on the dayside. This conclusion is in agreement with MESSENGER observation of magnetic reconnection at Mercury (DiBraccio et al., 2013). Unlike the reconnection at Earth (e.g., Birn et al., 2001; Sonnerup et al., 1981), MESSENGER's statistical survey of the magnetopause reconnection surprisingly revealed that the reconnection rate at Mercury is independent of the IMF angle (magnetic shear angle) (DiBraccio et al., 2013), which is perhaps a result of the low plasma $\beta$ and low Alfvén Mach number at the orbit of Mercury (DiBraccio et al., 2013; Massetti et al., 2017).

In addition to double peak emissions, single peak emissions near the equator also observed (e.g., Mangano et al., 2015; Orsini et al., 2018; Potter et al., 1999). Mangano et al. (2015) reported that the single peak emission is more common when the IMF is northward (74%). Such a correlation with northward IMF is again not observed in our simulations. Our model suggests that for the typical solar wind dynamic pressure, plasma precipitates to both hemispheres on the dayside with relatively higher flux to the northern (southern) hemisphere when the IMF is planetward (sunward). As shown in Figure 8, the only condition for which the solar wind plasma impacts the low latitude region close to the equator on the dayside occurs when the solar wind dynamic pressure is extremely high (i.e., during CMEs). This conclusion is in agreement with recent ground-based observations of Na emission, reported by Orsini et al. (2018), found Na emission over the subsolar region (close to the equator) when MESSENGER detected the passage of two ICMEs.

Mercury’s Na exosphere shows temporal and spatial variability, reported by both ground-based telescopes and MESSENGER spectrometer observations (Cassidy et al., 2015, 2016; Doressoundiram et al., 2010; Killen et al., 2001; Leblanc et al., 2008, 2009; Leblanc & Johnson, 2010; Mangano et al., 2013, 2015; Massetti et al., 2017; Orsini et al., 2018; Potter & Morgan, 1990; Potter et al., 1999; Schmidt et al., 2010). The temporal variability has a broad time-range from tens of minutes to days (e.g., Cassidy et al., 2015; Mangano et al., 2013, Massetti et al., 2017; Leblanc et al., 2009; Potter & Morgan, 1990; Schmidt et al., 2010). While the long-term variations are mainly attributed to the changes in Mercury's position in its highly eccentric orbit around the Sun (e.g., Cassidy et al., 2015; Mangano et al., 2013), the short-term variations are suggested to be related to the rapid changes in the solar wind plasma and IMF orientation (e.g., Killen et al., 2001; Leblanc et al., 2009; Mangano et al., 2015; Orsini et al., 2018). Our simulation results presented here further support the idea that the solar wind plasma precipitation to the surface of Mercury is highly responsive to the IMF orientation and solar wind plasma parameters.

Short-term temporal variability of Mercury’s Na exosphere has been observed by Earth-based ground telescopes (Leblanc et al., 2009; Potter et al., 1999). Leblanc et al. (2009) from a single day observation of Mercury’s exosphere found that the high Na emission brightness in the northern hemisphere vanished after a few hours while the high emission in the southern hemisphere showed a more persistent peak. They found a correlation between high Na emission in the southern hemisphere and a strong sunward component of the IMF; a feature which was predicted before by simulations (Massetti et al., 2007) and reported again later by...
ground-based observations (Mangano et al., 2013; Mangano et al., 2015). Our simulation results (Figures 5, 9, and 10) also show a strong dependence between sunward IMF and a high flux of solar wind proton precipitation to the southern hemisphere. Our results suggest that for the event observed by Leblanc et al. (2009), if the solar wind dynamic pressure remained relatively constant over the course of their observation, it could be possible that the radial component of the IMF had changed from planetward, which causes a higher plasma precipitation to the northern hemisphere (e.g., Figure 4), to sunward (e.g., Figure 5). However, we cannot necessarily constrain changes in the $z$ component of the IMF from our simulations.

Our simulation results suggest a noticeable north-south asymmetry in the solar wind plasma precipitation to the surface of Mercury, which is controlled by the IMF orientation (Figure 9). Ground-based observations also found a north-south asymmetry in the Na emission intensity at high latitudes (e.g., Mangano et al., 2015; Potter et al., 1999; Potter et al., 2006; Schleicher et al., 2004; Yoshikawa et al., 2008). Our model suggests that when the IMF is perfectly along the $z$ axis (Figure 2) and when the IMF is sunward with a strong radial component (Figure 5), there is a noticeable north-south asymmetry in the solar wind flux impacting the surface. However, when the IMF is planetward (Figure 4), the incident flux to the northern hemisphere increases, although the southern hemisphere is exposed to a higher flux overall. In addition, Korth et al. (2014) used MESSENGER observations to show a north-south asymmetry in plasma pressure on the nightside, with lower fluxes at low altitudes in the northern hemisphere compared to the south. They suggested that this asymmetry is associated with the higher access of the solar wind plasma to the southern hemisphere due to the magnetic dipole offset. In general, our model also shows a higher incidence rate to the southern hemisphere compared to the northern hemisphere (Figure 10d), which is associated with the northward offset of the planet's magnetic dipole. Furthermore, ground-based and MESSENGER observations both showed a north-south asymmetry in the antisunward Na tail with an excess in the northern tail (e.g., Baumgardner et al., 2008; McClintock et al., 2008; Potter & Killen, 2008; Vervack et al., 2010; Schmidt, 2013). Using a Monte Carlo simulation, Schmidt (2013) showed that the main source of Na in the northern tail is in fact the Na from the southern hemisphere that drifts to the opposite hemisphere of the tail as they are pushed antisunward by radiation pressure.

Our simulations show a considerable solar wind flux impacts Mercury's nightside (Table 9), with a high concentration at low latitudes close to the equator, especially when the IMF has a northward component (e.g., Figures 3d and 5d). Despite the observations of plasma at low latitudes on the nightside (e.g., Korth et al., 2014; Raines et al., 2015) and predictions of plasma precipitation onto those regions by MHD simulations (Benna et al., 2010; Burger et al., 2010), hybrid simulation results presented prior to our study (e.g., Chanteur et al., 2014; Kallio & Janhunen, 2003; Trávníček et al., 2010; Wang et al., 2010) did not show plasma precipitation at low latitudes in the nightside surface of Mercury.

As discussed earlier in section 2.3, for simplicity we ignored the large conductive core of Mercury and assumed that Mercury is a fully resistive body with resistivity $10^7$ Ohm-m. The large conductive body of Mercury (Smith et al., 2012; Hiremath, 2012; Hauck et al., 2013) is known to respond to changes in the IMF and solar wind dynamic pressure and push the magnetopause further upstream compared to conditions when the conductive core is not taken into account (Glassmeier et al., 2007; Grosser et al., 2004; Heyner et al., 2011; Jia et al., 2015). However, our simulation results (Figures 5b and 8d) suggest that even a 42 nPa solar wind dynamic pressure is not enough to expose the entire dayside surface of Mercury's to the solar wind plasma and a higher dynamic pressure (over 70 nPa, shown in Figure 8f) is required. Addition of conductive core effects would presumably raise the dynamic pressure required for collapse of the dayside magnetosphere to higher values. Using an MHD simulation, Jia et al. (2019) also found that 56 nPa dynamic pressure is sufficient for the magnetopause to reach Mercury's surface if the induction is not taken into account. When induced fields are considered, they found that 107 nPa dynamic pressure is not enough to collapse the magnetopause to the surface. Thus, it is possible that the precipitating flux of particles to the surface of Mercury computed here from the extreme Events E1–E3 could be lessened with the inclusion of induced fields (although such an effect would depend also on the decay time of the induced fields relative to the period of extended upstream solar wind pressures). Such an investigation is noted as an area for future research.

In summary, this study provides a better understanding of the solar wind proton precipitation to the surface of Mercury. The impact of the solar wind ions to the surface of Mercury produces ion sputtering and backsattering (e.g., Mura et al., 2009; Sarantos et al., 2007). The surface-sputtered and backsattered particles, which are often neutralized, populate the neutral exosphere of Mercury (e.g., Killen et al., 2007;
Lammer & Bauer, 1997). If the energy of the neutrals is higher than a few electron-volts, they are called energetic neutral atoms (ENAs) (e.g., Lukyanov et al., 2004; Mura et al., 2006). ENAs originating from the surface can be used to visualize the precipitation regions in the same way that the terrestrial auroral maps to magnetospheric dynamics (i.e., ENA "aurora" on Mercury). In addition, measurements of ENAs are important for understanding the contribution of sputtering to the formation of Mercury’s neutral exosphere (e.g., Mura et al., 2006; Orsini et al., 2007). ESA’s and JAXA’s BepiColombo mission (Benkhoff et al., 2010; Millillo et al., 2010), which was launched in 2018 and will arrive in its final orbit around Mercury by the end of 2025, carries two ENA sensors to investigate Mercury's surface response to precipitating solar wind plasma. These two sensors include Emitted Low-Energy Neutral Atoms, which is a part of the SERENA (Search for Exosphere Refilling and Emitted Neutral Abundances) particle instrument suite (Orsini et al., 2010) on Mercury Planetary Orbiter, and ENA (Energetic Neutrals Analyzer), which is a part of the Mercury Plasma/Particle Experiment package (Saito et al., 2010) on Mercury Magnetospheric Orbiter, now called Mio. Our simulation results presented here will help us to better understand future observations at Mercury by ENA and Emitted Low-Energy Neutral Atoms sensors on BepiColombo.

Acknowledgments

S. Fatemi acknowledges support from Swedish National Research Council, Grant 2018-0345, Swedish National Space Agency, Grants 2018-C and 2018-N, and Europlanet BepiColombo Young Scientist Working Group (YSWG). A. R. Poppe acknowledges support from the NASA SSERVI DREAM2/LEADER team, Grant NNX14AG16A. This research was conducted using computational resources provided by the Swedish National Infrastructure for Computing (SNIC), Projects SNIC2018/1-10 and SNIC2019/3-178 at the High Performance Computing Center North (HPC2N), Umeå University, Sweden. The simulation results are publicly available online (https://data.irf.se/data/fatemi2019/gr/). The authors acknowledge the reviewers for their helpful comments that improved this manuscript.

References

Acuña, M. H., Connerney, J., Lin, R., Mitchell, D., Carlson, C., McFadden, J., et al. (1999). Global distribution of crustal magnetization discovered by the Mars Global Surveyor MAG/ER experiment. Science, 284(5415), 790–793.

Anderson, B. J., Acuña, M. H., Korth, H., Purucker, M. E., Johnson, C. L., Slavin, J. A., & McNutt, R. L. (2008). The structure of Mercury’s magnetic field from MESSENGER’s first flyby. Science, 321(5885), 82–85.

Anderson, B. J., Acuña, M. H., Korth, H., Slavin, J. A., Uno, H., Johnson, C. L., & McNutt, R. L. (2010). The magnetic field of Mercury. Space Science Reviews, 152(1), 307–339.

Anderson, B. J., Johnson, C. L., Korth, H., Purucker, M. E., Winslow, R. M., Slavin, J. A., & Zurbuchen, T. H. (2011). The global magnetic field of Mercury from MESSENGER orbital observations. Science, 333(6051), 1859–1862.

Anderson, B. J., Slavin, J. A., Korth, H., Boardens, S. A., Zurbuchen, T. H., Raines, J. M., & Solomon, S. C. (2011). The dayside magnetospheric boundary layer at Mercury. Planetary and Space Science, 59(15), 2037–2050.

Bame, S., Ashbride, J., Feldman, W., Montgomery, M., & Kearney, P. (1975). Solar wind heavy ion abundances. Solar Physics, 42(2), 463–473.

Bame, S., Ashbride, J., Hunderhausen, A., & Montgomery, M. D. (1970). Solar wind ions: 56Fe+8, 56Fe+12, 28Si+7, 28Si+8, 28Si+9, and 16O+6. Journal of Geophysical Research, 75(31), 6360–6365.

Bauermann, T. J., Wilson, J., & Mendillo, M. (2008). Imaging the sources and full extent of the sodium tail of the planet Mercury. Geophysical Research Letters, 35, L03201. https://doi.org/10.1029/2007GL032337

Benkhoff, J., van Casteren, J., Hayakawa, H., Fujimoto, M., Laakso, H., Novara, M., & Ziehe, R. (2010). BepiColombo—Comprehensive exploration of Mercury: Mission overview and science goals. Planetary and Space Science, 58(1), 2–20.

Benna, M., Anderson, B. J., Baker, D. N., Boardens, S. A., Gloeckler, G., Gold, R. E., et al. (2010). Modeling of the magnetosphere of Mercury at the time of the first MESSENGER flyby. Icarus, 209(1), 3–10.

Bida, T. A., & Killen, R. M. (2017). Observations of the minor species AI and Fe in Mercury’s exosphere. Icarus, 289, 227–238.

Bida, T. A., Killen, R. M., & Morgan, T. H. (2000). Discovery of calcium in Mercury’s atmosphere. Nature, 404(6774), 159.

Birn, J., Drake, J., Shay, M., Rogers, B., Denton, R., Hesse, M., et al. (2001). Geospace Environmental Modeling (GEM) magnetic reconnection challenge. Journal of Geophysical Research, 106(A3), 3715–3719.

Bochsler, P. (2007). Minor ions in the solar wind. Astronomy and Astrophysics Reviews, 14(1), 1–40.

Broadfoot, A., Shemansky, D., & Kumar, S. (1976). Mariner 10: Mercury atmosphere. Geophysical Research Letters, 3(1), 577–580.

Burger, M. H., Killen, R. M., Vervack Jr, R. J., Bradley, E. T., McClintock, W. E., Sarantos, M., & Mouawad, N. (2010). Monte Carlo modeling of sodium in Mercury’s exosphere during the first two MESSENGER flybys. Icarus, 209(1), 63–74.

Burlaga, L. F. (2001). Magnetic fields and plasmas in the inner heliosphere: Helios results. Geophysical Research Letters, 28(8), 790–793.

Eastwood, J., Lucek, E., Mazelle, C., Meziane, K., Narita, Y., Pickett, J., & Treumann, R. (2005). The foreshock. Advances in Geosciences: Exploration of Mercury: Mission Overview and Science Goals. Planetary and Space Science, 53(1), 1–40. Retrieved from https://iopscience.iop.org/article/10.1016/j.pss.2004.11.002

Exner, W., Heyner, D., Lüuzzo, L., Motschmann, U., Shiota, D., Kusano, K., & Shiibayama, T. (2018). Coronal mass ejection hits mercury: A.I.K.E.F. hybrid-c ode results compared to MESSENGER data. Planetary Space Science, 153, 89–99.
Fatemi, S., Holmström, M., & Futaana, Y. (2012). The effects of lunar surface plasma absorption and solar wind temperature anisotropies on the solar wind proton velocity space distributions in the low-altitude lunar plasma wake. Journal of Geophysical Research, 117, A10105. https://doi.org/10.1029/2011JA017353

Fatemi, S., Poirier, N., Holmström, M., Lindkvist, J., Wieser, M., & Barabash, S. (2018). A modelling approach to infer the solar wind dynamic pressure from magnetic field observations inside Mercury’s magnetosphere. Astronomy & Astrophysics, 614, A132. https://doi.org/10.1051/0004-6361/201832764

Fatemi, S., & Poppe, A. R. (2018). Solar wind plasma interaction with asteroid 16 Psyche: Implication for formation theories. Geophysical Research Letters, 45, 39–40. https://doi.org/10.1002/2017GL073980

Fatemi, S., Poppe, A. R., Delory, G. T., & Farrell, W. M. (2017). AMITIS: A 3D GPU-based hybrid-PIE model for space and plasma physics. Journal of Physics: Conference Series, 837(1), 12.017.

Fatemi, S., Poppe, A., Khurana, K., Holmström, M., & Delory, G. (2016). On the formation of Ganymede’s surface brightness asymmetries: Kinetic simulations of Ganymede’s magnetosphere. Geophysical Research Letters, 43, 4745–4748. https://doi.org/10.1002/2016GL068363

Fujiyoshi, M., Baumjohann, W., Kabin, K., Nakamura, R., Slavin, J., Terada, N., & Zelenyi, L. (2008). Hermean magnetosphere-solar wind interaction. In A. Balogh, L. Ksanfomality, & R. von Steiger (Eds.), Mercury, Space Sciences Series of ISSI (Vol. 26, pp. 347–368). New York, NY: Springer. https://doi.org/10.1007/978-0-387-75739-5_12

Fuqua Haviland, H., Poppe, A., Fatemi, S., Delory, G., & de Pater, I. (2019). Time-dependent hybrid plasma simulations of lunar electromagnetic induction in the solar wind. Geophysical Research Letters, 46, 4151–4160. https://doi.org/10.1029/2018GL080523

Gamborino, D., Vorburger, A., & Wurz, P. (2019). Mercury’s subsolar sodium exosphere: An ab initio calculation to interpret MASCS/UVVS observations from MESSENGER. Annales Geophysicae, 37(4), 455–470.

Garrick-Bethell, I., Poppe, A. R., & Fatemi, S. (2019). The lunar paleo-magnetosphere: Implications for the accumulation of polar volatile deposits. Geophysical Research Letters, 46, 5778–5787. https://doi.org/10.1029/2019GL082548

Glass, A., Tracy, P., & Raines, J. (2019). First identification of foreshock plasma populations at Mercury. In AGU Fall Meeting Abstracts. San Francisco, CA.

Glassmeier, K. H., Auster, H. U., & Motschmann, U. (2007). A feedback dynamo generating Mercury’s magnetic field. Geophysical Research Letters, 34, 22. http://doi.org/10.1029/2007GL031662

Gloeckler, G., Geiss, J., Balsiger, H., Bedini, P., Cain, J. C., Fischer, J., Fisk, L. A., Galvin, A. B., Gliem, F., Hamilton, D. C., Hollweg, J. V., Ipavich, F. M., Joos, R., Livi, S., Lundgren, R. A., Mall, U., McKenzie, J. F., Ogilvie, K. W., Ottens, F., Rieck, W., Tums, E. O., von Steiger, R., Weiss, W., & Wilken, B. (1992). The solar wind ion composition spectrometer. Astronomy and Astrophysics Supplement Series, 92, 267–289.

Grosser, J., Glassmeier, K. H., & Stadelmann, A. (2004). Induced magnetic field effects at planet Mercury. Planetary Space Science, 52(14), 1251–1260.

Hauk, S. A., Margot, J. L., Solomon, S. C., Phillips, R. J., Johnson, C. L., Lemoine, F. G., et al. (2013). The curious case of Mercury’s internal structure. Journal of Geophysical Research: Planets, 118, 1204–1220. https://doi.org/10.1002/jgre.20091

Herčík, D., Trávníček, P. M., Šverák, S., & Hellinger, P. (2016). Properties of Hermean plasma belt: Numerical simulations and comparison with MESSENGER data. Journal of Geophysical Research: Space Physics, 121, 413–431. https://doi.org/10.1002/2015JA021938

Heyner, D., Wicht, J., Göme, P. F., Schmitt, D., Auster, H. U., & Glassmeier, K. H. (2011). Evidence from numerical experiments for a feedback dynamo generating Mercury’s magnetic field. Science, 334(6063), 1690–1693.

Hiremath, K. (2012). Magnetic field structure of Mercury. Planetary Space Science, 63, 8–14.

Hood, I. L. (2015). Initial mapping of Mercury’s crustal magnetic field: Relationship to the Caloris impact basin. Geophysical Research Letter, 42, 10–565. https://doi.org/10.1002/2015GL066451

Hood, I. L. (2016). Magnetic anomalies concentrated near and within Mercury’s impact basins: Early mapping and interpretation. Journal of Geophysical Research: Planets, 121, 1016–1025. https://doi.org/10.1002/2016JE005048

Hood, I., Zakharian, A., Halikas, I., Mitchell, D., Liu, R., Acuña, M., & Binder, A. (2001). Initial mapping and interpretation of lunar crustal magnetic anomalies using Lunar Prospector magnetometer data. Journal of Geophysical Research, 106(E1), 27,825–27,839.

Ipavich, F. M., Parás, R., Livi, S., Lundgren, R. A., Mall, U., McKenzie, J. F., Ogilvie, K. W., Ottens, F., Rieck, W., Tums, E. O., von Steiger, R., Weiss, W., & Wilken, B. (1992). The solar wind ion composition spectrometer. Astronomy and Astrophysics Supplement Series, 92, 267–289.

Jarvinen, R., Alho, M., Kallio, E., & Pulkkinen, T. (2020). Ultra-low frequency waves in the ion foreshock of Mercury: A global hybrid modeling study. Monthly Notices of the Royal Astronomical Society, 493(3), 4147–4161.

Jia, X., Slavin, J. A., Gombosi, T. I., Daldorff, L. K., Toth, G., & Holst, B. (2015). Global MHD simulations of Mercury’s magnetosphere with coupled planetary interior: Induction effect of the planetary conducting core on the global interaction. Journal of Geophysical Research: Space Physics, 120, 4763–4775. https://doi.org/10.1002/2015JA021143

Jia, X., Slavin, J. A., Poh, G., DiBarrico, G. A., Toth, G., Chen, Y., & Gombosi, T. I. (2019). MESSENGER observations and global simulations of highly compressed magnetospheric events at Mercury. Journal of Geophysical Research: Space Physics, 124, 229–247. https://doi.org/10.1029/2018JA026166

Johnson, C. L., Phillips, R. J., Purucker, M. E., Anderson, B. J., Byrne, P. K., Denevi, B. W., et al. (2015). Low-altitude magnetic field measurements by MESSENGER reveal Mercury’s ancient crustal field. Science, 348(6237), 892–895.

Kabin, K., Gombosi, T., DeZeeuw, D., & Powell, K. (2000). Interaction of Mercury with the solar wind. Icarus, 143(2), 397–406.

Kallio, E., & Janhunen, P. (2003). Solar wind and magnetospheric ion impact on Mercury’s surface. Geophysical Research Letters, 30(17), 1877.

Kameda, S., Kagitani, M., Okano, S., Yoshikawa, I., & Ono, J. (2008). Observation of Mercury’s sodium tail using Fabry–Perot interferometer. Advances in Space Research, 41(9), 1381–1385.

Kameda, S., Yoshikawa, I., Kagitani, M., & Okano, S. (2009). Interplanetary dust distribution and temporal variability of Mercury’s atmospheric Na. Geophysical Research Letter, 36, L15201. https://doi.org/10.1029/2009GL039036

Killen, R. M., Bida, T. A., & Morgan, T. H. (2005). The calcium exosphere of Mercury. Icarus, 173(2), 300–311.

Killen, R. M., Cremonese, G., Lammer, H., & Orsi, S. (2007). Processes that promote and deplete the exosphere of Mercury. Space Science Reviews, 132(2–4), 31–327.

Killen, R. M., & Ip, W. H. (1999). The surface-bound atmospheres of Mercury and the Moon. Reviews of Geophysics, 37(3), 361–406.

Killen, R. M., Potter, A., Reiff, P., Sarantos, M., Jackson, B., Hick, P., & Giles, B. (2001). Evidence for space weather at Mercury. Journal of Geophysical Research, 106(E9), 20,509–20,525.

Killen, R. M., Sarantos, M., Potter, A., & Reiff, P. (2004). Source rates and ion recycling rates for Na and K in Mercury’s atmosphere. Icarus, 171(1), 1–19.
Pope, A. R., Fatemi, S., & Khurana, K. (2018). Thermal and energetic ion dynamics in Ganymede’s magnetosphere. Journal of Geophysical Research: Space Physics, 123, 4614–4637. https://doi.org/10.1002/2018JA025312

Potter, A. E., & Killen, R. (2008). Observations of the sodium tail of Mercury. Icarus, 194(1), 1–12.

Potter, A. E., Killen, R., & Morgan, T. (1999). Rapid changes in the sodium exosphere of Mercury. Planetary Space Science, 47(12), 1441–1448.

Potter, A. E., Killen, R., & Morgan, T. (2002). The sodium tail of Mercury. Meteoritics & Planetary Science, 37(9), 1165–1172.

Potter, A. E., Killen, R. M., & Morgan, T. H. (2007). Solar radiation acceleration effects on Mercury sodium emission. Icarus, 186(2), 571–580.

Potter, A. E., Killen, R., Reardon, K. P., & Bida, T. (2013). Observation of neutral sodium above Mercury during the transit of November 8, 2006. Icarus, 226(1), 172–185.

Potter, A. E., Killen, R., & Sarantos, M. (2006). Spatial distribution of sodium on Mercury. Icarus, 181(1), 1–12.

Potter, A. E., & Morgan, T. (1985). Discovery of sodium in the atmosphere of Mercury. Science, 229(474), 651–653.

Potter, A. E., & Morgan, T. (1990). Evidence for magnetospheric effects on the sodium atmosphere of Mercury. Science, 248(4957), 835–838.

Potter, A. E., & Morgan, T. (1997). Sodium and potassium atmospheres of Mercury. Planetary Space Sciences, 45(1), 95–100.

Raines, J. M., DiBiaggio, G. A., Cassidy, T., Delcourt, D., Fujimoto, M., Jia, X., et al. (2015). Plasma sources in planetary magnetospheres: Mercury. Space Science Reviews, 192(1-4), 91–144.

Raines, J. M., Gershman, D. J., Slavin, J. A., Zurbuchen, T. H., Korth, H., Anderson, B. J., & Solomon, S. C. (2014). Structure and dynamics of Mercury’s magnetospheric cusp: MESSENGER measurements of protons and planetary ions. Journal of Geophysical Research: Space Physics, 119, 6587–6602. https://doi.org/10.1002/2014JA020120

Sarantos, M., Gershman, D. J., Zurbuchen, T. H., Sarantos, M., Slavin, J. A., Gilbert, J. A., & Solomon, S. C. (2013). Distribution and compositional variations of plasma ions in Mercury’s space environment: The first three Mercury years of MESSENGER observations. Journal of Geophysical Research: Space Physics, 118, 1604–1619. https://doi.org/10.1029/2012JA018073

Schleicher, H., Wiedemann, G., Wöhl, H., Berkefeld, T., & Soltau, D. (2004). Detection of neutral sodium above Mercury during the transit on 2003 May 7. Astronomy & Astrophysics, 425(3), 1119–1124.

Schmidt, C. A. (2013). Monte Carlo modeling of north-south asymmetries in Mercury’s sodium exosphere. Journal of Geophysical Research: Space Physics, 118, 4566–4571. https://doi.org/10.1002/jgra.50396

Schmidt, C. A., Baumgardner, J., Mendillo, M., & Wilson, J. K. (2012). Escape rates and variability constraints for high-energy sodium sources at Mercury. Journal of Geophysical Research, 117, A03101. https://doi.org/10.1029/2011JA017217

Schmidt, C. A., Wilson, J. K., Baumgardner, J., & Mendillo, M. (2010). Orbital effects on Mercury’s escaping sodium source. Icarus, 207(1), 9–16.

Schröter, D., Trávníček, P. M., Anderson, B. J., Ashour-Abdalla, M., Baker, D. N., Benna, M., et al. (2011). Quasi-trapped ion and electron populations at Mercury. Geophysical Research Letters, 38, L23103. https://doi.org/10.1029/2011GL049629

Slavin, J. A., Acuña, M. H., Anderson, B. J., Baker, D. N., Benna, M., Boardset, S. A., et al. (2009). MESSENGER observations of magnetic reconnection in Mercury’s magnetosphere. Science, 324(5927), 606–610.

Slavin, J. A., Acuña, M. H., Anderson, B. J., Baker, D. N., Benna, M., Gloeckler, G., & Zurbuchen, T. H. (2008). Mercury’s magnetosphere after MESSENGER’s first flyby. Science, 321(5855), 85–89.

Slavin, J. A., Anderson, B. J., Baker, D. N., Benna, M., Boardset, S. A., Gold, R. E., & Zurbuchen, T. H. (2012). MESSENGER and Mariner 10 flyby observations of magnetotail structure and dynamics at Mercury. Journal of Geophysical Research, 117, A01215. https://doi.org/10.1029/2011JA016900

Slavin, J. A., DiBiaggio, G. A., Gershman, D. J., Imber, S. M., Poh, G. K., Raines, J. M., et al. (2014). MESSENGER observations of Mercury’s dayside magnetosphere under extreme solar wind conditions. Journal of Geophysical Research: Space Physics, 119, 8087–8116. https://doi.org/10.1002/2014JA024904

Slavin, J. A., & Holzer, R. E. (1979). The effect of ejection on the solar wind stand-off distance at Mercury. Journal of Geophysical Research, 84(A5), 2076–2082.

Smith, D. E., Zuber, M. T., Phillips, R. J., Solomon, S. C., Hauck, S. A., Lemoine, F. G., et al. (2012). Gravity field and internal structure of Mercury from MESSENGER. science, 336(6087), 214–217.

Solomon, S. C., McClintock, R. L., Gold, R. E., & Domingue, D. L. (2007). MESSENGER mission overview. Space Science Review, 131(1), 3–39.

Sonnerup, B.Ö., Paschmann, G., Papamastorakis, I., Schepke, N., Haerenfeld, G., Barne, S., & Russell, C. (1981). Evidence for magnetic field reconnection at the Earth’s magnetopause. Journal of Geophysical Research, 86(A12), 10,049–10,067.

Sprague, A., Kozlovski, R., Hunten, D., Schneider, N., Domingue, D., Wells, W., & Fink, U. (1997). Distribution and abundance of sodium in Mercury’s atmosphere, 1985-1988. Icarus, 129(2), 506–527.

Sundberg, T., Boardset, S. A., Slavin, J. A., Anderson, B. J., Korth, H., Zurbuchen, T. H., & Solomon, S. C. (2012). MESSENGER orbital observations of large-amplitude Kelvin-Helmholtz waves at Mercury’s magnetopause. Journal of Geophysical Research, 117, 4216. https://doi.org/10.1029/2011JA017288

Sundberg, T., & Slavin, J. (2015). Mercury’s magnetotail. In Magnetotails in the solar system, Geographical Monograph (Vol. 207, pp. 21–42). Washington, DC: American Geophysical Union.

Trávníček, P. M., Hellinger, P., & Schriver, D. (2007). Structure of Mercury’s magnetosphere for different pressure of the solar wind: Three dimensional hybrid simulations. Geophysical Research Letters, 34, L05104. https://doi.org/10.1029/2006GL028518

Trávníček, P. M., Schriver, D., Hellinger, P., Hercík, D., Anderson, B. J., Sarantos, M., & Slavin, J. A. (2010). Mercury’s magnetosphere-solar wind interaction for northward and southward interplanetary magnetic field. Hybrid simulation results. Icarus, 209(1), 11–22.
Varela, J., Pantellini, F., & Moncuquet, M. (2015). The effect of interplanetary magnetic field orientation on the solar wind flux impacting Mercury's surface. *Planetary Space Science, 119*, 264–269.

Vervack, R. J., Killen, R., McClintock, W., Merkel, A., Burger, M., Cassidy, T., & Sarantos, M. (2016). New discoveries from MESSENGER and insights into Mercury's exosphere. *Planetary and Space Science, 126*, 5992, 672–675.

Vervack, R. J., McClintock, W. E., Killen, R. M., Sprague, A. L., Anderson, B. J., Burger, M. H., & Izenberg, N. R. (2010). Mercury's complex exosphere: Results from MESSENGER's third flyby. *Science, 329*, 672–675.

Von Steiger, R., Schwadron, N., Fisk, L., Geiss, J., Gloeckler, G., Hefti, S., & Zurbuchen, T. (2000). Composition of quasi-stationary solar wind flows from Ulysses/Solar Wind Ion Composition Spectrometer. *Journal of Geophysical Research, 105*(A12), 27,217–27,238.

Wang, Y. C., Mueller, J., Motschmann, U., & Ip, W. H. (2010). A hybrid simulation of Mercury's magnetosphere for the MESSENGER encounters in year 2008. *Icarus, 209*, 46–52.

Winslow, R. M., Anderson, B. J., Johnson, C. L., Slavin, J. A., Korth, H., Purucker, M. E., & Solomon, S. C. (2013). Mercury's magnetopause and bow shock from MESSENGER Magnetometer observations. *Journal of Geophysical Research: Space Physics, 118*, 2213–2227. https://doi.org/10.1002/jgra.50237

Winslow, R. M., Johnson, C. L., Anderson, B. J., Gershman, D. J., Raines, J. M., Lillis, R. J., Korth, H., Slavin, J. A., Solomon, S. C., Zurbuchen, T. H., & Zuber, M. T. (2014). Mercury's surface magnetic field determined from proton-reflection magnetometry. *Geophysical Research Letter, 41*, 4463–4470. https://doi.org/10.1002/2014GL060258

Winslow, R. M., Johnson, C. L., Anderson, B. J., Korth, H., Slavin, J. A., Purucker, M. E., & Solomon, S. C. (2012). Observations of Mercury's northern cusp region with MESSENGER's Magnetometer. *Geophysical Research Letters, 39*, L08112. https://doi.org/10.1029/2012GL051472

Winslow, R. M., Lugaz, N., Farrugia, C. J., Johnson, C. L., Anderson, B. J., Paty, C. S., & Asad, M. A. (2019). First observations of an ICME compressing Mercury's dayside magnetosphere to the surface. arXiv preprint arXiv:1903.00577.

Winslow, R. M., Lugaz, N., Philpott, L., Farrugia, C. J., Johnson, C. L., Anderson, B. J., & Al Asad, M. (2020). Observations of extreme ICME ram pressure compressing Mercury's dayside magnetosphere to the surface. *The Astrophysical Journal, 889*(2), 184.

Wurz, P., & Lammer, H. (2003). Monte-Carlo simulation of Mercury's exosphere. *Icarus, 164*(1), 1–13.

Wurz, P., Whitby, J., Rohner, U., Martín-Fernández, J., Lammer, H., & Kolb, C. (2010). Self-consistent modelling of Mercury's exosphere by sputtering, micro-meteorite impact and photon-stimulated desorption. *Planetary Space Science, 58*(12), 1599–1616.

Yakishinsky, B. V., & Madey, T. E. (1999). Photon-stimulated desorption as a substantial source of sodium in the lunar atmosphere. *Nature, 400*, 642–644.

Yoshikawa, I., Ono, J., Yoshioka, K., Murakami, G., Ezawa, F., Kameda, S., & Ueno, S. (2008). Observation of Mercury's sodium exosphere during the transit on November 9, 2006. *Planetary Space Science, 56*(13), 1676–1680.

Zurbuchen, T. H., Raines, J. M., Gloeckler, G., Krimigis, S. M., Slavin, J. A., Koehn, P. L., & Solomon, S. C. (2008). MESSENGER observations of the composition of Mercury's ionized exosphere and plasma environment. *Science, 317*(5855), 90–92.

Zurbuchen, T. H., Raines, J. M., Slavin, J. A., Gershman, D. J., Gilbert, J. A., Gloeckler, G., & Solomon, S. C. (2011). MESSENGER observations of the spatial distribution of planetary ions near Mercury. *Science, 333*(6051), 1862–1865.