

MESSENGER Observations of a Possible Alfvén Wing at Mercury Driven by a Low Alfvénic Mach Number ICME

Charles F. Bowers¹, Caitríona M. Jackman¹, Xianzhe Jia², James A. Slavin²,
Joachim Saur³, Mika K. G. Holmberg¹, Ryan M. Dewey², Daniel Heyner⁴,
Filip Elekes³, Lina Z. Hadid⁵, Benoit Lavraud^{6,7}, Yang Wang⁸, Hans L. F.
Huybrighs¹, Matthew J. Rutala¹, Alexandra R. Fogg¹, Stephenie Brophy Lee¹,
Daragh M. Hollman¹

¹Astronomy & Astrophysics Section, School of Cosmic Physics, Dublin Institute for Advanced Studies,
DIAS Dunsink Observatory, Dublin, Ireland

²Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI,
USA

³Institute of Geophysics and Meteorology, University of Cologne, Cologne, DE

⁴Institut für Geophysik und Extraterrestrische Physik, Technische Universität Braunschweig, Braunschweig,
DE

⁵LPP, CNRS, Observatoire de Paris, Sorbonne Université, Université Paris Saclay, école polytechnique,
Institut Polytechnique de Paris, Palaiseau, France

⁶Laboratoire d'Astrophysique de Bordeaux, Univ. Bordeaux, France

⁷IRAP, CNRS, CNES, Université de Toulouse, France

⁸Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing PRC

Key Points:

- MESSENGER observed Mercury's magnetosphere under rare, low-Alfvénic Mach number conditions during an ICME impact.
- During the ICME, Mercury's magnetosphere exhibited properties distinct from the nominal interaction.
- Nightside plasma and magnetic field measurements suggest that MESSENGER traversed an Alfvén wing generated at Mercury.

Corresponding author: Charles F. Bowers, charlie.bowers33@gmail.com

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1029/2024JA033619](https://doi.org/10.1029/2024JA033619).

This article is protected by copyright. All rights reserved.

Abstract

We investigate Mercury's response to rare, low Alfvénic Mach number (M_A) solar wind conditions using observations from the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission. This study provides compelling evidence of Mercury's altered magnetospheric state under these extreme conditions, including the first observational confirmation of Alfvén wing formation at the planet. Our analysis estimates that the upstream conditions during the ICME were sub- to trans-Alfvénic ($M_A \leq 1.5$). These unusually low M_A solar wind conditions were driven by large interplanetary magnetic fields (IMF) associated with an interplanetary coronal mass ejection (ICME) impact observed by MESSENGER on December 30, 2011. During this ~ 17 hour event, MESSENGER completed one orbital pass through Mercury's magnetosphere, capturing magnetic field and plasma observations of its altered state. We compare these observations to a three-dimensional magnetohydrodynamic simulation of the event and to MESSENGER observations under typical M_A conditions ($M_A \approx 5.0$). Compared with its nominal state, the dayside magnetosphere during the ICME exhibited a weaker, more expanded bow shock and significantly lower plasma density within the magnetosheath. On the nightside, MESSENGER observed a highly inclined magnetic field relative to the typical magnetospheric magnetic field, populated with high-density plasma consistent with the formation of an Alfvén wing— a characteristic feature of sub-Alfvénic magnetospheric interactions. This investigation of Mercury under extreme M_A conditions provides insights into the nominal, sub-Alfvénic interactions between many outer planet moons and their host planet's magnetosphere and also informs our understanding of the many exoplanetary-stellar wind interactions occurring in low- M_A environments.

Plain Language Summary

The flow of plasma emitted by the Sun, known as the solar wind, typically flows faster than any wave may travel within the plasma itself. However, on rare occasions, the properties of the solar wind plasma may dramatically change, allowing for waves to travel faster than the speed of the solar wind flow. This shift has a direct impact on the interaction between the solar wind and a planetary magnetic field environment. In this study, we present observations of one of these extreme solar wind events impacting the magnetic field environment of Mercury. Using both a three-dimensional computer simulation, and observations from the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft, we investigate the ways in which this rare solar wind regime altered Mercury's magnetic field environment. We draw interesting comparisons between the solar wind-Mercury interaction under this extreme case to the typical interaction between the near-Jupiter plasma environment and Jupiter's moon Ganymede. Investigations of rare solar wind conditions at planets within our own solar system also inform us of the range of possible regimes that characterize interactions between planets and stars outside our solar system.

1 Introduction

A key characteristic of the stream of charged particles emitted by the Sun, known as the solar wind, is the ratio of the flow speed to the Alfvén speed – the speed at which magnetic field disturbances propagate in the solar wind plasma. This ratio, known as the Alfvénic Mach number (M_A), increases with radial distance from the Sun and typically reaches a value of 1 at a heliocentric distance around 0.08 AU (Cravens et al., 1997). Beyond this distance, the solar wind speed (v_{SW}) mostly exceeds both the Alfvén speed (v_A) and the fast-mode wave speed (v_f), which is the fastest wave mode in a plasma. Planetary interactions with the solar wind in the solar system are therefore nominally both super-Alfvénic ($M_A \gg 1$) and super-fast ($M_f \gg 1$), where M_f is the ratio of v_{SW} to v_f . This super-fast solar wind results in various magnetospheric phenomena including the forma-

tion of a planetary bow shock upstream of the planet and the windsock-like shape of the magnetopause and magnetosphere, where magnetic field lines are stretched tailward by the solar wind flow.

In contrast, moons in orbit within planetary magnetospheres are often embedded in a sub-Alfvnic, sub-fast ($M_A, M_F < 1$) flow, resulting in a distinct interaction between the moon and upstream magnetospheric plasma of their parent planet. In the sub-Alfvnic/sub-fast regime, no bow-shock forms. Instead, the unshocked magnetospheric plasma interacts directly with the moons, unlike the super-Alfvnic planetary interactions in which the shocked magnetosheath plasma separates the solar wind from the magnetosphere. The moons form an obstacle to the flow of magnetospheric plasma and thus perturb the plasma and magnetic field environment around them, generating Alfvn waves (Drell et al., 1965; Neubauer, 1980; Kivelson et al., 2004; Jia et al., 2008; Saur, 2021). These Alfvn waves are simultaneously convected downstream, forming a pair of Alfvn wings connected to either side of the moon. Alfvn wings and their influence on the plasma environment have been detected at Io (Szalay et al., 2018, 2020b; Sulaiman et al., 2023; Szalay et al., 2024), Europa (Volwerk et al., 2007; Allegrini et al., 2020), Ganymede (Szalay et al., 2020a; Hue et al., 2022), and Titan (Kim et al., 2024). Moreover, global simulations of the environments of Callisto (Liuzzo et al., 2018) and Triton (Simon et al., 2021) strongly suggest that these moon-magnetospheric interactions are also characterized by Alfvn wing formation.

Under rare conditions, the solar wind is sub-Alfvnic at 1 AU. At Earth, these sub-Alfvnic conditions occur on average once every two years (Chané et al., 2012; Hajra & Tsurutani, 2022) and are most often associated with extreme solar wind conditions within interplanetary coronal mass ejections (ICMEs) (Lavraud & Borovsky, 2008). ICMEs are often associated with enhanced interplanetary magnetic field (IMF) strength and typically low solar wind plasma density, both of which increase the Alfvn speed and decrease M_A . Magnetohydrodynamic (MHD) simulations of the terrestrial magnetosphere have demonstrated that sub-Alfvnic upstream conditions transform Earth's magnetosphere and lead to the complete retreat of the bow shock away from the planet and the formation of Alfvn wings in place of the windsock-like magnetopause and magnetotail (Ridley, 2007; Chané et al., 2015; Burkholder et al., 2024). These simulations demonstrated that Earth's magnetosphere begins to transform from the purely super-Alfvnic interaction regime for trans-Alfvnic solar wind ($1 < M_A < 2$). Low M_A conditions at Earth lead to various alterations to the terrestrial magnetosphere compared to the nominal case ($M_A \approx 7.5$), including asymmetric magnetosheath flows, cross polar cap potential saturation, the development of Alfvn wings, and a drop-out of high energy electron populations within the radiation belt environment (Lavraud & Borovsky, 2008; Lugaz et al., 2016). Alfvn wings were first observed at Earth under extremely low upstream plasma density through simultaneous measurements of the WIND and Geotail spacecraft (Chané et al., 2012), and have recently been observed by the Magnetospheric Multi-Scale (MMS) mission during an ICME event (Chen et al., 2024).

The M_A of the solar wind at Mercury's eccentric orbit (0.31–0.47 AU) is the lowest on average compared to all planets in the solar system, with an average value of ≈ 5.4 (Russell et al., 1988; Slavin & Holzer, 1981; Sun et al., 2022), compared to the median M_A at Earth of 7.5 (Lavraud & Borovsky, 2008). As a result, Mercury is subjected to sub-Alfvnic solar wind conditions more frequently than at Earth (Liu et al., 2005; Sarantos & Slavin, 2009; Diego et al., 2020; Lai et al., 2024). Sarantos and Slavin (2009) argued that the large magnitude IMF during ICME impacts may form Alfvn wings at Mercury given sufficient effective conductivity of the planet. The impact of an ICME on Mercury's magnetosphere was first observed by the MErcury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft (Slavin et al., 2014; Sun, Slavin, Dewey, et al., 2020). Winslow et al. (2015, 2017) created a dataset of 69 ICME impacts during MESSENGER's orbital lifetime (March 2011 – April 2015), statistically analyzing how

ICMEs impact Mercury's cusp and magnetopause boundary (Winslow et al., 2020). However, due to the nature of single spacecraft observations and the lack of upstream solar wind information during MESSENGER's magnetospheric traversal, an investigation into the impact of sub-Alfvénic solar wind conditions at Mercury has yet to be performed.

We present an analysis of MESSENGER observations of Mercury's magnetosphere under low M_A conditions driven by ICME impact at the planet, chosen from the list of ICMEs provided by Winslow et al. (2015). The properties of this ICME along with MESSENGER's orbital trajectory make it an ideal case study to investigate the impact of low M_A conditions at the planet. We estimate the upstream M_A during this event to be among the lowest 5% of all ICME impacts at Mercury, with an M_A value of ≤ 1.5 . This ICME exhibited strong southward pointed IMF that likely lasted throughout MESSENGER's traversal of Mercury's magnetosphere. The spacecraft primarily sampled the noon-midnight plane, making it well-suited for analyzing potential Alfvén wing structures, which would be confined to this plane given the southward IMF orientation. We run a 3D global MHD simulation of Mercury's magnetosphere using the estimated ICME conditions, the results of which are in good agreement with MESSENGER observations and highlight the physics of a trans-Alfvénic solar wind interaction with a planetary system. Studying the planetary response to rare low- M_A solar wind conditions offers an opportunity to not only better understand the dynamics involved in moon-magnetospheric interactions within our own solar system, but also to provide insights into exoplanet interactions with their host star, many of which are likely embedded in a nominally sub-Alfvénic stellar wind due to their proximity to their host star (Saur et al., 2013).

The manuscript is organized as follows: Section 2 describes the MESSENGER instrumentation used in this study. Section 3 covers the ICME event (3.1), our method for estimating upstream conditions from MESSENGER observations (3.23.4), and the expected differences in magnetospheric interactions under super-Alfvénic and sub-Alfvénic upstream conditions (3.5). It also details the MHD simulation setup (3.6) and examines how MESSENGER's observations reflect changes in Mercury's magnetosphere under these extreme conditions (3.73.10). Section 4.1 provides an overview of Mercury's magnetosphere under low M_A conditions. Finally, Sections 4.2 and 4.3 contextualize these findings within previous studies of extreme solar wind conditions at Mercury and discuss implications for future spacecraft missions.

2 Methodology

We investigate Mercury's magnetospheric response to low- M_A conditions via analysis of data obtained by the magnetometer (MAG) instrument onboard MESSENGER (Anderson et al., 2007) and the Fast Imaging Plasma Spectrometer (FIPS) instrument (Andrews et al., 2007). MAG measures the three components of the magnetic field at a maximum sampling rate of 20 Hz. In this study, we focus on the large-scale magnetospheric response and therefore downsample the data to 1 Hz resolution. The magnetic field data are reported in the aberrated Mercury Solar Magnetospheric MSM' coordinate frame. This coordinate system is centered on Mercury's dipole magnetic field, which is offset northward from Mercury's center of mass by $\sim 0.2 R_M$ (Anderson et al., 2011), where R_M is the radius of Mercury ($1R_M = 2440$ km). $Z_{MSM'}$ points towards Mercury's northern magnetic pole. $X_{MSM'}$ points in the opposite direction to the solar wind flow in the rest frame of Mercury, which is not exactly sunward due to aberration effects from Mercury's orbital motion. The aberration angle between Mercury's orbital velocity and the vector that points radially outward from the Sun is calculated daily and is used to determine $X_{MSM'}$, assuming an average solar wind velocity of 400 km/s. This aberration angle ranges from 5.6° at aphelion to 8.4° at perihelion. $Y_{MSM'}$ completes the right-handed coordinate system.

FIPS measured the energy per unit charge (E/q), time of flight, and angle of incidence for ions within an energy range 0.05–13 keV taken over 64 energy bins. Energy spectra within this energy range were taken within the instantaneous 1.4π sr field of view (FOV) of FIPS. MESSENGER’s sunshade partially blocked plasma incoming from the antisunward direction into the detector, resulting in an effective field of view of $\sim 1.15\pi$ sr. FIPS measurements are therefore more limited to plasma traveling transverse to the Mercury–Sun line, which excludes cold plasma flows that move radially outward from the Sun within the solar wind (Raines et al., 2011; Gershman et al., 2013). This FOV effect is less relevant for hot plasma populations present within Mercury’s magnetosphere and within parts of the magnetosheath, particularly near the subsolar point.

ICMEs are characterized by extremes in solar wind datasets and can exhibit very low M_A within their structures. A list of 61 MESSENGER observations of ICME impacts for the first 3.5 years of the MESSENGER mission (March 18, 2011 through 17 September 2014) was compiled in Winslow et al. (2015). These observations were identified via a set of visual criteria within the MAG dataset time series. These criteria included observations of an interplanetary shock, followed by a sheath region and magnetic ejecta region within the solar wind. To be included in the list of ICMEs, observations of the magnetic ejecta must have been observed both before and after MESSENGER’s traversal through the magnetosphere, and produce visible disturbances in the magnetospheric magnetic fields. These criteria were designed to be strict to unambiguously detect ICMEs observed by MESSENGER to analyze their magnetospheric impact. This likely results in the omission of some ICME impacts that do not meet these strict criteria, likely due to orbital trajectory (MESSENGER must be in the solar wind at the time of the ICME onset), and the duration of the ICME, among other factors. Winslow et al. (2017) statistically analyzed the properties of these ICMEs and added to the list 8 ICME impacts for the remaining ~ 1 year of MESSENGER data, resulting in 69 total ICME impacts. From this list, we select the best candidate orbit to study the impact of low M_A conditions on Mercury’s magnetosphere. Many of the distinguishing phenomena of sub-Alfvénic magnetospheric interaction occur within the plane of the upstream magnetic field. Therefore, the ideal case for studying sub-Alfvénic conditions at Mercury would be an ICME impact with very low M_A and an IMF direction that is aligned with MESSENGER’s orbital plane throughout the spacecraft’s traversal through the magnetosphere.

3 Results

3.1 MESSENGER Observations of the ICME Event

Based on the criteria described in the previous section, we identify and analyze the single ICME event that is most likely to exhibit a number of observable features of low M_A solar wind interactions with Mercury’s magnetosphere. From the Winslow et al. (2015) and Winslow et al. (2017) ICME event list, we show the impact of an ICME that arrived at MESSENGER at 16:27:22 on December 30, 2011, and ended $\sim 09:19:52$ on December 31, 2011, as shown by the red vertical lines in Figure 1. The orbital trajectory of MESSENGER during this event was largely in the $XZ_{MSM'}$ plane, entering the magnetosphere on the dayside north of the subsolar point and exiting the magnetosphere on the nightside of the planet. The same event was shown and discussed as an example ICME impact at Mercury in Figure 1 of Winslow et al. (2015), although its effects on Mercury’s magnetosphere were not examined in detail. The approximately 17-hour duration of this ICME entirely encompasses a single 12-hour orbital period of MESSENGER during this stage in the mission.

The start of the ICME was distinguishable by a discontinuity in the magnitude of the magnetic field, characteristic of the ICME shock. This discontinuity resulted in a sharp increase of $|B|$ from ~ 23 nT to 57 nT. At the arrival of the ICME, MESSENGER was near apoapsis, sampling the upstream solar wind directly. The ICME shock was followed

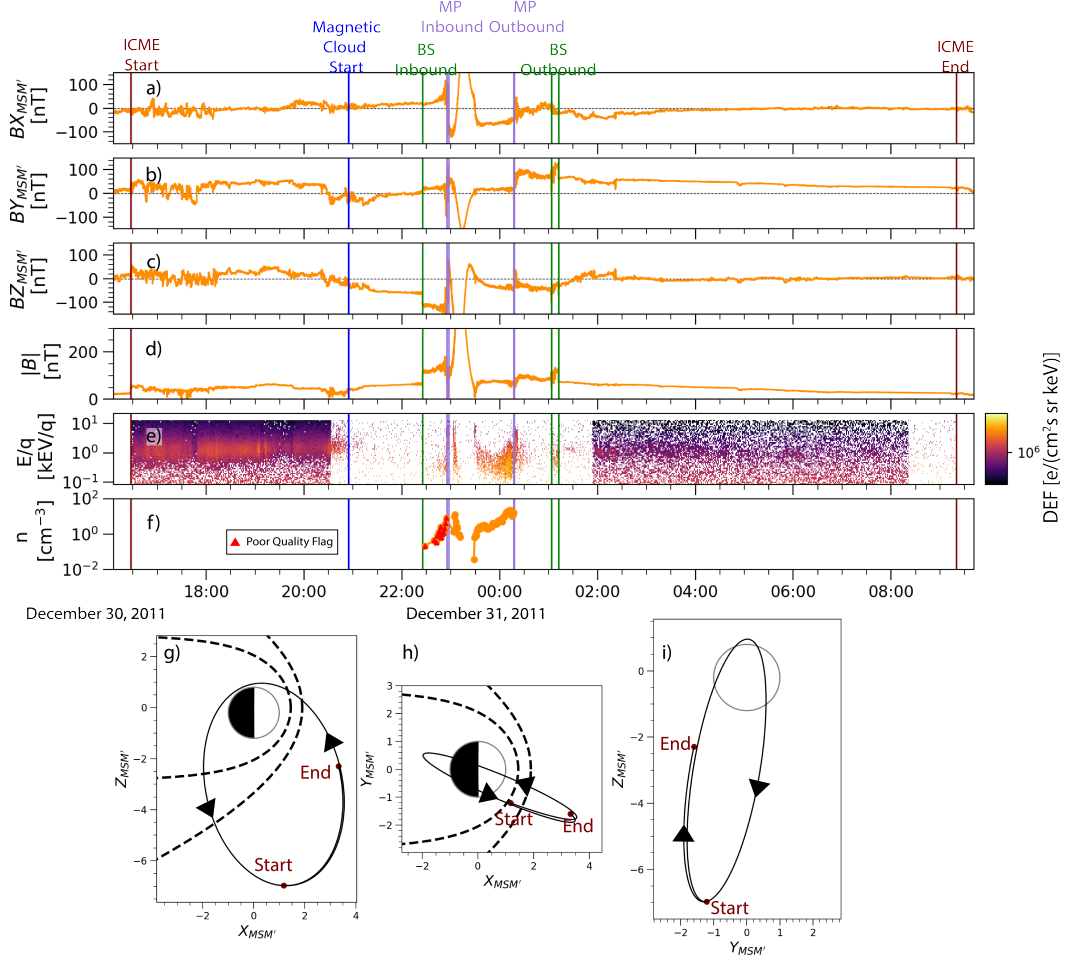


Figure 1. MESSENGER MAG data at 1 s resolution in the MSM' coordinate frame from 2012-12-30/15:15:00 to 2011-12-31/11:15:00. Panels a-c display the $X_{MSM'}$, $Y_{MSM'}$, $Z_{MSM'}$ components of the magnetic field in nT. Panel d shows the magnitude of the magnetic field, $|B|$ in nT. Panel e shows the differential energy flux spectrogram measured by FIPS. Panel f shows the estimated densities provided by Raines 2021. Red dots represent densities with poor quality fits. The ICME impact was from 2011-12-30 16:27:22 – 2011-12-31 09:19:52, as indicated by the vertical red lines. The first green line represents the instantaneous bow shock crossing on the inbound portion of the orbit. The second two green lines show the time range of multiple bow shock crossings on the outbound portion. The purple lines represent magnetopause crossing intervals. The blue line represents the start of the magnetic cloud of the ICME. Panels g-i show MESSENGER's orbital trajectory plotted in the time series above in the $XZ_{MSM'}/XY_{MSM'}/YZ_{MSM'}$ planes. MESSENGER's position during the start and end of the ICME are indicated on the panels as red circles. The outer and inner dashed black lines represent the nominal bowshock and magnetopause distances determined by Winslow et al. (2013) based on the form provided by Shue et al. (1997).

by an ICME sheath region ($\sim 16:27:22 - 20:54:00$) consisting of a strong magnetic field that is highly variable and high FIPS counts. The magnetic field becomes smoother following the ICME sheath region, and FIPS counts dramatically decrease, indicative of the start of the magnetic cloud of an ICME. The magnetic field is initially dominated

by the $+Z_{MSM'}$ and $+Y_{MSM'}$ components ($\sim 18:14 - 20:28$). The ICME magnetic field then rotated, resulting in an IMF orientation that is primarily in the $-Z_{MSM'}$ direction from 21:30 to the inbound bow shock crossing. This smooth magnetic field rotation indicates that part of the ICME flux rope passed over MESSENGER while the spacecraft was in the solar wind (Burlaga et al., 1981; Song et al., 2020). After crossing Mercury's planetary bow shock during the inbound portion of its orbit at 22:25:08, MESSENGER traversed the magnetosheath and magnetosphere, crossing the bow shock multiple times on the outbound portion. This series of bow shock crossings began at 01:03:11 on December 31 and ended with the final crossing into the solar wind at 01:12:03. The magnetic field in the ICME then slowly decreased from 01:12:03 to 09:19:52, where a small discontinuity occurred in $|B|$, sharply decreasing from 22 nT to 17 nT and marking the end of the ICME. The magnetopause and bow shock crossing locations were determined via the published list of visually identified boundary crossings throughout MESSENGER's orbital lifetime, provided by Philpott et al. (2020)

For the ICME event presented in Figure 1, the IMF is pointing primarily in the $-Z_{MSM'}$ direction just upstream of the bow shock. This highly negative IMF B_Z configuration is also observed within the dayside magnetosheath (December 30, 22:25 – 22:55) and nightside magnetosheath (December 31 00:18 – 01:12), suggesting that the IMF remained primarily southward throughout MESSENGER's traversal of Mercury's magnetosphere, which lasted 2.1 hours. MESSENGER's orbit during this ICME is approximately aligned with the $XZ_{MSM'}$ plane, ensuring that the spacecraft trajectory during this ICME is ideal for studying an Alfvnic interaction that mostly lies within the plane defined by the plasma velocity direction ($-X_{MSM'}$) and magnetic field direction ($-Z_{MSM'}$, in this case).

The differential energy flux of particles measured by FIPS is displayed in Figure 1e. As mentioned above, the FIPS instrument was particularly limited in measuring the properties of the solar wind due to its limited field of view and sunshade (Raines et al., 2011; Gershman et al., 2013). Therefore, MESSENGER cannot consistently measure solar wind plasma density, making precise estimates of M_A challenging. We cannot retrieve the plasma density n , velocity v_{SW} , or temperature T from in situ measurements of the ICME within the magnetic cloud due to extremely low counts (Figure 1e), which are likely the result of the limited FOV of FIPS that prevents plasma populations moving antisunward from reaching the instrument. However, within the ICME sheath region, FIPS measures sufficient counts to reconstruct estimates for n , v , and T likely due to higher temperatures in the sheath compared to the magnetic cloud. This statistical reconstruction technique was developed by Dewey et al. (2018, 2020) and combines multiple FIPS scans to construct a more complete spatial flux distribution of the plasma. A software model of the FIPS sensor simulates the instrument's measurements to many different drifting Maxwellian plasma distributions given the FOV constraints during the selected interval. The best fit for the plasma moments is then applied to the observations to estimate n , v , and T within the ICME sheath. From FIPS measurements just before the magnetic cloud (20:37:00 – 20:50:00), this technique estimates that $n \approx 1 \text{ cm}^{-3}$, $v \approx 450 \text{ km/s}$, $T \approx 8.5 \text{ MK}$ within the ICME sheath.

3.2 Estimates of M_A

The Alfvn speed, v_A , is defined as:

$$v_A = \frac{|B_{IMF}|}{\sqrt{\mu_0 \rho}} \quad (1)$$

Here, $|B_{IMF}|$ is the amplitude of the magnetic field, μ_0 is the permeability of free space, and ρ is the mass density of the solar wind. The average $|B|$ measured within the ICME sheath just before the magnetic cloud of 26 nT yields an M_A estimate of $M_A \approx 0.8$, based on the plasma moments described above. However, MESSENGER traverses Mercury's

magnetosphere during the magnetic cloud interval of the ICME, within which the M_A value is different to that within the ICME sheath. Based on average ICME properties at Earth, compared to the ICME sheath, $|B|$ within the magnetic cloud is larger and the mass density, ρ , is likely lower (Lavraud & Borovsky, 2008; Kilpua et al., 2017). This would result in larger v_A and lower M_A within the magnetic cloud compared to the ICME sheath. However, v within the magnetic cloud may also be higher compared to the sheath, making it difficult to estimate the M_A within the magnetic cloud exclusively from measurements within the ICME sheath.

To approximate M_A within the magnetic cloud, we determine a proxy for M_A just upstream of the bow shock based on MAG data surrounding boundaries within Mercury's plasma environment in the same manner as described in Winslow et al. (2017). This method assumes a pressure balance between the upstream solar wind (P_{SW}) and Mercury's magnetosphere (P_M). P_{SW} is comprised of both a dynamic pressure term (P_{SW}^{dyn}) and a magnetic pressure term (P_{SW}^{mag}), which is non-negligible due to the high intensity magnetic field regime of the ICME. We assume thermal pressure is negligible in the ICME. The magnetic pressure supplied by Mercury's dipole field is the dominant pressure source within Mercury's magnetosphere. The pressure balance argument also assumes that the magnetopause is stationary and not in the process of compression or expansion during MESSENGER's observations near the boundary. The final pressure balance expression is shown in Equation (2):

$$P_{SW}^{dyn} + P_{SW}^{mag} = P_M^{mag} \quad (2)$$

P_{SW}^{dyn} depends on the angle between Mercury's magnetopause normal and v_{SW} , and is expressed via Equation 3:

$$P_{SW}^{dyn} = \rho v_{SW}^2 * K \cos^2 \theta \quad (3)$$

The angle between the normal to Mercury's magnetopause and the direction of the solar wind flow ($-X_{MSM'}$) is represented by θ . The scaling factor, K , is set to 0.88 based on numerical modeling of gas dynamics and acts as a drag coefficient of plasma around a planetary obstacle within a supersonic flow (Spreiter et al., 1966). This supersonic assumption may not be valid for extreme solar wind conditions (Kivelson & Russell, 1995). The implications of this for the estimate of M_A during the ICME are discussed below.

Next, we solve for M_A in terms of these pressure values. Solving for v_{SW} in Equation 3 and rearranging Equation 2:

$$v_{SW} = \sqrt{\frac{P_{SW}^{dyn}}{\rho * K \cos^2 \theta}} = \sqrt{\frac{P_M^{mag} - P_{SW}^{mag}}{\rho * K \cos^2 \theta}} \quad (4)$$

We can now express M_A in terms of P_{SW}^{mag} , P_M^{mag} :

$$M_A = \frac{v_{SW}}{v_A} = \frac{\sqrt{\frac{P_M^{mag} - P_{SW}^{mag}}{\rho * K \cos^2 \theta}}}{\frac{B_{IMF}}{\sqrt{\mu_0 \rho}}} = \sqrt{\frac{\mu_0 (P_M^{mag} - P_{SW}^{mag})}{B_{IMF}^2 * K \cos^2 \theta}} \quad (5)$$

Thus, M_A is estimated via only MAG measurements and an estimate of the angle of the solar wind flow to the magnetopause, θ . For our study, P_M^{mag} is estimated as the average of the top 20% of $|B|$ measurements within 1 minute of the innermost magnetopause crossing, following the same methodology as Winslow et al. (2017), to mitigate underestimation due to diamagnetic depression effects. We determine B_{IMF} by averaging $|B|$ for the 30 minutes upstream of the outermost bow shock crossing. P_{SW}^{mag} is then determined from this B_{IMF} value ($P_{SW}^{mag} = \frac{B_{IMF}^2}{2\mu_0}$). The normal to the magnetopause was

determined by first fitting the position of the magnetopause crossing to the nominal magnetopause shape as described by Shue et al. (1997) and Winslow et al. (2013), assuming a constant flaring angle, and taking the normal vector to that curve at the measured magnetopause crossing. Reliable values for P_{SW}^{dyn} are only possible for low values of θ ($\theta < 60^\circ$). As a result, only the inbound portion of the orbit during the ICME yields reliable estimates for P_{SW}^{dyn} and M_A .

3.3 Comparisons between the ICME and Nominal Solar Wind Conditions

It is informative to analyze Mercury's magnetospheric response to the extreme case of an ICME event via a comparison to Mercury's magnetosphere under more nominal solar wind conditions. To do this, we compare MESSENGER observations over the orbit with the ICME to the 5 orbits before and 5 orbits after the ICME. These surrounding orbits sample a similar spatial regime to that during the ICME, so the changes in boundary positions and upstream estimates are more likely to be the result of changing upstream conditions rather than being influenced by orbital sampling effects. We estimate the parameters described above for the MESSENGER orbit during the magnetic cloud of the ICME event and the surrounding orbits under more nominal solar wind conditions, displaying the results in Figure 2. The estimate for M_A during the ICME event is 1.5

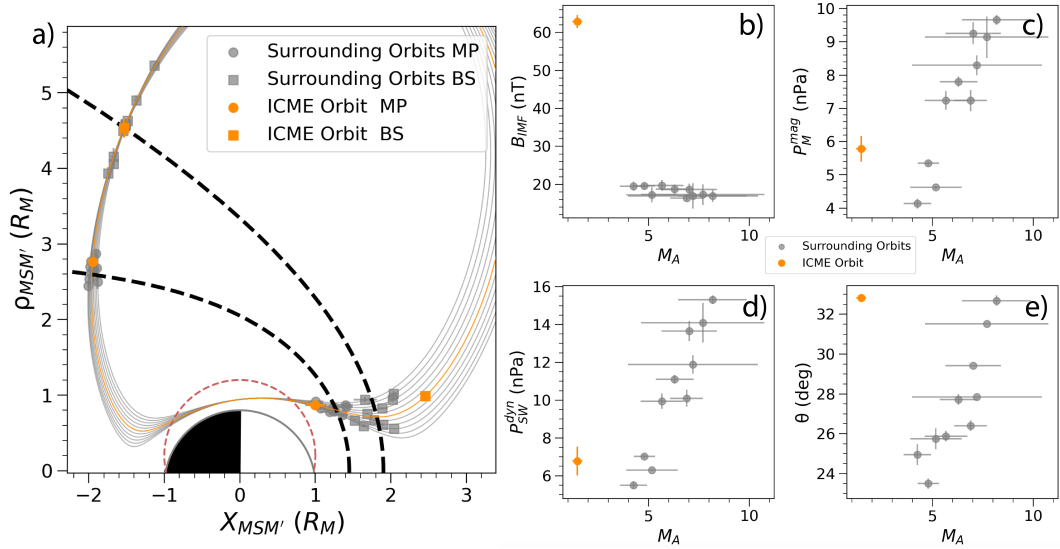


Figure 2. Panel (a) shows orbital trajectories in cylindrical coordinates ($\rho_{MSM'} = \sqrt{Y_{MSM'}^2 + Z_{MSM'}^2}$) for the ICME orbit (orange) and the surrounding orbits (grey). The circles and squares represent the measured location at the center of the magnetopause interval and bow shock interval, respectively. The northern portion of Mercury's surface in the MSM' frame is shown as the gray half-circle, while the southern portion of Mercury's surface is shown as the dashed red half-circle. Error bars on bow shock and magnetopause crossings represent the extent of each crossing interval identified by (Philpott et al., 2020). The outer and inner dashed black lines represent the nominal bowshock and magnetopause distances determined by Shue et al. (1997) and Winslow et al. (2013). The horizontal axes of panels b-e represent the estimated M_A for the inbound portion of the orbit. The vertical axes are the calculated (b) B_{IMF} [nT], (c) P_M^{mag} [nPa], (d) P_{SW}^{dyn} [nPa], (e) θ [deg]. Error bars represent the propagated errors from the standard deviation of the mean of the time range used to calculate B_{IMF} , the magnetic field just inside the magnetopause, and the time range of magnetopause position.

± 0.2 , which is significantly lower than the surrounding orbits with M_A values ranging from 3.5–7.7, which are more typical for Mercury’s orbital distance. Both P_M and $|B_{IMF}|$ were calculated by averaging magnetic field strength over a specific time range defined above. To calculate the uncertainty in our M_A estimates, we propagate the standard deviation of the mean over these time ranges within Equation (6). However, this uncertainty calculation does not account for all assumptions underlying the M_A estimates and it is likely that the propagated standard deviation is not the dominant source of error. As a result, the reported uncertainty of 0.2 should not be regarded as a fully reliable measure of the true error of our M_A estimate.

The drag coefficient, K , used in Equation (6), depends on the sonic Mach number of the plasma, with lower sonic Mach numbers increasing the value of K up to a maximum value of 1 (Kivelson & Russell, 1995). We therefore keep $K=0.88$ for all M_A calculations to remain consistent as we apply this methodology to other orbits, but note that setting $K = 1.0$ would not significantly change our calculation for M_A during the ICME. For example, if $K = 1.0$, M_A during the ICME event, is 1.4 ± 0.2 , which is a 7% decrease in M_A estimate.

The average M_A at Mercury’s orbit (0.31 – 0.47 AU) is 5.4 ± 3.2 , as determined by Russell et al. (1988) using HELIOS 1 and 2 observations. Much of the uncertainty in this estimate is due to variations with heliocentric distance. This ICME passed over Mercury when Mercury was at a heliocentric distance of 0.42 AU. Based on fits from more recent Parker Solar Probe (PSP) measurements near Mercury’s orbit (Sun et al., 2022), the average M_A in the nominal solar wind at 0.42 AU is 6.6, with an average M_f of ~ 5.0 . This low M_A during the ICME is due in large part to the greatly enhanced values of $|B_{IMF}|$ compared to the surrounding orbits and average values at this heliocentric distance (Figure 2b). Our estimate for $|B_{IMF}|$ during the ICME event is 63 ± 2 nT, while $|B|$ in the IMF for the surrounding orbits range from 16–22 nT. This range is more indicative of the nominal $|B_{IMF}|$ at 0.42 AU of 16 nT as calculated via the relationships of solar wind parameters with heliocentric distance measured by PSP and described in Sun et al. (2022).

The M_A during the ICME discussed above is in the bottom 5% of all ICMEs in the Winslow et al. (2015, 2017) catalogue in which this estimating method is valid (mean value of M_A for all ICMEs is 3.7). The other 4 orbits during ICMEs with lower predicted M_A values ($M_A \approx 1.0, 1.2, 1.3$, and 1.4) exhibit highly variable IMF conditions upstream of the bow shock and/or MESSENGER’s orbital trajectory is out of the symmetry plane organized by the upstream IMF, making an analysis of the Alfvnic effects on Mercury’s magnetosphere during these ICMEs more difficult. The $|B_{IMF}|$ estimate during the ICME described above is slightly higher compared to the other ICMEs, which have a mean value of 55 nT.

It is important to note that the estimate for M_A within the magnetic cloud of ≈ 1.5 is almost certainly an overestimate of the true M_A value. The pressure balance technique described above accounts for a possible thermal pressure component within Mercury’s magnetosphere by considering only the top 20% of $|B|$ measurements just inside the magnetopause. This approach raises the magnetic pressure, P_M^{mag} , which may lead to an overestimated M_A value. Also, we assume that the thermal pressure within the solar wind is negligible. A non-negligible thermal pressure within the solar wind would decrease our estimate for P_{dyn}^{SW} , resulting in a lower M_A value. Moreover, only the component of the magnetospheric magnetic field that is tangential to the magnetopause surface should contribute to P_M^{mag} . Recalculating M_A using an updated P_M^{mag} value that only considers the tangential magnetospheric field based on the average magnetopause shape yields a slightly lower M_A estimate of ≈ 1.3 . This approach assumes that the average magnetopause shape is a good approximation for the measured magnetopause during the ICME event, which may not be appropriate given the extreme magnetospheric conditions imposed by the ICME. The estimate of M_A within the ICME sheath region of ≈ 0.8 also suggests a very low M_A upstream solar wind within the magnetic cloud. It is therefore

possible that the plasma flow in the magnetic cloud was actually sub-Alfvnic rather than trans-Alfvnic. However, for consistency with M_A estimate techniques for the surrounding orbits, and those provided by Winslow et al. (2017), we will proceed with the most conservative estimate of $M_A \approx 1.5$ within the magnetic cloud for this analysis. While determining a precise M_A value for this event is challenging, multiple approaches indicate that the flow within the magnetic cloud was in the sub- to trans-Alfvnic regime, with M_A likely ≤ 1.5 .

Next, we compare other properties of Mercury's magnetospheric environment during the ICME compared to the nominal conditions. The estimated P_{SW}^{dyn} for the ICME event is 6.8 ± 0.8 nPa which lies at the lower end of the range observed during the surrounding orbits (ranging from 5.5 – 14.1 nPa, Figure 2d) and best-fit curve calculated using PSP measurements (8.5 nPa, (Sun et al., 2022)). The mean P_{SW}^{dyn} for all ICMEs is much larger at 35 nPa. Low P_{SW}^{dyn} is due to low plasma density and/or low solar wind velocity. ICMEs are more often associated with large solar wind velocities, suggesting the low P_{SW}^{dyn} estimate during the ICME is due to an abnormally low solar wind plasma density, which is characteristic of magnetic clouds. The inbound magnetopause crossing of the orbit during the ICME was planetward of the nominal magnetopause curve (Figure 2a), indicating the magnetosphere was compressed and/or eroded during the ICME. This compression/erosion leads to higher estimates for θ during the ICME compared to the surrounding orbits (Figure 2e). Typically, we would expect a compressed magnetosphere to also result in larger magnetic pressure at the magnetopause. Interestingly, the magnetic pressure just inside the magnetopause during the ICME event was moderate ($P_M^{mag} = 5.8 \pm 0.4$ nPa) compared to the surrounding orbits (ranging from 4.1-9.2 nPa). Weaker magnetic flux near the magnetopause during the ICME is likely caused by magnetic erosion due to increased reconnection rates under southward IMF conditions and the elevated magnetic pressure from the strong $|B_{IMF}|$ conditions (Heyner et al., 2016). Along the magnetopause during the ICME, we see rapid fluctuations of the magnetic field characteristic of many flux transfer events (FTEs) (Sun, Slavin, Smith, et al., 2020), indicative of enhanced reconnection as expected by the low M_A , low β , and high magnetic shear conditions along the magnetopause (Li et al., 2023, 2024).

We also note that the bow shock for the inbound portion of the orbit was expanded well beyond the nominal bow shock location. The fast Mach number (M_f) is roughly equivalent to M_A due to the low plasma β environment in the ICME ($\beta < .01$). So, an M_f value slightly greater than unity predicts a shock to form at a much greater distance upstream of the planet compared to the nominal bow shock location. The outbound bow shock crossing, on the other hand, is aligned with the nominal bow shock curve defined by Winslow et al. (2013), suggesting the M_A and M_f conditions increased by the time MESSENGER returned to the solar wind.

3.4 Estimates for n , v , and T during the ICME

Our estimate of M_A is based on a pressure balance argument using MAG data alone. We know that $M_A \propto \sqrt{n} * v_{SW}$, but we cannot solve for n and v_{SW} directly. To estimate v_{SW} , we identify the likely launch time of the CME from coronagraph observations made by the Solar and Heliospheric Observatory (SOHO) and Solar TERrestrial RELations Observatory (STEREO). A list of automatically detected CME events was compiled by the Computer Aided CME Tracking software (CACTus) from coronagraph observations of SOHO, STEREO A and STEREO B (Brueckner et al., 1995; Robbrecht et al., 2009). This procedure was first performed by Winslow et al. (2015) and was reproduced for this study.

To identify the most likely candidate CME from within the CACTus database, we search the catalogue for CMEs that launch from the Sun sometime between 58 and 12 hours before the ICME detection by MESSENGER (i.e. between December 28, 06:27:22 and

December 30 04:27:22). This time range was based on a minimum CME speed of 300 km/s and a maximum CME speed of 1500 km/s based on ranges measured at Earth (Cane & Richardson, 2003; Guo et al., 2010). During our ICME event, STEREO A was nearly radially aligned with Mercury (107° west of the Sun-Earth line), while STEREO B was located behind the Sun from Mercury’s perspective (110° east of the Sun-Earth line). Therefore, the CME of interest in the coronagraph database must occur within the specified time range, be identified as a forward halo CME by STEREO A, a back-sided halo CME by STEREO B, and a westward limb CME by SOHO. Only one CME fits these criteria, with the first coronagraph image of a western limb CME taken by SOHO at 16:24 on December 29. The SOHO database for this event estimates that the start of the CME was at 15:52 on December 29, 2011. We then calculate the time between CME onset and MESSENGER’s observations of the magnetic cloud, which occurred at 20:54:00 on December 30. Assuming no acceleration or deceleration of the CME in this time, the estimated velocity of the magnetic ejecta (v_{SW}) is 660 km/s. This value matches the estimated velocity of the magnetic ejecta for this event as reported by Winslow et al. (2015). We note that ICMEs accelerate in the lower corona due to magnetic reconnection (Zhuang et al., 2022), so it is possible that our calculation v_{SW} is a slight overestimation. Using our estimates of v_{SW} and M_A , we determine $n = 9.7 \text{ cm}^{-3}$, much smaller than the average n_{sw} , based on the best-fit line using PSP data of 44 cm^{-3} at this orbital distance (Sun et al., 2022). While direct measurements of the solar wind density by FIPS are not possible during this interval, energy spectra of the magnetosheath on both the inbound and outbound portions of the orbit contain few counts compared to the nominal magnetosheath, suggesting a low plasma density in the solar wind (Figure 1e). The temperature of the ICME, T , was based on the average temperature of the solar wind at Mercury.

3.5 Super-Alfvnic versus Sub-Alfvnic Regimes

In the previous section, we established that Mercury was in a very low M_A regime during the ICME. Here, we discuss how these extreme conditions would alter Mercury’s magnetosphere compared to the nominal case. MHD theory makes various predictions regarding the differences between the magnetospheric response to purely super-Alfvnic and purely sub-Alfvnic upstream conditions, from both the perspective of the Jovian moons interaction with Jupiter’s magnetosphere (Neubauer, 1980, 1998; Kivelson et al., 2004) and the terrestrial magnetosphere under extreme solar wind conditions (Ridley, 2007; Chané et al., 2012). Some key differences are highlighted in the schematics shown in Figure 3. We compare these two scenarios under the same southward upstream IMF orientation to focus on the differences in magnetospheric characteristics that result from the two M_A conditions rather than changes in IMF orientation. In the super-Alfvnic, super-fast case, a bow shock forms upstream of the planet, creating a magnetosheath characterized by higher plasma densities compared to the upstream solar wind. No bow shock is present in the sub-Alfvnic case, and the unshocked solar wind interacts directly with Mercury’s magnetosphere. In both cases, magnetic reconnection on the dayside magnetopause generates open magnetic field lines connected to the northern and southern magnetic pole. These open field lines then propagate tailward and form either the magnetotail lobe (super-Alfvnic) or Alfvn wings (sub-Alfvnic). The open magnetic field lines in the lobe of the super-Alfvnic regime quickly propagate to the magnetotail due to the high v_{SW} compared to v_A , forming the windsock-shaped magnetopause on the nightside and magnetotail lobes. In the sub-Alfvnic regime, Alfvn waves form where the flow slows due to the planetary obstacle. These waves propagate bidirectionally along magnetic field lines in the plasma rest frame while being convected by the flow, creating Alfvn wings at an angle Θ_A to the upstream IMF. The wing’s field lines are elevated at a steeper angle to the solar wind flow than in the super-Alfvnic regime.

It is important to recognize that even under sub-Alfvnic conditions, we would not expect Mercury’s magnetosphere to resemble the purely Alfvnic interaction that we would

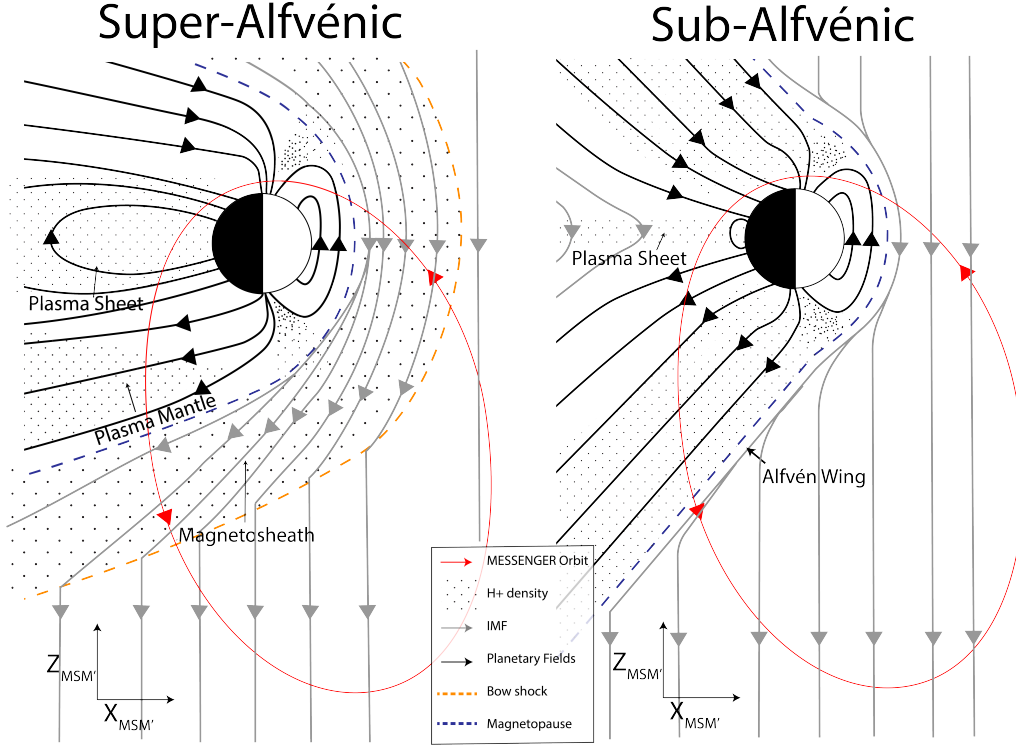


Figure 3. Schematics of Mercury's magnetosphere under purely super-Alfvénic, super-fast (left) and purely sub-Alfvénic, sub-fast (right) conditions. Black dots represent the density of protons. Orange dashed line represent the bow shock. Gray arrows represent the IMF, while black arrows represent the planetary magnetic fields (i.e., magnetic field lines with at least one end connected to Mercury). MESSENGER's orbit during the ICME is shown in red for reference.

expect at many of the outer planet moons such as Europa and Io (Neubauer, 1980, 1998; Saur et al., 1999). This is because Mercury's intrinsic magnetic field plays a major role in governing the interaction in both the super- and sub-Alfvénic regimes. Therefore, Mercury's magnetosphere under sub-Alfvénic conditions is most likely to resemble that of Ganymede, in which Alfvén wings are comprised of open field lines formed via magnetic reconnection between the IMF (Jovian planetary fields in the case of Ganymede) and the intrinsic magnetic field of the object (Kivelson et al., 2004; Saur, 2021; Jia & Kivelson, 2021). Mercury and Ganymede have similar sizes ($R_M = 2440$ km, $R_G = 2634$ km) and possess intrinsic magnetic field strengths within the same order of magnitude, with an equatorial field strength of 200 and 750 nT, respectively. The magnetic dipole field of Ganymede also closes northward and is consistently antiparallel to the Jovian magnetic field that closes southward. Interestingly, in our case study, MESSENGER sampled Mercury's magnetosphere under strong southward IMF conditions, suggesting that the relative orientation of the object's dipole field and the upstream magnetic field are similar between Mercury during the ICME and Ganymede; both are highly susceptible to undergo magnetic reconnection. Furthermore, the nominal external magnetic field strength upstream of Ganymede is ≈ 64 nT, almost exactly equal to our estimate during the ICME of 63 nT. However, a couple of key differences between these two regimes are important to keep in mind. First, the nominal upstream M_A for Ganymede is 0.74 (Saur, 2021), while M_A during the ICME at Mercury may be more in the trans-Alfvénic regime. This is because nominal plasma density upstream of Ganymede is typically ≈ 5 cm $^{-3}$, moving at a velocity of ≈ 140 km/s, which is smaller than our predictions for these values during the

ICME. Second, Ganymede possesses an ionosphere, which can carry currents produced in the Alfvénic interactions through Pedersen and Hall conductances (Jia et al., 2009). While Mercury has a non-negligible conductance largely due to the iron core (Slavin et al., 1997; Anderson et al., 2014), the lack of a significant current carrying ionosphere will likely affect the sub-Alfvénic interaction in comparison to Ganymede. Despite these distinctions, the similarities between these two regimes allow us to use previous observations and modeling efforts of the nominal conditions at Ganymede as a useful reference point to enhance our understanding of Mercury during this extreme event.

The upstream M_A will also influence the plasma populations of the magnetotail lobe/Alfvén wing region of the magnetosphere. For both the super/sub-Alfvénic cases, plasma originating in the solar wind enters either the lobe/Alfvén wing due to magnetic reconnection on the dayside generating the open magnetic field lines and mixing the previously separated plasma populations of the magnetosheath/solar wind and the magnetosphere. In the super-Alfvénic case, propagation of the open field lines into the magnetotail can form a boundary layer of the magnetosheath plasma known as the plasma mantle (DiBraccio et al., 2015; Jasinski et al., 2017). The net flow of the plasma around the planet is sum of the antisunward flow of the solar wind and the $\mathbf{E} \times \mathbf{B}$ flow that is perpendicular to the magnetic field, which results in a net motion of particles towards the magnetotail plasma sheet. The downtail distance in which the particles reach the plasma sheet is proportional to their initial antisunward velocity. This causes the thickness of the plasma mantle to expand with increasing downtail distance, generating a fan shape (Siscoe & Sanchez, 1987). The plasma density at the outer edge of the plasma mantle is approximately equal to the magnetosheath plasma density. The region that separates the plasma sheet from the plasma mantle is the magnetotail lobe, which is characterized by very low plasma density compared to the plasma sheet and magnetosheath (Fairfield & Jones, 1996; Bowers et al., 2024).

In the sub-Alfvénic case, unshocked solar wind plasma is injected into the Alfvén wings via dayside magnetic reconnection. The Alfvén waves generated at Mercury approximates standing wave obstacles to the solar wind flow. Global simulations of Ganymede’s magnetosphere indicate that plasma flow speed within Ganymede’s Alfvén wings decreases compared to the upstream Jovian plasma environment (Jia et al., 2009). This reduction in flow speed results in increased plasma density within the Alfvén wings compared to the surrounding Jovian plasma, due to the conservation of momentum (Fatemi et al., 2016, 2022; Duling et al., 2022). In these simulations, plasma density gradually decreases downtail as the plasma moves into the thin central plasma sheet, creating a plasma density gradient perpendicular to the Alfvén wing. This gradient is highest on the upstream side, near the boundary with the Jovian plasma. However, due to the lack of in situ observations of Ganymede’s Alfvén wings near the moon’s surface, these model predictions have yet to be validated by spacecraft measurements, making the details of their predictions within this regime uncertain. Nevertheless, the increased rate of dayside reconnection and the slower solar wind propagation speed at Mercury under sub-Alfvénic conditions should lead to a denser Alfvén wing structure compared to the low-density magnetotail lobe observed in the super-Alfvénic regime, even though the exact plasma distribution within Alfvén wings remains unknown.

3.6 MHD Model Results

The schematics shown in Figure 3 highlight idealized, purely super-Alfvénic and purely sub-Alfvénic solar wind scenarios. Next, we explore the influence of trans-Alfvénic solar wind via a comparison between MESSENGER observations and a 3D Block Adaptive Tree Solar wind Roe-type Upwind Scheme [BATSRUS, (Powell et al., 1999)] magnetohydrodynamic (MHD) model of Mercury’s magnetosphere.

Previous studies have demonstrated that departures from the purely super-Alfvnic magnetospheric interaction become evident even for M_A values greater than 1. Ridley (2007) presented results from BATSRUS simulations to demonstrate how the terrestrial magnetosphere transitions from a purely super-Alfvnic interaction ($M_A \geq 8$) to a sub-Alfvnic interaction ($M_A \leq 1$). As M_A decreases, the magnetotail shortens, and the northern and southern magnetotail lobes begin to separate. These separated lobes are Alfvn wings, comprised of open magnetic field lines that protrude at a much higher inclination angle to the solar wind flow compared to the super-Alfvnic case. Additionally, the bow shock moves further upstream from the planet with decreasing Mach numbers, eventually disappearing within the simulation when M_f reaches below 1. $M_f \leq M_A$, so the disappearance of the bow shock can occur when $M_A > 1$. This distinction is obvious for the purely sub-Alfvnic case presented in Ridley (2007), but some differences in magnetospheric configuration begin to emerge at M_A values of ~ 2.7 and are clearly present in the trans-Alfvnic solar wind case with an M_A value of 1.6.

To investigate the impact of a trans-Alfvnic ICME on Mercury's magnetosphere, we run a 3D BATSRUS simulation of Mercury's plasma environment given the upstream conditions as observed by MESSENGER. The BATSRUS code is a component of the Space Weather Modeling Framework, which was designed to provide a flexible, comprehensive, physics-based approach to modeling solar system objects' magnetospheric response to variable surrounding plasma environments (Tóth et al., 2012; Gombosi et al., 2021). We utilize the same BATSRUS model as applied to Mercury's magnetospheric environment described in Jia et al. (2015, 2019). This code solves the governing equations of MHD (conservation of mass, momentum, and energy along with Faraday's law) within the solar wind and Mercury's plasma environment. The model takes into account Mercury's conducting iron core, treating it as a spherically symmetric object with very high conductivity (10^5 S/m) within the iron core ($r < 0.8 R_M$) and very low (10^{-7} S/m) conductivity within the regolith ($0.8 R_M \leq r \leq 1 R_M$). This conductivity profile couples to the space environment by controlling the way in which magnetic field lines diffuse due to its direct influence in the solution to the generalized Ohm's law and magnetic induction equation in the resistive MHD equations.

Table 1 shows the upstream conditions used as the input to the BATSRUS simulation

BATSRUS Input for ICME	
Input Variable	
B_{IMF}^X	19 nT
B_{IMF}^Y	0 nT
B_{IMF}^Z	-60 nT
n	9.7 cm^{-3}
v_{SW}	660 km/s
T	$8.7 \times 10^4 \text{ K}$
M_A^*	1.5
β^*	0.006

Table 1. Inputs to BATSRUS model for the upstream conditions at Mercury during the ICME impact. B_{IMF}^X , B_{IMF}^Y , and B_{IMF}^Z are the 30-minute average of the magnetic field just upstream of the inbound bow shock crossing. n is the estimate for the upstream density. v_{SW} is the estimate for the velocity of the ICME. T is the estimated temperature of the ICME. M_A^* and β^* are dimensionless variables calculated from the other input parameters and is not a standalone input into the model.

for the ICME event described above. B_{IMF}^X , B_{IMF}^Y , and B_{IMF}^Z are determined by averaging the magnitude of each component of the IMF 30 minutes upstream of the inbound bow shock crossing (21:55:08 – 22:25:08), just as $|B_{IMF}|$ was estimated in the previous section.

The results of the BATSRUS simulation for this ICME impact highlight a number of fascinating phenomena induced by these extreme solar wind conditions (Figure 4). The mag-

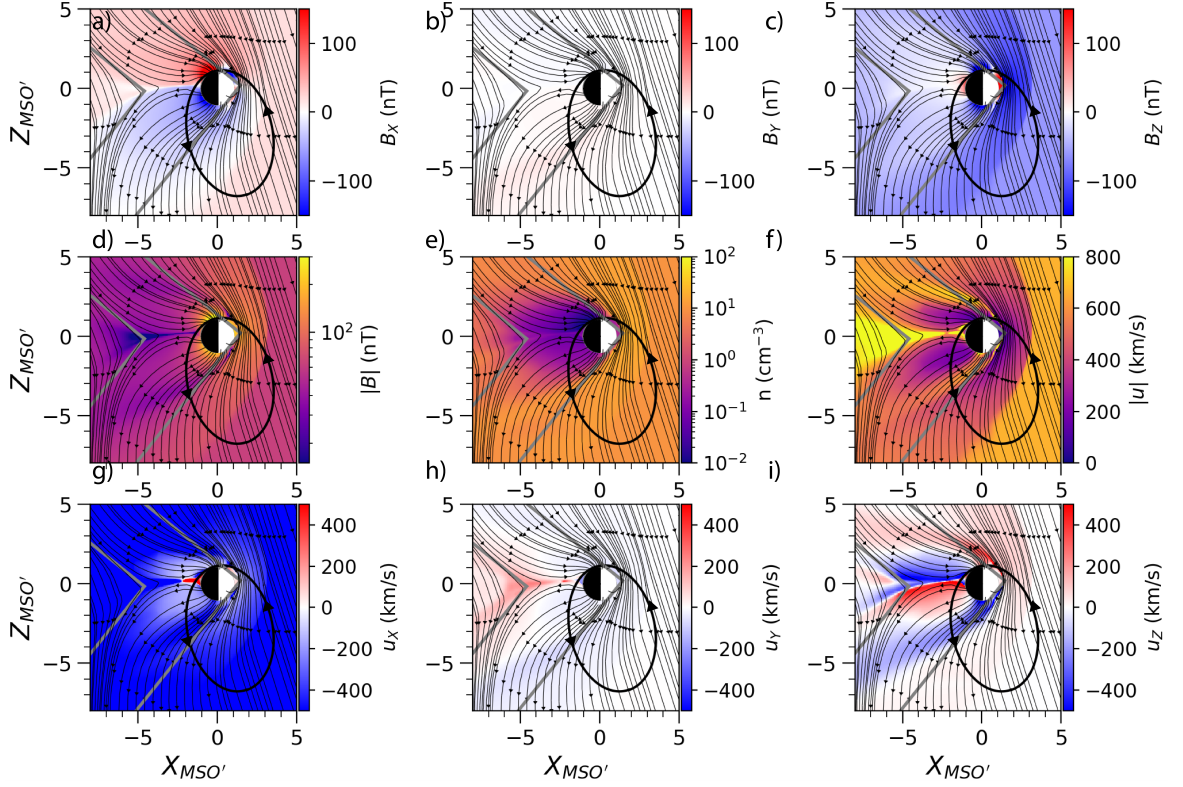


Figure 4. Results from the BATSRUS simulation of Mercury's magnetosphere given the upstream conditions detailed in Table 1. The plots are displayed in the aberrated MSO coordinate system (MSO'). The panels are colored by B_X [nT] (a), B_Y [nT] (b), B_Z [nT] (c), $|B|$ [nT] (d), plasma density, n [cm^{-3}] (e) and speed $|u|$ [km/s] (f), u_X [km/s] (g), u_Y [km/s] (h), u_Z [km/s] (i). The thin black lines represent traces of the magnetic field lines. The thick black lines represent MESSENGER's orbit during the ICME. The thick gray lines represent the predicted orientation of the Alfvén wings based on the upstream M_A and B_{IMF} values.

netic field lines in the magnetotail are primarily open due to the enhanced magnetic reconnection at the dayside magnetopause with this strongly southward field. Proton acceleration away from magnetopause X-line is prevalent in the simulation due to this enhanced magnetic reconnection, in agreement with studies at Ganymede (Jia et al., 2010; Collinson et al., 2018; Zhou et al., 2020; Ebert et al., 2022; Gershman et al., 2024). These field lines are stretched behind the planet but are at a high inclination angle compared to the direction of the solar wind flow ($-X_{MSO'}$). Furthermore, the plasma density within the magnetotail seems to gradually increase from the central plasma sheet to the magnetosheath, suggesting the lack of a clear magnetotail lobe that is nearly void of plasma

in comparison to the plasma sheet and plasma mantle/magnetosheath. However, some key characteristics of super-Alfvnic, super-fast magnetospheric interactions are also present in the simulation, including the bow shock that slows the incoming solar wind plasma, illustrated by the region of low plasma velocity upstream of Mercury (Figure 4f). This suggests that this trans-Alfvnic ICME event acts as a hybrid between the purely super-Alfvnic and sub-Alfvnic magnetospheric interactions, displaying some characteristics of both interaction types.

In the sub-Alfvnic regime, the value of M_A is a characteristic feature of the geometry of the Alfvn wings. As the IMF encounters Mercury's dayside magnetopause, Alfvn waves launched from the subsolar point propagate along the bent magnetic field lines at v_A . Simultaneously, the solar wind plasma attached to the IMF above and below Mercury continue to propagate away from the Sun at v_{SW} . In the frame of the upstream magnetic field, the Alfvn wave therefore travels at an angle

$$\Theta_A = \tan^{-1} \left(\frac{v_{SW}}{v_A} \right) = \tan^{-1} (M_A) \quad (6)$$

For an M_A value of 1.5, the angle of the Alfvn wing with respect to the upstream IMF is $\Theta_A = 56^\circ$. The geometry of these Alfvn wings are shown as thick gray lines in Figure 4. The lines pass through the subsolar point on the dayside ($X_{MSO'} \approx 1.35 R_M$) and the downstream end of the plasma sheet on the nightside ($X_{MSO'} \approx -4.6 R_M$) to roughly bound the open field lines that comprise the wings. As M_A increases, these wings become more and more parallel with the solar wind flow. In a purely super-Alfvnic regime, these wings overlap and form the magnetotail lobes and the windsock-shape magnetopause. For $M_A = 1$, $\Theta_A = 45^\circ$.

In the MSM' frame, the orientation of the wings are defined by the Elsässer variables (Elsässer, 1950), also known as Alfvn characteristics:

$$\mathbf{c}_A^\pm = \mathbf{v}_{SW} \pm \mathbf{v}_A \quad (7)$$

in which the northern and southern wings are defined by the negative and positive characteristics, respectively. We note that the upstream IMF is not perfectly perpendicular to v_{SW} , so there is a slight asymmetry in the northern and southern Alfvn wings in the MSM' frame. As a result, the southern wing is more aligned along the $Z_{MSM'}$ axis compared to the northern wing. For the upstream conditions listed in Table 1, in the MSM' coordinates, $\mathbf{c}_A^- = [-0.88, 0, 0.47]$ represents the northern Alfvn wing and $\mathbf{c}_A^+ = [-0.78, 0, -0.622]$ represents the southern wing.

3.7 The ICME, Surrounding Orbits, and BATSRUS Results

The orbital trace of the magnetic field and proton density through the BATSRUS simulation is shown as the magenta line in Figure 5. The model results are shown alongside the MESSENGER observations during the ICME in orange, as well as the observations from the 5 orbits before and after the orbit in which the ICME was observed in gray, as in Figure 2. To plot these data on the same horizontal axis, we determine the time between a measurement and the most recent apoapsis of the spacecraft. This allows us to compare time series measurements among neighboring orbits that sample very similar spatial regimes but are separated in time. The black lines in Figure 5 represent the average value of each measurement across all 10 of the surrounding orbits around the orbit in which the ICME was observed. As discussed in Section 3.3, the surrounding orbits occur under more nominal upstream conditions and the magnetic field and plasma measurements along these orbits provide a useful reference to compare to those under the extreme case of the ICME.

Figure 5 further demonstrates that MESSENGER magnetic field signatures during the ICME impact are extreme and distinct from the surrounding orbits upstream of the bow

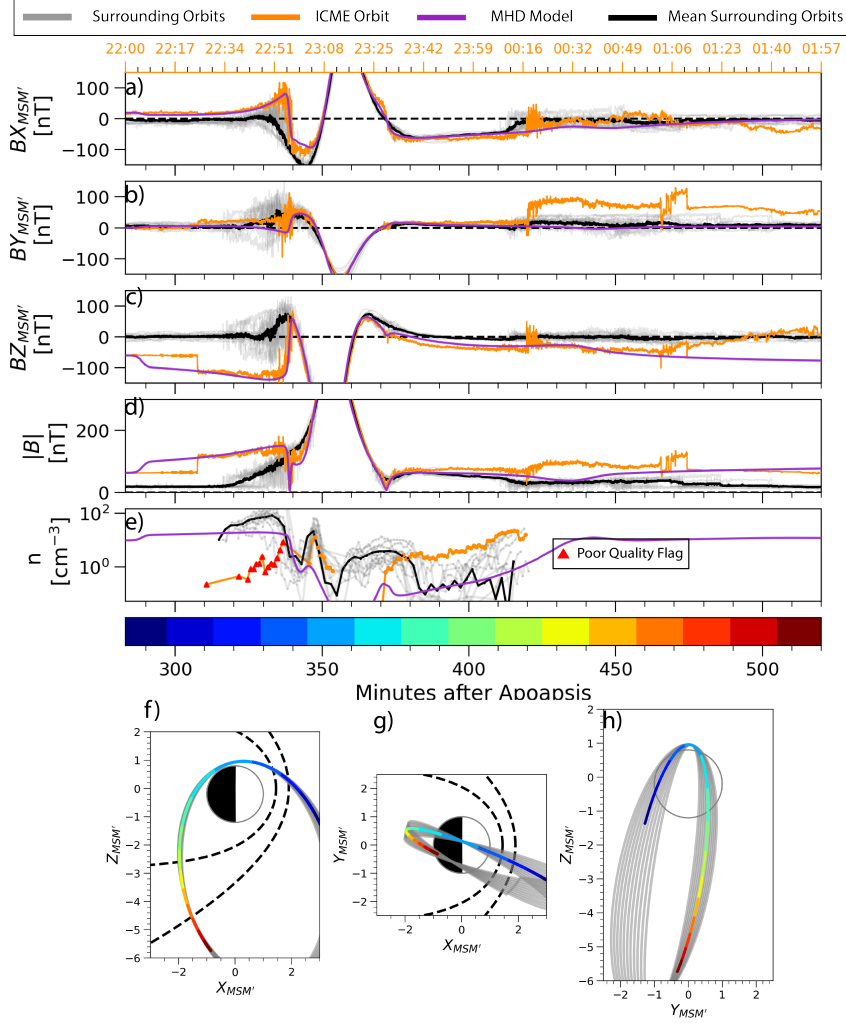


Figure 5. MESSENGER MAG data at 1 s resolution in the MSM' coordinate frame. Panels a-c display the $X_{MSM'}$, $Y_{MSM'}$, $Z_{MSM'}$ coordinates of the magnetic field in nT. Panel d shows the magnitude of the magnetic field, $|B|$ in nT. MAG data during the ICME impact on Mercury are shown in dark blue, and MAG data from the 5 orbits before and 5 orbits after the CME impact are shown in gray. The average of all the surrounding orbits at each time step is shown in black. The total time range for all 11 orbits is 2011-12-28 06:21:38 – 2012-01-02 16:00:51. The ICME impact was from 2011-12-30 16:27:22 – 2011-12-31 09:19:52. Panel e shows the estimated number density predicted by FIPS measurements. The red triangles represent periods with a poor quality fit. The bottom horizontal axis is the minutes from the orbit's apoapsis, and the top horizontal axis shows the date and time for the orbit during the ICME. Panels f-h show MESSENGER's orbital trajectory plotted during the time series above in the $XZ/XY/YZ_{MSM'}$ planes. The orbit during the ICME impact is colored by the minutes from the apoapsis. The outer and inner dashed black lines represent the nominal bowshock and magnetopause distances determined by Shue et al. (1997) and Winslow et al. (2013).

shock (~ 0 -300 min and 500-700 min), within the magnetosheath (~ 300 -340 min and 425-500 min), and within the magnetotail (~ 375 -425 min). Notably, $|B|$ is higher during the ICME impact than the surrounding orbits, particularly upstream of the bow shock.

There is no significant difference between the magnetic field during the ICME and the surrounding orbits near MESSENGER's periapsis (~ 340 - 375 min), suggesting Mercury's very inner magnetosphere is not significantly disturbed during this ICME event. We also see a general agreement between the BATSRUS MHD model predictions and the measurements during the ICME orbit throughout the traversal of the magnetosphere. However, during the ICME orbit at 00:16 (420 minutes after apoapsis), we see a clear jump in $BY_{MSM'}$ from 16 – 70 nT. This jump was not predicted by the BATSRUS simulation, suggesting that the upstream IMF conditions during the ICME may have shifted significantly from the conditions measured along the inbound portion of MESSENGER's orbit and used as the input to the model. The general close agreement between the MHD model and observations through the magnetospheric traversal suggests that the upstream IMF conditions remained steady and similar to the input of the model for a majority of MESSENGER's magnetospheric traversal. This point of disagreement between model and MESSENGER observations in $BY_{MSM'}$ marks the end in which we can be confident that the upstream conditions input in the model are representative of the actual upstream conditions at Mercury. We will compare the BATSRUS model predictions, measurements during the ICME, and measurements during the surrounding orbits in the following two sections. Section 3.8 will focus on the MESSENGER's dayside approach into the magnetosphere, and Section 3.9 will focus on the traversal of Mercury's magnetotail on the nightside of the planet.

3.8 ICME impact on Mercury's Dayside Plasma Environment

We focus our analysis of the ICME's impact on Mercury's plasma environment for the inbound portion on the dayside of the planet alongside some predictions for the idealized super-Alfvnic and sub-Alfvnic regimes (Figure 6). In the purely super-Alfvnic scenario, we would expect a bow shock to form upstream of the planet. Downstream of the bow shock, the spacecraft samples the plasma depletion layer near the subsolar point (Gershman et al., 2013). The dynamics within this region lead to an enhanced $|B|$ and depleted n near the subsolar point as magnetic flux piles-up and magnetosheath plasma is diverted around the obstacle. However, in the purely sub-Alfvnic regime, we do not expect a bow shock, magnetosheath, or a thick plasma depletion layer (Figure 6g). Instead the solar wind plasma density remains steady as the spacecraft approaches the magnetosphere, only experiencing a small enhancement in density and magnetic field strength very close to the magnetopause (Figure 6h) as has been predicted at Ganymede (Fatemi et al., 2022).

The solar wind conditions during the trans-Alfvnic ICME do produce a bow shock in the BATSRUS simulation and was observed by MESSENGER. This bow shock is expanded well beyond the nominal bow shock (Figure 2), resulting in an earlier inbound bow shock crossing compared to the surrounding orbits. Interestingly, the BATSRUS simulation predicts a bow shock that is even further expanded away from Mercury than that measured by MESSENGER. Our estimate for the upstream M_A is based on measurements made just inside the magnetopause, which is approximately 30 minutes after MESSENGER crossed the bow shock. It is therefore possible that during the ICME, M_A was decreasing in time and MESSENGER's crossing of the bow shock occurred as the bow shock expanded away from Mercury in response to the changing solar wind conditions. The BATSRUS simulation therefore predicts the final location of the bow shock after this retreat, while MESSENGER traversed the bow shock in the process of its retreat away from Mercury. The single crossing of the bow shock by MESSENGER during the ICME further supports this notion because multiple bow shock crossings are indicative of a variable bow shock moving inward and outward with a changing M_A around a mean value, whereas a single crossing suggests a bow shock that is either expanding or steady. Indeed, BATSRUS predictions of $|B|$ in the magnetosheath agree with MESSENGER observations downstream of the measured shock, suggesting that BATSRUS correctly predicts the strength of the bow shock during the ICME. $|B|$ increased by a factor of 2 across the bow shock both in the BATSRUS model and during the ICME,

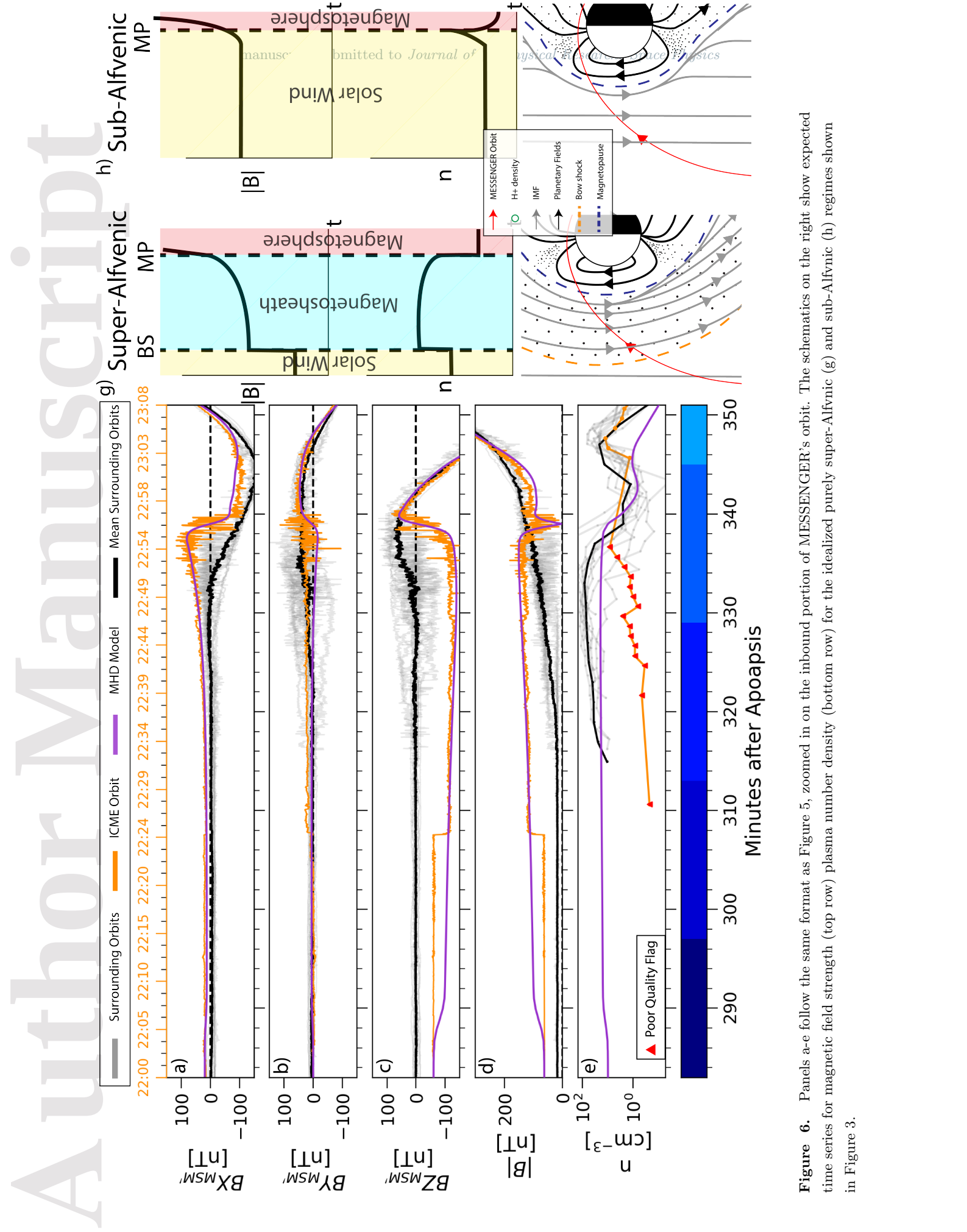


Figure 6. Panels a-e follow the same format as Figure 5, zoomed in on the inbound portion of MESSENGER's orbit. The schematics on the right show expected time series for magnetic field strength (top row) plasma number density (bottom row) for the idealized purely super-Alfvénic (g) and sub-Alfvénic (h) regimes shown in Figure 3.

which is lower than the average for bow shock crossings, which typically increases $|B|$ by a factor of 3 – 4. Each of the surrounding orbits crosses the bow shock at slightly different times, resulting in a smoothing-out of the bow shock crossing when averaging the orbits together (black curve). Downstream of the shock, $|B_{model}|$ and $|B_{ICME}|$ remain steady as MESSENGER approaches the magnetopause, whereas $|B|$ steadily increases for the surrounding orbits as expected for measurements within the super-Alfvnic regime.

Interpreting the FIPS estimates for plasma density, n , shown in Figure 6e requires a brief discussion of the limitations of FIPS and the techniques for estimating n . Proton density is estimated by taking the zeroth order moment of best-fit full Maxwellian velocity distribution that is the best-fit distribution to the observed proton flux, (Raines et al., 2011; Gershman et al., 2013; James et al., 2020). However, as discussed in Section 2.1, FIPS field of view was obstructed throughout MESSENGER's orbital lifetime resulting in only partial velocity distributions being available for fitting. This technique of fitting partial distributions has been shown to be accurate when assuming a subsonic, isotropic plasma. These assumptions are typically valid near the subsolar magnetopause due to the stagnation of the magnetosheath plasma as is typical of the super-Alfvnic regime (Gershman et al., 2013; Raines et al., 2014; James et al., 2020), providing accurate estimates of density within this region.

During the orbits surrounding the ICME displayed in Figure 6, MESSENGER sampled the low-latitude magnetosheath, and FIPS provided measurements that estimated a magnetosheath density of $\sim 60 \text{ cm}^{-3}$ on average. However, during the ICME, FIPS measured considerably fewer counts within this region compared to the surrounding orbits, both within the inbound and outbound magnetosheath (see Figure 1). This results in an extremely low density estimate of $\sim 1 \text{ cm}^{-3}$ with a poor quality flag that is given to data that have a poor fit to the estimated full distribution, shown as red triangles in Figure 6e. We note that the κ distribution fits of the plasma performed by James et al. (2020) output 2 high-quality fits within the magnetosheath region during the ICME with density estimates of approximately 5 cm^{-3} , in rough agreement with the poor quality Maxwellian fits shown in Figure 6e. The poor quality n estimates are the result of very low counts measured by FIPS within this region during the ICME (Figure 1e). So, while the exact value of n in this region during the ICME is likely inaccurate due to poor statistics, the extreme lack of plasma counts during the ICME compared to the surrounding orbits within this region suggests that the plasma density was much lower than average. The BATSRUS model also predicted lower plasma density measurements within the magnetosheath than the nominal case.

The directional motion of the plasma measured by FIPS within this region also highlights some interesting effects of the ICME. We integrate all directional proton flux measured by FIPS during the ICME from 310-335 minutes after apoapsis and plot the flux in 10 degree bins on a flux map (Figure 7a). For the orbits surrounding the ICME event, we average all flux maps generated for each of the 10 surrounding orbits to produce an average flux map from within this time range along all surrounding orbital trajectories (Figure 7b). The lack of counts during the ICME compared to the surrounding orbits is clear when comparing these two flux maps, further demonstrating the abnormally low plasma density within the magnetosheath during the ICME. In addition, the proton flux during the ICME seems to be concentrated closer to the antisunward direction, characteristic of unshocked solar wind flow. For the surrounding orbits, the plasma within this region is much more isotropic, only a slight enhancement of flux in the $+Z_{MSM'}/+Y_{MSM'}$ direction likely due to the magnetosheath plasma motion around the magnetopause.

3.9 ICME Impact on the Nightside Plasma Sheet

In both the super- and sub-Alfvnic scenarios, we expect the spacecraft to first pass through the nightside plasma sheet characterized by a dip in $|B|$ and increase in plasma density.

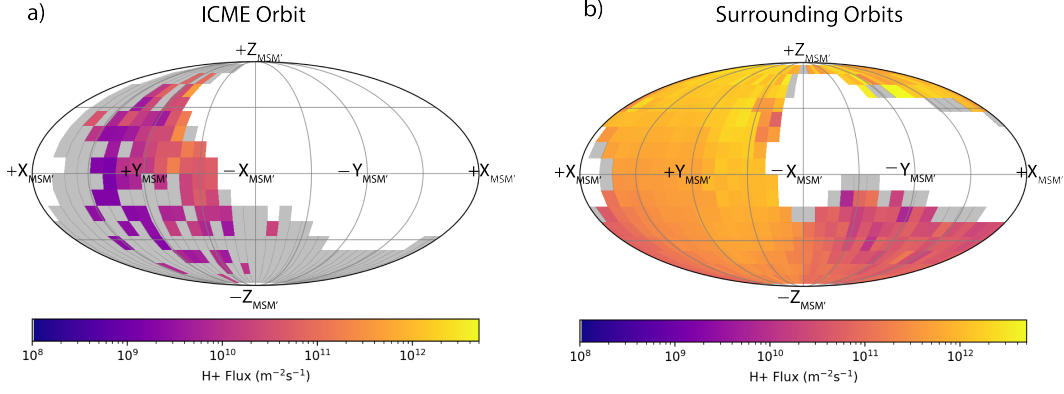


Figure 7. Flux maps of protons measured by FIPS integrated from 310 minutes to 335 minutes after apoapsis for the MESSENGER measurements during the ICME event (a) and averaged for the surrounding events (b). These flux maps are separated into 10 degree bins, with 36 bins in the azimuthal direction and 18 bins in the polar direction. Each bin is colored by the measured H+ flux in units of $\text{m}^{-2} \text{s}^{-1}$. Gray bins are within FIPS field of view but with no observed counts. White bins are outside of FIPS field of view.

The nightside plasma sheet within the super-Alfvnic solar wind is populated with high β , isotropic plasma centered in between the two magnetotail lobes. This region is identifiable by the transition from positive to negative $BX_{MSM'}$ as the spacecraft moves from the northern to southern lobe (Figure 5a). These oppositely oriented lobe fields generate a current sheet at the center known as the magnetotail current sheet. The transition from $+BX_{MSM'}$ to $-BX_{MSM'}$ during the orbits surrounding the ICME is gradual compared to those during the ICME (Figure 8a). The $+BX_{MSM'}$ to $-BX_{MSM'}$ predicted by the BATSRUS model is notably sharper than the surrounding orbits, but not quite as sharp as the orbit during the ICME. We estimate the thickness of the current sheet using the Harris current sheet model (Harris, 1962) as has been used in previous studies of Mercury's magnetotail (Poh et al., 2017; Rong et al., 2018). This model describes an equilibrium solution to the Maxwell-Vlasov equations describing the behavior of $BX_{MSM'}$ with a symmetric magnetotail in the $Z_{MSM'}$ direction:

$$BX_{MSM'} = B_0 \tanh\left(\frac{Z_{MSM'} - Z_0}{L}\right) \quad (8)$$

Here, B_0 is the asymptotic lobe field, Z_0 is the position of the current sheet center along the $Z_{MSM'}$ axis, and L is the half-thickness of the current sheet. We solve for B_0 and L as free parameters via a least squares fitting procedure of the Harris model to the MESSENGER measurements. Z_0 was determined by finding the nearest point along $Z_{MSM'}$ to transition point of $BX_{MSM'}$ from positive values to negative values.

Using the Harris model, Rong et al. (2018) statistically analyzed the half-thickness of current sheets measured within different regions of Mercury's magnetotail to investigate how the current sheet morphology changes in space (see Table 2 in their manuscript). The current sheets we have analyzed in this study all fall within a single region defined in Rong et al. (2018). The average L value for current sheets within this region was $0.46 \pm 0.11 R_M$, which is in good agreement with the average value of L for the orbits surrounding the ICME ($\bar{L}_{SO} = 0.39 \pm 0.1 R_M$). However, the average L value reported by Rong et al. (2018) is nearly four times thicker than that measured during the ICME ($L_{ICME} = 0.12 R_M$). The plasma sheet during the ICME is thinner than predicted by the BATSRUS model for this event by about $0.05 R_M$. The plasma sheet is thinnest near the reconnection X-line, where pairs of open magnetic field lines in the tail reconnect and re-

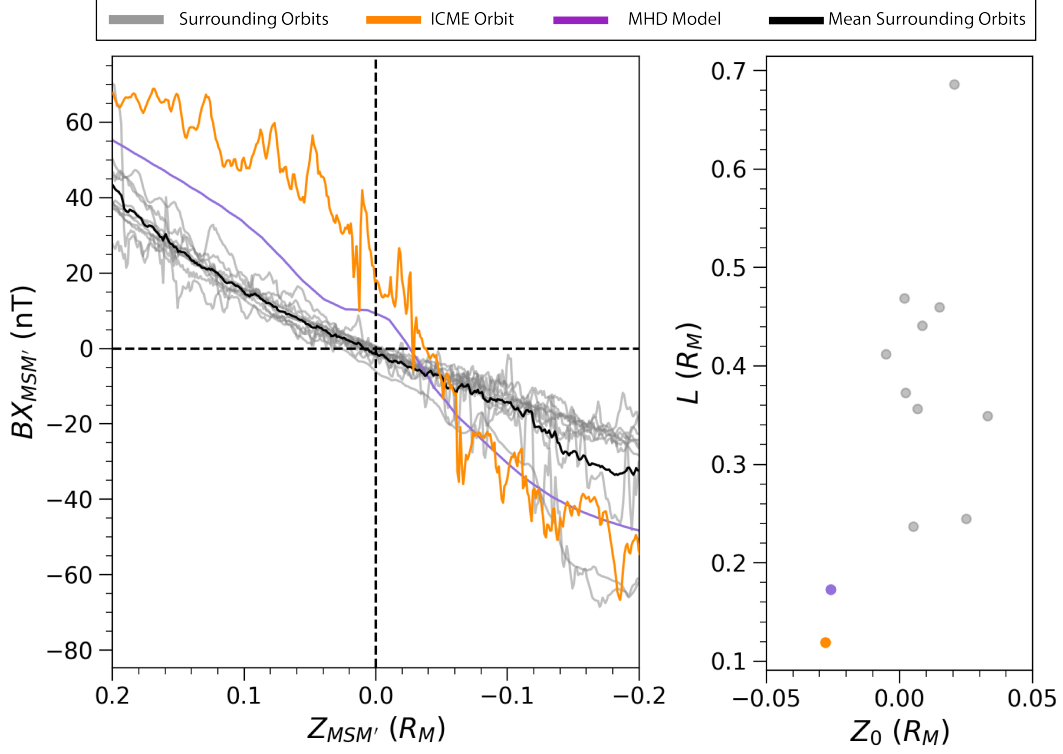


Figure 8. Comparison of the structure of the plasma sheet between the orbit during the ICME (orange), the surrounding orbits (gray, average in black), and the prediction made by the BATSRUS MHD model (purple). Panel (a) shows the $BX_{MSM'}$ component of the magnetic field as a function of spacecraft position on the $Z_{MSM'}$ axis. Panel (b) shows the estimated half-thickness of the current sheet, L , based on the Harris fitting technique as a function of position of the center of the current sheet along the $Z_{MSM'}$ axis (Harris, 1962).

store closed magnetic flux to the nightside of the planet. The BATSRUS simulation predicts that MESSENGER passed planetward of the tail reconnection X-line (Figure 4g). MHD simulations of the terrestrial magnetosphere show that the nightside X-line in the plasma sheet moves planetward with decreasing M_A , further suggesting that the M_A input into BATSRUS is an overestimate. Lower M_A values may move the X-line planetward, resulting in a thinner estimate for the plasma sheet than predicted under $M_A = 1.5$ conditions.

Simulations of Ganymede's magnetosphere have suggested that the moon's plasma sheet is also quite thin and the reconnection point is close to the moon (Jia et al., 2008; Fatemi et al., 2016; Stahl et al., 2023). This thin plasma sheet supports high rates of nightside magnetic reconnection at Ganymede, consistently supplying the dayside with magnetic flux that is subsequently transferred again to the nightside via dayside magnetic reconnection. The thin plasma sheet measured during the ICME further highlights the similarities between the nominal conditions at Ganymede and the extreme conditions at Mercury during ICMEs, and likely provide insights into the role of magnetic reconnection at both of these objects during these low M_A conditions.

3.10 ICME Impact on Mercury's Nightside Magnetosphere

We turn our attention to MESSENGER's traversal of Mercury's magnetotail and out-bound trajectory out of the magnetosphere (Figure 9). After traversing the plasma sheet, the spacecraft would then enter into either a magnetotail lobe in the super-Alfvnic scenario or the Alfvn wing in the sub-Alfvnic scenario. Within the magnetotail lobe, $|B|$ decreases with radial distance from the planet (Bowers et al., 2024), as shown in Figure 9g). According to theory, $|B|$ within the Alfvn wing should remain more steady than in the lobe, particularly in the far-field region away from the planet (Neubauer, 1980; Chané et al., 2012), as show in Figure 9h. For the surrounding orbits, the average $|B|$ value at the inner edge (closer to the plasma sheet) of this region (≈ 380 minutes from apoapsis) is 65 nT, while that towards the outer edge (closer to the magnetosheath and ≈ 410 minutes from apoapsis) is 45 nT. Within this region during the ICME, $|B|$ remained steady at ≈ 75 nT. The BATSRUS simulation predicted a slight drop in $|B|$ throughout this region, dropping from 67 nT to 60 nT.

The super-Alfvnic and sub-Alfvnic scenarios would also produce different orientations of the magnetic field within this region. The super-Alfvnic scenario would produce field lines that are more aligned with the $-X_{MSM'}$ direction, whereas the field lines within an Alfvn wing would be inclined more towards the $-Z_{MSM'}$ orientation. The average $BZ_{MSM'}$ direction throughout this region for the surrounding orbits gradually shifts from slightly positive to slightly negative, while the $BX_{MSM'}$ curve remains highly negative, as expected for the super-Alfvnic case. $BZ_{MSM'}$ for both the BATSRUS model and MESSENGER observations during the ICME are much more negative throughout this region, distinct from the surrounding orbits, while $BX_{MSM'}$ is similar to the surrounding orbits. We define the magnetic field inclination angle, $\Psi = \tan^{-1}(|B_Z|/|B_X|)$, which characterizes the magnetic field orientation within in the $XZ_{MSM'}$ plane, with 90° representing a field line along the $Z_{MSM'}$ axis. For the surrounding orbits, Ψ is $\leq 10^\circ$ within the lobes (minutes 380-410), indicative of a windsock shaped magnetosphere. During the ICME and within the BATSRUS simulation, Ψ within this region reaches 40° , indicative of a highly inclined nightside magnetic field, as predicted by the sub-Alfvnic scenario.

The magnetospheric lobe region under super-Alfvnic conditions is also characterized by a decrease in plasma density (n) compared to the plasma sheet and magnetosheath (Figure 9g). For the pure lobe configuration in the absence of a plasma mantle, n would remain low until MESSENGER encountered the magnetosheath where the density would increase sharply as the spacecraft traversed the magnetopause. If the spacecraft encountered the plasma mantle, we would expect a more gradual increase in n to begin towards the outer edge of this region until the spacecraft reached the magnetosheath where n would plateau. In the sub-Alfvnic scenario, slow-moving plasma contained within the Alfvn wings populates this region, and n would be enhanced throughout the structure (Figure 9h). Simulations within the magnetosphere of Ganymede predict that n would gradually enhance as the spacecraft moves from the plasma sheet towards the upstream edge of the wing, even exceeding the plasma density in the upstream solar wind (Fatemi et al., 2016, 2022; Duling et al., 2022), but these predictions have yet to be validated by spacecraft observations.

The average n behavior for the surrounding orbits within this region matches the super-Alfvnic scenario, exhibiting a clear drop in n compared to the plasma sheet that remained steady and low throughout the traversal. This behavior varies from orbit to orbit, with some of the surrounding orbits showing an increase in plasma density near the outer edge of the lobe before the magnetopause, indicative of the plasma mantle. Both the BATSRUS model and ICME event show a gradual increase in n from the plasma sheet to the outer edge of this region (Figure 9e), more in-line with the purely sub-Alfvnic scenario predicted from simulations at Ganymede.

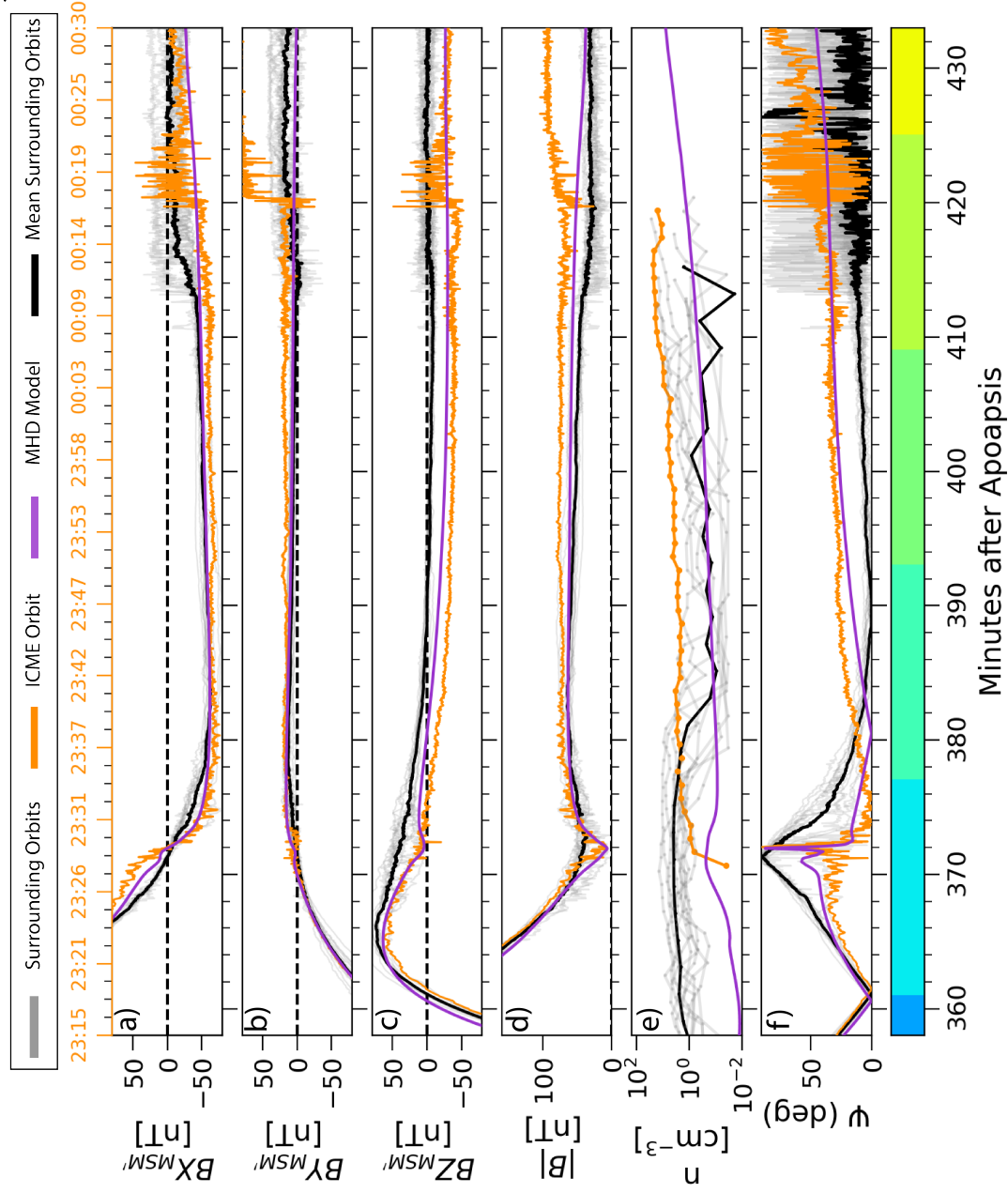


Figure 9. Panels a-e follow the same format as Figure 5, zoomed in on the outbound portion of MESSENGER's orbit. Panel f now shows the inclination angle Ψ in degrees, where $\Psi = \tan^{-1}(|B_Z|/|B_X|)$. The schematics on the right show expected time series for magnetic field strength (top row) plasma number density (bottom row) for the idealized purely super-Alfvénic (g) and sub-Alfvénic (h) regimes shown in Figure 3.

During the ICME at 00:16, we see a clear shift in the magnetic field orientation marked by a jump in $BY_{MSM'}$. This shift marks the magnetopause and the entry into the magnetosheath. We note that FIPS was not able to obtain estimates for n outside of the magnetopause due to the highly anisotropic flows surrounding the nightside magnetosheath, so it is difficult to know if n_{ICME} at $\approx 410 - 420$ minutes after apoapsis exceeds the density upstream as predicted by the sub-Alfvnic scenario. Interestingly, $|B_{ICME}|$ upstream of the magnetopause (425-430 minutes after apoapsis) exceeds $|B_{ICME}|$ downstream, which is quite abnormal and not the case for any of the other surrounding orbits. Typically, along the nightside magne-

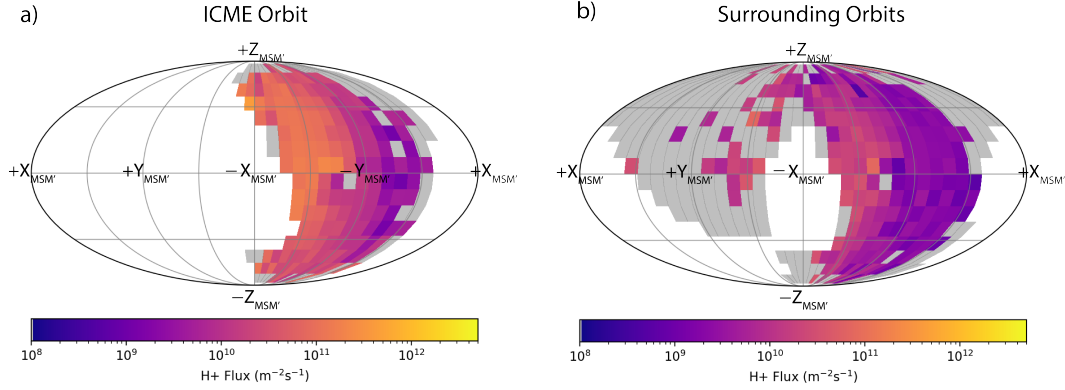


Figure 10. Flux maps of protons measured by FIPS integrated from 385 minutes to 410 minutes after apoapsis for the MESSENGER measurements during the ICME event (a) and averaged for the surrounding events (b). The units are in H+ flux, or $m^{-2} s^{-1}$. These flux maps are separated into 10 degree bins. Gray bins are within FIPS field of view but with no observed plasma. White bins are outside of FIPS field of view.

topause, high magnetic pressure within the lobes is balanced by the sum of moderate thermal and magnetic pressures within the magnetosheath. In the case of the ICME, this scenario is flipped, in which magnetic pressure upstream is balanced by the sum of magnetic and thermal pressure downstream. This suggests that plasma density downstream of the boundary indeed may exceed that upstream of the boundary as predicted within the Alfvn wings of Ganymede (Fatemi et al., 2022).

The FIPS proton flux maps integrated from 385 – 410 minutes after apoapsis further demonstrate the differences in plasma environment between trans-Alfvnic and super-Alfvnic conditions (Figure 10). Proton flux during the ICME within this region is larger than the average for the surrounding orbits. The direction of flux during the ICME is predominantly field-aligned, clustering near the $-X_{MSM'}$ and slightly towards the $+Z_{MSM'}$ direction. The average flux map for the surrounding orbits is oriented in a similar direction, but the fluxes are around 1 order of magnitude less than those of the orbit during the ICME. The preferred direction of these flows is expected because plasma velocity in this regime is a superposition of antisunward flow of the solar wind and the $\mathbf{E} \times \mathbf{B}$ drift that points northward within this region.

4 Discussion and Conclusions

4.1 Evidence for Low M_A Impact and Alfvn Wing Traversal

By comparing measurements during an ICME event to both a 3D BATSRUS simulation and MESSENGER measurements of the surrounding 10 orbits, we identify

some key differences between Mercury’s magnetospheric response to the nominal solar wind conditions and this extreme solar wind event:

1. The planetary bow shock is weaker and much further away from Mercury during the ICME compared to the nominal planetary bow shock.
2. Within the magnetosheath, $|B|$ remains constant as MESSENGER approaches Mercury’s magnetosphere during the ICME. Nominally, $|B|$ steadily increases as the spacecraft approaches the nose of the magnetopause.
3. The density of the plasma within the magnetosheath is much lower during the ICME compared to the nominal magnetosheath plasma.
4. The plasma sheet is about a factor of 4 times thinner during the ICME than during nominal solar wind conditions.
5. Along the nightside traversal of Mercury, $|B|$ remained steady as MESSENGER moves away from the planet during the ICME. Nominally, $|B|$ within the magnetotail lobes decreases with radial distance from Mercury.
6. The nightside magnetic field was more inclined to the solar wind flow direction during the ICME compared to the nominal conditions by nearly 40° .
7. The plasma density is higher throughout the nightside magnetospheric traversal during the ICME compared to the nominal conditions.

Using arguments based on MHD theory, MHD and hybrid model results from the Ganymede environment, and the 3D BATSRUS simulation of the ICME event at Mercury, we show for the first time that these differences can be explained through the changes in magnetospheric environment imposed by the extremely low-Alfvnic ($M_A \leq 1.5$) solar wind conditions during the ICME. MESSENGER’s plasma and magnetic field measurements along its nightside traversal of Mercury during the ICME are more in-line with an Alfvn wing structure compared to the super-Alfvnic, magnetotail lobes. This notion is supported by the BATSRUS simulation, which shows that the windsock-shaped magnetopause is replaced by two collections of open magnetic field lines at a high inclination to the solar wind flow (Figure 4) indicative of Alfvn wing formation.

4.2 Implications for Mercury Science

It is highly likely that Mercury was subjected to other trans-Alfvnic and sub-Alfvnic conditions during MESSENGER’s orbital lifetime. Hajra and Tsurutani (2022) demonstrated that sub-Alfvnic conditions at Earth tend to occur either during ICME impacts or in the trailing portion of high-speed stream (HSS) solar wind events. On average, sub-Alfvnic conditions within the near-Earth environment occur once every two years, but this varies with solar cycle, and there are years near solar max in which the solar wind was sub-Alfvnic on more than four separate occasions at Earth. Sub-Alfvnic solar wind conditions should occur more frequently at Mercury compared to Earth because Mercury is closer to the Sun. However, the nature of single spacecraft observations and the lack of full phase-space plasma measurements within the solar wind make identification and analysis of these intervals difficult with MESSENGER observations. The ICME event analyzed within this study was ideal for estimating the impact of low M_A conditions for the following reasons:

1. The ICME reached Mercury when MESSENGER was sampling the solar wind, allowing for a clear identification of the ICME via the interplanetary shock.
2. The magnetic field within the ICME rotated from north-to-south just before MESSENGER crossed into Mercury’s magnetosphere. The magnetic field within a magnetic cloud is steadier than the ICME sheath and nominal so-

lar wind conditions, allowing us to assume that the upstream IMF remained consistent throughout MESSENGER's magnetospheric traversal.

3. MESSENGER crossed the magnetopause near the subsolar point, allowing us to estimate M_A through the procedure discussed in Section 3.2, which requires a small angle between the solar wind flow and the magnetopause normal.
4. MESSENGER's orbit was within the same plane as the upstream IMF, allowing for sampling of the Alfvén wing structure.

While it is likely that a fraction of the ICMEs within the Winslow et al. (2015, 2017) catalog also exhibited trans-Alfvénic or sub-Alfvénic conditions, the event described here is the only event that met these necessary observational criteria for the analysis performed in this study.

This extremely low Alfvén Mach number (M_A) event at Mercury offers valuable insights into the planet's dynamic response to the intense solar wind conditions of the inner heliosphere. We compare some key similarities and differences between Mercury's magnetospheric response to this ICME event, and the disappearing dayside magnetopause (DDM) events discussed in Slavin et al. (2019). The combined effects of greatly enhanced dayside magnetic reconnection and extreme magnetospheric compression can lead to a DDM, allowing shocked solar wind plasma to impact the planet's surface directly. Both the DDM events and our example of a potential Alfvén wing magnetospheric configuration occurred during ICME events, but the properties of the ICME upstream of Mercury differ between these two scenarios. DDM events are associated with extremely large dynamic pressure conditions ($P_{dyn}^{SW} \geq 140$ nPa) within the ICME, which compress Mercury's magnetosphere and increase the M_A . In contrast, Alfvén wing configurations are more likely under moderate-low P_{dyn}^{SW} values because low M_A conditions occur more frequently under a combination of low solar wind velocity and density. The planetary bow shock during a DDM event is strong and located very close to the planet (Guo et al., 2023), while the bow shock during Alfvén wing events is either missing or weak and at very high altitudes. Interestingly, both the DDM events and the Alfvén wing event discussed here took place under strongly southward IMF orientations. A strongly southward IMF enhances dayside magnetic reconnection and magnetic erosion, making a DDM event more likely. The formation of Alfvén wings, however, is more dependent on the strength of the IMF due to its impact on the Alfvén velocity than on its orientation. Unlike DDM events, Alfvén wing formation does not depend on the upstream IMF orientation (Ridley, 2007; Saur et al., 2013). Future studies of low M_A events at Mercury may observe cases with northward or dawn-dusk oriented IMF. In the latter case, Alfvén wings could align along the dawn-dusk direction, similar to observations at Earth (Chané et al., 2012; Chen et al., 2024).

Many open questions remain regarding Alfvén wing formation at Mercury. As mentioned above, Mercury lacks a conductive ionosphere but does possess a highly conductive iron core that sits beneath a low-conductivity mantle. This iron core supports currents in response to changing magnetospheric conditions, generating enhanced magnetic flux surrounding the planet through magnetic induction (Johnson et al., 2016). Dynamic simulations of Mercury's magnetospheric response to decreasing M_A conditions could investigate the role induction plays in Alfvén wing formation at Mercury. This lack of a conducting ionosphere likely also affects the field-aligned current (FAC) systems that flow along Alfvén wings (Neubauer, 1980). Thus, the details of the physics of Alfvén wings at Mercury directly relate to our understanding of FACs at the planet, which hold interesting implications regarding the electrical conductance of Mercury's surface and interior (Slavin et al., 1997; Anderson et al., 2014). Furthermore, the eroded magnetopause, series of FTEs along the dayside magnetopause, and thin current sheet observed during this ICME event suggest an enhanced rate of magnetic reconnection. How is magnetic flux transferred through-

out Mercury's magnetosphere during low M_A conditions? This question is directly relevant to Ganymede's magnetosphere, which has been hypothesized to be an example of a steady-state reconnection with Jupiter's planetary magnetic field (Kivelson et al., 2004).

4.3 Implications for Future Missions

The upcoming dual-probe BepiColombo mission to Mercury will provide an unprecedented view of Mercury's magnetospheric response to the solar wind. BepiColombo will enter into orbit around Mercury in November 2026, with a possible extended mission to last until April 2029. Based on statistics of low M_A conditions at Earth, it is likely that M_A in the solar wind will drop into the trans-Alfvénic and even into the sub-Alfvénic regime during the BepiColombo mission. The two spacecraft, Mio and MPO, will enter into polar orbits of different eccentricities. MPO will orbit at a lower altitude and focus on the near-Mercury environment, sampling along the magnetopause boundary, while Mio will focus on the outer magnetospheric environment, frequently sampling upstream of the bow shock (Milillo et al., 2020; Benkhoff et al., 2021). Both spacecraft are equipped with a suite of plasma science instrumentation that measure properties of plasma populations within the solar wind and Mercury's magnetospheric environment (Baumjohann et al., 2020; Heyner et al., 2021). As a result, the properties of the solar wind could be identified and directly analyzed by the instrumentation onboard Mio, allowing for a dynamic estimate of M_A based on plasma moments, as opposed to the single estimate of M_A based on the pressure balance assumptions discussed in our work. Mio measurements of low M_A conditions within upstream solar wind could be compared with concurrent MPO measurements near Mercury to assess the planet's real-time magnetospheric response. Future coordinated analyses of low M_A solar wind conditions with the BepiColombo spacecraft will allow us to explore many more important and interesting effects that take place at planetary environments in our solar system (Lavraud & Borovsky, 2008).

The Europa Clipper (Pappalardo et al., 2024) and Jupiter Icy Moons Explorer (JUICE) spacecraft (Grasset et al., 2013) are the first dedicated efforts to understand the complex dynamics that govern the Jovian moon interaction with Jupiter's magnetospheric plasma. Future studies utilizing Europa Clipper and JUICE observations will allow for a direct comparison between moon-magnetospheric interactions and solar wind-planetary interactions under similar upstream M_A conditions, which will isolate the key variables that characterize these complex magnetospheric environments. Furthermore, Mercury is the best planetary analog to many exoplanetary environments. A substantial amount of detected exoplanetary environments are close-in, terrestrial, and likely consistently exposed to sub-Alfvénic solar wind (Saur et al., 2013). Many of these exoplanets orbit M-dwarf stars, resulting in a larger number of ICMEs compared to our own Sun. Thus, studies of extreme solar wind events at Mercury, such as the ICME presented here, offer a brief window of time into which in-situ observations of a planetary magnetospheric response to the conditions frequently faced by exoplanetary environments.

5 Open Research

In accordance with the AGU data policy, MESSENGER data are publicly available through the Planetary Plasma Interactions Node of the Planetary Data System (Korth, 2021). The results of the BATSRUS model run during the ICME can be downloaded via (Bowers, 2024a). A user guide to generate the figures in this manuscript can be found here: (Bowers, 2024b).

Acknowledgments

Work at DIAS was supported by Taighde ireann - Research Ireland awards to: Laureate Consolidator award SOLMEX (CFB and CMJ); President of Ireland award 18/FRL/6199 (MJR, ARF, CMJ) and Postgraduate Scholarship GOIPG/2024/3906 (DMH). RMD is supported by NASA's Discovery Data Analysis Program grant 80NSSC24K0059. D.Heyner is supported by the German Ministerium fr Wirtschaft und Klimaschutz and the German Zentrum fr Luft und Raumfahrt under contract 50QW2202. MKGH's work at DIAS is supported by Taighde ireann - Research Ireland award 18/FRL/6199 and the Discovery programme of the European Space Agency (Contract No: 4000137683/22/NL/GLC/my). HH's work at DIAS was supported by a DIAS Research Fellowship in Astrophysics and by Taighde ireann - Research Ireland award 22/FFP-P/11545.

References

- Allegri, F., Gladstone, G. R., Hue, V., Clark, G., Szalay, J. R., Kurth, W. S., ... Wilson, R. J. (2020). First Report of Electron Measurements During a Europa Footprint Tail Crossing by Juno. *Geophysical Research Letters*, 47(18). doi: 10.1029/2020GL089732
- Anderson, B. J., Acuña, M. H., Lohr, D. A., Scheifele, J., Raval, A., Korth, H., & Slavin, J. A. (2007). The Magnetometer instrument on MESSENGER. *The MESSENGER mission to Mercury*, 417–450.
- 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. doi: 10.1126/science.1211001
- Anderson, B. J., Johnson, C. L., Korth, H., Slavin, J. A., Winslow, R. M., Phillips, R. J., ... Solomon, S. C. (2014). Steady-state field-aligned currents at Mercury. *Geophysical Research Letters*, 41(21), 7444–7452. doi: 10.1002/2014GL061677
- Andrews, G. B., Zurbuchen, T. H., Mauk, B. H., Malcom, H., Fisk, L. A., Gloeckler, G., ... Raines, J. M. (2007). The energetic particle and plasma spectrometer instrument on the MESSENGER spacecraft. *Space Science Reviews*, 131(1–4), 523–556. doi: 10.1007/s11214-007-9272-5
- Baumjohann, W., Matsuoka, A., Narita, Y., Magnes, W., Heyner, D., Glassmeier, K.-H., ... others (2020). The bepicolombo-mio magnetometer en route to mercury. *Space Science Reviews*, 216, 1–33.
- Benkhoff, J., Murakami, G., Baumjohann, W., Besse, S., Bunce, E., Casale, M., ... Zender, J. (2021). *BepiColombo - Mission Overview and Science Goals* (Vol. 217) (No. 8). Springer Science and Business Media B.V. doi: 10.1007/s11214-021-00861-4
- Bowers, C. F. (2024a). *Batsrus_model_results*. Zenodo. doi: 10.5281/zenodo.14262636
- Bowers, C. F. (2024b). *Pub_bowers_mercury_alfven_wing*. Zenodo. doi: 10.5281/zenodo.14262613
- Bowers, C. F., Jackman, C. M., Sun, W., Holmberg, M. K. G., Jia, X., & Griton, L. (2024). Statistical Analysis of Mercury's Magnetotail Lobe Field Using MESSENGER Observations. *Journal of Geophysical Research: Space Physics*, 129(2). doi: 10.1029/2023JA032162
- Brueckner, G. E., Howard, R. A., Koomen, M. J., Korendyke, C. M., Michels, D. J., Moses, J. D., ... Eyles, C. J. (1995). The Large Angle Spectroscopic Coronagraph (LASCO). *Solar Physics*, 162(1–2), 357–402. doi: 10.1007/BF00733434
- Burkholder, B. L., Chen, L. J., Sarantos, M., Gershman, D. J., Argall, M. R., Chen, Y., ... Gurram, H. (2024). Global Magnetic Reconnection During Sustained Sub-Alfvénic Solar Wind Driving. *Geophysical Research Letters*, 51(6). doi:

- 10.1029/2024GL108311
- Burlaga, L., Sittler, E., Mariani, F., & Schwenn, R. (1981). Magnetic loop behind an interplanetary shock: Voyager, Helios, and IMP 8 observations. *Journal of Geophysical Research: Space Physics*, 86(A8), 6673–6684. doi: 10.1029/ja086ia08p06673
- Cane, H. V., & Richardson, I. G. (2003). Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002. *Journal of Geophysical Research: Space Physics*, 108(A4). doi: 10.1029/2002JA009817
- Chané, E., Raeder, J., Saur, J., Neubauer, F. M., Maynard, K. M., & Poedts, S. (2015). Simulations of the Earth’s magnetosphere embedded in sub-Alfvénic solar wind on 24 and 25 May 2002. *Journal of Geophysical Research: Space Physics*, 120(10), 8517–8528. doi: 10.1002/2015JA021515
- Chané, E., Sau, J., Neubauer, F. M., Raeder, J., & Poedts, S. (2012). Observational evidence of Alfvén wings at the Earth. *Journal of Geophysical Research: Space Physics*, 117(9). doi: 10.1029/2012JA017628
- Chen, L. J., Gershman, D., Burkholder, B., Chen, Y., Sarantos, M., Jian, L., ... Burch, J. (2024). Earth’s Alfvén Wings Driven by the April 2023 Coronal Mass Ejection. *Geophysical Research Letters*, 51(14). doi: 10.1029/2024GL108894
- Collinson, G., Paterson, W. R., Bard, C., Dorelli, J., Gloer, A., Sarantos, M., & Wilson, R. (2018). New Results From Galileo’s First Flyby of Ganymede: Reconnection-Driven Flows at the Low-Latitude Magnetopause Boundary, Crossing the Cusp, and Icy Ionospheric Escape. *Geophysical Research Letters*, 45(8), 3382–3392. doi: 10.1002/2017GL075487
- Cravens, T. E., Dessler, A. J., Houghton, J. T., & Rycroft, M. J. (1997). *Physics of solar system plasmas*. Cambridge University Press Cambridge.
- Dewey, R. M., Raines, J. M., Sun, W., Slavin, J. A., & Poh, G. (2018). MESSENGER Observations of Fast Plasma Flows in Mercury’s Magnetotail. *Geophysical Research Letters*, 45(19), 110–10. doi: 10.1029/2018GL079056
- Dewey, R. M., Slavin, J. A., Raines, J. M., Azari, A. R., & Sun, W. (2020). MESSENGER Observations of Flow Braking and Flux Pileup of Dipolarizations in Mercury’s Magnetotail: Evidence for Current Wedge Formation. *Journal of Geophysical Research: Space Physics*, 125(9). doi: 10.1029/2020JA028112
- DiBraccio, G. A., Slavin, J. A., Raines, J. M., Gershman, D. J., Tracy, P. J., Boardson, S. A., ... Solomon, S. C. (2015). First observations of Mercury’s plasma mantle by MESSENGER. *Geophysical Research Letters*, 42(22), 9666–9675. doi: 10.1002/2015GL065805
- Diego, P., Piersanti, M., Laurenza, M., & Villante, U. (2020). Properties of Solar Wind Structures at Mercury’s Orbit. *Journal of Geophysical Research: Space Physics*, 125(9). doi: 10.1029/2020JA028281
- Drell, S. D., Foley, H. M., & Ruderman, M. A. (1965). *Drag and Propulsion of Large Satellites in the Ionosphere; An Alfvén Propulsion Engine in Space* (Vol. 14; Tech. Rep. No. 6).
- Duling, S., Saur, J., Clark, G., Allegrini, F., Greathouse, T., Gladstone, R., ... Sulaiman, A. H. (2022). Ganymede mhd model: Magnetospheric context for juno’s pj34 flyby. *Geophysical Research Letters*, 49(24), e2022GL101688. (e2022GL101688 2022GL101688) doi: https://doi.org/10.1029/2022GL101688
- Ebert, R. W., Fuselier, S. A., Allegrini, F., Bagenal, F., Bolton, S. J., Clark, G., ... Wilson, R. J. (2022). Evidence for Magnetic Reconnection at Ganymede’s Upstream Magnetopause During the PJ34 Juno Flyby. *Geophysical Research Letters*, 49(23). doi: 10.1029/2022GL099775
- Elsässer. (1950). *The Hydromagnetic Equations* (Vol. 78; Tech. Rep.). Philadelphia: Randel Morgan Laboratory of Physics, University of Pennsylvania.
- Fairfield, D. H., & Jones, J. (1996). Variability of the tail lobe field strength. *Journal of Geophysical Research: Space Physics*, 101(A4), 7785–7791. doi:

- 10.1029/95JA03713
- Fatemi, S., Poppe, A. R., Khurana, K. K., Holmström, M., & Delory, G. T. (2016). On the formation of Ganymede's surface brightness asymmetries: Kinetic simulations of Ganymede's magnetosphere. *Geophysical Research Letters*, 43(10), 4745–4754. doi: 10.1002/2016GL068363
- Fatemi, S., Poppe, A. R., Vorburger, A., Lindkvist, J., & Hamrin, M. (2022). Ion Dynamics at the Magnetopause of Ganymede. *Journal of Geophysical Research: Space Physics*, 127(1). doi: 10.1029/2021JA029863
- Gershman, D. J., Fuselier, S. A., Cohen, I. J., Turner, D. L., Liu, Y. H., Chen, L. J., ... Swisdak, M. (2024). *Magnetic Reconnection at Planetary Bodies and Atmospheres* (Vol. 220) (No. 1). Springer Science and Business Media B.V. doi: 10.1007/s11214-023-01017-2
- Gershman, D. J., Slavin, J. M., J. A. and Raines, Zurbuchen, T. H., Anderson, B. J., Korth, H., Baker, D. N., & Solomon, S. C. (2013). Magnetic flux pileup and plasma depletion in Mercury's subsolar magnetosheath. *Journal of Geophysical Research: Space Physics*, 118(11), 7181–7199. doi: <https://doi.org/10.1002/2013JA019244>
- Gombosi, T. I., Chen, Y., Gloer, A., Huang, Z., Jia, X., Liemohn, M. W., ... Zou, S. (2021). What sustained multi-disciplinary research can achieve: The space weather modeling framework. *Journal of Space Weather and Space Climate*, 11, 42. doi: 10.1051/swsc/2021020
- Grasset, O., Dougherty, M. K., Coustenis, A., Bunce, E. J., Erd, C., Titov, D., ... Van Hoolst, T. (2013). *Jupiter ICy moons Explorer (JUICE): An ESA mission to orbit Ganymede and to characterise the Jupiter system* (Vol. 78). Elsevier Ltd. doi: 10.1016/j.pss.2012.12.002
- Guo, J., Feng, X., Zhang, J., Zuo, P., & Xiang, C. (2010). Statistical properties and geoefficiency of interplanetary coronal mass ejections and their sheaths during intense geomagnetic storms. *Journal of Geophysical Research: Space Physics*, 115(9). doi: 10.1029/2009JA015140
- Guo, J., Lu, S., Lu, Q., Slavin, J. A., Sun, W., Ren, J., ... Wang, R. (2023). Three-dimensional global hybrid simulations of mercury's disappearing day-side magnetosphere. *Journal of Geophysical Research: Planets*, 128(12), e2023JE008032. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2023JE008032> (e2023JE008032 2023JE008032) doi: <https://doi.org/10.1029/2023JE008032>
- Hajra, R., & Tsurutani, B. T. (2022). Near-Earth Sub-Alfvénic Solar Winds: Interplanetary Origins and Geomagnetic Impacts. *The Astrophysical Journal*, 926(2), 135. doi: 10.3847/1538-4357/ac4471
- Harris, E. (1962). *On a Plasma Sheath Separating Regions of Oppositely Directed Magnetic Field* (Tech. Rep.). Nuovo Cimento.
- Heyner, D., Auster, H.-U., Fornaçon, K.-H., Carr, C., Richter, I., Mieth, J., ... others (2021). The bepicolombo planetary magnetometer mpo-mag: what can we learn from the hermean magnetic field? *Space Science Reviews*, 217, 1–71.
- Heyner, D., Nabert, C., Liebert, E., & Glassmeier, K.-H. (2016). Concerning reconnection-induction balance at the magnetopause of mercury. *Journal of Geophysical Research: Space Physics*, 121(4), 2935–2961. doi: <https://doi.org/10.1002/2015JA021484>
- Hue, V., Szalay, J. R., Greathouse, T. K., Bonfond, B., Kotsiaros, S., Louis, C. K., ... Mauk, B. H. (2022). A Comprehensive Set of Juno In Situ and Remote Sensing Observations of the Ganymede Auroral Footprint. *Geophysical Research Letters*, 49(7). doi: 10.1029/2021GL096994
- James, M. K., Imber, S. M., Raines, J. M., Yeoman, T. K., & Bunce, E. J. (2020). A Machine Learning Approach to Classifying MESSENGER FIPS Proton Spectra. *Journal of Geophysical Research: Space Physics*, 125(6). doi: 10.1029/2019JA027352

- Jasinski, J. M., Slavin, J. A., Raines, J. M., & DiBraccio, G. A. (2017). Mercury's Solar Wind Interaction as Characterized by Magnetospheric Plasma Mantle Observations With MESSENGER. *Journal of Geophysical Research: Space Physics*, 122(12), 12153–12169. doi: 10.1002/2017JA024594
- Jia, X., & Kivelson, M. G. (2021). The Magnetosphere of Ganymede. In *Magnetospheres in the solar system* (pp. 557–573). Wiley. doi: 10.1002/9781119815624.ch35
- Jia, X., Slavin, G., J. A. and Poh, DiBraccio, G. A., Toth, G., Chen, Y., Raines, J. M., & Gombosi, T. I. (2019). MESSENGER Observations and Global Simulations of Highly Compressed Magnetosphere Events at Mercury. *Journal of Geophysical Research: Space Physics*, 124(1), 229–247. doi: https://doi.org/10.1029/2018JA026166
- Jia, X., Slavin, J. A., Gombosi, T. I., Daldorff, L. K., Toth, G., & Van Der 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(6), 4763–4775. doi: 10.1002/2015JA021143
- Jia, X., Walker, R. J., Kivelson, M. G., Khurana, K. K., & Linker, J. A. (2008). Three-dimensional MHD simulations of Ganymede's magnetosphere. *Journal of Geophysical Research: Space Physics*, 113(6). doi: 10.1029/2007JA012748
- Jia, X., Walker, R. J., Kivelson, M. G., Khurana, K. K., & Linker, J. A. (2009, September). Properties of Ganymede's magnetosphere inferred from improved three-dimensional MHD simulations. , 114, 9209. doi: 10.1029/2009JA014375
- Jia, X., Walker, R. J., Kivelson, M. G., Khurana, K. K., & Linker, J. A. (2010, December). Dynamics of Ganymede's magnetopause: Intermittent reconnection under steady external conditions. , 115, 12202. doi: 10.1029/2010JA015771
- Johnson, C. L., Philpott, L. C., Anderson, B. J., Korth, H., Hauck II, S. A., Heyner, D., ... Solomon, S. C. (2016). Messenger observations of induced magnetic fields in mercury's core. *Geophysical Research Letters*, 43(6), 2436–2444. doi: https://doi.org/10.1002/2015GL067370
- Kilpua, E., Koskinen, H. E., & Pulkkinen, T. I. (2017). Coronal mass ejections and their sheath regions in interplanetary space. *Living Reviews in Solar Physics*, 14(1). doi: 10.1007/S41116-017-0009-6
- Kim, K., Edberg, N. J., Wahlund, J. E., & Vigrén, E. (2024). Alfvén Wing-Like Structures in Titan's Magnetotail During T122-T126 Flybys. *Journal of Geophysical Research: Space Physics*, 129(6). doi: 10.1029/2023JA032265
- Kivelson, M. G., Bagenal, F., Kurth, W. S., Neubauer, F. M., Paranicas, C., & Saur, J. (2004). *Magnetospheric Interactions with Satellites* (Tech. Rep.).
- Kivelson, M. G., & Russell, C. T. (1995). *Introduction to space physics*. Cambridge University Press.
- Korth, H. (2021). *MESSENGER MAG Time-Averaged Calibrated MSO Coordinates Science Data Collection*. Planetary Data System. doi: https://doi.org/10.17189/1522377
- Lai, S. H., Yang, Y.-H., & Ip, W.-H. (2024). Magnetohydrodynamic Perspective on the Disappearance of Mercurys Bow Shock by Helios Data Exploration. *The Astrophysical Journal*, 961(1), 83. doi: 10.3847/1538-4357/ad0a8a
- Lavraud, B., & Borovsky, J. E. (2008). Altered solar wind-magnetosphere interaction at low Mach numbers: Coronal mass ejections. *Journal of Geophysical Research: Space Physics*, 113. doi: 10.1029/2008JA013192
- Li, C., Jia, X., Chen, Y., Toth, G., Zhou, H., Slavin, J. A., ... Poh, G. (2023, May). Global Hall MHD Simulations of Mercury's Magnetopause Dynamics and FTEs Under Different Solar Wind and IMF Conditions. *Journal of Geophysical Research (Space Physics)*, 128(5), e2022JA031206. doi: 10.1029/2022JA031206
- Li, C., Jia, X., Chen, Y., Toth, G., Zhou, H., Slavin, J. A., ... Poh, G. (2024,

- June). Kinetic Signatures, Dawn-Dusk Asymmetries, and Flux Transfer Events Associated With Mercury's Dayside Magnetopause Reconnection From 3D MHD-AEPIC Simulations. *Journal of Geophysical Research (Space Physics)*, 129(6), e2024JA032669. doi: 10.1029/2024JA032669
- Liu, Y., Richardson, J., & Belcher, J. (2005). A statistical study of the properties of interplanetary coronal mass ejections from 0.3 to 5.4AU. *Planetary and Space Science*, 53(1-3), 3–17. doi: 10.1016/j.pss.2004.09.023
- Liuzzo, L., Simon, S., & Feyerabend, M. (2018). Observability of Callisto's Inductive Signature During the JUPITER ICy Moons Explorer Mission. *Journal of Geophysical Research: Space Physics*, 123(11), 9045–9054. doi: 10.1029/2018JA025951
- Lugaz, N., Farrugia, C. J., Huang, C.-L., Winslow, R. M., Spence, H. E., & Schwadron, N. A. (2016). Earth's magnetosphere and outer radiation belt under sub-alfvénic solar wind. *Nature Communications*, 7(1), 13001.
- Milillo, A., Fujimoto, M., Murakami, G., Benkhoff, J., Zender, J., Aizawa, S., ... Wahlund, J. E. (2020). *Investigating Mercurys Environment with the Two-Spacecraft BepiColombo Mission* (Vol. 216) (No. 5). Springer. doi: 10.1007/s11214-020-00712-8
- Neubauer, F. M. (1980). Nonlinear standing Alfvén wave current system at Io: Theory. *Journal of Geophysical Research: Space Physics*, 85(A3), 1171–1178. doi: 10.1029/ja085ia03p01171
- Neubauer, F. M. (1998). The sub-Alfvénic interaction of the Galilean satellites with the Jovian magnetosphere. *Journal of Geophysical Research: Planets*, 103(3339), 19843–19866. doi: 10.1029/97je03370
- Pappalardo, R. T., Buratti, B. J., Korth, H., Senske, D. A., Blaney, D. L., Blankenship, D. D., ... Niebur, C. (2024). Science Overview of the Europa Clipper Mission. *Space Science Reviews*, 220(4). doi: 10.1007/s11214-024-01070-5
- Philpott, L. C., Johnson, C. L., Anderson, B. J., & Winslow, R. M. (2020). The Shape of Mercury's Magnetopause: The Picture From MESSENGER Magnetometer Observations and Future Prospects for BepiColombo. *Journal of Geophysical Research: Space Physics*, 125(5), e2019JA027544. doi: <https://doi.org/10.1029/2019JA027544>
- Poh, G., Slavin, J. A., Jia, X., Raines, J. M., Imber, S. M., Sun, W. J., ... Smith, A. W. (2017). Mercury's cross-tail current sheet: Structure, X-line location and stress balance. *Geophysical Research Letters*, 44(2), 678–686. doi: 10.1002/2016GL071612
- Powell, K. G., Roe, P. L., Linde, T. J., Gombosi, T. I., & De Zeeuw, D. L. (1999). A Solution-Adaptive Upwind Scheme for Ideal Magnetohydrodynamics. *Journal of Computational Physics*, 154(2), 284–309. doi: 10.1006/jcph.1999.6299
- 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(8), 6587–6602. doi: 10.1002/2014ja020120
- Raines, J. M., Slavin, J. A., Zurbuchen, T. H., Gloeckler, G., Anderson, B. J., Baker, D. N., ... McNutt, R. L. (2011). MESSENGER observations of the plasma environment near Mercury. *Planetary and Space Science*, 59(15), 2004–2015. doi: 10.1016/j.pss.2011.02.004
- Ridley, A. J. (2007). *Alfvén wings at Earth's magnetosphere under strong interplanetary magnetic fields* (Vol. 25; Tech. Rep.). Retrieved from www.ann-geophys.net/25/533/2007/
- Robbrecht, E., Berghmans, D., & Van Der Linden, R. A. (2009). Automated LASCO CME catalog for solar cycle 23: Are CMEs scale invariant? *Astrophysical Journal*, 691(2), 1222–1234. doi: 10.1088/0004-637X/691/2/1222
- Rong, Z. J., Ding, Y., Slavin, J. A., Zhong, J., Poh, G., Sun, W. J., ... Shen,

- C. (2018). The Magnetic Field Structure of Mercury's Magnetotail. *Journal of Geophysical Research: Space Physics*, 123(1), 548–566. doi: 10.1002/2017JA024923
- Russell, C. T., Baker, D. N., & Slavin, J. A. (1988). The magnetosphere of Mercury. In F. Vilas, C. R. Chapman, & M. S. Matthews (Eds.), *Mercury, university of arizona press* (pp. 514–561).
- Sarantos, M., & Slavin, J. A. (2009). On the possible formation of Alfvén wings at Mercury during encounters with coronal mass ejections. *Geophysical Research Letters*, 36(4). doi: 10.1029/2008GL036747
- Saur, J. (2021, May). Overview of Moon-Magnetosphere Interactions. In R. Maggiolo, N. André, H. Hasegawa, & D. T. Welling (Eds.), *Magnetospheres in the solar system* (Vol. 2, p. 575). doi: 10.1002/9781119815624.ch36
- Saur, J., Grambusch, T., Duling, S., Neubauer, F. M., & Simon, S. (2013). Magnetic energy fluxes in sub-Alfvénic planet star and moon planet interactions. *Astronomy and Astrophysics*, 552. doi: 10.1051/0004-6361/201118179
- Saur, J., Neubauer, F. M., Strobel, D. F., & Summers, M. E. (1999). Three-dimensional plasma simulation of Io's interaction with the Io plasma torus: Asymmetric plasma flow. *Journal of Geophysical Research: Space Physics*, 104(A11), 25105–25126. doi: 10.1029/1999ja900304
- Shue, J.-H., Chao, J. K., Fu, H. C., Russell, C. T., Song, P., Khurana, K. K., & Singer, H. J. (1997). A new functional form to study the solar wind control of the magnetopause size and shape. *Journal of Geophysical Research: Space Physics*, 102(A5), 9497–9511. doi: https://doi.org/10.1029/97JA00196
- Simon, S., Liuzzo, L., & Addison, P. (2021). Role of the Ionospheric Conductance Profile in Sub-Alfvénic Moon-Magnetosphere Interactions: An Analytical Model. *Journal of Geophysical Research: Space Physics*, 126(7). doi: 10.1029/2021JA029191
- Siscoe, G. L., & Sanchez, E. (1987). An MHD model for the complete open magnetotail boundary. *Journal of Geophysical Research: Space Physics*, 92(A7), 7405–7412. doi: 10.1029/ja092ia07p07405
- Slavin, J. A., Dibraccio, G. A., Gershman, D. J., Imber, S. M., Poh, G. K., Raines, J. M., ... Solomon, S. C. (2014). MESSENGER observations of Mercury's dayside magnetosphere under extreme solar wind conditions. *Journal of Geophysical Research: Space Physics*, 119(10), 8087–8116. doi: 10.1002/2014JA020319
- Slavin, J. A., & Holzer, R. E. (1981). Solar wind flow about the terrestrial planets 1. Modeling bow shock position and shape. *Journal of Geophysical Research: Space Physics*, 86(A13), 11401–11418. doi: 10.1029/JA086iA13p11401
- Slavin, J. A., Middleton, H. R., Raines, J. M., Jia, X., Zhong, J., Sun, W. J., ... Mays, M. L. (2019). MESSENGER Observations of Disappearing Dayside Magnetosphere Events at Mercury. *Journal of Geophysical Research: Space Physics*, 124(8), 6613–6635. doi: 10.1029/2019JA026892
- Slavin, J. A., Owen, J., Connerney, J., & Christon, S. (1997). Mariner 10 observations of field-aligned currents at mercury. *Planetary and Space Science*, 45(1), 133–141. (Mercury: The Planet and its Magnetosphere) doi: https://doi.org/10.1016/S0032-0633(96)00104-3
- Song, H. Q., Zhang, J., Cheng, X., Li, G., Hu, Q., Li, L. P., ... Chen, Y. (2020). Do All Interplanetary Coronal Mass Ejections Have a Magnetic Flux Rope Structure Near 1 au? *The Astrophysical Journal Letters*, 901(2), L21. doi: 10.3847/2041-8213/abb6ec
- Spreiter, J. R., Summers, A. L., & Alksne, A. Y. (1966). *HYDROMAGNETIC FLOW AROUND THE MAGNETOSPHERE* (Vol. 14; Tech. Rep.).
- Stahl, A., Addison, P., Simon, S., & Liuzzo, L. (2023). A Model of Ganymede's Magnetic and Plasma Environment During the Juno PJ34 Flyby. *Journal of Geophysical Research: Space Physics*, 128(12). doi: 10.1029/2023JA032113

- Sulaiman, A. H., Szalay, J. R., Clark, G., Allegrini, F., Bagenal, F., Brennan, M. J., ... Bolton, S. J. (2023). Poynting Fluxes, Field-Aligned Current Densities, and the Efficiency of the Io-Jupiter Electrodynamical Interaction. *Geophysical Research Letters*, 50(10). doi: 10.1029/2023GL103456
- Sun, W., Dewey, R. M., Aizawa, S., Huang, J., Slavin, J. A., Fu, S., ... Bowers, C. F. (2022). *Review of Mercurys dynamic magnetosphere: Post-MESSENGER era and comparative magnetospheres* (Vol. 65) (No. 1). Science Press (China). doi: 10.1007/s11430-021-9828-0
- Sun, W., Slavin, J. A., Dewey, R. M., Chen, Y., DiBraccio, G. A., Raines, J. M., ... Akhavan-Tafti, M. (2020). MESSENGER Observations of Mercury's Nightside Magnetosphere Under Extreme Solar Wind Conditions: Reconnection-Generated Structures and Steady Convection. *Journal of Geophysical Research: Space Physics*, 125(3), e2019JA027490. doi: https://doi.org/10.1029/2019JA027490
- Sun, W., Slavin, J. A., Smith, A. W., Dewey, R. M., Poh, G. K., Jia, X., ... Zhao, J. T. (2020). Flux Transfer Event Showers at Mercury: Dependence on Plasma β and Magnetic Shear and Their Contribution to the Dungey Cycle. *Geophysical Research Letters*, 47(21), e2020GL089784. doi: https://doi.org/10.1029/2020GL089784
- Szalay, J. R., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond, B., Clark, G., ... Wilson, R. J. (2020a). Alfvénic Acceleration Sustains Ganymede's Footprint Tail Aurora. *Geophysical Research Letters*, 47(3). doi: 10.1029/2019GL086527
- Szalay, J. R., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond, B., Clark, G., ... Wilson, R. J. (2020b). A New Framework to Explain Changes in Io's Footprint Tail Electron Fluxes. *Geophysical Research Letters*, 47(18). doi: 10.1029/2020GL089267
- Szalay, J. R., Bonfond, B., Allegrini, F., Bagenal, F., Bolton, S., Clark, G., ... Wilson, R. J. (2018). In situ observations connected to the io footprint tail aurora. *Journal of Geophysical Research: Planets*, 123(11), 3061–3077. doi: 10.1029/2018JE005752
- Szalay, J. R., Saur, J., Allegrini, F., Ebert, R. W., Valek, P. W., Clark, G., ... Wilson, R. J. (2024). Ion Precipitation Into Io's Poles Driven by a Strong Sub-Alfvénic Interaction. *Geophysical Research Letters*, 51(15). doi: 10.1029/2024GL110205
- Tóth, G., van der Holst, B., Sokolov, I. V., De Zeeuw, D. L., Gombosi, T. I., Fang, F., ... Opher, M. (2012). Adaptive numerical algorithms in space weather modeling. *Journal of Computational Physics*, 231(3), 870–903. doi: 10.1016/j.jcp.2011.02.006
- Volwerk, M., Khurana, K., & Kivelson, M. (2007). Europa's Alfvén wing: Shrinkage and displacement influenced by an induced magnetic field. *Annales Geophysicae*, 25(4), 905–914. doi: 10.5194/angeo-25-905-2007
- Winslow, R. M., Anderson, B. J., Johnson, C. L., Slavin, H., J. A. and Korth, W., Rucker, M. E., Baker, D. N., & Solomon, S. C. (2013). Mercury's magnetopause and bow shock from MESSENGER Magnetometer observations. *Journal of Geophysical Research: Space Physics*, 118(5), 2213–2227. doi: https://doi.org/10.1002/jgra.50237
- Winslow, R. M., Lugaz, N., Philpott, L., Farrugia, C. J., Johnson, C. L., Anderson, B. J., ... Asad, M. A. (2020). Observations of Extreme ICME Ram Pressure Compressing Mercurys Dayside Magnetosphere to the Surface. *The Astrophysical Journal*, 889(2), 184. doi: 10.3847/1538-4357/ab6170
- Winslow, R. M., Lugaz, N., Philpott, L. C., Schwadron, N. A., Farrugia, C. J., Anderson, B. J., & Smith, C. W. (2015). Interplanetary coronal mass ejections from MESSENGER orbital observations at Mercury. *Journal of Geophysical Research: Space Physics*, 120(8), 6101–6118. doi: 10.1002/2015JA021200

- Winslow, R. M., Philpott, L., Paty, C. S., Lugaz, N., Schwadron, N. A., Johnson, C. L., & Korth, H. (2017). Statistical study of ICME effects on Mercury's magnetospheric boundaries and northern cusp region from MESSENGER. *Journal of Geophysical Research: Space Physics*, 122(5), 4960–4975. doi: 10.1002/2016JA023548
- Zhou, H., Tóth, G., Jia, X., & Chen, Y. (2020, August). Reconnection-Driven Dynamics at Ganymede's Upstream Magnetosphere: 3-D Global Hall MHD and MHD-EPIC Simulations. *Journal of Geophysical Research (Space Physics)*, 125(8), e28162. doi: 10.1029/2020JA028162
- Zhuang, B., Lugaz, N., Temmer, M., Gou, T., & Al-Haddad, N. (2022). Acceleration and expansion of a coronal mass ejection in the high corona: Role of magnetic reconnection. *The Astrophysical Journal*, 933(2), 169.