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Cross-comparison of global simulation models applied to Mercury's dayside magnetosphere

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Abstract

We present the first comparison of multiple global simulations of the solar

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wind interaction with Mercury’s dayside magnetosphere, conducted in the framework of the international collaborative project SHOTS - Studies on Hermean magnetosphere Oriented Theories and Simulations. Two magneto-hydrodynamic and two hybrid simulation codes are used to investigate the global response of the Hermean magnetosphere to a northward-oriented interplanetary magnetic field. We cross-compare the results of the four codes for a theoretical case and a MESSENGER orbit with similar upstream plasma conditions. The models agree on bowshock and magnetopause locations at 2.1 ± 0.1 and 1.4 ± 0.08 Mercury planetary radii, respectively. The latter locations may be influenced by subtle differences in the treatment of the plasma boundary at the planetary surface. The predicted magnetosheath thickness varies less between the codes. Finally, we also sample the plasma data along virtual trajectories of BepiColombo’s Magnetospheric and Planetary Orbiter. Our ability to accurately predict the structure of the Hermean magnetosphere aids the analysis of the onboard plasma measurements of past and future magnetospheric missions.

Keywords: Mercury, BepiColombo, Modeling

1. Introduction

Mercury is a planet of extremes that is continuously battered by a harsh and dynamic solar wind. Combined with interplanetary magnetic field (IMF) magnitudes up to 30 nT and a small Parker spiral angle, Mercury’s weak internal magnetic field produces a unique magnetosphere in the solar system [1, 2, 3, 4, 5]. For example, the Hermean magnetosphere is twenty times smaller in volume than Earth’s magnetosphere and Mercury’s volume frac-

8 tion in its magnetosphere is approximately five hundred times larger than
9 the equivalent terrestrial number. As a result, the solar wind can directly
10 interact with the surface, even outside the magnetospheric cusps [6]. In
11 addition, the significant offset between the magnetic dipole origin and the
12 center of the planet results in a surface magnetic field strength in the north-
13 ern hemisphere that is double the nominal value estimated for the southern
14 hemisphere [7, 8, 9]. These particularities culminate in fascinating particle
15 precipitation patterns and differential space weathering that is as variable as
16 the upstream solar wind [10, 11, 12]. The absence of a significant ionosphere
17 makes Mercury’s conductive core an integral part of the electrodynamic cur-
18 rent closure and complicates the evolution of the complex local plasma envi-
19 ronment even more [13, 14].

20
21 Numerical simulations of the solar wind interaction with the Hermean
22 magnetosphere have thus far adopted multi-fluid/magnetohydrodynamic [15,
23 16, 17, 18] and hybrid approaches (representing the ions as computational
24 particles and the electron populations as a (massless) fluid) [19, 20, 21, 22,
25 23, 24, 25, 26, 12]. These models, designed to focus on the ion kinetics,
26 have been successful in recreating the general structure of Mercury’s local
27 plasma environment. For example, with a hybrid model Müller et al. [27]
28 characterised a diamagnetic current system that originates from the proton
29 pressure gradients at Mercury’s inner magnetosphere to explain the day- and
30 night-side diamagnetic decreases observed by MESSENGER [28, 29]. In ad-
31 dition, recent numerical developments have produced the first fully kinetic,
32 global simulations of the Hermean magnetosphere [30, 31, 32].

33

34 Due to mission constraints, both the Mariner-10 and MESSENGER space-
35 craft were limited to measure the Hermean plasma environment and thus, to
36 fully disentangle plasma processes such as finite-gyroradius effects and com-
37 plex electron dynamics [4]. Complementary to the previous missions, Bepi-
38 Colombo's Magnetospheric (Mio) [33]) and Planetary Orbiter (MPO) [34])
39 allow for multi-spacecraft coordinated observations. Their plasma instru-
40 ments focus on direct measurements of the response of Mercury's magneto-
41 sphere and its near-space environment to dynamic changes in the solar wind,
42 including plasma-wave-charged-particle resonances, kinetic-scale instabilities
43 and particle distributions, and energy transfer via field-aligned currents and
44 waves [4].

45

46 In order to optimally prepare for the measurement campaign and to be
47 able to fully interpret and analyse the data during the forthcoming Mercury
48 flybys and during the orbital phase, or in other words, to exploit most effi-
49 ciently the multi-point measurements allowed by the dual spacecraft and the
50 synergies between the various sensors of the onboard plasma suite, sophis-
51 ticated modelling tools are required. Hence, the SHOTS (Studies on Her-
52 mean magnetosphere Oriented Theories and Simulations) project has been
53 established as an integral part of the BepiColombo Young Scientist Working
54 Group. Its aim is to share and compare simulations results among the Bepi-
55 Colombo Science Working Team in order to prepare the scientific analysis of
56 the in-situ magnetospheric observations gathered by Mio and MPO.

57

58 In this first comparative study, we identify the differences between fluid
59 and hybrid simulation approaches to model the structure of the Hermean
60 magnetosphere and its plasma environment. We compare the bow shock
61 and magnetopause locations with a representative set of MESSENGER mea-
62 surements and predict the plasma environment along virtual trajectories of
63 BepiColombo’s Mio and MPO spacecraft.

64

65 **2. Model descriptions and methodology constraints**

66 The four computer models used in this comparison study are briefly de-
67 scribed here, with special emphasis on their inner boundary conditions. We
68 find that subtle differences in the treatment of the plasma boundary at the
69 planetary surface affect the global solar wind - magnetosphere structure. Two
70 magnetohydrodynamic (MHD) and two hybrid codes have been employed to
71 identify the consequences of the different assumptions that are implemented
72 in the physical model of the codes. In Table 1, we summarize the general nu-
73 merical settings adopted for the four codes, such as the number of cells used,
74 the size of the simulation domain and the spatial resolution. The output from
75 all models are stored and discussed using the Mercury Solar Orbital (MSO)
76 frame. The X-axis points towards the Sun and the Y-axis is chosen opposite
77 to the orbital motion of Mercury. The Z-axis points to the geophysical north
78 and completes the right-handed coordinate system. The intrinsic magnetic
79 field of the planet is set as a dipole with a 480 km offset towards the north
80 from the planetary center [35]. The dipole moment is $200 \text{ nT} \times R_M^3$. To avoid
81 further numerical complexities, we do not include the tenuous Mercury’s ex-

82 osphere in our simulations just yet.

83

84 *2.1. MHD models*

85 The three-dimensional MPI-AMRVAC code (hereafter AMRVAC) inte-
86 grates the MHD equations using a two-step Lax-Friedrichs-type scheme as-
87 sociated with a Woodward gradient limiter [36, 37]. A Powell correction
88 is also used to satisfy the $\nabla \cdot \mathbf{B} = 0$ condition at each time step [38]. In
89 order to limit magnetic diffusion, the magnetic field \mathbf{B} is split into an an-
90 alytically prescribed background field \mathbf{B}_0 and a residual field \mathbf{B}_1 [39]. The
91 full system of equations is solved on a spherical grid that is linearly spaced
92 along the angular coordinates θ and ϕ and logarithmically spaced along the
93 radial coordinate r . Hence, the simulation domain itself is a spherical shell.
94 At the outer boundary, free slip conditions ($\partial/\partial r = 0$) are applied to all
95 fields where the angle between the solar wind direction and the normal to
96 the boundary direction is $< 80^\circ$. Ambient (upstream) solar wind conditions
97 are set at the remaining sides of the domain. At the inner boundary of
98 the simulation domain, here the planetary surface, the radial velocity is set
99 to zero. A free slip condition is applied to the tangential components of
100 the momentum $\rho\mathbf{v}$. If the radial velocity immediately above the surface is
101 positive (i.e. in case of outflow), the plasma number density and the total
102 fluid pressure are set to $n_p = n_e = 15 \text{ cm}^{-3}$ and $p = 0.1 \text{ nPa}$, respectively.
103 On the other hand, if the radial velocity immediately above the surface is
104 negative (i.e. in case of inflow), n_p and p are allowed to float within 15-
105 150 cm^{-3} and 0.1-1 nPa. A free slip condition is also applied to the normal
106 component of \mathbf{B}_1 at the surface. The tangential components are set to zero.

107 Note from Table 1 that only AMRVAC employs a spherical coordinate sys-
108 tem. With a total number of cells of $(N_r, N_\theta, N_\phi) = (36, 36, 72)$, covering
109 the radial interval $r \in R_M [1, 10]$, the horizontal and vertical cell size near
110 the surface are 213 km and 161 km, respectively. Postmortem, the results
111 of AMRVAC are interpolated to a uniform Cartesian grid with a spatial res-
112 olution of 81.5^3 km^3 for ease of comparison with the other simulation models.

113

114 YAGI’s code is the second three-dimensional MHD model we use [40, 41].
115 In contrast to AMRVAC, a uniform Cartesian grid is adopted and the vector
116 potential \mathbf{A} is computed instead of the magnetic field, ensuring $\nabla \cdot \mathbf{B} = 0$
117 by definition. In addition, a Rational-CIP algorithm is implemented to solve
118 the advection term [41]. A fourth-order Runge Kutta and a fourth-order
119 central difference method are used to solve the non-advection terms needed
120 to advance the numerical scheme in time and space. The inner boundary of
121 the computational domain is the planetary surface. Mercury is treated as a
122 reflective obstacle, allowing no flux to penetrate across the surface (obsta-
123 cle). We also do not allow any radial pressure and density gradient at the
124 planetary surface. The inner boundary conditions accommodate a smooth
125 convection of the magnetic field in the vicinity of the planet, mimicking ob-
126 stacle with low conductivity.

127

128 *2.2. Hybrid models*

129 AIKEF (Adaptive Ion Kinetic Electron Fluid) is a hybrid code that oper-
130 ates on a Cartesian grid. The mesh is capable of automatically adapting its
131 resolution in regions where large field gradients exist [42, 26]. For simplicity,

132 we do not activate this function here and use a fixed spatial resolution of
 133 100 km^3 instead. Contrary to MHD, a hybrid model treats ions kinetically
 134 and uses computational macro-particles to represent their velocity distribu-
 135 tion. The number of macro-particles per cell is set to 25 to describe the
 136 initial Maxwellian distribution. Electrons are included as a massless charge-
 137 neutralizing fluid. To include induction effects, a radial resistivity profile
 138 is applied. The maximum resistivity is set to $1.21 \times 10^7 \Omega m$ within the
 139 mantle [17]. Mercury’s surface is treated as a perfect plasma absorber, i.e.,
 140 particles impacting the surface are removed. Within the vacuum regions of
 141 the nightside magnetosphere, ghost-particles with the same charge-to-mass
 142 ratio as the upstream solar wind protons are inserted to allow local magnetic
 143 field diffusion. Their density is tenuous so that no physical feedback onto
 144 the dynamics of the magnetosphere is present. A 2% smoothing parameter
 145 is applied between the grid points to ensure numerical stability [43].

146

147 The Amitis (advanced modeling infrastructure in space simulations) is
 148 a GPU-based (Graphics Processing Units) three-dimensional hybrid model
 149 of plasma that currently runs only on a single CPU-GPU pair. It has been
 150 developed to reduce the computational resources that are typically needed
 151 for running global simulations and resulted in performance enhancement of
 152 10x-100x over its CPU-based predecessor [24]. The model kinetically tracks
 153 positively charged macro-particles, i.e., the ion population, by solving the
 154 Lorentz equation of motion while using a fluid description for mass-less elec-
 155 trons. The electric field \mathbf{E} is directly calculated from the electron momentum
 156 equation and Faraday’s law, $\partial \mathbf{B} / \partial t = -\nabla \times \mathbf{E}$, is used to advance the mag-

157 netic field \mathbf{B} in time. The model is grid-based and uses regular-spaced, cell-
158 center Cartesian grids to solve all the equations. We choose a spatial resolu-
159 tion of 170 km^3 with 12 macro-particles per cell. The model self-consistently
160 couples the geophysical, induced electromagnetic response of the interior of
161 a planetary body to the electromagnetic response of the incident plasma and
162 magnetic fields by solving Maxwell’s equations for the plasma and a mag-
163 netic diffusion equation ($\partial\mathbf{B}/\partial t = -\nabla \times \nabla \times \mathbf{B}/\mu_0\sigma$) for the interior of an
164 object, where μ_0 is the permeability of free space and σ is the conductive
165 profile for the interior of the planetary body [24]. When a particle impacts
166 the planetary surface, it is removed from the simulation domain. Vacuum re-
167 gions that form within the computational domain are assumed a resistivity
168 $10^7 \Omega \text{ m}$. Note that AIKEF uses ghost particles instead. Amicitis adopts pe-
169 riodic outer boundary conditions for its particles and electromagnetic fields
170 along the axes perpendicular to the solar wind flow. Parallel to the flow
171 the code continuously injects solar wind ions at the most upstream grid cell.
172 The downstream boundary, identical to its implementation of the planetary
173 surface, is a perfect plasma absorber.

174

175 *2.3. Common visualization tools*

176 We use netCDF as a multidimensional format with meta information for
177 all simulations. It allows us to have a unified format for comparative vi-
178 sualizations, data interoperability and reusability. In the present study, we
179 employ Paraview for 3D data visualization and analysis. In addition, we
180 use 3Dview and AMDA, which makes use of the SPASE simulation data
181 model [44, 45, 46, 47]. Using SPICE kernels, 3Dview is a 3D JAVA tool that

	Grid type	#cells	Domain size	Resolution	particles/cell
AMRVAC	Spherical	(36, 36, 72)	$r \in R_M [1, 10]$	213×161 km	-
YAGI	Cartesian	(300, 300, 300)	$(-10:+6,\pm 5,\pm 5) R_M$	122 km	-
AIKEF	Cartesian	(320, 224, 224)	$(-6:+8,\pm 9,\pm 9) R_M$	100 km	25
Amitis	Cartesian	(180, 280, 280)	$(\pm 7,\pm 10,\pm 10) R_M$	170 km	12

Table 1: Summary of the numerical settings. For AMRVAC the finest spatial resolution is quoted.

182 provides visualizations of the positions and attitudes of planetary missions
183 and bodies in combination with observational data, simulations, and analyt-
184 ical models. AMDA is an online database and analysis tool in which in-situ
185 observations, ground based observations, and models can be browsed, ma-
186 nipulated and downloaded (a workspace is available for each user). AMDA
187 and 3Dview are developed by the CDPP (Centre de Données de la Physique
188 de Plasmas) and available to contributing developers under a GPLv3 licence.

189 3. Science cases

190 In this work we discuss two cases: (a) a classical textbook case under
191 purely northward IMF conditions, and (b) a direct comparison with a pre-
192 selected MESSENGER orbit.

193

194 3.1. Case a: Northward IMF

195 Northward IMF conditions are chosen to anticipate a stable dayside mag-
196 netosphere structure. Typically, a southward IMF gives rise to more unstable
197 magnetosphere conditions as continuous dayside magnetic reconnection in

198 combination with a relatively short Dungey cycle does not allow the system
199 to relax in between [8]. In the case of a northward IMF, the reconnection
200 sites move to high latitudes near the magnetospheric cusps.

201

202 We set the IMF magnitude to 20 nT and adopt a solar wind proton den-
203 sity of 30 cm^{-3} , an Alfvén Mach number of 5 and a total plasma beta (β)
204 of 1.3. The solar wind speed measures 400 km s^{-1} [48, 6]. The MHD mod-
205 els assume a total density equal to the proton density, whereas the plasma
206 temperature (43 eV) is set to the sum of the electron (21.5 eV) and proton
207 (21.5 eV) temperatures (Table 2).

208

209 3.2. Case b: *MESSENGER* comparison

210 We select a *MESSENGER* orbit that allows a simulation setup as close
211 as possible to our theoretical northward IMF case. Due to its mid-day to
212 midnight orientation (X-Z plane), orbit 1415 (November 8, 2012) provides
213 a close comparison. The orbit has a Disturbance Index of less than 25 [49],
214 the lowest magnetic activity quartile, the Z-components of the IMF at the
215 inbound and outbound bow shock crossings are positive and within 2 nT of
216 each other, and the IMF variability along the entire orbit is less than 10 nT.
217 Combined these parameter values indicate stable solar wind conditions.

218

219 We use the inbound part of the orbit to compute the average IMF vector
220 to be inserted in our models. Further, the Alfvén Mach number is set to 5, the
221 solar wind speed equals 459 km s^{-1} and the proton and electron temperature
222 measure 12 eV, and 18 eV, respectively [50, 51].

Table 2: Summary of the common input plasma parameters. *SW* denote the solar wind.

	Northward case	MESSENGER case
Planetary radius R_M [km]	2440	2440
Planetary dipole moment [nT $\times R_M^3$]	200	200
Northward dipole offset [km]	480	480
SW proton density [cm ⁻³]	30	40
SW proton + electron temperature [eV]	21.5+21.5	12+18
SW total plasma β	1.3	0.69
SW Alfvén Mach number	5	5
SW plasma velocity [km s ⁻¹]	400	459
SW Sonic Mach number	6.8	8.5
IMF (X,Y,Z) components [nT]	(0, 0, +20)	(25, -6, 4.9)

223 **4. Results**

224 *4.1. Case a: Northward IMF*

225 A purely northward IMF configuration provides a stable magnetosphere
 226 configuration. We find that all simulation models reach quasi-steady state
 227 after roughly 300 seconds. Figure 1 shows the solar wind proton density maps
 228 in the $X - Z$ plane on a logarithmic scale, including also magnetic field lines.
 229 The two left panels are the results from the MHD codes while the two right
 230 panels present the results from the hybrid codes. All models have converged
 231 to a very similar global structure for the Hermean magnetosphere and the
 232 characteristic feature are present: the shape of bowshock, the higher density
 233 magnetosheath, and the magnetospheric cusps. However, the models do not
 234 agree on the proton density near the planet and inside the nightside magne-

235 tosphere. We also observe different locations of the magnetopause structure.

236

237 AMRVAC (Figure 1, upper left panel) shows a less sharp shock structure
238 at the bow shock, a low density dayside magnetosphere, patches of higher
239 density close to the surface in the cusp and tail regions, and an asymmetric
240 (southward) magnetic field structure for the nightside magnetosphere. The
241 latter is uniquely present in AMRVAC. The model also has the largest mag-
242 netopause flaring angle among the four models. YAGI’s MHD code (bottom
243 left panel) presents a sharper bow shock as compared to AMRVAC, most
244 likely due to the model’s less diffusive scheme. In addition, the dayside mag-
245 netosphere is not dilute and houses a similar density as the magnetosheath.
246 The nightside structure of the magnetic field is more symmetric and slightly
247 tilted northward. The density concentration we find near the tail region in
248 the AMRVAC model is not present here. Finally, only YAGI’s model results
249 show a north-south symmetric cusp region. AIKEF (upper right panel), sim-
250 ilar to AMRVAC and Amitis, produces a sharp bowshock and a more dilute
251 dayside magnetosphere region. Both hybrid codes concur on narrower cusps
252 as compared to the MHD models. The nightside magnetic field structure is
253 tilted slightly northward, similar to YAGI’s model. Note that upstream of
254 the magnetosphere the magnetic field lines are curved due to the numerical
255 smoothing algorithm AIKEF applies. Amitis (bottom right panel) does not
256 employ any smoothing routines. Operating with a lower number of particles
257 per cell as compared to AIKEF, the density maps therefore seem to contain
258 more numerical noise. However, the bowshock and magnetopause are clearly
259 captured and the solar wind plasma is denied from penetrating through the

260 dayside magnetosphere. The narrow cusp structure is similar to the results
261 from AIKEF. The magnetic field configuration at the nightside of the planet
262 is most symmetric. Amitis computes the lowest density in the magnetotail
263 of our four models because the model does not depend on ghost particles in
264 the lowest density areas of the simulation domain.

265

266 In order to quantify the differences between the four models, Figure 2
267 presents the pressure profile along the subsolar line (X-axis). The dynamic
268 and magnetic pressure are extracted and the locations of the bowshock and
269 magnetopause have been identified. The four panels correspond to the four
270 simulations. The solid lines show the dynamic (ram) pressure, ρv^2 , while
271 the dashed lines represents the magnetic pressure, $B^2/2\mu$. The gray dash-
272 dotted line is the magnetic pressure produced by an uncompressed dipole
273 magnetic field with the same dipole moment as the models, providing infor-
274 mation on how much the planetary magnetic field is compressed by the solar
275 wind. The gray vertical line at $x = 1.12 R_M$ indicates the point where the
276 dynamic pressure equals the uncompressed magnetic pressure and serves as
277 a reference for the magnetopause location. For each model, the position of
278 the bow shock (BS) has been identified as the maximum velocity and density
279 gradient (red vertical solid line). The location of the magnetopause (MP;
280 red vertical dashed line) has been identified in three different ways: (1) using
281 the position of the most distant closed planetary field line that crosses the
282 X-axis, (2) using the position where the gas and magnetic pressure are equal,
283 and (3) using the position where the current density has its maximum. All
284 three methods were in excellent agreement for all four models (Table 3).

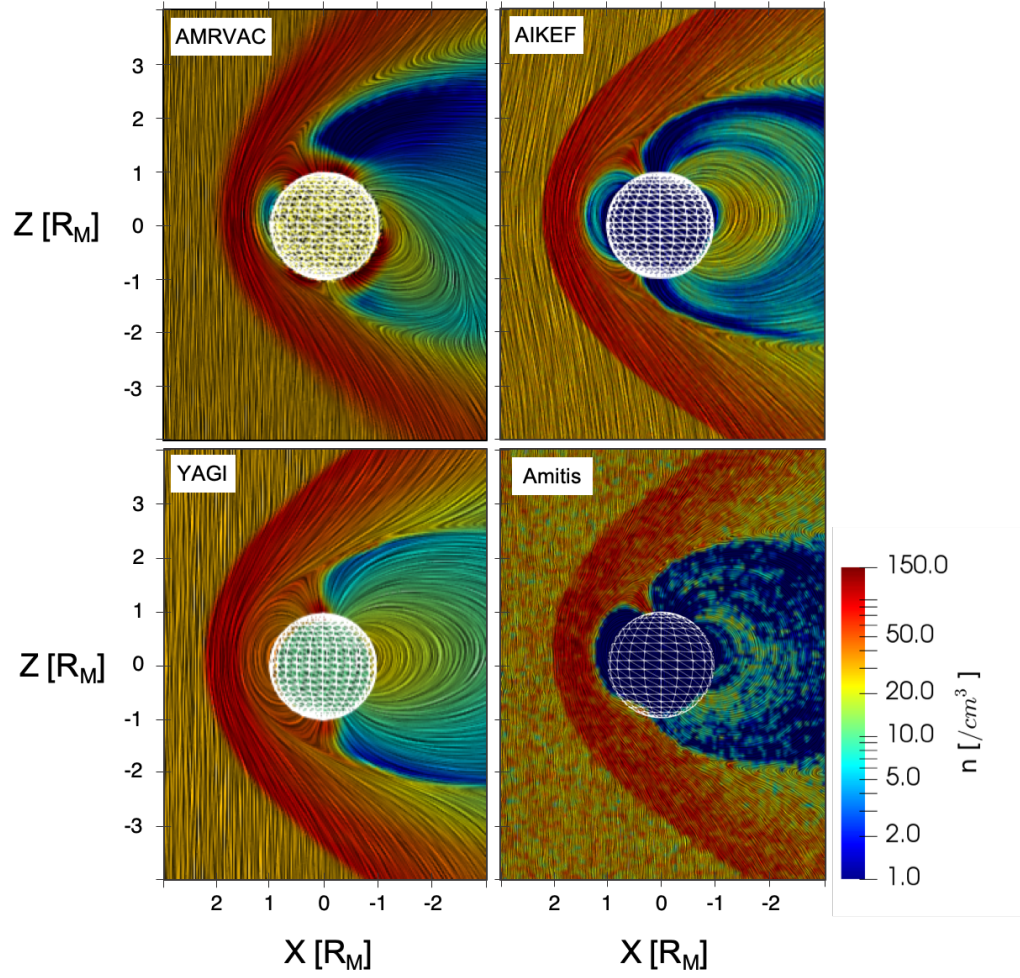


Figure 1: Maps of the solar wind proton density in the X-Z plane at steady-state for the four simulation models. The panels on the left (right) are the results from the MHD (hybrid) codes. Length scales are normalized to the Mercury radius.

Table 3: Summary of the bow shock and magnetopause locations, and the thickness of the magnetosheath for the four simulation models.

		BS [R_M]	MP [R_M]	Sheath thickness [R_M]
MHD	AMRVAC	1.99	1.30	0.69
	YAGI	2.21	1.50	0.71
Hybrid	AIKEF	2.18	1.42	0.76
	Amitis	2.22	1.48	0.74
Mean value		2.14	1.41	0.73
Standard Deviation		0.094	0.078	0.027

285

286 The locations of both the bow shock and magnetopause vary among the
 287 models with a range of $0.23 R_M$ and $0.2 R_M$, respectively (Figure 2 and Ta-
 288 ble 3). The mean position of the bow shock and magnetopause is found at
 289 $2.15 R_M$, and $1.41 R_M$, with a standard deviation of $\sigma = 0.094$ and $\sigma = 0.078$.
 290 The variation of the magnetopause location is greater than that of the bow
 291 shock as the former is more sensitive to the boundary condition applied at
 292 the surface and inside the planet. In effort to eliminate the effects of the
 293 numerical implementation for comparison purposes, we compute the average
 294 thickness of the magnetosheath and find $0.73 R_M$ with a standard deviation
 295 of 0.027 . We find that the hybrid models predict a slightly thicker magne-
 296 tosheath as compared to the MHD models. Note that the mean BS and MP
 297 locations simulated here with a purely northward IMF are within the ranges
 298 measured by MESSENGER [6].

299

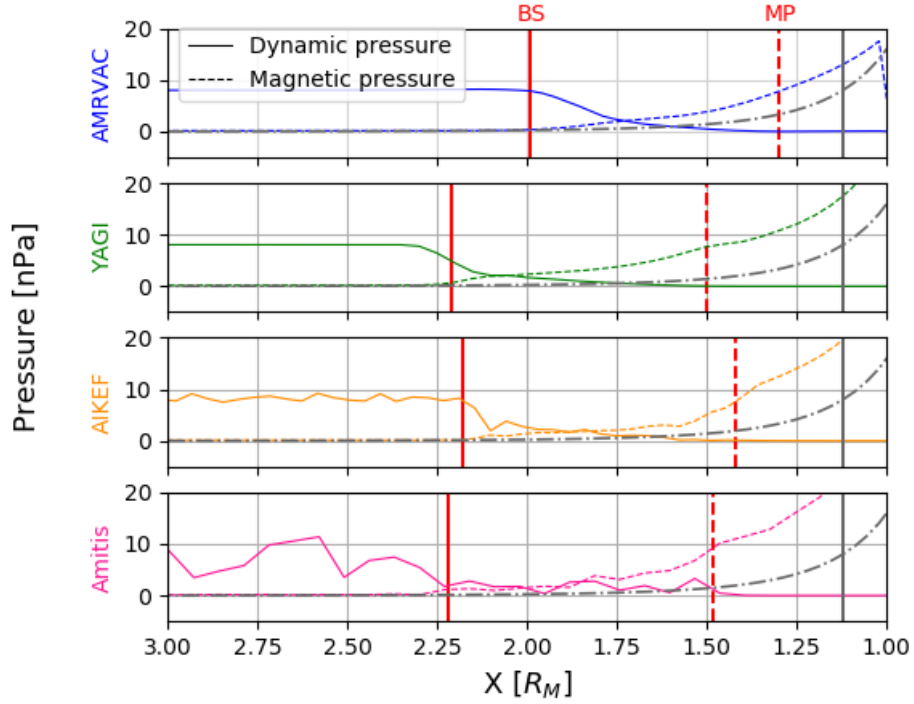


Figure 2: Dynamic (ram) and magnetic pressure profiles along the X-axis (Sun-Mercury direction) from $3 R_M$ upstream to the planet surface on the dayside for the four simulation codes. The results from the two MHD codes are shown on the top two panels and the hybrid model results on the two bottom panels. The gray dash-dotted line is the magnetic pressure produced by an uncompressed dipole magnetic field with the same dipole moment as the models. The positions of the bow shock (BS) and magnetopause (MP) are shown with red vertical solid and dashed lines. The grey vertical line gives the theoretical expected position of the magnetopause.

300 In addition to the bow shock and magnetopause locations along the sub-
 301 solar line, we further characterize the Hermean magnetosphere by means of
 302 the reconnection sites. Figure 3 shows a map in the X-Z plane with its origin
 303 at the center of the planet. For reference, the two gray dashed lines repre-
 304 sent the bow shock and magnetopause locations as predicted by the models
 305 of Slavin et al. [52], Shue et al. [53], Winslow et al. [6]. The positions of the
 306 reconnection site, i.e. the null points, identified from the simulated magnetic
 307 field structure by our four models are indicated with full colored circles. The
 308 locations of the magnetopause at $X = -2 R_M$ are represented with colored
 309 crosses. On average, the null points near the northern cup are located more
 310 towards the nightside, whereas the null point near the southern cusp are clus-
 311 tered more towards the terminator plane (with exception of YAGI’s model).
 312 Due to the dipole offset towards the north, the southern null points are clos-
 313 est to the planet. Note that apart from the chosen plasma field conditions
 314 also various code-specific parameters, such as numerical resistivity, may play
 315 a role in where the reconnection sites develop. AMRVAC shows the largest
 316 north-south asymmetry on the location of null points, which is consistent
 317 with the tilted magnetic structure seen in Figure 1. The locations of the
 318 magnetopause on the nightside of the planet are obtained from the gradients
 319 of the density and the current density. With the exception of AMRVAC,
 320 these are located within the reference magnetopause model ($R_{ss} = 1.45 R_M$
 321 and $\alpha = 0.5$ [53, 6]). Given the purely northward IMF, all four simulations
 322 can be considered in good agreement with the reference models.

323

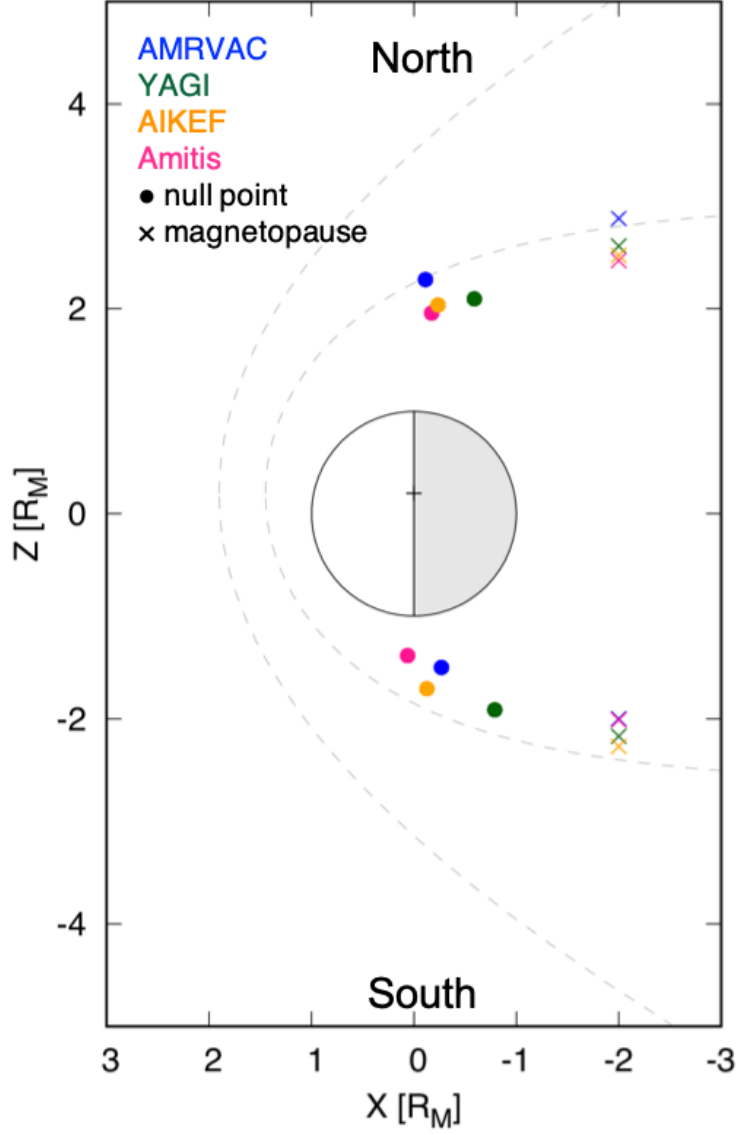


Figure 3: The locations of null points (colored circles) and magnetopause (colored crosses) in the X-Z plane. The dashed lines show the bow shock and magnetopause models defined by Slavin et al. [52] and Shue et al. [53], respectively. The magnetopause paraboloid has parameters $R_{ss} = 1.45 R_M$ and $\alpha = 0.5$. The bow shock model parameters are $p = 2.75 R_M$, $\epsilon = 1.04$, and $X_0 = 0.5 R_M$.

324 *4.2. Case b: MESSENGER comparison*

325 Figure 4 presents the magnetic field, density and plasma velocity profile
326 along MESSENGER orbit 1415 from 4:30 UT to 10:00 UT (see also sec-
327 tion 3.2). The spacecraft entered the magnetosphere at the nightside along
328 a south to north trajectory, roughly in the meridian plane with its closest
329 approach near the magnetic north of Mercury, thus crossing the bow shock
330 and magnetopause twice. Four vertical black lines indicate the bow shock
331 and magnetopause locations for both the inbound and outbound crossings
332 observed by MESSENGER. Superimposed on their respective panels are the
333 simulated profiles from Case a along the same trajectory. The red vertical
334 lines are the averaged simulated shock crossings from the four models. Over-
335 all, our models are in close agreement with the MESSENGER data for the
336 inbound part of the orbit. With time differences of up to 12 min, equal to
337 $\sim 0.28 R_M$ along the spacecraft trajectory for the inbound orbit, and 17 min
338 ($\sim 1.1 R_M$) for the outbound orbit, the locations of the BS and MP agree less
339 well for the outbound section of the MESSENGER orbit. The BS locations
340 match better for the inbound part of the orbit.

341

342 Since we used the inbound part of the orbit to constrain the upstream
343 plasma parameters to initialize the simulations, it is possible that variations
344 in the solar wind dynamic pressure during the orbit may be responsible for
345 the larger discrepancy in the outbound part of the orbit. Interestingly, there
346 are distinct differences between the MHD and the hybrid codes (panel 4 of
347 Figure 4). Around 7:50 UT, when the spacecraft is inside the dayside mag-
348 netosheath, the results from the two hybrid simulations are in agreement

349 with the observations, while both MHD models predict a lower magnetic
350 field intensity. The spacecraft passes through the northern cusp and then
351 moves towards the dayside region. At 8:10 UT, near the peak density, we
352 find the compressed magnetosheath plasma. As expected, also the density
353 and velocity profiles predicted by the hybrid codes show steeper profiles at
354 the shock crossing compared to the MHD models.

355

356 **5. Discussion**

357 Due to the limited particle instrumentation on board the single-spacecraft
358 MESSENGER mission, it is not possible to constrain the exact solar wind
359 plasma parameters to set up a comparison simulation. In addition, the solar
360 wind varies in time and may even be changing significantly while MESSEN-
361 GER crosses the magnetosphere. This may be the reason for some of the
362 discrepancies between simulated and measured profiles. In Figure 5 we com-
363 pute the difference between the observed and modeled magnetic fields along
364 our chosen MESSENGER orbit. We exclude the time frame between the
365 two MP crossings (from 6:15 UT to 7:45 UT) while MESSENGER passed
366 the nightside region of the magnetosphere, hence, focusing on the cusp and
367 dayside region.

368

369 Just before 5:00 UT, MESSENGER crosses the BS for the first time,
370 about 3 min before the predicted averaged time stamp from our models. Con-
371 tinuing along the trajectory, both the modeled X- and Z-component agree
372 well with MESSENGER, whereas the models underestimate the magnetic

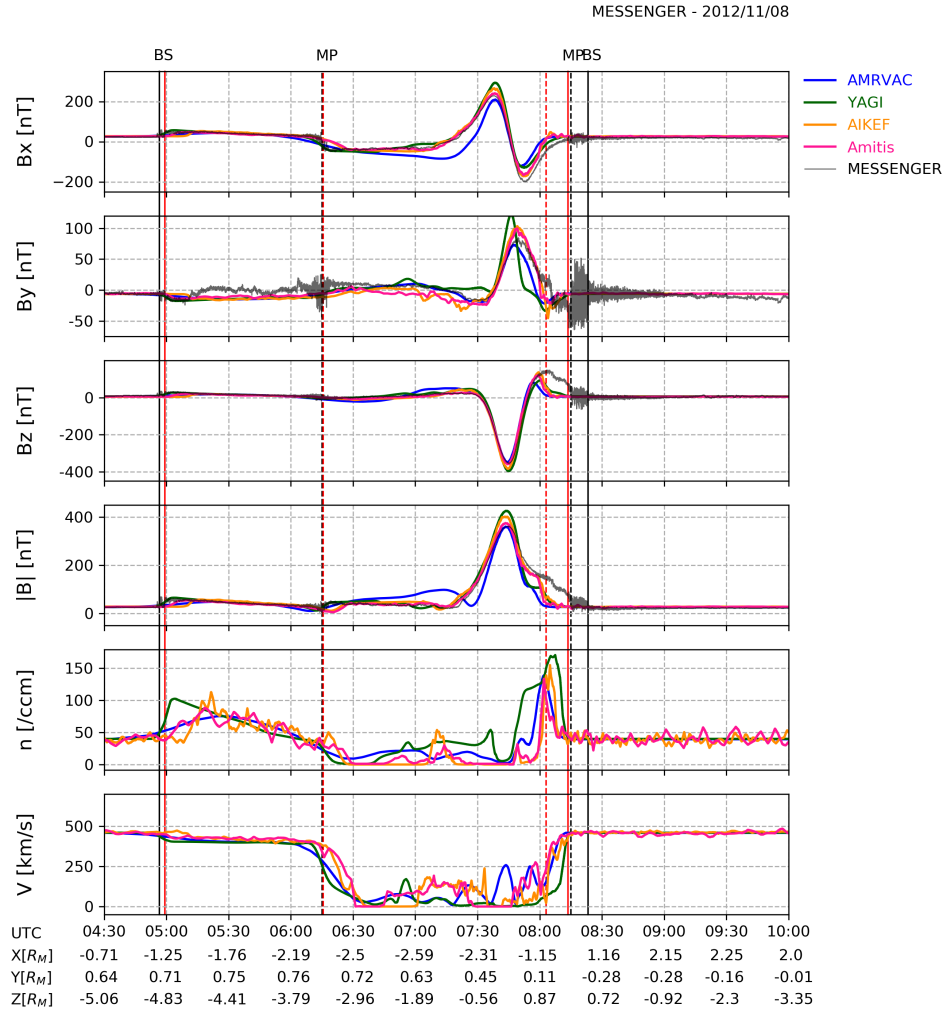


Figure 4: Modeled and observed magnetic field and modeled particle data along orbit 1415 of MESSENGER. Blue, green, orange, and red lines shows the results from AMRVAC, YAGI, AIKEF and Amitis, respectively. The black lines shows the magnetometer data measured by MESSENGER. The bow shock (BS) and magnetopause (MP) crossings identified from the observations are indicated using a vertical solid and dashed black line. The averaged simulated shock and magnetopause crossings are shown by red solid and dashed lines.

373 field contribution by roughly 15 nT along the Y direction. Our models agree
374 on the inbound MP crossing time at 6:15 UT within a 5 min time range. At
375 7:50 UT, when MESSENGER moves from the nightside to the dayside in the
376 northern hemisphere, all four models predict a magnetic pile-up, although
377 none of the models fully reproduces the fine-scale structure. Immediately fol-
378 lowing the pile-up, the models underestimate the magnetic field strength by
379 roughly 100 nT. Note that the different profiles in Figure 4 show no real ‘win-
380 ner’ among the four simulation models as all codes show different small-scale
381 discrepancies with the MESSENGER measurements at the boundaries be-
382 tween the distinct plasma regions of Mercury’s magnetosphere. It shows the
383 need for a multi-spacecraft mission, such as BepiColombo, to simultaneously
384 measure the local Hermean and upstream plasma environment in order to
385 fine-tune numerical models and in turn characterize Mercury’s global plasma
386 environment.

387

388 *5.1. Virtual sampling along Mio/MPO orbits*

389 One of the major goals of the SHOTS project, next to comparing differ-
390 ent simulation approaches with available MESSENGER measurements, is to
391 help prepare the community for the forthcoming BepiColombo mission by
392 making available a catalog of simulation case that study the plasma struc-
393 ture and dynamics of Mercury’s magnetosphere under different solar wind
394 conditions. In the first step of this project, we chose four different (MHD
395 and hybrid) simulation models. Figures 6 and 7 show the plasma character-
396 istics expected along a typical Mio and MPO orbit, respectively, during the
397 nominal orbital phase of BepiColombo. We chose the upstream solar wind

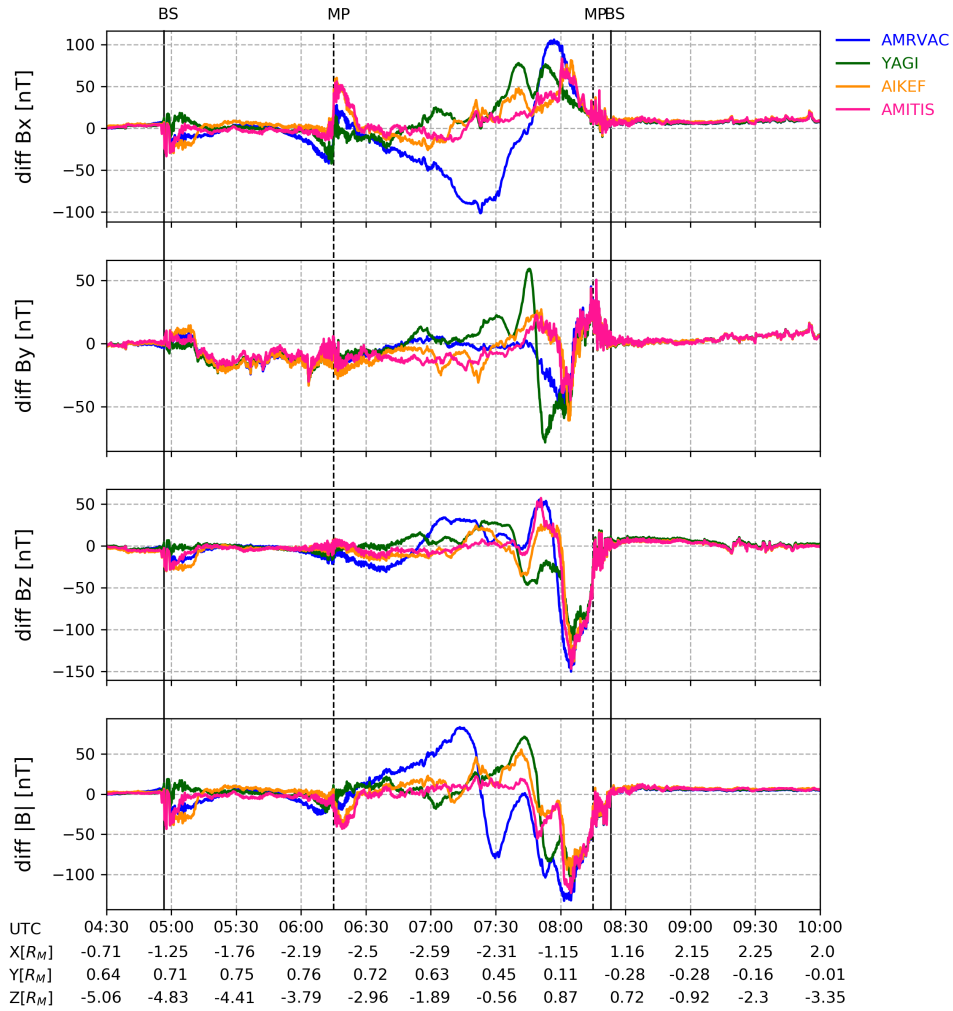


Figure 5: Difference between the simulation results and the MESSENGER magnetic field measurements. The bow shock (BS) and magnetopause (MP) crossings identified from the observations are indicated with a vertical solid and dashed line, respectively.

398 conditions identical to the MESSENGER case studied above (Table 2). For
399 ease of comparison, the orbital plane is set perpendicular to the X direc-
400 tion, corresponding to BepiColombo’s operations planned for April 4, 2026.
401 During this period, both Mio and MPO remain inside the magnetosphere
402 and the plasma environment will be fully observed by the magnetometers
403 on board Mio and MPO [54, 55], the Mercury Plasma Particle Experiment
404 (MPPE) [56] and the Plasma Wave Investigation (PWI) [57] onboard Mio,
405 and the Search for Exospheric Refilling and Emitted Natural Abundances
406 (SERENA) on board MPO [58].

407

408 In both Figures 6 and 7 the solid vertical lines indicate the southern (T_S)
409 and northern (T_N) terminator crossing and the dashed vertical line is the
410 time when the spacecraft crosses the sub-solar point (SSP). During this pe-
411 riod, Mio will be moving along the frontside magnetopause (from 15:15 UT
412 to 15:35 UT) where our models predict an enhancement of the magnetic field
413 intensity and plasma velocity. Note that the predicted profiles closest to the
414 planet are not in agreement, possibly due to the numerical treatment of the
415 planetary boundary condition. Next, Mio will move across the cusp region
416 and re-enter the nightside magnetosphere from the north. After crossing the
417 northern terminator at 15:50 UT, the density and velocity profiles diverge.
418 A similar trend is not visible in the magnetic field predictions. This may be
419 the region where the ion dynamics has the largest impact, hence producing
420 the largest differences between the hybrid and MHD models.

421

422 MPO will orbit significantly closer to the planet. The spacecraft will leave

423 the southern magnetosphere via the nightside, then crosses the terminator
424 and enters the dayside magnetosphere. Just before 15:00 UT and around
425 15:35 UT, the two hybrid models predict a significant density enhancement,
426 indicating the presence of trapped particles. The spacecraft passes through
427 the cusp region (gray areas in Figure 7). MPO's trajectory will be most use-
428 ful to better understand the structure and dynamics of the magnetosphere
429 closest to the planet and in particular near the southern hemisphere. This
430 region has been explored less due to MESSENGER's highly inclined and ec-
431 centric orbit.

432

433 Sampling the virtual orbits of Mio and MPO for a variety of solar wind
434 parameters and/or models, we will be able to predict when the spacecraft
435 most likely cross the cusp, the plasma sheet and the shocked regions within
436 certain margins. These margins depend on the characteristics of the sim-
437 ulation and the physical processes included in the model. The combined
438 measurements from the two spacecraft will provide a wealth of information
439 on the Hermean plasma environment, making predictive simulations a ne-
440 cessity to maximize the scientific return of the mission. To this effect, the
441 simulation domain needs to be extended farther downstream of the planet to
442 capture better the magnetotail region. Also temporal information needs to
443 be included. Finally, also simulation tools that include the electron dynamics
444 are needed.

445

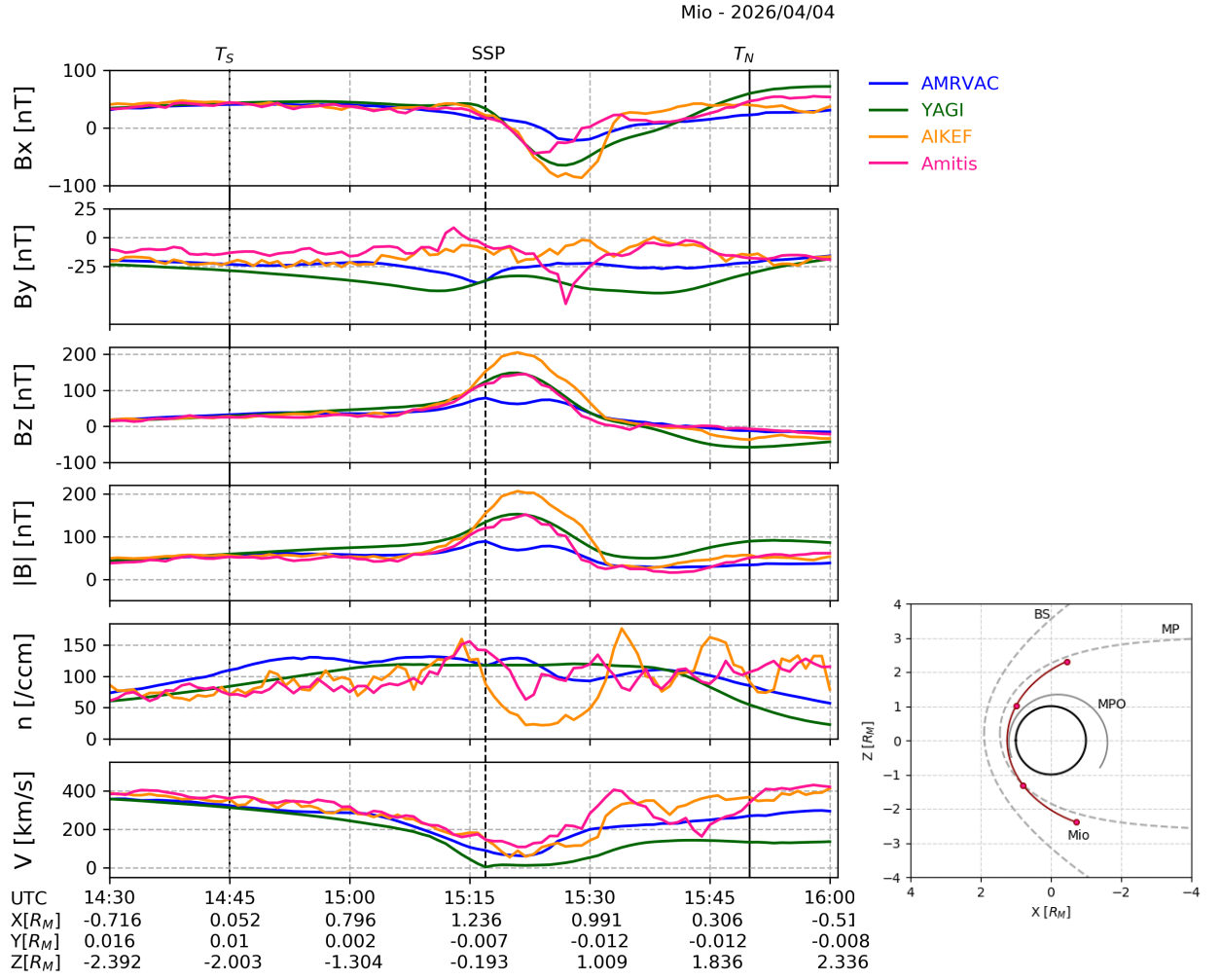


Figure 6: Magnetic field and particle data along a representative Mio orbit. The red dots along the trajectory in the inset panel show the position of the spacecraft along 30 min intervals. The solid vertical lines indicate the crossing of the southern (T_S) and northern (T_N) terminator, the dashed vertical line is the time when the spacecraft crosses the subsolar point (SSP).

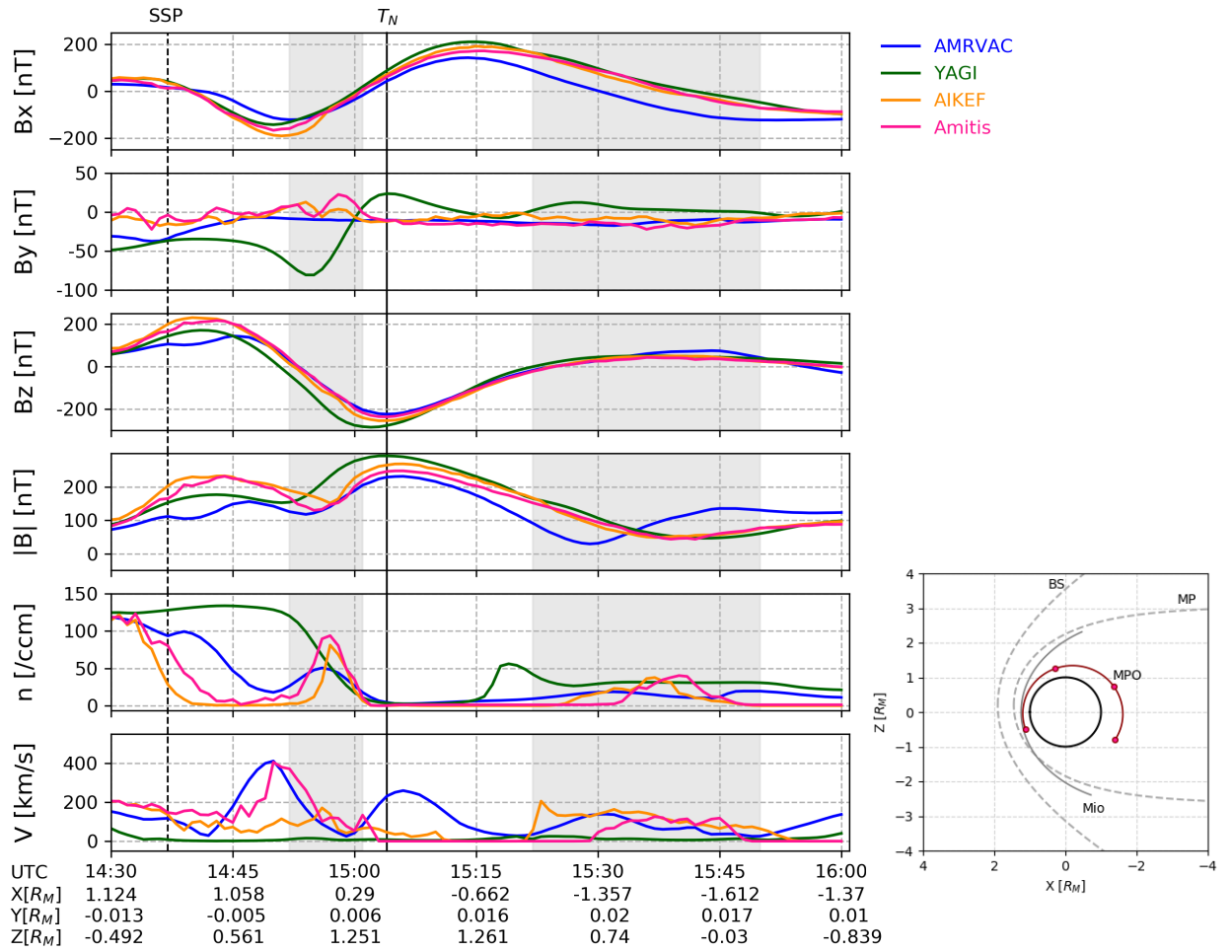


Figure 7: Magnetic field and particle data along a representative MPO orbit. The red dots along the trajectory in the inset panel show the position of the spacecraft along 30 min intervals. The solid vertical lines indicate northern (T_N) terminator and the dashed vertical line is the time when the spacecraft crosses the subsolar point (SSP).

446 6. Conclusions

447 We have compared the results of four different (MHD and hybrid) sim-
448 ulation models with the same input parameters to predict the solar wind
449 interaction with Mercury’s magnetosphere. All our models produced a sim-
450 ilar global structure consistent with analytical model for the locations of
451 the bow shock and the magnetopause. We note that small differences be-
452 tween the model predictions seem to be caused by the manner the planetary
453 boundary conditions are implemented, rather than by having self-consistent
454 ion kinetics included in the model.

455
456 We cross-compared our results with a theoretical northward IMF scenario
457 (Case a) and MESSENGER orbit 1415 (Case b), indicated to have stable so-
458 lar wind conditions with a northward IMF similar to the theoretical case. In
459 Case a, the standard deviations for the predicted mean locations of the bow
460 shock, magnetopause and the thickness of magnetosheath are small. For Case
461 b, during the inbound part of the orbit, time differences for the bow shock
462 and the magnetopause crossings are found up to 12 minutes, corresponding
463 to a distance along the orbit of $0.28 R_M$. For the outbound section of the
464 orbit, the maximum time difference increased to 17 minutes, equivalent to
465 $1.1 R_M$.

466
467 One of the major goals of SHOTS is to prepare a catalog of simulations
468 that can predict the plasma environment in- and outside the Hermean mag-
469 netosphere under different solar wind conditions, in this way contributing to
470 maximizing the scientific return of the forthcoming BepiColombo observa-

471 tions. Here, for the first time, we have extracted the data from our mod-
472 els along representative Mio and MPO orbits. A long-lasting project-based
473 and community-wide effort will be important both for the forthcoming Bepi-
474 Colombo’s Mercury flybys and during its nominal orbital phase.

475

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499

500 All data necessary to validate the findings presented in this manuscript
501 can be found at https://github.com/jandeca/Aizawa_etal_PSS_2020 (DOI:
502 to be provided) in accordance with the FAIR principles. The magnetome-
503 ter data from the MESSENGER observations are available in the Planetary
504 Data System.

505

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