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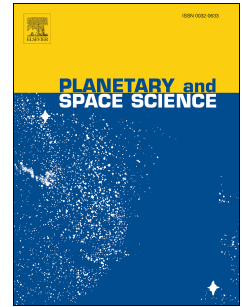
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1 **Author statement for the paper :**

2 **Cross-comparison of global simulation models applied to**
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- 50

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 so-

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lar 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 3D magnetohydrodynamic and two 3D hybrid simulation codes are used to investigate the global response of the Hermean magnetosphere without its exosphere 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 Slavin et al. [6], Slavin et al. [7, 8]. As a
10 result, the solar wind can directly interact with the surface, even outside the
11 magnetospheric cusps [9]. In addition, the significant offset between the mag-
12 netic dipole origin and the center of the planet results in a surface magnetic
13 field strength in the northern hemisphere that is double the nominal value
14 estimated for the southern hemisphere [10, 11, 12, 13]. These particularities
15 culminate in fascinating particle precipitation patterns and differential space
16 weathering that is as variable as the upstream solar wind [14, 15, 16]. The
17 absence of a significant ionosphere makes Mercury’s conductive core an inte-
18 gral part of the electrodynamic current closure and complicates the evolution
19 of the complex local plasma environment even more [17, 18].

20
21 Numerical simulations of the solar wind interaction with the Hermean
22 magnetosphere have thus far adopted multi-fluid/magnetohydrodynamic [19,
23 20, 17, 21] and hybrid approaches (representing the ions as computational
24 particles and the electron populations as a (massless) fluid) [22, 23, 24, 25, 26,
25 27, 28, 29, 30, 31, 32, 16, 33]. These models, designed to focus on the ion ki-
26 netics, have been successful in recreating the general structure of Mercury’s
27 local plasma environment. For example, with a 3D hybrid model, Müller
28 et al. [34] characterised a diamagnetic current system that originates from the
29 proton pressure gradients at Mercury’s inner magnetosphere to explain the
30 day- and night-side diamagnetic decreases observed by MESSENGER [6, 35].
31 In addition, recent numerical developments have produced the first fully ki-
32 netic, global simulations of the Hermean magnetosphere [36, 37, 38].

33

34 Due to mission constraints such as limited field of view and energy range
35 to detect ions, both the Mariner-10 and MESSENGER spacecraft were lim-
36 ited to measure the Hermean plasma environment and thus, to fully disen-
37 tangle plasma processes such as finite-gyroradius effects and complex elec-
38 tron dynamics [4]. Complementary to the previous missions, BepiColombo's
39 Magnetospheric (Mio) [39]) and Planetary Orbiter (MPO) [40]) allow for
40 multi-spacecraft coordinated observations [41]. Their plasma instruments
41 focus on direct measurements of the response of Mercury's magnetosphere
42 and its near-space environment to dynamic changes in the solar wind, in-
43 cluding plasma-wave-charged-particle resonances, kinetic-scale instabilities
44 and particle distributions, and energy transfer via field-aligned currents and
45 waves [4].

46

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

58

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

65

66 2. Model descriptions and methodology constraints

67 The four computer models used in this comparison study are briefly de-
68 scribed here, with special emphasis on their inner boundary conditions. We
69 find that subtle differences in the treatment of the plasma boundary at the
70 planetary surface affect the global solar wind - magnetosphere structure. Two
71 magnetohydrodynamic (MHD) and two hybrid codes have been employed to
72 identify the consequences of the different assumptions that are implemented
73 in the physical model of the codes. In Table 1, we summarize the general
74 numerical settings adopted for the four codes, such as the number of cells
75 used, the size of the simulation domain, the spatial resolution, and the time
76 step. The output from all models are stored and discussed using the Mer-
77 cury Solar Orbital (MSO) frame. The X-axis points towards the Sun and
78 the Y-axis is chosen opposite to the orbital motion of Mercury. The Z-axis
79 points to the geophysical north and completes the right-handed coordinate
80 system. The intrinsic magnetic field of the planet is set as a dipole with a
81 480 km offset towards the north from the planetary center [42]. The dipole

82 moment is $200 \text{ nT} \times R_M^3$. To avoid further numerical complexities, we do not
 83 include the tenuous Mercury’s exosphere in our simulations just yet. In a
 84 recent hybrid study, Exner et al. [33] investigated the kinetic effects of dif-
 85 ferent sodium exosphere surface densities onto the Hermean magnetsphere.
 86 Authors found that an average sodium exosphere based on a realistic model
 87 of [cite Gamborino Monte-Carlo Paper] does not pose a significant factor to
 88 the magnetic field structure inside the magnetosphere. Therefore, we do not
 89 include the tenuous sodium exosphere in this study.

90

91 2.1. MHD models

92 The three-dimensional MPI-AMRVAC (MPI-Adaptive Mesh Refinement
 93 Versatile Advection Code) code (hereafter AMRVAC) is the first three-dimensional
 94 MHD model we use in this study. This code integrates the MHD equations
 95 using a two-step Lax-Friedrichs-type scheme associated with a Woodward
 96 gradient limiter [43, 44]. A Powell correction is also used to satisfy the
 97 $\nabla \cdot \mathbf{B} = 0$ condition at each time step [45]. In order to limit magnetic diffu-
 98 sion, the magnetic field \mathbf{B} is split into an analytically prescribed background
 99 field \mathbf{B}_0 and a residual field \mathbf{B}_1 [46]. The full system of equations is solved
 100 on a spherical grid that is linearly spaced along the angular coordinates θ
 101 and ϕ and logarithmically spaced along the radial coordinate r . Hence, the
 102 simulation domain itself is a spherical shell. Note from Table 1 that only
 103 AMRVAC employs a spherical coordinate system. With a total number of
 104 cells of $(N_r, N_\theta, N_\phi) = (36, 36, 72)$, covering the radial interval $r \in R_M [1, 10]$,
 105 the horizontal and vertical cell size near the surface are 213 km and 161 km,
 106 respectively. At the outer boundary, free slip conditions ($\partial/\partial r = 0$) are ap-

107 plied to all fields where the angle between the solar wind direction and the
 108 normal to the boundary direction is $< 80^\circ$. Ambient (upstream) solar wind
 109 conditions are set at the remaining sides of the domain. At the inner bound-
 110 ary of the simulation domain, here the planetary surface, the radial velocity
 111 is set to zero. A free slip condition is applied to the tangential components
 112 of the momentum $\rho\mathbf{v}$. If the radial velocity immediately above the surface
 113 is positive (i.e. in case of outflow), the plasma number density and the total
 114 fluid pressure are set to $n = 30 \text{ cm}^{-3}$ and $p = 0.1 \text{ nPa}$, respectively. On the
 115 other hand, if the radial velocity immediately above the surface is negative
 116 (i.e. in case of inflow), n and p are allowed to evolve within $15 - 150 \text{ cm}^{-3}$ and
 117 $0.1 - 1 \text{ nPa}$. A free slip condition is also applied to the normal component of
 118 \mathbf{B}_1 at the surface. The tangential components are set to zero. The results
 119 of AMRVAC are interpolated to a uniform Cartesian grid with a spatial res-
 120 olution of 81.5^3 km^3 for ease of comparison with the other simulation models.

121

122 Yagi's code is the second three-dimensional MHD model we use [47, 48].
 123 In this code, a Rational-CIP (Constrained Interpolation Profile) algorithm
 124 is implemented to solve the advection term [48] and a fourth-order Runge-
 125 Kutta and a fourth-order central difference method are used to solve the
 126 non-advection terms needed to advance the numerical scheme in time and
 127 space. In contrast to AMRVAC, the magnetic vector potential \mathbf{A} is com-
 128 puted instead of the magnetic field, ensuring $\nabla \cdot \mathbf{B} = 0$ by definition and a
 129 uniform Cartesian grid is adopted. In this study, the grid resolution is set
 130 to 122 km^3 . The simulation domain measures $(-10 : +6, \pm 5, \pm 5) R_M$, with
 131 the number of cells of $(Lx, Ly, Lz) = (300, 300, 300)$. The inner boundary of

132 the computational domain is the planetary surface. Mercury is treated as a
 133 reflective obstacle, allowing no flux to penetrate across the surface (obsta-
 134 cle). We also apply the free slip condition which does not allow any radial
 135 pressure and density gradient at the planetary surface. The inner boundary
 136 conditions accommodate a smooth convection of the magnetic field in the
 137 vicinity of the planet, mimicking obstacle with low conductivity.

138

139 2.2. Hybrid models

140 AIKEF (Adaptive Ion Kinetic Electron Fluid) is the first three-dimensional
 141 hybrid model we employ in this study. Contrary to MHD, a hybrid model
 142 treats ions kinetically while electrons are included as a massless charge-
 143 neutralizing fluid. In this study, the number of computational macro-particle
 144 per cell is set to 25 to represent their Maxwellian velocity distribution. The
 145 magnetic and electric fields are obtained by solving the Maxwell equations,
 146 i.e., the electric field \mathbf{E} is directly calculated from the electron momentum
 147 equation and Faraday's law, $\partial\mathbf{B}/\partial t = -\nabla \times \mathbf{E}$, is used to advance the mag-
 148 netic field \mathbf{B} in time. The fields propagate between the grid points with
 149 a Runge-Kutta-algorithm. AIKEF operates on a Cartesian grid and the
 150 mesh is capable of automatically adapting its resolution in regions where
 151 large field gradients exist [49, 32]. For simplicity, we do not activate this
 152 function here and use a fixed spatial resolution of 100 km^3 instead, and the
 153 simulation domain is set to $(-6 : +8, \pm 9, \pm 9) R_M$ with the number of cells
 154 of $(Lx, Ly, Lz) = (320, 224, 224)$. To include magnetic induction processes
 155 within Mercury, Mercury's core is assumed to be highly conductive leading
 156 the resistivity in the core region is set to zero. The magnetic diffusion in the

157 mantle is facilitated by applying a maximum resistivity of $1.21 \cdot 10^7 \Omega \cdot m$
 158 [17, 32] and employing a Crank-Nicolson algorithm. The resistivity profile
 159 is smoothed at the surface and core-mantle-boundary, identical to Jia et al.
 160 [17]. Mercury’s surface is treated as a perfect plasma absorber, i.e., particles
 161 impacting the surface are removed. To ensure numerical stability, 0.2% of
 162 smoothing parameter is applied between the grid points [50].

163

164 The Amitis is a GPU-based (Graphics Processing Units) three-dimensional
 165 hybrid model of plasma that currently runs only on a single CPU-GPU
 166 pair [30]. It has been developed to reduce the computational resources that
 167 are typically needed for running global simulations and resulted in perfor-
 168 mance enhancement of 10x-100x over its CPU-based predecessor. Identical
 169 to AIKEF, the model kinetically tracks positively charged macro-particles,
 170 i.e., the ion population, by solving the Lorentz equation of motion while us-
 171 ing a fluid description for mass-less electrons. The electric field and magnetic
 172 field are obtained by solving Maxwell equations. The model is grid-based and
 173 uses regular-spaced, cell-center Cartesian grids to solve all the equations. We
 174 choose a spatial resolution of 125 km^3 with 16 macro-particles per cell, and
 175 simulation domain is set to $(\pm 7, \pm 10, \pm 10) R_M$. The model self-consistently
 176 couples the geophysical, induced electromagnetic response of the interior of
 177 a planetary body to the electromagnetic response of the incident plasma and
 178 magnetic fields by solving Maxwell’s equations for the plasma and a mag-
 179 netic diffusion equation ($\partial \mathbf{B} / \partial t = -\nabla \times \nabla \times \mathbf{B} / \mu_0 \sigma$) for the interior of the
 180 object, where μ_0 is the permeability of free space and σ is the conductive
 181 profile for the interior of the planetary body [30]. Amitis adopts periodic

182 outer boundary conditions for its particles and electromagnetic fields along
183 the axes perpendicular to the solar wind flow. Parallel to the flow the code
184 continuously injects solar wind ions at the most upstream grid cell. The
185 downstream boundary, identical to its implementation of the planetary sur-
186 face, is a perfect plasma absorber. Unlike AIKEF, a smoothing routine is
187 not applied in Amitis.

188

189 When plasma impacts onto the surface, a vacuum is formed in the down-
190 stream regions. In contrast to MHD codes where a minimum charge density
191 is present in these regions of vacuums to enable the continued calculation
192 of the field equations, hybrid models need special handlings of the vacuum
193 regions. AIKEF employs ghost-ions with the same charge-to-mass ratio as
194 solar wind ions but in tenuous densities to propagate the electric and mag-
195 netic fields in the vacuum regions. This approach enables a smooth density
196 profile at the vacuum region edges without large gradients, while also increas-
197 ing the numerical resource usage due to the handling of an additional species
198 Trávníček et al. [25]. A different approach is used in Amitis, where, each
199 time step, the cells within the vacuum regions obtain a flat resistivity value.
200 This approach allows for the emergence of localized currents that propagate
201 the electric and magnetic fields instead of ions. The vacuum state of the cells
202 is checked every time step which does not increase numerical resources by
203 a significant amount. However, this approach leads to unphysical resistivity
204 gradients throughout the downstream regions that might lead to unphysi-
205 cal currents. Therefore, the resistivity value is capped at $10^7 \Omega \text{m}$ so limit
206 the resistivity gradients. As both approaches result in good agreement with

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

	Grid type	#cells	Domain size	Resolution	Time step	particles/cell
AMRVAC [43]	Spherical	(36, 36, 72)	$r \in R_M [1, 10]$	213×161 km	0.03 sec	-
Yagi [47]	Cartesian	(300, 300, 300)	$(-10: +6, \pm 5, \pm 5) R_M$	122 km	0.02 sec	-
AIKEF [49]	Cartesian	(320, 224, 224)	$(-6: +8, \pm 9, \pm 9) R_M$	100 km	0.08 sec	25
Amitis [30]	Cartesian	(234, 396, 396)	$(\pm 7, \pm 10, \pm 10) R_M$	125 km	0.001 sec	16

207 spacecraft data [32, 31], we do not investigate how these approaches relate
 208 to each other in this study.

209 2.3. Common visualization tools

210 We use netCDF as a multidimensional format with meta information for
 211 all simulations. It allows us to have a unified format for comparative vi-
 212 sualizations, data interoperability and reusability. In the present study, we
 213 employ Paraview for 3D data visualization and analysis. In addition, we
 214 use 3Dview and AMDA (Automated Multi-Dataset Analysis), which makes
 215 use of the SPASE (Physics Archive Search and Extract) simulation data
 216 model [51, 52, 53, 54]. Using SPICE kernels, 3Dview is a 3D JAVA tool that
 217 provides visualizations of the positions and attitudes of planetary missions
 218 and bodies in combination with observational data, simulations, and analyt-
 219 ical models. AMDA is an online database and analysis tool in which in-situ
 220 observations, ground based observations, and models can be browsed, manip-
 221 ulated and downloaded (a workspace is available for each user). AMDA and
 222 3Dview are developed by the CDPP (Centre de Données de la Physique des
 223 Plasmas) and available to contributing developers under a GPLv3 licence.

224 3. Science cases

225 In this work we discuss two cases: (a) a classical textbook case under
 226 purely northward IMF conditions to obtain the characteristics of each code,
 227 and (b) a direct comparison with a pre-selected MESSENGER orbit.

228

229 3.1. Case a: Northward IMF

230 Northward IMF conditions are chosen to anticipate a stable dayside mag-
 231 netosphere structure. Typically, a southward IMF gives rise to more unstable
 232 magnetosphere conditions as continuous dayside magnetic reconnection in
 233 combination with a relatively short Dungey cycle does not allow the system
 234 to relax [12]. In the case of a northward IMF, the reconnection sites move to
 235 high latitudes near the magnetospheric cusps.

236

237 We set the typical solar wind condition around 0.3 AU, e.g., IMF magni-
 238 tude to 20 nT and adopt a solar wind proton density of 30 cm^{-3} , an Alfvén
 239 Mach number of 5 and a total plasma beta (β) of 1.3. The solar wind speed
 240 measures 400 km s^{-1} [55, 9]. The MHD models assume a total density equal to
 241 the proton density, whereas the plasma temperature (43 eV) is set to the sum
 242 of the electron (21.5 eV) and proton (21.5 eV) temperatures (Table 2) [56, 57].

243

244 3.2. Case b: MESSENGER comparison

245 We select a MESSENGER orbit that allows a simulation setup as close
 246 as possible to our theoretical northward IMF case. Due to its mid-day to
 247 midnight orientation (X-Z plane), orbit 1415 (November 8, 2012) provides a

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

	Case (a) Northward IMF	Case (b) MESSENGER
Planetary radius R_M [km]		2440
Planetary dipole moment [nT $\times R_M^3$]		200
Northward dipole offset [km]		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 Magnetosonic Mach number	3.5	8.5
IMF (X,Y,Z) components [nT]	(0, 0, +20)	(25, -6, 4.9)
IMF magnitude [nT]	20	26.6

248 close comparison. The orbit has a Disturbance Index of less than 25 [58],
 249 the lowest magnetic activity quartile, the Z-components of the IMF at the
 250 inbound an outbound bow shock crossings are positive and within 2 nT of
 251 each other, and the IMF variability along the entire orbit is less than 10 nT.
 252 Combining these parameter values indicate stable solar wind conditions.

253

254 We use the inbound part of the orbit to compute the average IMF vector
 255 to be inserted in our models. Further, the Alfvén Mach number is set to 5, the
 256 solar wind speed equals 459 km s $^{-1}$ and the proton and electron temperature
 257 measure 12 eV, and 18 eV, respectively [56, 59].

258 4. Results

259 4.1. Case a: Northward IMF

260 A purely northward IMF configuration provides a stable magnetosphere
 261 configuration. We let each model run for 5 minutes, that is, 5 Dungey cycles,
 262 to reach their respective quasi-stationary states.. Figure 1 shows the solar
 263 wind proton density maps in the $X - Z$ (top) and $X - Y$ (bottom) plane on
 264 a logarithmic scale, including also velocity lines. The two left panels are the
 265 results from the MHD codes while the two right panels present the results
 266 from the hybrid codes. All models have converged to a very similar global
 267 structure for the Hermean magnetosphere and the characteristic features are
 268 present: the shape of bowshock, the higher density magnetosheath, and the
 269 magnetospheric cusps. However, the models do not agree on the proton den-
 270 sity near the planet and inside the nightside magnetosphere. We also observe
 271 different locations of the magnetopause structure.

272

273 The $X - Z$ cut of AMRVAC (Figure 1, upper left-most panel) shows a less
 274 sharp shock structure at the bow shock, a low density dayside magnetosphere,
 275 patches of higher density close to the surface in the cusp (which is defined by
 276 the magnetic field topology) and tail regions, and an asymmetric structure
 277 for the nightside magnetosphere. The latter is uniquely present in AMRVAC.
 278 The model also has the largest magnetopause flaring angle among the four
 279 models. The $X - Y$ cut of AMRVAC (bottom left-most panel) shows the
 280 symmetric structure in the dawn-dusk plane. Yagi's MHD code in the $X - Z$
 281 plane (upper middle-left panel) presents a sharper bow shock as compared to
 282 AMRVAC, most likely due to the model's less diffusive scheme. In addition,

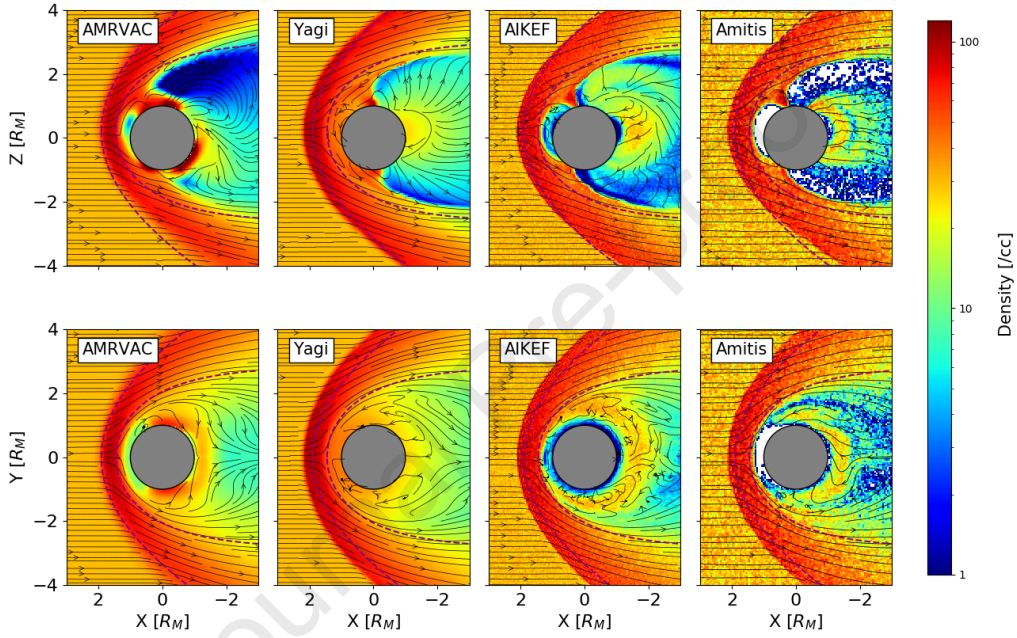


Figure 1: Maps of the solar wind proton density in the X-Z (top) and X-Y (bottom) plane at steady-state for the four simulation models under the northward IMF. The two panels on the left (right) are the results from the MHD (hybrid) codes. Length scales are normalized to the Mercury radius. Black arrows show the bulk velocity stream line and dashed two curves represent the averaged location of bowshock and magnetopause obtained by MESSENGER. [9]

283 the dayside magnetosphere is not dilute and houses a similar density as the
 284 magnetosheath. The nightside structure is more symmetric and slightly tilted
 285 northward. The density concentration we find near the tail region in the
 286 AMRVAC model is not present here. The $X - Y$ cut of Yagi's model (bottom
 287 middle-left panel) also shows symmetric structure. Compared to AMRVAC,
 288 AMRVAC shows more detailed structure than that of Yagi's. Finally, only
 289 Yagi's model results show a north-south symmetric cusp region. The $X -$
 290 Z cut of AIKEF (upper middle-right panel), similar to Yagi and Amitis,
 291 produces a sharp bowshock and a more dilute dayside magnetosphere region.
 292 Both hybrid codes concur on narrower cusps as compared to the MHD models
 293 which visually identified. The structure in the nightside is tilted slightly
 294 northward, similar to Yagi's model. AIKEF in the $X - Y$ plane (bottom
 295 middle-right panel) show small asymmetric structure in the density, e.g.,
 296 higher density inside the magnetosphere in the dawnside while lower density
 297 appears in the duskside.

298 Amitis does not employ any smoothing routines. Operating with a lower
 299 number of particles per cell as compared to AIKEF, the density maps in the
 300 $X - Z$ plane (upper right-most panel) therefore seem to contain more numer-
 301 ical noise. However, the bowshock and magnetopause are clearly captured
 302 and the solar wind plasma is denied from penetrating through the dayside
 303 magnetosphere as in the other simulations. The narrow cusp structure is
 304 similar to the results from AIKEF. The density configuration at the night-
 305 side of the planet seems to tend to northward. On the contrary to AIKEF,
 306 the $X - Y$ cut (bottom right-most panel) shows the opposite trend, e.g., the
 307 dayside magnetosphere seems to tend to dawnward while in the nightside

308 there is denser plasma close to the surface.

309

310 In order to quantify the differences between the four models, Figure 2
 311 presents the pressure profile along the subsolar line (X-axis). The dynamic
 312 and magnetic pressure are extracted and the locations of the bowshock and
 313 magnetopause have been identified. The four panels correspond to the four
 314 simulations. The solid lines show the dynamic (ram) pressure, $\rho \mathbf{v}^2$ where ρ
 315 and \mathbf{v} indicate the plasma density and the bulk velocity of the upstream solar
 316 wind, while the dashed lines represents the magnetic pressure, $B^2/2\mu_0$ where
 317 B and μ_0 denote the magnetic field magnitude and the vacuum permeability,
 318 respectively. The gray dash-dotted line is the magnetic pressure produced
 319 by an uncompressed dipole magnetic field with the same dipole moment as
 320 the models, providing information on how much the planetary magnetic field
 321 is compressed by the solar wind in each simulation run. The gray vertical
 322 line at $x = 1.12 R_M$ indicates the point where the dynamic pressure equals
 323 the uncompressed magnetic pressure and serves as a reference for the mag-
 324 netopause location. For each model, the position of the bow shock (BS) has
 325 been identified as the maximum current density (red vertical solid line). The
 326 location of the magnetopause (MP; red vertical dashed line) has been identi-
 327 fied in three different ways: (1) using the position of the most distant closed
 328 planetary field line that crosses the X-axis, (2) using the position where the
 329 gas and magnetic pressure are equal, and (3) using the position where the
 330 current density has its maximum. All three methods were in excellent agree-
 331 ment for all four models (Table 3).

332

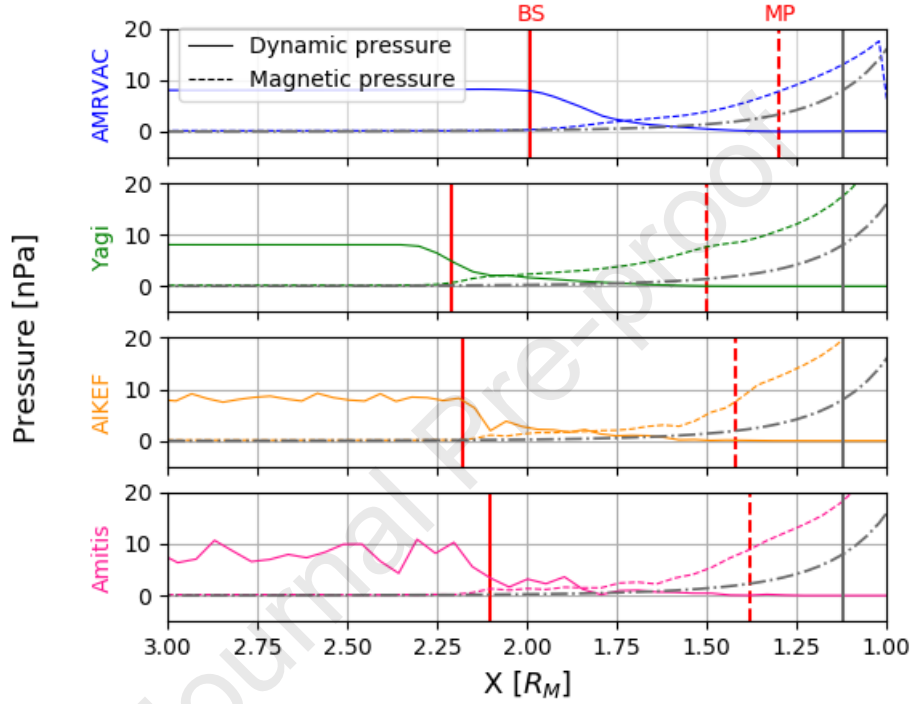


Figure 2: Dynamic (ram) and magnetic pressure profiles along the X-axis (Sun-Mercury direction) from $3 R_M$ upstream to the planet surface on the dayside for the four simulation codes. The results from the two MHD codes are shown on the top two panels and the hybrid model results on the two bottom panels. 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 in the case of a radially diminishing magnetic field.

Table 3: Bow shock and magnetopause locations at the subsolar point, and the thickness of the magnetosheath for the four simulation models.

		BS [R_M]	MP [R_M]	Sheath thickness [R_M]	Grid size in X[R_M]
MHD	AMRVAC	1.99	1.30	0.69	0.06
	Yagi	2.21	1.50	0.71	0.05
Hybrid	AIKEF	2.18	1.42	0.76	0.04
	Amitis	2.10	1.38	0.72	0.05
Mean value		2.12	1.40	0.72	
Standard Deviation		0.085	0.072	0.026	

333 The locations of both the bow shock and magnetopause vary among the
 334 models with a range of $0.23 R_M$ and $0.2 R_M$, respectively (Figure 2 and Ta-
 335 ble 3). The mean position of the bow shock and magnetopause is found at
 336 $2.12 R_M$, and $1.40 R_M$, with a standard deviation of $\sigma = 0.085$ and $\sigma = 0.072$.
 337 The variation of the magnetopause location is greater than that of the bow
 338 shock as the former is more sensitive to the boundary condition applied at
 339 the surface and inside the planet. In an effort to eliminate the effects of the
 340 numerical implementation for comparison purposes, we compute the average
 341 thickness of the magnetosheath and find $0.72 R_M$ with a standard deviation of
 342 0.026 . Thus, differences among models are small and within the uncertainty
 343 defined by the grid resolution. Note that the mean BS and MP locations
 344 simulated here with a purely northward IMF are within the ranges measured
 345 by MESSENGER [9].

346

347 In addition to the bow shock and magnetopause locations along the sub-
 348 solar line, we further characterize the Hermean magnetosphere by means of

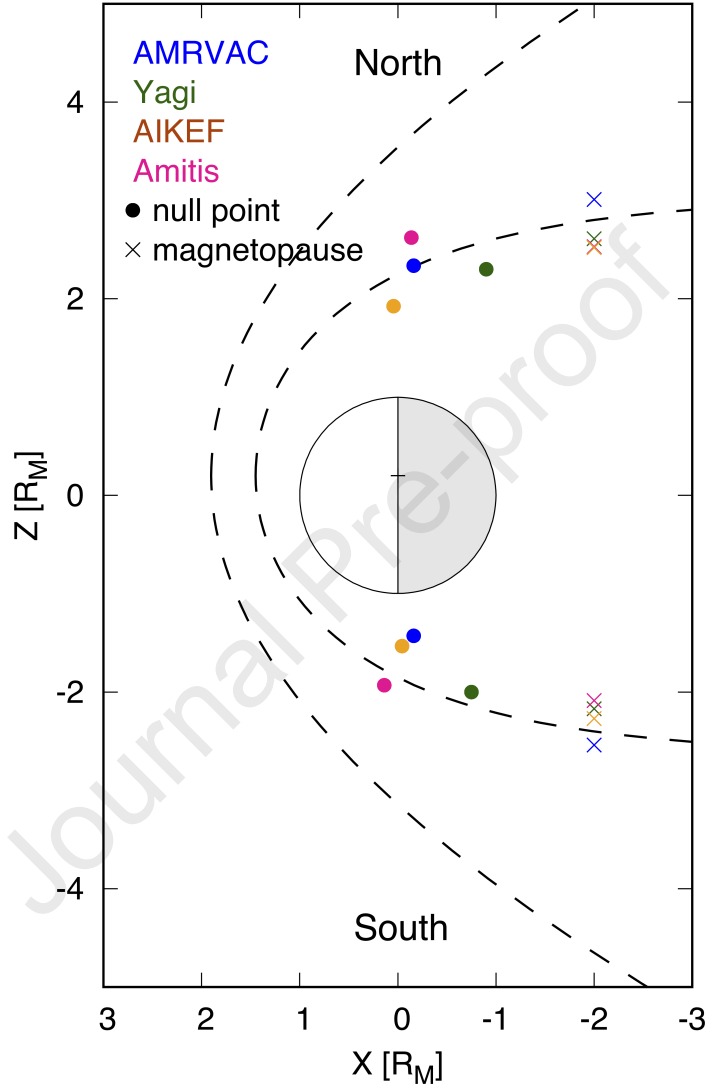


Figure 3: The locations of null points (colored circles) and magnetopause (colored crosses) in the X-Z plane. The dashed lines show the bow shock and magnetopause models defined by Slavin et al. [60] and Shue et al. [61], respectively. The magnetopause paraboloid has parameters $R_{ss} = 1.45 R_M$ and $\alpha = 0.5$. The bow shock model parameters are $p = 2.75 R_M$, $\epsilon = 1.04$, and $X_0 = 0.5 R_M$.

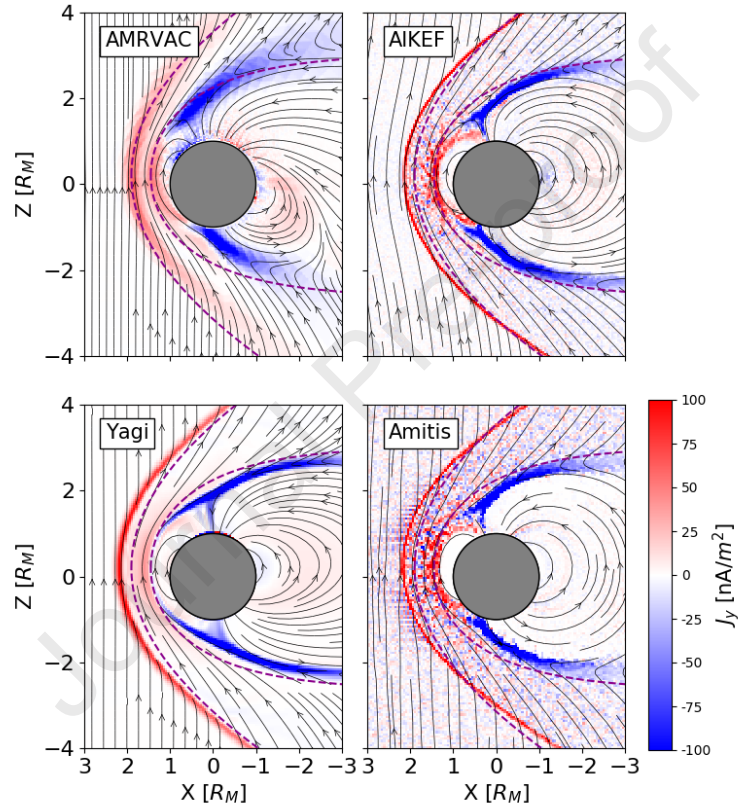


Figure 4: The y component of the current density in $X - Z$ plane. Black lines with arrow represent the magnetic field line and dashed purple lines are the empirical models of bowshock and magnetopause.

349 the reconnection sites. Figure 3 shows a map in the $X - Z$ plane with its
 350 origin at the center of the planet. For reference, the two gray dashed lines
 351 represent the bow shock and magnetopause locations as predicted by the
 352 models of Slavin et al. [60], Shue et al. [61], Winslow et al. [9]. The positions
 353 of the reconnection sites, i.e. the null points, identified from the simulated
 354 magnetic field structure by our four models are indicated with full colored
 355 circles. The locations of the magnetopause at $X = -2 R_M$ are represented
 356 with colored crosses. On average, the null points near the northern cusp are
 357 located more towards the nightside, whereas the null point near the south-
 358 ern cusp are clustered more towards the terminator plane (with exception of
 359 Yagi's model). Due to the dipole offset towards the north, the southern null
 360 points are closest to the planet. Note that apart from the chosen plasma field
 361 conditions also various code-specific parameters, such as numerical resistivity,
 362 may play a role in where the reconnection sites develop. AMRVAC shows the
 363 largest north-south asymmetry on the location of null points, which is consis-
 364 tent with the tilted magnetic structure seen in Figure 1. The locations of the
 365 magnetopause on the nightside of the planet are obtained from the gradients
 366 of the density and the current density. With the exception of AMRVAC,
 367 these are located within the reference magnetopause model ($R_{ss} = 1.45 R_M$
 368 and $\alpha = 0.5$ where R_{ss} is the magnetopause distance at the subsolar and α
 369 is the flaring parameter [61, 9]). Given the purely northward IMF, all four
 370 simulations can be considered in good agreement with the reference models.

371

372 Lastly in this section, the y-component of the current density in $X -$
 373 Z plane is presented in Figure 4. Since the IMF is purely northward in

374 this case, we have highlighted only the y -component of the current density.
375 Overall, 4 models show similar appearances, i.e., the current enhancement at
376 the bowshock, positive current at the dayside magnetopause while negative
377 current generated along the magnetopause in other region. AMRVAC shows
378 the thicker layer at the bowshock and magnetopause, which is likely due to
379 the lower grid resolution and Yagi's less diffusive numerical scheme, however,
380 on the other hand, shock locations in dayside are in good agreement with
381 the empirical models. Yagi's code shows sharp current structure than that
382 of AMRVAC and since the magnetic field structure is more symmetric in the
383 nightside, the current structure also shows more symmetric feature. Although
384 both two hybrid codes show more busy figure because they treat ions as
385 the particles, it is difficult to see the peak at the dayside magnetopause.
386 Compared to Figure 1, since the density inside the dayside magnetosphere
387 in AIKEF is low, those ions do not affect to the current system.

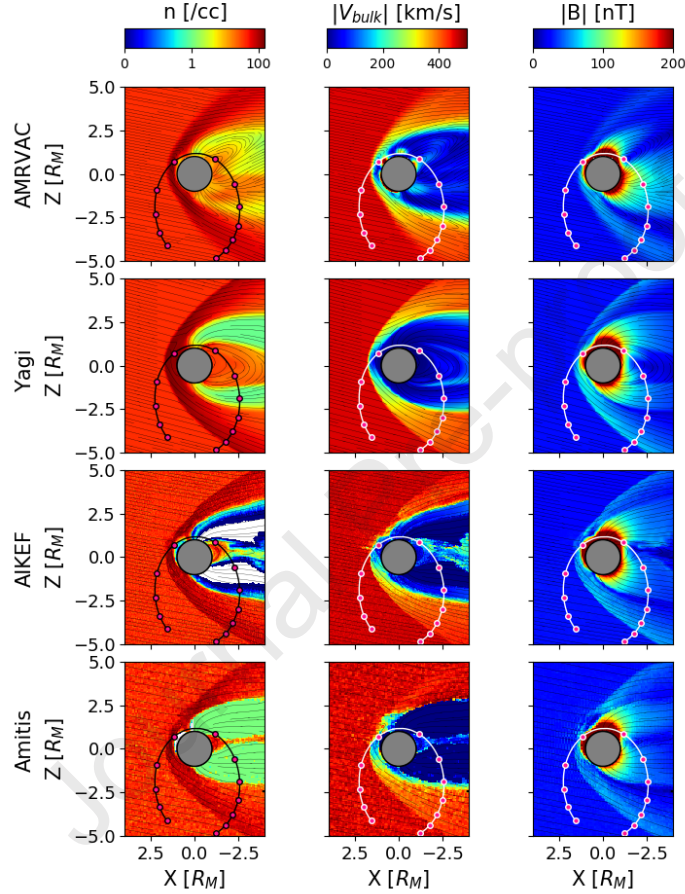


Figure 5: The overview of case b , from left to right, the panel shows the plasma density, bulk velocity, and magnitude of the magnetic field in $X - Z$ plane with magnetic field lines. MESSENGER trajectory is marked every 30 min. In this orbit, MESSENGER was first crossing the boundaries in the southern hemisphere, moving into the nightside magnetosphere.

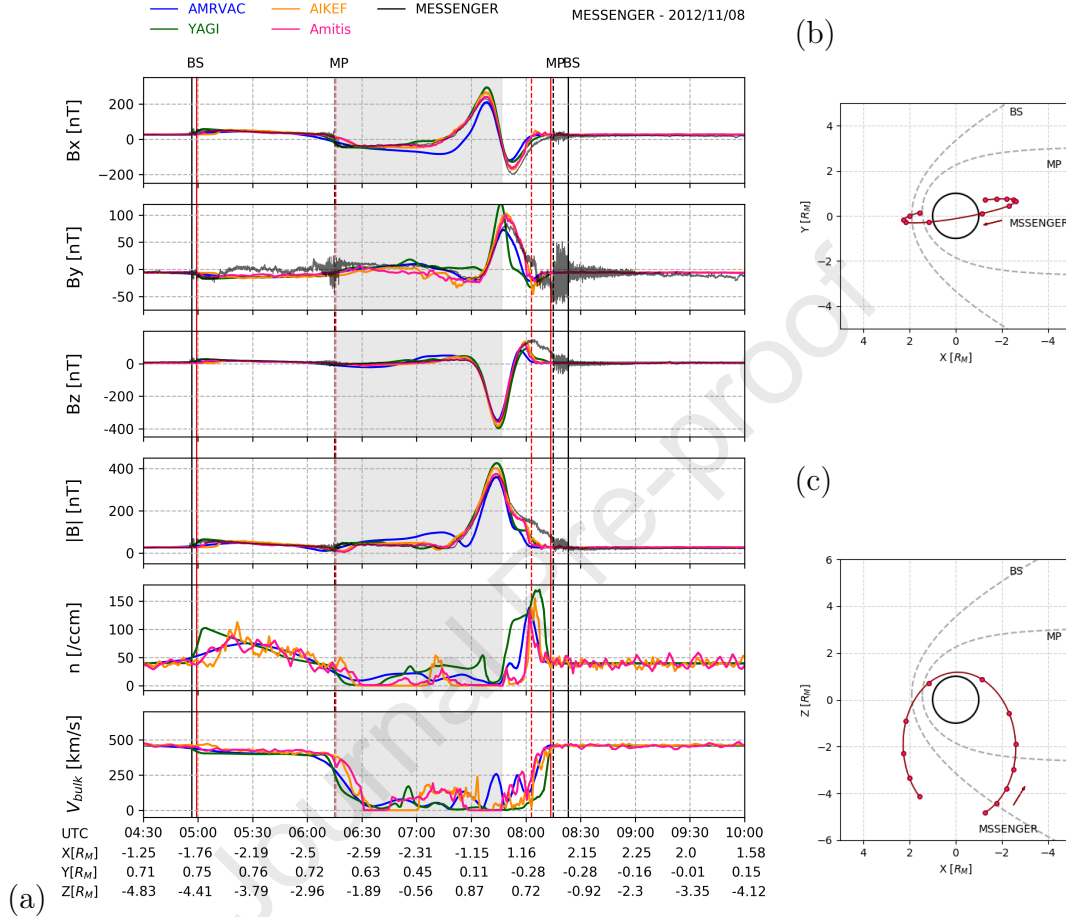


Figure 6: (a) Modeled and observed magnetic field and modeled particle data along orbit 1415 of MESSENGER. Blue, green, orange, and red lines shows the results from AMRVAC, Yagi, AIKEF and Amitis, respectively. The black lines shows the magnetometer data measured by MESSENGER. The bow shock (BS) and 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, respectively. The nightside magnetosphere is indicated by a gray background. (b) and (c): the trajectory of MESSENGER spacecraft in $X-Y$ and $X-Z$ plane, respectively and the dots indicate 30 minute intervals of the MESSENGER trajectory.

388 *4.2. Case b: MESSENGER comparison*

389 Figure 5 presents overview of the plasma density, the bulk velocity, and
 390 the magnetic field in $X - Z$ plane with the MESSENGER trajectory. All
 391 model results indicate similar features and magnitudes especially in the day-
 392 side magnetosphere. Interestingly, two hybrid models show the perturbed
 393 northern magnetopause. Figure 6 presents the magnetic field, density and
 394 plasma velocity profile along MESSENGER orbit 1415, on 8th of November,
 395 2012, from 4:30 UT to 10:00 UT (see also section 3.2). The spacecraft en-
 396 tered the magnetosphere at the nightside along a south- to north-trajectory,
 397 roughly in the meridian plane with its closest approach near the magnetic
 398 north of Mercury, thus crossing the bow shock and magnetopause twice. Four
 399 vertical black lines indicate the bow shock and magnetopause locations for
 400 both the inbound and outbound crossings observed by MESSENGER. Su-
 401 perimposed on their respective panels are the simulated profiles from Case *a*
 402 along the same trajectory. The red vertical lines are the averaged simulated
 403 shock crossings from the four models. Overall, our models are in close agree-
 404 ment with the MESSENGER data for the inbound part of the orbit. With
 405 time differences of up to 12 min, equal to $\sim 0.28 R_M$ along the spacecraft tra-
 406 jectory for the inbound orbit, and 17 min ($\sim 1.1 R_M$) for the outbound orbit,
 407 the locations of the BS and MP agree less well for the outbound section of
 408 the MESSENGER orbit. The BS locations match better for the inbound
 409 part of the orbit.

410

411 The variations of the magnetic field along the trajectory seem to be in
 412 good agreement among codes and with MESSENGER data, while more per-

413 turbed variations in density and bulk velocity profiles. The small fluctuations
414 in two hybrid are results of particle noises.

415 Since we used the inbound part of the orbit to constrain the upstream
416 plasma parameters to initialize the simulations, it is possible that variations
417 in the solar wind dynamic pressure during the orbit may be responsible for
418 the larger discrepancy in the outbound part of the orbit. Interestingly, there
419 are distinct differences between the MHD and the hybrid codes (panel 4 of
420 Figure 6). Around 7:50 UT, when the spacecraft is inside the dayside magne-
421 tosheath, the results from the two hybrid simulations are in agreement with
422 the observations, while both MHD models predict a lower magnetic field in-
423 tensity. The spacecraft passes through the northern cusp and then moves
424 towards the dayside region. At 8:10 UT, near the peak density, we find the
425 compressed magnetosheath plasma. As expected, also the density and veloc-
426 ity profiles predicted by the hybrid codes show steeper profiles at the shock
427 crossing compared to the MHD models.

428

429 5. Discussion

430 5.1. Case b: MESSENGER comparison

431 Due to the limited particle instrumentation on board the single-spacecraft
432 MESSENGER mission, it is not possible to constrain the exact solar wind
433 plasma parameters to set up a comparison simulation. More precisely, be-
434 cause the particle instrument onboard MESSENGER was protected by the
435 sun shield and thus it had a limited field of view, this condition prevented the
436 instrument from observing the majority of solar wind. Therefore, density and

437 velocity, temperature of solar wind cannot be derived and those parameters
438 must be assumed when input parameters were considered [62] In addition,
439 the solar wind varies in time and may even be changing significantly while
440 MESSENGER crosses the magnetosphere. This may be the reason for some
441 of the discrepancies between simulated and measured profiles. In Figure 7
442 we compute the difference between the observed and modeled magnetic fields
443 along our chosen MESSENGER orbit. We exclude the time frame between
444 the two MP crossings (from 6:15 UT to 7:45 UT) while MESSENGER passed
445 the nightside region of the magnetosphere (indicated by a gray background),
446 to focus on the cusp and boundary layer locations.

447

448 Just before 5:00 UT, MESSENGER crosses the BS for the first time,
449 about 3 min before the predicted averaged time stamp from our models. Con-
450 tinuing along the trajectory, both the modeled X- and Z-component agree
451 well with MESSENGER, whereas the models underestimate the magnetic
452 field contribution by roughly 15 nT along the Y direction. Our models agree
453 on the inbound MP crossing time at 6:15 UT within a 5 min time range. At
454 7:50 UT, when MESSENGER moves from the nightside to the dayside in the
455 northern hemisphere, all four models predict a magnetic pile-up, although
456 none of the models fully reproduces the fine-scale structure. Immediately
457 following the pile-up, the models underestimate the magnetic field strength
458 by roughly 100 nT. Note that the different profiles in Figure 6 show no real
459 ‘winner’ among the four simulation models as all codes show different small-
460 scale discrepancies with the MESSENGER measurements at the boundaries
461 between the distinct plasma regions of Mercury’s magnetosphere. It shows

462 the need for a multi-spacecraft mission, such as BepiColombo, to simulta-
463 neously measure the local Hermean and upstream plasma environment in
464 order to fine-tune the inputs to numerical models and in turn characterize
465 Mercury’s global plasma environment.

466

467 *5.2. Virtual sampling along Mio/MPO orbits*

468 One of the major goals of the SHOTS project, next to comparing differ-
469 ent simulation approaches with available MESSENGER measurements, is to
470 help prepare the community for the forthcoming BepiColombo mission by
471 making available a catalog of simulation that showcases the plasma struc-
472 ture and dynamics of Mercury’s magnetosphere under different solar wind
473 conditions. In the first step of this project, we chose four different (MHD
474 and hybrid) simulation models. Figures 8 and 9 show the plasma character-
475 istics expected along a typical Mio and MPO orbit, respectively, during the
476 planned nominal orbital phase of BepiColombo. We chose the upstream solar
477 wind conditions identical to the MESSENGER case studied above (Case *b*
478 in Table 2). For ease of comparison, the orbital plane is set perpendicular
479 to the X direction, corresponding to BepiColombo’s operations planned for
480 April 4, 2026. During this period, both Mio and MPO remain inside the
481 magnetosphere and the plasma environment will be fully observed by the
482 magnetometers on board Mio and MPO [63, 64], the Mercury Plasma Parti-
483 cle Experiment (MPPE) [65] and the Plasma Wave Investigation (PWI) [66]
484 onboard Mio, and the Search for Exospheric Refilling and Emitted Natural
485 Abundances (SERENA) on board MPO [67].

486

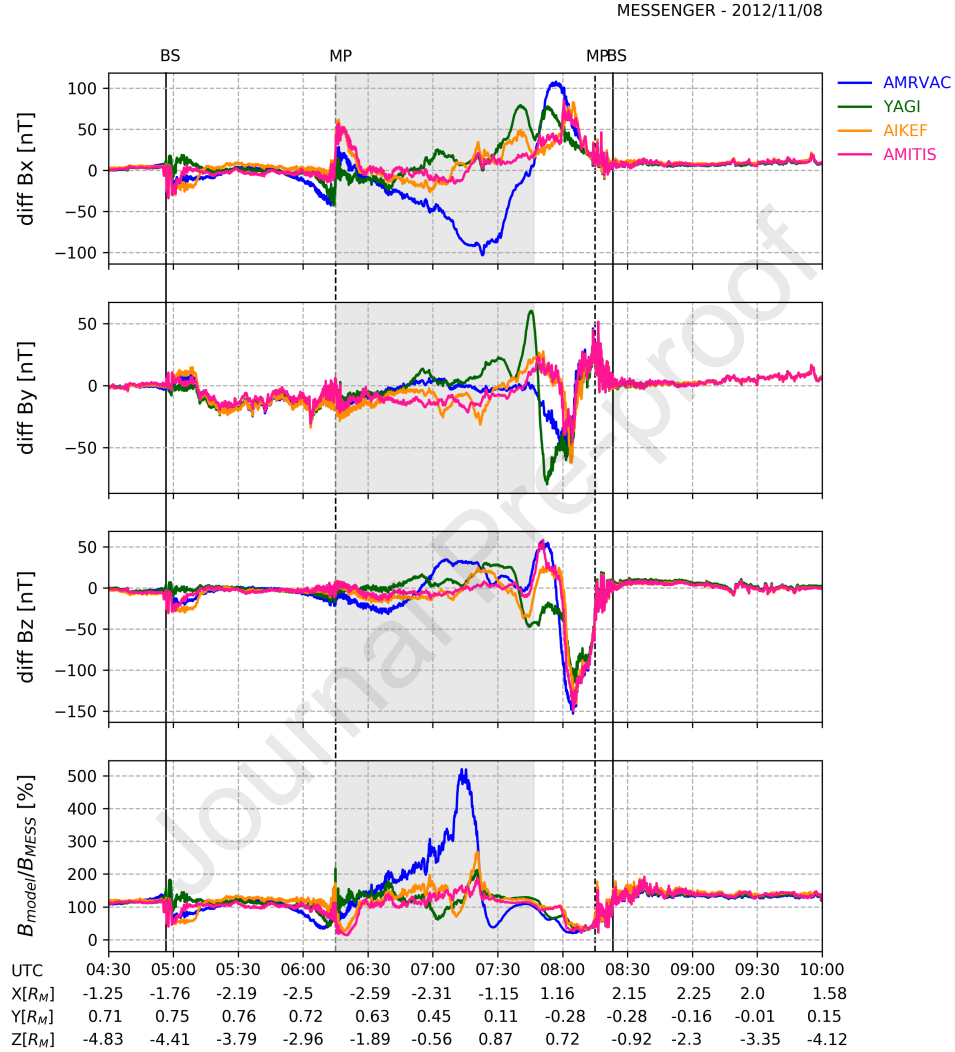


Figure 7: Difference between the simulation results and the MESSENGER magnetic field measurements ($B_{model} - B_{MESS}$). The bow shock (BS) and magnetopause (MP) crossings identified from the observations are indicated with a vertical solid and dashed line, respectively and the region MESSENGER passing through inside the nightside magnetosphere is indicated by a gray background.

487 In both Figures 8 and 9 the solid vertical lines indicate the southern
488 (T_S) and northern (T_N) terminator crossing and the dashed vertical line is
489 the time when the spacecraft crosses the sub-solar point (SSP). During this
490 period, Mio will be moving along the frontside magnetopause (from 15:15
491 UT to 15:35 UT) where our models predict an enhancement of the magnetic
492 field intensity and plasma velocity. Note that the predicted profiles closest to
493 the planet are not in agreement, possibly due to the numerical treatment of
494 the planetary boundary condition (see also Figure 1). Next, Mio will move
495 across the cusp region and re-enter the nightside magnetosphere from the
496 north. Large discrepancies among models around the subsolar point to the
497 northern terminator can be explained by the orbit of the Mio spacecraft.
498 Since Mio is moving along the magnetopause, different locations of the mag-
499 netopause in each model are critical. Mio is clearly inside the magnetopause
500 in AIKEF and Amitis around the subsolar point but probably not in Yagi
501 and AMRVAC. After crossing subsolar point around 15:17 UT, the density
502 and velocity profiles diverge. A similar trend is not visible in the magnetic
503 field predictions. This may be the region where the ion dynamics has the
504 largest impact, i.e., the finite Larmor radius effect of particle must be taken
505 into account in the magnetosheath, hence producing the largest differences
506 between the hybrid and MHD models.

507

508 MPO will orbit significantly closer to the planet. The spacecraft will leave
509 the southern magnetosphere via the nightside, then crosses the terminator
510 and enters the dayside magnetosphere. Just before 15:00 UT and around
511 15:35 UT, the two hybrid models and AMRVAC predict a significant density

512 enhancement, indicating the presence of trapped particles while Yagi show
513 significantly different appearance. In Yagi's model, the dayside magneto-
514 sphere is not clearly seen (see Figure 5), and thus, the spacecraft seems to
515 observe rather the magnetosheath component than the component inside the
516 magnetopause at the time between 14:30 UT to 14:50 UT. The spacecraft
517 passes through the cusp region (light blue areas in Figure 9). MPO's tra-
518 jectory will be most useful to better understand the structure and dynamics
519 of the magnetosphere closest to the planet and in particular near the south-
520 ern hemisphere. This region has been explored less due to MESSENGER's
521 highly inclined and eccentric orbit.

522

523 Sampling the virtual orbits of Mio and MPO for a variety of solar wind
524 parameters and/or models, we will be able to predict when the spacecraft
525 most likely cross the cusp, the plasma sheet and the shocked regions within
526 certain margins. These margins depend on the characteristics of the sim-
527 ulation and the physical processes included in the model. The combined
528 measurements from the two spacecraft will provide a wealth of information
529 on the Hermean plasma environment, however, to reproduce adequately the
530 environment in 3D, numerical 3D models are essential. Thus, making predic-
531 tive simulations with the information by combined spacecraft measurements
532 a necessity to maximize the scientific return of the mission. To this effect, the
533 simulation domain needs to be extended farther downstream of the planet
534 to capture better the magnetotail region. Also temporal information needs
535 to be included. In this study, our hybrid models have not implemented its
536 tenuous exosphere based on the previous works [23, 33] that shows Mercury's

537 exosphere is tenuous enough to not significantly affect on Mercury's magne-
538 topheric system. Our first goal was to purely compare between MHD and
539 hybrid simulations so that we see the ion kinetics. However revealing the role
540 of the exosphere is also the one of the key questions of Mercury's science. It
541 will be investigated further in near future. Finally, also Particle-In-Cell and
542 Vlasov simulations that include the electron dynamics are needed.

543

544 **6. Conclusions**

545 We have compared the results of four different (MHD and hybrid) global
546 simulation models with the same input parameters to simulate the solar wind
547 interaction with Mercury's dayside magnetosphere. Because the effect of the
548 existence of its tenuous exosphere is small to affect the structure of Mercury's
549 magnetosphere, the exosphere has not been implemented in our models. All
550 our models produced a similar global structure in the dayside consistent with
551 empirical (analytical) fits for the locations of the bow shock and the mag-
552 netopause. In contrast to the dayside magnetosphere, although it is out of
553 our scope, the magnetic field configuration in the nightside magnetosphere
554 differs among models, and the plasma distribution and bulk velocity close
555 to the surface are also different. The significant difference between MHD
556 and hybrid models is not seen in this study, thus, the differences between
557 the simulations predictions seem to be caused numerically, i.e., the planetary
558 boundary conditions, different size of the grid, numerical scheme, rather than
559 the self-consistent ion kinetics included in the model.

560

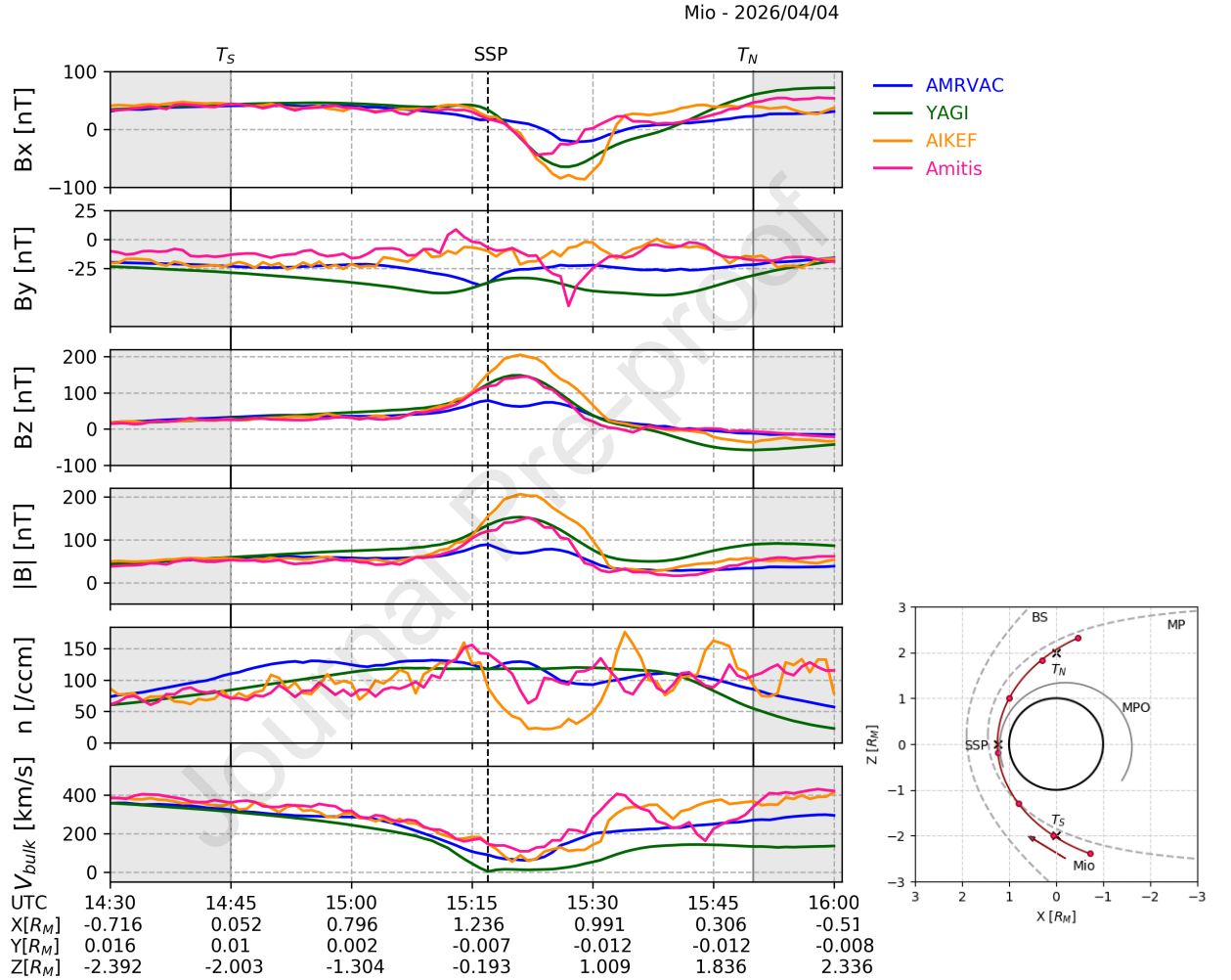


Figure 8: Magnetic field and particle data along a representative Mio orbit. The red dots along the trajectory in the inset panel show the position of the spacecraft along 15 min intervals. The solid vertical lines indicate the crossing of the southern (T_S) and northern (T_N) terminator, the dashed vertical line is the time when the spacecraft crosses the subsolar point (SSP). The nightside region ($X < 0$) is indicated by a gray background.

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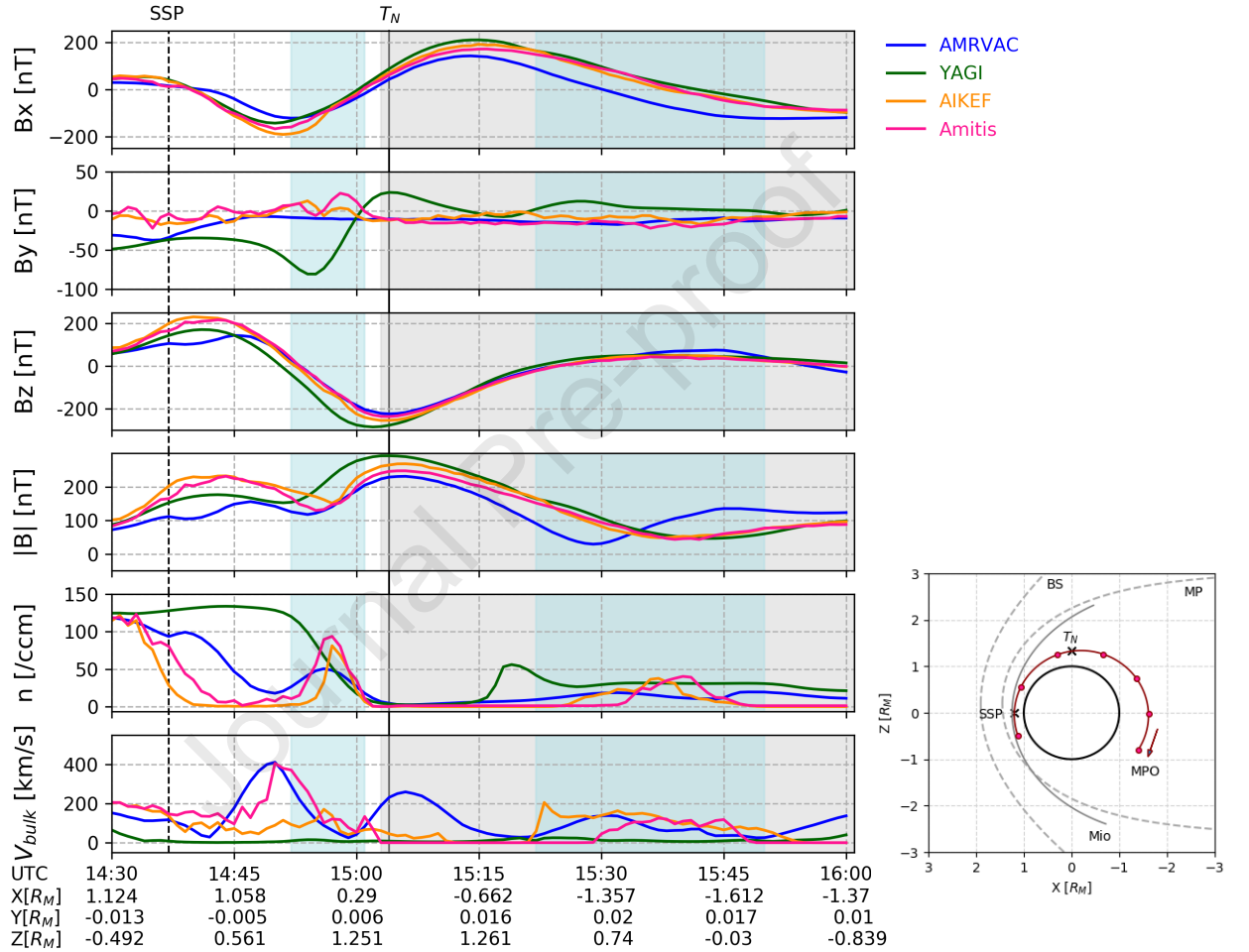


Figure 9: Magnetic field and particle data along a representative MPO orbit. The red dots along the trajectory in the inset panel show the position of the spacecraft along 15 min intervals. The solid vertical lines indicate northern (T_N) terminator and the dashed vertical line is the time when the spacecraft crosses the subsolar point (SSP). The nightside region ($X < 0$) is indicated by a gray background.

561 We cross-compared our results with a theoretical northward IMF scenario
562 (Case *a*) and MESSENGER orbit 1415 (Case *b*), indicated to have stable so-
563 lar wind conditions with a northward IMF similar to the theoretical case. In
564 Case *a*, the standard deviations for the predicted mean locations of the bow
565 shock, magnetopause and the thickness of magnetosheath are small. For Case
566 *b*, during the inbound part of the orbit, time differences for the bow shock
567 and the magnetopause crossings are found up to 12 minutes, corresponding
568 to a distance along the orbit of $0.28 R_M$. For the outbound section of the
569 orbit, the maximum time difference increased to 17 minutes, equivalent to
570 $1.1 R_M$.

571

572 One of the major goals of SHOTS is to prepare a catalog of simulations
573 that can predict the plasma environment in- and outside the Hermean mag-
574 netosphere under different solar wind conditions, in this way contributing to
575 maximizing the scientific return of the forthcoming BepiColombo observa-
576 tions. Here, for the first time, we have extracted the data from our mod-
577 els along representative Mio and MPO orbits. A long-lasting project-based
578 and community-wide effort will be important both for the forthcoming Bepi-
579 Colombo's Mercury flybys and during its nominal orbital phase.

580

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604

605 All data necessary to validate the findings presented in this manuscript
606 can be found at https://github.com/jandeca/Aizawa_etal_PSS_2020 (DOI:
607 to be provided) in accordance with the Findability Accessibility, Interoper-
608 ability, and Reuse (FAIR) principles. The magnetometer data from the MES-
609 SENDER observations are available in the Planetary Data System (<https://>

610 //pds-ppi.igpp.ucla.edu).

611

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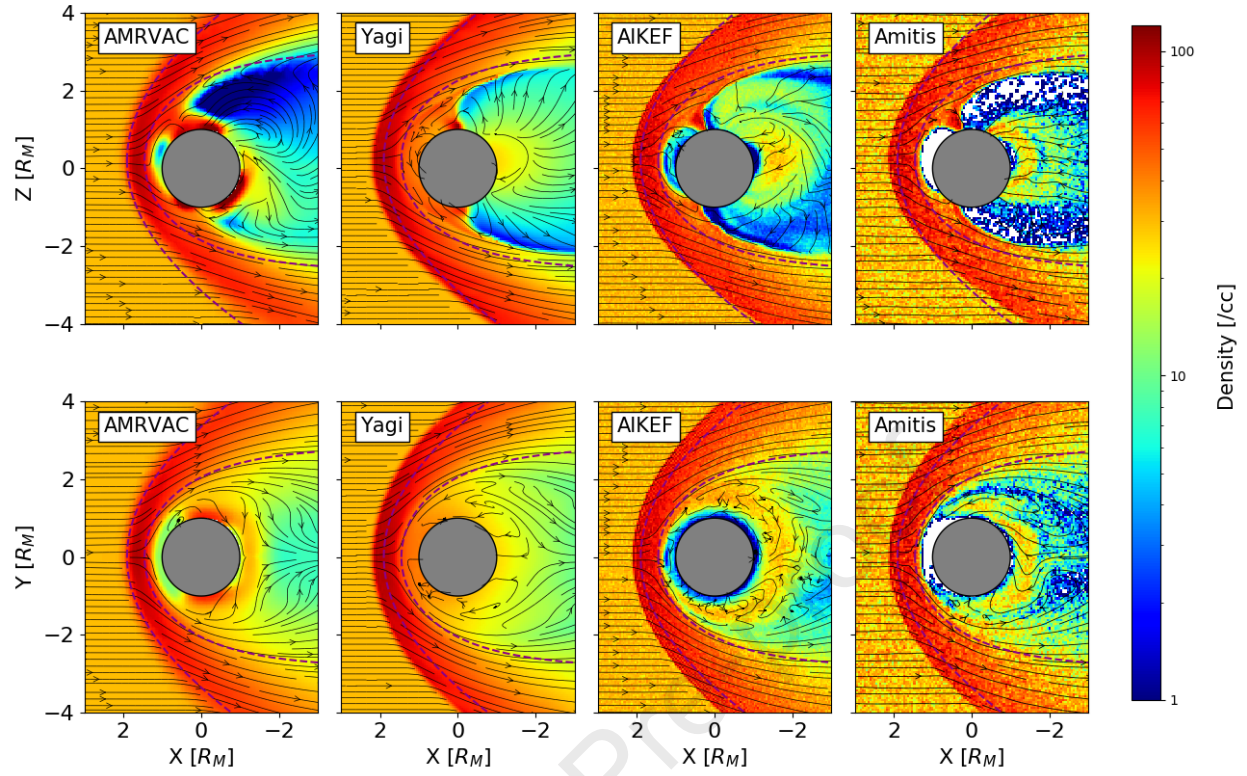
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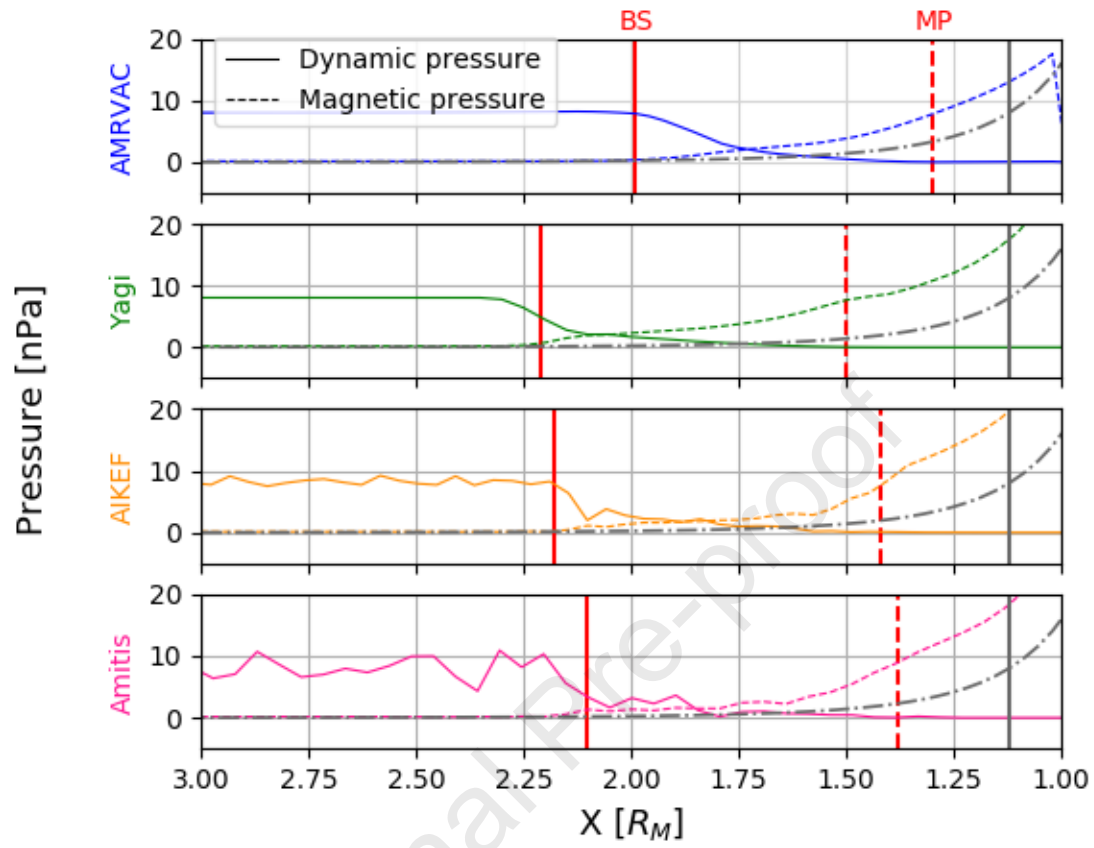
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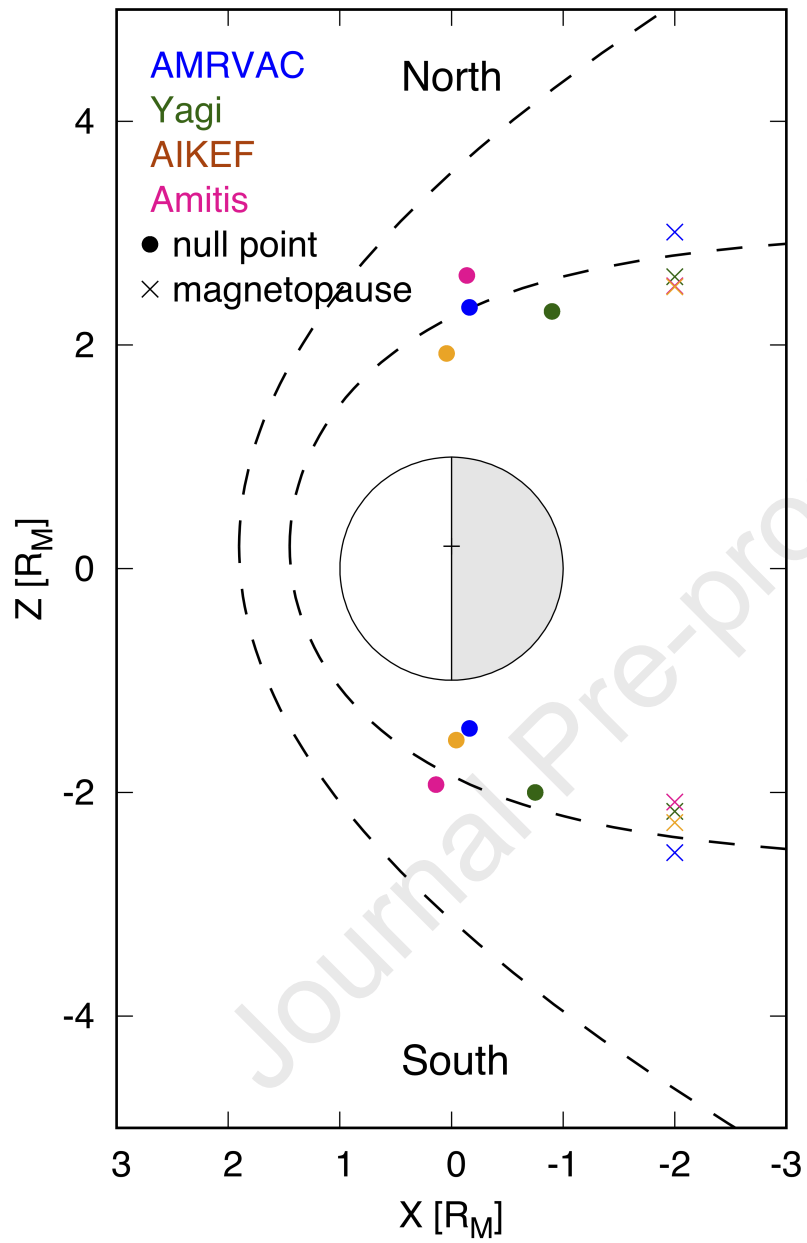
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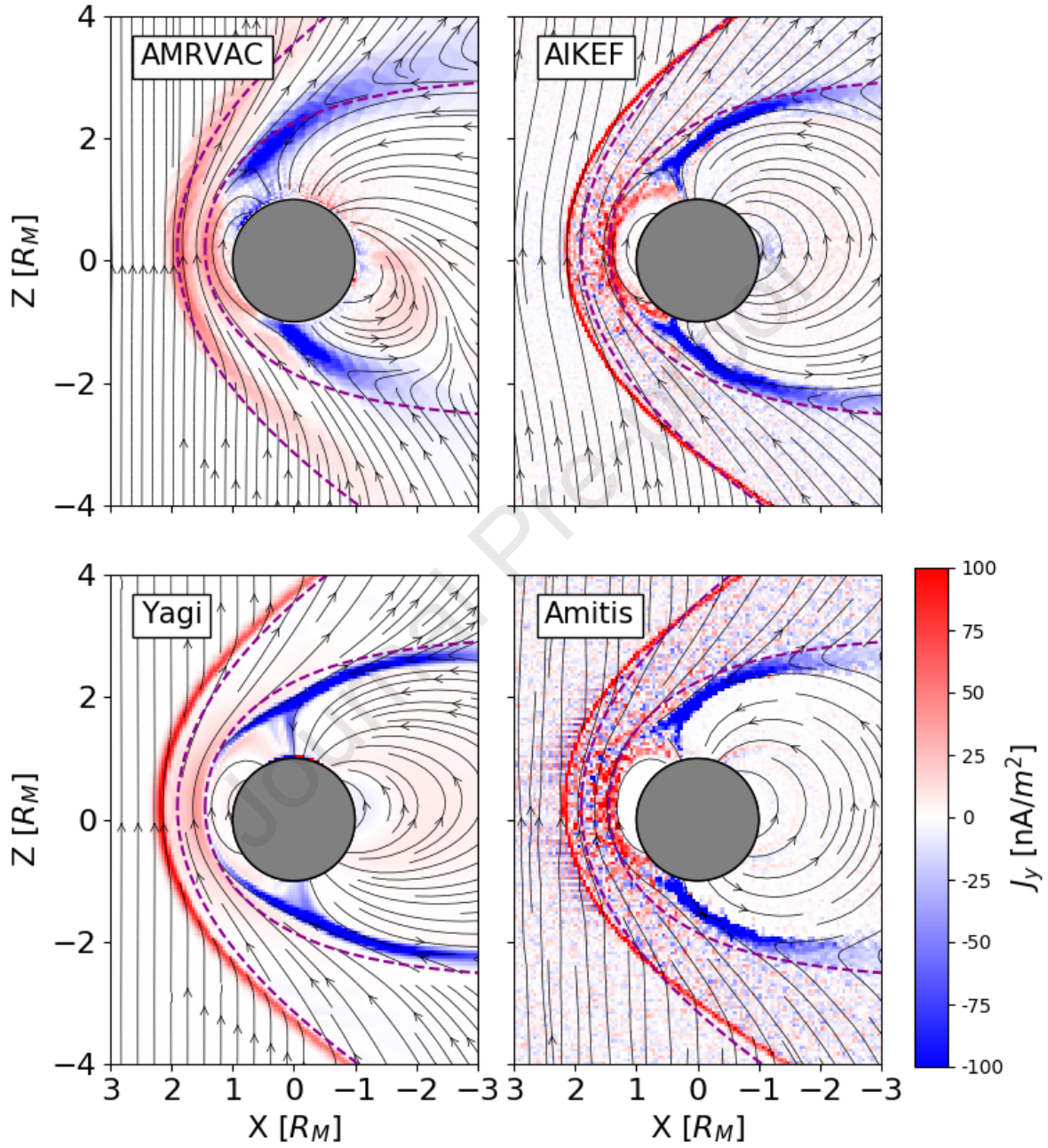
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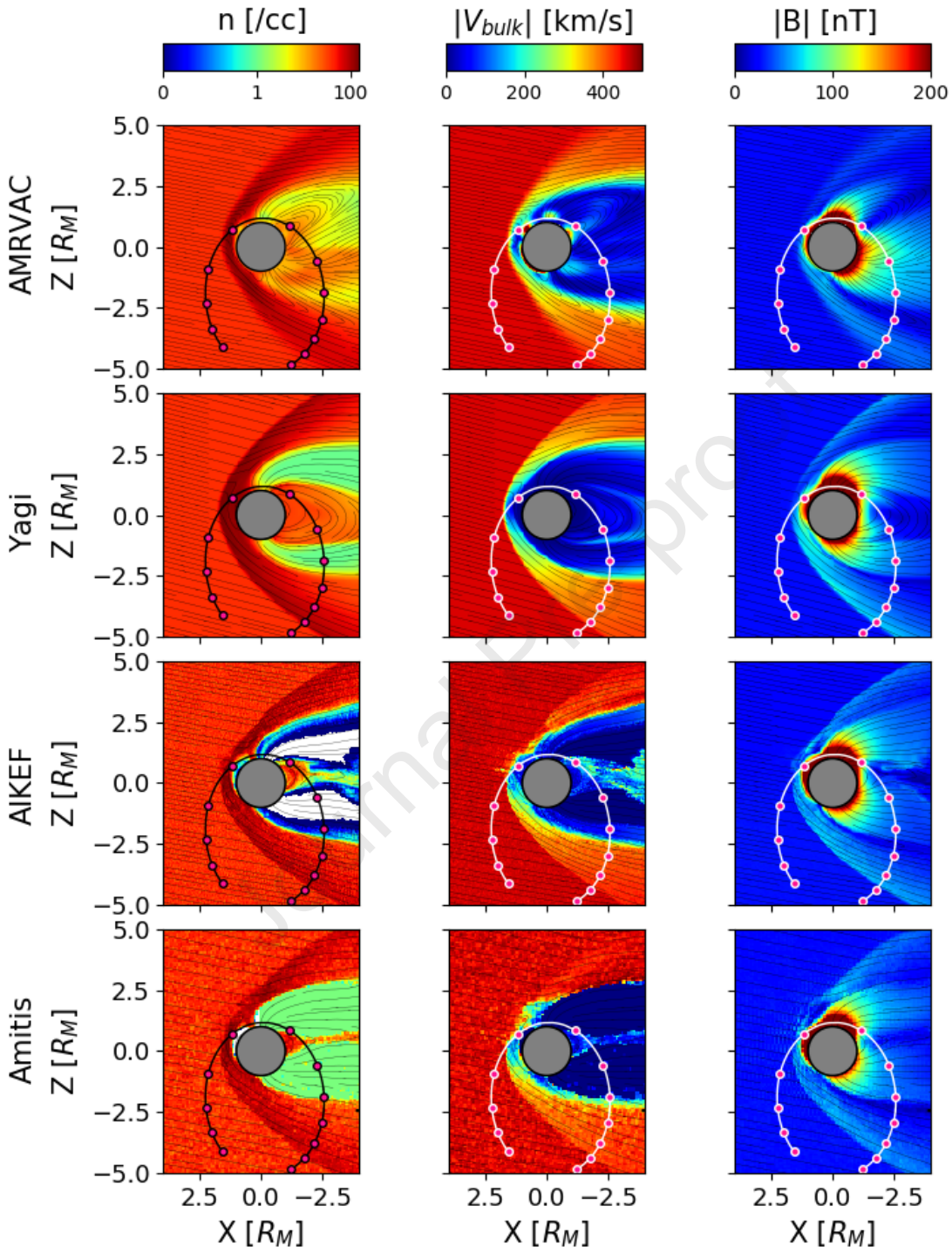
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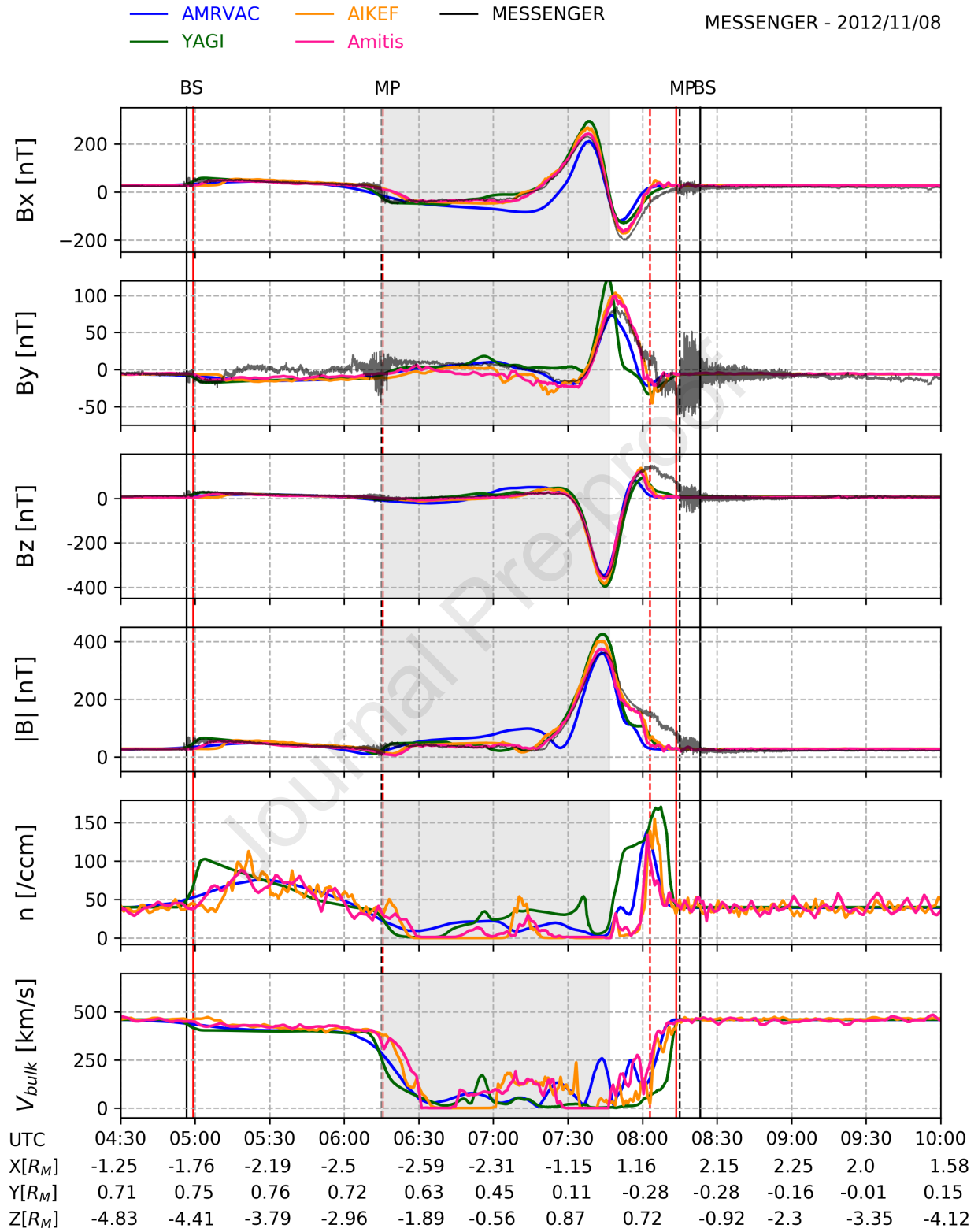


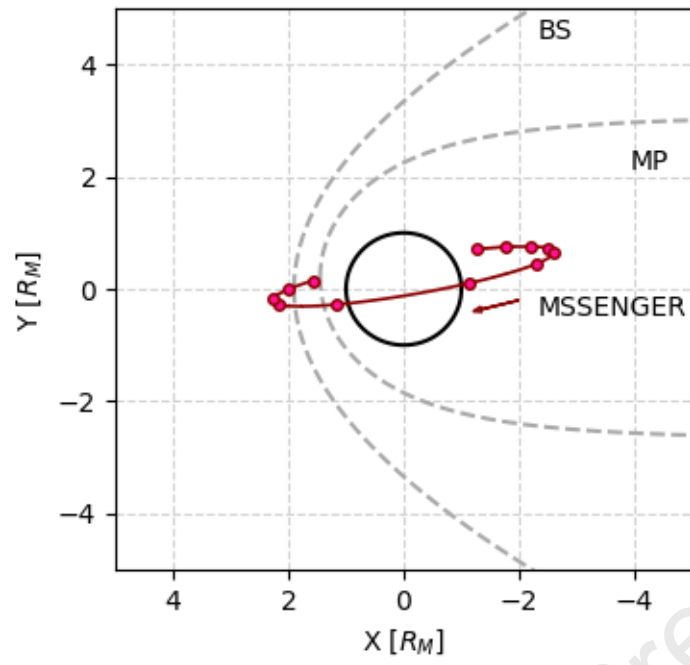


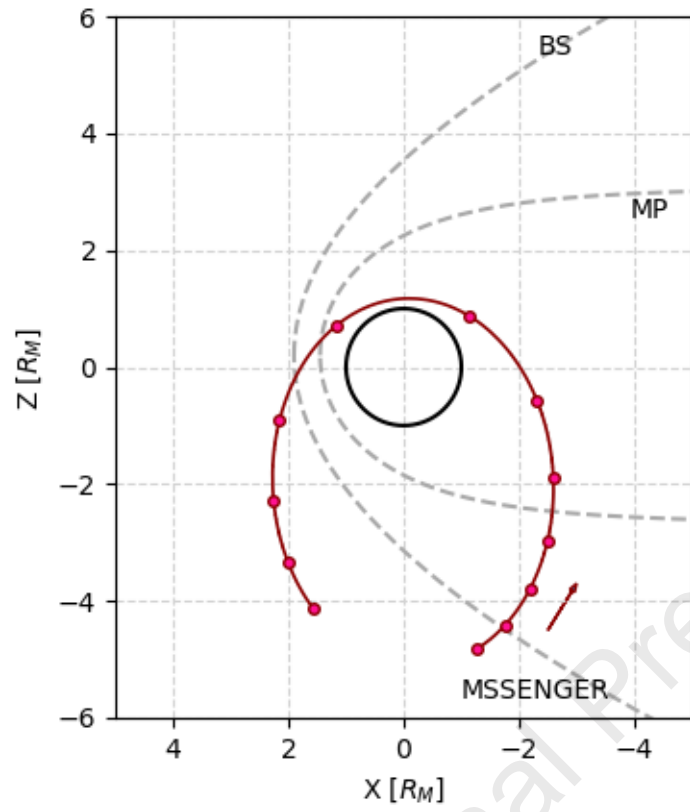




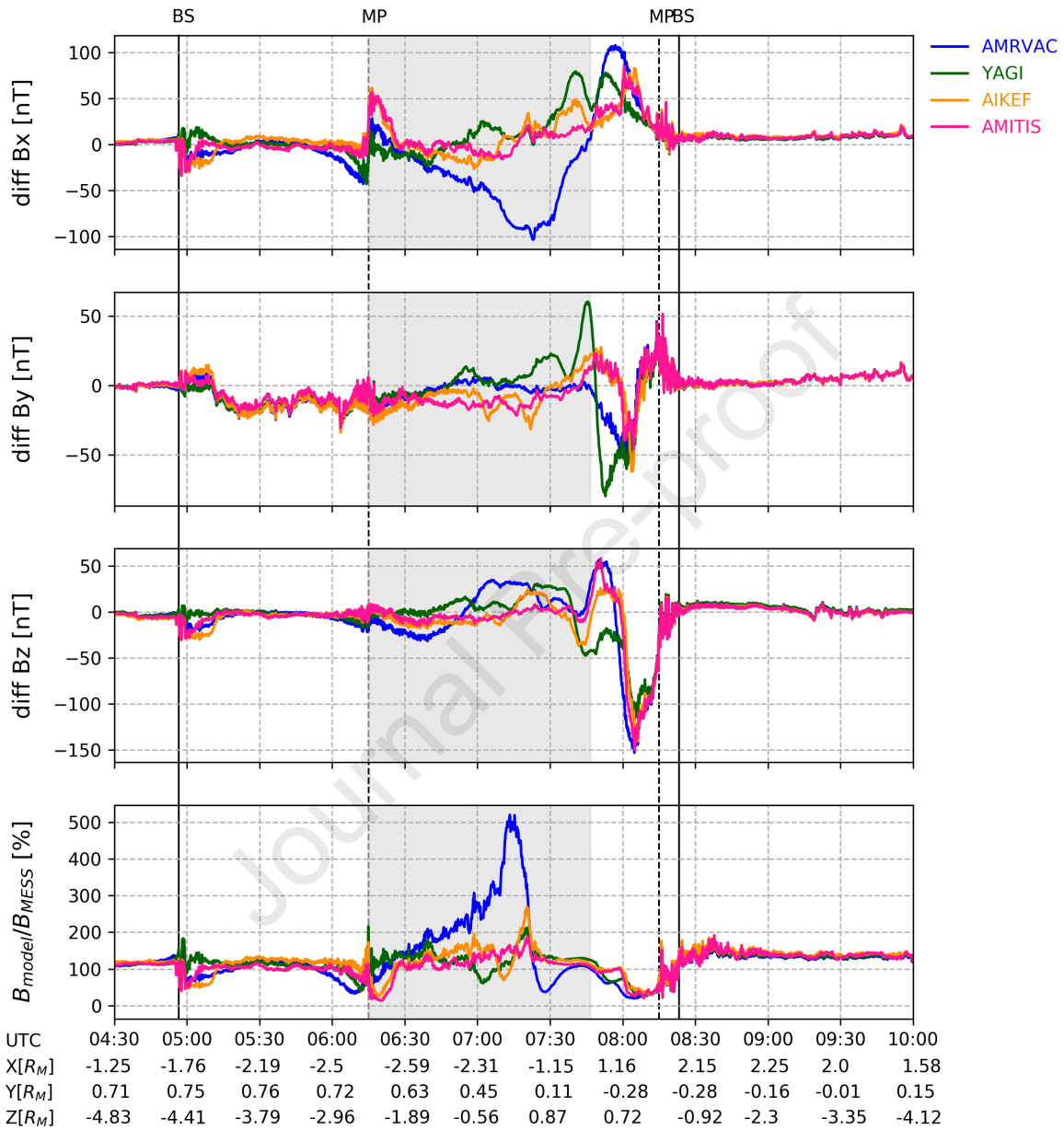




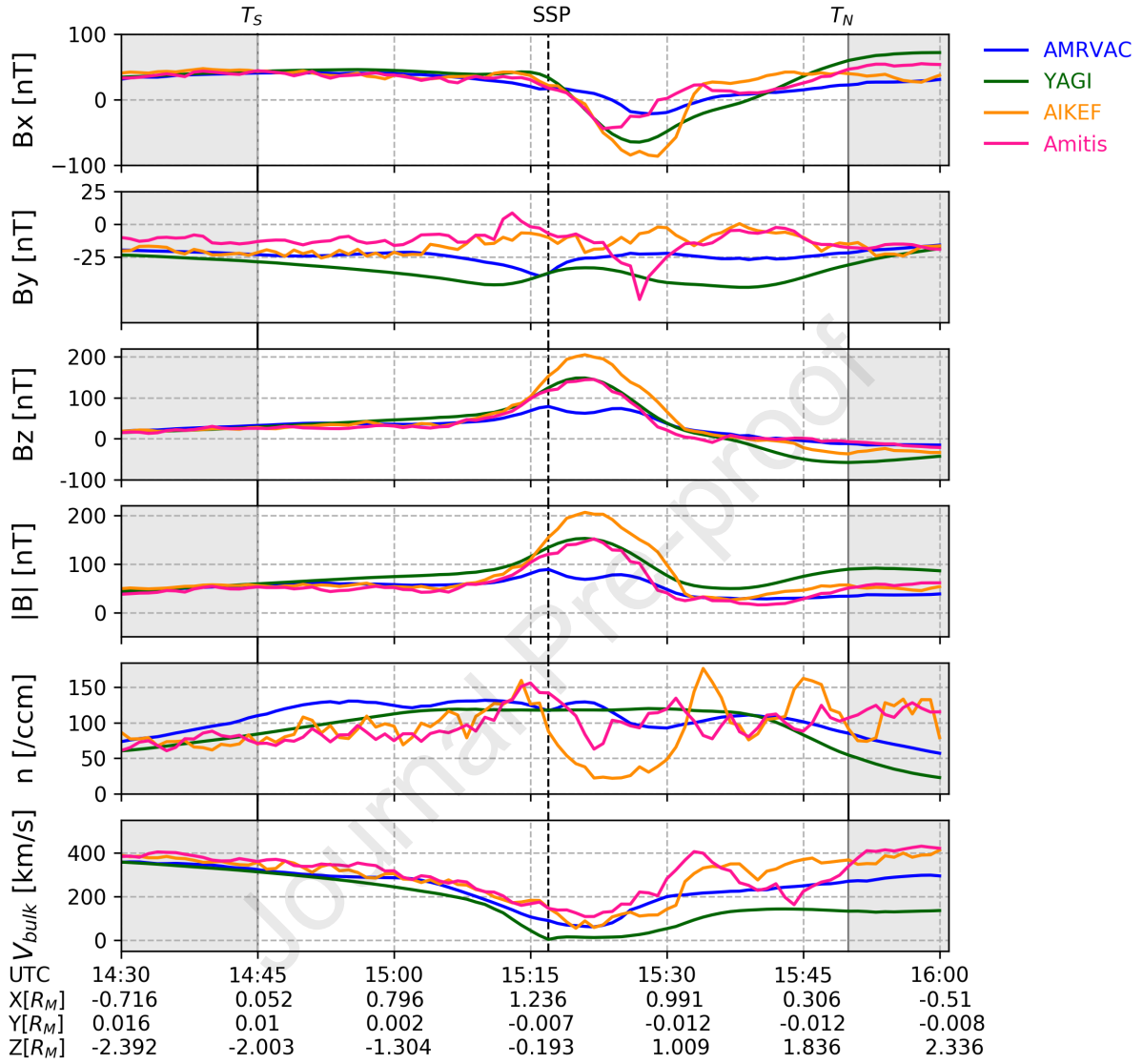


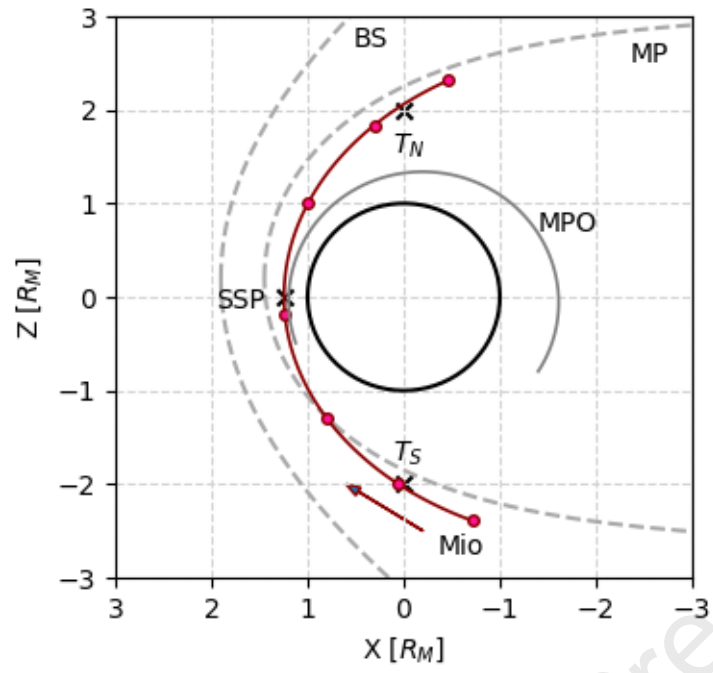


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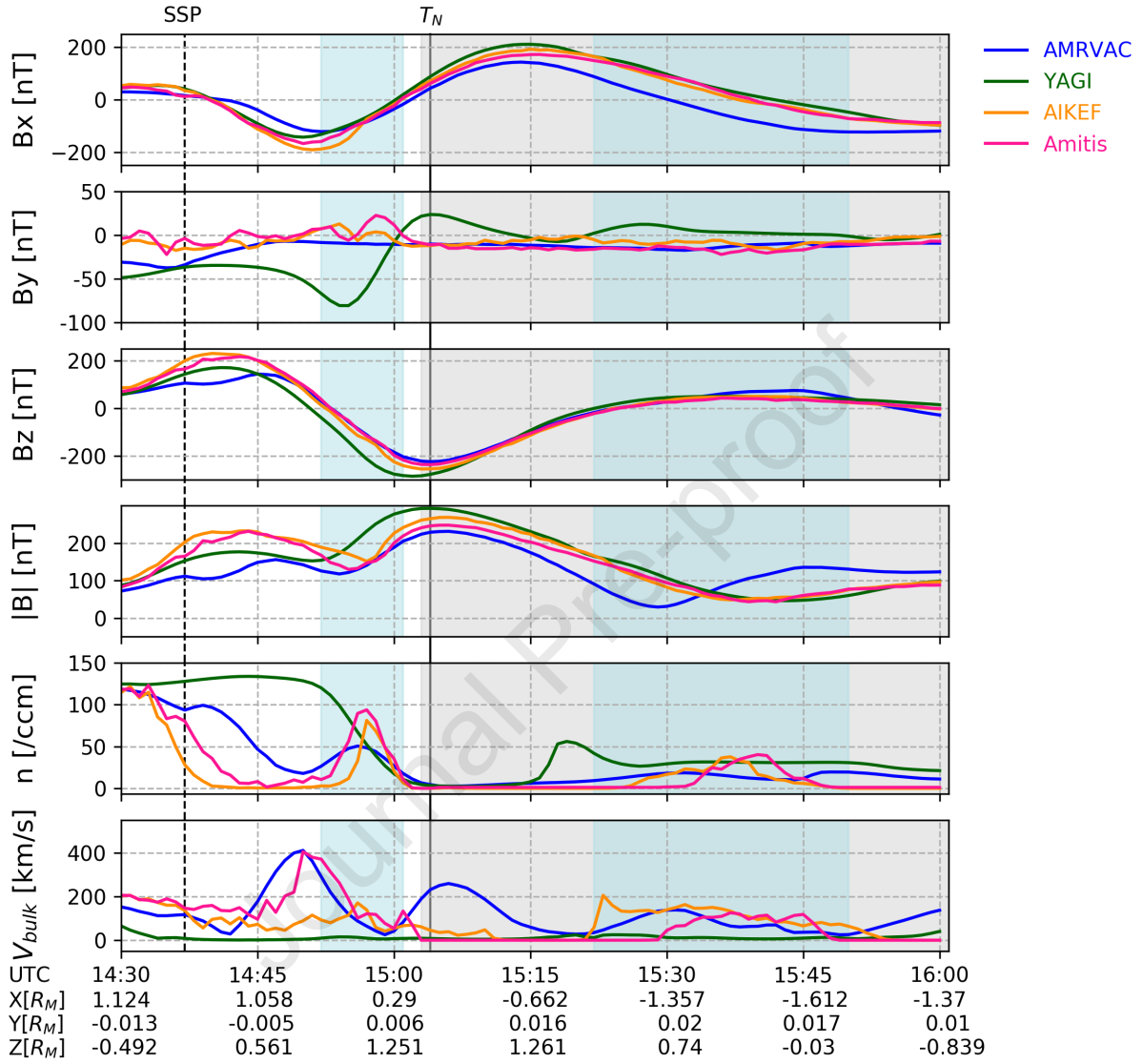


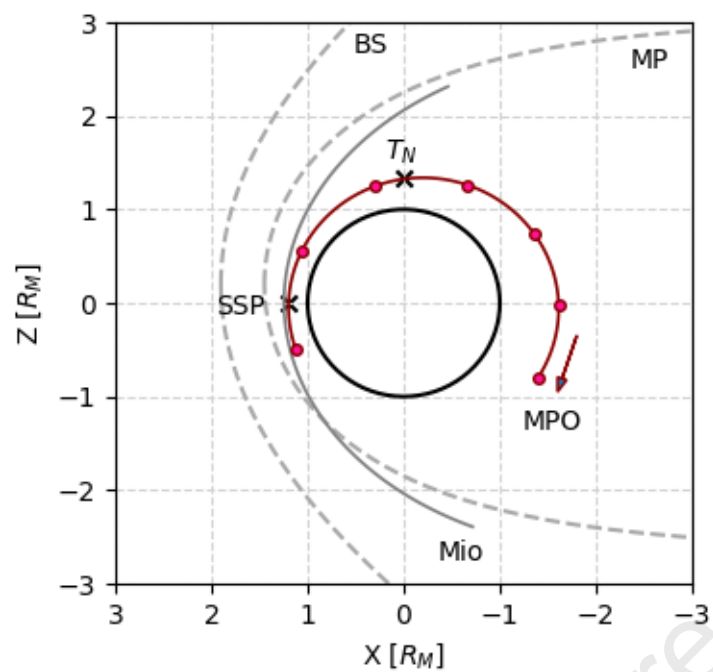
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1 **Highlights for the paper :**

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

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29 **Key Points :**

30 **1) First comparison of multiple global simulations of the solar wind interaction**
 31 **with Mercury's dayside magnetosphere**

32 **2) The results of four distinct simulation approaches are juxtaposed with**
 33 **MESSENGER observations**

34 **3) In contrast to the magnetosheath thickness, the simulated shock locations**
 35 **depends on the inner boundary condition of the model**

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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