A modelling approach to infer the solar wind plasma parameters upstream of Mercury from magnetic field observations

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BepiColombo is getting ready for launch!

BepiColombo is a Joint ESA/JAXA mission to Mercury

BepiColombo configuration:

- Mercury Planetary Orbiter (MPO)

- Mercury Magnetospheric Orbiter (MMO)

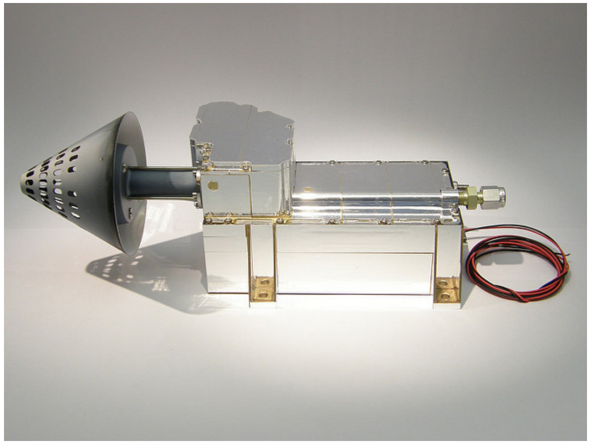
- Mercury Transfer Module (MTM)

- Sunshield (MOSIF)

Launch: Oct 2018
One Earth flyby: 2020
Two Venus flybys: 2020, 2021
Five Mercury flybys: 2021-2025
Arrival: Dec 2025 for one year

IRF sensors on BepiColombo

- Miniature Ion Precipitation Analyzer (MIPA) on MPO/SERENA
- Energetic Neutral Analyzer (ENA) on MMO/MPPE



Parameter	Value
Energy range, keV	0.01 – 15
Energy resolution, $\Delta E/E$	7%
Field of view	90° x 360°
Angular resolution	20° x 60°
Mass range, amu	1 – 50
Mass resolution, $M/\Delta M$	~5
Sampling time, msec	7.8125
Time resolution, sec	18
Efficiency	1 – 10%*
Geometrical factor	in cm^2 sr eV
maximum possible	0.12 – 0.19
base line	0.024 – 0.038
Mass	610 g
Power	1.7 - 2.1
TM (after compression)	64-512 bits/s

* adjustable to decrease G-factor

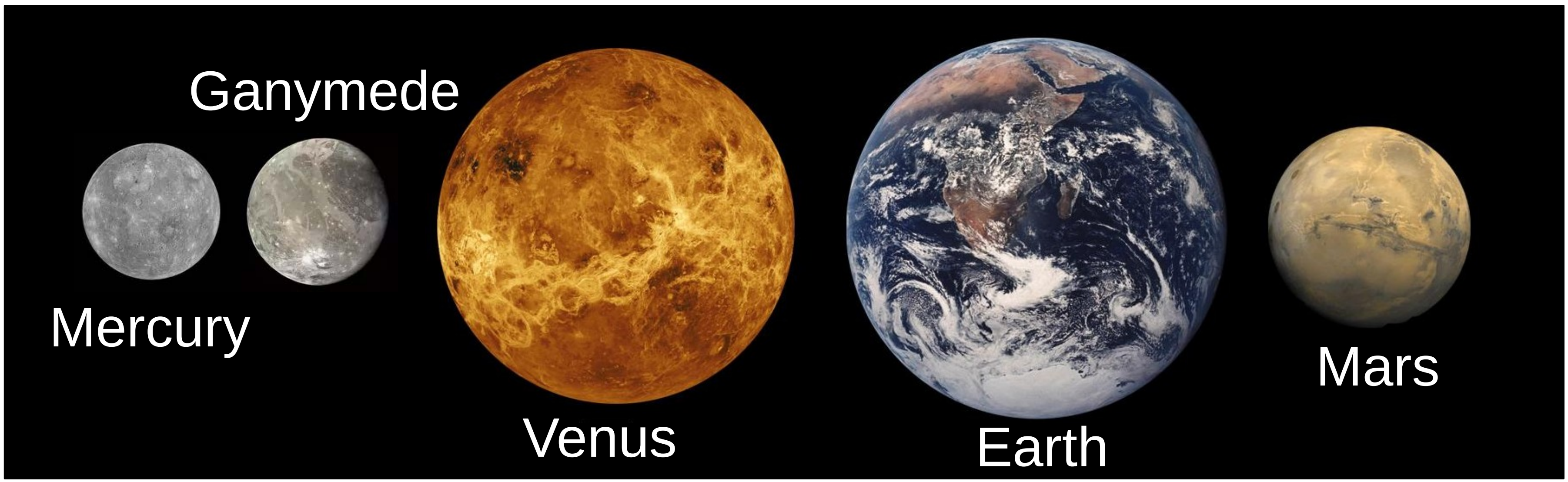
Parameter	Value
Energy Range	10 eV – 2 keV
Energy Resolution	50% $\Delta E/E$
Mass Resolution	H, O, Na/Mg-group K/Ca-group, Fe
Pure G-Factor/sector	10^{-2} cm^2 sr eV / eV
Total Efficiency	~1 %
Angular resolution	9° (el) x 25° (az)
Field of view	15° x 160°
Mass (no thermal h/w)	2075 g
Power, W	5.0
TM, kbps	0.1 – 1

Mercury

- Average radius is 2440 km
  38% of the Earth radius
  93% of Ganymede (a Galilean moon), 0.95% of Titan (a Saturnian moon)

- Exosphere (Na, Ca, K, H, He, Mg, and perhaps O and Al)
  The most dominant ion species is Na^+ with density ~0.01-0.7 cm^{-3}

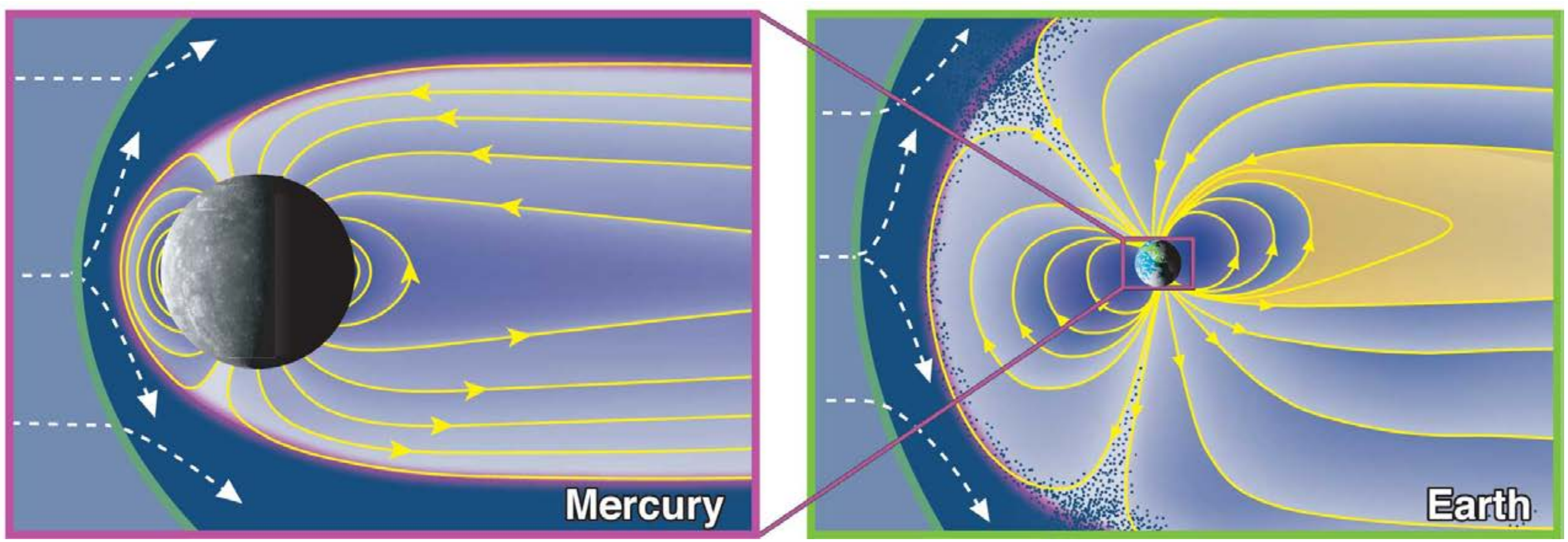
- Mercury has a very large metallic core (0.8 R)



Global magnetic field

Mercury has a weak global, intrinsic magnetic field that supports a small magnetosphere.

	Surface fields strength [uT]	Tilt from rotational axis [deg]	Central offset [h/R]	Dipole moment
Mercury	~0.2	<1	0.20	South
Earth	~35	~11	0.08	South
Jupiter	~430	~10	Small! (JUNO!)	North



Courtesy of C. Arridge, F. Bagenal and S. Bartlett.

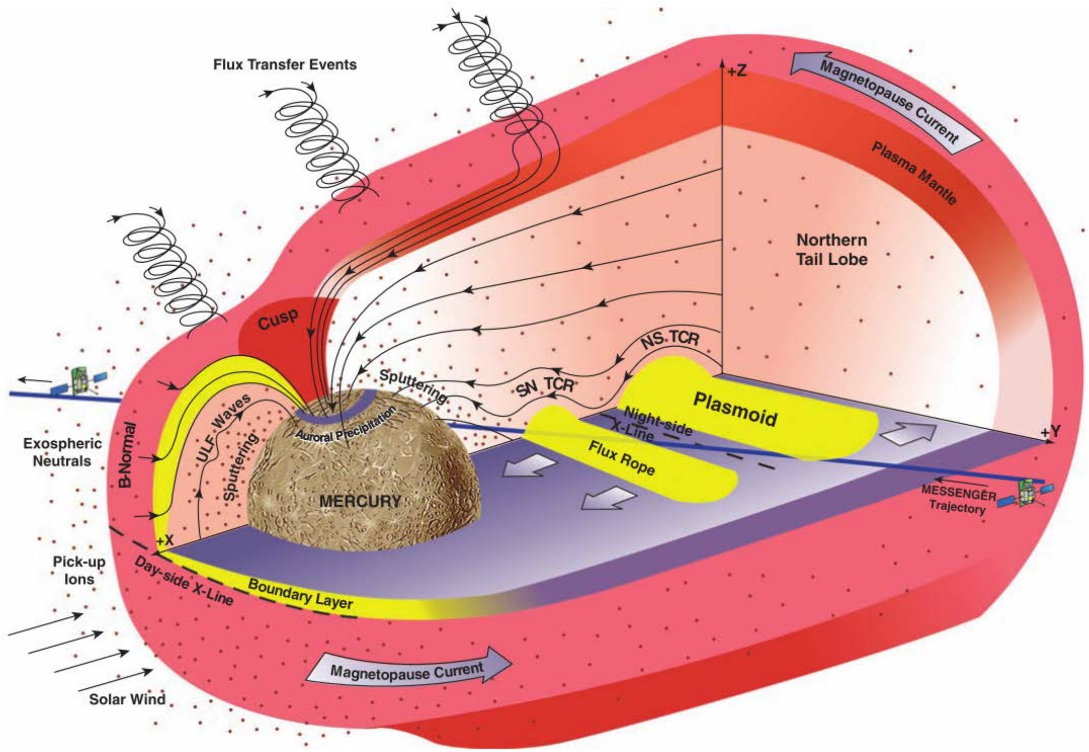
Solar wind interaction with Mercury

- Bow shock: ~1.9 RM
- Magnetopause: ~1.4 RM
- Most of the magnetosphere is filled by the planet itself

- Mercury's mini-magnetosphere is highly dynamic and responsive to the solar wind and magnetic field variations:

Dungey cycle
Earth: ~1 h
Mercury: ~2 min

Reconnection rate
Earth: ~0.05
Mercury: ~0.15

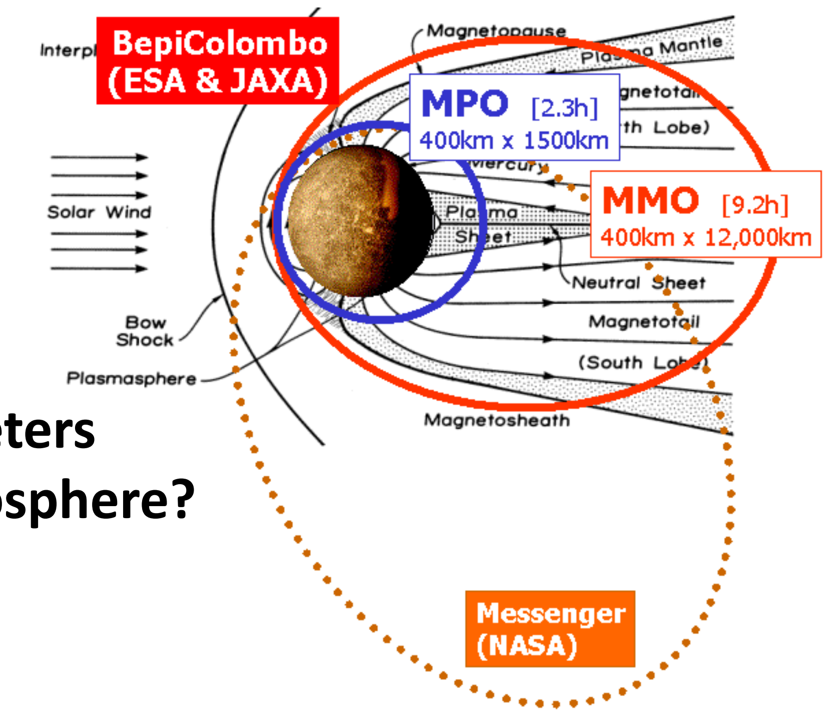


[Slavin et al., 2009]

A challenge for observations!

The lack of an upstream solar wind plasma monitor when a spacecraft is inside the dynamic magnetosphere of Mercury limits interpretations of observed magnetospheric phenomena and their correlations with upstream solar wind variations.

It is important to separate the internal and external magnetic fields.



[stp.isas.jaxa.jp]

What are the solar wind plasma parameters when a spacecraft is inside the magnetosphere?

Different methods have been applied

For example

- Winslow et al., 2013 used WSA-ENLIL model
- Slavin et al., 2014 used pressure balance

AMITIS: A GPU-based hybrid model of plasma

Inverse problem approach using a hybrid plasma model

- **AMITIS:** a 3D hybrid model of plasma (kinetic ions and fluid electrons)
- Runs on a GPU (Graphical Processing Unit): **<=1 day for one simulation**
- Well-tested against several observations
- Implicit solver for the interior coupled with an explicit plasma solver

[Fatemi et al., 2017]

~10x faster than a CPU-based hybrid model using ~380 CPUs!

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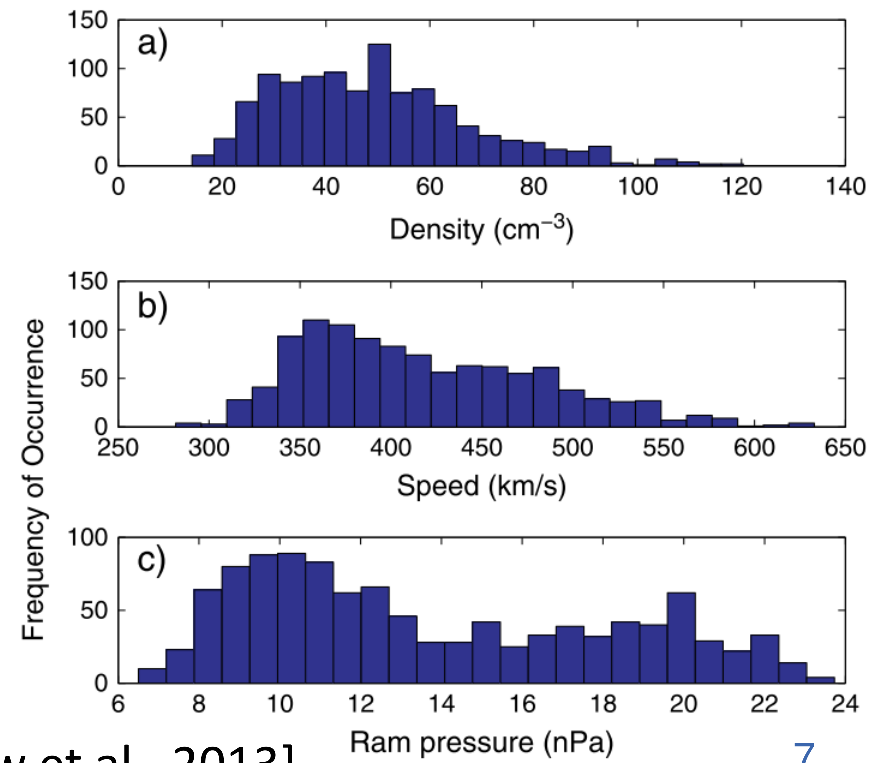
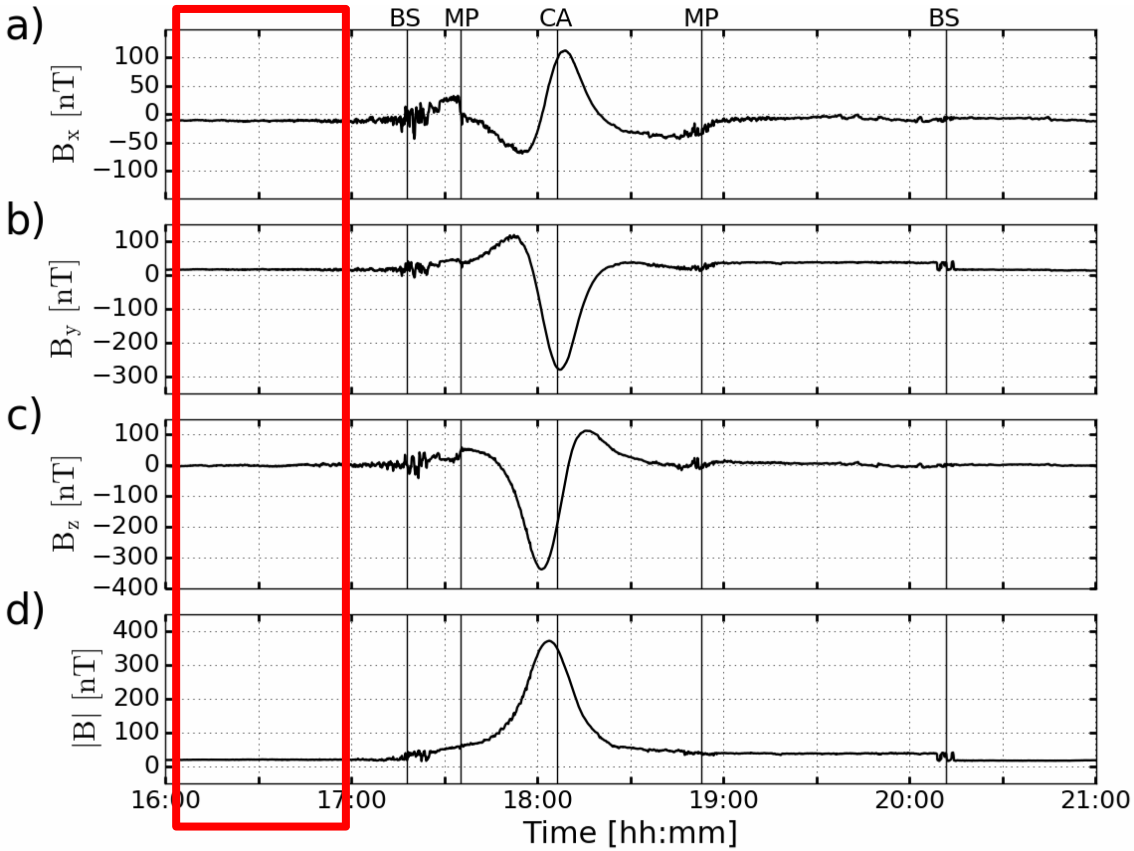
- The only known parameter: Magnetic field (MESSENGER/MAG)
- Magnetospheric boundaries are also known from MAG observations.
- A range of the solar wind plasma parameters



[Winslow et al., 2013]

MESSENGER magnetic field observations

BS: bow shock   MP: magnetopause   CA: closest approach



2011; DOY 113

Known parameters:

- One hour averaged (Bx, By, Bz) = (-10.7, +15.4, +0.5) nT
- Magnetospheric boundaries

MESSENGER magnetic field observations

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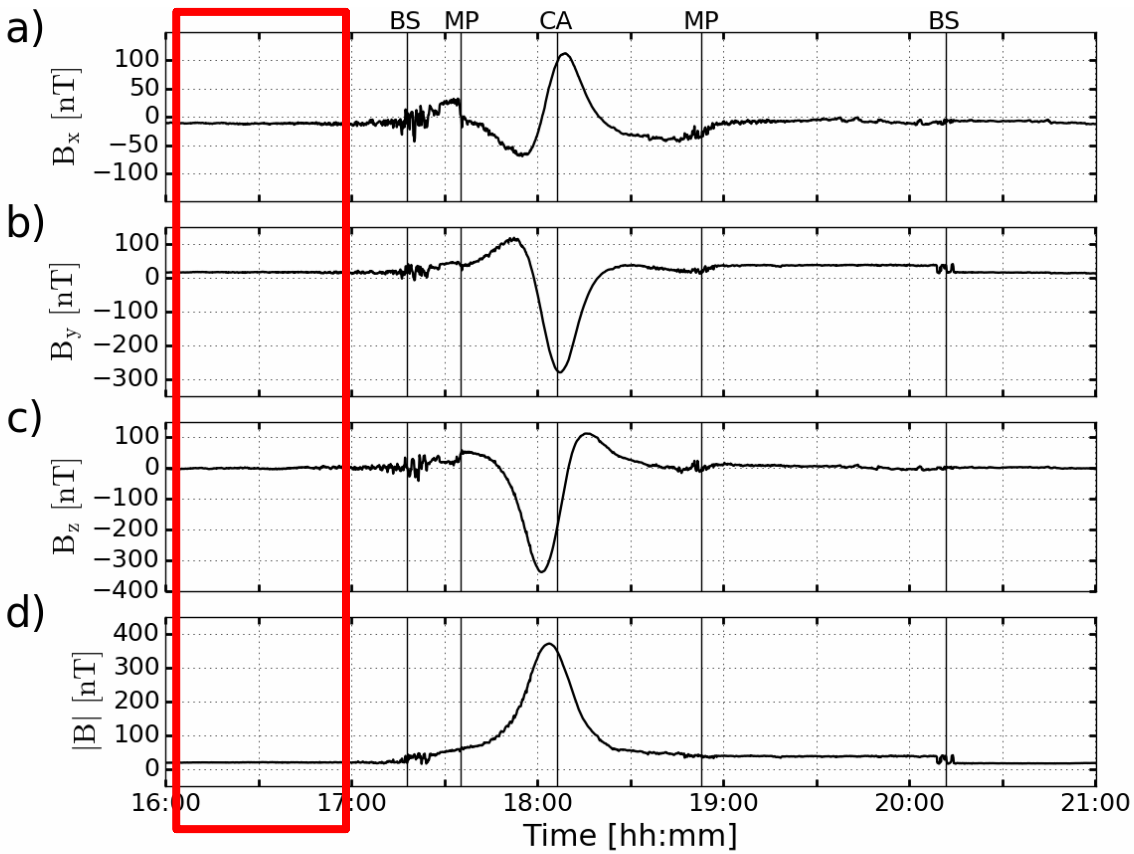


2011; DOY 113

Solar wind plasma:

n_{sw}: 16...26 : 2 /cm3

v_{sw}: 270...340 : 10 km/s

Ti = Te = 12 eV

Total: 48 simulations

No exosphere

No conductive core

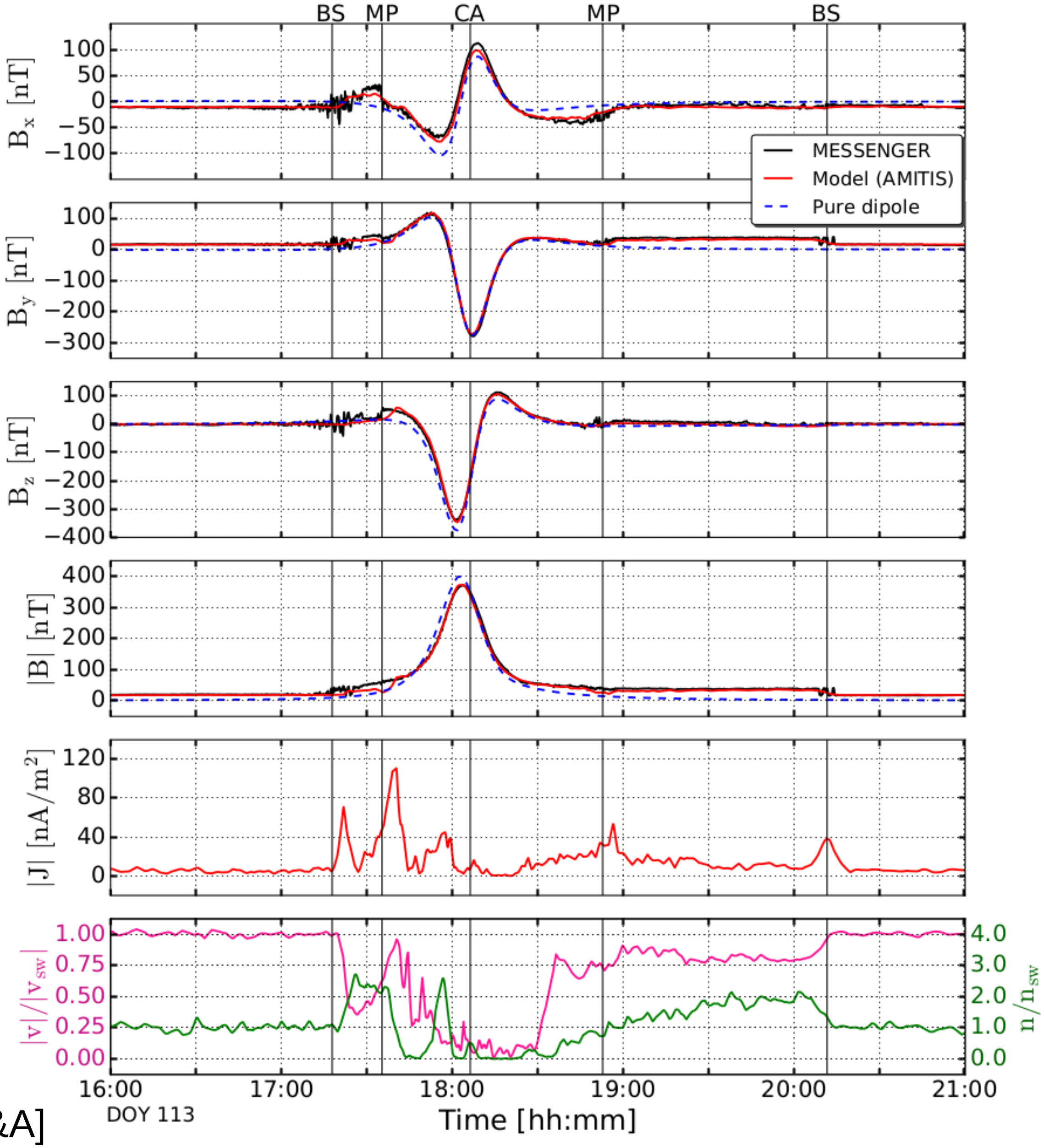
Known parameters:

- One hour averaged (Bx, By, Bz) = (-10.7, +15.4, +0.5) nT
- Magnetospheric boundaries

Comparison with MESSENGER (2011/113)

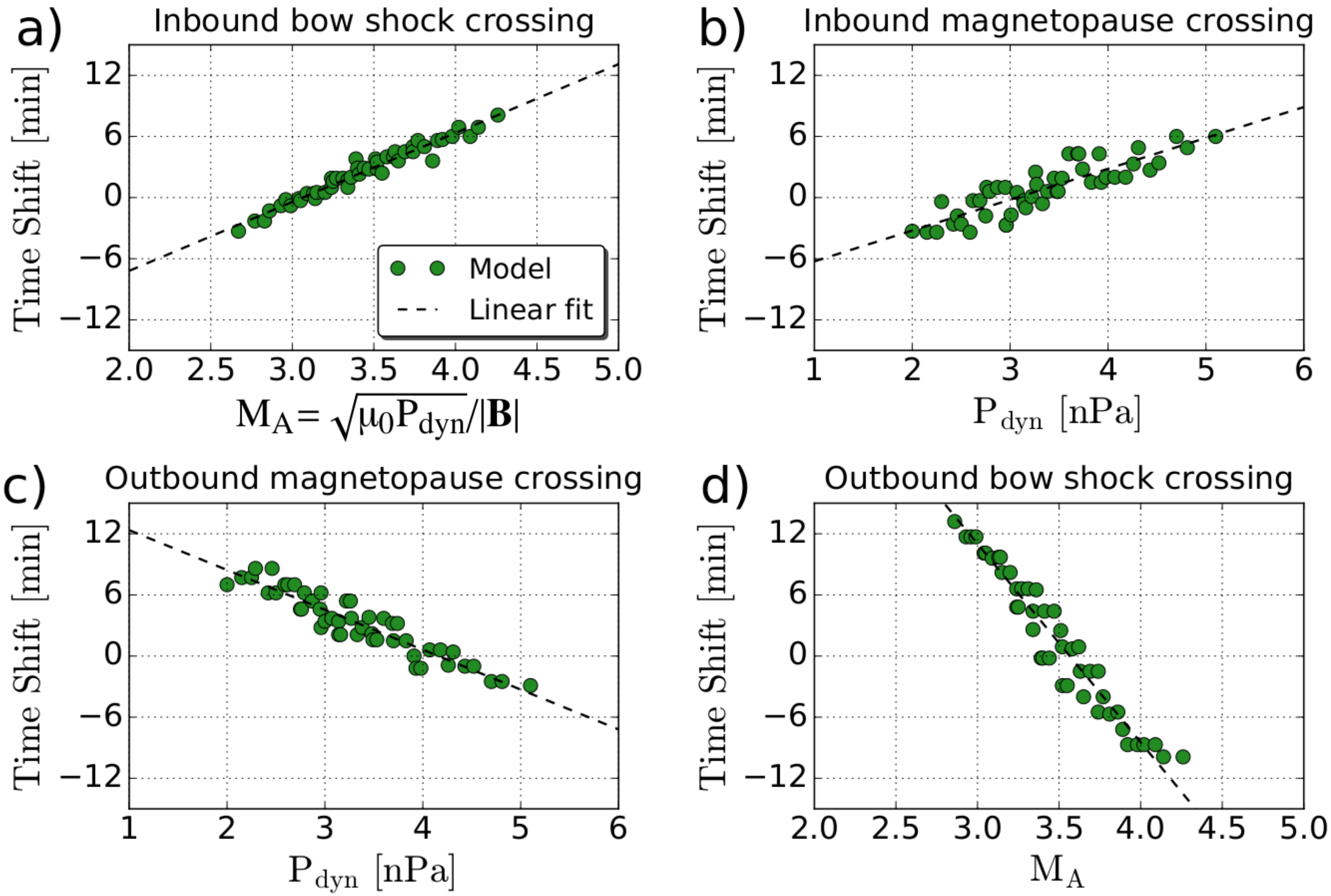
n_sw = 22 /cm^3
v_sw = 300 km/s
Pdyn = 3.6 nPa
MA = 3.6
Beta = 0.28

Current density →



[Fatemi et al., 2018; A&A]

Inferred plasma parameters by AMITIS

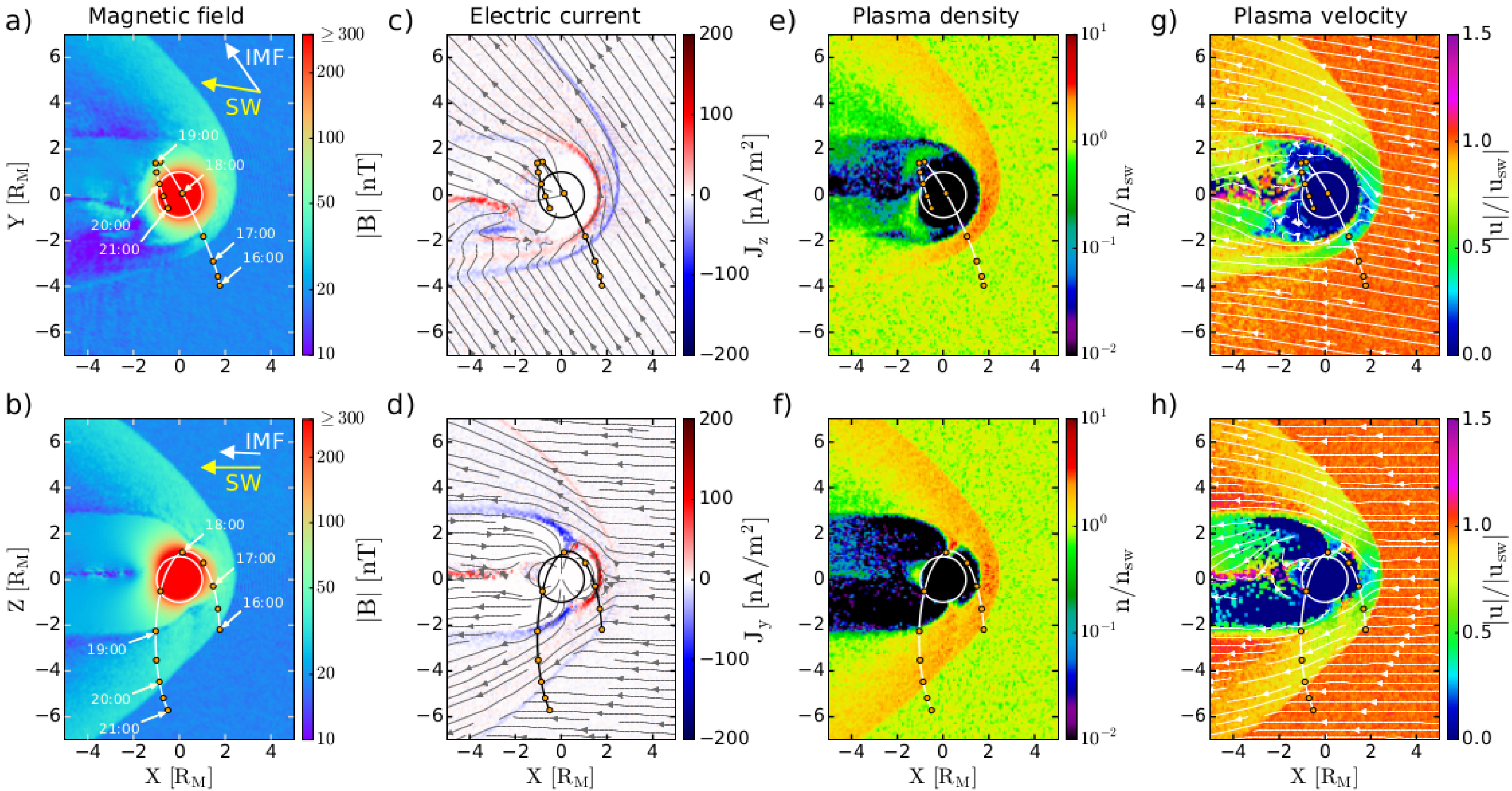


[Fatemi et al., 2018; A&A]

	Bow shock [nPa]	Magnetopause [nPa]
Inbound	2.7±0.3	3.1±0.5
Outbound	3.6±0.4	4.2±0.5

WSA-ENLIL: ~7 nPa

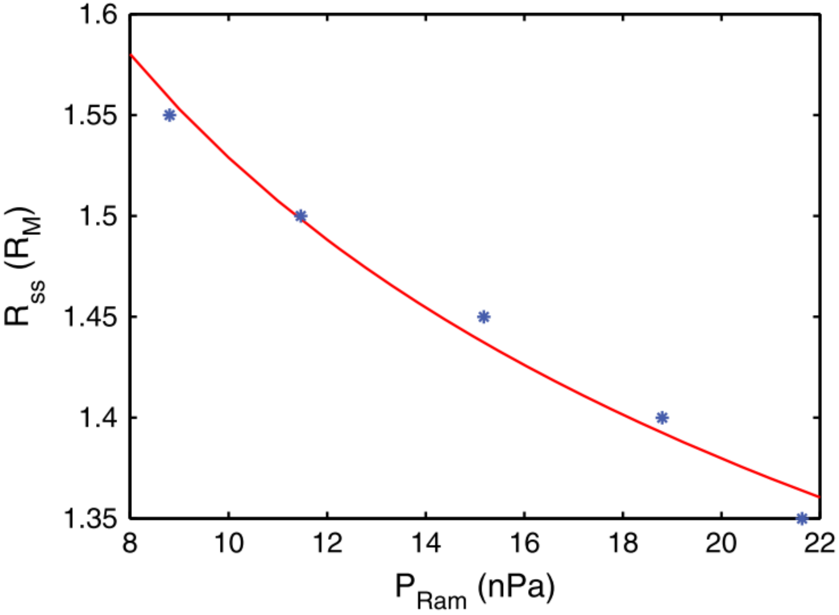
Global view of the interaction (2011/113)



Magnetopause response

Magnetopause response
[Winslow et al., 2013]:

$$R_{SS} = (2.15 \pm 0.10) P_{dyn}^{[(-1/6.75) \pm 0.024]}$$



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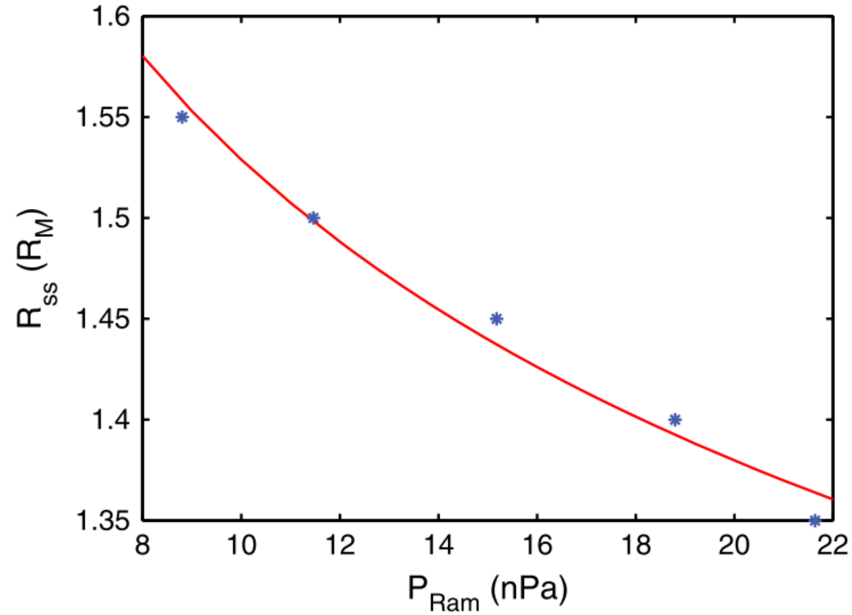

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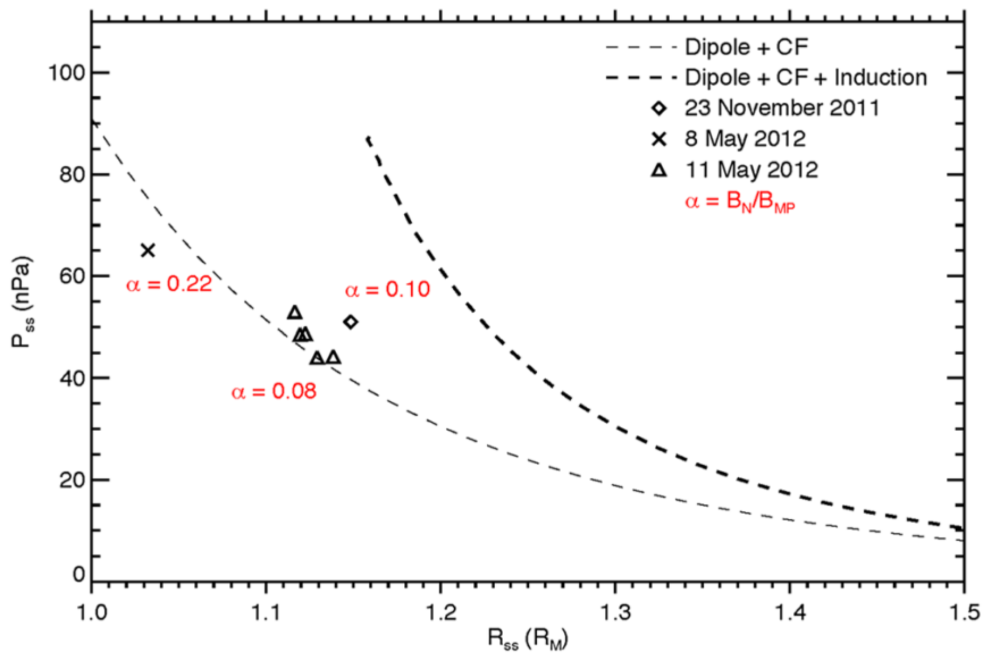

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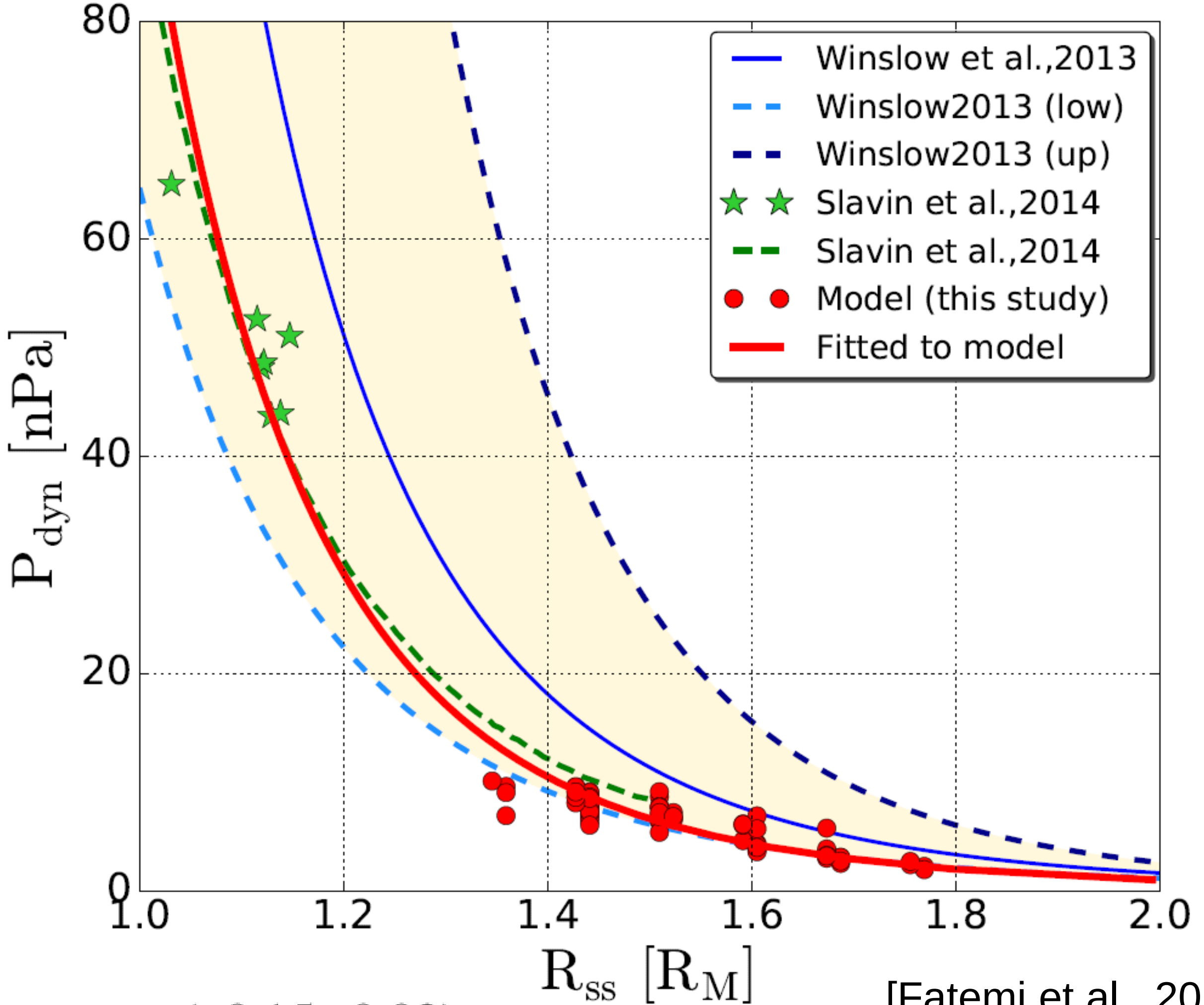
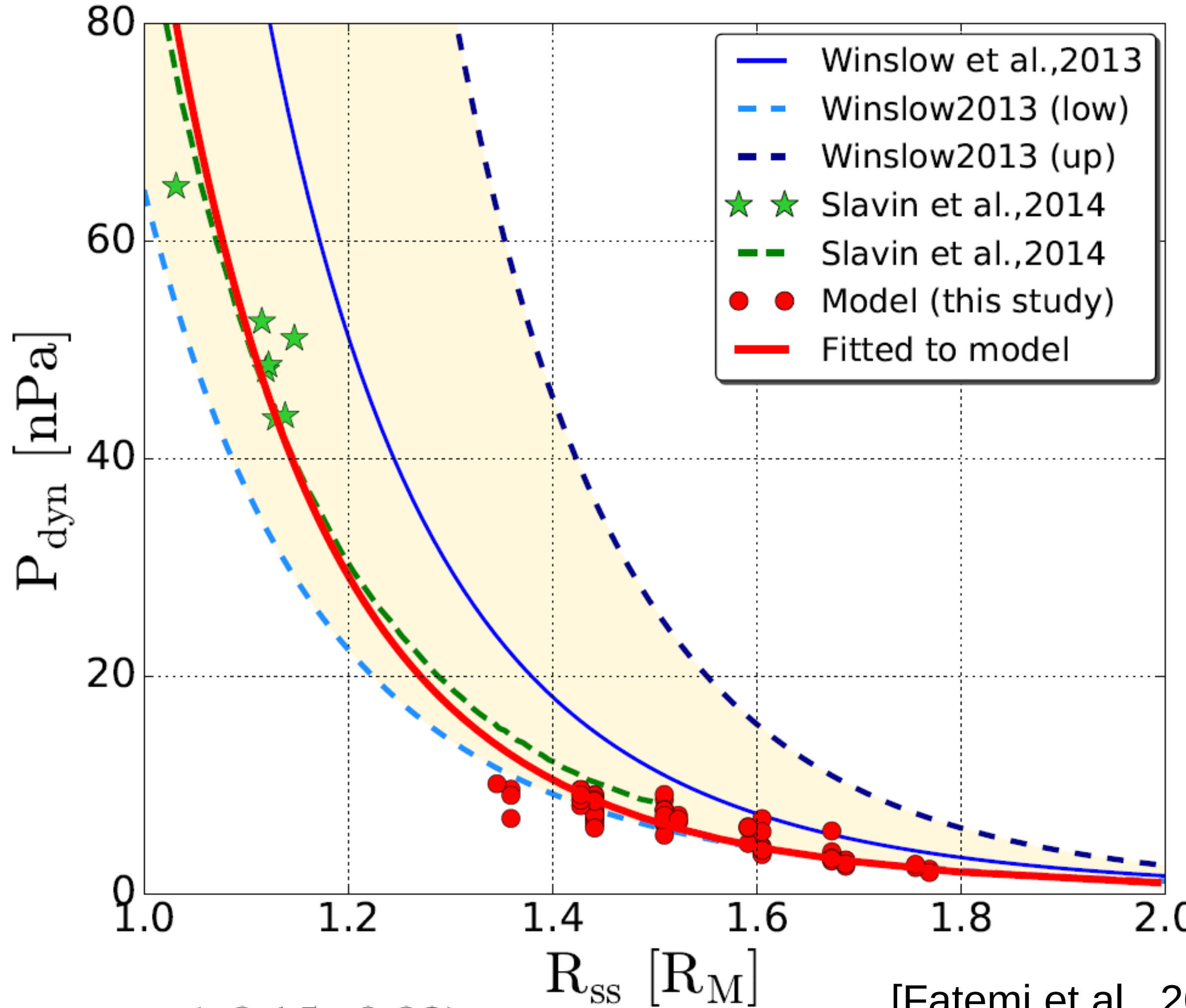


[Fatemi et al., 2018; A&A]

$$R_{ss} = (1.99 \pm 0.1)\, P_{dyn}^{(-0.15 \pm 0.02)}$$

Magnetopause response



[Fatemi et al., 2018; A&A]

$$R_{SS} = (1.99 \pm 0.1)\, P_{dyn}^{(-0.15 \pm 0.02)}$$

What is the role of the core?

Summary

- We have developed a tool to estimate the solar wind plasma parameters upstream of Mercury based on magnetic field observations.

- Our model estimates the location of Mercury's magnetospheric boundaries quiet accurately!

- We have successfully validated our simulations against MESSENGER.

- We can run similar campaigns for every orbit of BepiColombo and MESSENGER, as long as the IMF remains relatively constant before and after the bow shock crossing.

Future work:
- MIPA and ENA response in the magnetosphere
- Mercury's core and plasma interaction!

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MESSENGER orbit selections

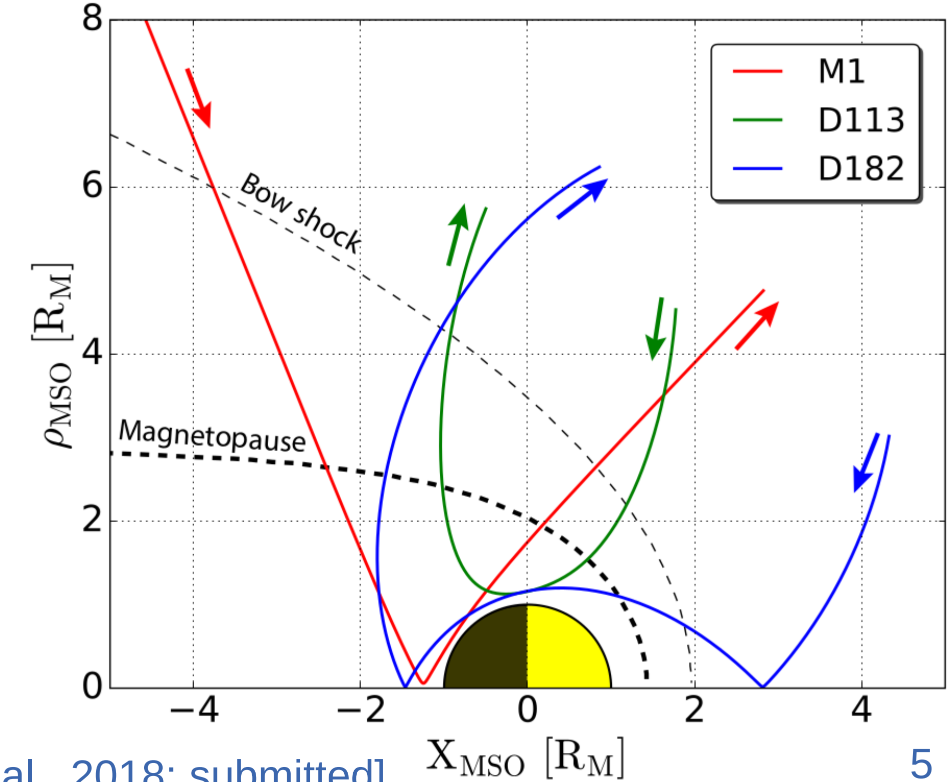
- A few well-studied orbits

Orbit	Date	B_x [nT]	B_y [nT]	B_z [nT]	$\|\mathbf{B}\|$ [nT]
M1	14 Jan 2008	-18.1	0.0	+4.0	18.5
D113	23 Apr 2011	-10.7	+15.4	+0.5	18.7
D182 (inbound)	01 Jul 2011	-16.7	-8.7	-1.8	18.9
D182 (outbound)		-21.7	+1.3	+5.7	22.5

The selected orbits cover different magnetospheric regions!

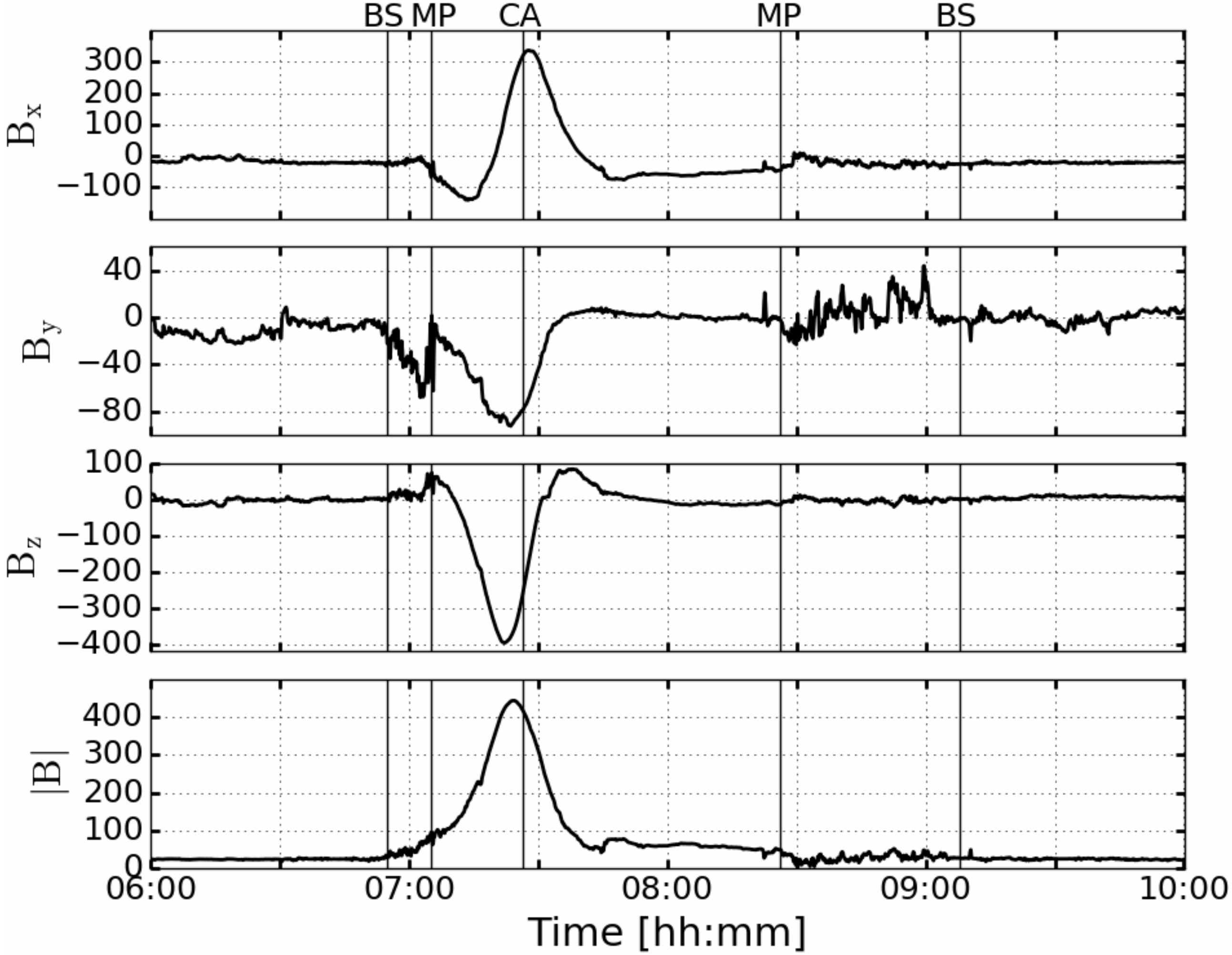
The only known parameter:
magnetic field (MAG)

1h average of the B-field



[Fatemi et al., 2018; submitted]

2011.07.01 (D182) MAG observations



Orbit	Date	B_x [nT]	B_y [nT]	B_z [nT]	**|B|** [nT]
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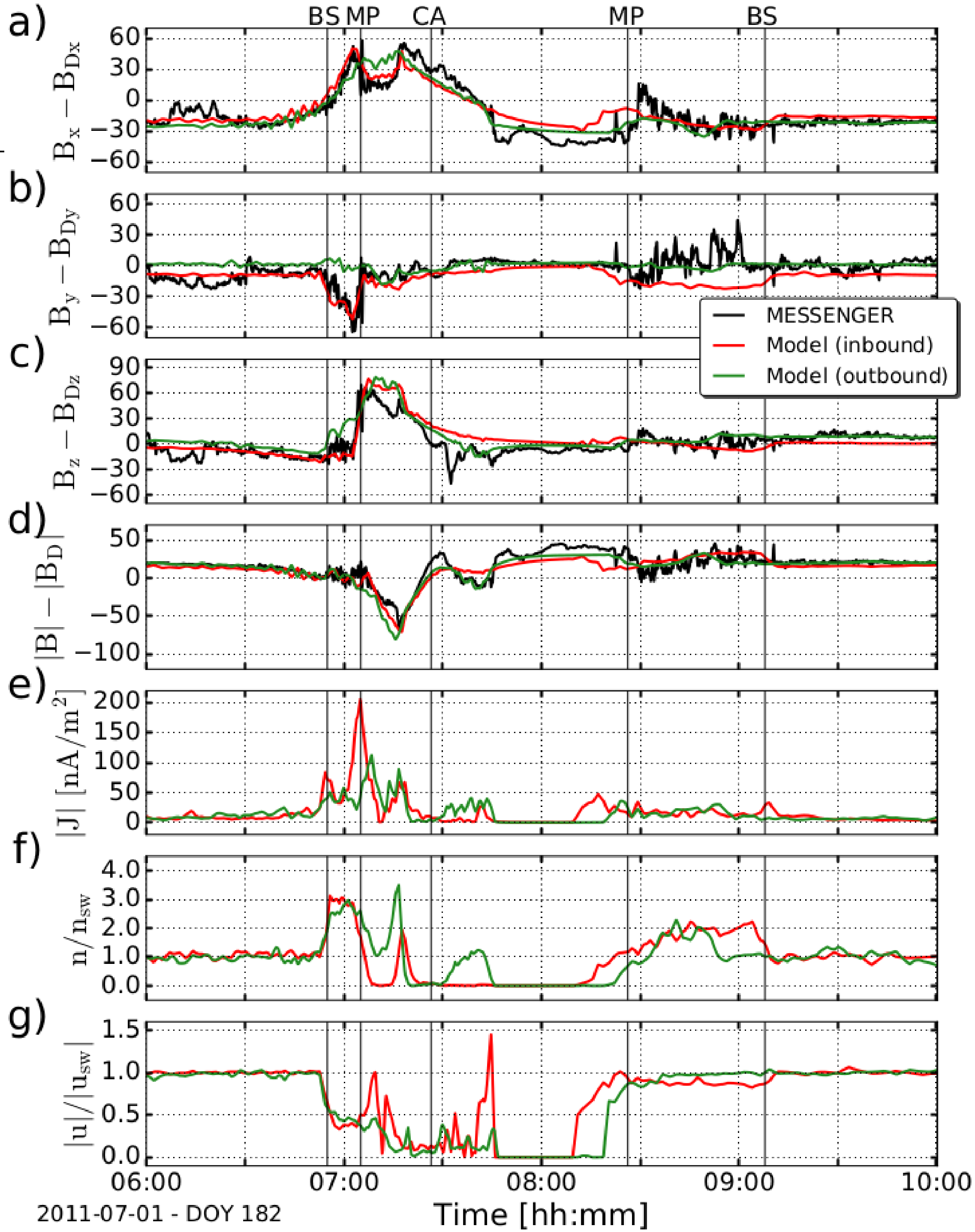
D182 (inbound) **D182** (outbound)	01 Jul 2011	-16.7 -21.7	-8.7 +1.3	-1.8 +5.7	18.9 22.5

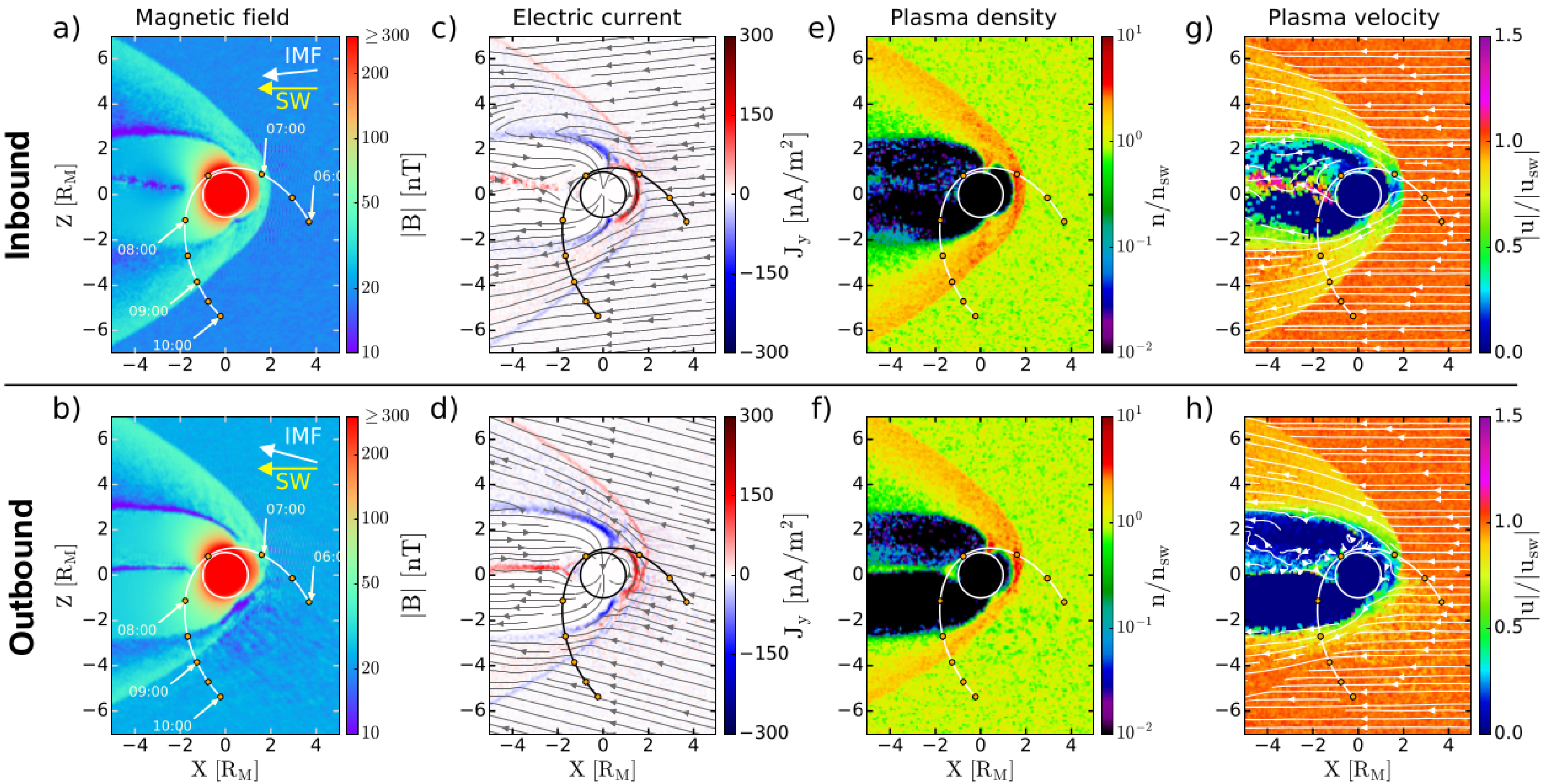
Comparison

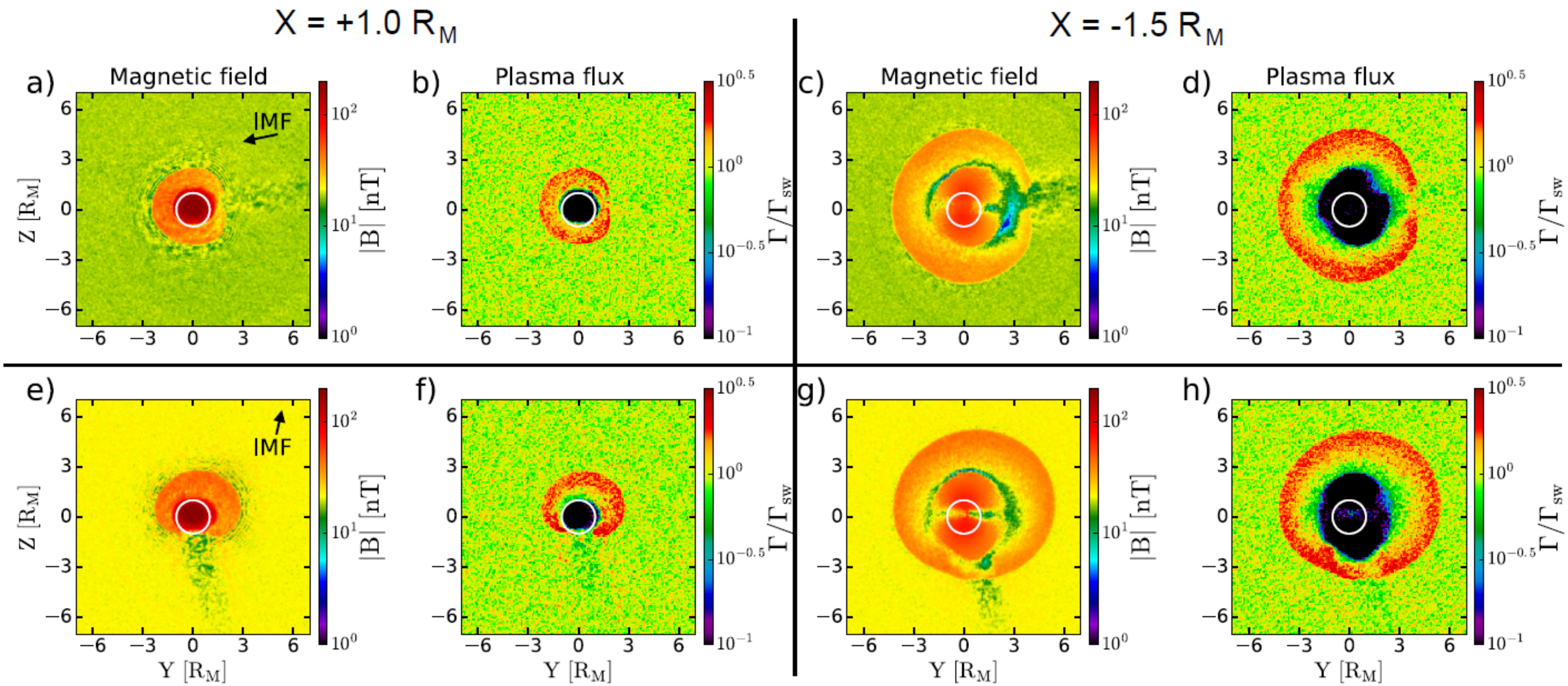


[Fatemi et al., 2018; A&A]

Global view of the interaction (D182)

Our model estimated P_{dyn}~7.5 nPa
WSA-ENLIL predicted P_{dyn}~10.5 nPa

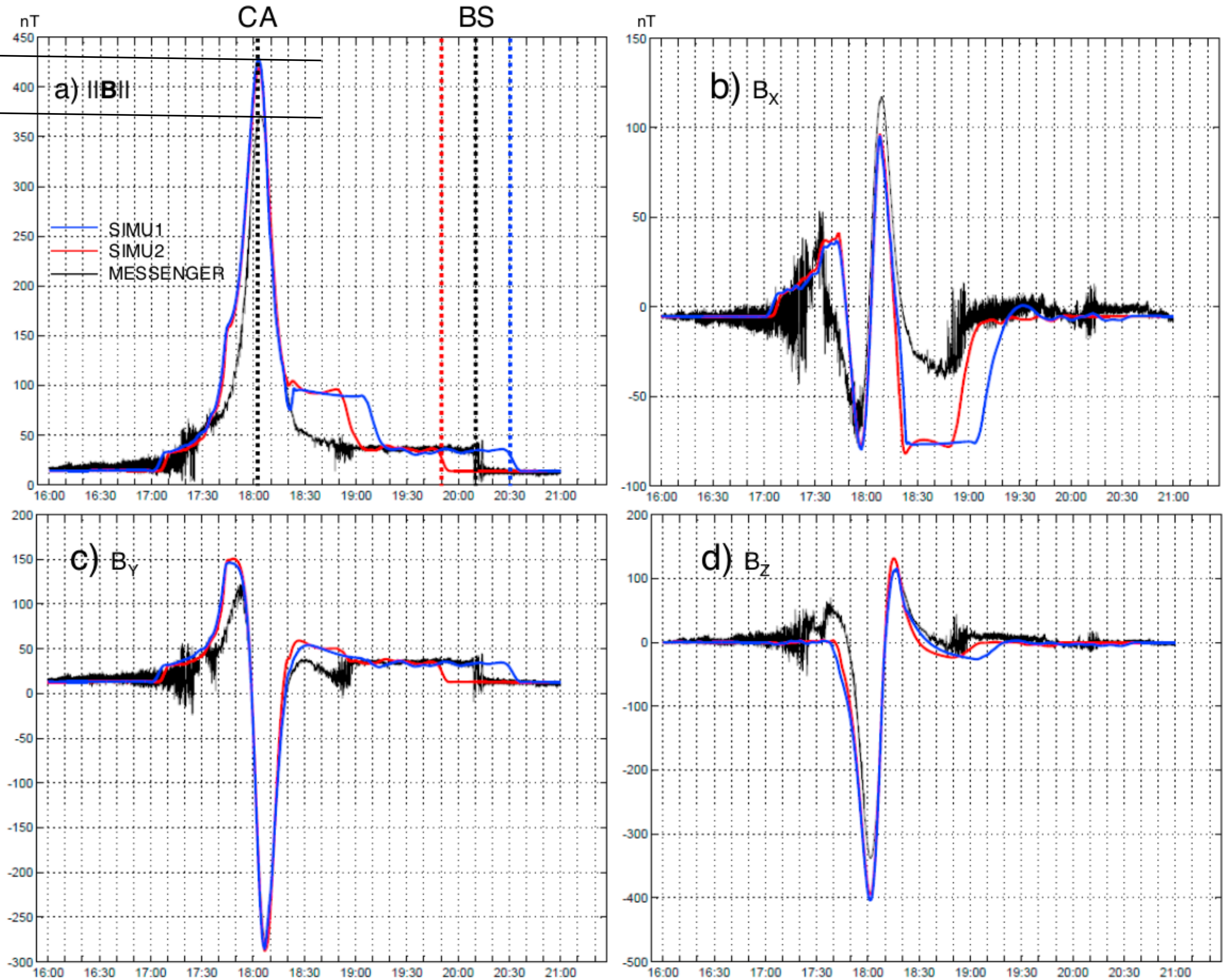




X = +1.0 R_M
X = -1.5 R_M
a) Magnetic field
b) Plasma flux
c) Magnetic field
d) Plasma flux
e)
f)
g)
h)
IMF
IMF
|B| [nT]
Γ/Γ_sw
Z [R_M]
Y [R_M]

Another model results

~50 nT



[Richer et al., 2012]