Exploring Magnetosphere-Exosphere Coupling at Mercury:
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Max Planck Institute for Solar System Research

Hybrid Simulations
Exospheric and Magnetospheric Responses to Large Solar Wind Disturbances

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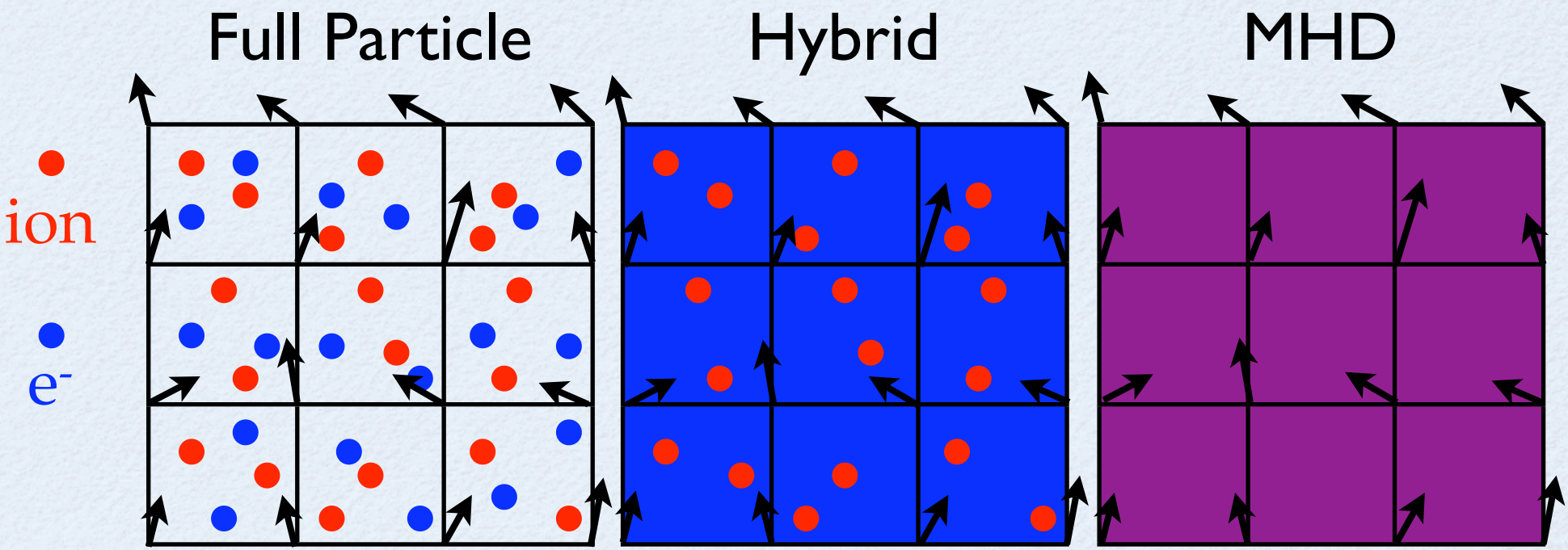
OUTLINE

- Introduction
  - 3D Hybrid Model
  - Mercury Simulations
- ICMEs/Low Mach Number Solar Wind Interactions
  - Helios 1/2 data (1975-1983)
  - Adaptive Hybrid Simulation

PART I

3D Hybrid Model and Mercury Simulations

3D HYBRID MODEL (1)



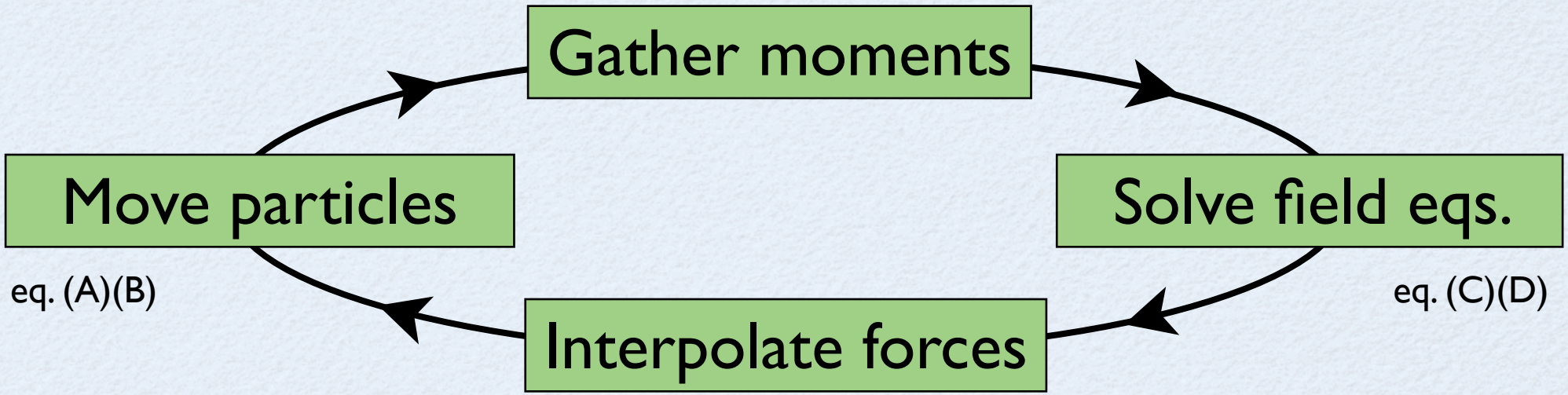
Full Particle:
System ~ $r_{g,e}$

Hybrid Model:
System dimension > $r_{g,e}$
in the order of ~ $r_{g,i}$

MHD:
System >> $r_{g,i}$

3D HYBRID MODEL (2)

"Particle-in-Cell" (PIC) method



Basic eqs. in Hybrid Model

$$\frac{d\vec{x}_s}{dt} = \vec{v}_s \qquad \text{(A)}$$

$$\frac{d\vec{v}_s}{dt} = \frac{q_s}{m_s}\left(\vec{E}' + \vec{v}_s \times \vec{B}\right) \qquad \text{(B)}$$

$$\vec{E}' = -\vec{u}_i \times \vec{B} + \frac{\nabla \times \vec{B} \times \vec{B}}{\rho_c} - \frac{1}{2}\beta_{e0}\frac{\nabla \rho_c^{\kappa}}{\rho_c} \qquad \text{(C)}$$

$$\partial_t \vec{B} = \nabla \times \left(\vec{u}_i \times \vec{B}\right) - \nabla\left(\frac{\nabla \times \vec{B} \times \vec{B}}{\rho_c}\right) - \eta \nabla \times \nabla \times \vec{B} \qquad \text{(D)}$$

$$\vec{E}' = \vec{E} - \eta \nabla \times \vec{B}$$

Bagdonat, 2004

MESSENGER FLYBYS

Input parameters

$B_{IMF} = 21$ nT [a]

$n_{sw0} = n_{sw[H^+]0} = 32$ cm^{-3} [a]

$\vec{V}_{sw0} = (+430, 0, 0)$ km/s [a]

$\vec{M} = (0, 0, -300)$ nT R_M^3 [a]

$R_M = 2440$ km [a]

$\sigma_{surface} = 10^{-4}$ S/m [b]

Normalized parameters

$t_0 = \Omega_{i0}^{-1} \approx 0.5$ s

$x_0 = c/\omega_{p,i0} \approx 40$ km

$v_0 = V_{A0} \approx 81$ km/s

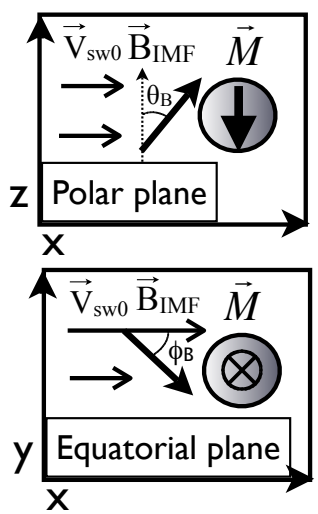
Normalized parameters

$E_0 = V_{A0} B_{IMF} \approx 1.7$ mV/m

$P_0 = B_{IMF}^2/(2\mu_0) \approx 0.18$ nPa

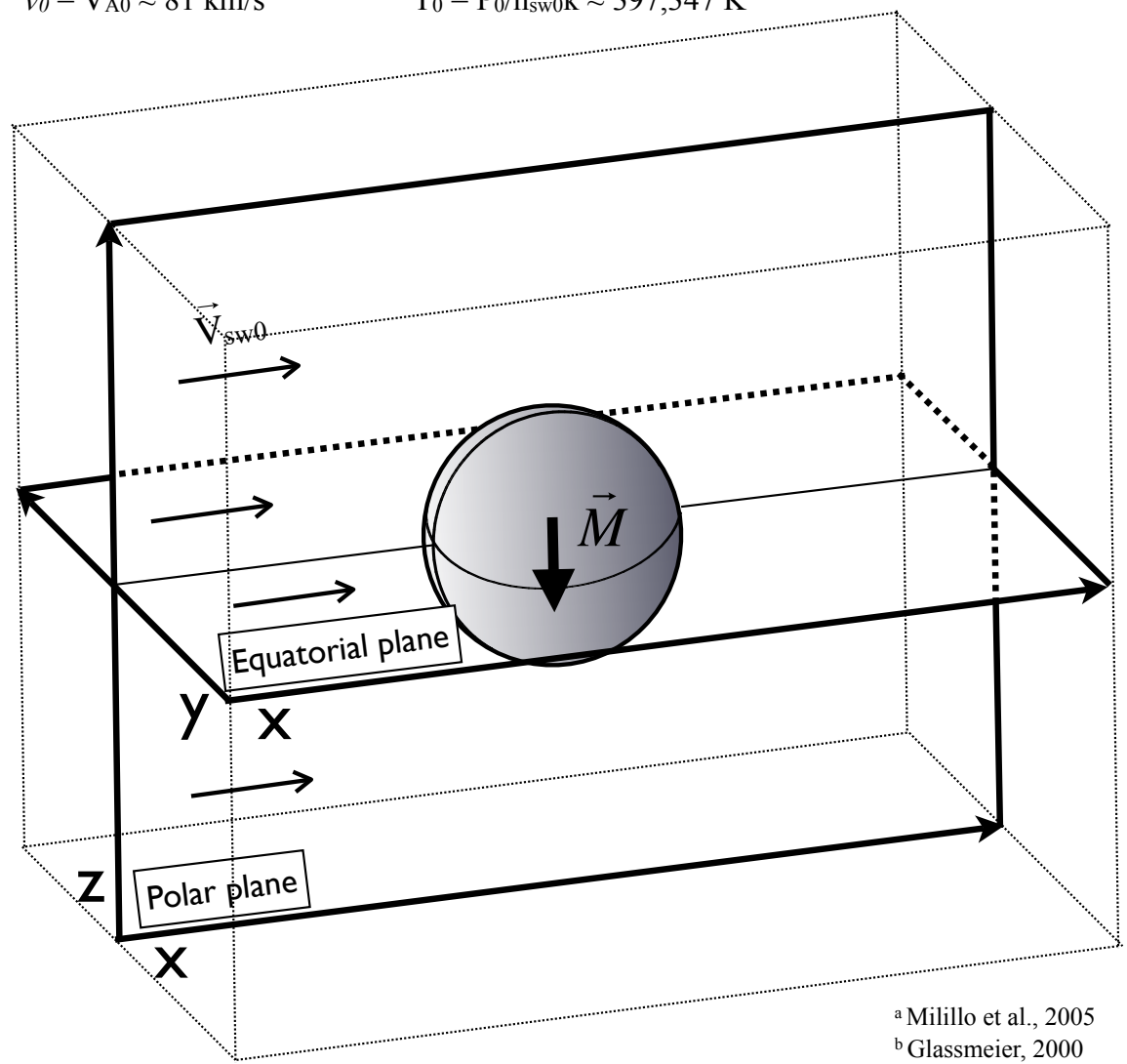
$T_0 = P_0/n_{sw0}k \approx 397{,}347$ K

IMF direction: θ_B & ϕ_B



Case (1): $\theta_B = 53^\circ$
$\phi_B = 27^\circ$

Case (2): $\theta_B = 118^\circ$
$\phi_B = 37^\circ$

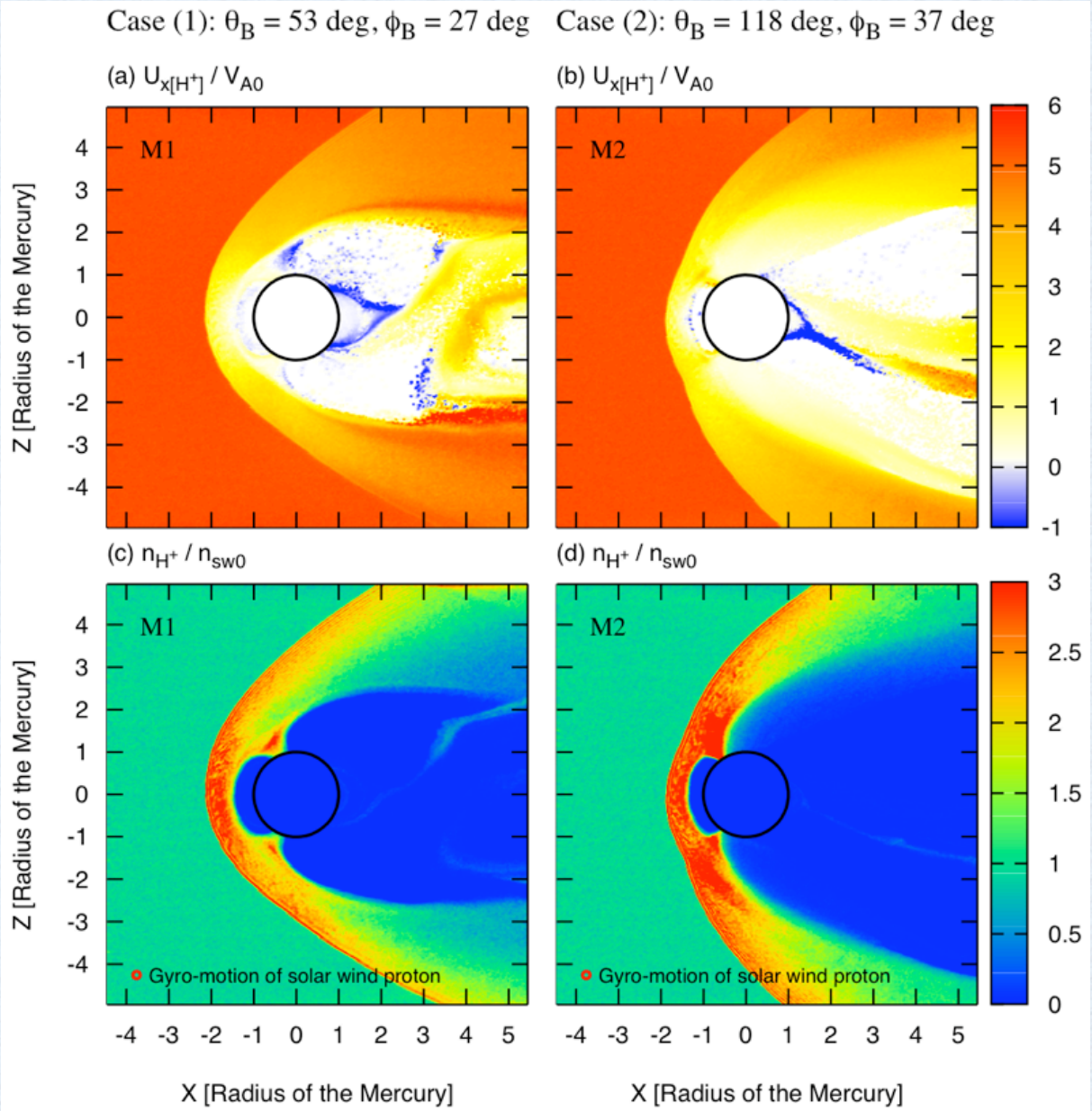


[a] Milillo et al., 2005
[b] Glassmeier, 2000

ION FLOW & DENSITY (1)

Polar Plane

- No exospheric ions are injected in the simulation.
- Bow shock shape is controlled by IMF direction.

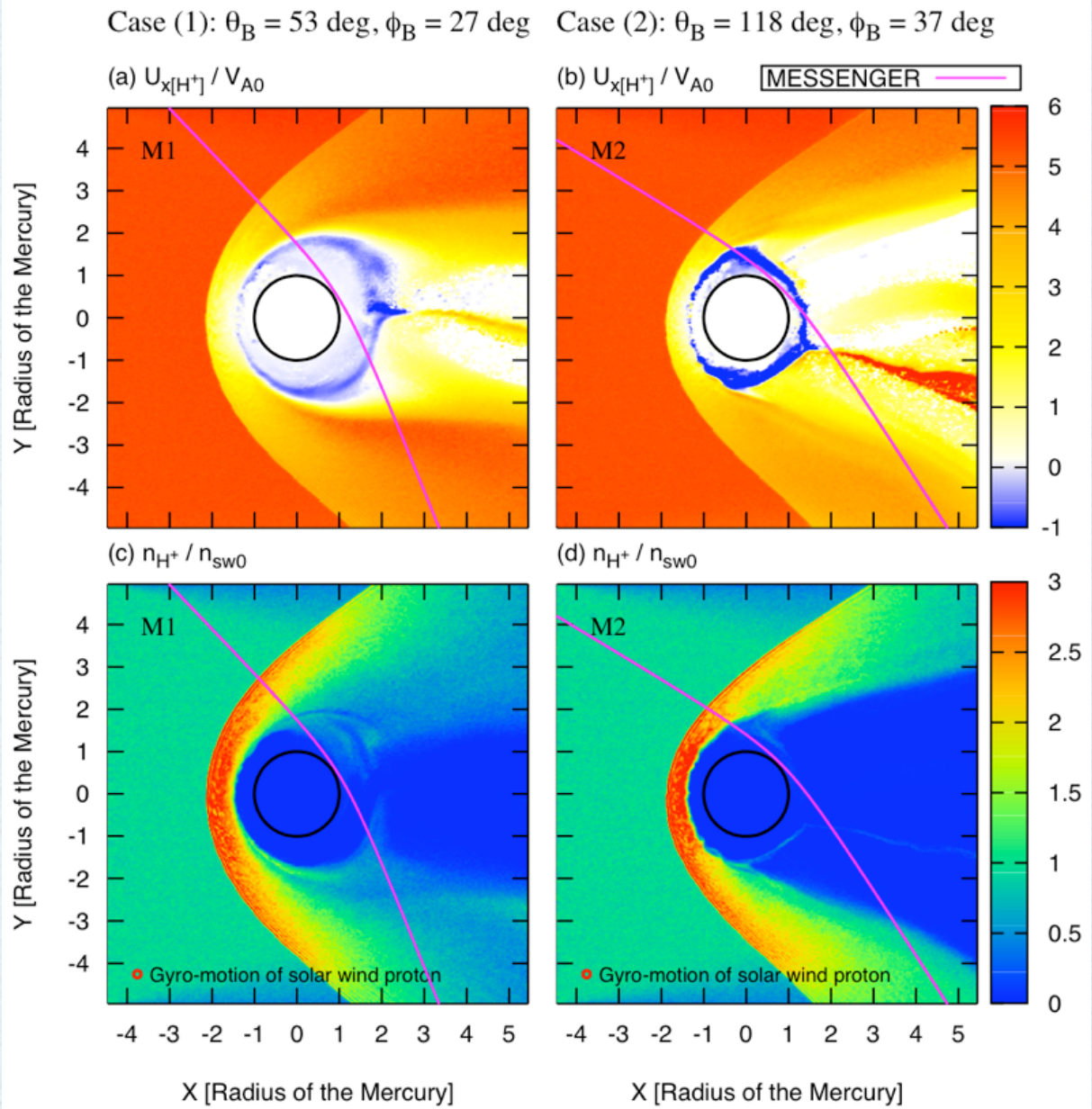


Wang et al., 2010

ION FLOW & DENSITY (2)

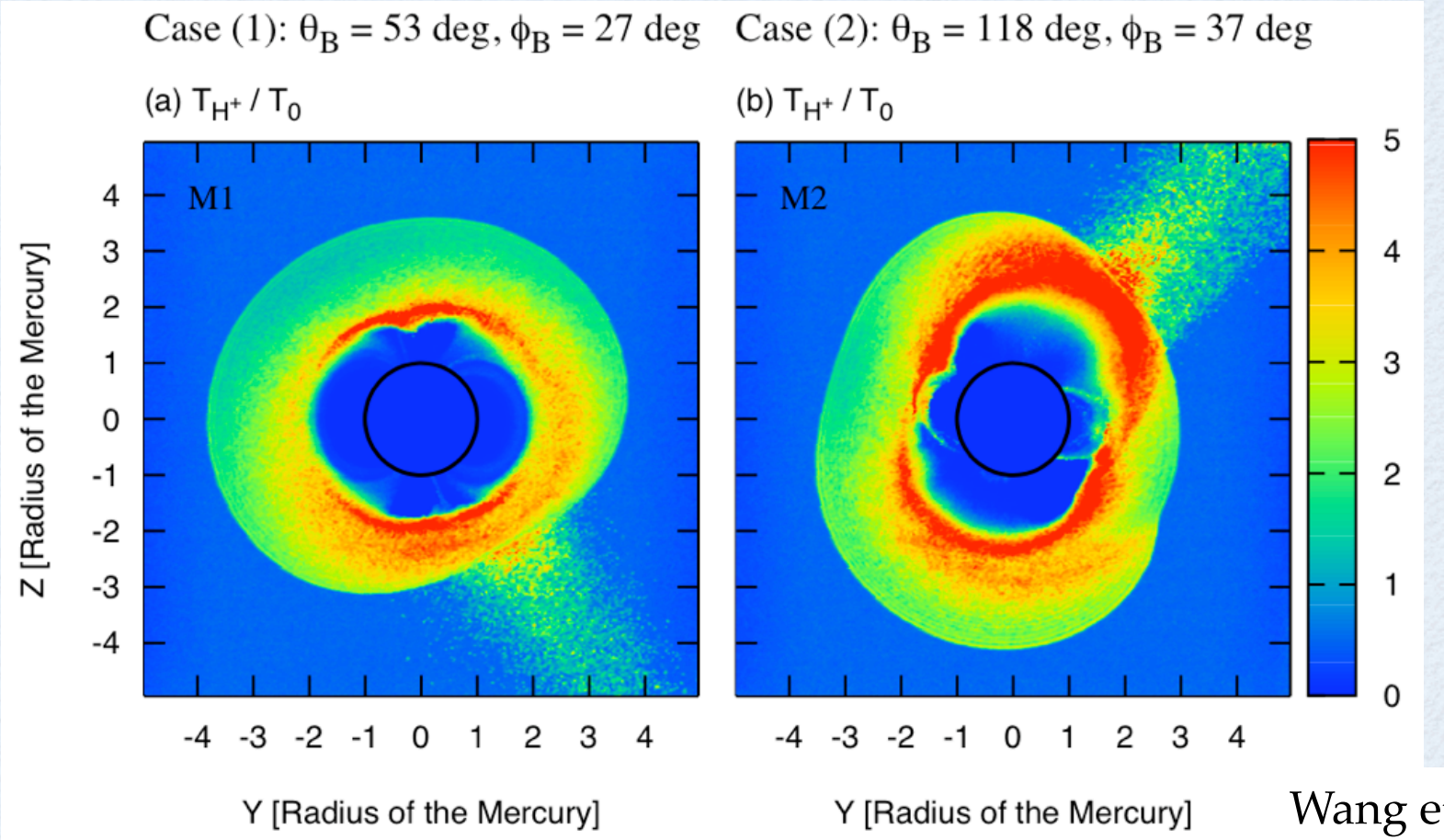
Equatorial Plane

- No stable drift belt.
- Protons would tend to flow sunward toward the magnetosphere.



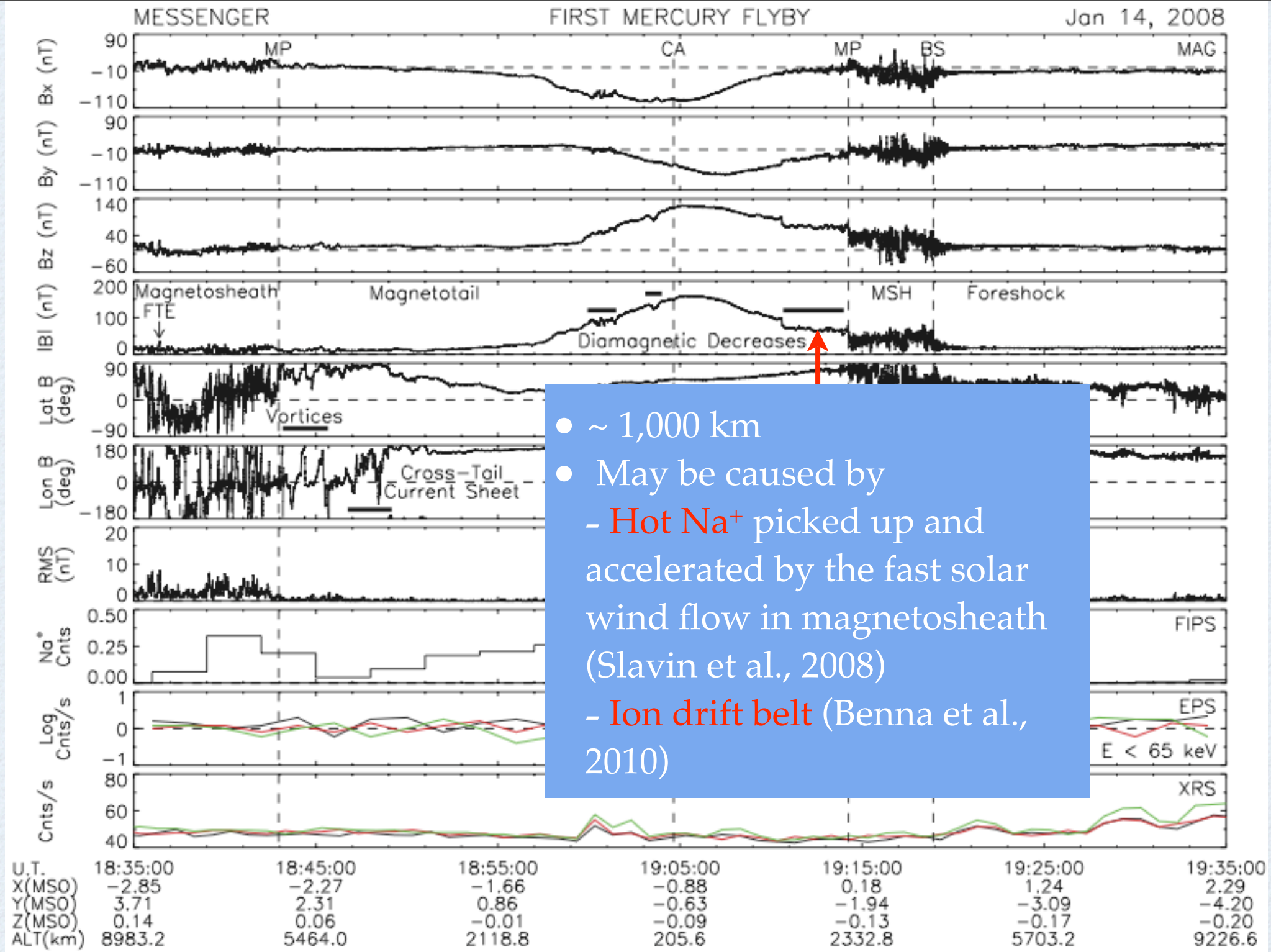
Wang et al., 2010

Bow Shock Structure



Wang et al., 2010

- Proton temperature shows foreshock ions along the open field lines (Trávníček et al., 2007)

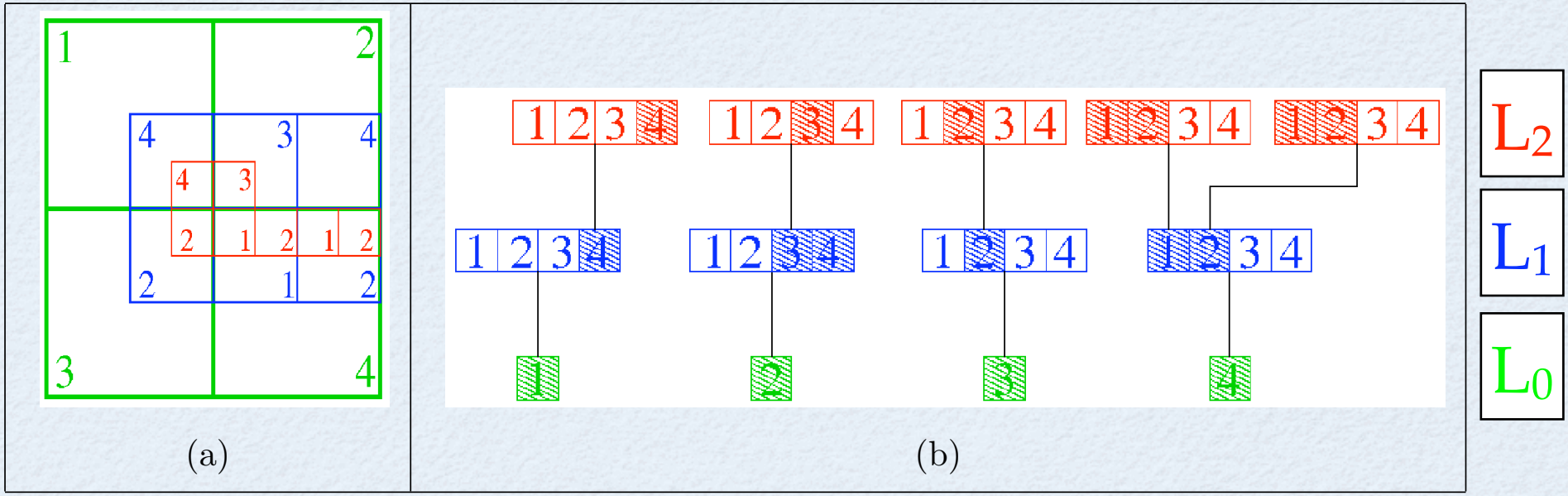


- ~ 1,000 km
- May be caused by
  - Hot Na^+ picked up and accelerated by the fast solar wind flow in magnetosheath (Slavin et al., 2008)
  - Ion drift belt (Benna et al., 2010)

Slavin et al., 2008

ADAPTIVE HYBRID

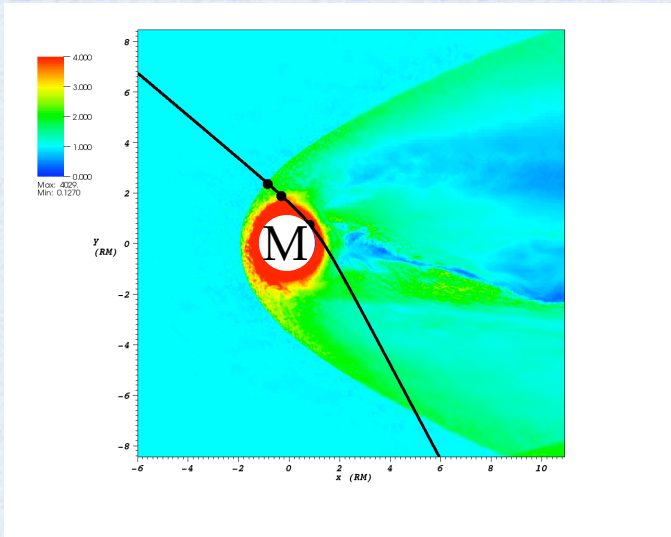
- A new adaptive hybrid code A.I.K.E.F. (Adaptive Ion Kinetic Electron Fluid). (Müller et al., 2010)
- The code could adapt to the physical structures in both space and time.
- Refinement/removement criterions



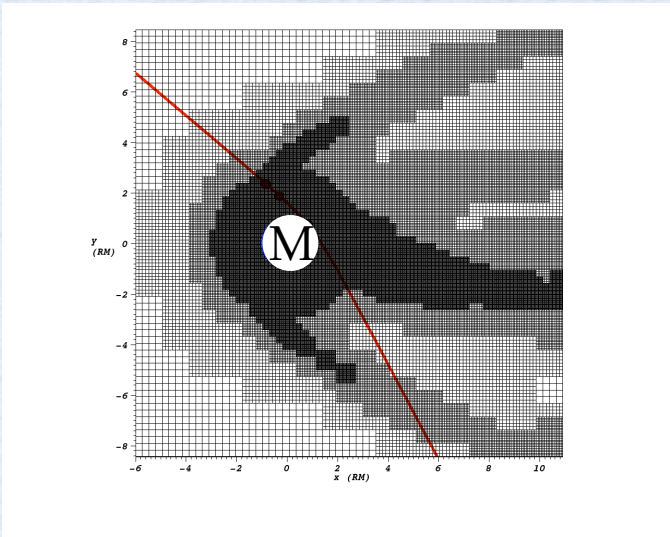
Müller et al., 2010

MESSENGER FLYBYS

flyby 1

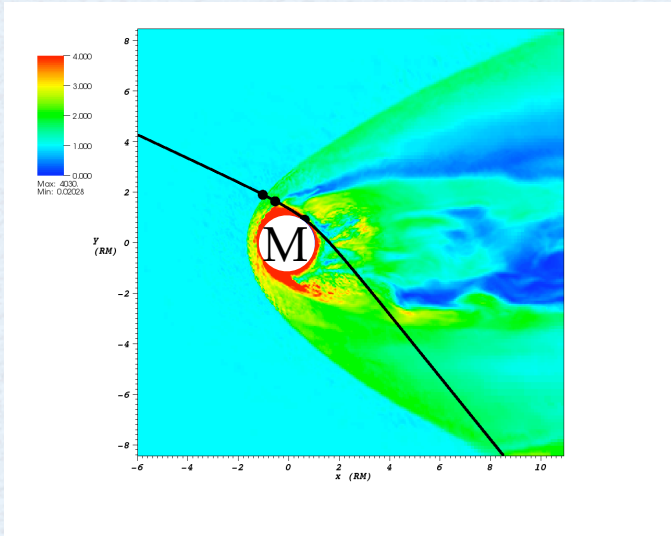


(e)



(f)

flyby 2



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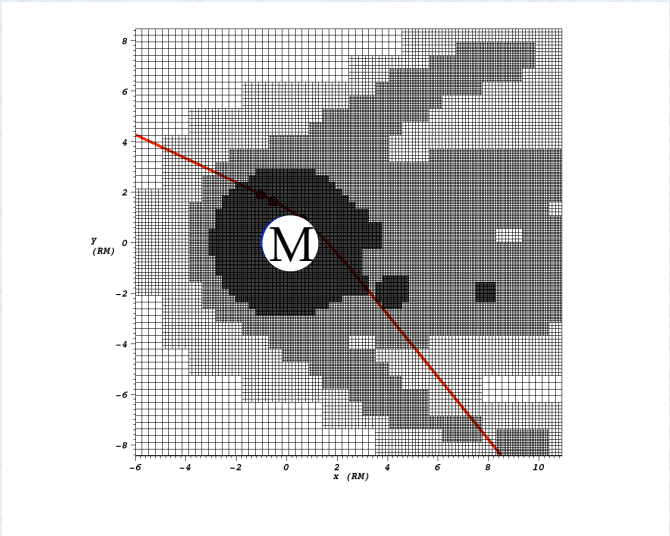
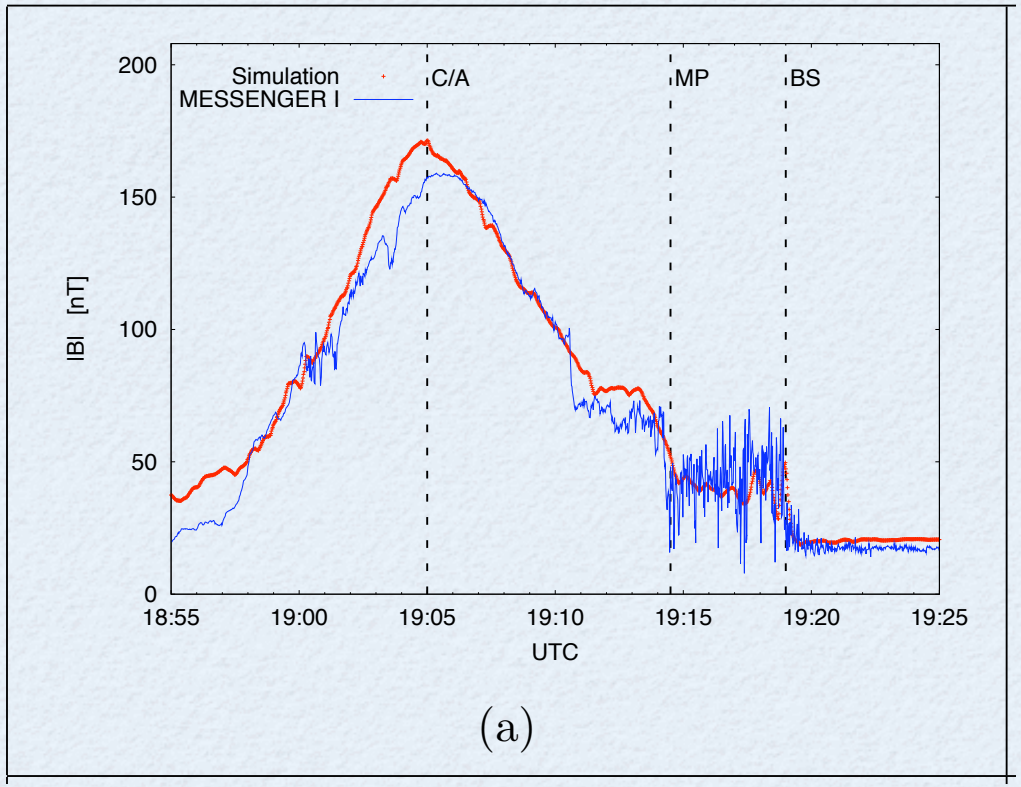


(f)

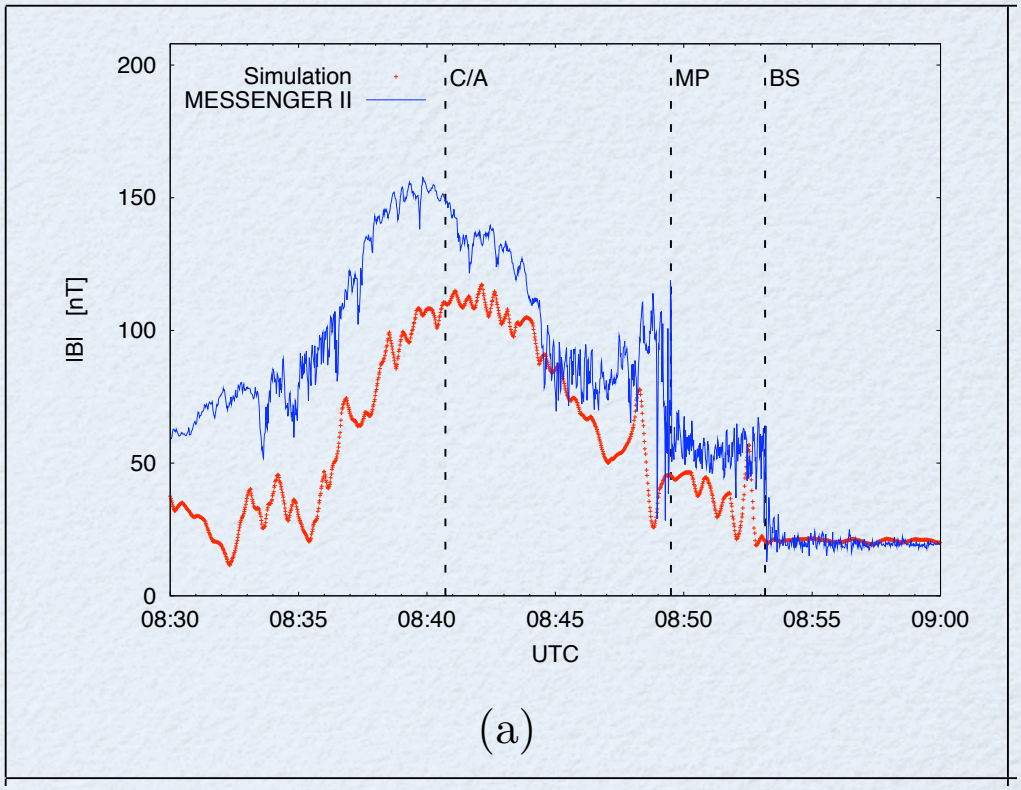
Müller et al., 2010

Magnetic strength

flyby 1



flyby 2



Müller et al., 2010

Magnetopause

- The MP double structure observed could be reproduced by adaptive hybrid (A.I.K.E.F.) simulations without injecting any exospheric ions.
- Details of the plasma flow around Mercury could by studied by the adaptive hybrid (A.I.K.E.F.) model.

PART II

Recent Work on Low Mach Number Solar Wind Interactions

Low Mach Solar Wind

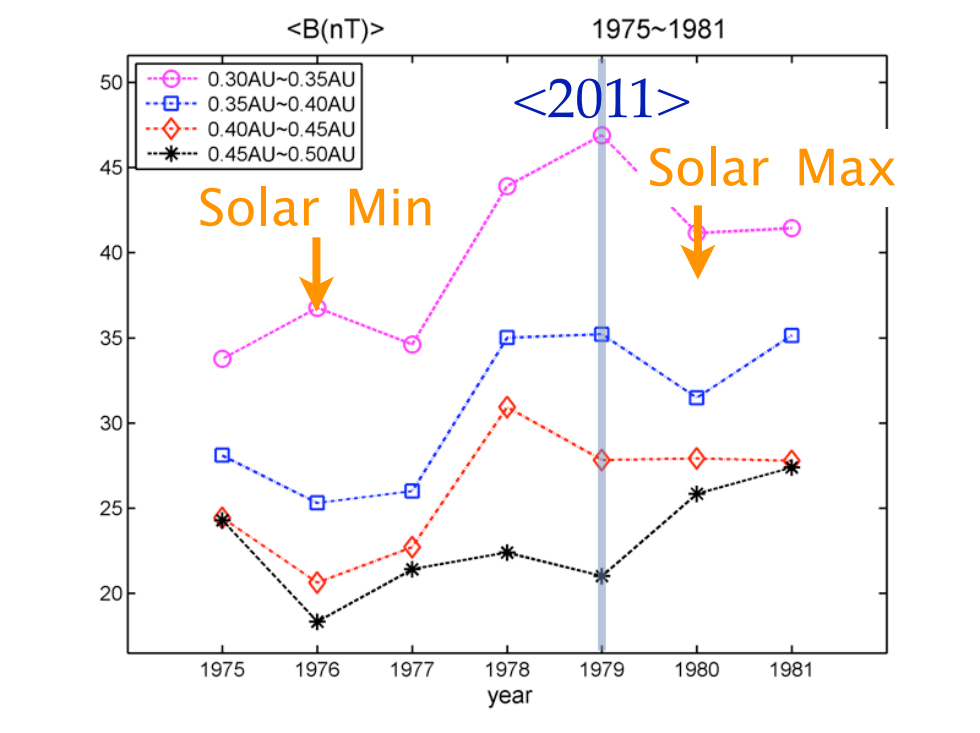
- Lower Alfvén Mach number solar wind near Mercury's orbit. (Russell et al., 1988)
- Na exosphere reactions through larger ion sputtering rate. (Killen et al., 2001)
- ICME events (Liu et al., 2005) → Helios ~ 4 months near Mercury's orbit

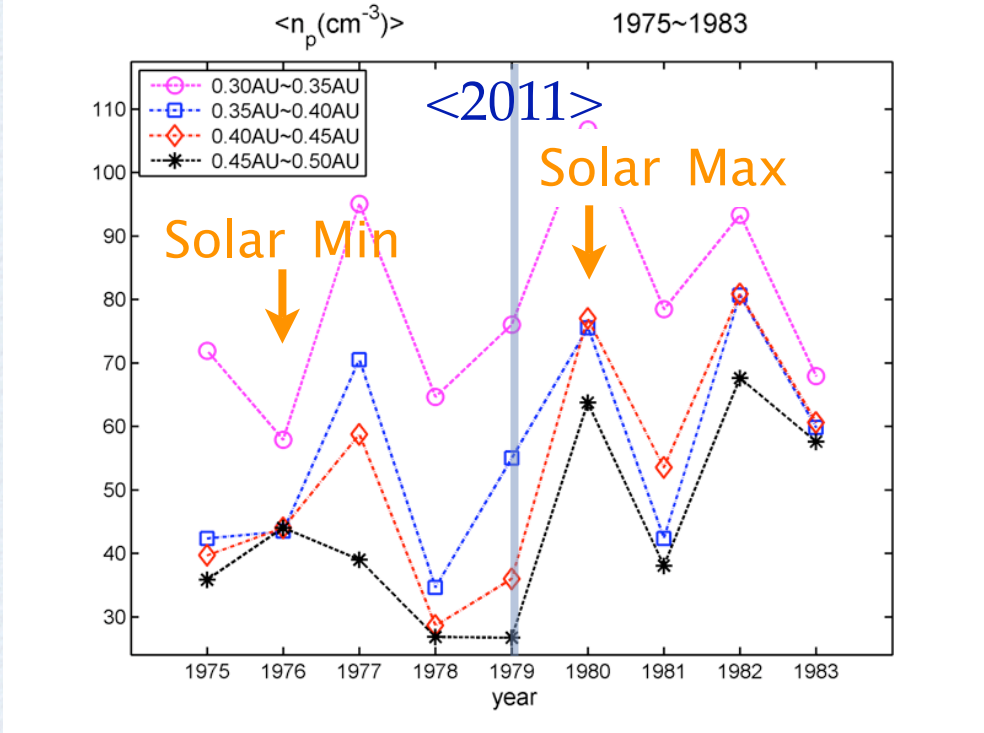
Year	0.3-0.98 AU	0.3-0.5 AU
1975	1	0
1976	0	0
1977	9	2
1978	21	5
1979	22	0
1980	10	0
1981	10	2
1982	1	0
Total	74	9

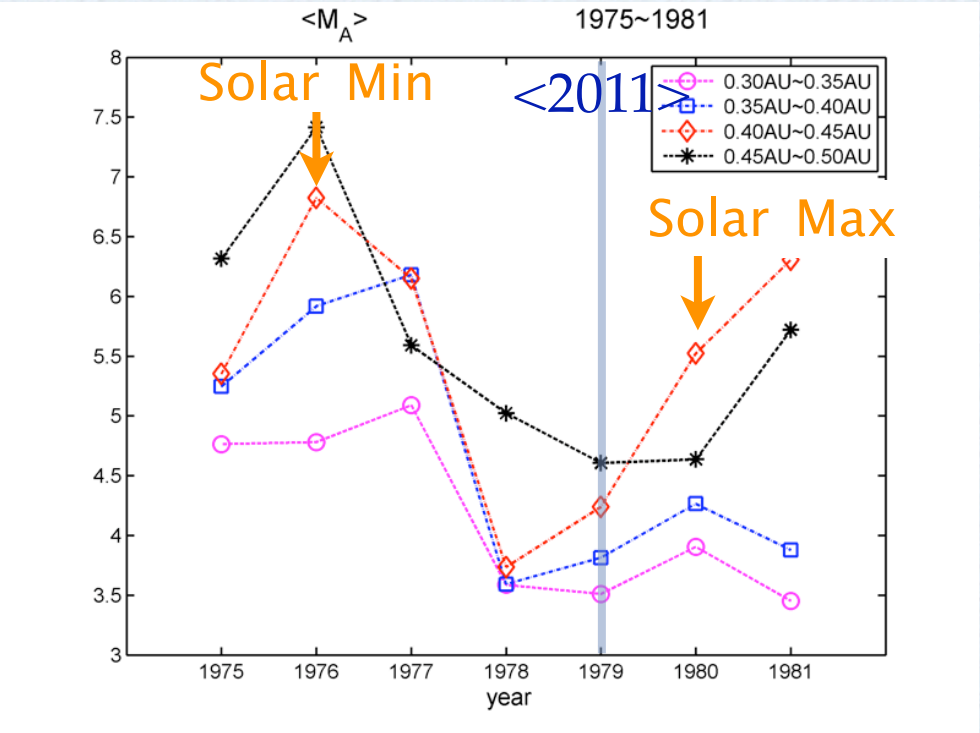
Solar Minimum

Increasing phase <2011>

Solar Maximum


<B(nT)>
1975~1981
0.30AU~0.35AU
0.35AU~0.40AU
0.40AU~0.45AU
0.45AU~0.50AU
<2011>
Solar Min
Solar Max
year


<n_p(cm^-3)>
1975~1983
0.30AU~0.35AU
0.35AU~0.40AU
0.40AU~0.45AU
0.45AU~0.50AU
<2011>
Solar Max
Solar Min
year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Solar Min
<2011>
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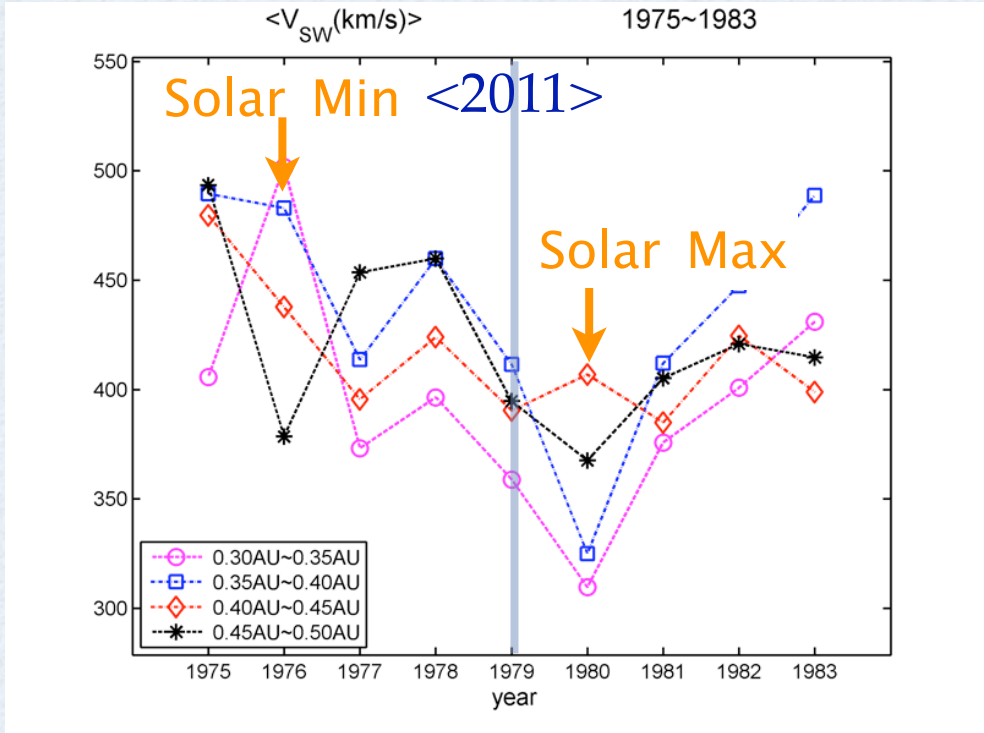
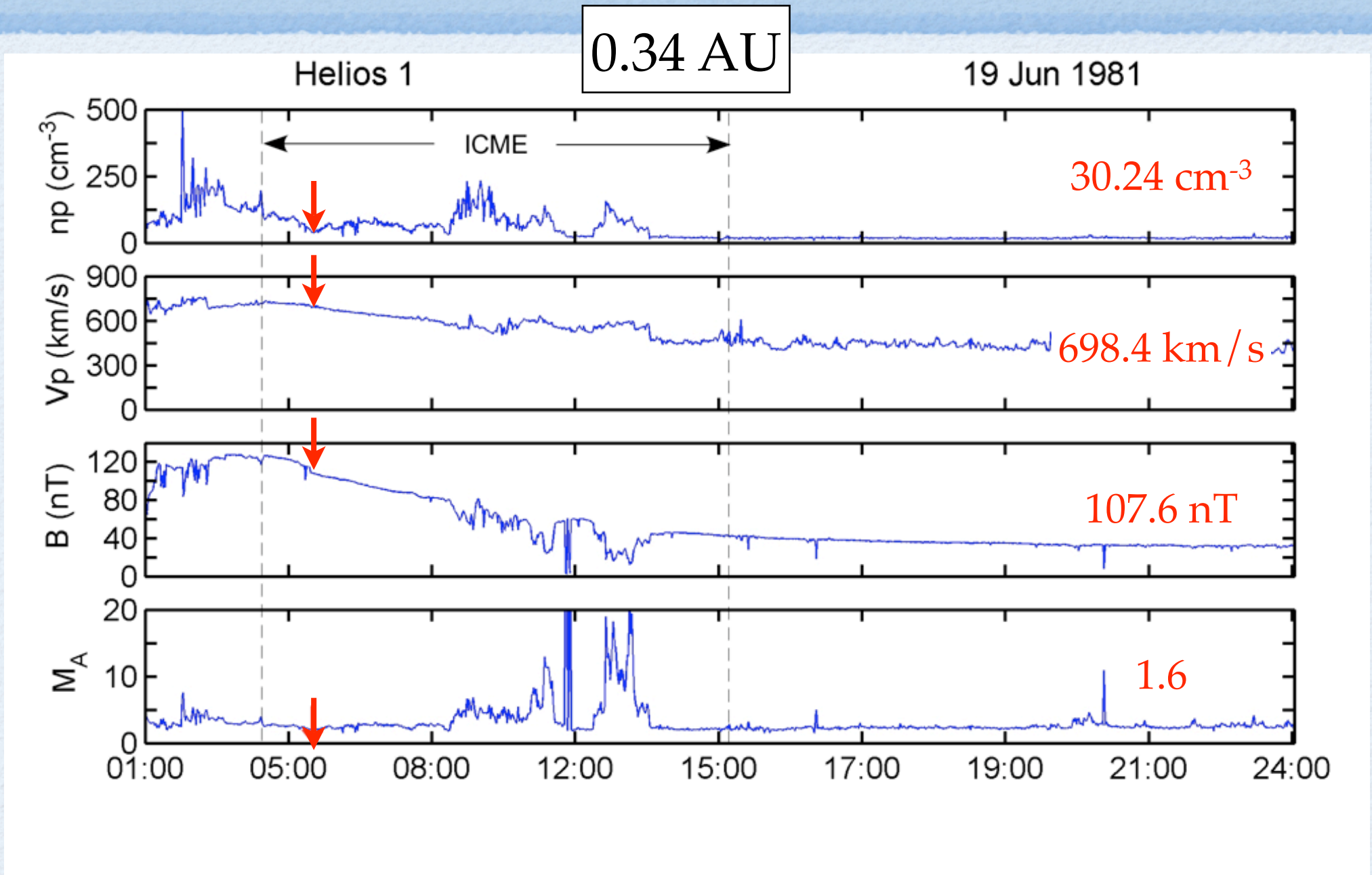
0.40AU~0.45AU
0.45AU~0.50AU
Solar Max
year


<V_SW(km/s)>
1975~1983
Solar Min
<2011>
Solar Max
0.30AU~0.35AU
0.35AU~0.40AU
0.40AU~0.45AU
0.45AU~0.50AU
year

ICME ON 19 JUNE, 1981



INITIALIZATION

	MESSENGER flyby cases	ICME cases
B_{IMF} [nT]	21	107.6
n_{sw0} [cm^{-3}]	32	30.24
V_{sw0} [km/s]	430	698.4
t_0 ($= \Omega_{i0}^{-1}$) [s]	0.496	0.097
v_0 ($= V_{A0}$) [km/s]	81	427
x_0 ($= c/\omega_{p,i0}$) [km]	40.2	41.4
Solar wind ram pressure [nPa]	9.88	24.63
Stand-off distance[a] [R_M]	~ 1.6	~ 1.4
Solar wind flux [cm^{-2} s^{-1}]	1.38×10^9	2.11×10^9
M_{A0} ($= V_{sw0}/V_{A0}$)	5.3	1.6
M_{F0} ($= V_{sw0}/V_{F0}$)	3.76	1.16

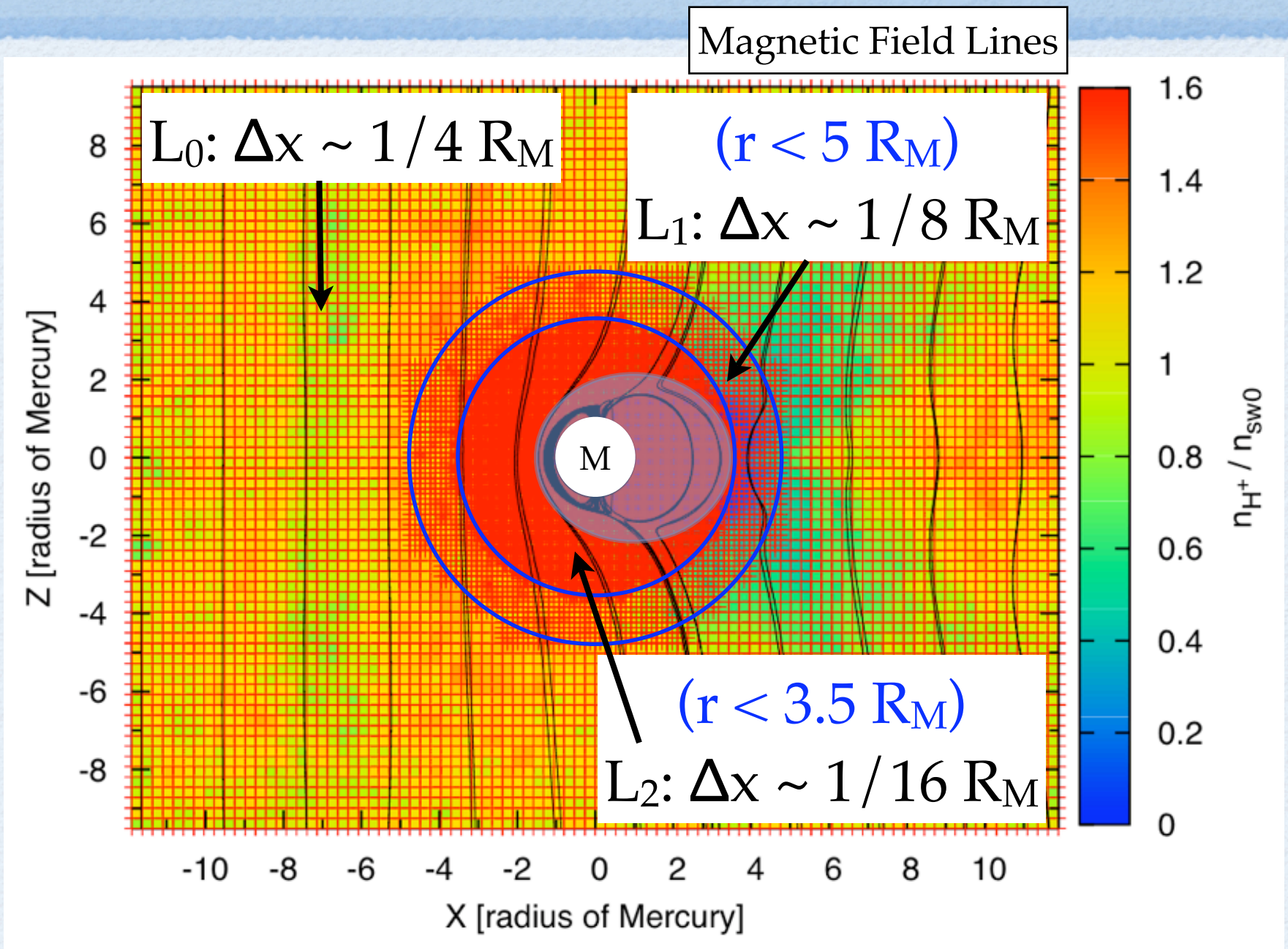
[a]Siscoe and Christopher, 1975

$$V_{S0} \approx \sqrt{\frac{\gamma(\beta_{i0} + \beta_{e0})}{2}} V_{A0}$$

$$V_{F0} \approx \sqrt{V_{S0}^2 + V_{A0}^2} = \sqrt{2} V_{A0} \text{ , if } \gamma = 2,\ \beta_{i0} = \beta_{e0} = 0.5$$

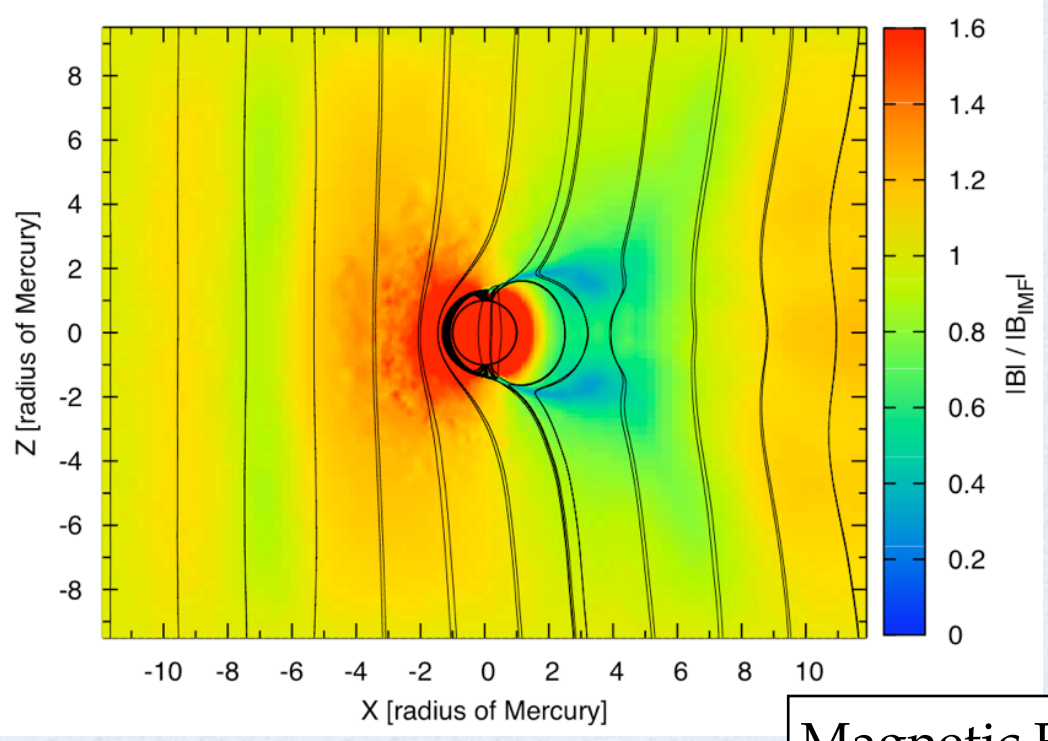
(β_{i0} might be much smaller in reality)

ADAPTIVE MESHES

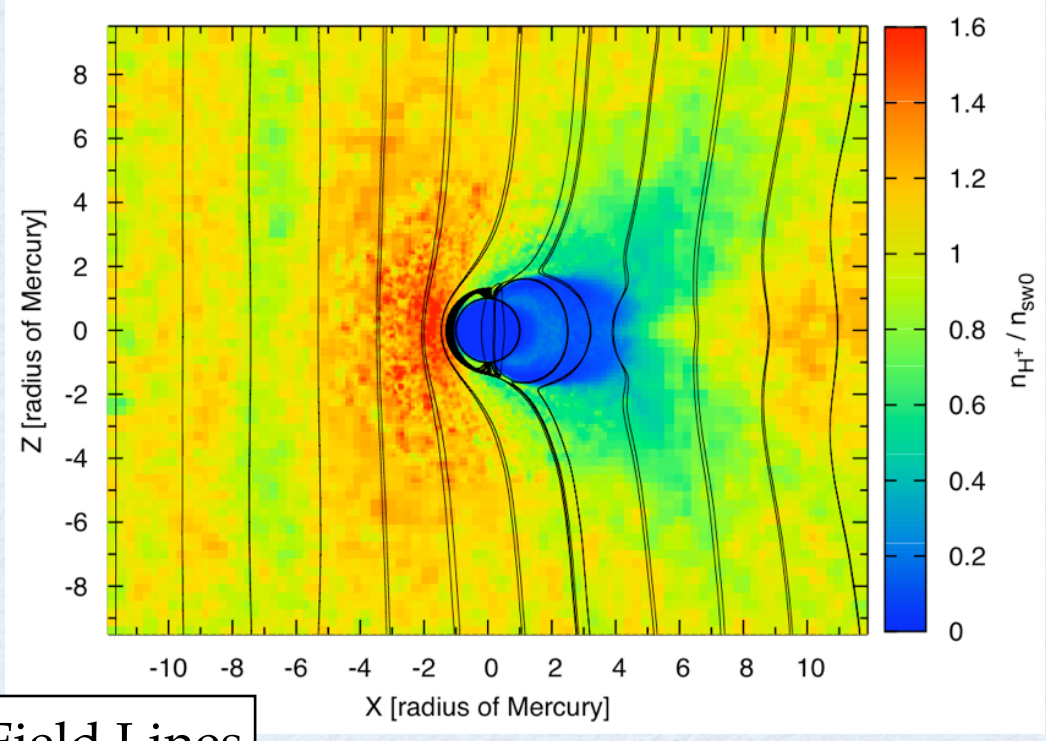


Northward IMF: B_{IMF} = (0,0,+107) nT

| B |



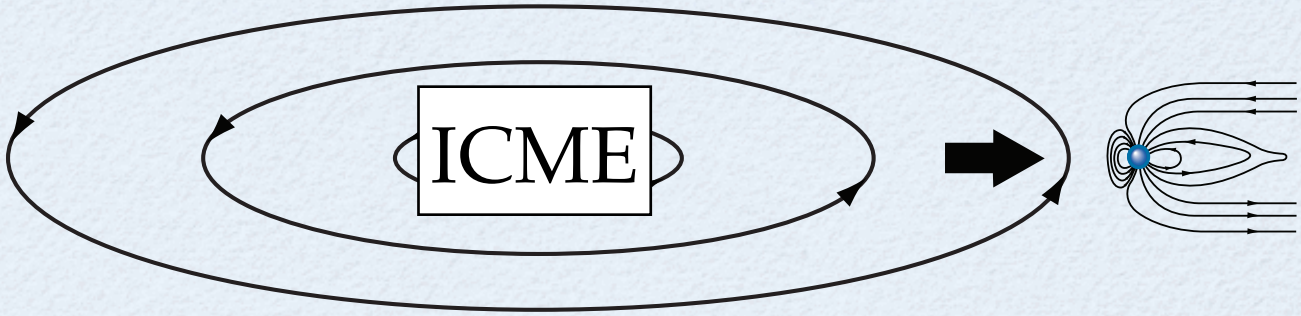
n_{H+}

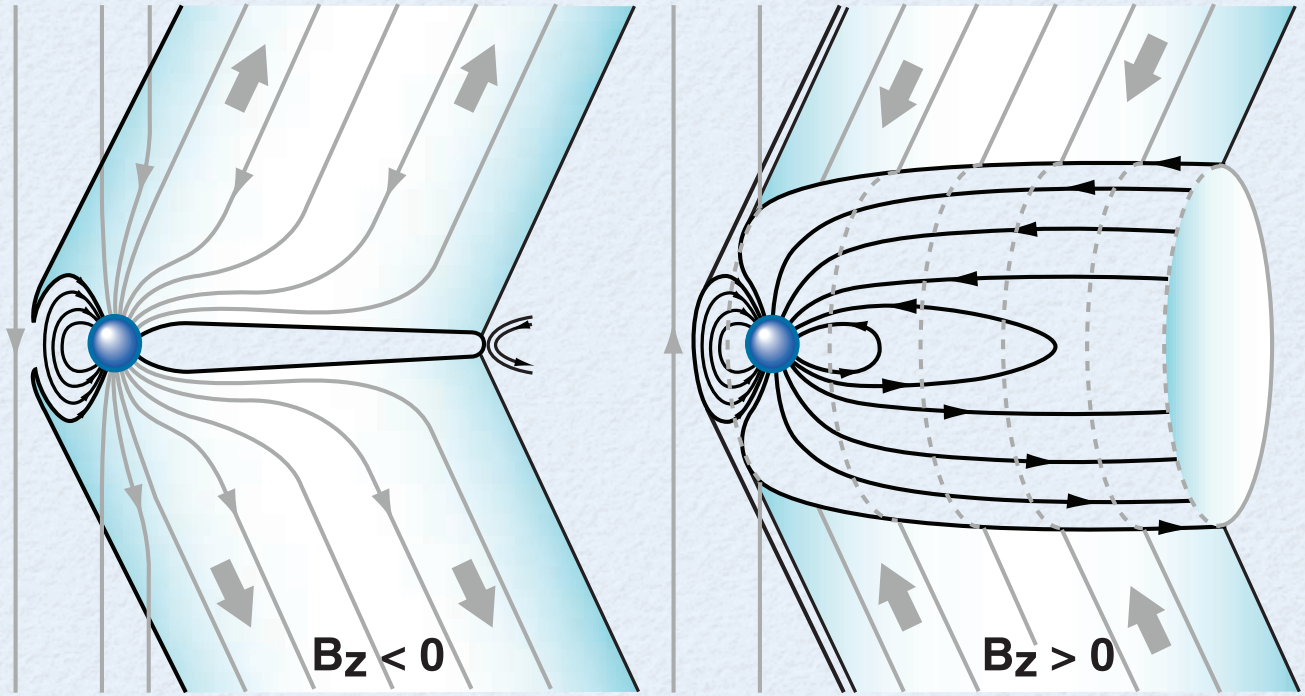


Magnetic Field Lines

- Alfvén wing perturbation (Sarantos and Slavin, 2009)

Alfvén Wing Perturbations

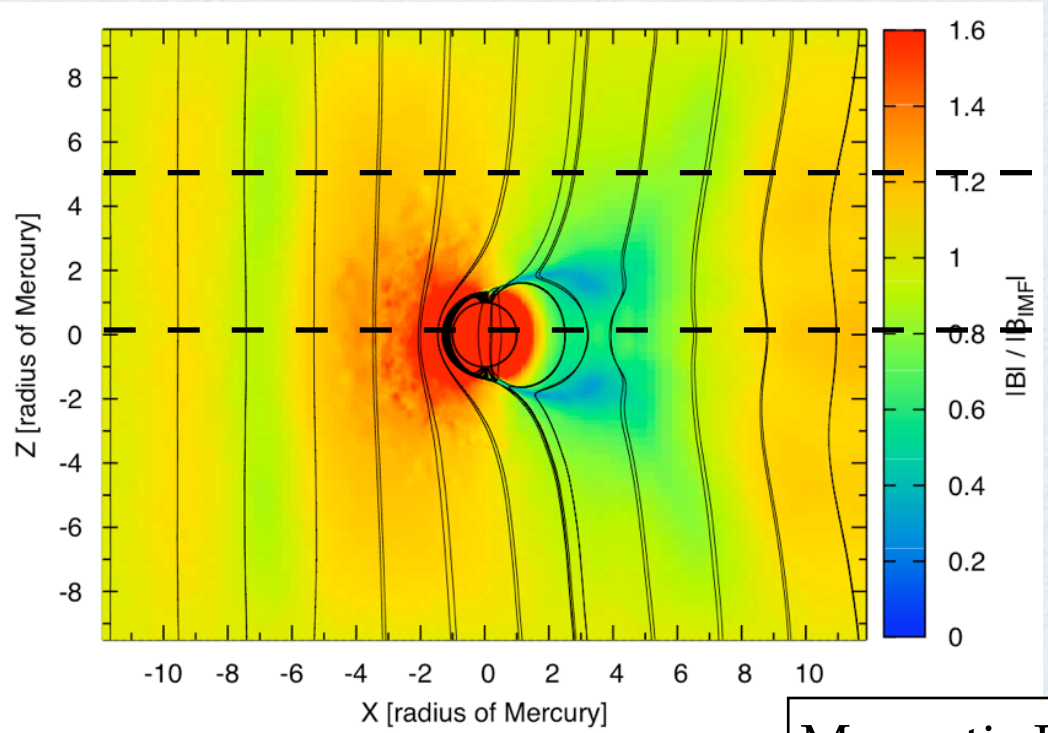




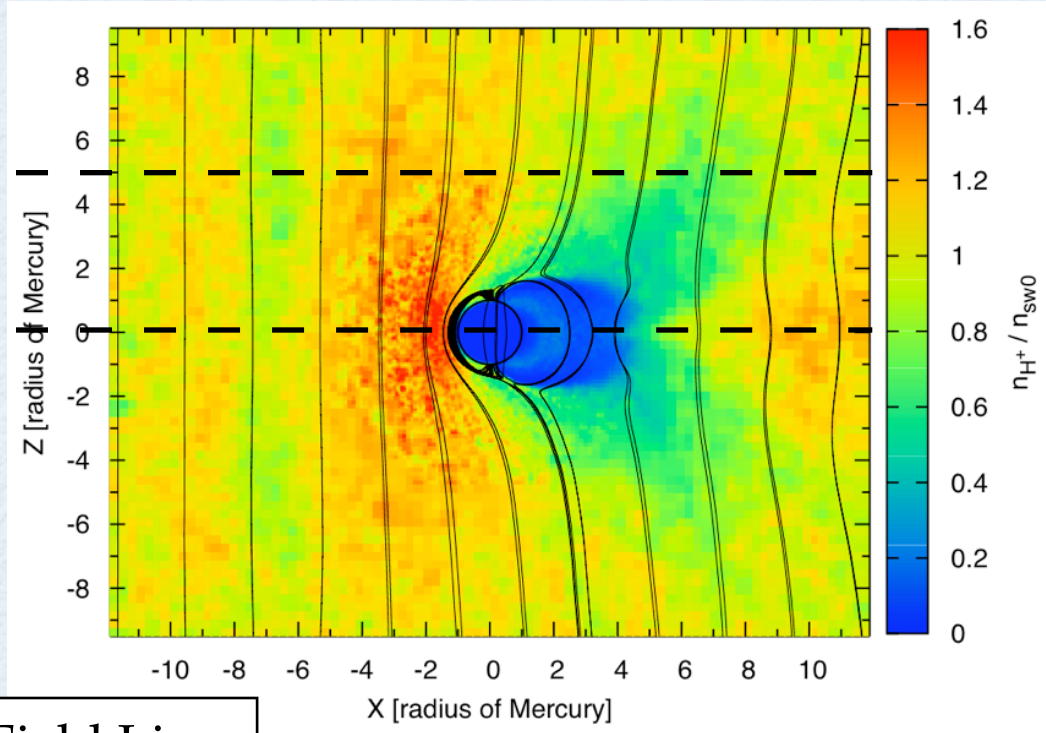
Sarantos and Slavin, 2009

Northward IMF: B_{IMF} = (0,0,+107) nT

| B |



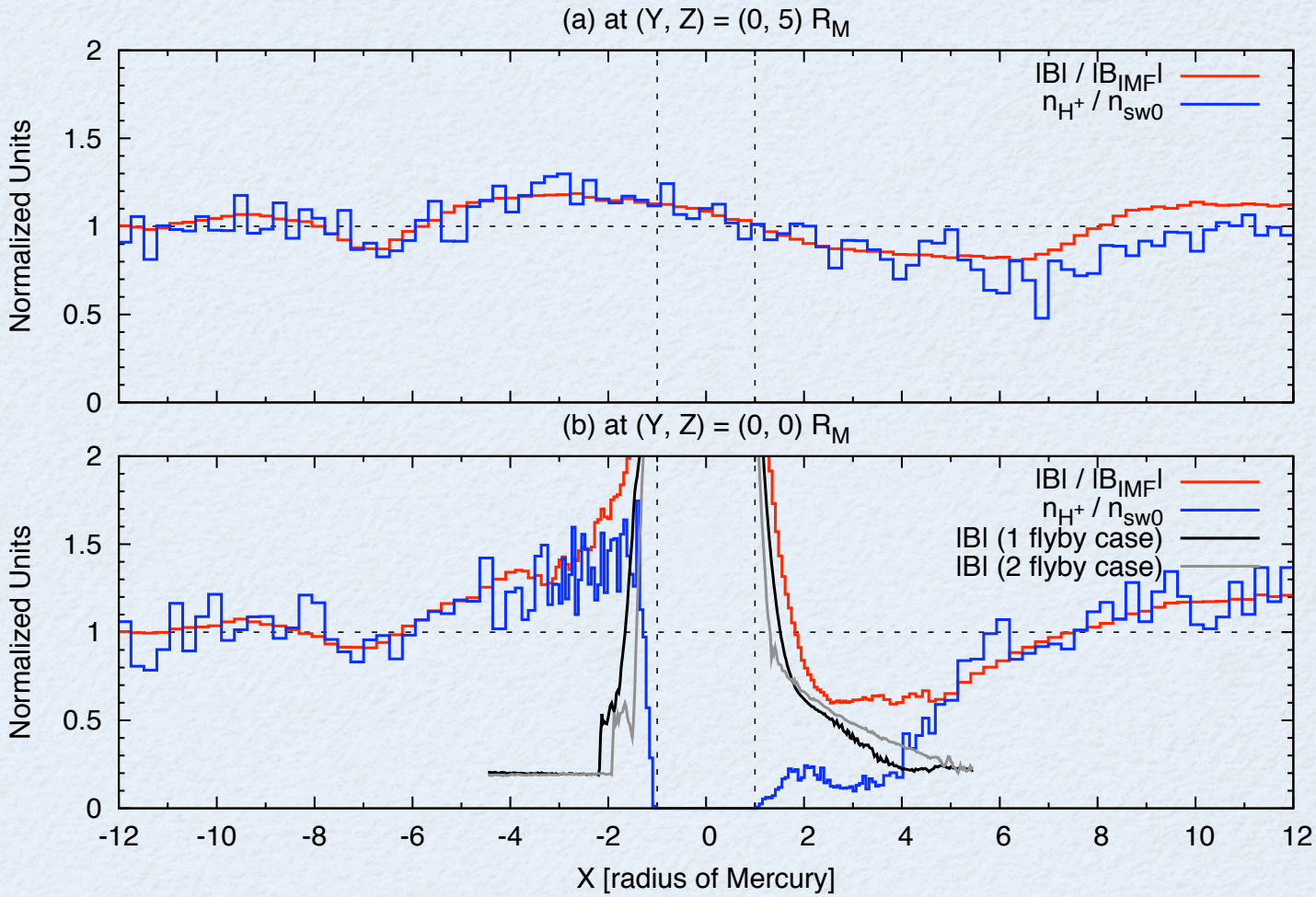
n_{H+}



Magnetic Field Lines

- Bow shock ? → Fast-mode wave

FAST-MODE WAVE

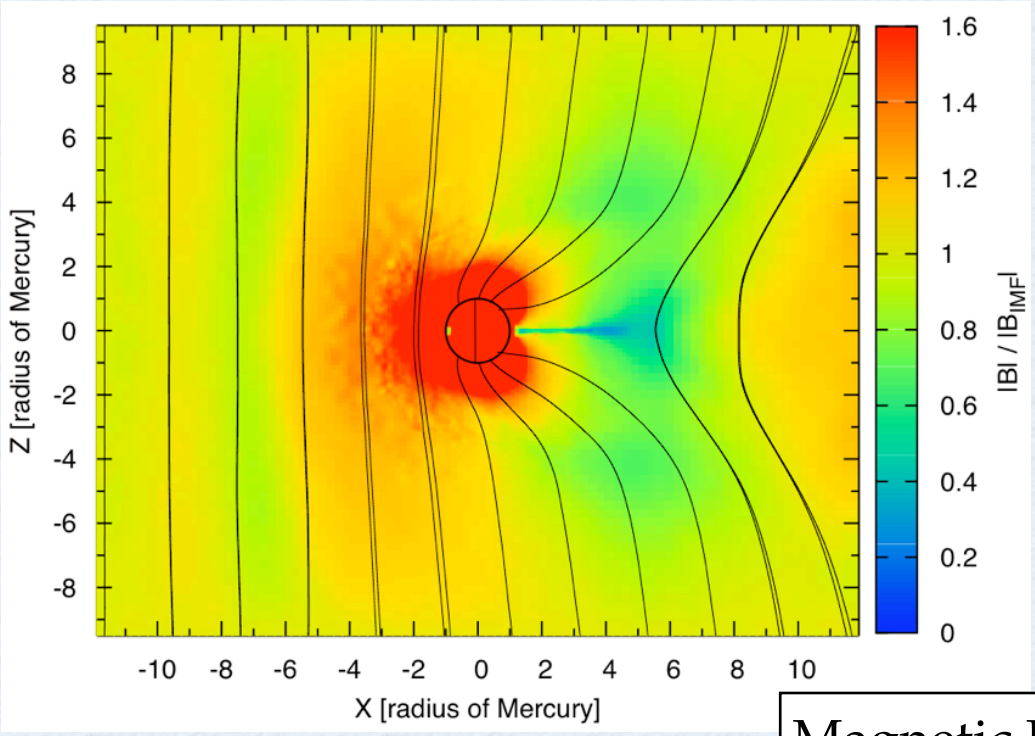


- Fast-mode wave → Amplitude ~ 20% of the solar wind value

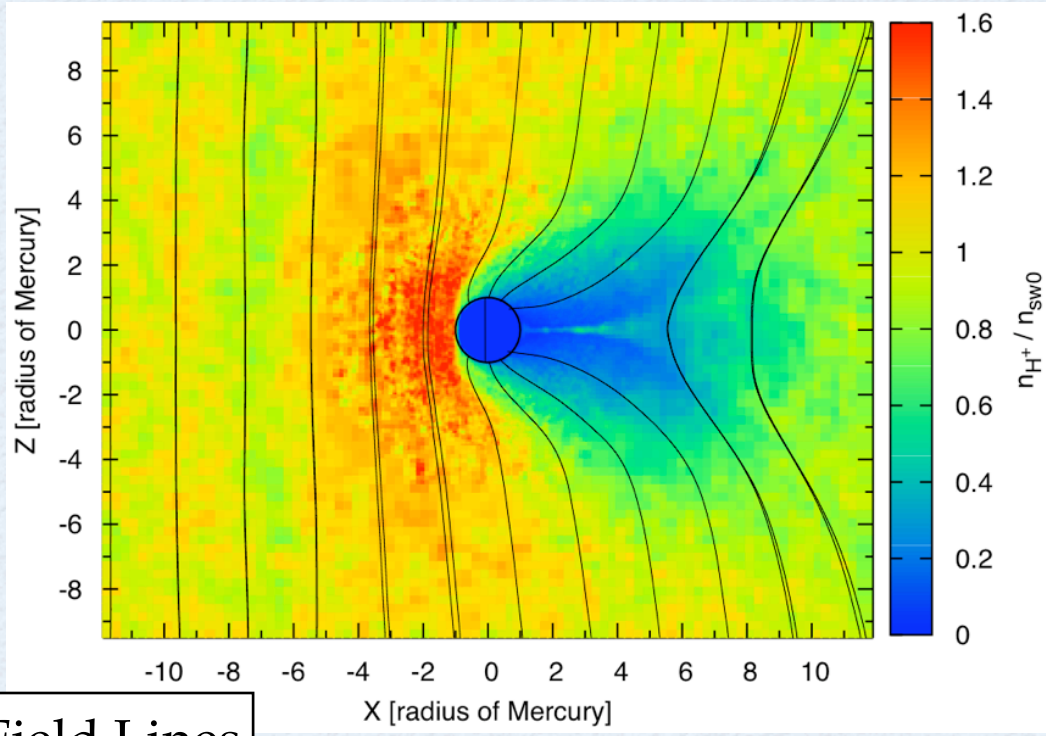
  Wavelength ~ 14 R_M (-6 ~ 8 R_M)

Southward IMF: B_{IMF} = (0,0,-107) nT

| B |



n_{H+}



Magnetic Field Lines

- Fast-mode wave and Alfvén wing perturbation
- Reconnection sites locate near the equatorial surface of Mercury.

➡ Direct impact of solar wind ions is possible

PART II.2

Low Mach Number Solar Wind Interactions

Exospheric Responses

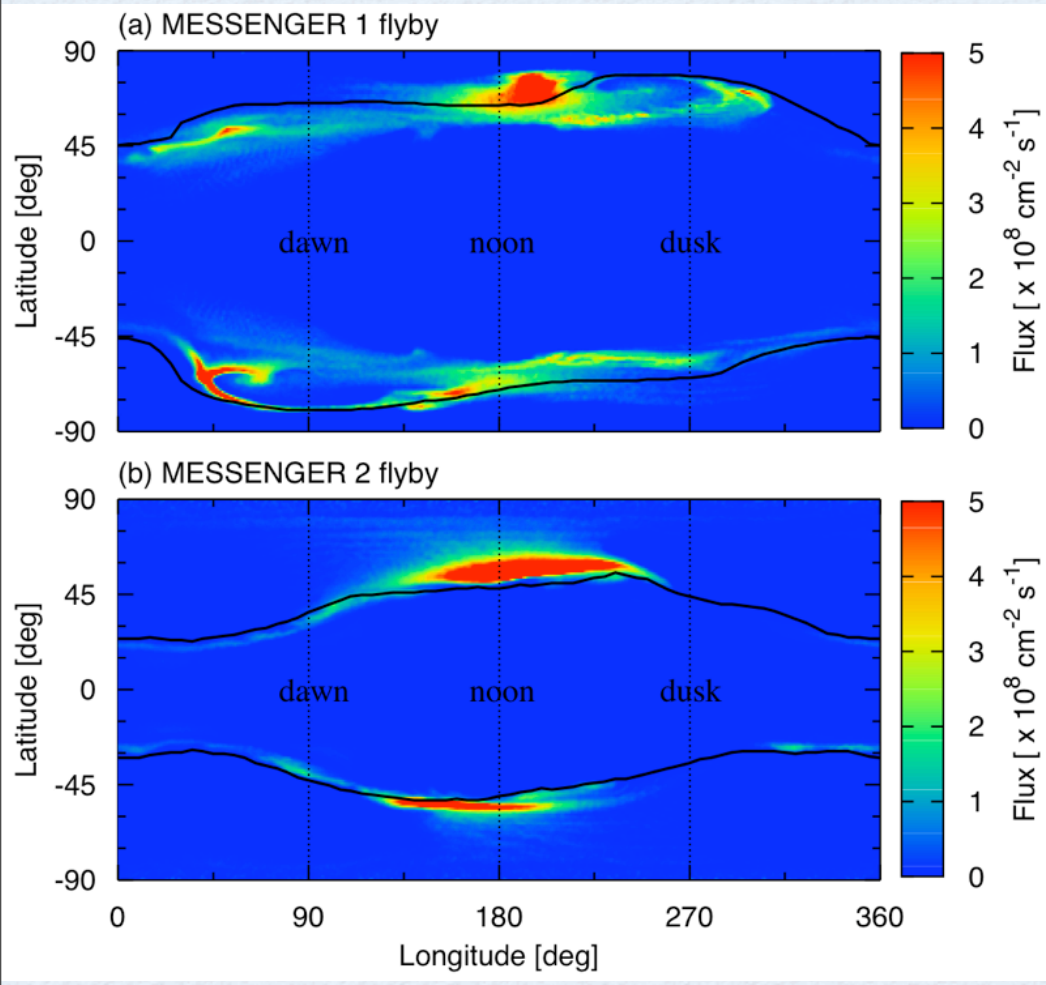
Ion Precipitation Rate

	MESSENGER 1 flyby	ICME (northward IMF)
Total precipitation rate [$\times 10^{25}$ s^{-1}]	1.58	6.91
Day-side precipitation rate [$\times 10^{25}$ s^{-1}]	0.94	5.69
Day-side precipitation percentage	59.3%	82.3%
	MESSENGER 2 flyby	ICME (southward IMF)
Total precipitation rate [$\times 10^{25}$ s^{-1}]	1.51	18.86
Day-side precipitation rate [$\times 10^{25}$ s^{-1}]	1.38	16.08
Day-side precipitation percentage	91.8%	85.3%
	MESSENGER flyby cases	ICME cases
$F_{sw0} \times \pi R_M^2$ [$\times 10^{26}$ s^{-1}]	2.57	3.95
Solar wind precipitation rate	(6 ± 0.15)%	$(17.49 \sim 47.75)$%
Gird size near surface [$c/\omega_{p,i0}$]	1.5	3.89

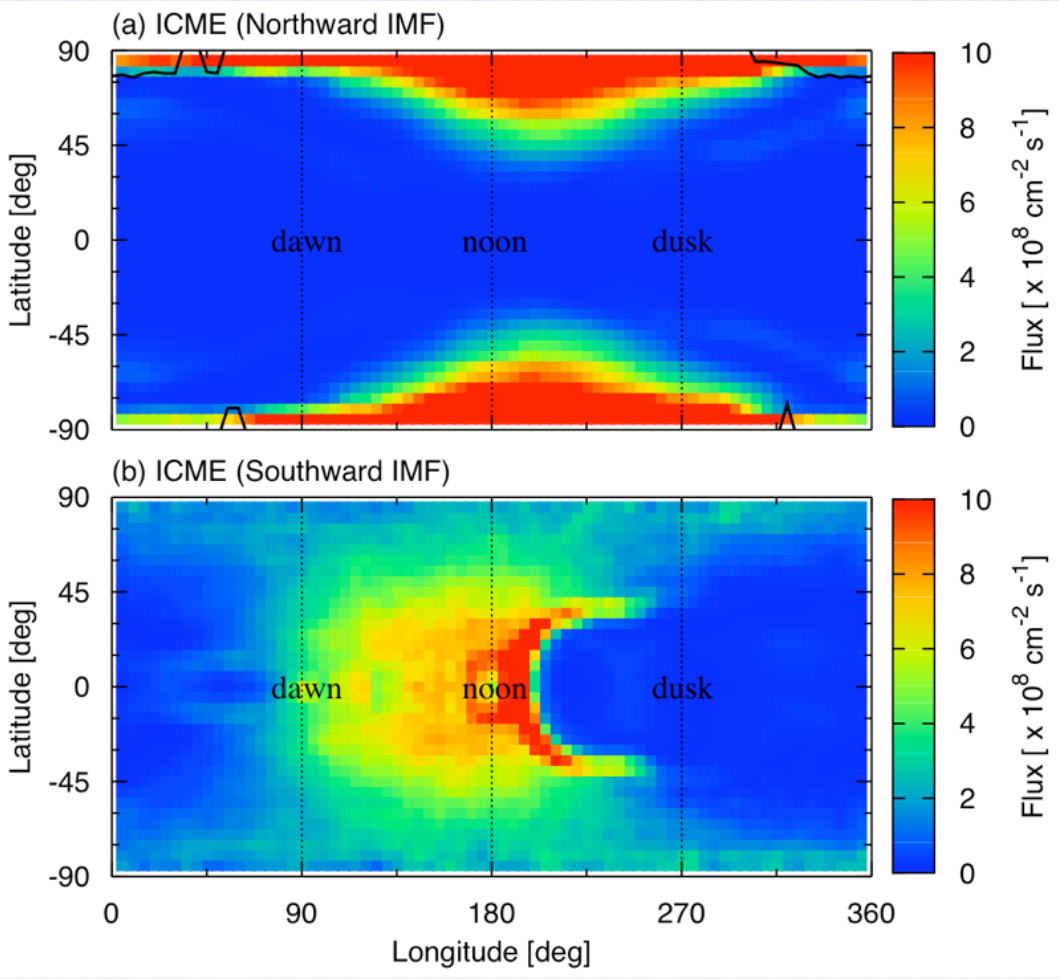
- ➡ICME seems to induce more ion precipitation on the surface.
- ➡However, the errors arose from the grid size differences should be notified.

ION PRECIPITATION MAP

MESSENGER flyby cases



ICME cases



Na Exosphere Model

- Monte-Carlo method is used to trace 10,000 Na atoms with the influence of solar radiation pressure.
- Thermal accommodation rate (β) and photoionization rate ($R_{loss} \sim 1.08 \times 10^{-4}\ s^{-1}$ at 0.386 AU) are taken into consideration.
- Ion precipitation distributions are treated as the ion sputtering source distributions.

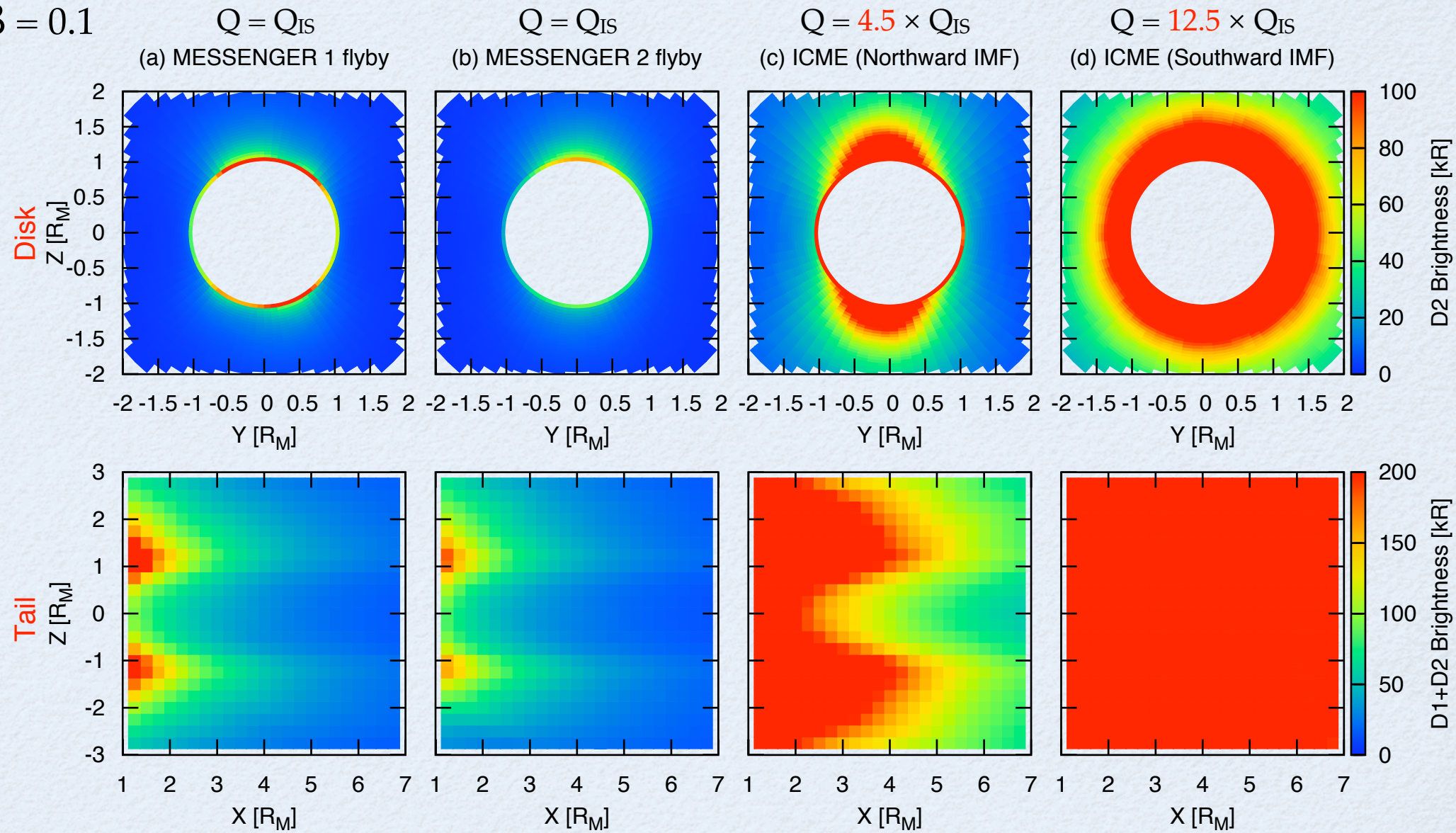
Ion Sputtering

Steady-State Na exosphere

$\theta_{TAA} = 290$ deg

$\beta = 0.1$

Assume $Q_{IS} = 3.2 \times 10^{24}\ s^{-1}$



Photon Stimulated Desorption (PSD)

- Mura et al., 2009
  - $2H + Na_2SiO_3 \rightarrow 2Na + SiO_2 + H_2O$ (Potter, 1995)
  - H reacts with the Na bearing rock and liberate Na atoms from their chemical bounds in crystal.
  - Atomic Na can be easily released into the exosphere by thermal desorption or photon stimulated desorption (PSD).

➡ Day-side precipitation for PSD

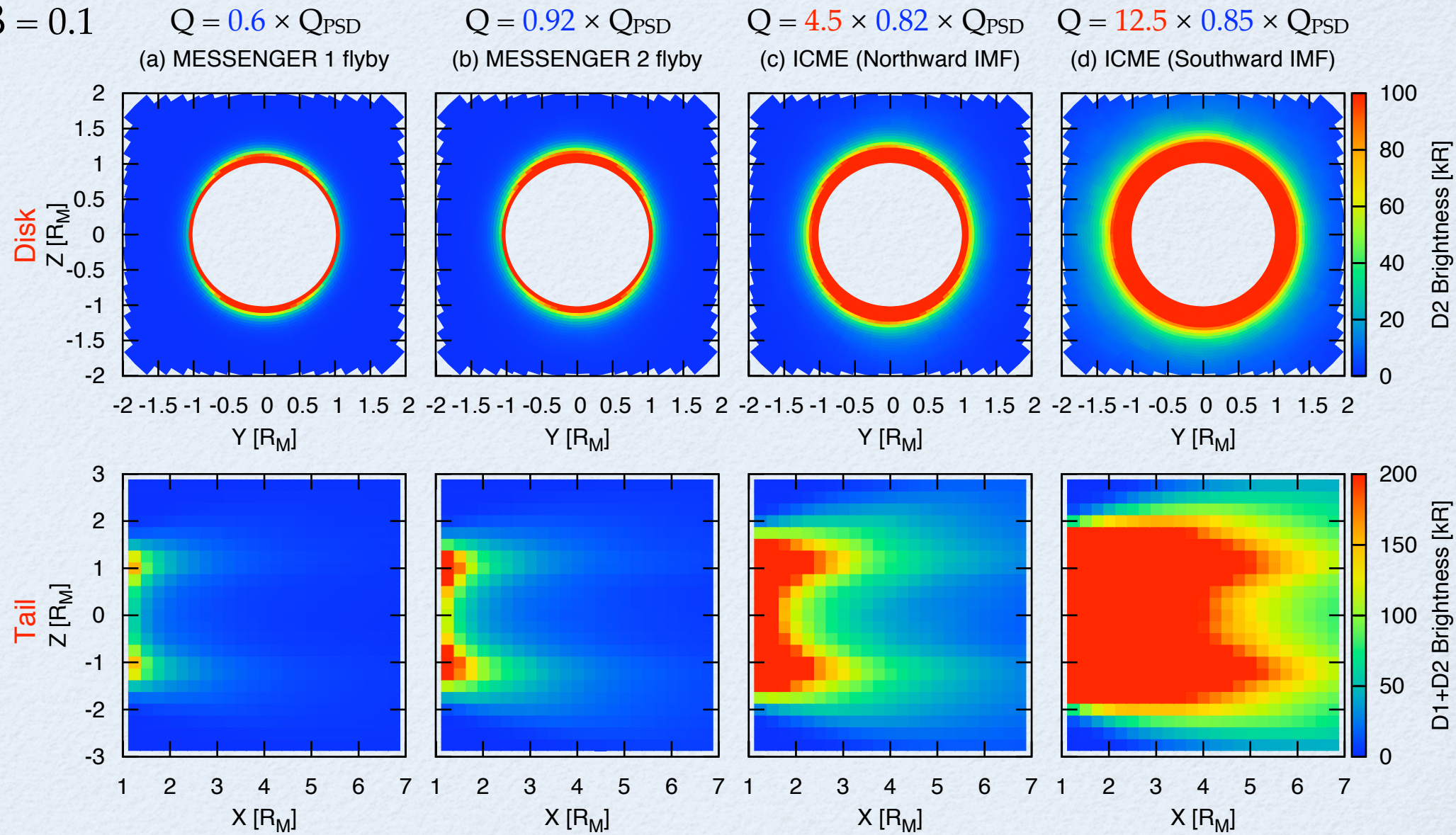
PSD FROM PROTON LIBERATION

Steady-State Na exosphere

$\theta_{TAA} = 290$ deg

$\beta = 0.1$

Assume $Q_{PSD} = 3 \times 10^{24}\ s^{-1}$



SUMMARY

- In the phase of increasing solar activities, more low Mach solar wind interactions are expected. (MESSENGER in orbit)
- Fast-mode wave and Alfvén wing perturbations could be observed with $M_A \sim 1.6$
- Direct impact of solar wind ions at subsolar region is possible with ICME interactions while IMF is southward.
- Ion precipitation rates should be verified with finer grid simulations in the future.

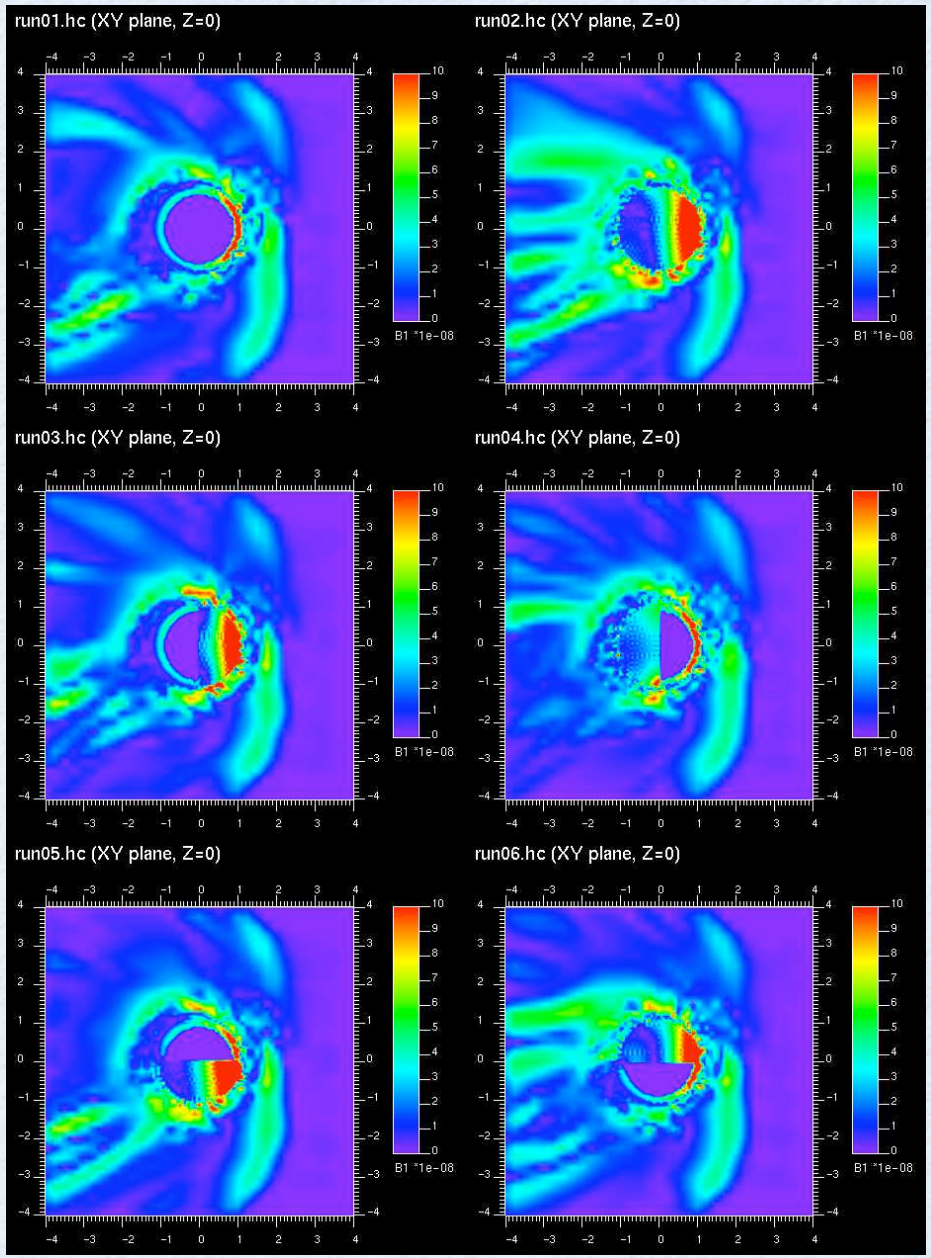
FUTURE WORK

- Distributions of pick up Na^+ and other exospheric ions could be studied with 3D hybrid model or the resultant electromagnetic fields from hybrid simulation.
- Time-dependent model is needed to investigate the dynamical magnetosphere-exosphere coupling in the future.
- Comments and suggestions are most welcome.

THANK YOU

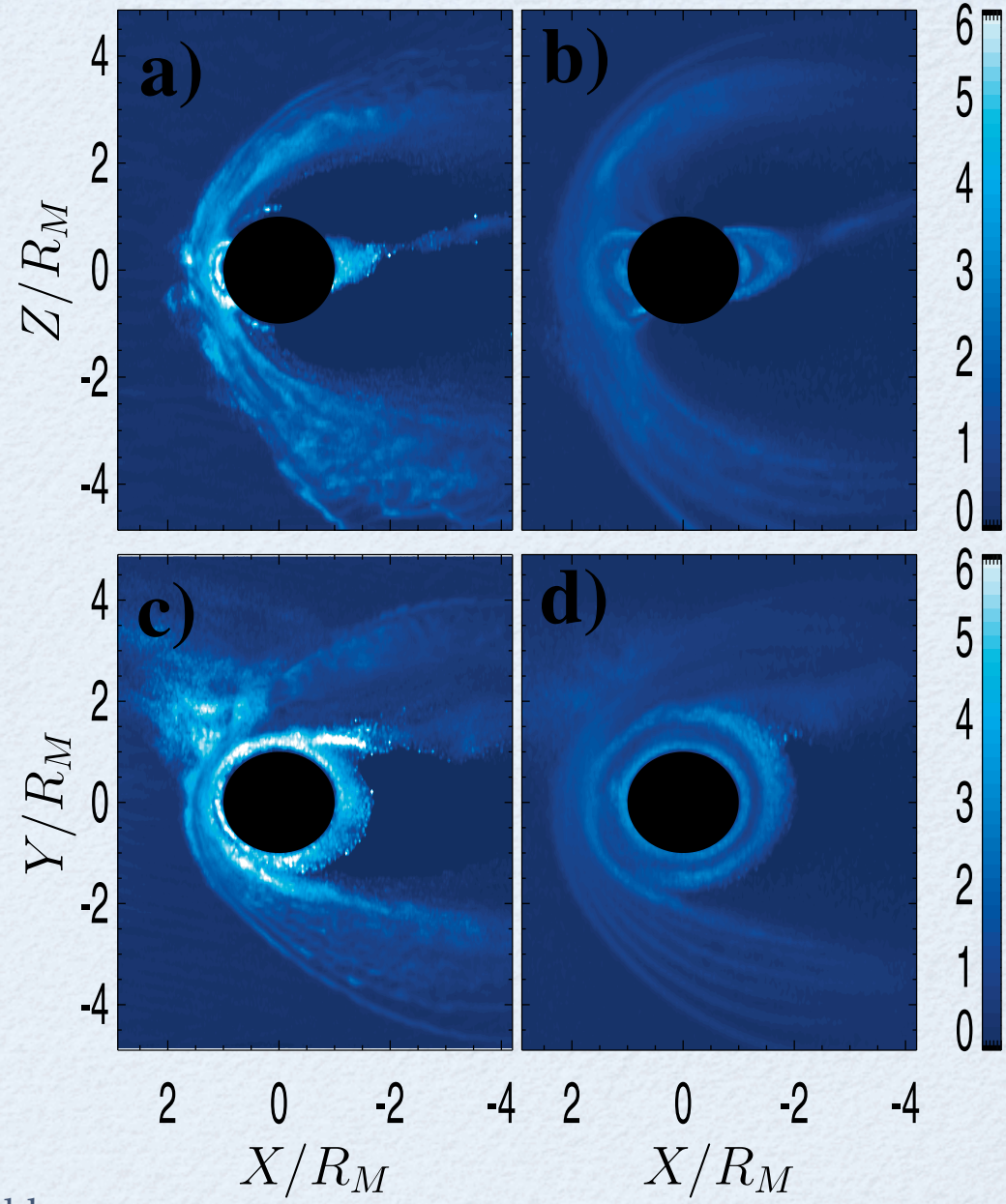
SURFACE CONDUCTIVITY

- Janhunen and Kallio, 2004
  - Perturbation magnetic field B_1 in the equatorial plane.
  - B_1 field penetrates only the poorly conducting parts of the planet.

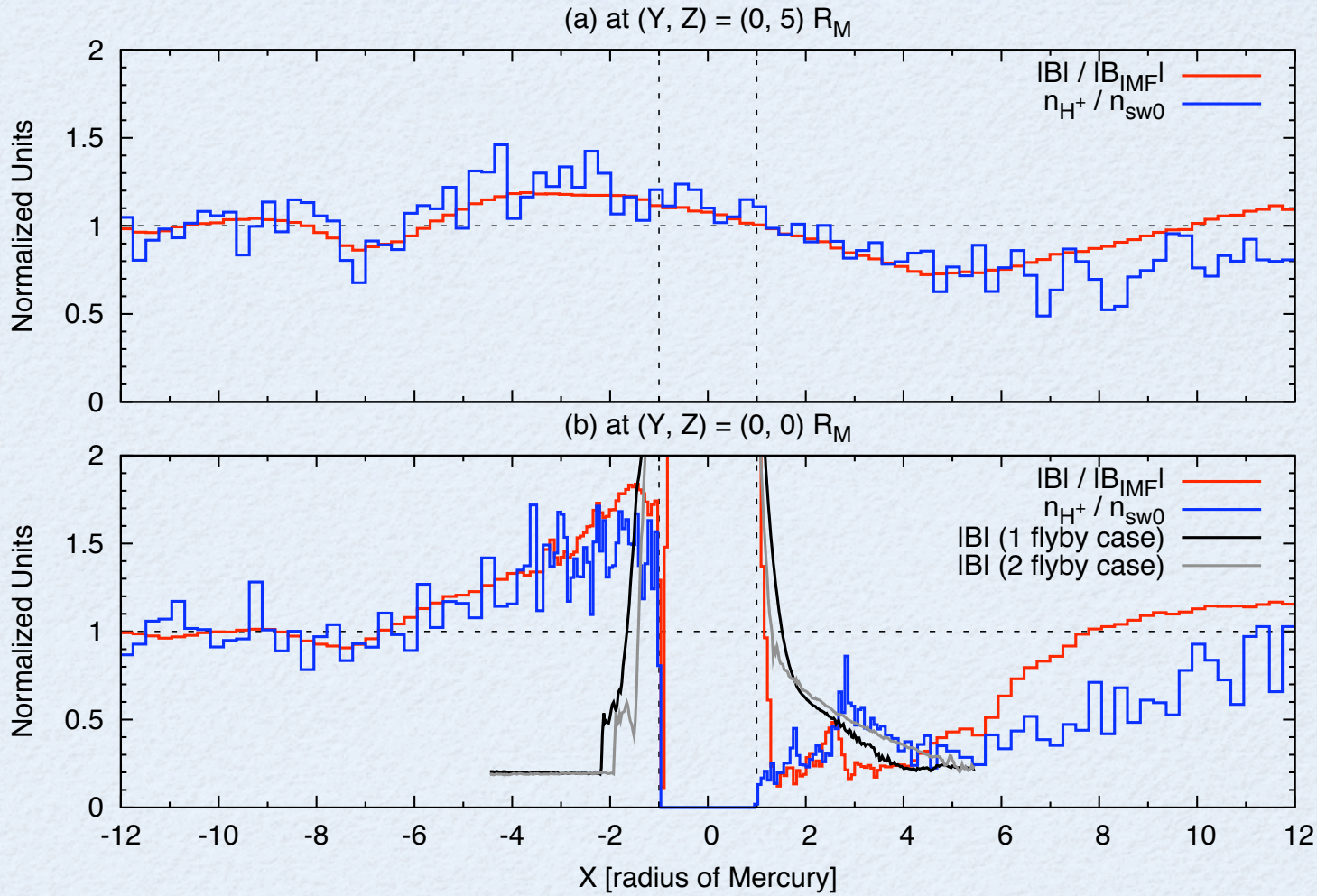


FORESHOCK

- Trávníček et al., 2007
  - plasma temperature
  - Some suprathermal protons are reflected back upstream in the quasi-perpendicular portion of the shock wave and move further upstream forming a proton foreshock.



B_{IMF} = (0,0,-107) nT



- Fast wave → identical with northward case