Comparison of Induced Magnetospheres

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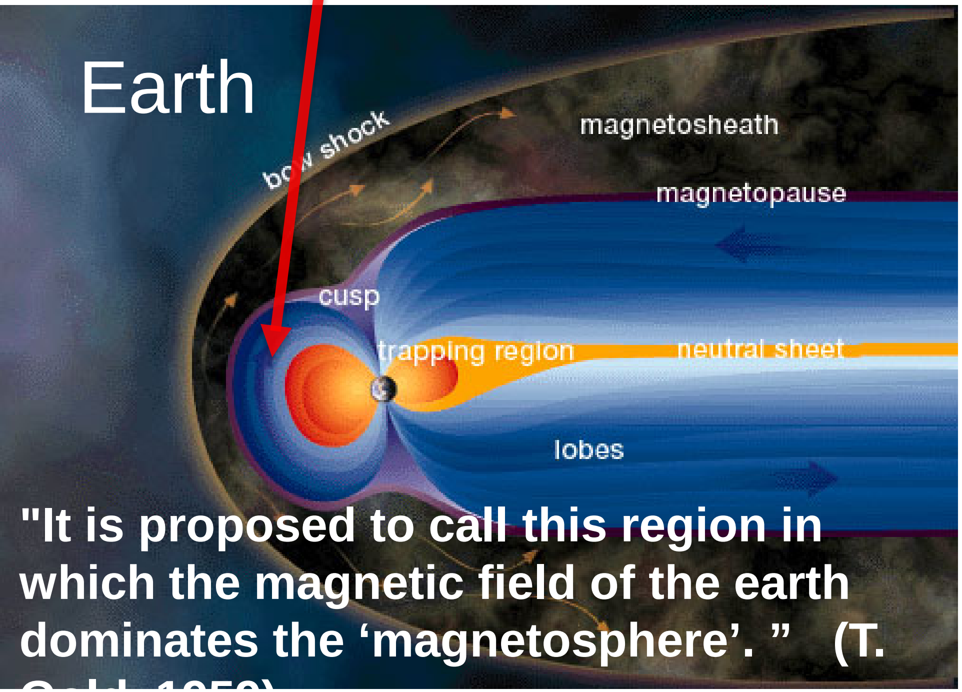
52nd ESLAB Symposium

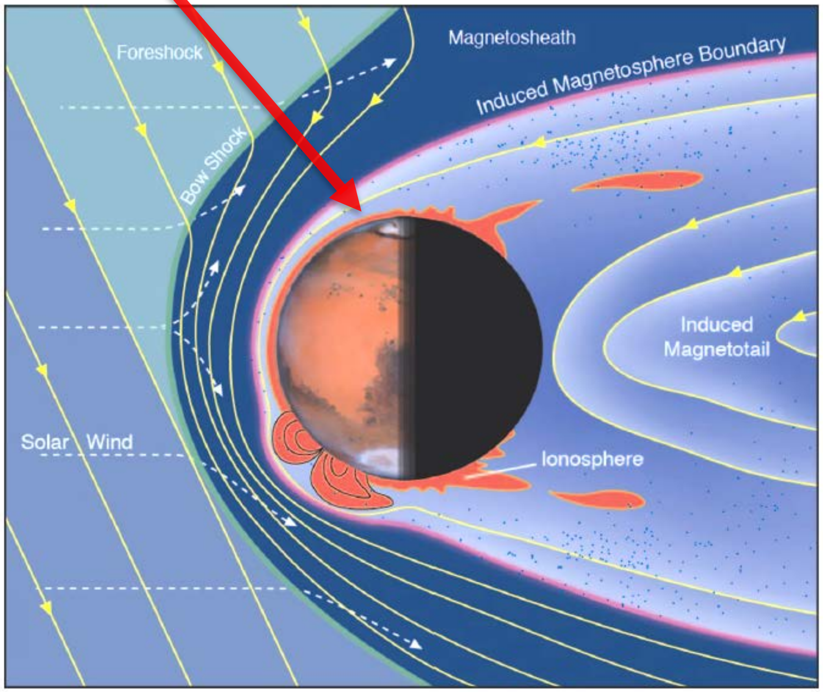
Intrinsic Magnetosphere vs. Induced Magnetosphere

Dominated by planetary magnetic field

Determined by solar wind

Lillis et al., 2015





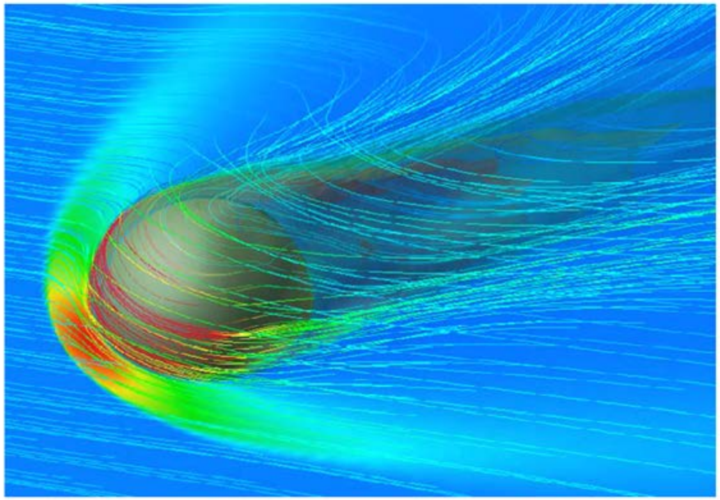
According to wiki: **A magnetosphere** is the region of space surrounding an astronomical object in which charged particles are manipulated or affected by ~~that object's~~ magnetic field. **(Gringauz, 1981)**

Luhmann et al., 2004: **An induced magnetosphere** occurs in plasma interactions with nonmagnetic bodies, and is the less well-defined region in which magnetic forces dominate the dynamics of the plasma.

Common Features of the Induced Magnetospheres of Venus, Mars and Titan :

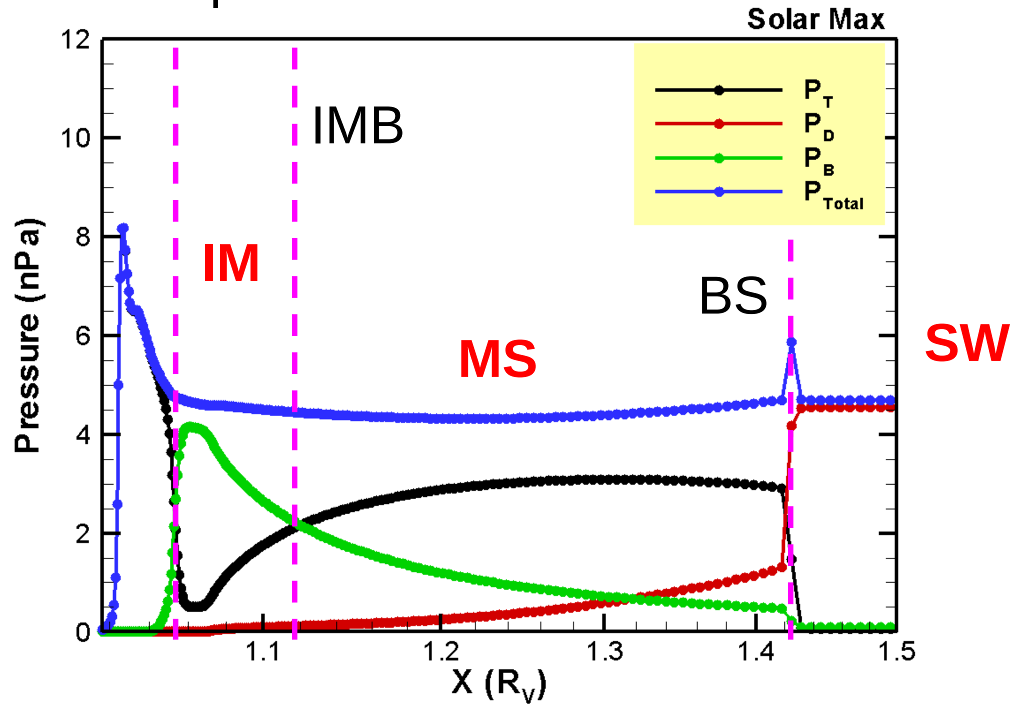
1. It is formed around unmagnetized (or weakly magnetized) obstacle with substantial atmosphere/ionosphere.
2. The highly conducting ionosphere and the ion pickup process (or mass loading from a fluid point of view) are two main processes of the formation of the induced magnetosphere.
3. IMB is often characterized by a sudden increase of the magnetic field strength, a change in the plasma composition (from upstream to ionospheric plasma), and a decease of magnetic field perturbation and electron flux (in case of super-magnetosonic upstream flow).
4. It is mainly controlled by the properties of the upstream flow (field orientation and dynamic pressure) and EUV flux.

A Prototype of the Induced Magnetosphere: Venus



Terada et al., 2009
Multi-species Single Fluid MHD

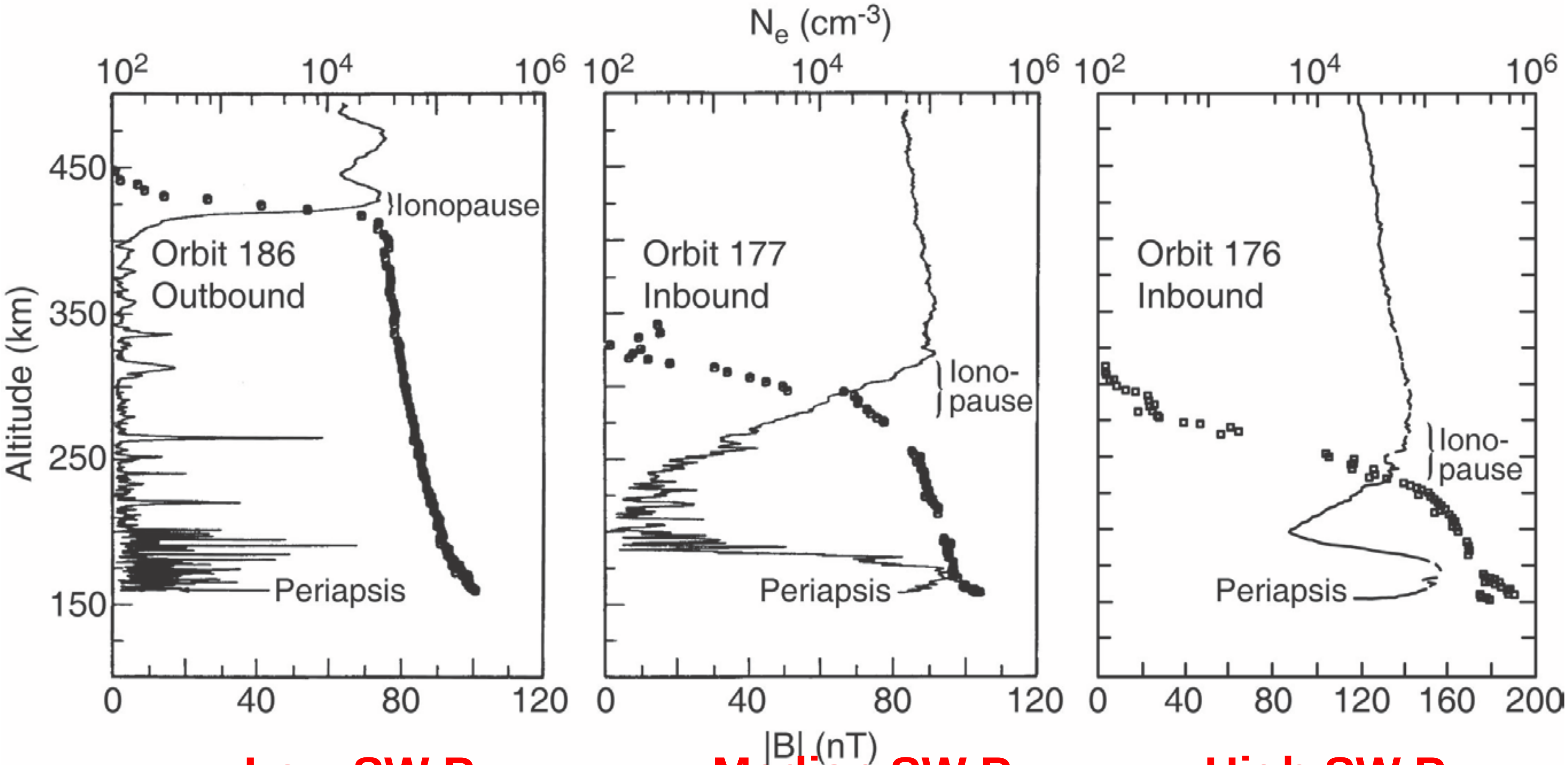
Ionopause



Ma et al., 2013

- From the solar wind to ionosphere, the dominant pressure changes from dynamic pressure to thermal pressure, magnetic pressure, and ionospheric thermal pressure.
- The induced magnetosphere is the region dominated by magnetic pressure.
- The lower boundary of IM is the ionopause, where the ionospheric thermal pressure is the same as the solar wind dynamic pressure.

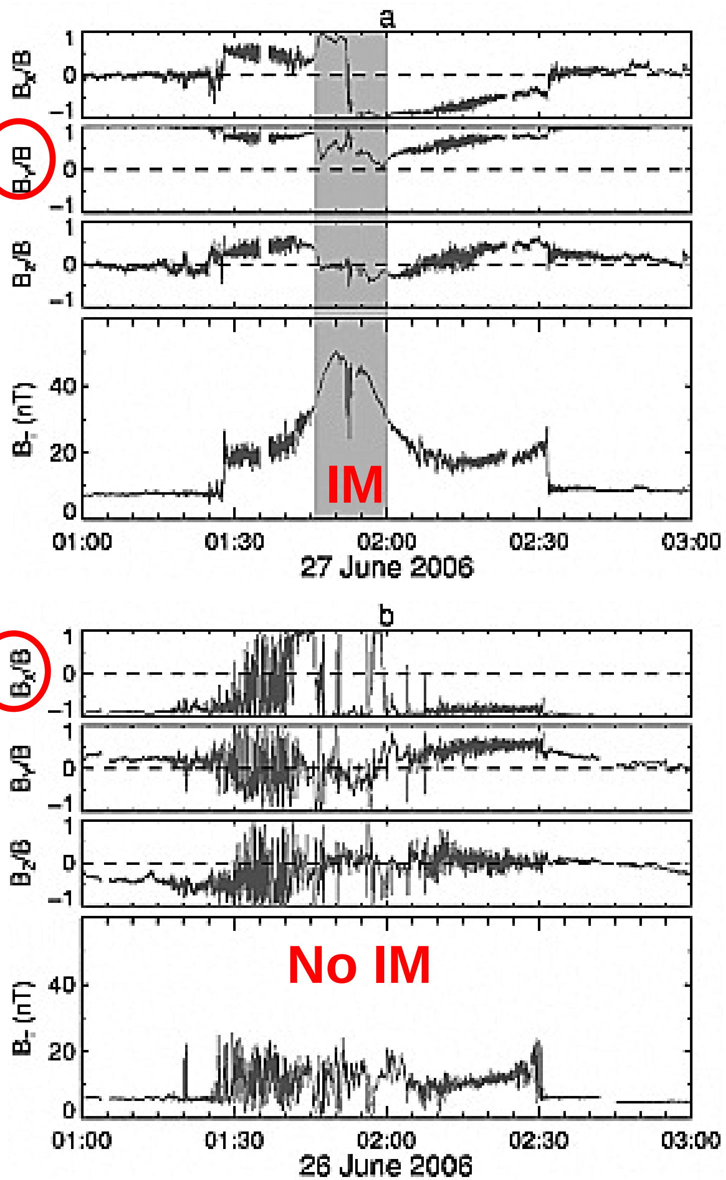
Effects of Solar Wind Dynamic Pressure



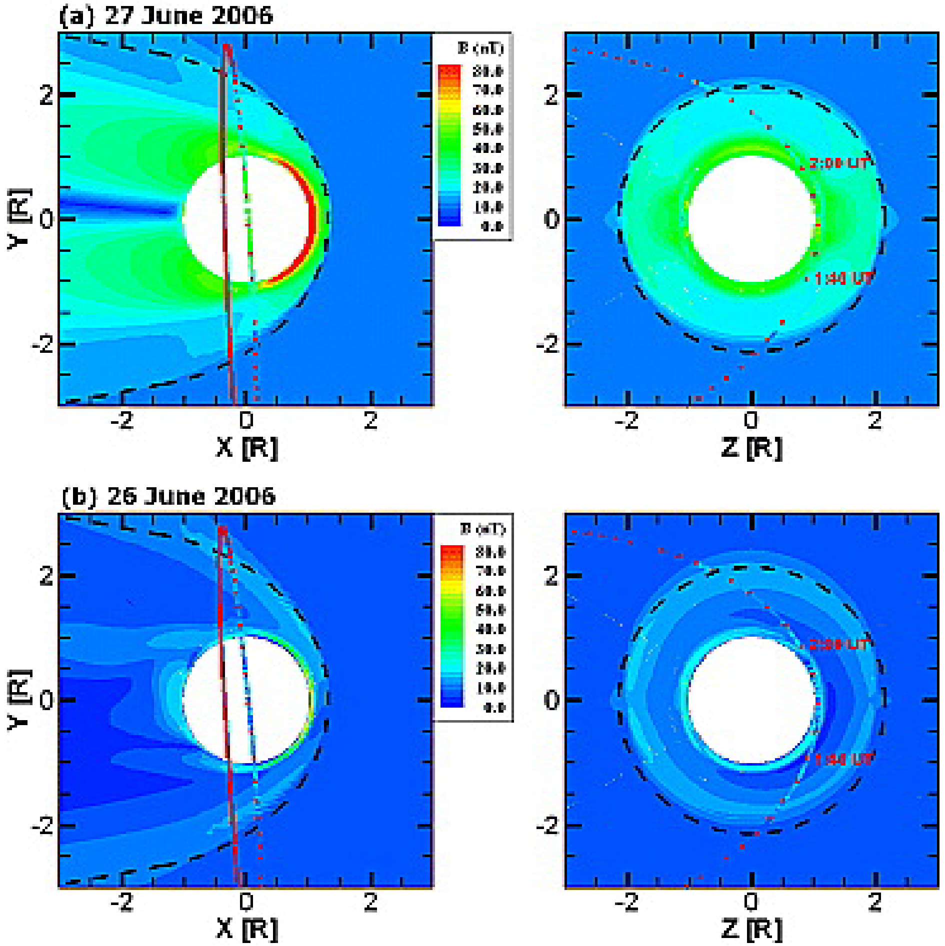
Low SW P_D **Median SW P_D** **High SW P_D**

Three altitude profiles of the ionospheric magnetic field and electron density for different solar wind pressure (*Russell and Vaisberg, 1983*).

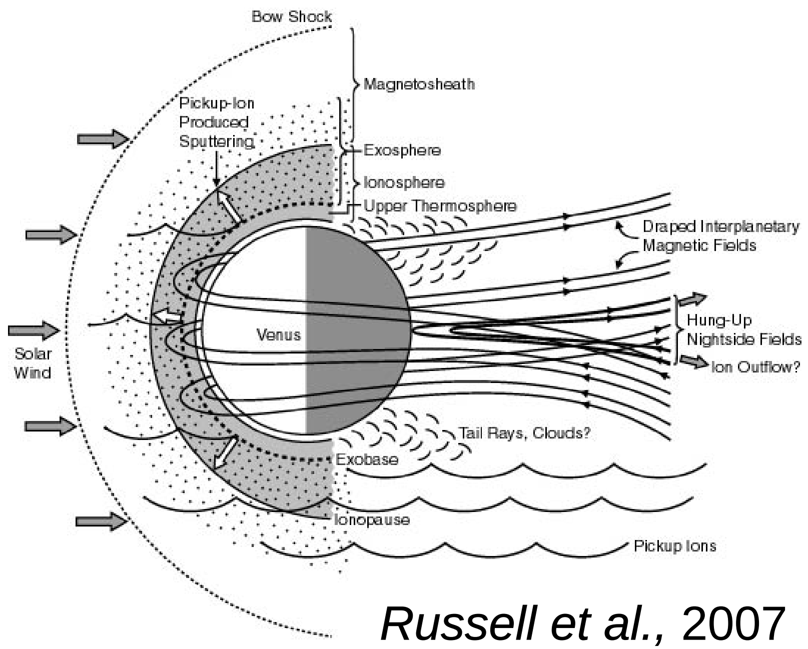
Is the Induced Magnetosphere “Permanent”?



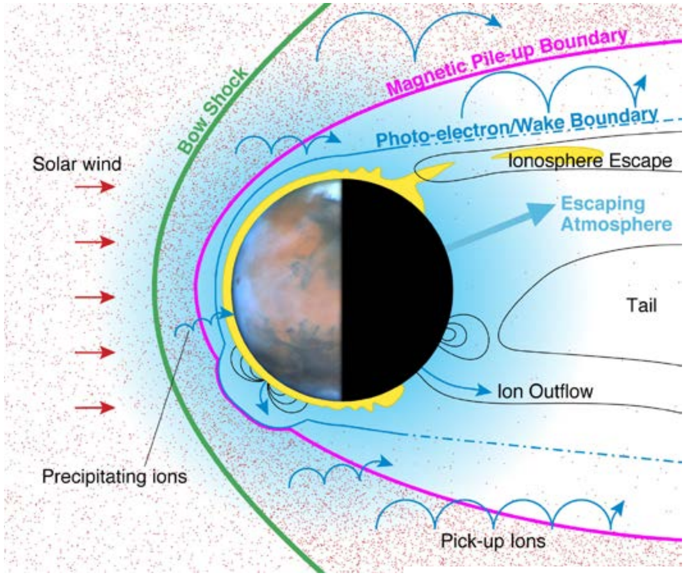
Zhang et al., 2009



Venus vs Mars



Russell et al., 2007



Brain, 2006

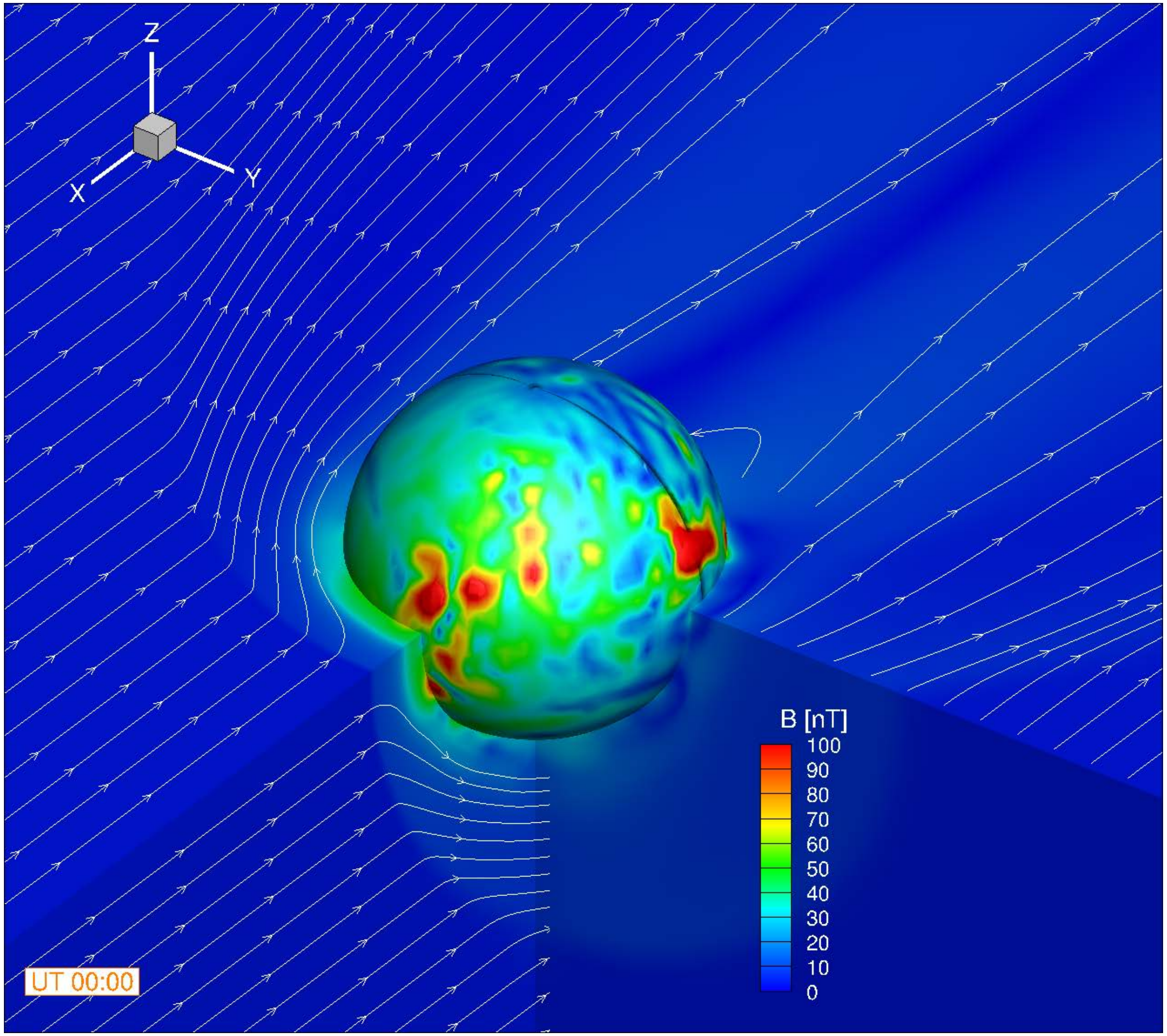
Similarities:

- Similar neutral atmospheric and ionospheric composition

Differences

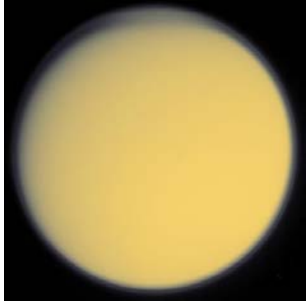
- R_V (6050 km) ~ 2 R_M (3396 km)
- Different Sun-planet distances (0.7AU vs 1.5 AU) => different solar wind conditions & EUV flux
- Different atmosphere pressure/ ionospheric thermal pressure
- **Crustal fields at Mars**

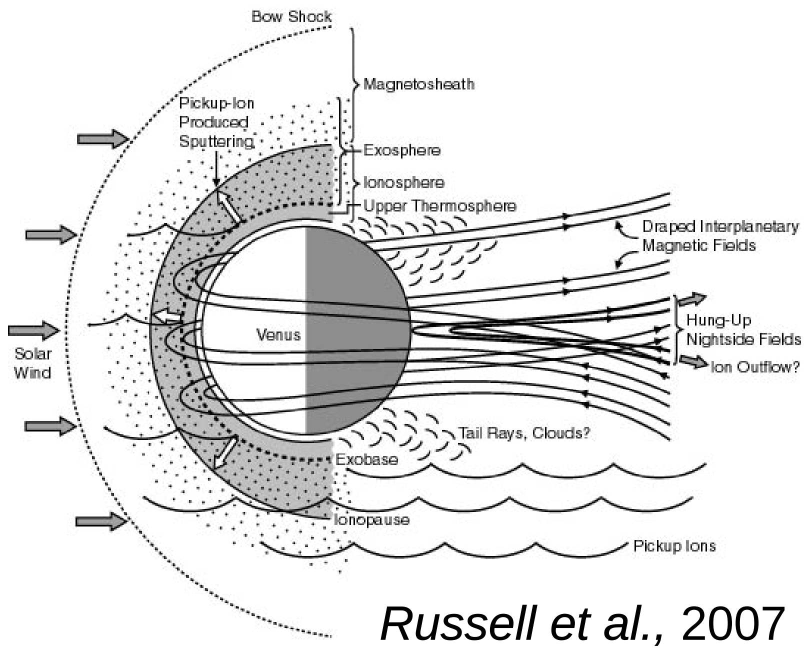
Effects of Diurnal Rotation of the Crustal Field



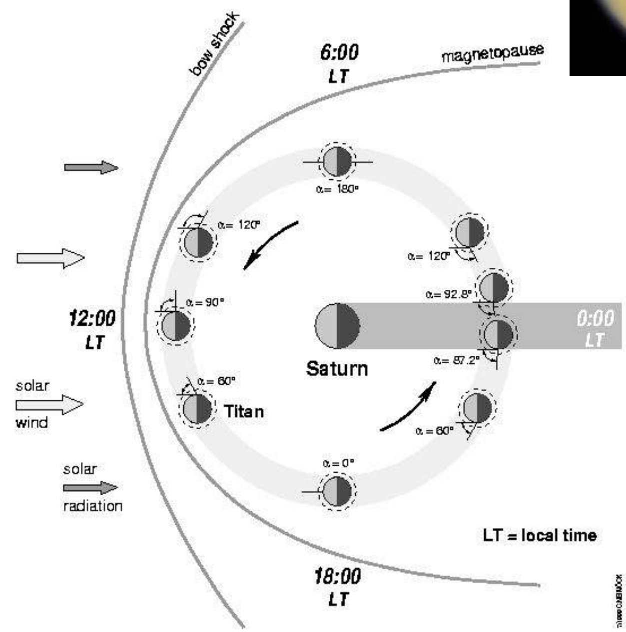
IMB is further away from Mars on average at southern latitudes than at northern latitudes (Crider et al., 2002, Brain et al., 2005). Model Results has been compared with MGS observations (Ma et al., 2014).

Venus vs. Titan



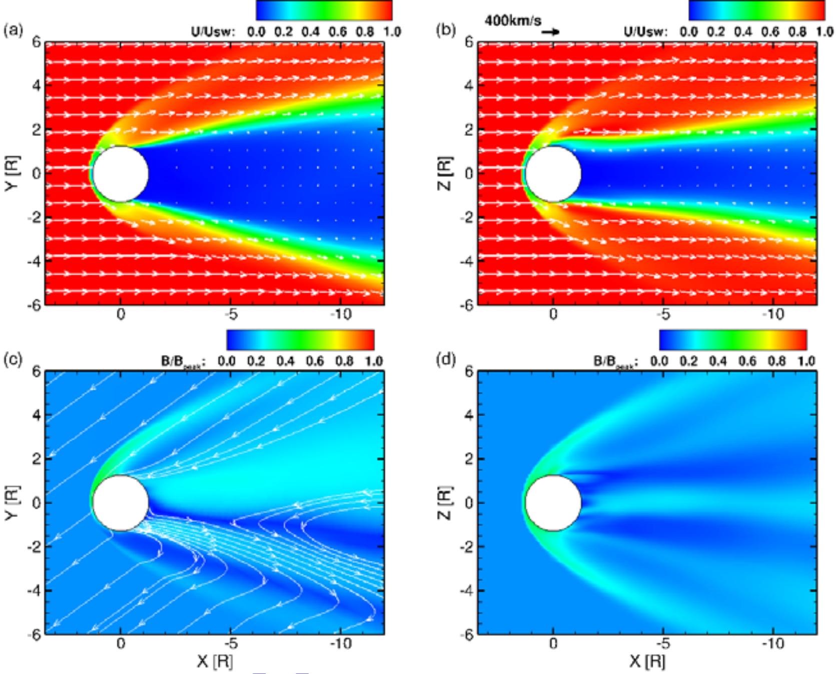


Russell et al., 2007

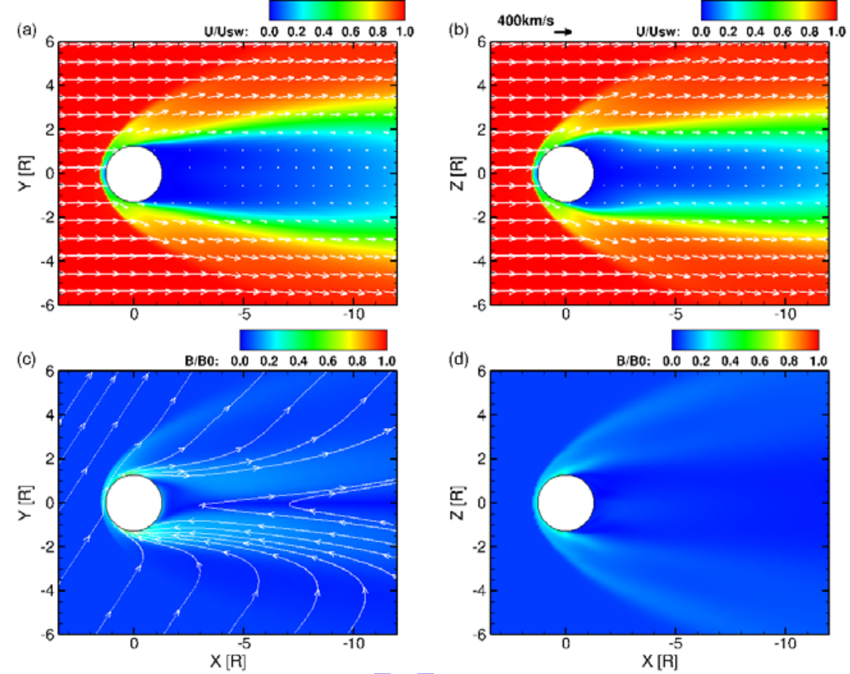


Differences

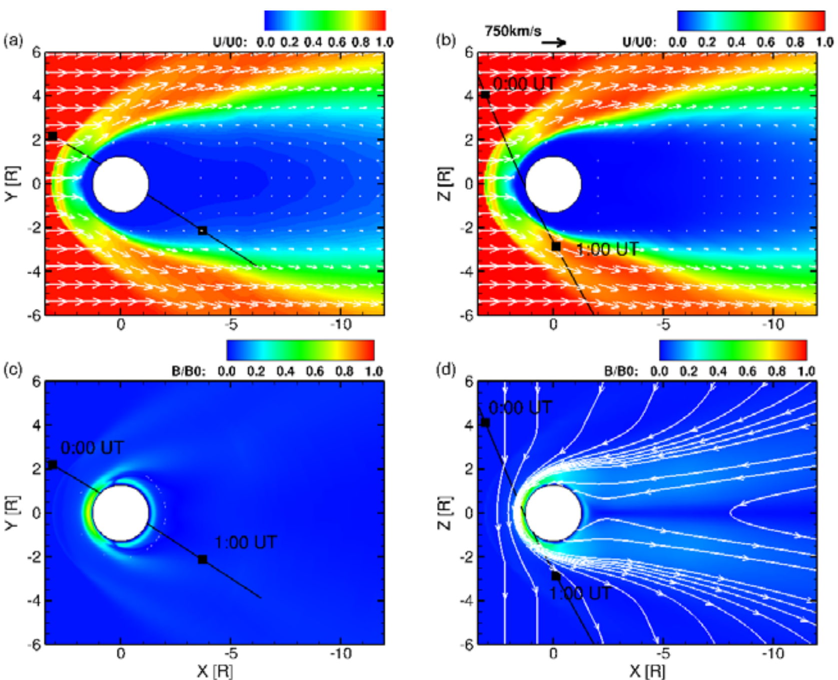
- R_V (6050 km) ~ 2.4 R_T (2575 km)
- Different Sun-object distances (0.7AU vs 9.6 AU) => different EUV flux
- Different atmosphere pressure/ ionospheric thermal pressure
- Normally sub-magnetosonic corotational flow, interaction varies with Titan's orbit location.



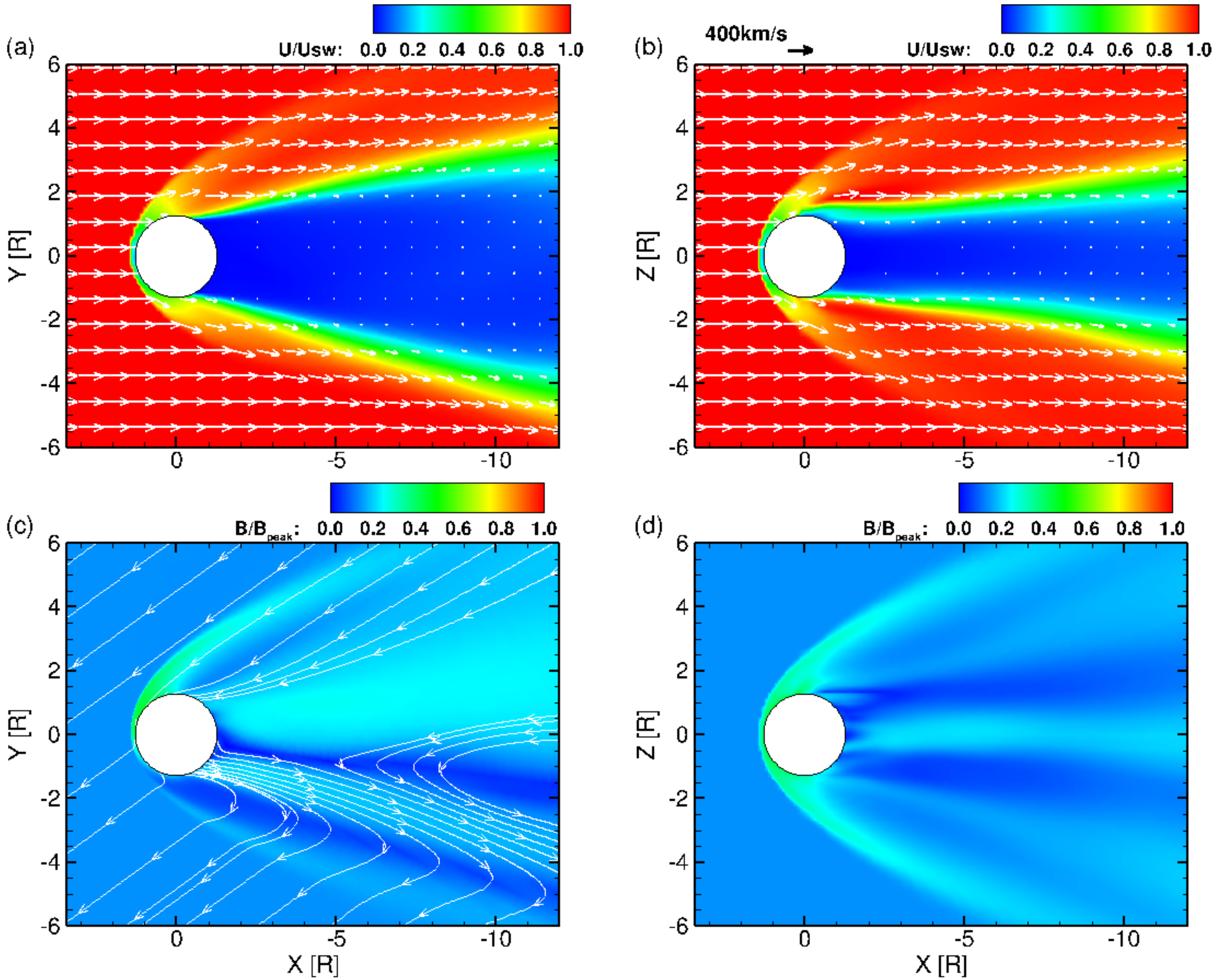
Venus



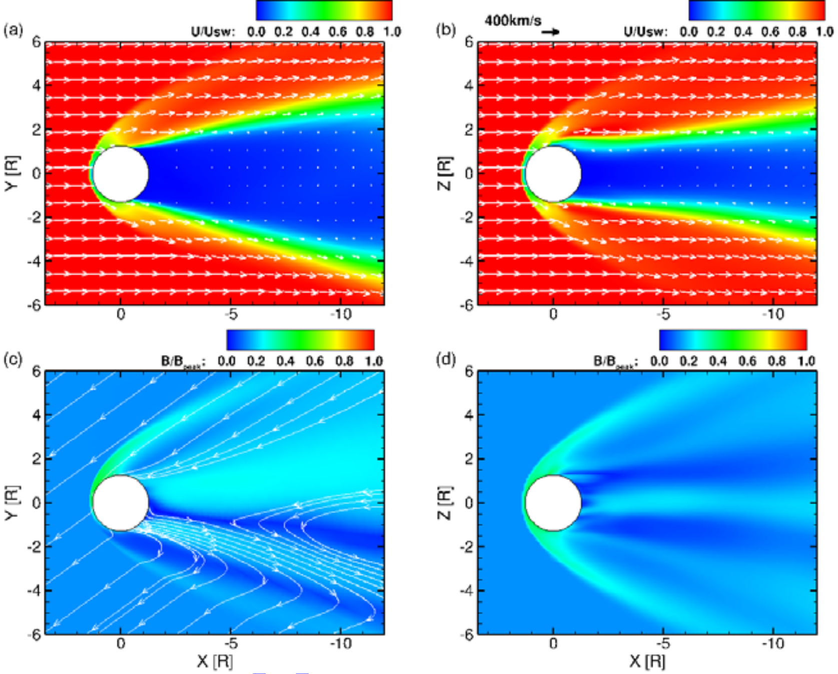
Mars



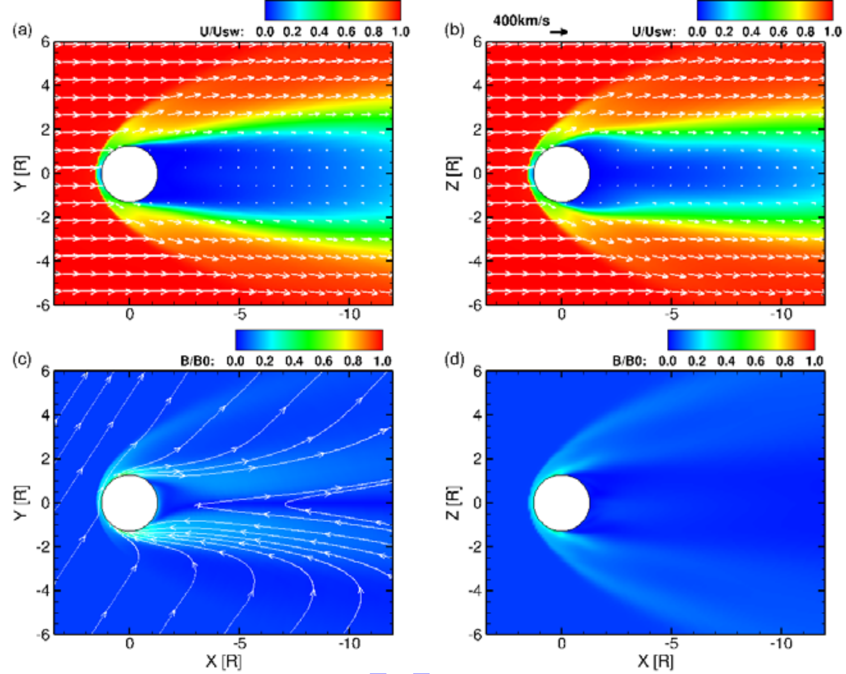
Titan in the Solar Wind (T96)



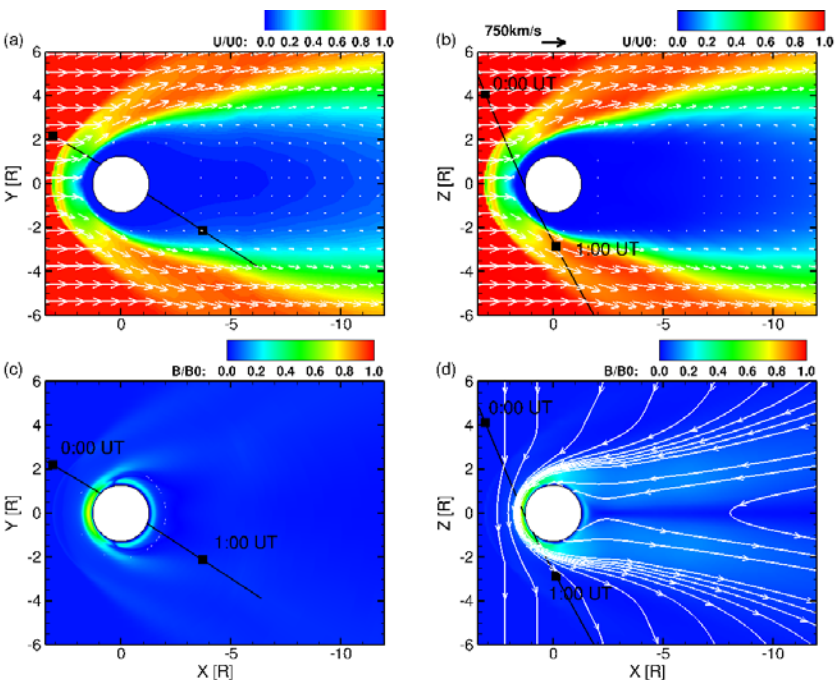
Venus (Based on MS MHD model)



Venus



Mars



Titan in the Solar Wind (T96)

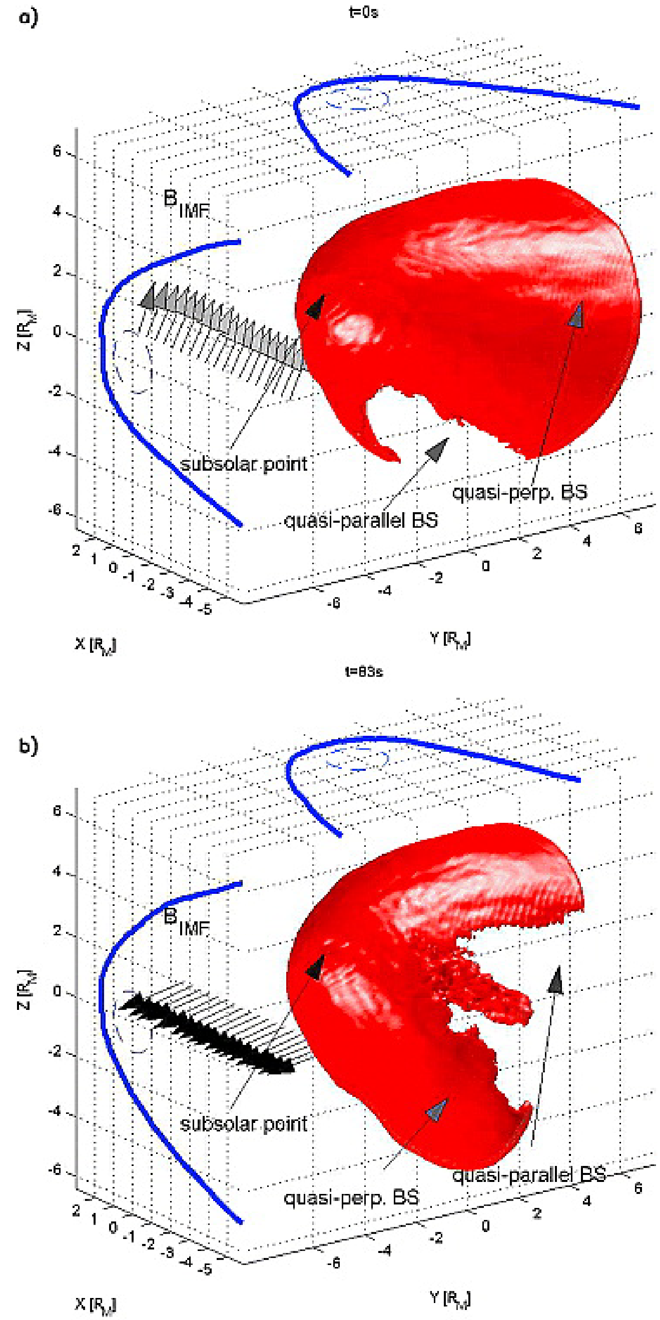
Response to IMF Direction Change (*Modolo et al.*, 2012)

Based on hybrid model results of Mars:

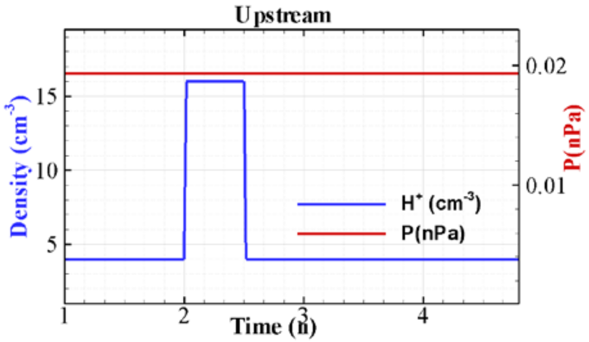
BS: almost instantaneously

IM and the **magnetic lobes**: 1–2 min

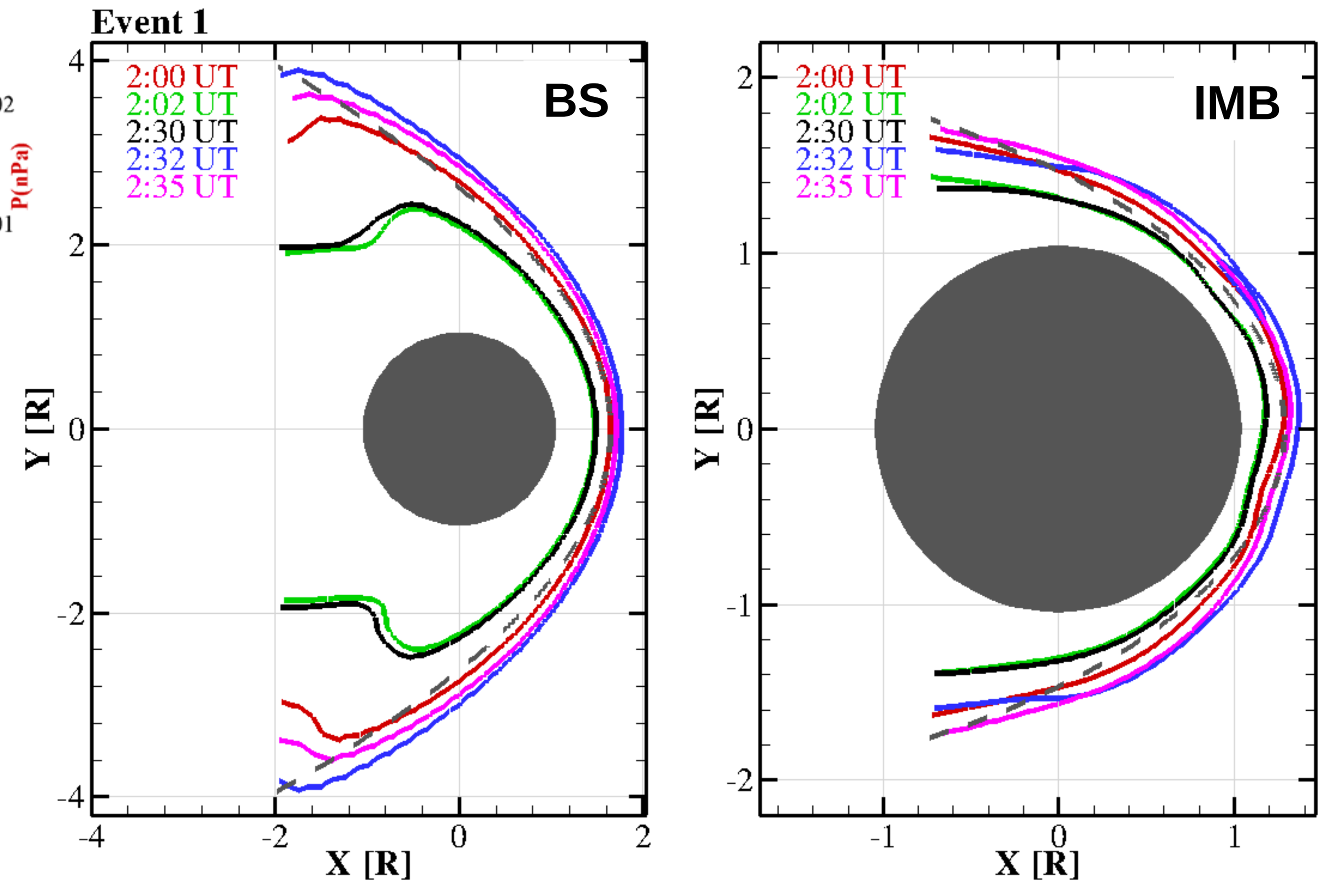
Ion plume: ~2 min.



Responses to Variations of the Solar Wind Dynamic Pressure (*Ma et al.*, 2014)



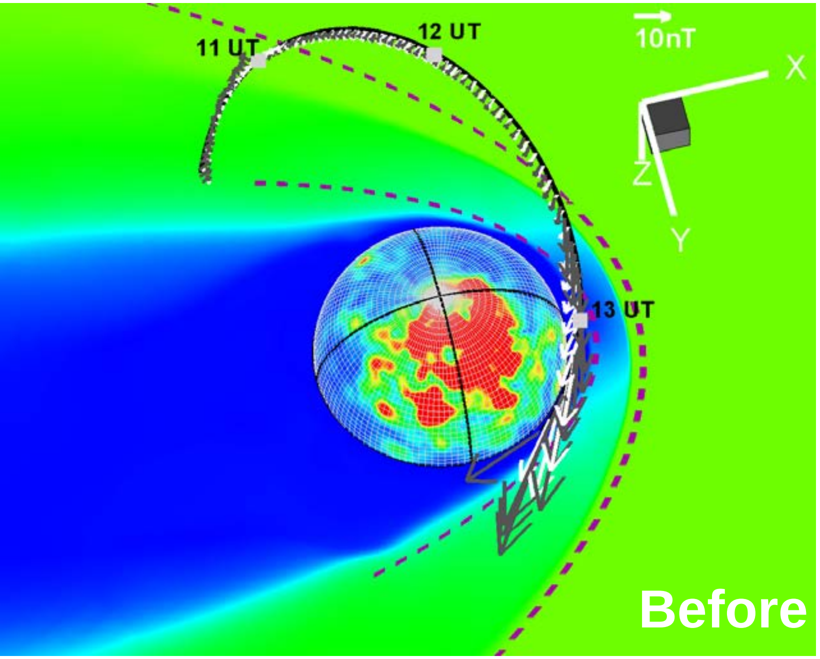
The density of the solar wind was enhanced by a factor of 4 and lasted for 30 min.

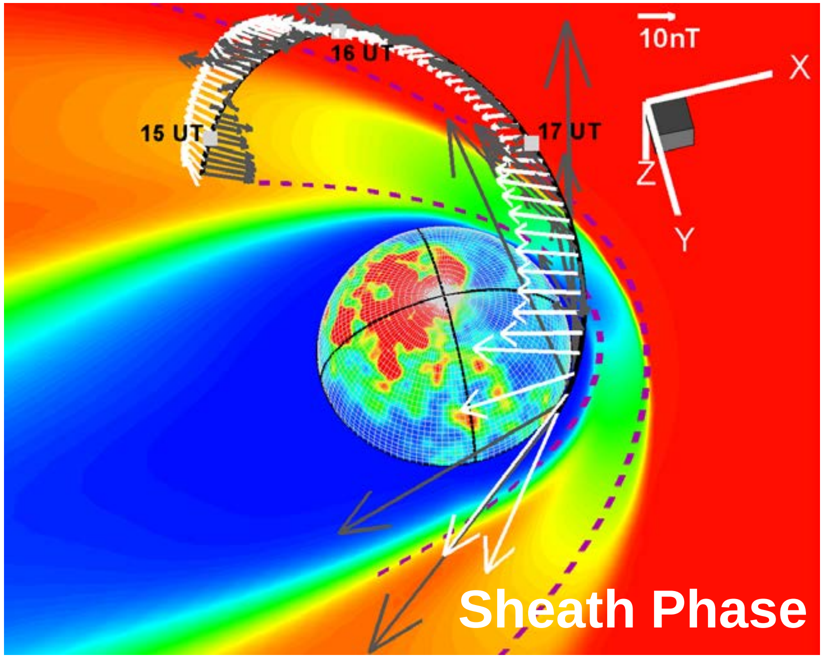


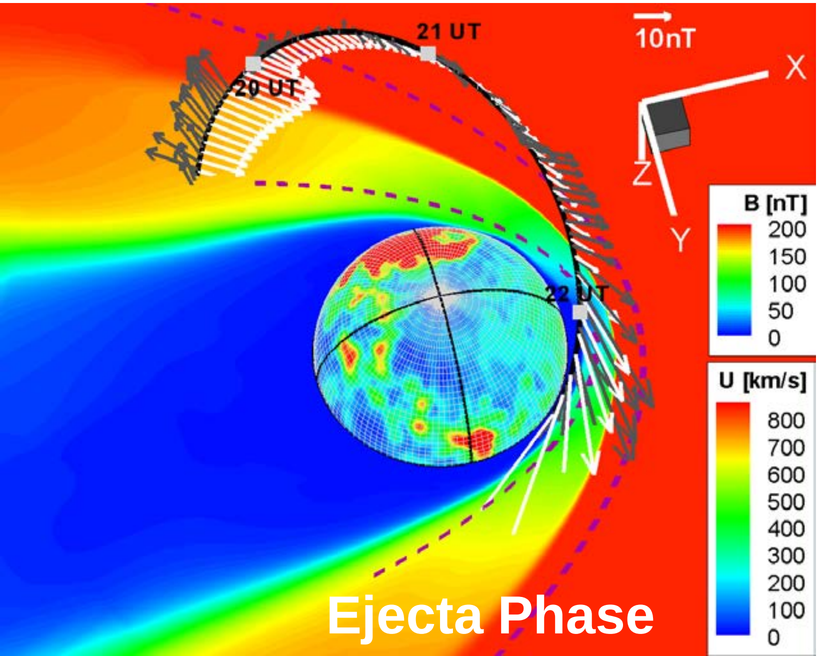
Depends on the type of variation. Simulation showed that it takes only minutes for the IMB to adjust to a pressure enhancement in the solar wind, while it takes more than 10 minutes for a pressure decrease.

Responses to an ICME event

(*Jakosky et al.*, 2015, Science)

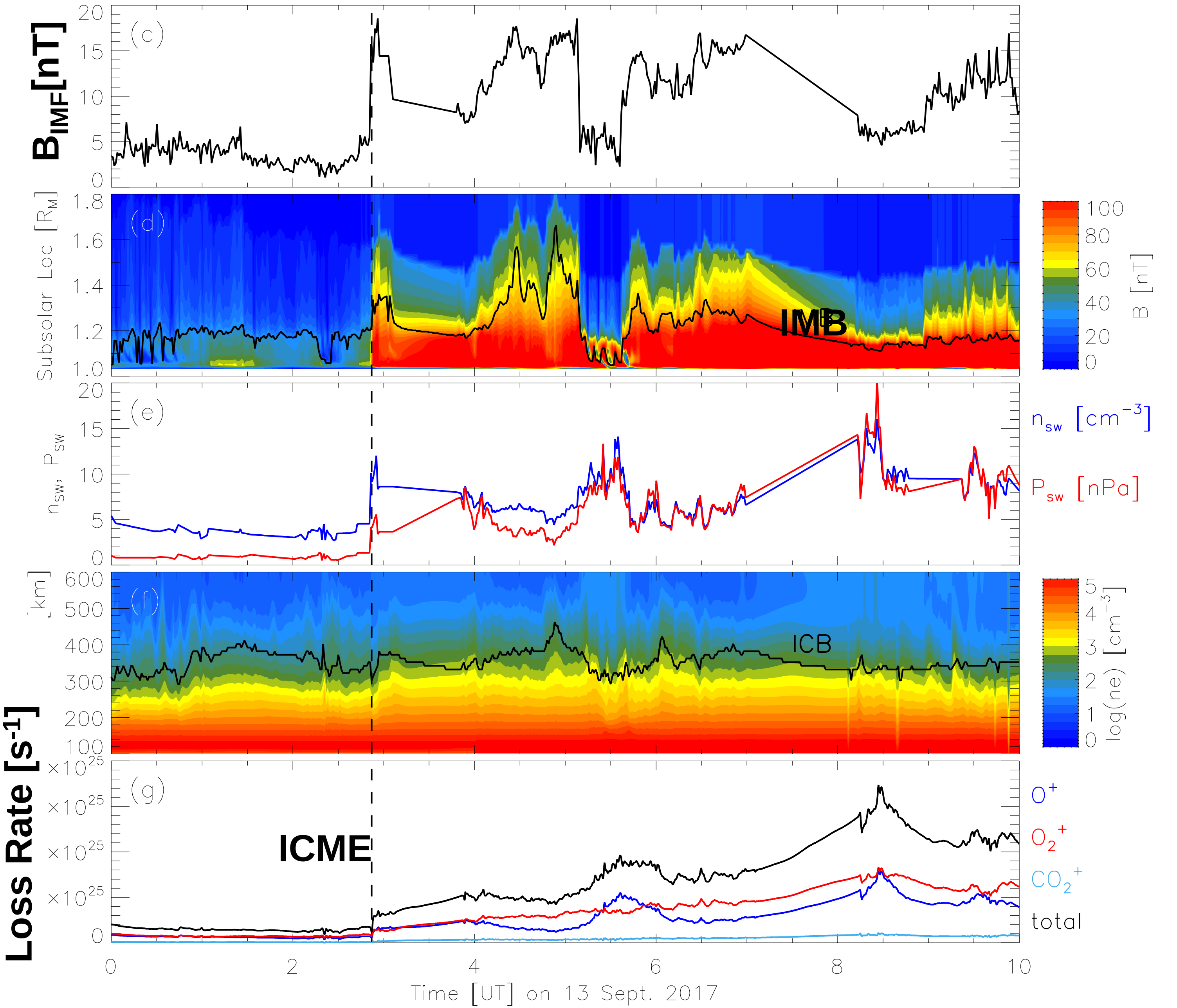






Significant variations of the magnetospheric structure during the March 8th, 2015 ICME event (Curry et al., 2015; Dong et al., 2015; Hara et al., 2016; Ma et al., 2017).

2017 September ICME Event and Its Impact on Mars



(Ma et al., 2018, in press)

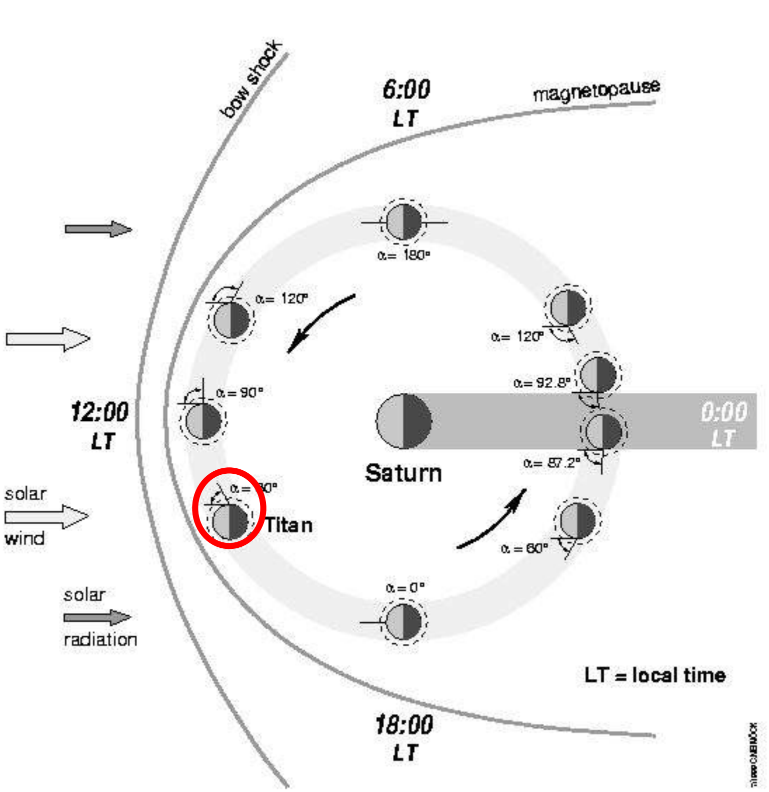
Summary

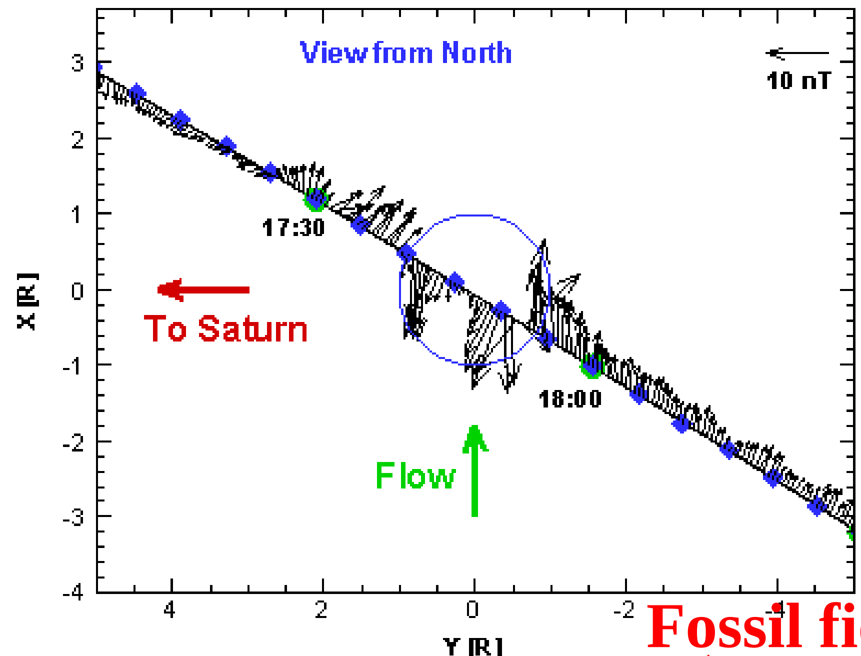
- Despite the differences in size, atmospheric thickness, existence of localized crustal field, EUV strength and upstream flow conditions, the induced magnetospheres show remarkable similarities due to the common physical processes that dominate.
- The induced magnetosphere is highly dynamic, largely depends on the upstream flow and field conditions.
- The response of the induced magnetospheres to variations in the upstream plasma flow, such as IMF direction change, solar wind dynamic pressure variations, space weather events has been studied to some extent, based on observations and numerical model results.
- Our understanding can be greatly enhanced by multi-point observations (MAVEN, MEX, INSIGHT …) at right places, right times.

Thank You

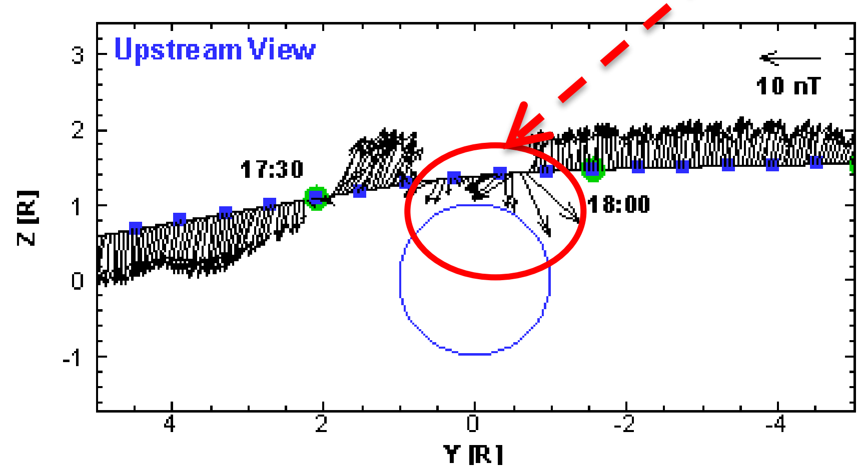
Fossil field in Titan's ionosphere (Bertucci et al., 2008)

T32 flyby
CA Time:
JUN 13, 2007 17:46:12
CA Altitude: 975 km
Location of Titan: 13.6 SLT

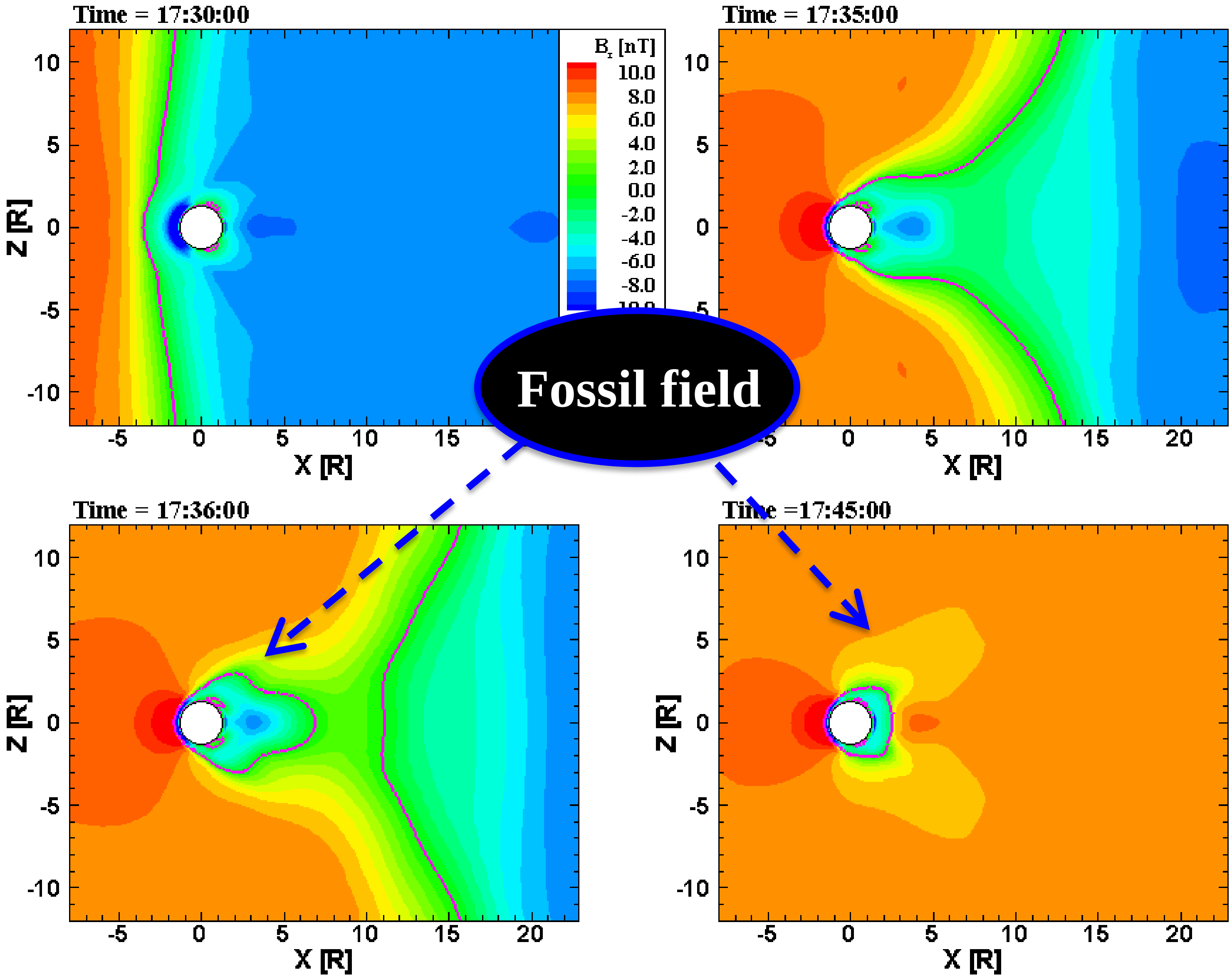




Fossil field

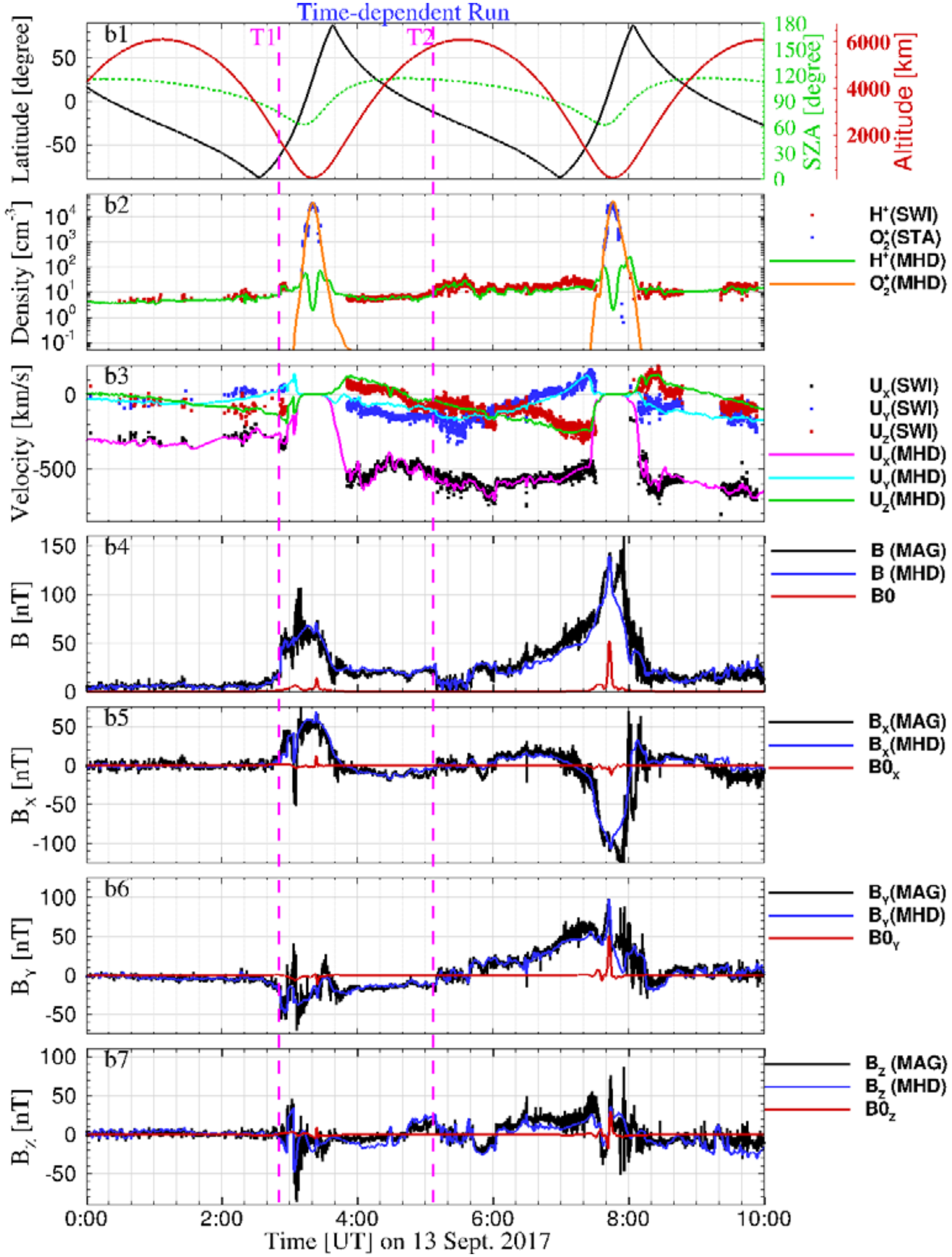


Formation of fossil field (From *Ma et al.*, 2009)



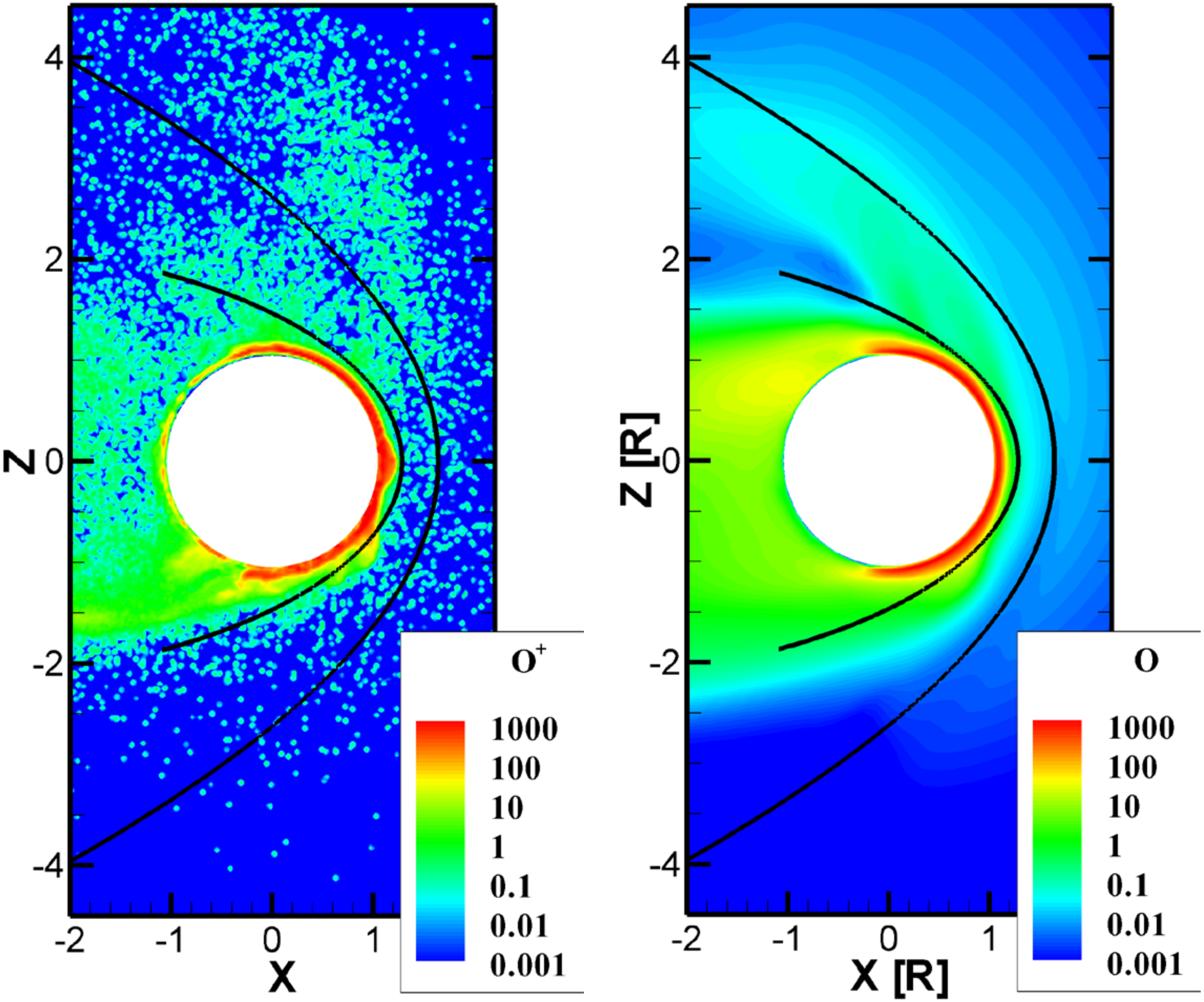
The figure shows the B_Z contour during the magnetopause crossing at 4 different times. The purple lines in this figure are $B_Z=0$ contour lines as an indication of the interface between the old field and the new field. The fossil field was formed mainly due to different convection time around Titan.

2017 September ICME Event and Its Impact on Mars

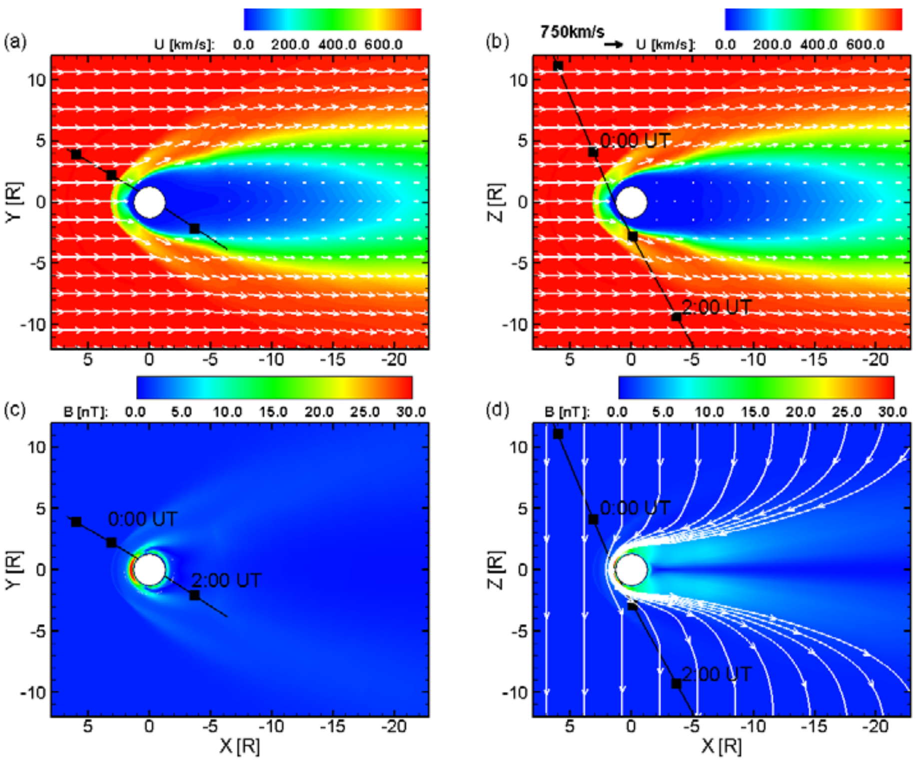


(Ma et al., 2018, in press)

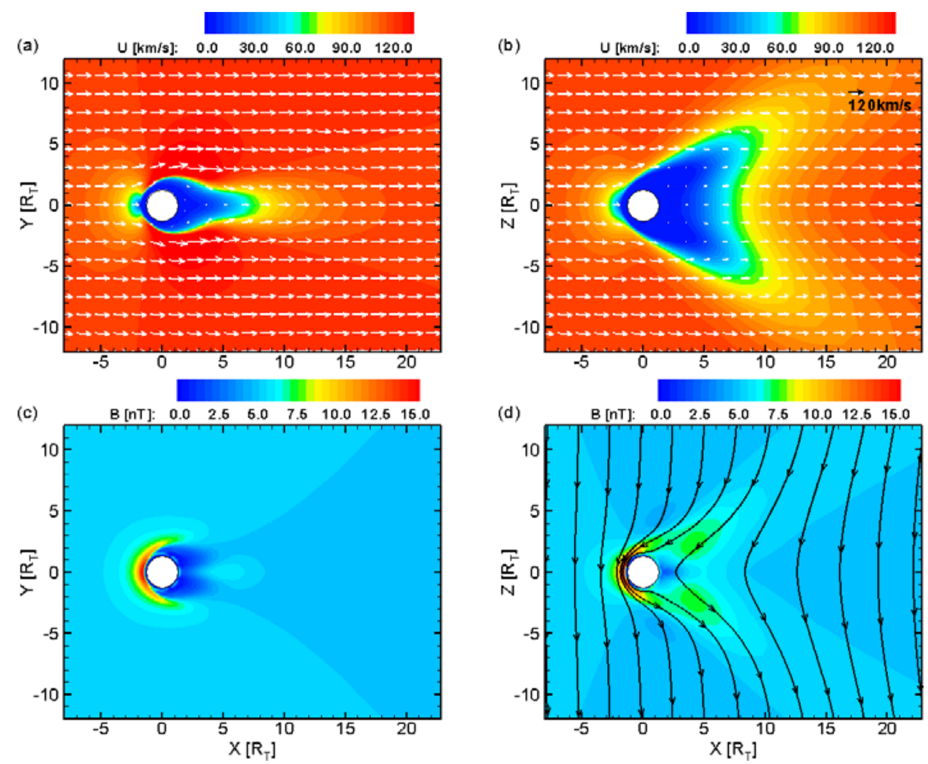
Multi-fluid vs. Hybrid



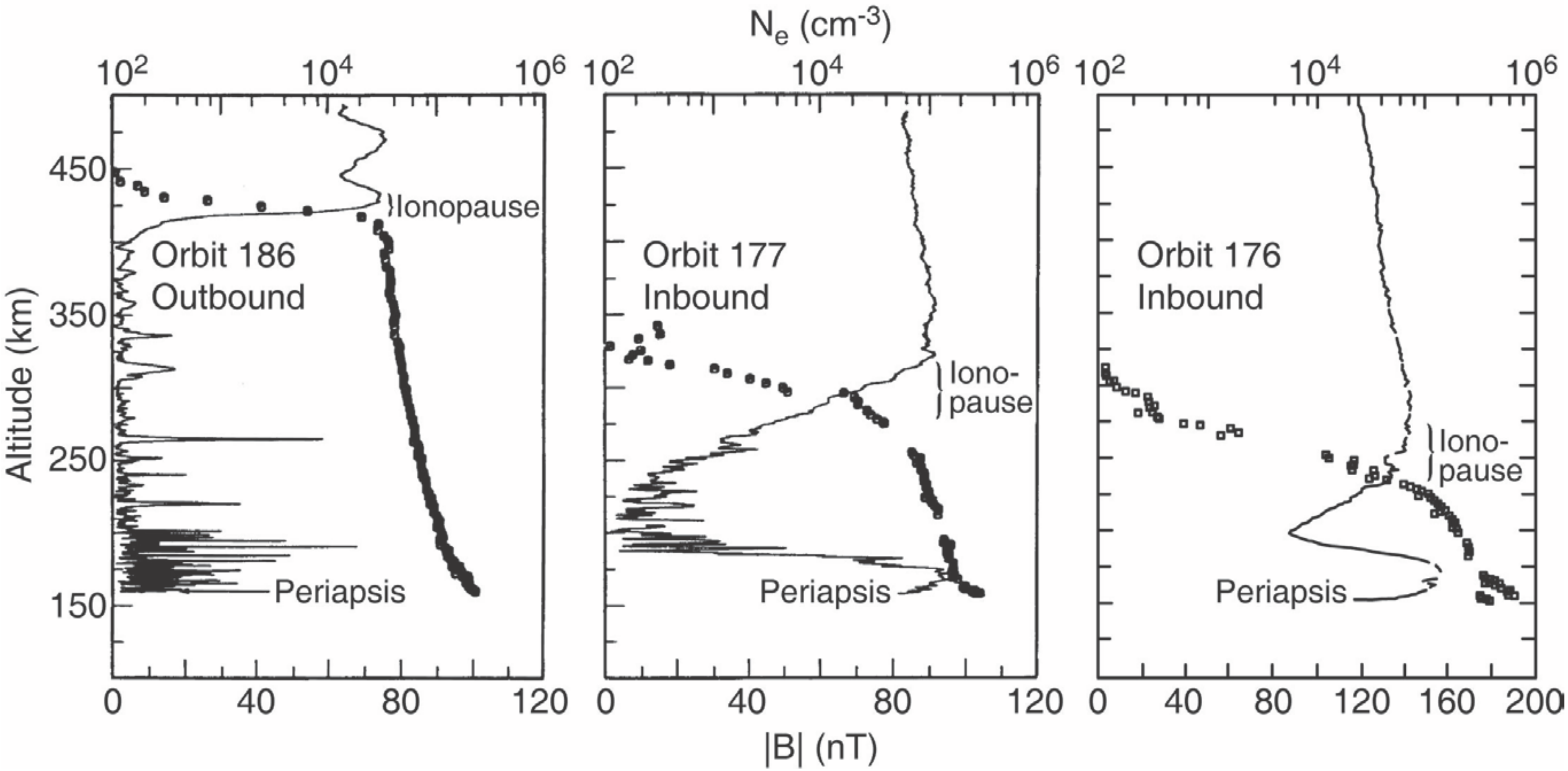
Titan in the Solar Wind



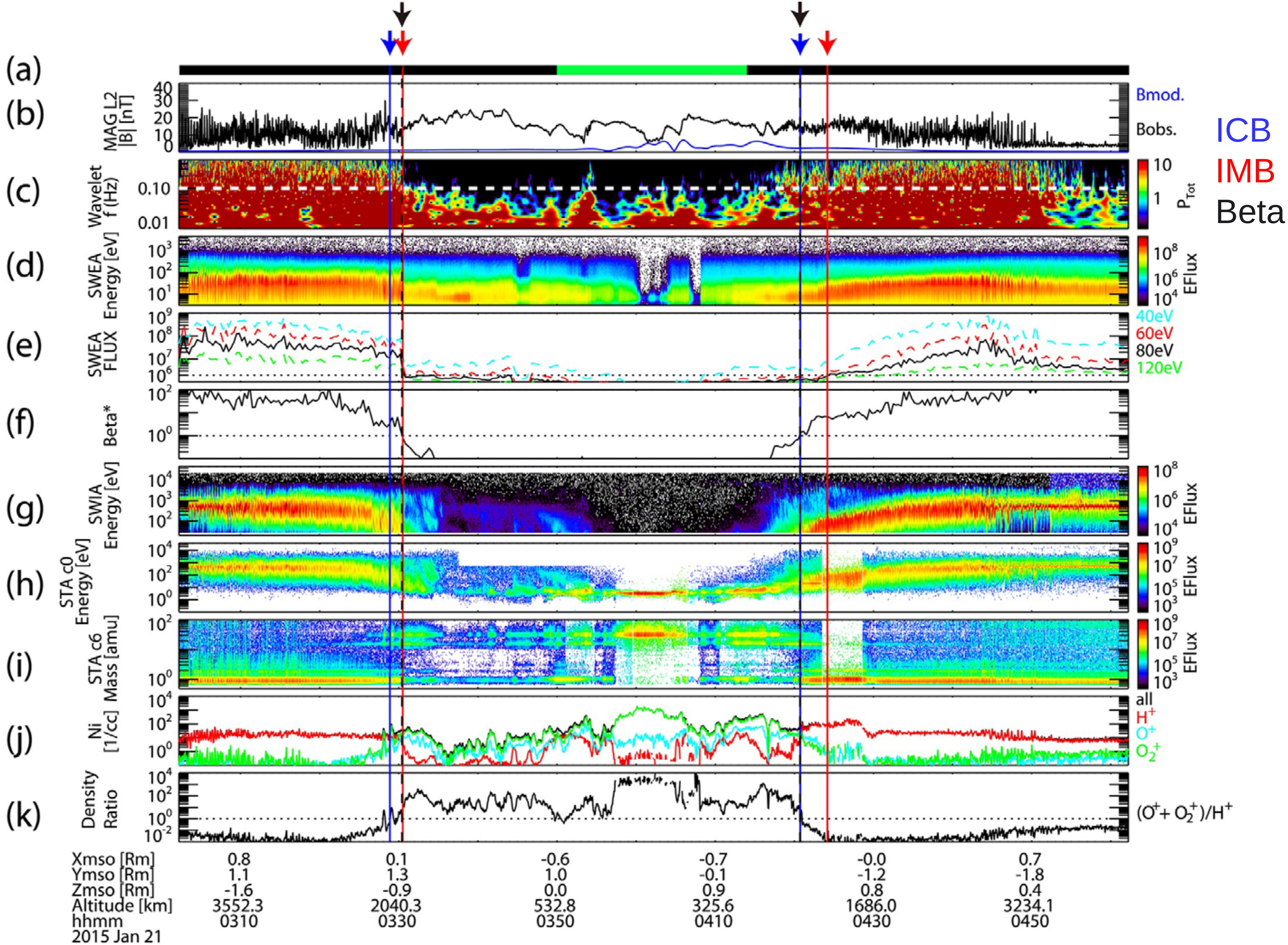
Titan in the Magnetosphere



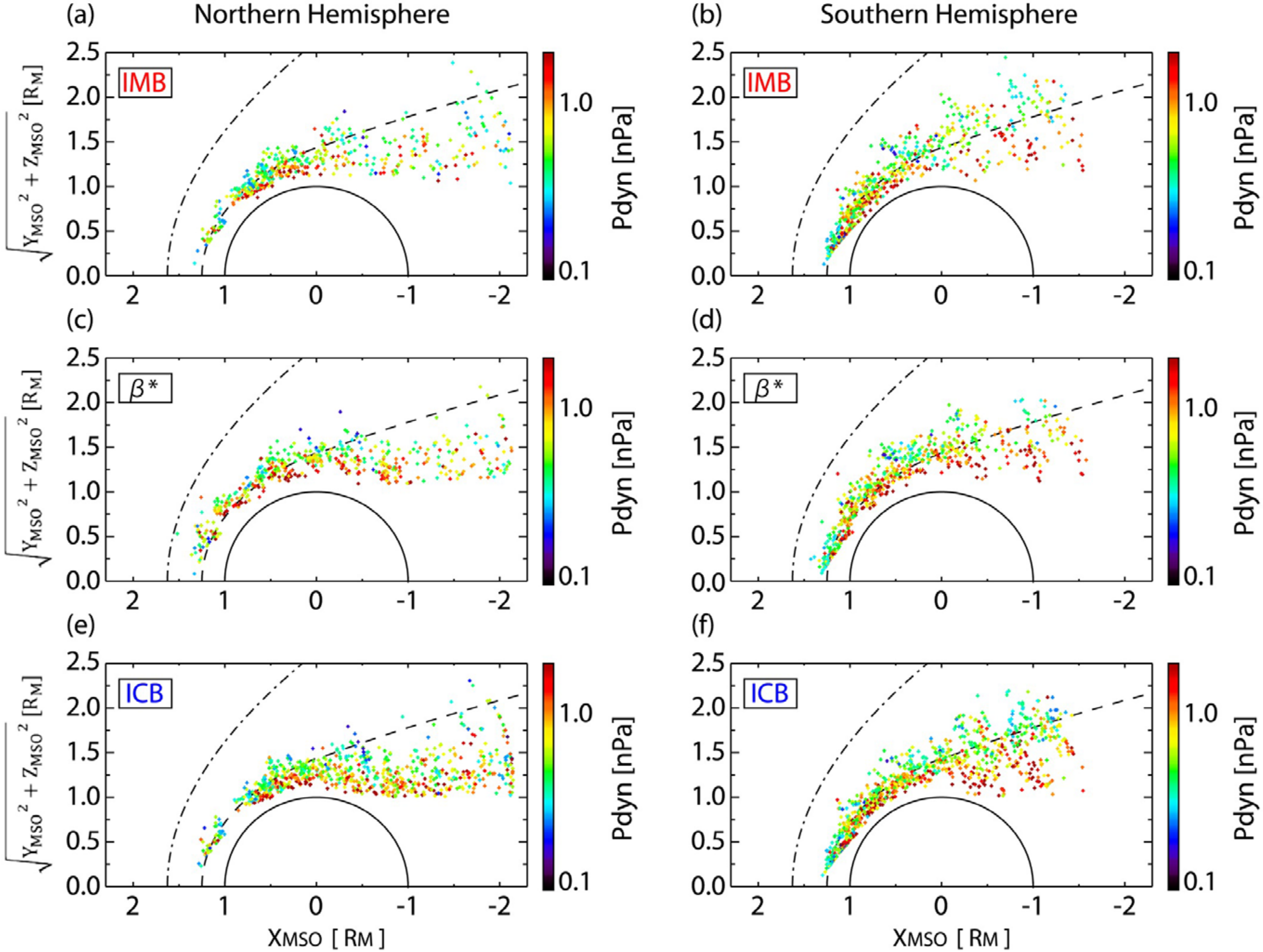
Fossil field at Venus / Mars ?



Three altitude profiles of the ionospheric magnetic field and electron density for different solar wind pressure (*Russell and Vaisberg, 1983*).



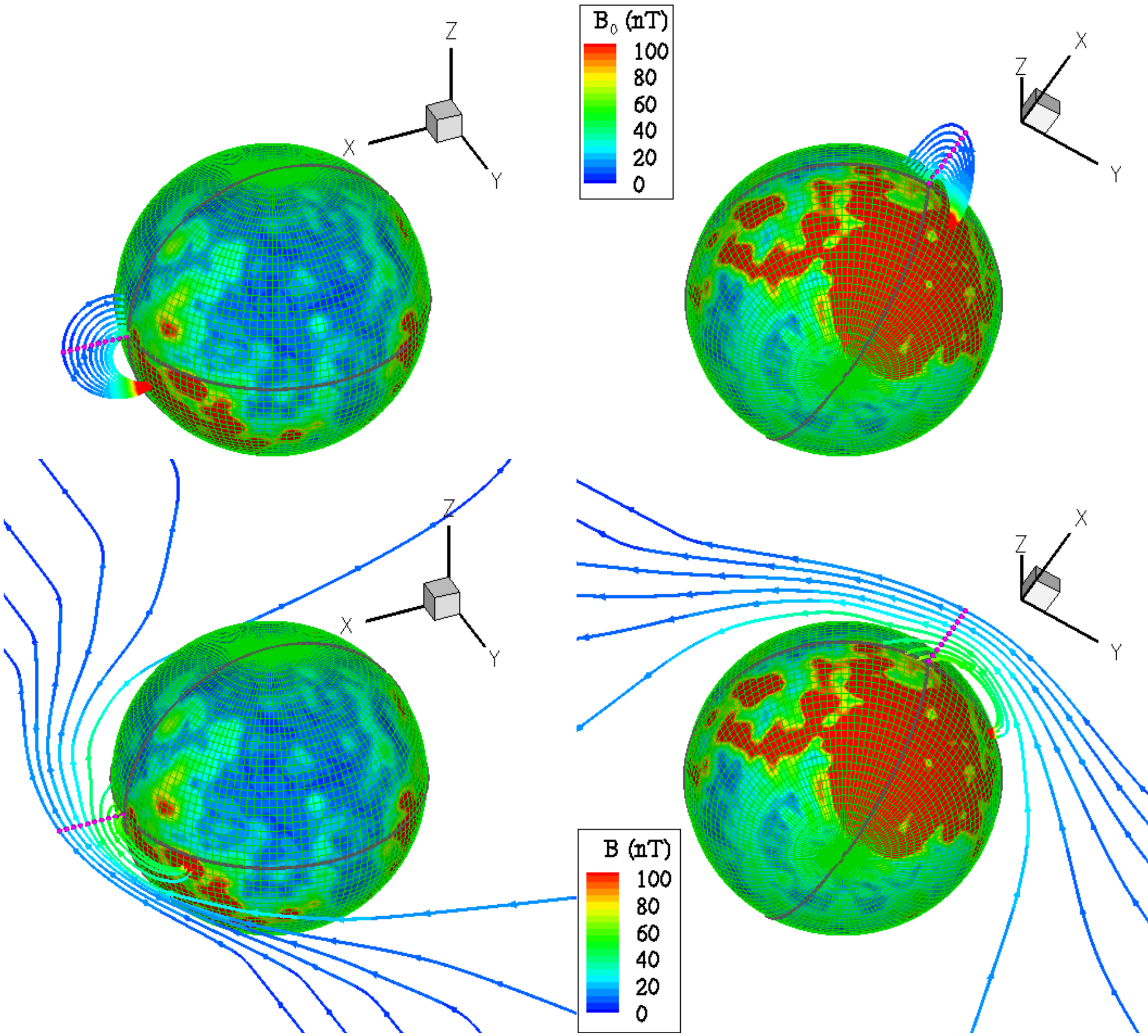
Plasma Boundaries based on MAVEN (Matsunaga et al., 2017)



Plasma Boundaries based on MAVEN (Matsunaga et al., 2017)

B_0(crustal magnetic field)
from Arkani-Hamed **[2001]**

$B(Total) = B_0+B_I$



The geometry of magnetic field lines passing through selected subsolar points. The top panels show the crustal magnetic field lines from two different points of view, the bottom panels are the total magnetic field lines (crustal field + induced field) at steady state. (*Ma et al.*, 2014)

The Most Important Process: Ion Pickup

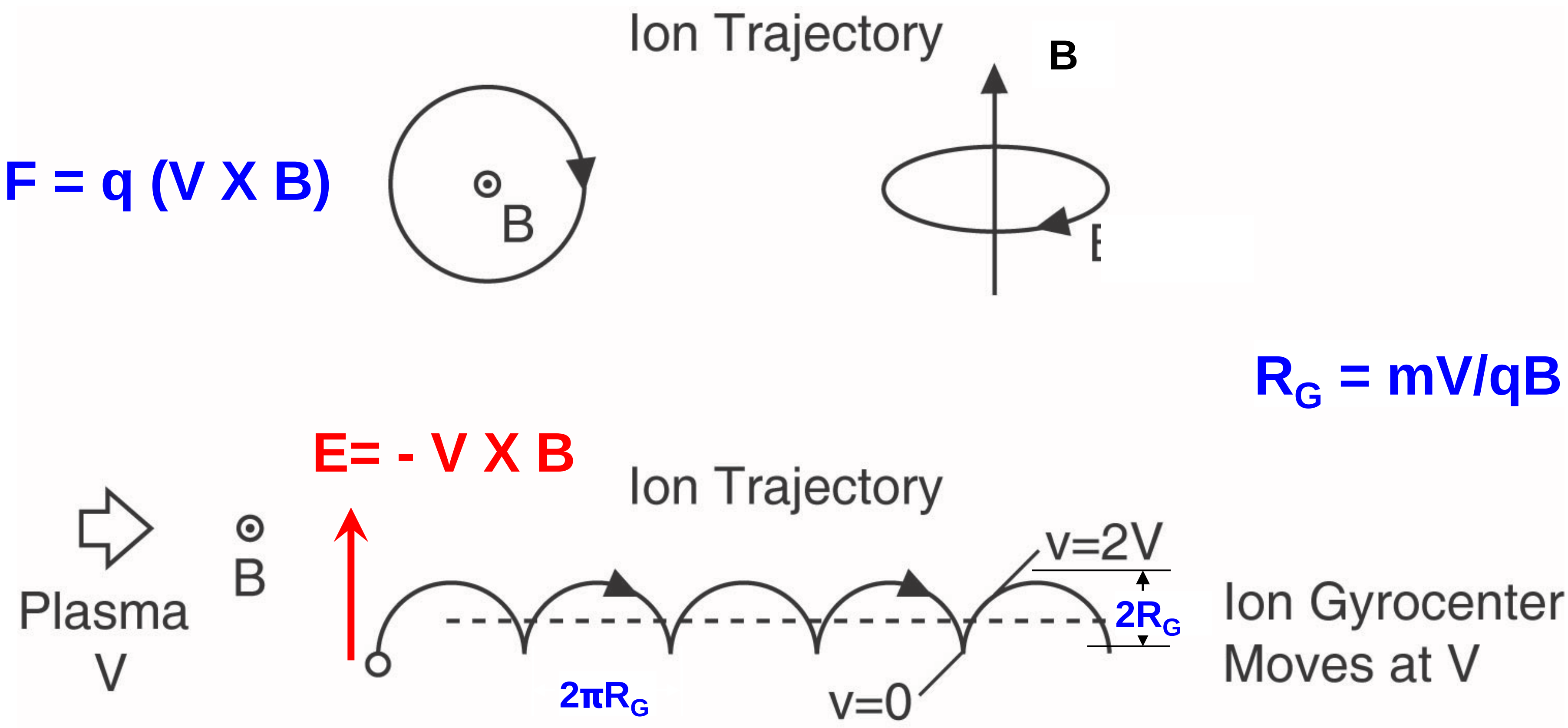
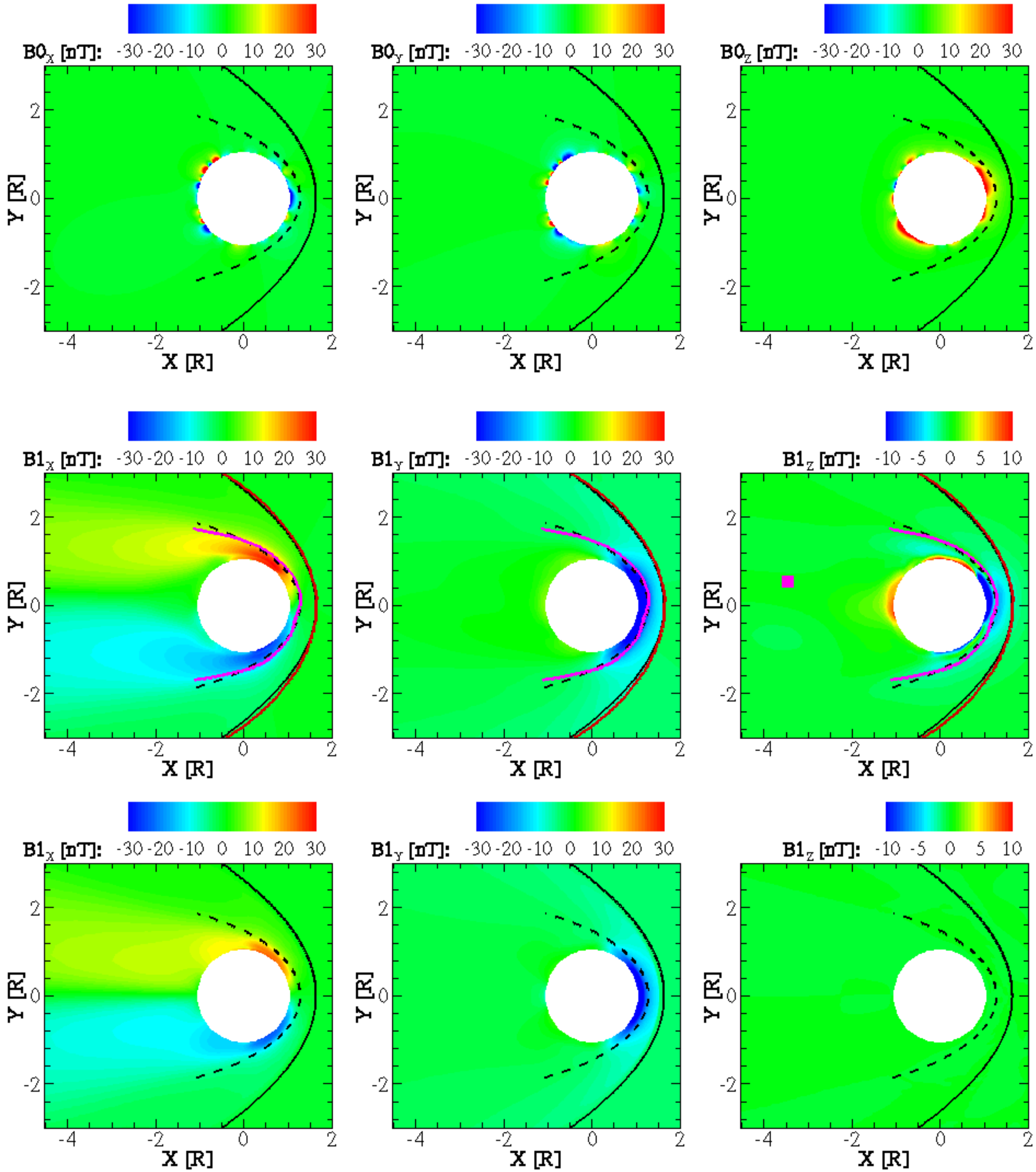


Illustration ion pickup in perpendicular electric (E= -V_{SW}XB) and magnetic (B) fields. The ion in this case is initially at rest. After generation, ion moves on the cycloidal trajectory oscillate between zero and 2 V_{SW} velocities, while the gyrocenter moves at V_{SW}.

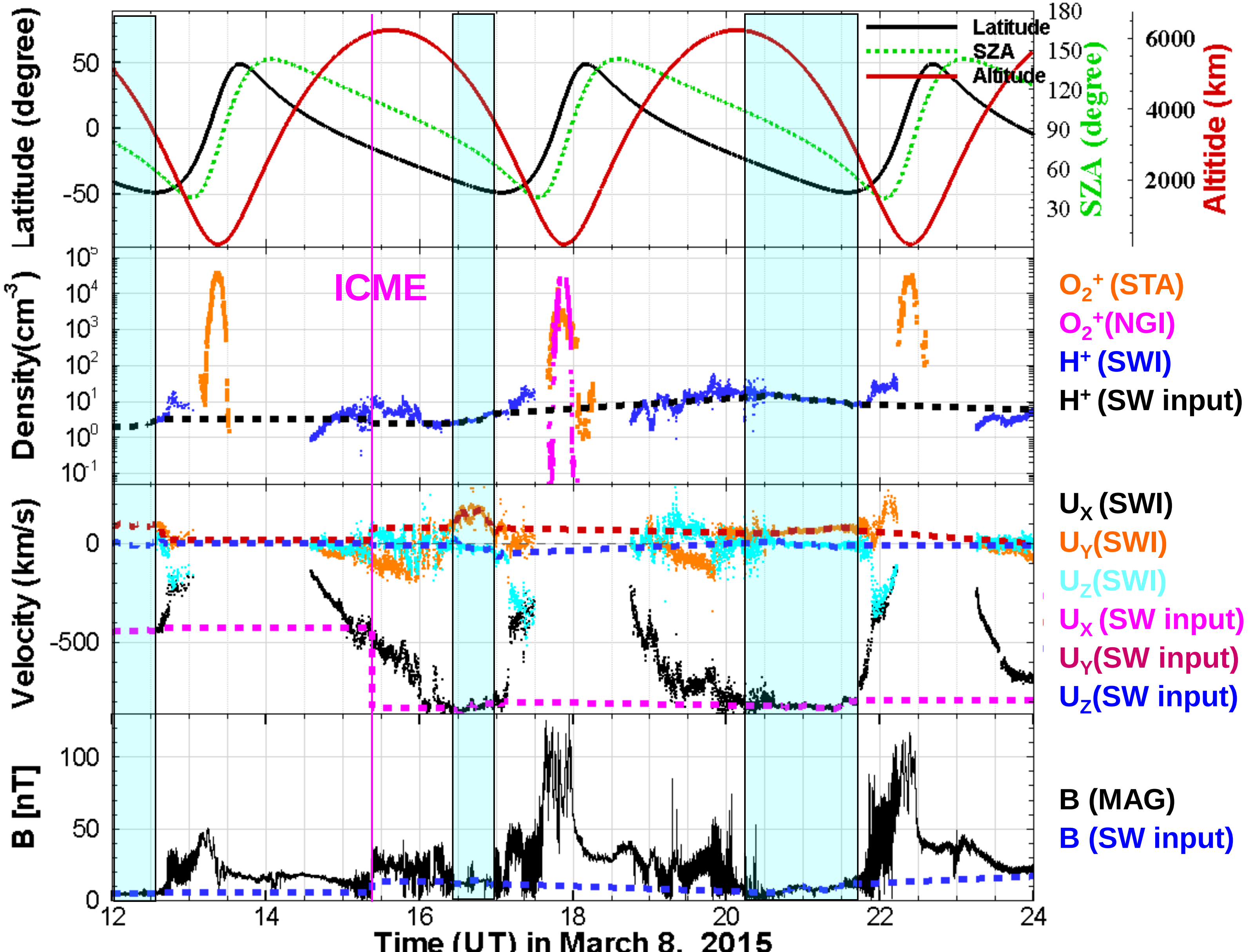
B_0(crustal magnetic field)

B_I (Induced Magnetic field)

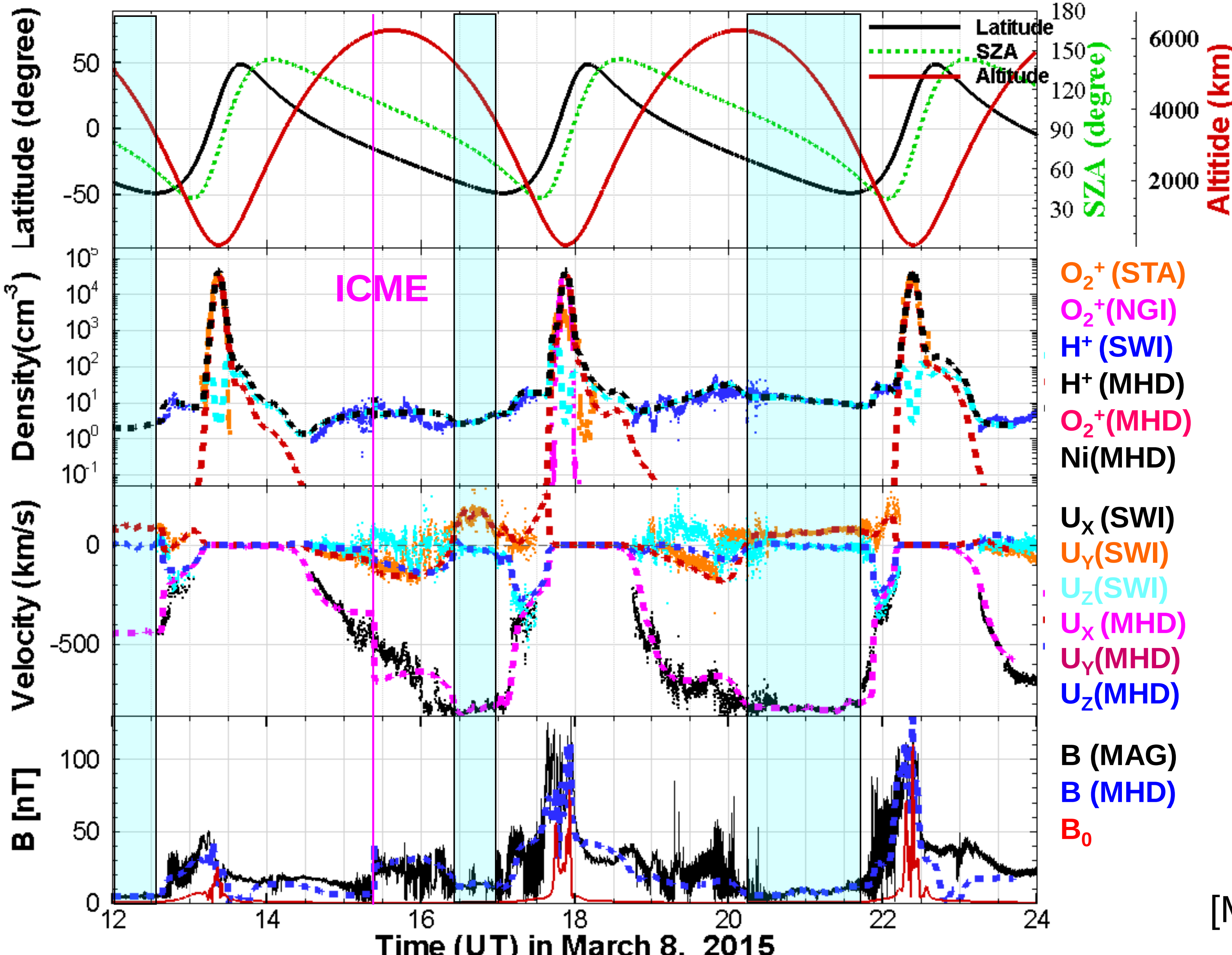
B_I (Induced Magnetic field w/o crustal field)



Solar Wind Input of the ICME in the Time-dependent MHD Simulation

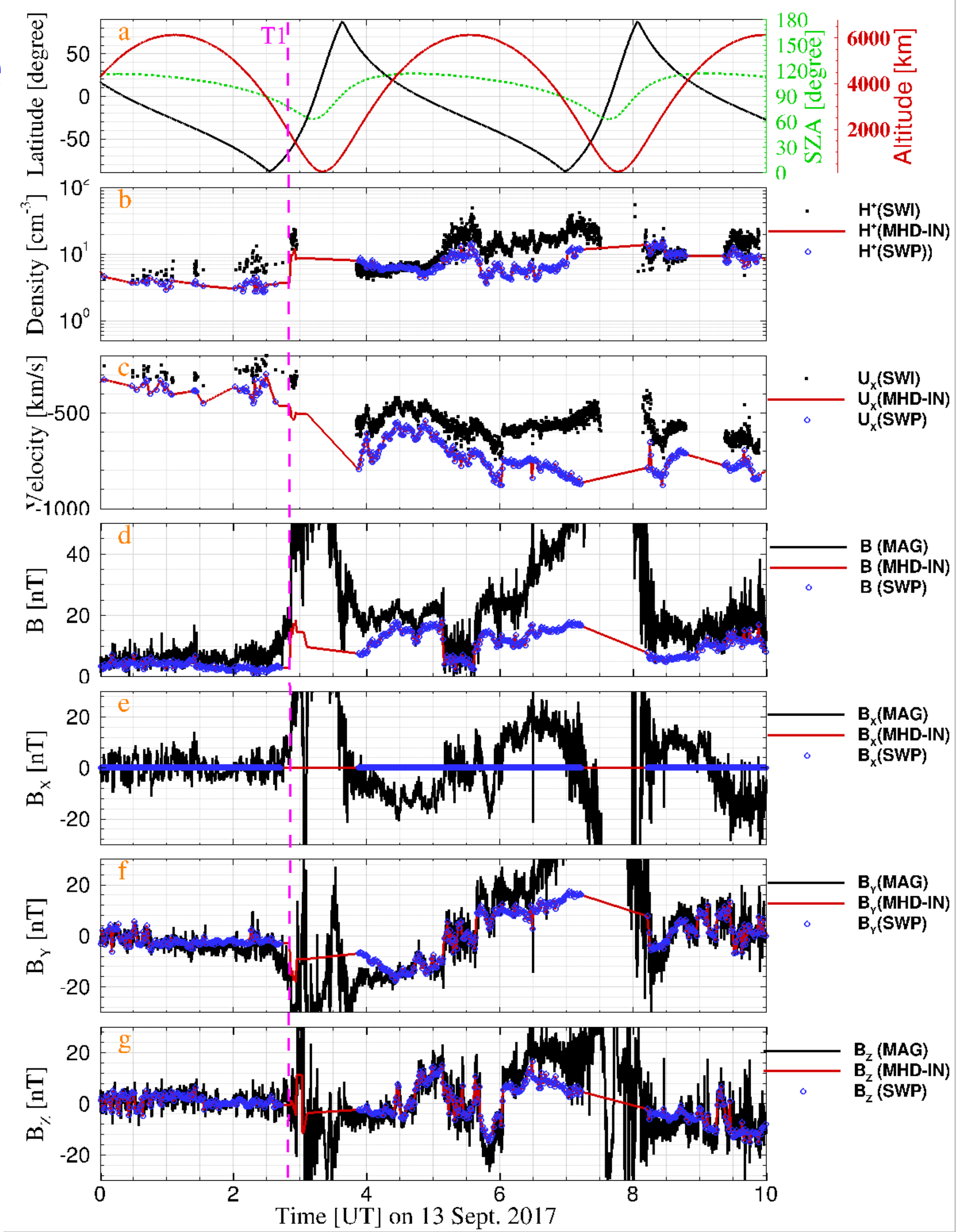


Time-dependent MHD Model Results and Comparison with MAVEN

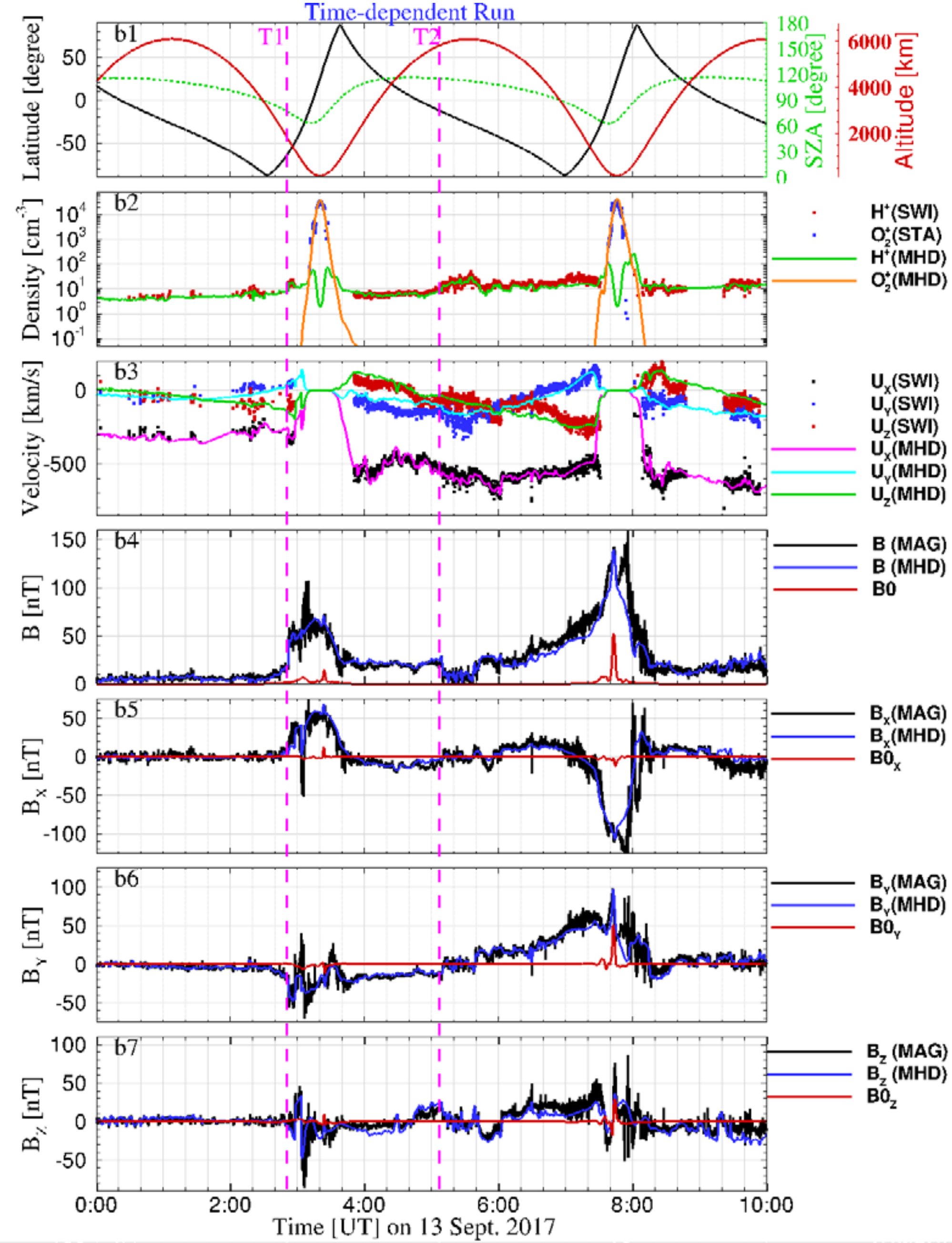


[Ma et al., 2017]

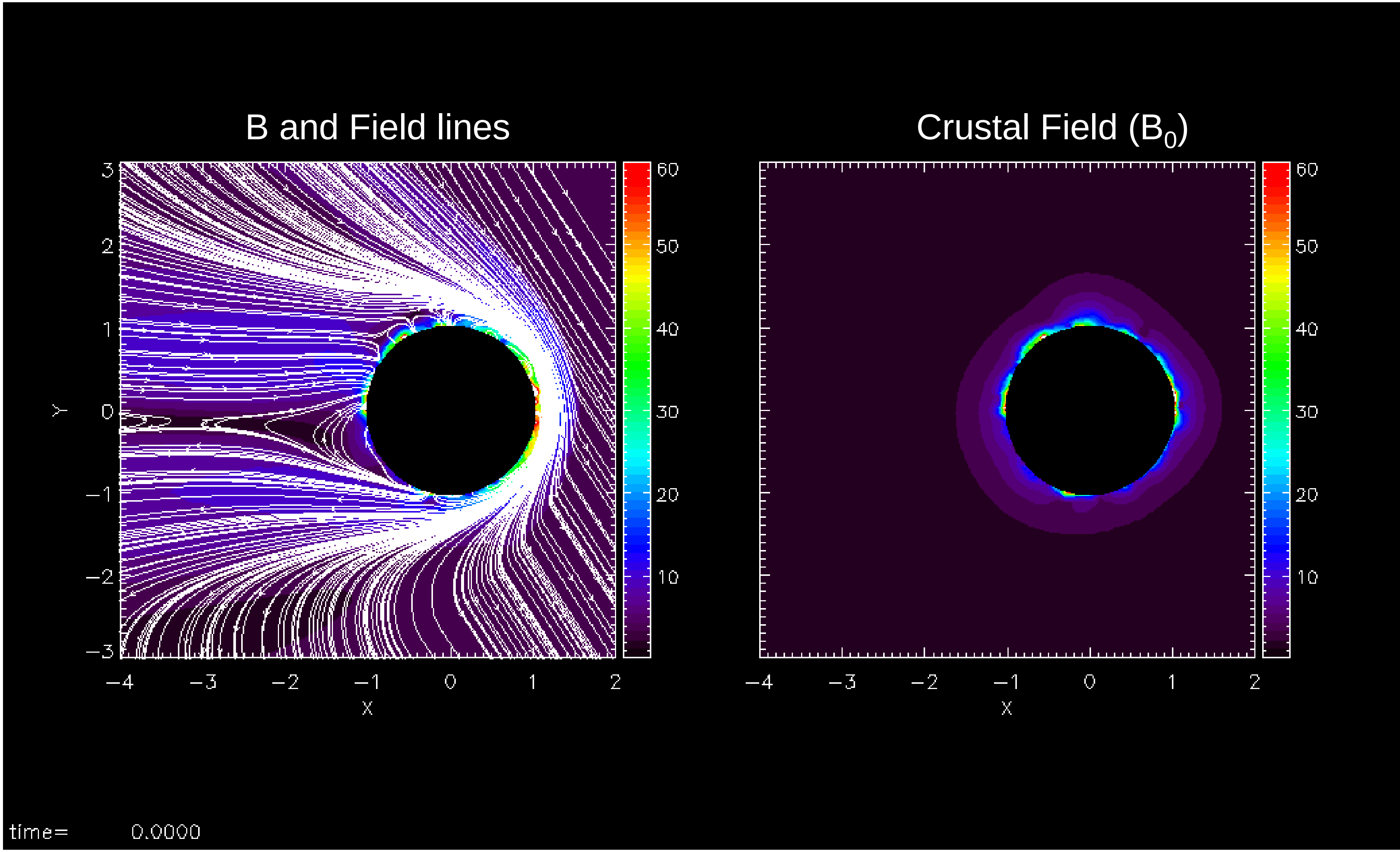
Response … 2017, Ma



Responses to an real ICME event [Ma et al., 2018]



Effects of the Diurnal Rotation of the Crustal Field (Time-dependent MS MHD)

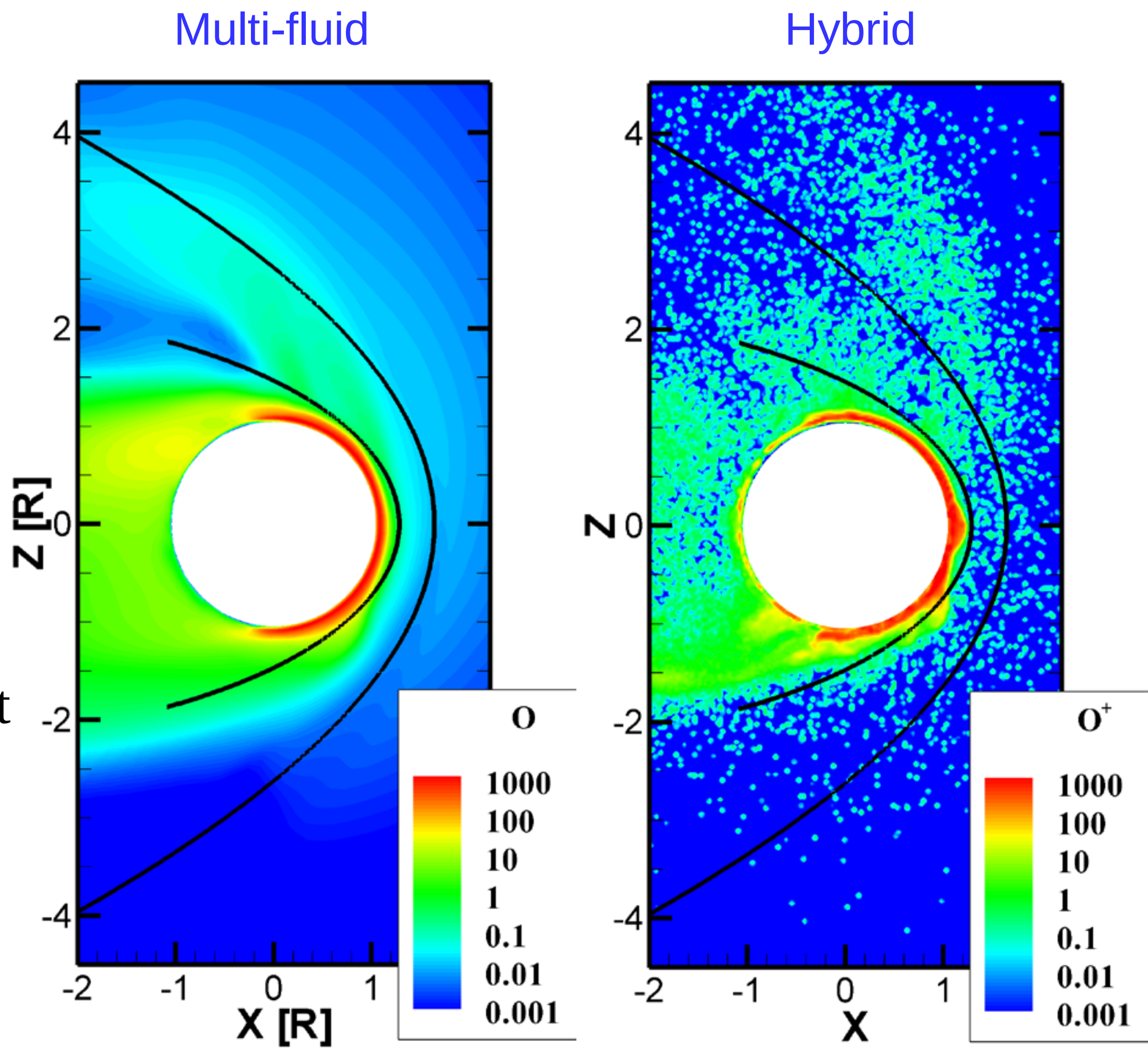


As the planet rotates, the size and shape of the obstacle to the solar wind varies. As a results, the induced magnetic field also varies with time. (*Ma et al.*, 2014)

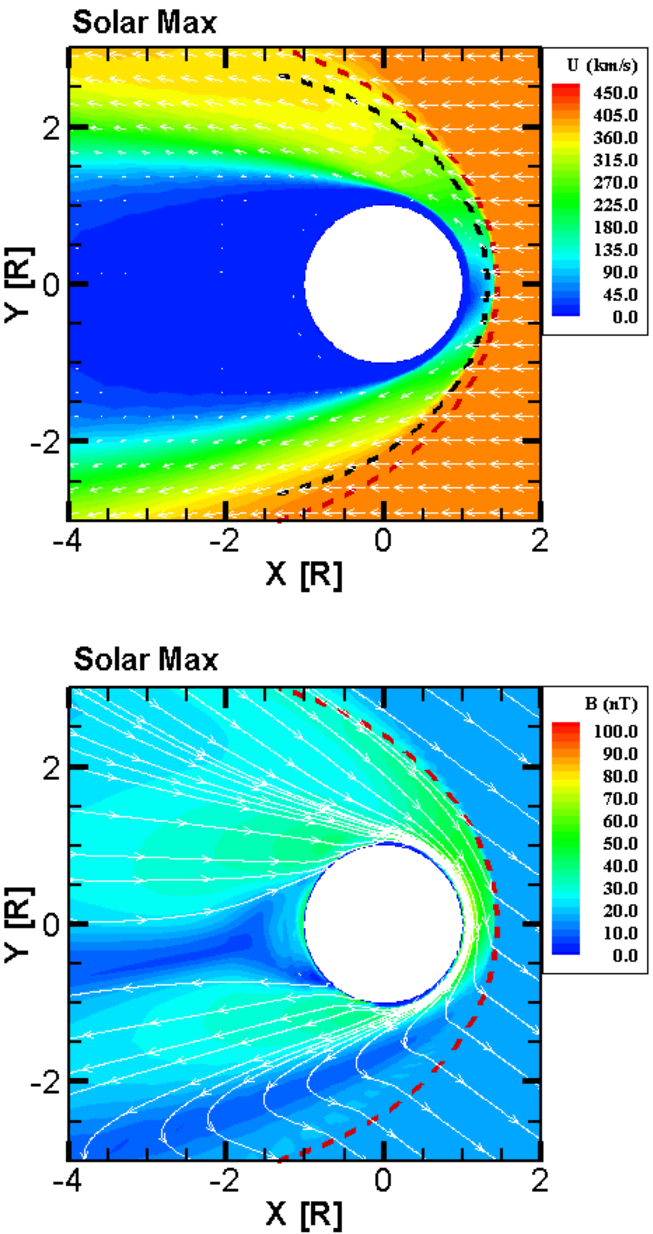
Multi-fluid vs. Hybrid

Both the Michigan multi-fluid MHD model [*Dong et al.*, 2015] and the multi-species hybrid model [*Modolo et al.*, 2012] are chosen for use in the MAVEN library. Further validation and improvement are needed based on the recent MAVEN observations.

[*Lillis et al.*, 2015]



Solar Cycle Dependence of the IM of Venus



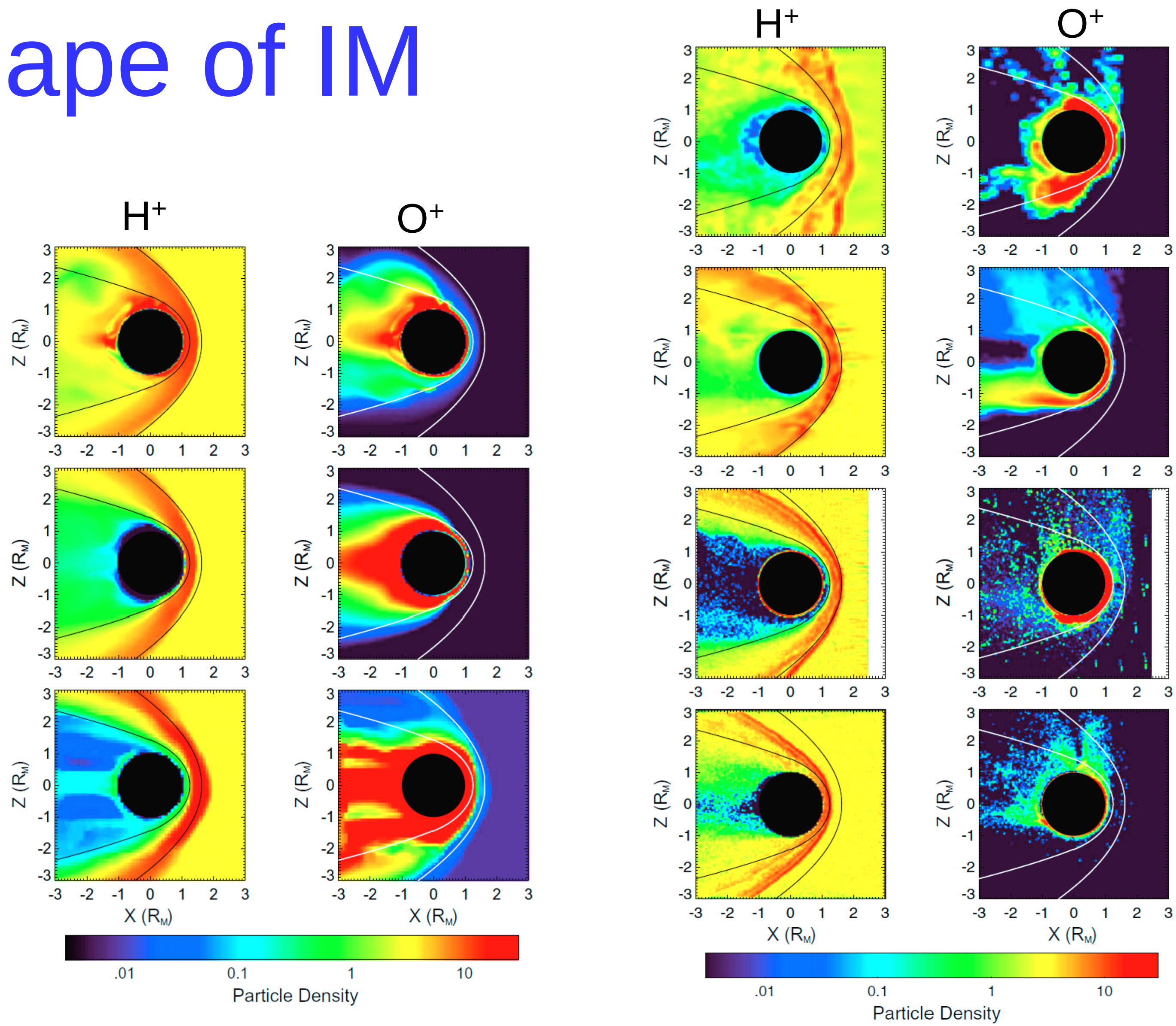
Subsolar shock location
Solar max: 1.44 R_V
Solar min : 1.33 R_V

Without ionosphere
Subsolar shock location
Solar max: 1.32 R_V
Solar min : 1.25 R_V

Contour of plasma speed and magnetic field in the equatorial plane for solar max (left panels) and solar min (right panels) cases. The red dashed line is the average bow shock location at solar max condition from Zhang et al. (1990), while the black dashed line is for solar min condition from Zhang et al. (2008).

(From *Ma et al.*, 2013)

Shape of IM



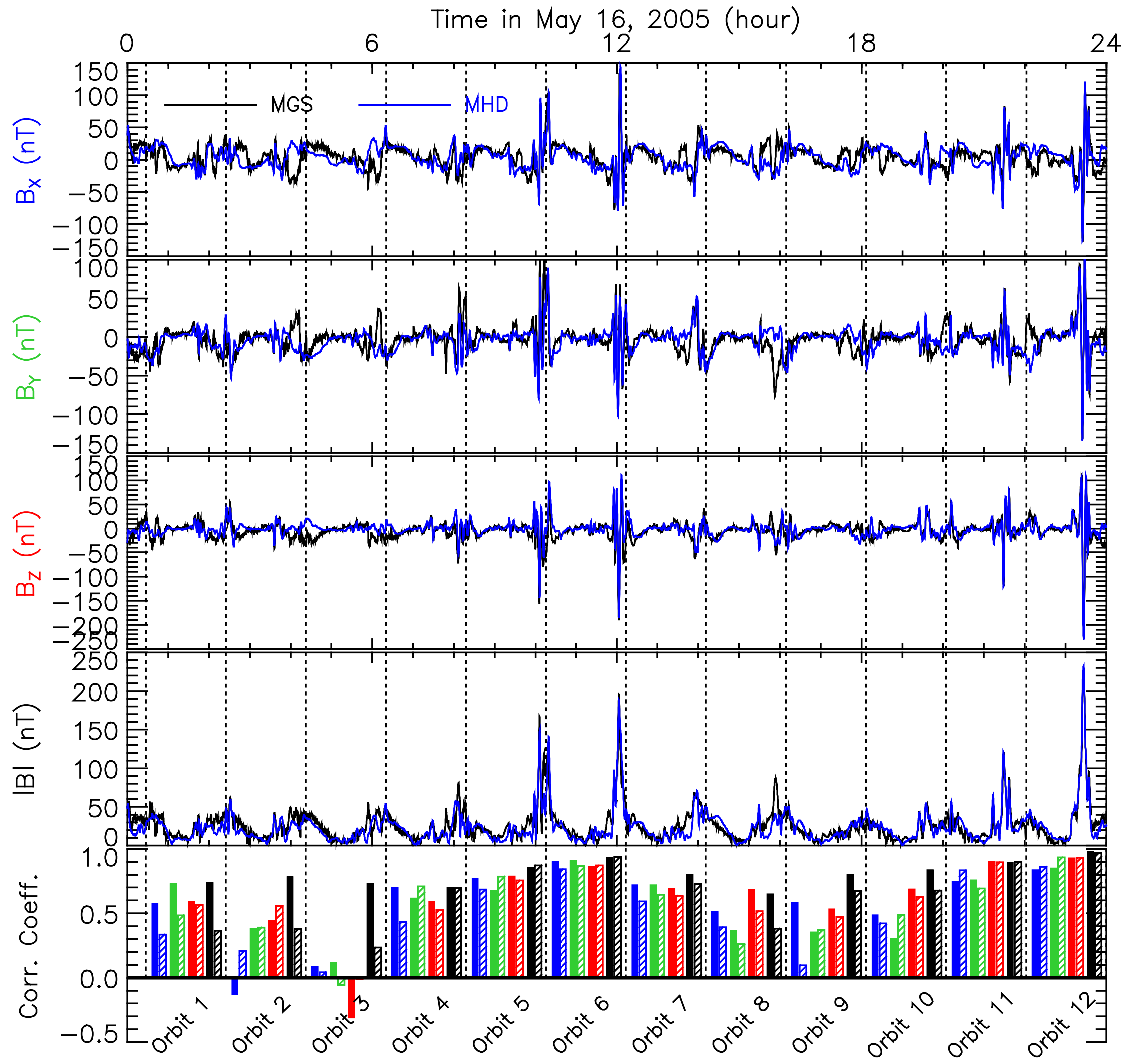
Mars Model results of Ma, Terada, Harnett on the left panels, and of Brecht, Kallio, Modolo, and Boesswetter models on the right panels. [*Brain et al.*, 2010]

Comparison with MGS observations on May 16, 2005

*Overall good agreement between model results and MGS observations.

*The agreement is the best for B magnitude (corr. Coeff =0.88, RMSE = 10.9 nT).

*The corr. Coeff for components of magnetic field is not as good mostly due to IMF direction change during the day.



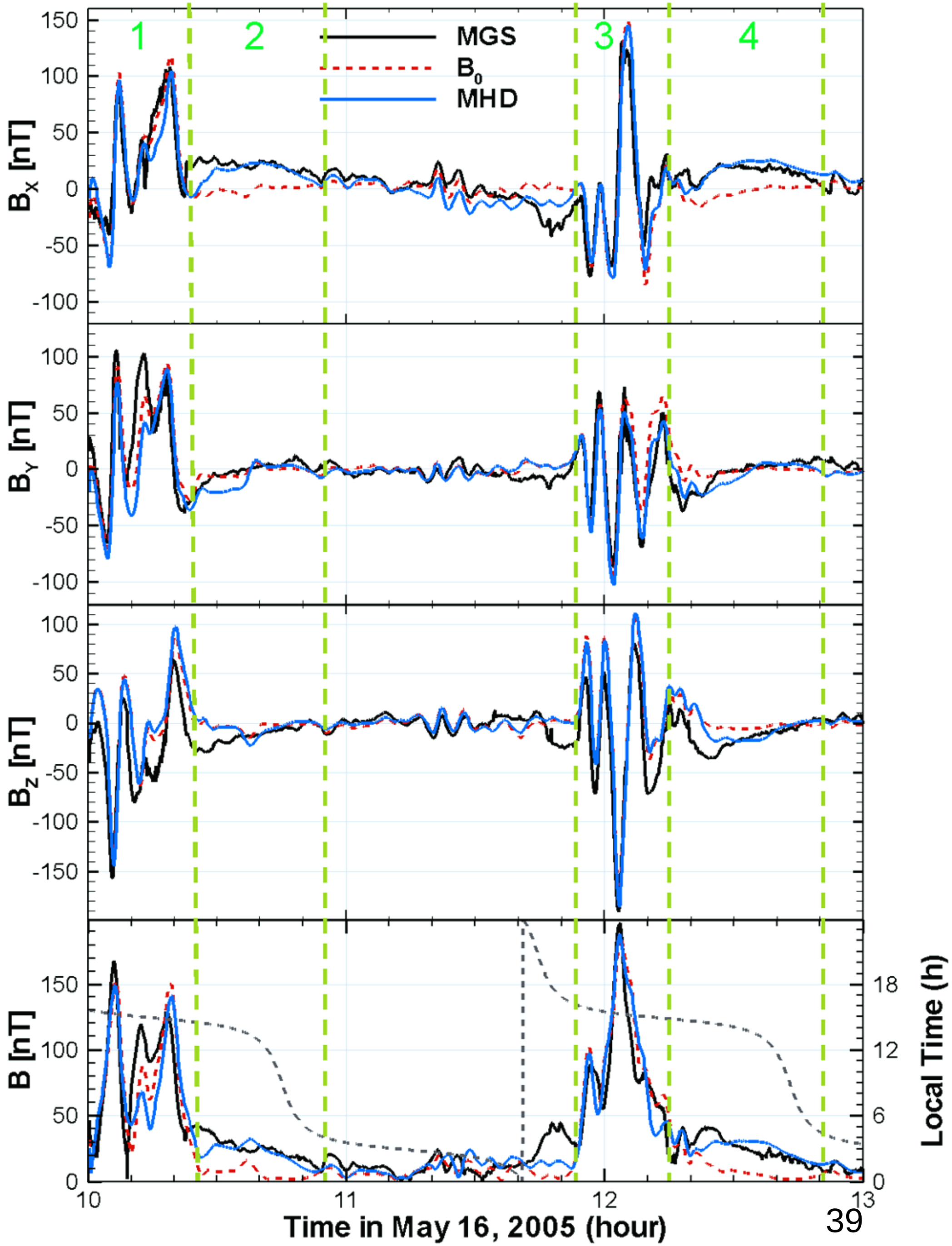
IMF condition used in the MHD model
B_X =1.6 nT, B_Y=-2.5 nT

Zoom in view of the comparison with MGS observations on May 16, 2005, over-plotted with local time.

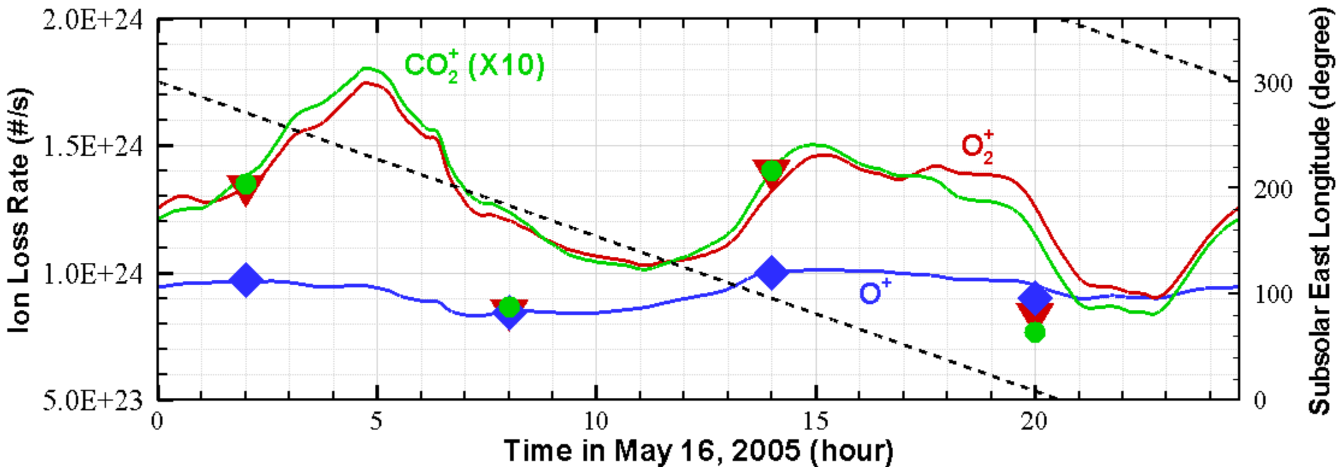
*Good agreement near strong crustal field region indicates that the crustal field model included in the MHD model is quite accurate.

*Around dayside weak crustal field region, the induced field is important to fit with the data.

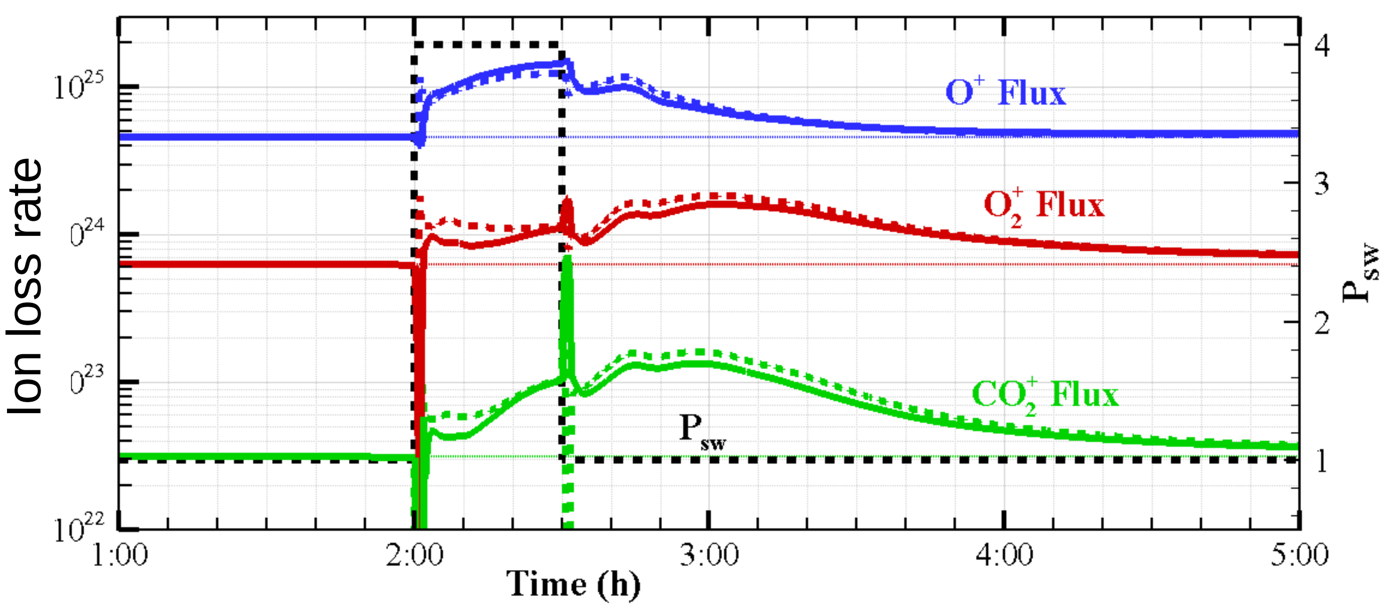
*In some region, it is hard to distinguish what is the cause for the discrepancy (IMF, crustal source, or model limitation).



Two Important Controlling Factors for Ion Loss Rate

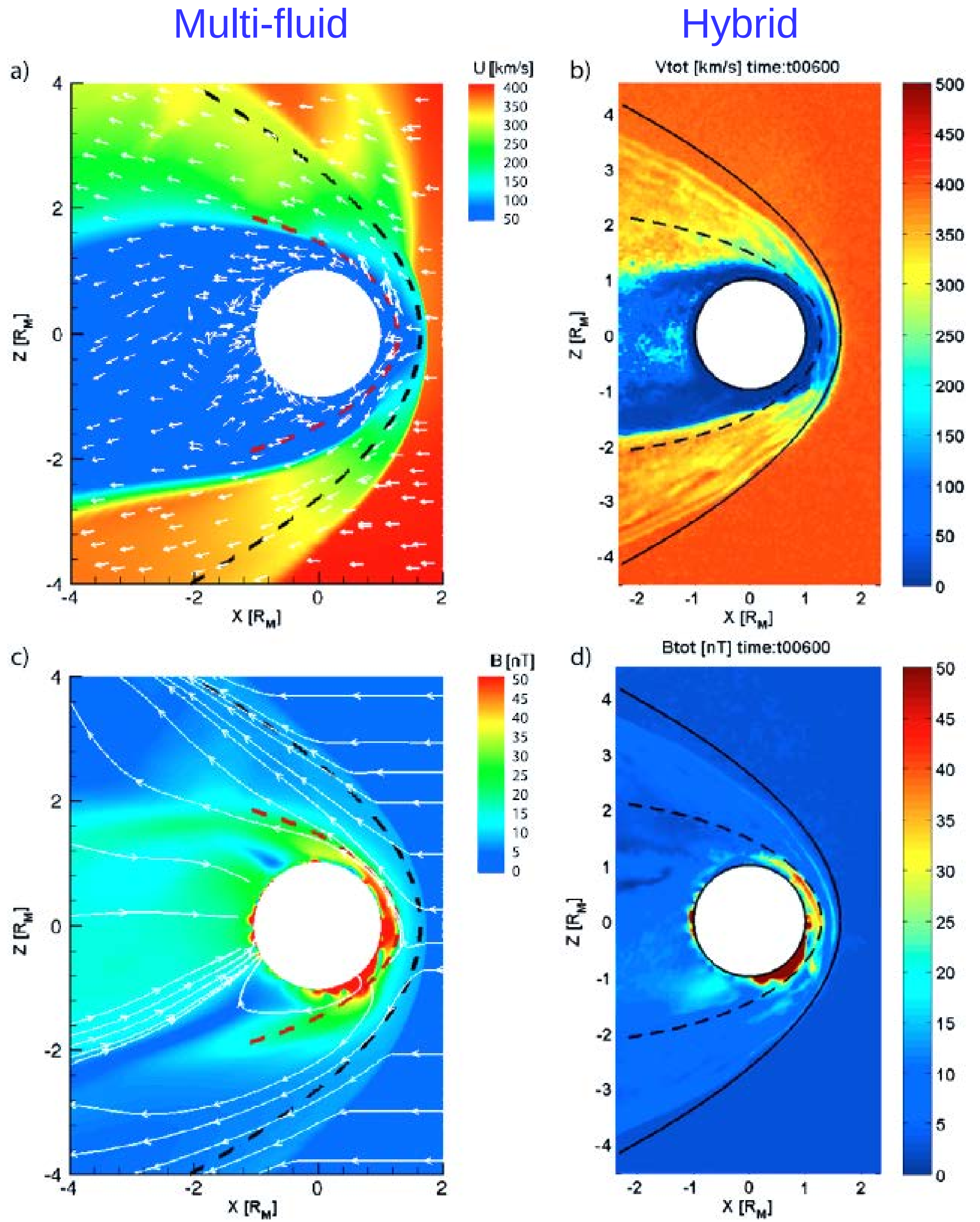


Rotation of the Crustal Field (*Ma et al.*, 2014, GRL)



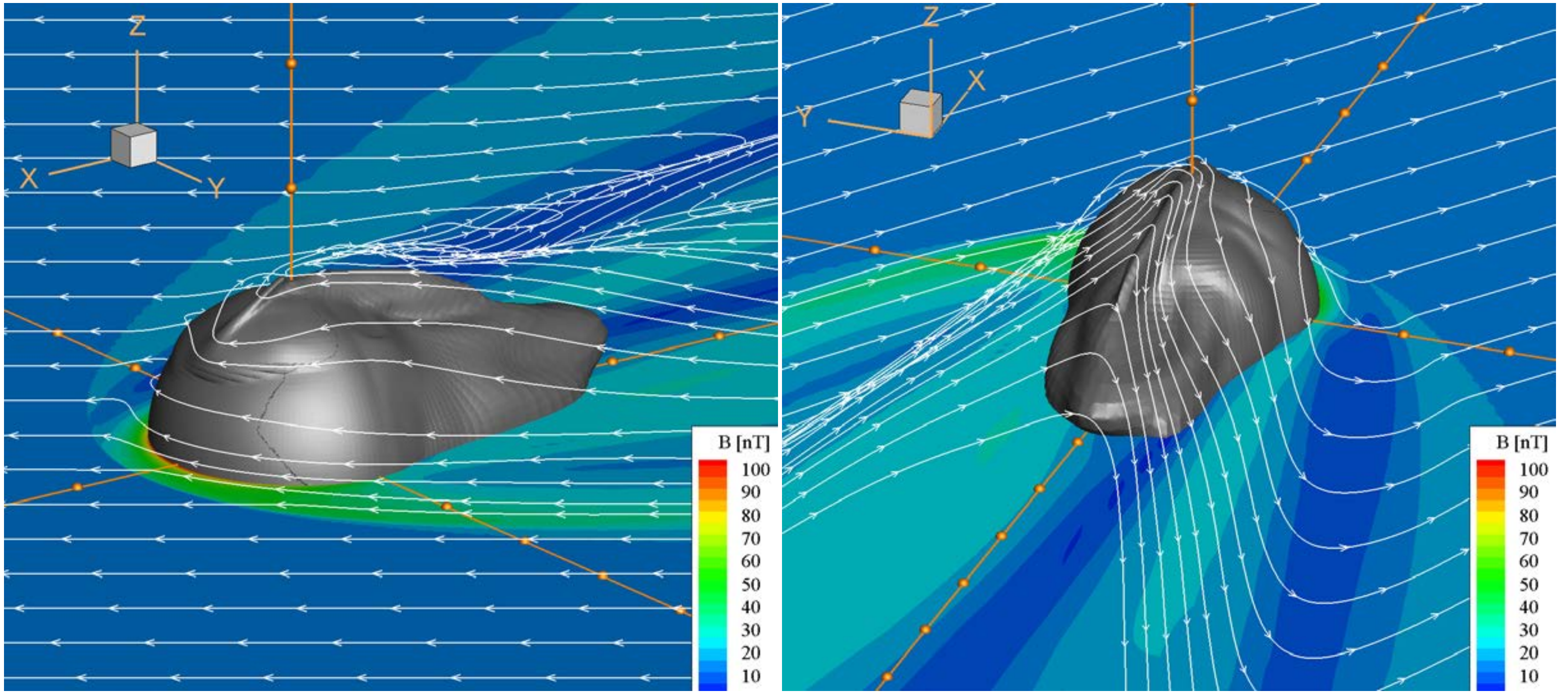
Solar Wind Dynamic Pressure (*Ma et al.*, 2014, JGR)

Multi-fluid vs. Hybrid



Both the Michigan multi-fluid MHD model [*Dong et al.*, 2015] and the multi-species hybrid model [*Modolo et al.*, 2012] are chosen for the use in MAVEN library. Further validation and improvement are needed based on the recent MAVEN observations.

[*Lillis et al.*, 2015]



This figure shows both the upstream and downstream views of the interaction process. The gray isosurface represents a density contour with planetary O^+ density equals to 50/cc as an indication of Venus ionosphere, which is around 400 km altitude along the subsolar line, but extends nearly to 5 R_V in the nightside. This figure shows how field lines wrap around the obstacle on the upstream side, but slip over the obstacle on the night side.

The field lines at high latitude are kinked because the plasma closer to the planet have been mass-loaded by planetary ion production and so significantly slowed down as compared with plasma further away from the planet.

The draped field exerts a JxB force on the plasma in the wake, speeding it up to escape velocity as down-tail distance increases. (*Ma et al., 2013*)

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