Solar wind-magnetosphere coupling via magnetic reconnection likely becomes less efficient the further a planetary magnetosphere is from the Sun

Although most of the planets in the Solar System have an intrinsic magnetic field that produces a surrounding magnetosphere and shields them from the solar wind, magnetic reconnection is a process by which solar wind energy can still penetrate such magnetic shields. Spacecraft missions to the magnetized planets have revealed how conditions at the magnetopause boundary of a magnetosphere varies between planets, which may produce differing solar wind-magnetosphere interactions via magnetic reconnection. Here I present the hypothesis that this coupling through magnetic reconnection becomes less efficient the greater the heliocentric distance of a planetary magnetosphere. Simple modeling is used to highlight that we expect the increasing solar wind Mach numbers with heliocentric distance to produce magnetosheath solar wind regions around planetary magnetospheres (between the bow shock and magnetopause) where plasma β (ratio of plasma to magnetic pressure) conditions also rise. Further modeling is then used to apply current understanding of the reconnection process to show that higher magnetosheath plasma β conditions should place increasingly severe restrictions on the fraction of the dayside magnetopause surface where reconnection can occur.

Conditions at planetary magnetopauses further from the Sun are probably less favourable for magnetic reconnection

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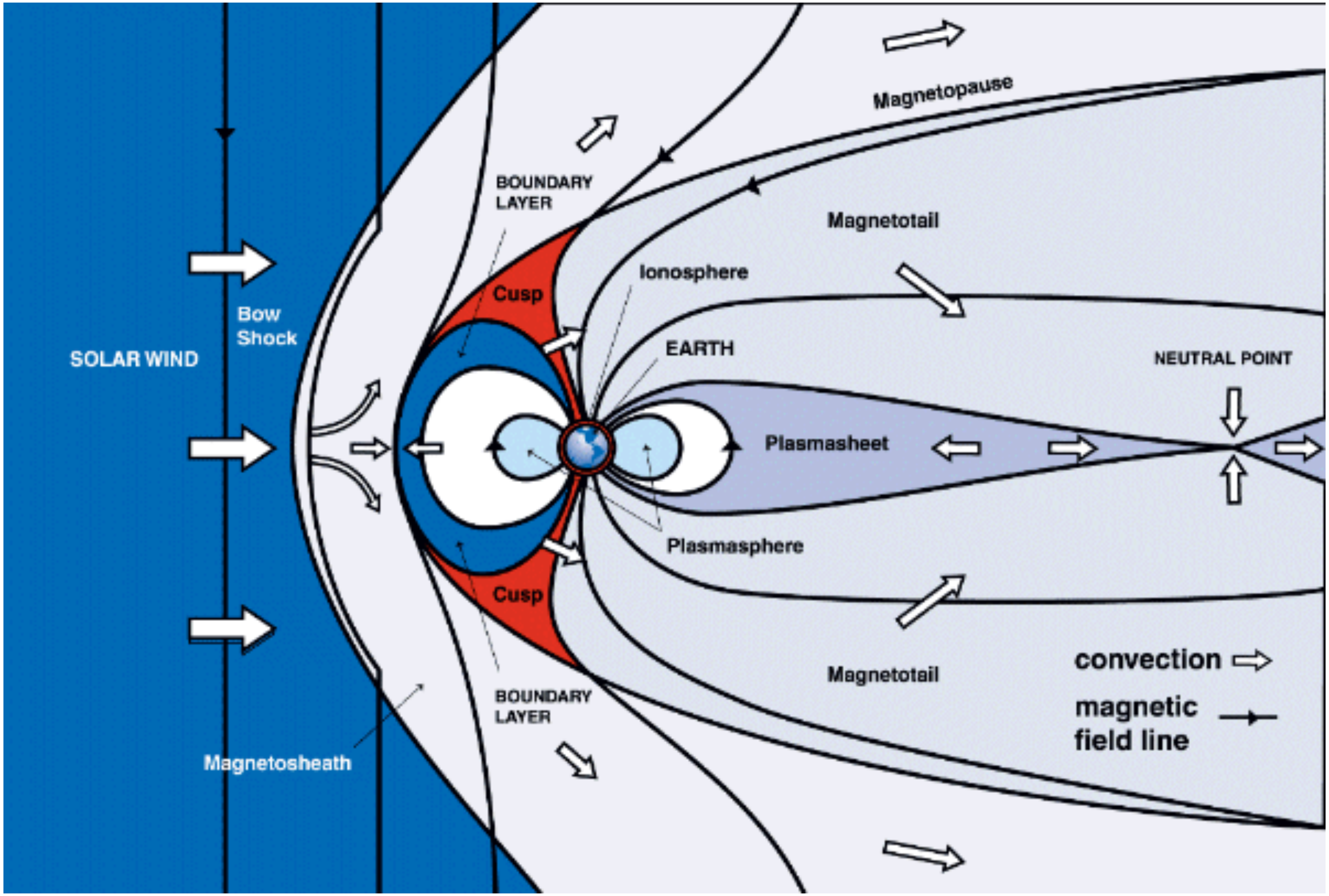
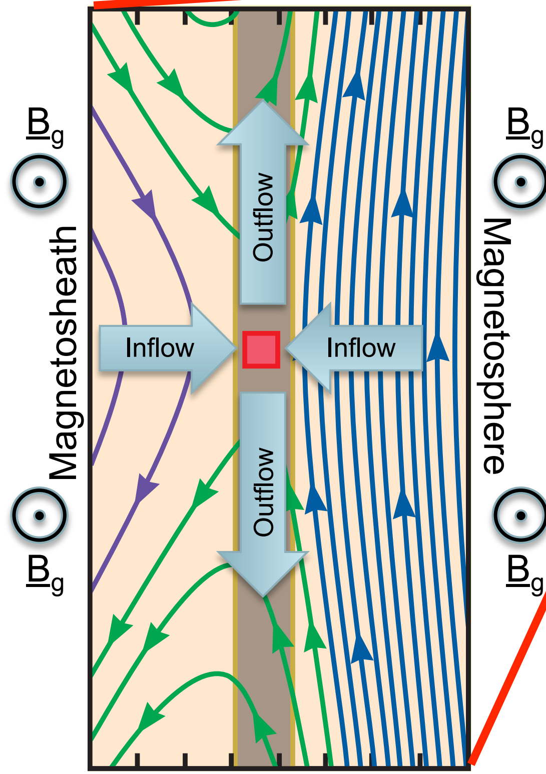
What is a planetary magnetosphere?



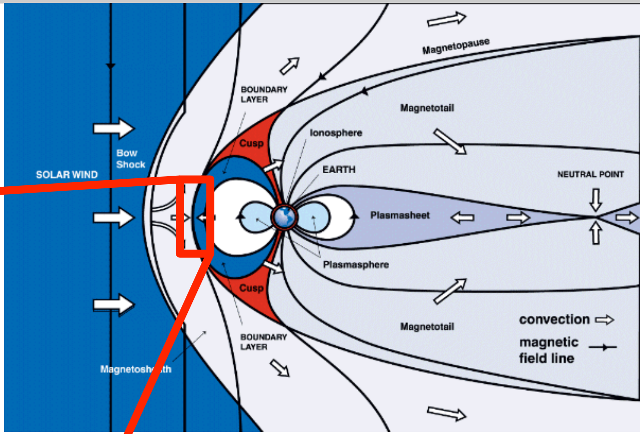
Magnetic reconnection at a planetary magnetopause

- Understanding of all magnetospheres is largely based on Earth's magnetosphere
- One of the major processes by which solar wind energy can enter Earth's magnetosphere is magnetic reconnection
- Magnetic reconnection is a fundamental plasma process, which occurs in many space environments
- Reconnection changes the topology of the magnetic field and releases magnetic energy

Taken from Mozer and Pritchett (2010)



Magnetic shear ≲ 180°
Diffusion regions
Reconnected field lines



- Earth's magnetopause is a current layer where reconnection can occur
- Reconnection at Earth's magnetopause is often the primary driver of dynamics in the magnetosphere

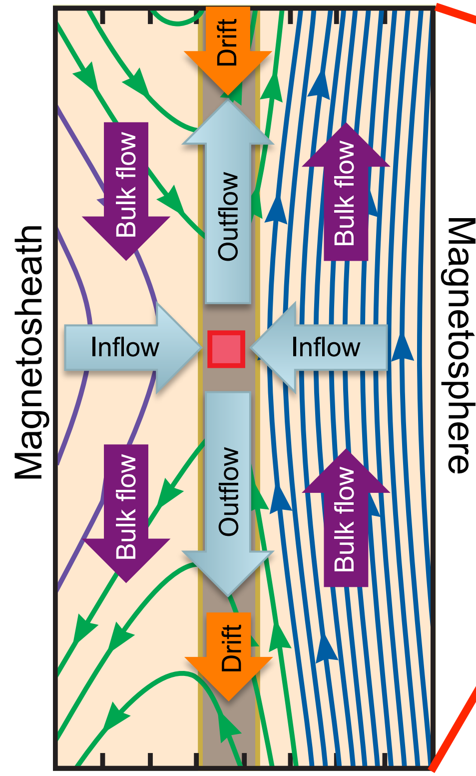
Conditions for magnetic reconnection onset

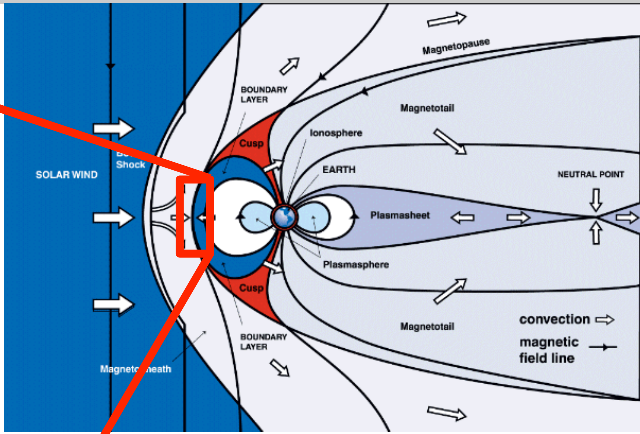
- Reconnection does not happen all the time and everywhere on Earth's magnetopause

- Proposed conditions for reconnection onset:
  - Thin current sheet (~an ion inertial length)
  - Slow diamagnetic drift (related to plasma β)
  - Small flow shear across the current sheet

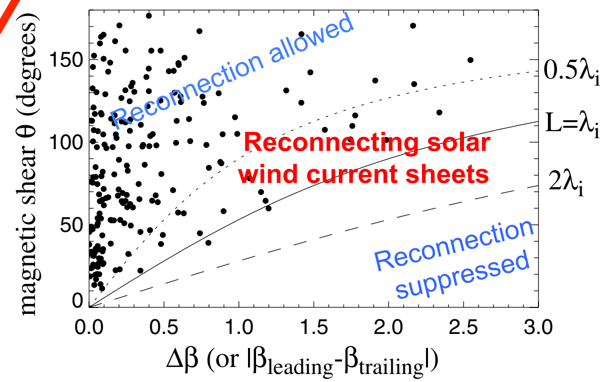
- The diamagnetic drift condition is strongly supported by observations of reconnection at both Earth's magnetopause and in the solar wind (Swisdak et al., 2003) (Phan et al., 2010, 2013)

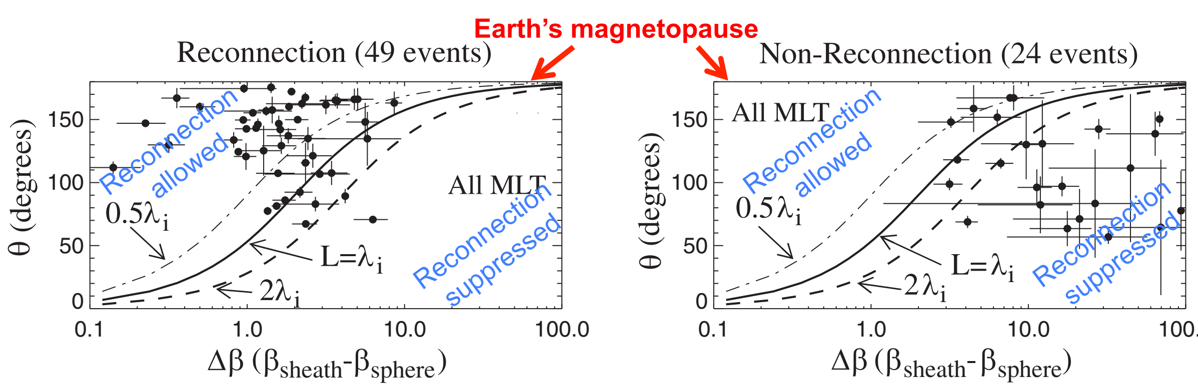
Taken from Mozer and Pritchett (2010)





Taken from Phan et al. (2010)

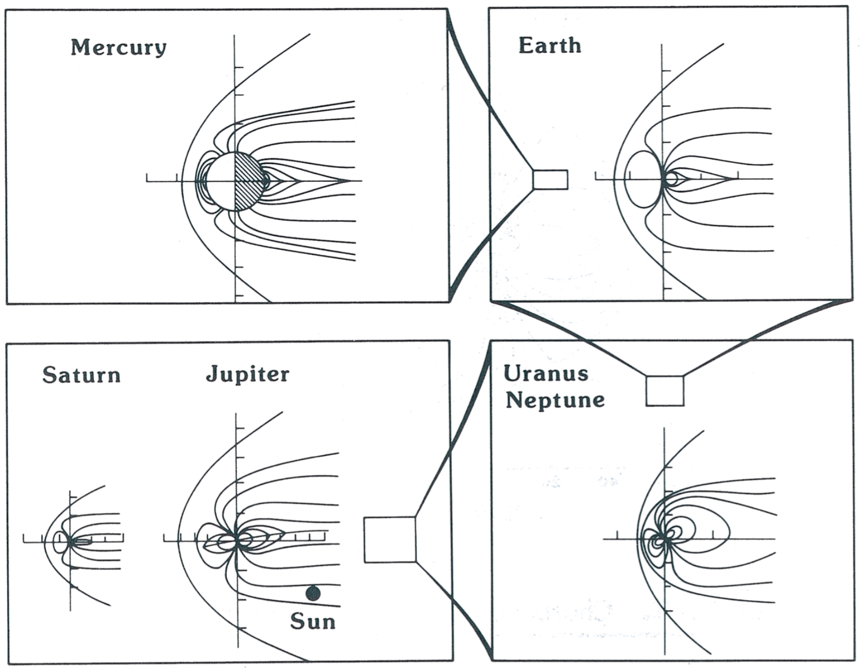




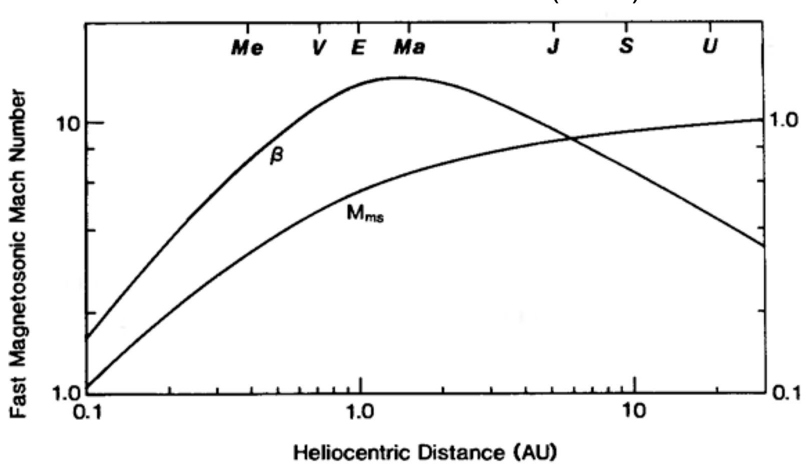
Taken from Phan et al. (2013)

- There are a range of very different magnetospheres in our solar system where we can test our understanding of how magnetospheres work
- Does reconnection take place at all planetary magnetopauses, and are there differences between planets?
- Observations at magnetised planets other than Earth are limited, and spacecraft instrumentation is often also more limited
- Should we expect a difference based on our understanding of these environments, and our understanding of magnetic reconnection?
- Scurry and Russell (1991) proposed that we should, because of solar wind Mach numbers

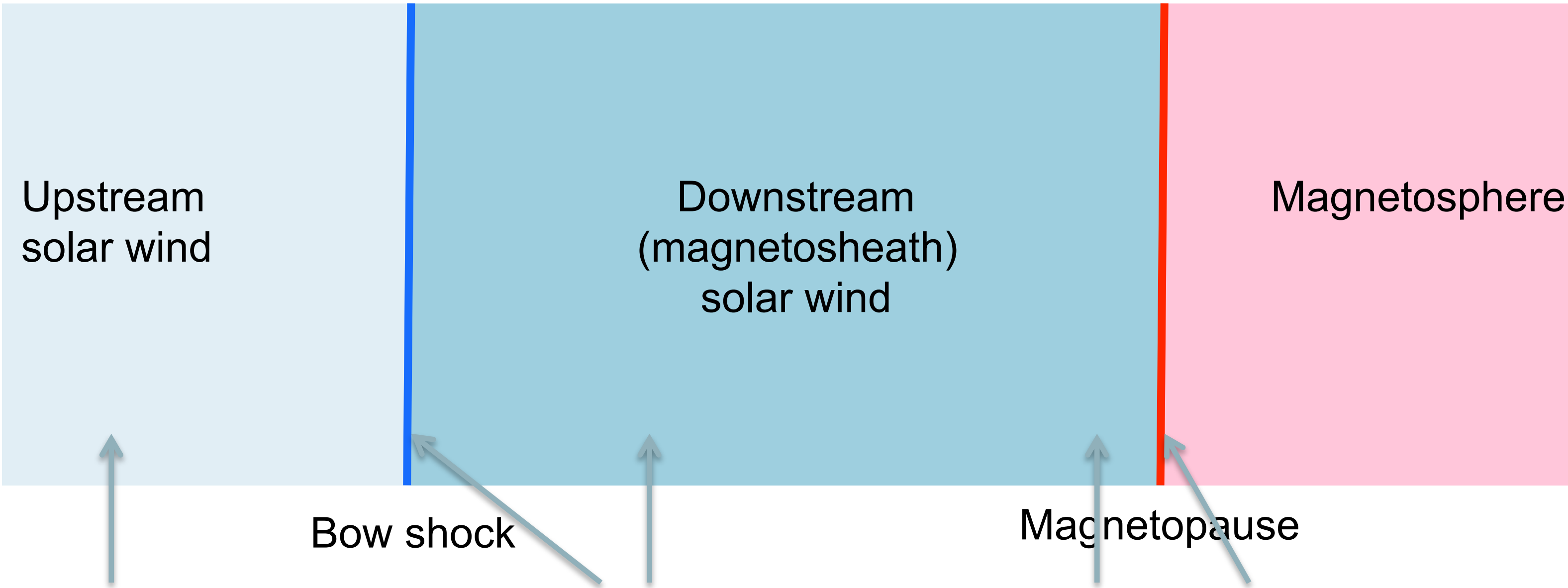
Taken from Walker and Russell (1995)



Taken from Russell et al. (1990)



The Scurry and Russell hypothesis



The solar wind flow has a Mach number, the smallest is the flow speed divided by the speed of fast magnetosonic waves

This Mach number gets larger the further the solar wind is from the Sun, because of how different parameters change

At a planetary bow shock a fraction of the solar wind flow energy is dissipated, heating and compressing the plasma

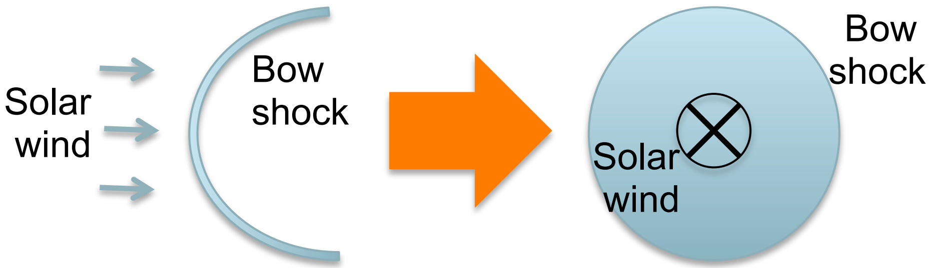
The plasma β (ratio of plasma to magnetic pressure) increases across the shock, and the higher the Mach number the higher the plasma β becomes

So, a higher Mach number shock is predicted to produce a higher β magnetosheath plasma, which interacts with the magnetopause

We have already seen that higher β is less favorable for magnetic reconnection

→ Planets further from the Sun have higher Mach number bow shocks, which make conditions less favorable for reconnection at the magnetopause

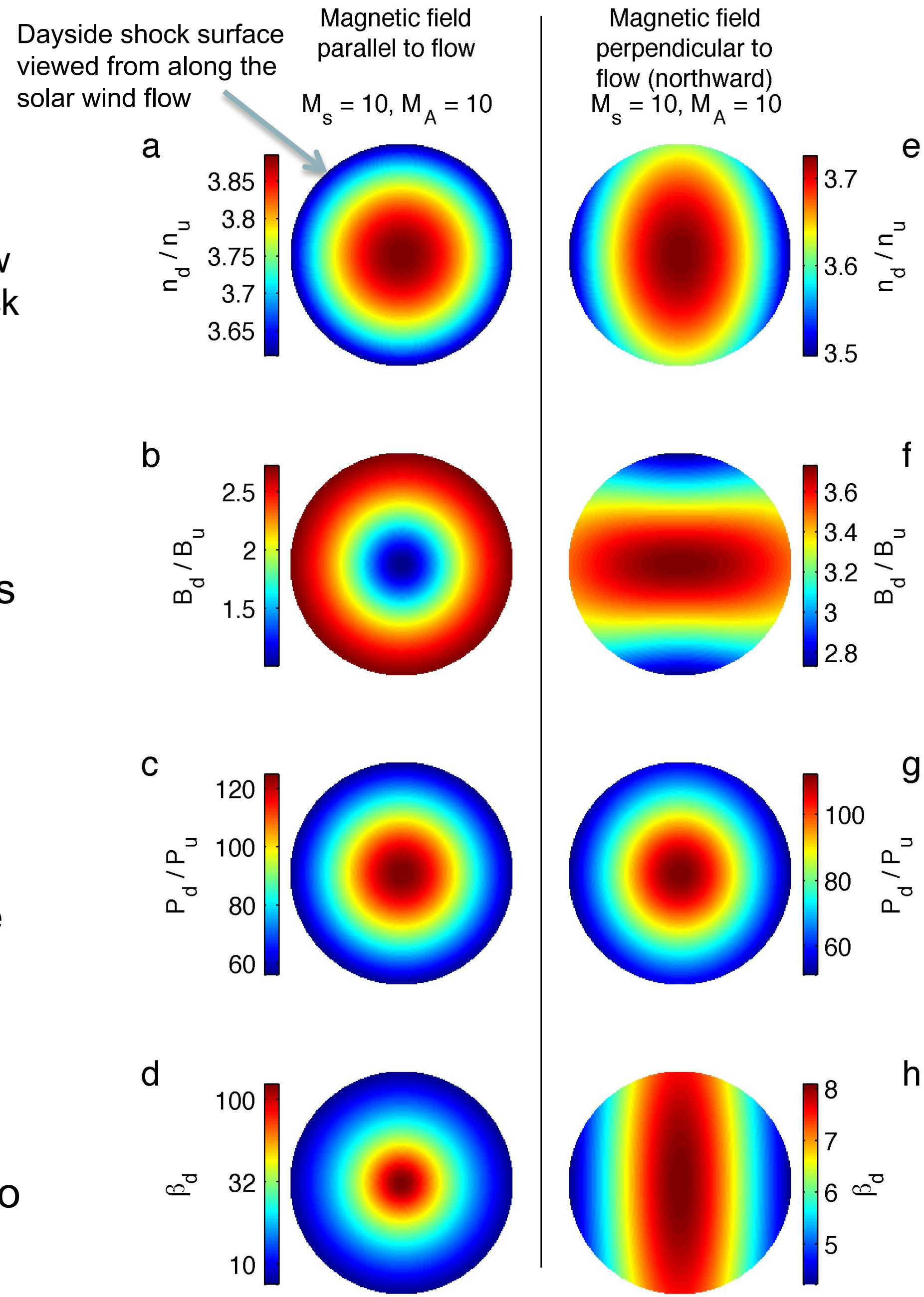
- Consider a model paraboloid bow shock surface, representing a 'general' dayside planetary bow shock



- The shock jump (Rankine-Hugoniot) conditions give the change in parameters across the shock surface based on conservation laws

  → For a chosen sonic and Alfvén Mach number we can predict the change in each plasma parameter across the shock surface

- The upstream magnetic field orientation is an additional parameter choice. Since this varies considerably in the solar wind we consider the two limiting cases: Field parallel to the flow, and field perpendicular to the flow



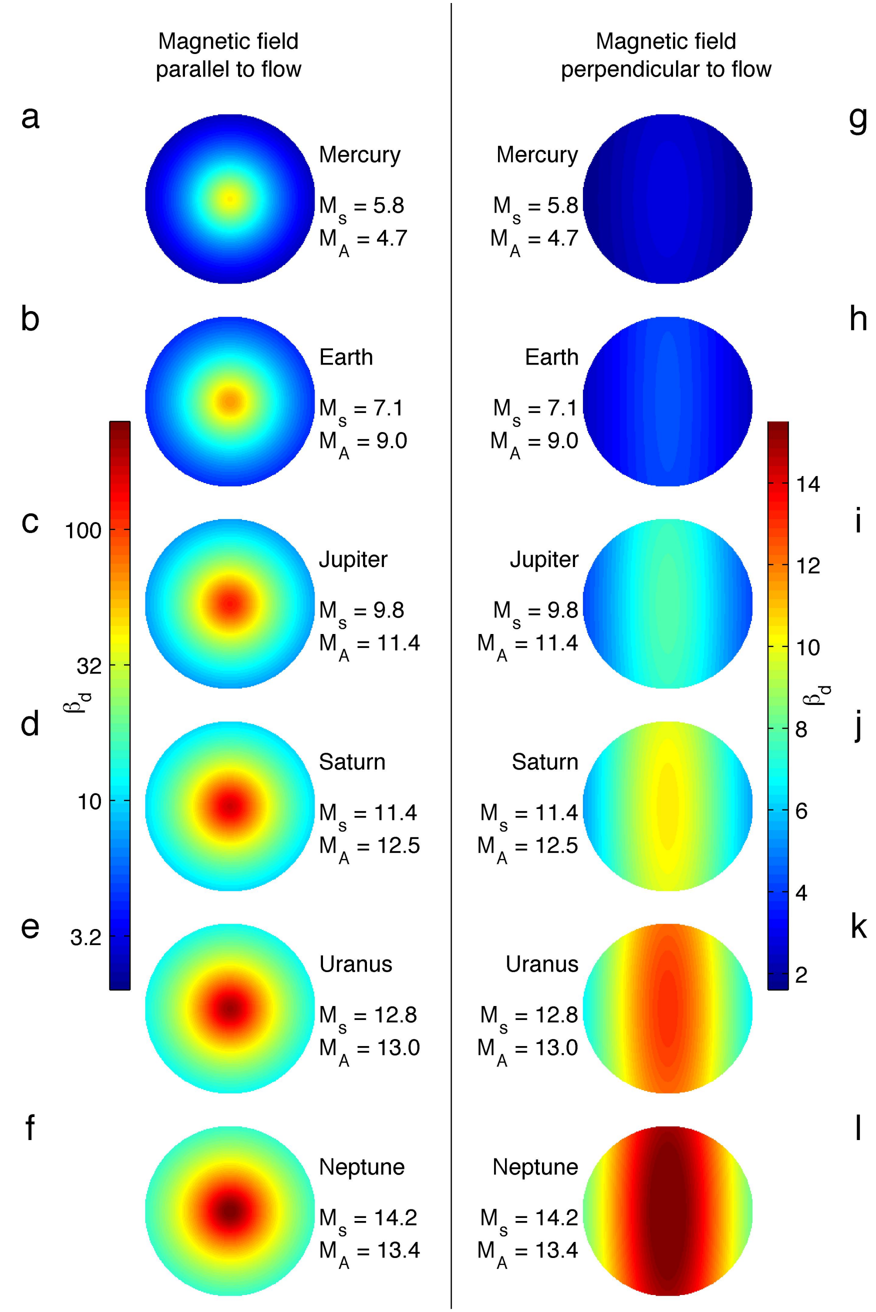
- Note: The choice of sonic and Alfvén Mach numbers define the upstream plasma β as

$$\beta_u = \frac{2}{\gamma}\left(\frac{M_A}{M_s}\right)^2$$

- If we choose the Mach numbers that correspond to each planetary bow shock (e.g. Fujimoto et al. (2007)) then we can compare plasma β immediately downstream of the bow shock

- It is clear that higher Mach numbers at the outer planets are expected to produce higher β conditions, this is consistent with the hypothesis

- The plasma β just downstream of the shock is essentially a boundary condition for the entire magnetosheath region



Treatment of the magnetosheath

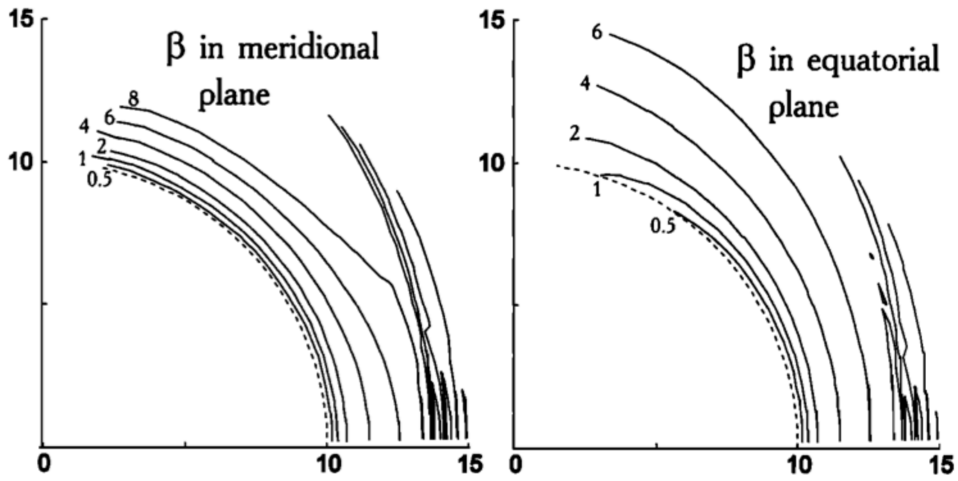
- The treatment of the evolution of magnetised plasma parameters within a planetary magnetosheath for a range of IMF orientations cannot be solved analytically, and require magnetohydrodynamic simulations (e.g. Petrinec and Russell, 1997)

- However, spacecraft observations have already provided evidence that plasma β conditions in planetary magnetosheaths further from the Sun are generally higher, consistent with our simple bow shock modelling, and consistent with the hypothesis

- Can we carry out similar simple modelling for planetary magnetopauses?

- Previous simulations suggest that the magnetosheath plasma β next to a magnetopause remains roughly constant across the dayside surface (Samsonov and Pudovkin, 2000)

Taken from Samsanov and Pudovkin (2000)



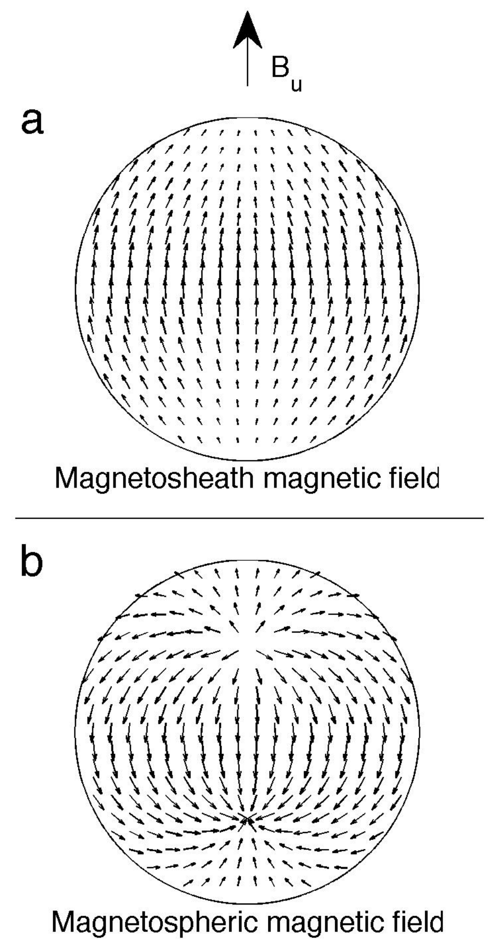
Testing the hypothesis: Modelling near-magnetopause conditions

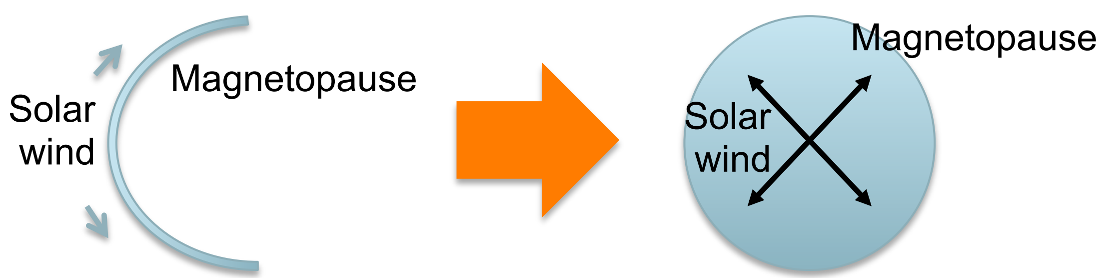
- Assumptions made in simple magnetopause modelling:

1. Draped interplanetary magnetic field given by Kobel and Fluckiger (1994) equations for an axis-symmetric magnetopause shape (no polar flattening)
2. Magnetospheric magnetic field corresponding to a dipolar planetary magnetic field with the dipole perpendicular to the solar wind flow, after Cooling et al. (2001)
3. Plasma β equal to 0 in the magnetosphere (a vacuum dipole)
4. Constant value of magnetosheath plasma β
5. Only consider diamagnetic suppression condition for reconnection onset

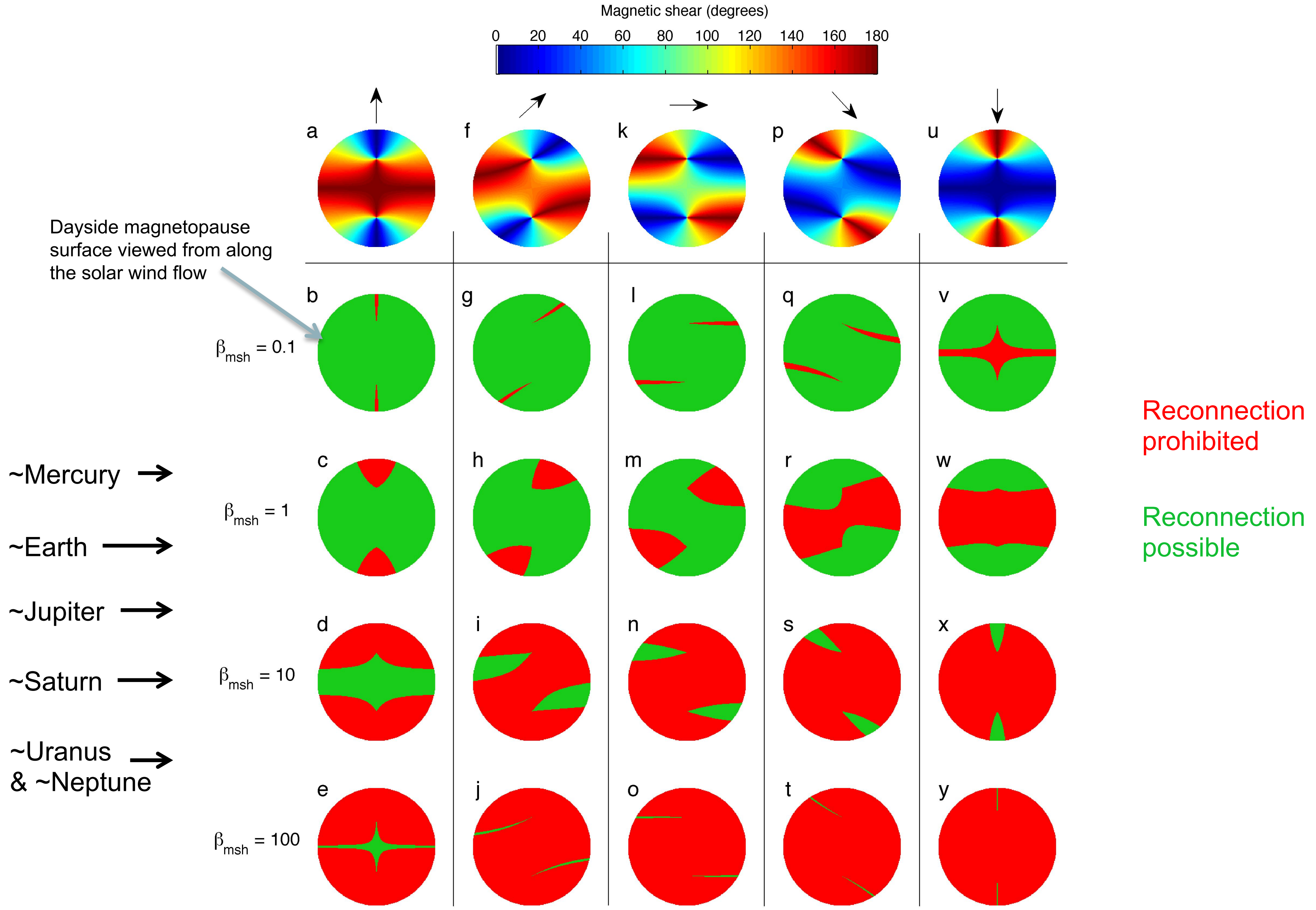
- By considering a range of magnetosheath β values we can then evaluate the diamagnetic suppression condition across the surface, and establish where reconnection onset can, and cannot take place

$$\Delta\beta > \frac{2L_p}{d_i}\tan\left(\frac{\theta}{2}\right)$$





Testing the hypothesis: Modelling near-magnetopause conditions



Summary

- Spacecraft observations at different planetary magnetopauses imply differences in the nature of magnetopause reconnection

- Current understanding of magnetic reconnection onset suggests that a large difference in plasma β across a current sheet limits reconnection to occasions when the magnetic shear across the current sheet is high

- Observations and simple modelling presented here confirm that plasma β conditions in a planetary magnetosheath increase with the distance of a magnetised planet from the Sun, due to the similar increase in shock Mach numbers

- A simple assessment of whether plasma β conditions are appropriate for reconnection at a planetary magnetopause, under different (uniform) β conditions, implies that the fraction of the dayside magnetopause surface where reconnection can occur decreases with increasing magnetosheath plasma β

- This simple modelling supports the hypothesis:

Conditions at a planetary magnetopause probably become less favourable for magnetic reconnection the further a planet orbits the Sun