Modeling Mercury's magnetosheath by the potential-mapping method

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Photography encouraged

This presentation participates in OSPP — Outstanding Student & PhD candidate Presentation contest

Abstract

Modeling the plasma and magnetic field state in Mercury's magnetosheath is one of the most urgent tasks in Mercury science in view of the upcoming BepiColombo mission. By considering the steady-state and constructing the Laplace equation for the scalar magnetic potential in the magnetosheath (eliminating the interplanetary magnetic field in the magnetosphere and vice versa), the plasma and magnetic field state is obtained as a function of the solar wind condition and the spatial coordinates of the magnetosphere. We make extensive use of the exact solution of the Laplace equation for the parabolically shaped magnetosheath and map the solution onto the realistic shape of magnetosheath by assuming the magnetosheath thickness is scalable between the parabolic shape and the realistic shape along the magnetopause-normal direction. The quality of the constructed model can successfully be tested against the global hybrid simulation of Mercury's magnetosheath, promising that the model serves as a useful tool for BepiColombo's detailed magnetosheath studies at Mercury.

1. Kobel-Flückiger model

- Magnetosheath is a current-free region to a good approximation, no absorption of particles
  → Laplace equation for magnetic potential and velocity potential
- Kobel and Flückiger (1994) solved the Laplace equation with parabolic boundaries (KF model)
- Parabolic coordinates (u, v, φ) (x_0: focal point)

$$x = x_0 + u\, v \cos(\varphi)$$
$$y = 1/2\,(u^2 - v^2)$$
$$z = u\, v \sin(\varphi)$$

- Magnetopause (MP) and bow shock (BS) as boundaries:

$$v_{mp} = \sqrt{R_{\mathrm{mp}}} \qquad v_{bs} = \sqrt{2R_{bs} - R_{mp}}$$

- In magnetosphere: Cancelation of interplanetary magnetic field (IMF)
- Magnetic potential has five parameters:

$$R_{mp}, R_{bs}, B_x^{IMF}, B_y^{IMF}, B_z^{IMF}$$

- Velocity potential has three parameters:

$$R_{mp}, R_{bs}, U_x$$

2. Empirical model

- Shue et al. (1997) model for magnetopause:

$$r_{MP} = R_{MP}\sqrt{\frac{2}{1+\cos\theta}}$$

- Slavin et al. (2009) conic section bow shock:

$$r_{BS} = \frac{p\varepsilon}{1+\varepsilon\cos\theta}$$

- Best-fit parameters for simulated data:

$$R_{mp} = 1.45\, R_M,\ p = 2.35\, R_M,\ \varepsilon = 1.01$$

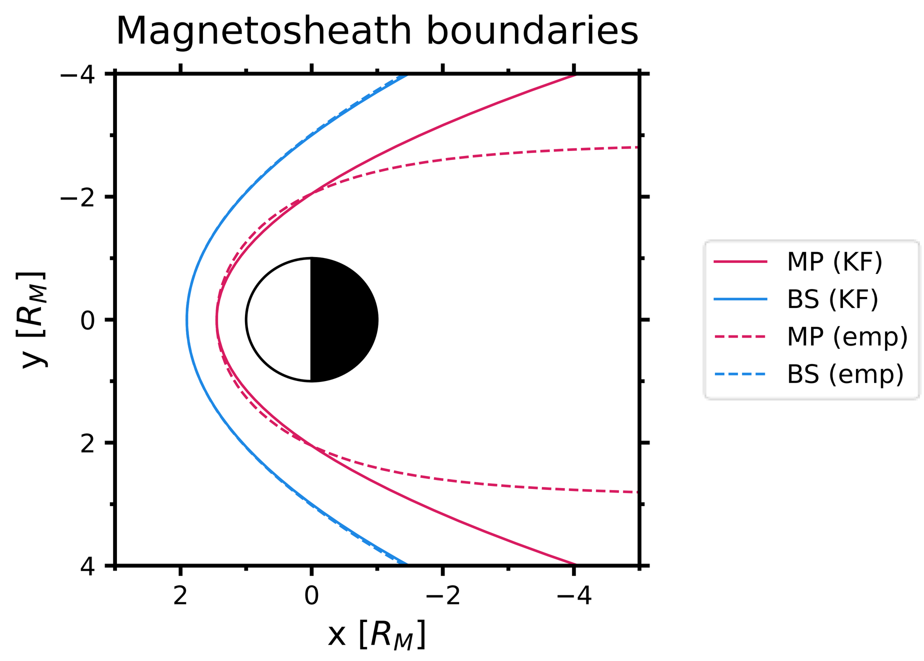

Fig. 1: Empirical and KF magnetosheath boundaries.

3. Scalar potential mapping

- Mapping the position vector from empirical (emp.) magnetosheath into KF magnetosheath model
- Assumption:

Distance to magnetopause remains constant when scaled to magnetosheath thickness in magnetopause normal direction

→ **MP normal mapping**

- Allows computation of potentials for custom shaped, convex BS and MP shapes as boundaries

Procedure

1. Compute distance to MP in MP normal direction
2. Compute thickness of empirical magnetosheath
3. Compute thickness of KF magnetosheath
4. Map the position vector onto the KF system
5. Evaluate u and v in the KF system
6. Compute the potentials

- Non-conformal map
  → Result is not an exact solution of the Laplace equation
- Grid orthogonality along magnetopause

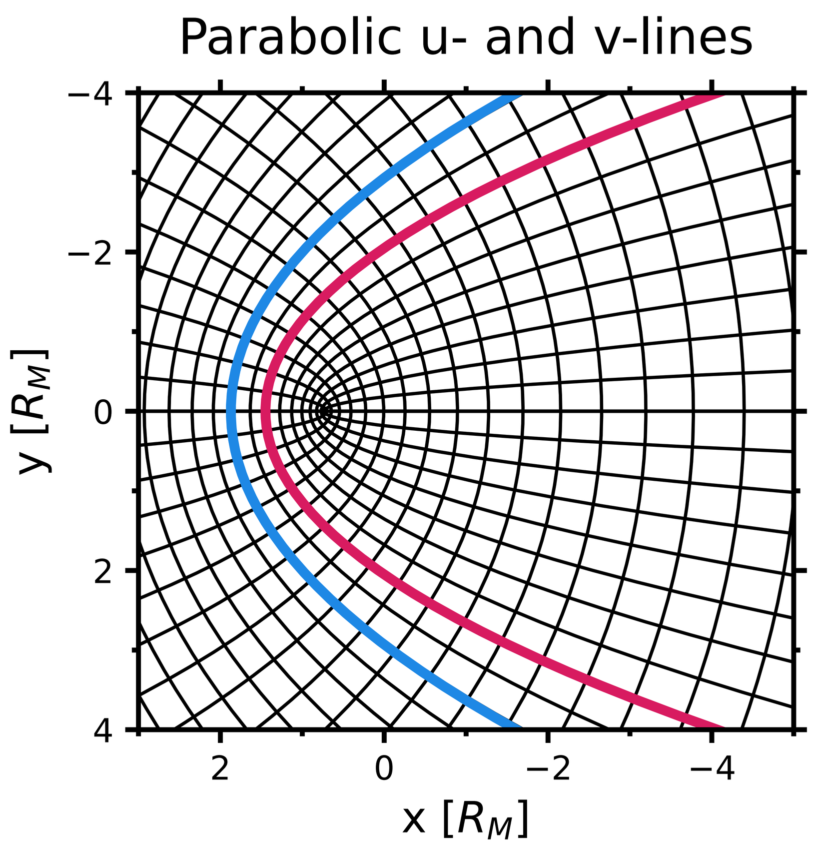

Fig. 2: Iso-contour lines with u = const. and v = const. in the KF magnetosheath model.

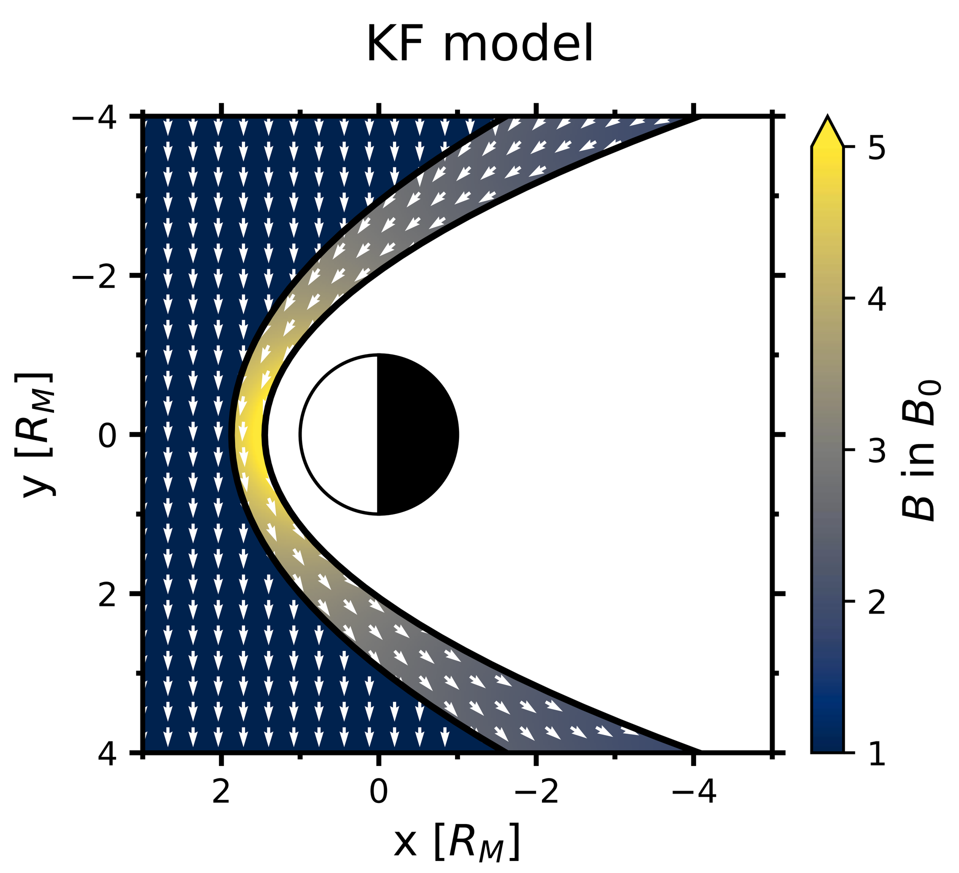

Fig. 3: Magnetic field in KF magnetosheath domain and duskward iMF.

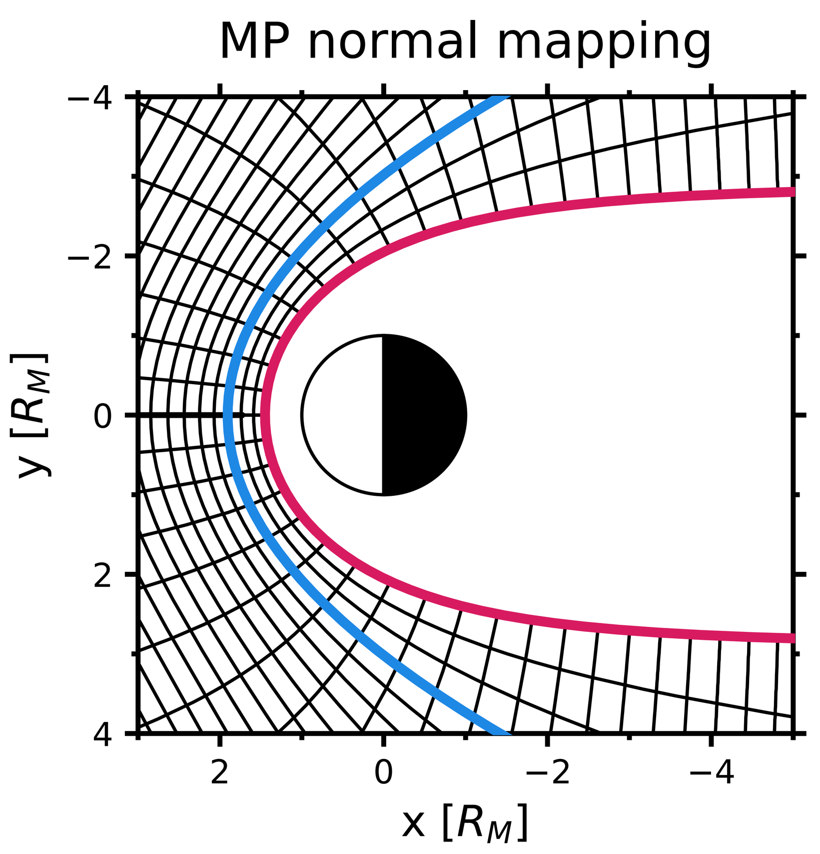

Fig. 4: Iso-contour lines with u = const. and v = const. in the emp. magnetosheath model.

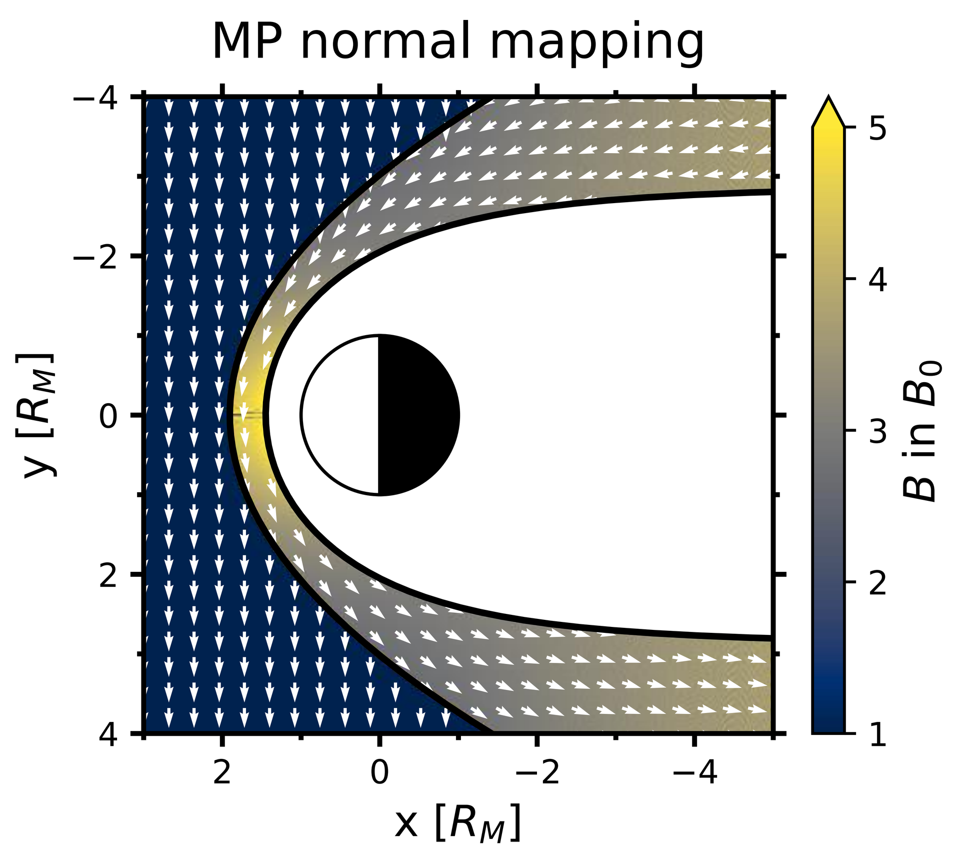

Fig. 5: Magnetic field in emp. magnetosheath domain and duskward IMF.

4. Simulation

- Hybrid code A.I.K.E.F. (Müller et al., 2011)
- Kinetic description of ions
- Electrons treated as a fluid
- Duskward IMF with $B_0 = 20$ nT
- Solar wind density $n_0 = 30\ \mathrm{cm}^{-3}$
- Solar wind velocity $u_0 = 400\ \mathrm{km\ s}^{-1}$
- Data from x-y-plane in MSM coordinate system

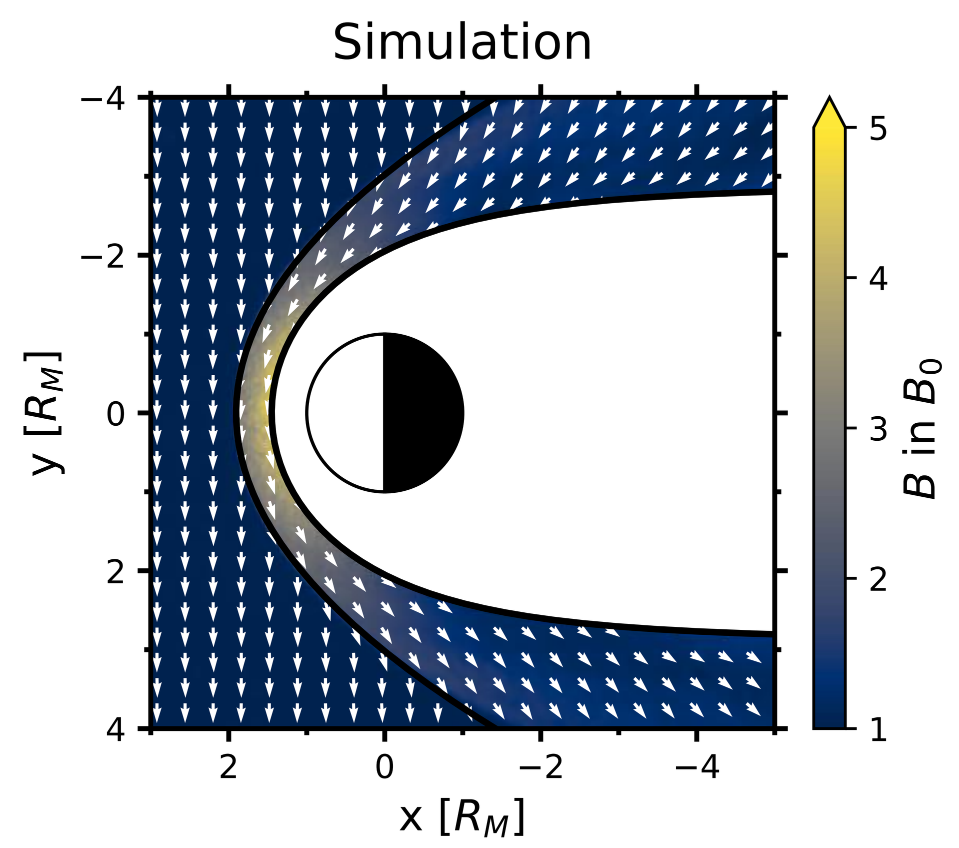

Fig. 6: Simulated magnetic field around Mercury.

5. Results

- KF model is not able to account for the realistic magnetosheath boundaries
- Scalar potential mapping is a significant improvement of the KF model
- Lack of modeling of the MP currents causes deviations in the direction and strength of the magnetic field

6. Outlook

Conformal mapping

- Harmonic transformation in 2D
- Analytic solution for custom MP and BS shapes
- Currently working on the numerical solution of the Cauchy-Riemann equations

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}\ ,\qquad \frac{\partial v}{\partial x} = -\frac{\partial u}{\partial y}$$

→ Aim: Model magnetosheath for asymmetric MP

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