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Speed of Magnetopause Motion: A New Hypothesis for Using Ion Speed

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Abstract. The magnetopause is the critical boundary where the shocked solar wind from the Sun meets the Earth's magnetic field. Once the upstream solar wind conditions alter, the magnetopause moves to (and oscillates about) a new position and changes its shape accordingly. Previous studies usually calculated the magnetopause moving speed from spatial and temporal differences of two crossings close in location and time observed by two spacecraft. However, based on observations, a magnetopause boundary layer with a thickness of hundreds of km is often observed. We propose a new way of estimating magnetopause speed by applying the ion speed in the boundary layer. This study aims to check whether our idea is correct by using numerous magnetopause crossings recorded by the THEMIS mission, and the magnetopause speed calculated by the traditional method is compared with the mean velocity inside the boundary layer.

Introduction

The solar wind is a continuous stream of charged particles emitted from the solar outer region, corona. The solar wind with the frozen-in interplanetary magnetic field (IMF) interacts with the Earth's magnetic field [*Chapman and Ferraro*, 1930] and creates a cavity around the Earth termed the magnetosphere [*Gold*, 1959]. When the magnetosphere interacts with the surrounding supersonic solar wind, a collision-less shock called the bow shock is created, moving opposite to the solar wind. The area between the bow shock and the magnetosphere where the magnetic field and solar wind parameters are highly fluctuating is known as the magnetosheath [*Dessler and Fejer*, 1963] and the boundary between the magnetosheath and magnetosphere, where the pressures between the shocked solar wind and the magnetospheric magnetic field are balanced, is the magnetopause.

Predicting the precise position of the magnetopause has been of utmost importance in space physics; therefore, since the late 1970s, researchers have studied its structure for various solar wind conditions. With this foundation, numerous authors have suggested models of the magnetopause shape and location [*Howe and Binsack*, 1972; *Formisano et al.*, 1979; *Sibeck et al.*, 1991; *Petrinec and Russell*, 1993, 1996; *Shue et al.*, 1997; *Lin et al.*, 2010]. Most of the models are empirical and were created using observed magnetopause crossings. Most models adopted either the equation of an ellipsoid with two parameters (eccentricity and standoff distance) or a more general quadratic equation. Some models [e.g., *Petrinec and Russell*, 1996] of the night-side magnetopause, use inverse trigonometric functions. The *Shue et al.* [1997] model is based on the standoff distance and the level of flaring angle, which can fit both open and closed magnetopause. In summary, the previous models use various functional forms to represent the shape and location of the magnetopause and are usually parameterized by the solar wind dynamic pressure, D_p and IMF B_z component. The basic findings of these studies are that the magnetopause scales roughly with pressure as $p^{-1/6}$ ($p^{-1/6.6}$ in *Shue et al.* [1997]) and that for decreasing IMF B_z, the magnetopause displaces inward near the nose and outward in the flank. Using more than 15000 magnetopause crossings, *Aghabozorgi et al.* [2024] denotes that the significant model error is due to uncertainty of upstream solar wind conditions.

Understanding the dynamic behaviour of the magnetopause is crucial for comprehending the complex interaction between the solar wind and Earth's magnetic field because, with the change in solar wind conditions, the magnetopause moves to a new balanced position and its shape changes accordingly. *Russell and Elphic* [1978] state that the magnetopause is constantly in motion with velocities greater than the speed of a spacecraft. Traditional methods of tracking magnetopause motion often rely on the separation and time difference of crossings by the two spacecraft [*Dunlop et al.*, 1995]. However, such events are relatively rare. *Lin and Xie* [1997] studied the hybrid simulation of the formation of a reconnection layer in the dayside magnetopause. There are large regions in the dayside magnetopause where there is no effect of reconnection, and magnetopause can be considered to be a closed region where particles cannot travel freely from one region to another. Therefore, the ion speed in the boundary layer parallel to the magnetopause normal should be a proxy of the magnetopause speed under changing conditions. On the other hand, if reconnection occurs, then magnetopause becomes an open region, and particles can freely go in or out of it.

Haaland et al. [2004] used four Cluster spacecraft analyzing one magnetopause event to compare predictions for determining the velocity, orientation, and thickness of the magnetopause current layer under various methods. They employed established as well as new multi-spacecraft techniques, in which time differences between the four spacecraft crossings, along with the duration of each crossing, are used to calculate the magnetopause speed, normal vector, and width. Nevertheless, the agreement between magnetopause speeds derived from single- and multi-spacecraft methods is quantitatively imprecise, and it is evident that the speed can change substantially from one crossing to the next within an event.

It is one reason why we use the ion velocity component normal to the magnetopause surface at the dayside region to track magnetopause motion for an extended period of time. We have adopted an idea inspired by *LLera et al.* [2023]. The paper suggested that accelerated plasmaspheric/cold ions in the magnetosphere close to the magnetopause can proxy magnetopause motion. *Silveira et al.* [2024] tracked the magnetopause and bow shock motion by implementing the velocity gradient in the magnetosheath, which is calculated using plasma velocities at different spacecraft positions along the Sun–Earth line. *Guo et al.* [2024] used Magnetospheric Multiscale (MMS) observations to investigate the fast-moving cold ions. They found that fast-moving ions at the magnetopause are related to the magnetopause deformation. We suggest to calculate the magnetopause motion from the motion of the ions inside the magnetopause boundary layer. We performed a short statistical study where we compared the results from two spacecraft, the traditional method of calculating magnetopause motion, with our method of calculating the magnetopause motion from one spacecraft and considering the ion motion inside the magnetopause boundary.

Methodology

We suggest a hypothesis that applies the ion speed in the magnetopause boundary layer to estimate the speed of the magnetopause motion. Even while reconnection is occurring, there are large regions of the magnetopause that do not observe signatures of reconnection (e.g., at low latitudes during northward IMF and vice versa). No ions can transfer from the magnetosheath to the magnetopause or from the magnetopause to the magnetosphere and vice versa. On the other hand, the ions present inside the magnetopause boundary layer are trapped but not static. They are always in motion, and we suggest that this ion motion can be related to the magnetopause motion.

The magnetopause velocity can thus be calculated using a single crossing, assuming that this velocity is equal to the ion velocity component along the magnetopause normal. Since we are analyzing the subsolar magnetopause, the normal is oriented along the x-axis in the Geocentric Solar Magnetospheric system. The median velocity (V_I):

$$V_I = \text{median}(v_x), \tag{1}$$

where v_x is the velocity of ions inside the boundary layer along the x-axis, can be considered as a proxy of the magnetopause velocity.

For comparison of our method with the traditional one, we apply a modified version of tracking a particular magnetopause crossing observed by two spacecraft located close in time and space. In this case, the radial distance, r, depends on the angle between the Sun–Earth line and the satellite position vector, θ, which is different for each magnetopause crossing. To avoid this problem, we recalculate the radial distance r to the magnetopause standoff distance, r_0. We are only concerned with the region near the Sun–Earth line where r_0 is a reasonable choice. We use the *Shue et al.* [1997] model that suggests

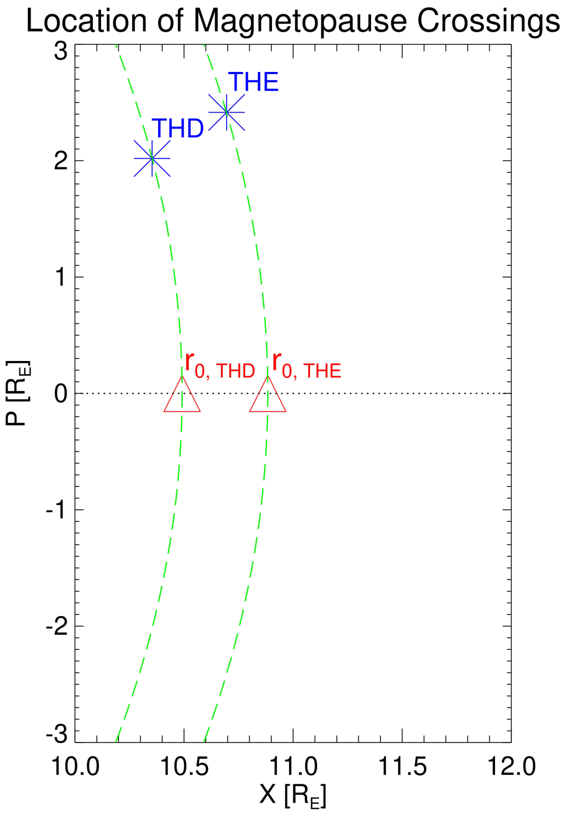


Figure 1. Location of magnetopause crossings. One example of the THD and THE crossing the magnetopause (shown in blue asterisk) and their standoff distances (shown in red triangles) is shown here. The green dashed lines show the magnetopause location from the Shue model. Here, $P = \sqrt{Y^2 + Z^2}$.

a functional form:

$$r = r_0 \left(\frac{2}{1 + cos\theta} \right)^{\alpha}. \tag{2}$$

The standoff distance r_0 and the tail flaring α are controlled by the solar wind dynamic pressure, D_p, and IMF B_z. We have taken the upstream solar wind observations from the OMNI database and considered a 5-minute resolution of both plasma and magnetic field parameters from each event.

$$\alpha = (0.58 - 0.01 B_z)(1 + 0.01 D_p) \tag{3}$$

$$r_0 = \begin{cases} (11.4 + 0.013 B_z)(D_p)^{-\frac{1}{6.6}}, & \text{for } B_z \geq 0 \\ (11.4 + 0.14 B_z)(D_p)^{-\frac{1}{6.6}}, & \text{for } B_z < 0 \end{cases} \tag{4}$$

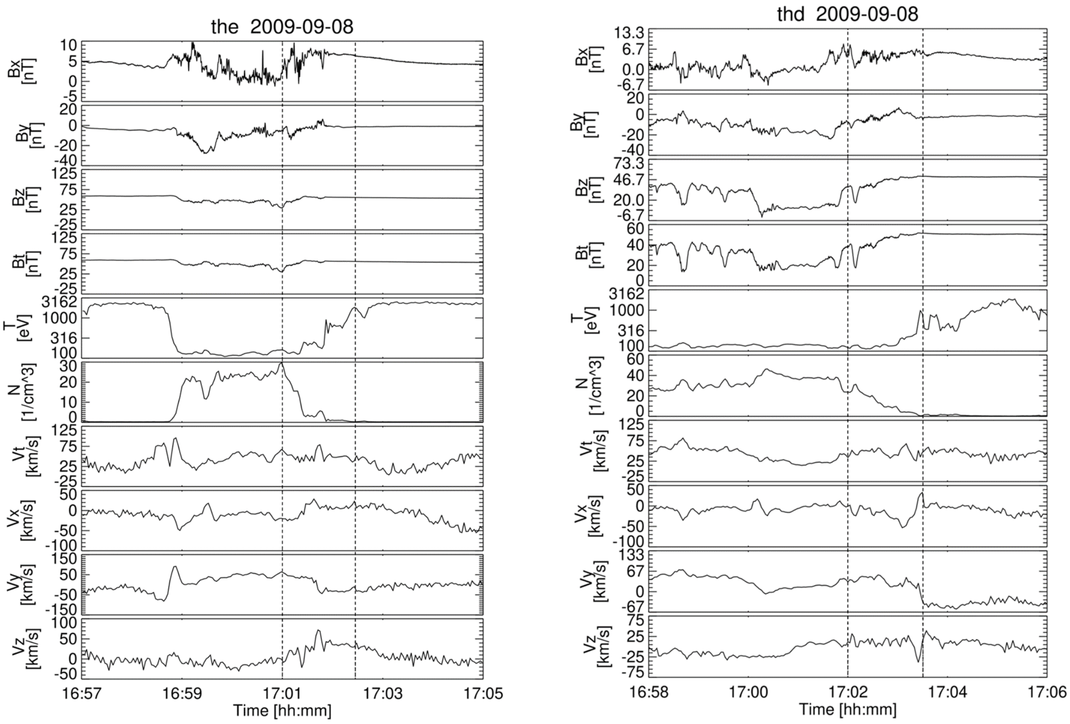
The example of such recalculation applied for two THEMIS spacecraft is in Figure 1.

To calculate r_0 for each crossing, we modified equation 2 as stated below:

$$r_0 = r \left(\frac{1 + cos\theta}{2} \right)^{\alpha}, \tag{5}$$

where, r, θ and α come from the observation. Finally, we calculated the magnetopause speed (V_{MP}) from two nearby crossings by taking the differences of r_0, i.e., position differences, dr_0 and the time differences, dt, of these two consecutive crossings.

$$V_{MP} = \left(\frac{dr_0}{dt} \right) \tag{6}$$



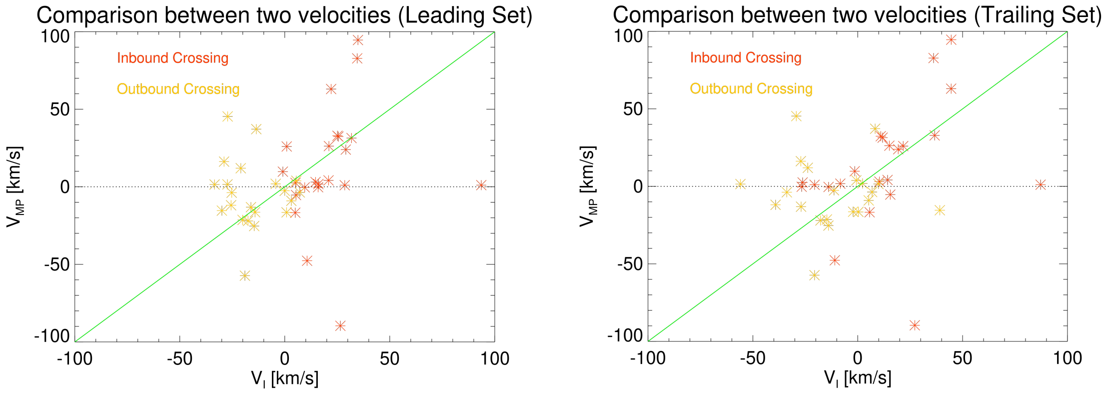
(a) (b)

Figure 2. Example of simultaneous measurements of (a) THE and (b) THD from top to bottom: The magnetic field components (B_x, B_y and B_z) and total magnetic field (B_t), the temperature (T), density (N), total velocity (V_t) and the velocity components (V_x, V_y and V_z)

Observations

The Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission consists of five identical probes travelling along elliptical orbits with different apogees [*Angelopoulos et al.*, 2008]. Until 2010, all the THEMIS probes were orbiting with apogees ranging from 10 to 30 R_E. Later, THB and THC became ARTEMIS and orbit the Moon, while the remaining three are still orbiting Earth. We use the crossing list from *Shue et al.* [2011] that contains 1162 crossings observed from 1 May 2007 to 14 December 2010. Each crossing was manually identified, and the crossings of the inner and outer edges of the magnetopause boundary layer were denoted. We selected crossings close to the Sun–Earth line, i.e., $Y < 2R_E$ and $Z < 2R_E$. A total of 575 crossings were selected. From them, we chose 78 pairs of crossings close to each other in distance and time to calculate the speed based on their locations and time differences. The spacecraft (THEMIS) speeds near the subsolar magnetopause are $<$ 2 km/s. For each pair of crossings recorded by THEMIS, we also obtained the magnetopause speed in the traditional way.

The magnetopause is always in continual motion. Thus, when the spacecraft passes through the layer, it experiences multiple crossings. Figure 2 shows the observations of a pair of crossings. In Figure 2a, there are two crossings at 16:59 (which isn't marked in the figure), when the spacecraft moves from the magnetosphere to the magnetosheath, referred to as Outbound Motion and the other one is at 17:01 (which is marked), when the spacecraft moves from the magnetosheath to the magnetosphere, referred to as Inbound Motion. The magnetic field data is obtained from the Fluxgate Magnetometer (FGM) [*Auster et al.*, 2008] instrument, and the plasma data is obtained from the Electrostatic Analyzer (ESA) [*McFadden et al.*, 2008] instrument. The dotted lines indicate the magnetopause boundary layer.



(a) (b)

Figure 3. Comparison between two different estimations of velocities. The comparison performed between the magnetopause velocity and the velocity of ions inside the magnetopause is shown here for (a) leading and (b) trailing sets. The data points in red symbolize inbound crossings, and the ones in yellow symbolize outbound crossings. The green solid line signifies the one-to-one line.

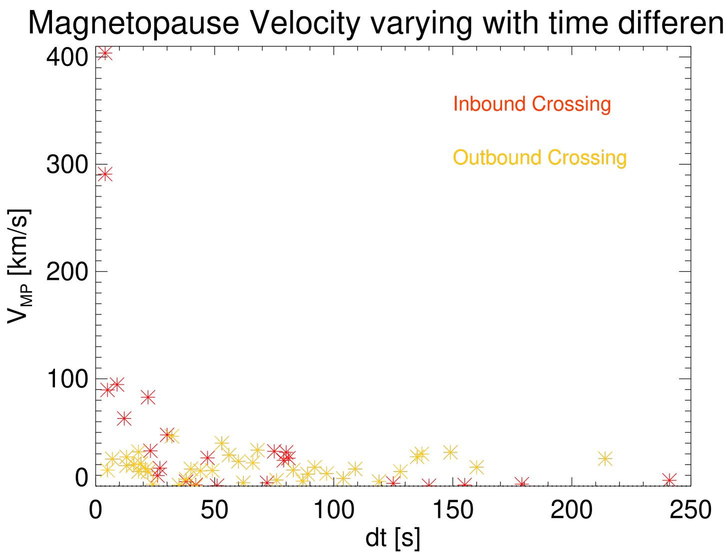


Figure 4. The absolute value of magnetopause velocity as a function of time difference. For a short time difference, there is more fluctuation in velocity. The data points in red symbolize inbound crossings, and the ones in yellow symbolize outbound crossings.

Magnetopause Velocity

The 78 pairs of crossings were used to calculate the velocity from two crossings, which are close in space and time. From each of them, we calculated the median velocity $[V_I]$ in the magnetopause boundary layer by equation 1. Therefore, we define the first observed crossing in a pair as the leading crossing (e.g., Figure 2a) and the second as trailing (e.g., Figure 2b). Figure 3 compares the two methods of magnetopause velocity calculations. To more clearly interpret the distribution, we limited the Y axis to a range from -100 to 100 km/s, but a few data points are still out of this range. Those outliers, which are not shown in Figure 3, will be shown in Figure 4. It is noticeable that some data points follow the hypothesis that the velocity inside the boundary layer is the magnetopause velocity, but some do not because the average correlation coefficient comes to be 0.08. This low correlation coefficient is consistent with the result in *Haaland et al.* [2004].

Discussion and Conclusion

The low correlation can be influenced by the data points that do not follow the hypothesis. Thus, we started to figure out the possible reasons for the cases in which the velocities calculated in two ways are inconsistent. We checked each crossing and found that, in some cases, there are signatures of reconnection characterised by velocity peaks in the y and z directions. When reconnection occurs, the magnetic fields change topologies. Then, the magnetopause becomes open. Our hypothesis is based on the situation when the magnetopause is closed; thus, it cannot work for open magnetopause. Moreover, reconnection erodes the magnetopause [*Le et al.*, 2016; *Kim et al.*, 2024], and thus can affect our estimation. We will remove the cases with magnetic reconnection in future work. Another factor influencing the magnetopause velocity calculation is shown in Figure 4, showing that the velocity calculated traditionally varies with the time difference. The absolute value of the magnetopause velocity is considered. It can be noticed that the fluctuation of the magnetopause velocity is more significant for a short time difference, and the velocity often reaches to very high values. There can be several sources of uncertainties in the determination of magnetopause velocity.

First, our calculations rely on the time of the crossing of the boundary layer edge, which is relatively complicated and limited by the time resolution of the THEMIS plasma measurements. Moreover, the magnetopause does not always exhibit a smooth surface. For example, when a magnetosheath jet hits the magnetopause, it will create an indentation and change the local structure of the magnetopause [*Shue et al.*, 2009; *Song et al.*, 2019; *Němeček et al.*, 2023]. The other mechanism is Kelvin–Helmholtz instability at the dayside magnetopause [*Grygorov et al.*, 2016]. The wavy structure also changes the shape of the local magnetopause. The unsmooth structure of local magnetopause will significantly affect the evaluation of magnetopause velocity from two-point observations, with a slight time difference. Moreover, the ion motion in the magnetopause boundary layer and its normal direction may also change. It will influence the estimation of the magnetopause velocity by using the suggested method. The other interesting thing shown in Figure 4 is that significant outliers always appear for the inbound crossings.

There may be more reasons leading to inconsistent velocities calculated by the two methods. A major reason for magnetopause oscillatory motion (even during steady solar wind) is due to convected foreshock waves [*Russell et al.*, 1997]. We will enhance our study in the near future, emphasizing the different effects that can affect the magnetopause velocity. We will concentrate on the events with the large positive Bz to exclude the impact of magnetic reconnection. If all influencing factors are removed, we believe that our new method will help us better understand the magnetopause dynamics.

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