Referee report on 'Investigation of the occurrence of significant deviations in the magnetopause location: Solar wind and foreshock effects', by Grimmich et al.

This study investigates possible sources of the scatter (deviations) of observed magnetopause locations about parameterized models of the average magnetopause shape and position. The deviations of the observed magnetopause position from that of the models is investigated as a function of the IMF orientation (i.e., defining the foreshock, leading to convected oscillations), and for different 'types' of solar wind. The cause(s) of deviations of the observed magnetopause location from that expected from statistical models is of interest, and has been examined by several investigators (though not appropriately referenced nor discussed here). Aside from an exploration of different 'types' of solar wind, it is not clear how this investigation improves upon these earlier efforts. There are also many questions about the methodologies employed within this study that need to be answered and comments to be addressed before this study can be considered for publication in Annales Geophysicae.

1) The schematic of Figure 1 is not even crudely representative of the magnetopause. The standoff position has long been known to be the smallest distance from Earth. Yet, the schematic shows this position to be the furthest distance from Earth and thus, very unrealistic. It would also be helpful to the reader to include in the schematic of Figure 1 the bow shock and angle(s) used.

2) Lines 146-157: It is confusing to the reader whether ϑ_{Bn} and θ_{Bn} are the same or different parameters. Inclusion of the relevant angle(s) in the Figure 1 schematic would be useful. Using the local theta_Bn value at the bow shock model, estimated using the vector normal to the model magnetopause and intersecting the observed magnetopause location, is not a very appropriate method for determining whether or not the spacecraft is downstream of the foreshock (i.e., in the downstream region associated with either the Quasi-parallel or Quasi-perpendicular shock region). When the spacecraft is near the terminator, the 'local' value of theta_Bn can be tens of degrees different from the theta_Bn value near the subsolar shock location; in the vicinity of the foreshock. Especially when the IMF is dominant Bx, or when the IMF Bx component is negligible with respect to the other components, the 'local' theta_Bn can suggest a quasi-parallel region while the magnetopause crossing is actually in a quasi-perpendicular region (or vice versa). Some examples of these regions propagating within the magnetosheath were provided for various IMF orientations by Russell et al., GRL, 663-666, 1983 and also shown in Luhmann et al., JGR, 1711-1715, 1986.

3) Line 38: Why the adjective 'so-called' foreshock? The existence of the ion and electron foreshock, in multiple planetary systems, has been well-established based on spacecraft observations for decades.

4) There are several very relevant published studies related to the foreshock and its effects on the magnetopause location and within the magnetosphere that are neglected in the Introduction. Some of these references include:

- As mentioned in point #2, Russell et al., GRL, 663-666, 1983 showed the occurrence rate of Pc 3,4 waves within the inner magnetosphere is much more frequent for small theta_Bn (radial IMF) than for transverse IMF. Although this study did not explicitly examine magnetopause deviations, it was postulated that magnetospheric ULF wave activity is associated with Kelvin-Helmholtz waves along the magnetopause as a consequence of convected foreshock activity.

- Luhmann et al., JGR, 1711-1715, 1986 examined transverse and compressional wave activity within the magnetosheath as a function of the IMF configuration and local time. The result of this study also implied that compressional and transverse oscillations originating upstream convect through the magnetosheath and affect the magnetopause location.

- Song et al., GRL, 744-747, 1988 described the magnetopause oscillation amplitude as a function of IMF configuration (their Table 1) and distance downtail (solar zenith angle).

- Russell et al., GRL, 1439-1441, 1997 showed a significant statistical dawn/dusk difference in observed multiple magnetopause boundary crossings (per pass) and average oscillation amplitude, attributed to convected foreshock effects. Differences as a function of IMF clock angle were also noted. Petrinec et al., JGR, 2022, doi:10.1029/2021JA029669 also observed very similar multiple magnetopause crossing statistics, consistent with convected oscillations from the foreshock region.

5) Lines 66-69: How can a *quantitative* assessment of the percentage of cases of significant magnetopause location deviations be attributed to foreshock effects, when there are multiple other parameters that are known to affect the average location; but are not accounted for in the models? In addition to those listed in the manuscript, some examples of neglected parameters include:

- The Region 1 current strength (Sibeck et al., JGR, 5489, 1991), also expressed through the ring current effect (Dst*) (e.g., Hayosh et al., Adv. Space Res., 2417-2422, 2005; Machkova et al., JGR, 905-914, 2019). This can affect the average magnetopause location by a few tenths of an RE.

- Earth's lowest-order magnetic moment is actually best described by an offset dipole (Laundal and Richmond). At the distance of the magnetopause, only this moment survives (higher order moments decrease much more rapidly with increasing distance from Earth). The offset is ~577 km, which translates into calculable variation of the magnetopause subsolar distance of up to ~±0.1 RE (depending on season (dipole tilt) and time of day of the crossings). This was shown in the empirical study of Machkova et al., JGR, 905-914, 2019.

- In addition, the average models do not capture the time history of the solar wind. The history can greatly affect the magnetopause location due to ongoing processes such as erosion due to reconnection.

- It is commended that Kelvin Helmholtz waves were mentioned; even if just briefly. It would be more helpful if there were a quantitative assessment of the contribution of KH to 'deviant' magnetopause crossings within the four dayside magnetopause regions (even if the instability is not fully developed (e.g., Hasegawa et al., JGR, 2003, doi:10.1029/2002JA009667; Henry et al., JGR, 11888-11900, 2017; Radhakrishnan et al., JGR, 2024, doi:10.1029/2024JA032869)), or at least an estimated assessment of the relative contribution of KH to that of convected foreshock oscillations in relation to 'deviant' magnetopause crossing locations.

6) Figs., 2,4,5 caption: The captions mention a 'reported 1 RE uncertainty'. Where has this number been reported, and why is it constant for all four magnetopause regions? It's typically understood that the

model uncertainty increases further away from the standoff point. While Shue et al. 1997 report a single value of 1.24 RE standard deviation between model and observations (their Fig.15), it's shown in their figure that there is increased scatter for larger magnetopause distances (typically flanks) when compared to smaller distances (typically standoff region). Shue et al. 1998 reported a standard deviation of 1.23 RE. The uncertainties of the individual fit coefficients $\{a_n\}$ should provide a more appropriate estimate of the magnetopause uncertainty in each of the four magnetopause regions. It may be that an uncertainty value of ~1 RE is reasonable for the dayside magnetopause; but it needs to be justified with a specific reference and/or an explicit calculation.

7) Lines 98-99: Although the GSE coordinate system is described in Laundal and Richmond, SSR, 2017, there is no description of aberration. Please describe whether the aberration as used in this study is a fixed angle applied to all observed crossings, or uses the actual measured solar wind speed for each magnetopause crossing, or uses the full solar wind velocity (all components) in the calculation of the aberration angles.

8) Line 134: It is stated that the Nguyen et al. 2022 model (N22b) is an extension of the SH98 model. Although the basic zenith angle functional form is the same, this model is quite different. The IMF Bz dependence of the N22b magnetopause standoff distance is very different from Shue et al. 1998. This N22b dependence on IMF Bz does not match what has been observed and described over decades of empirical magnetopause studies (including those by one of this manuscript's co-authors). Specifically, the erosion of the dayside magnetosphere (as documented by Δr_{0mp}) for a given value of southward IMF Bz has long been known to be much greater than the expansion of the dayside magnetosphere for an equivalent value (but opposite sign) of northward IMF Bz.

9) Lines 185-189: The treatment of orbital bias in the statistical analysis is curious. It appears that the authors are trying to weight the sampling of magnetopause regions so that rarely sampled regions have equal representation (coverage) with those regions that are more often sampled. If this is the case, then this is a different type of orbital bias than is normally of concern. Especially for studies of the average magnetopause location (and deviations from the average shape), the orbital bias of concern is primarily due to spacecraft apogees which are lower than the average boundary location; so the spacecraft can only sample the magnetopause during the innermost transient excursions, or for intervals of high solar wind pressure. For example, the THEMIS A,D,E missions only have apogees of ~13.2-13.7 RE, while the nominal magnetopause location near the terminator is ~14.5 RE. Similarly, the MMS spacecraft during the prime mission had an apogee of 12 RE; and so could only rarely and briefly sample the magnetopause a few hours away from local noon. Because of this small MMS apogee during the prime mission, those magnetopause crossings shouldn't be used in regions where they cannot adequately sample at least the average boundary location, for determination of the general magnetopause shape. It is very important to also address this orbital bias, and how it affects the statistical results of this study.

10) Lines 194-196, Lines 343-344: The significant skewing of the distributions relative to the N22b model suggests that either the functional form used for their model is not appropriate (cf., point #8), and/or the data set used to fit their model is afflicted by the orbital bias (i.e., limited spacecraft apogees) that is described in point #9. This should be addressed.

11) Fig.3: Are these histograms normalized such that each histogram distribution at theta_Bn = 45 degrees is set to ‘1’?

12) Figs.4,5, and lines 258-259: Are the magnetopause models including the aberration of the solar wind? If not, that would explain the differences between dawn and dusk between the observed and model magnetopause locations (orbital bias of limited apogee (e.g., THEMIS A,D,E) may also contribute to the observed dawn/dusk differences). The models and observations should be consistent with one another (i.e., in the same coordinate system). Please provide additional description.

13) There are several sentences in Sections 3 and 4 which are too convoluted and ambiguous for the reader to understand. This (along with several other issues described in this report) strongly suggests that the co-authors have not read this manuscript. A few examples include Lines 264-269; Lines 332-334; Lines 371-372.

Some additional minor comments:

- Lines 70-72: Re-arrange and separate this into two sentences.

“For example, high solar wind speeds appear to lead to an anti-Earthward expansion and outward displacement of the MP from the predicted model location, which is based on the assumption that the higher dynamic pressure in these cases compresses the MP (Grimmich et al., 2023a, 2024b).”

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For example, there is an assumption that higher dynamic pressure compresses the MP. However, high solar wind speeds appear to lead to an anti-Earthward expansion and outward displacement of the MP from the predicted model location (Grimmich et al., 2023a, 2024b).

- Line 72: ‘foreshock, is’ -> ‘foreshock is’
- Table 1, 1st column: kms^-1 -> km s^-1
- Table 1 footnote: ‘to the the four paramters’ -> ‘to the four parameters’
- Line 181: ‘a classification results from’ -> ‘a classification from’
- Table 2 caption, line 2: ‘in the’ -> ‘into the’
- Line 194: ever -> either
- Line 197: ‘In a next step,’ -> ‘For the next step,’
- Line 210: indention -> indentation
- Line 217: cause -> course
- Fig.4 caption, 2nd to last line: ‘a associated’ -> ‘an associated’
- Fig.4 caption, last line: line -> lines
- Line 276: ‘different magnetospheric regions’ -> ‘four different magnetopause regions’
- Line 283: ‘with EJC plasma’ -> ‘with only EJC plasma’
- Line 315: ‘in the table 2 which’ -> ‘in table 2, which’
- Line 322: cavities -> deficiencies

- Line 323: ‘was include here.’ -> ‘was included here.’
- Line 325: ‘cusp indents’ -> ‘cusp indentations’
- Line 338: ‘point out the similar errors of empirical modelling’ -> ‘point out similar uncertainties inherent in the empirical modelling’
- Line 376: quasi-radical -> quasi-radial
- Line 377: ‘the foreshock develops directly in front of the bow shock nose,’. This is not strictly true. The point of ‘attachment’ of the foreshock to the bow shock surface is not necessarily the nose of the bow shock; but wherever the IMF is tangent to the bow shock surface. Please reword.
- Line 391: ‘from a combined datasets’ -> ‘from combined datasets’
- Lines 408-409: ‘the EJC plasma composition’: What does this mean? Is this the general characteristics of Table 1? Or does this refer to a higher percentage of heavy ions (e.g., alphas)? Or does this refer to a composition that includes a higher than normal ‘hot’ plasma content? Please be specific.
- Line 420: indention -> indentation
- Line 429: errors -> uncertainties
- Lines 433-434: ‘(SMILE) mission … will again be a near-Earth, polar-orbiting satellite,’. This isn’t right. The SMILE mission is rather high inclination (70° or 98°); but not a polar mission (inclination of 90°). It’s also not in a near-Earth orbit: It’s to go into a highly-elliptical orbit with perigee of ~1.8 RE (5000 km altitude), and apogee of ~20 RE.
- Line 453: ‘relation the foreshock’ -> ‘relation to the foreshock’
- Lines 453-454: As described earlier, the Song et al. 1988 study examined the amplitude of MP motion, and the Russell et al. 1997 study already examined this amplitude in relation to the foreshock (IMF orientation and local time). How would this future study be different?
- Line 468: ‘study FP’ -> ‘study and FP’