Response of Referee 2

We would like to express our sincere gratitude to Referee 2 for the detailed and thoughtful comments on our manuscript. We greatly appreciate the time and effort devoted to the careful review. Below, we respond to the referee's comments point by point and explain our views on each of the issues raised.

General Comment:

- *In general, this manuscript reads more like a review article than a presentation of new research results. It's not clear what is new; though it is mentioned several times by the authors that this is a novel perspective of the classic descriptions and understanding of the interactions between the solar wind and the terrestrial magnetosphere. Specifically, the authors investigate separately the magnetic topology of superposed vacuum magnetic fields and the supersonic non-magnetized plasma flow about an obstacle. This approach (fields only investigation; unmagnetized gas only investigation) neglects several plasma characteristics that are unique to magnetized plasmas (Alfven waves, the MHD fast mode shock, etc). These extreme case investigations are combined later with the aid of a global MHD model. It's not clear that this is the first time this particular perspective has ever been considered; but this paper does present the topic in a rather rigorous manner, with proper historical context.*

We appreciate this comment on the novelty and scientific contribution of this study. We would like to clarify that the central contribution of this paper is to present a unified framework for understanding the large-scale magnetic-field structure of the solar wind–magnetosphere system by integrating the mechanical balance between the magnetic field and plasma dynamics with the constraints imposed by magnetic topology. Specifically, the topological constraints arise from the structure of the skeleton field, defined as the vacuum magnetic field, which contains two null points, two separators, and γ lines. The characteristic topological structure of the skeleton field is also reflected in the global magnetic-field structure of the actual solar wind–magnetosphere system, although the field is deformed by plasma dynamics. Under quasi-steady, obliquely northward IMF conditions, the interplay between this topological structure and plasma-driven magnetic-field deformation provides a basis for understanding the global magnetic-field configuration. (As will be discussed in a subsequent paper, this configuration also has

important implications for plasma dynamics and electromagnetic energy transport in the solar wind–magnetosphere system.)

Next, we would like to clarify that the field-only and unmagnetized-flow cases are thought experiments intended to isolate the respective roles of magnetic topology and plasma dynamics, rather than models intended to describe the actual solar wind–magnetosphere system. Accordingly, our interpretation is not based on a simple superposition of these two limiting cases. Instead, we examine the coupled physical processes governing the quasi-steady, large-scale magnetic-field structure in the context of global MHD simulation results. In particular, our interpretation incorporates the transport of magnetic flux into the magnetosphere by global magnetic reconnection. The magnetic effects associated with this flux transport contribute to the force balance against the plasma forces acting on the magnetopause in the magnetotail. This mechanism is not included in either limiting case considered separately. By considering magnetic topology and plasma dynamics together, we explain how the open-field cylinders are stretched antisunward in the near-Earth region by the dynamical action of the solar-wind flow, and how the magnetic-field structure in the distant magnetotail bends toward the IMF direction under the influence of the magnetic restoring action. These results illustrate how the combined framework can be used to interpret large-scale magnetic-field structures in different regions of the system.

We agree that Alfvén waves, as well as processes affecting the plasma and magnetic-field structure near the magnetopause, may need to be considered for a more comprehensive and quantitative description of the magnetospheric structure. The present study does not rule out the roles of these processes; rather, it focuses on identifying the basic physical mechanisms responsible for the large-scale magnetic-field deformation under quasi-steady, obliquely northward IMF conditions. We also recognize that ionospheric effects may need to be incorporated into a more comprehensive treatment. The roles of Alfvén waves, plasma depletion near the dayside magnetopause, and ionospheric coupling in determining the global magnetic-field structure remain topics for future investigation.

Specific Comments:

- *This manuscript is significantly longer than it needs to be. This is because there is an extensive repetition of multiple phrases throughout. Please present this narrative more concisely. As one example of a repetitive phrase:*

- *Lines 24-25: 'from the perspective of the interaction between plasma dynamics and deformation of the background magnetic field,'*
- *Lines 123-124: 'from the perspective of the interaction between the vacuum magnetic field and plasma dynamics.'*
- *Lines 129-130: 'from the perspective of the interaction between magnetic topology and plasma dynamics.'*
- *Lines 233-234: 'from the perspective of the interaction between magnetic topology and plasma dynamics.'*
- *Lines 240-241: 'from the perspective of the interaction between magnetic topology and plasma dynamics...'*
- *Lines 249-250: 'physical process in the solar wind-magnetosphere system as the interaction between the magnetic topology and plasma dynamics…'*
- *Lines 297-298: 'physical processes of the solar wind-magnetosphere system from the perspectives of magnetic topology and the plasma dynamics.'*

We thank the referee for this suggestion. We will revise the Abstract and Introduction to make the presentation more concise and reduce repetitive expressions. We will also streamline the text where appropriate to improve the clarity and readability of the manuscript.

- *Fig.1B (Lines 341-342): Nothing in this illustration represents a plasma distribution. The text describes a supersonic flow, but is not mentioned in the caption (nor is a detached shock wave illustrated).*
- *Fig.1B (Line 343): A conical shadow is illustrated, but no description is provided of what is in the shadow. Also no description is offered as to why this structure(?) is unstable.*

Thank you very much for these comments. We will revise Fig. 1B to clarify that it is a conceptual schematic of the supersonic solar-wind flow around the Earth in the absence of both the Earth's intrinsic magnetic field and the IMF. The revised figure explicitly identifies the bow shock and the downstream wake, and the caption clarifies that the illustration is a thought experiment rather than a plasma distribution obtained from numerical simulation. We have also removed the description of the structure as "unstable," since its instability was not explained in the original text. We insert the new Fig. 1 and its cation.

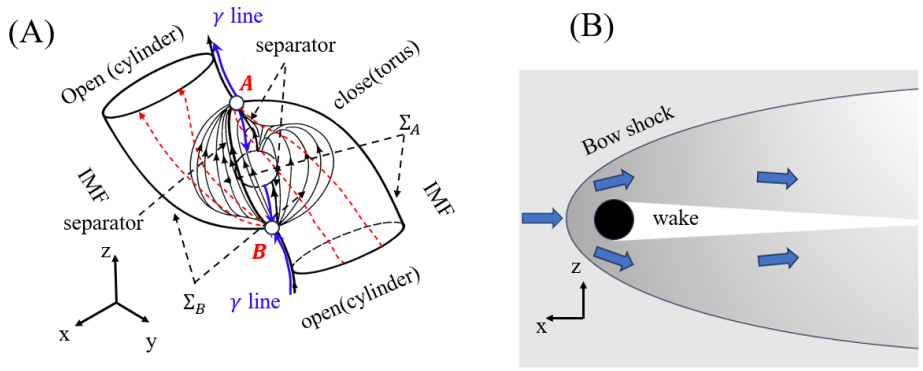


Figure 1. (A) Schematic view of the plasma-free magnetic field as viewed from the afternoon sector. It represents the superposition of the Earth's dipole field and a uniform IMF with + Bz and - By. The three axes (x, y, and z) shown in the lower-left corner denote the sunward, eastward, and northward directions, respectively. This figure provides an alternate perspective on Figure 5(b) of Lau and Finn (1990). The black and blue curves with thick arrows indicate the separators and γ lines, respectively. The red dashed lines indicate the magnetic field lines at the IMF-open field boundary. See the text for a detailed explanation. (B) Thought experiment illustrating the plasma flow around the Earth driven solely by the supersonic solar wind, in the absence of both the Earth's intrinsic magnetic field and the IMF. A wake forms downstream of the Earth, analogous to that behind the Moon. If the Earth's ionosphere is retained, the supersonic solar-wind flow can also produce a bow shock upstream, analogous to the interaction of the solar wind with Venus. The plasma is compressed and heated behind the dayside bow shock. In contrast, the plasma pressure in the distant downstream region decreases as the cross-sectional area of the expanding wake increases. This schematic is intended to illustrate the basic dynamical effects of the solar-wind flow and is not based on a numerical simulation.

- *The sentence flow within lines 248-251 is rather circular: '...consider the physical process in the solar wind-magnetosphere system … determine the structure of the solar wind-magnetosphere system.'. Please rewrite.*

Thank you for this comment. We will rewrite the sentence to avoid the circular wording as follows: "This study uses global MHD simulation results to investigate how magnetic topology and plasma dynamics jointly govern the deformation of the magnetic-field structure under obliquely northward IMF conditions."

- Lines 603-605: It should be noted that while it is true that the Spreiter et al. hydrodynamic approximation does reasonably well without including a magnetic field, it is also well-known that especially during northward IMF (+Bz, as is discussed and modeled in this manuscript), a

plasma depletion layer is observed in front of the magnetopause. This layer includes both a depletion of ion density in association with an enhancement in the magnetic field (draped IMF). Neither extreme investigated scenario captures this characteristic of the solar wind-magnetosphere interaction. The plasma depletion layer was described analytically by Zwan and Wolf (JGR, 1976) and observed by Crooker et al. (JGR, 1979) and others.

Thank you very much for this comment. We agree that the plasma depletion layer is an important feature of the solar wind–magnetosphere interaction under northward IMF conditions and is not captured by either of the two limiting cases considered in this study. As noted in our response to the general comment of the referee, incorporating the effects of plasma depletion near the dayside magnetopause into a more comprehensive description of the global magnetic-field structure remains a topic for future investigation.

- Lines 650-652: The twisting of the magnetotail was also observed statistically using spacecraft observations by White et al. (GRL, 1998). The twisted neutral sheet was described as part of a structure ('magnetospheric sash') which included flank magnetopause extensions containing the magnetic separator line. This reference and relation(s) to the current description (including the 'slit'?) should be noted within this manuscript.

We thank the referee for drawing our attention to the important work of White et al. (1998). Their description of the magnetospheric sash provides an observational example of how magnetic topology is manifested in the large-scale magnetospheric structure, including the twisted neutral sheet and flank magnetopause extensions containing the magnetic separator line. We will add a discussion of this work in relation to the magnetotail twisting described in our manuscript. We will also add discussion of other relevant studies raised by Referee 1 (Kaymaz et al., 1994; Maezawa and Hori, 1998; Fedder et al., 1995; Nishida and Ogino, 1998; and Tenfjord et al., 2018) in Introduction.

- Figure 7 is quite confusing. In Fig.7A, it appears that the +Y-axis is pointing in the wrong direction. Also, from this vantage point, the streamline path is difficult to understand. It appears to spiral, but perhaps the points 8-10 are just approaching local midnight and climbing to higher and higher altitude. The streamline path after point 10 is quite confusing. Is this following a convection cell in the ionosphere? If so, then it would be instructive for the reader to show another panel of the ionosphere as viewed from above the north magnetic pole, along with the projected streamline path footpoints.

Thank you very much for this comment.

The direction of the +Y axis in Fig. 7A will be corrected. In addition, the original caption incorrectly referred to the "cylindrical part"; this will be corrected to the "toroidal part."

The convection streamline will also be extended beyond point 10 to show its swirling path toward the ionosphere more clearly.

Figure 7B is intended to illustrate how the convection velocity of magnetic field lines transported into the magnetosphere varies along the streamline. To make small variations in the convection velocity more readily visible, the upper limit of the velocity color scale will be lowered. With this adjustment, the figure more clearly shows that the convection velocity in the distant magnetotail is higher than that in the near-Earth region as the magnetic field lines are transported from the dayside reconnection region toward the distant tail.

To make the convection streamline in Fig. 7A easier to interpret, Fig. 7C will focus on the near-Earth region and show the correspondence between each point along the streamline and its associated magnetic field line. For clarity, IMF field lines are shown in white, whereas open field lines are shown in red. Following the referee's suggestion, we will also add the ionospheric electric potential distribution, viewed from above the Northern Hemisphere, to show how the plasma convection shown in panel A corresponds to the ionospheric convection pattern.

We insert the new Fig. 7 and its cation.

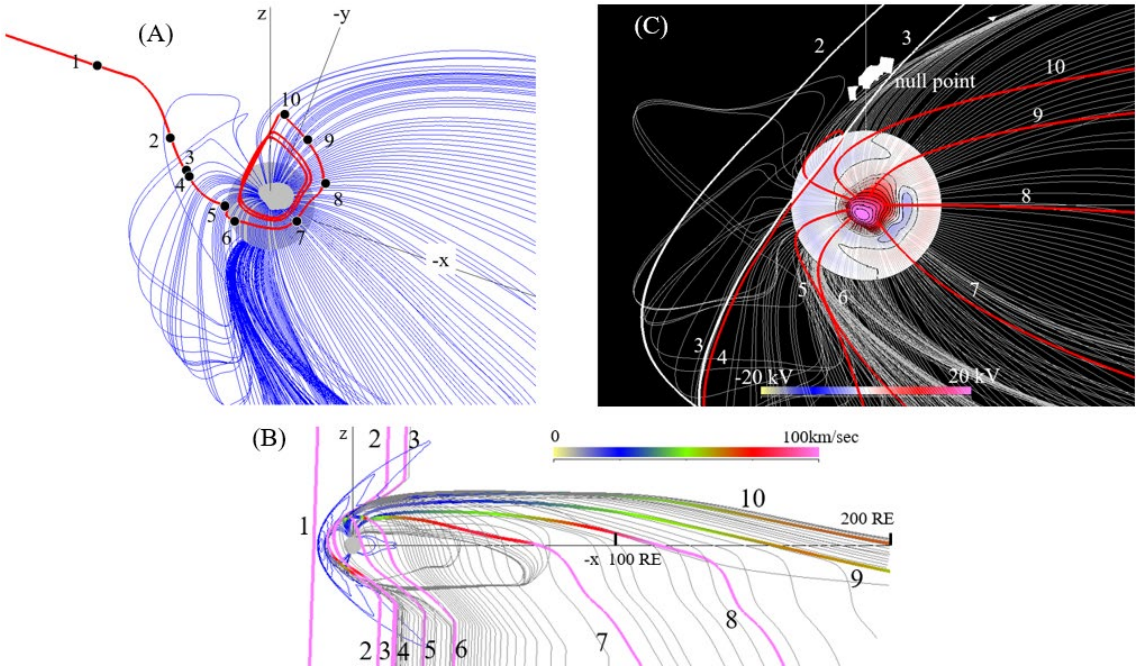


Figure 7. (A) The red line represents a plasma convection streamline extending from the solar wind (point 1) into the magnetosphere (point 10), viewed from above the Northern Hemisphere on the dusk side. Ten points are selected along the streamline. The streamline crosses the cylindrical surface between points 3 and 4 and circulates within the cylinder. The bundle of blue curves denotes the toroidal part of the Σ_A

surface. (B) Overall view of the magnetic field lines originating from the ten points selected along the convection streamline in panel A, viewed from 18 MLT. The field lines are color-coded according to the magnitude of the perpendicular plasma velocity. The blue contours show the plasma pressure distribution in the noon–midnight meridian, with a contour interval of 0.2 nPa. The bundle of gray curves denotes the cylindrical part of the Σ_A surface. As the convection streamline crosses the cylindrical surface between points 3 and 4, the IMF-connected field line traced from point 3 reconnects, changing its connectivity to that of the open field line traced from point 4. (C) Magnetic field lines #2–#10 shown in panel B, together with the ionospheric electric potential distribution viewed from the north. White curves represent IMF field lines, and red curves represent open field lines. The potential contour interval is 2 kV. The plasma convection shown in panel A corresponds to the lobe cell in the ionosphere. This panel also illustrates reconnection at the northern-hemisphere null point, through which the connectivity of IMF field line #3 changes to that of open field line #4.

- Lines 878-885, lines 900-908: Additional explanation is needed. This sounds contradictory, with the first section describing how magnetic flux is accumulated in the nightside lobe, and then magnetic flux is not accumulated in this region (the distant magnetotail). Since the lobes are part of the magnetotail, these statements as a set are confusing. If the authors mean that the lobes are not part of the distant magnetotail, then this needs to be described clearly (perhaps with a reference back to Fig.4D), along with some specified distance ranges.

We thank the referee for pointing out this ambiguity. We agree that the original text did not sufficiently distinguish between the nightside lobe in the near-Earth/mid-tail region, where magnetic flux accumulates, and the distant magnetotail, where such accumulation becomes less effective. Since the lobes extend throughout the magnetotail, our original wording could indeed be read as contradictory.

Our intended explanation is that the accumulation of magnetic flux differs between these regions. In the near-Earth/mid-tail region, the deceleration of plasma convection within the cylindrical surface contributes to an increase in magnetic-field strength and the accumulation of magnetic flux in the nightside lobe. In the distant magnetotail, by contrast, the deceleration of convection becomes less pronounced, and the convection velocity within the cylindrical surface approaches the solar-wind velocity outside it. Consequently, magnetic flux is accumulated less efficiently in the distant magnetotail. This does not mean that magnetic flux is absent from the distant magnetotail, but rather that its accumulation becomes less effective there.

This spatial variation in convection velocity is illustrated in Fig. 7C, which shows that the reduction in convection velocity on the nightside becomes less pronounced from the near-Earth region toward the distant magnetotail. This result is consistent with our interpretation that magnetic-flux accumulation becomes less efficient farther downtail.

We will revise the relevant passages to distinguish these spatial regions more clearly and to explain the physical difference between them. We have also clarified the relationship between the extension of the cylindrical surface beyond the bow shock, as described in the text and illustrated in Fig. 4D, and the reduced effectiveness of magnetic-flux accumulation in the distant magnetotail.

- Lines 934-937: The Park et al. study of substorm-like occurrences is a simulation with steady IMF conditions. Although the authors state that this is an exceptional circumstance, observational studies have long shown that substorms are often initiated with a northward turning of the IMF (McPherron (JGR, 2023)). That doesn't always mean that the IMF becomes northward (+Bz); sometimes it's still southward but Bz approaches zero. As McPherron explains in the 2023 article, statistical analyses suggest that most substorms are initiated by a sudden 'pulse' of a solar wind coupling function. This is just to say that the substorm initiation process is more complex than simply dismissing any northward IMF occurrences as an 'exceptional circumstance'.

Thank you very much for this comment. We agree that northward IMF conditions do not necessarily preclude magnetospheric disturbances, particularly when solar wind–magnetosphere coupling varies with time. On the other hand, our reference to Park et al. (2015) was intended to illustrate that a disturbed magnetospheric state can also occur under steady northward IMF conditions, rather than to imply that such disturbances are exceptional. The present study, in contrast, focuses on the quasi-steady magnetic-field structure under northward IMF conditions, rather than on the processes responsible for time-dependent disturbances. Accordingly, we will replace "exceptional circumstance" in the manuscript with "a disturbed state distinct from the quasi-steady state considered here" to clarify the distinction in the context of the present study.

More trivial comments:

- Section 1.3: Please be consistent between the usage of 'Sect.' and 'Section'
- Line 165: 'To discussing the reconnection, they described the characteristic magnetic field structures…' -> 'Reconnection was described in terms of characteristic magnetic field structures…'
- Line 229: investigations is -> investigations are

- Line 326: ‘downstream the obstacle’ -> ‘downstream of the obstacle’
- Line 490: ‘is roughly corresponds’ -> ‘roughly corresponds’
- Line 546: Xion -> Xiong
- Line 827: ‘employs that the IMF is’ -> ‘uses an IMF that is’
- Line 929: ‘the reconnection in deed occur’ -> ‘reconnection occurs’

Thank you for these helpful comments. We will address these typographical, grammatical, and consistency issues in the revised manuscript.