Response of Referee 1

(On September 12, we uploaded a reply plan for RC1 in which we proposed adding further discussion of the dependence of magnetotail bending on solar-wind conditions. However, upon further consideration, we concluded that replacing Figure 3 of the original manuscript with new simulation results would be a more effective way to demonstrate the implications of the proposed physical framework. We therefore submit this revised reply plan in place of the version previously uploaded as RC1.)

We sincerely appreciate the reviewer's comment pointing out that, although the paper reviews studies on three-dimensional magnetic reconnection, its review of magnetospheric dynamics is insufficient. In addition, we recognized that the current presentation could lead readers to misunderstand the main objective of this study as elucidating magnetospheric structures themselves. In revising the paper, we will clarify its central objective and strengthen the discussion of previous studies on magnetospheric dynamics. Based on these considerations, we will revise the paper according to the following plan.

① Revision plan

We will revise parts of the Abstract and Introduction in accordance with this plan. In particular, the Introduction will be streamlined by omitting detailed explanations of the 3D reconnection.

Previous studies of three-dimensional magnetic reconnection in the solar wind–magnetosphere system have examined the null–separator structure that characterizes the global magnetic-field topology, together with the associated Σ surfaces (fan surfaces) and γ lines (spines) [Lau and Finn, 1990; Priest and Forbes, 2000; Dorelli et al., 2007]. These studies have clarified the topology and geometrical structure of magnetic reconnection in terms of the magnetic skeleton formed by null points, separators, Σ surfaces, and γ lines. A complementary line of research has investigated the large-scale structure of the solar wind–magnetosphere system, particularly the deformation and twisting of open-field-line regions and the magnetotail, in response to solar-wind and IMF-driven plasma dynamics [Sibeck et al., 1985a, b; Raeder et al., 1995; Berchem et al., 1998].

These two lines of research have established important aspects of magnetic-field topology and plasma dynamics, respectively. However, how the global null–separator structure constrains the magnetic-field and plasma structures away from the reconnection regions remains an important question. In particular, the role of the two null points (more precisely, null clusters) with opposite signs of topological degree, and of the associated γ lines extending from their vicinity, in constraining the global magnetic-field structure warrants further examination.

In this study, we develop a physical 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, we examine how the characteristic topological structure of the skeleton field, defined as the superposition of the IMF and Earth's dipole field, is reflected in the global magnetic-field structure of the actual system, despite deformation by plasma dynamics. Under 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.

② Fundamental concepts of the quasi-steady solar wind–magnetosphere system under obliquely northward IMF conditions

Here, we explain the physical framework proposed in this study. This framework constitutes the central contribution of the present paper, and the discussion is based on Section 2 of the original manuscript, entitled "Fundamental physical processes in the quasi-steady solar wind–magnetosphere system." The content of this section will remain essentially unchanged in the revised manuscript.

Mechanical principle: The superposition of the Earth's dipole field and the IMF constitutes a current-free magnetic field. When the actual magnetic field is deformed by plasma dynamics, the resulting deformation gives rise to a magnetic restoring influence that tends to return the field toward the configuration of this current-free field.

Topology conservation property: The superposed current-free magnetic field has a 2-null–2-separator structure that provides a topological reference for the solar wind–

magnetosphere system. The associated Σ surfaces, which define the open–closed field-line boundary and the boundary between IMF field lines and open field lines, and the γ lines can also be identified in relation to the null points. Under quasi-steady, obliquely northward IMF conditions, this characteristic topology is preserved in the global magnetic-field structure, with the null points of the actual magnetic field remaining near those of the current-free field. We refer to this current-free magnetic field, which provides a topological reference for the actual magnetic field, as the *skeleton field*.

These two concepts provide a unified framework for understanding the global magnetic-field structure of the solar wind–magnetosphere system, including representative structures such as the magnetotail, the slit (window), and the plasma sheet.

③ The structure of the magnetotail

(4.1.1 Magnetic Field Structure of the Magnetotail as a Manifestation of the Mechanical Principle)

Section 4.1.1 discussed the large-scale structure of the magnetotail using the mechanical principle of competition between the restoring tendency toward the skeleton magnetic field and the deformation of the magnetic field caused by the solar-wind plasma. As a result, it can be understood that, in the region closer to the Earth, the effect of magnetic-field deformation by the solar-wind plasma is relatively strong, and the field lines on the nightside Σ surface are stretched along the solar-wind flow. In contrast, farther from the Earth, the restoring tendency toward the skeleton magnetic field becomes more pronounced, and the field lines gradually bend toward the IMF direction.

The bending of the magnetotail toward the IMF direction in the distant tail has long been studied as the twisting of the magnetotail [Sibeck et al., 1985a,b; Raeder et al., 1995; Nishida et al., 1995; Maezawa et al., 1997; Nishida and Ogino, 1998; Maezawa and Hori, 1998; Berchem et al., 1998; Nishida, 2000]. Previous studies have discussed the magnetic torque exerted by the IMF as a physical process responsible for the twisting of the magnetotail [Berchem et al., 1998; Maezawa and Hori, 1998]. This magnetic torque can be interpreted in terms of the magnetic effect that we interpret in the present study as the restoring tendency against deformation of the skeleton magnetic field.

Therefore, the result presented in this study regarding the structure of the magnetotail is consistent with the magnetotail twisting reported in previous studies and does not contradict their results. The distinctive feature of the present study is that we interpret

these structures in a unified manner as the result of the interaction between the skeleton magnetic field, which forms the basis of the solar wind–magnetosphere system, and its deformation by plasma dynamics. In other words, the skeleton magnetic field not only determines the global magnetic-field topology of the system but also provides a reference magnetic-field structure against which magnetic-field deformation by the plasma occurs. From this perspective, the magnetotail twisting and bending discussed individually in previous studies can be understood in a unified manner as a consequence of the interaction between magnetic-field topology and plasma dynamics.

At the end of this section, we will expand the discussion of magnetotail twisting by incorporating relevant previous studies.

To further examine the dependence of magnetotail bending on solar-wind conditions and assess the predictions of the proposed mechanical principle, we will replace Figure 3 of the original manuscript with numerical simulation results obtained for different IMF strengths and solar-wind plasma number densities. The new figure will demonstrate how the bending of the cylindrical parts of the Σ_A and Σ_B surfaces varies with these parameters. We will insert the new Figure 3 and its caption.

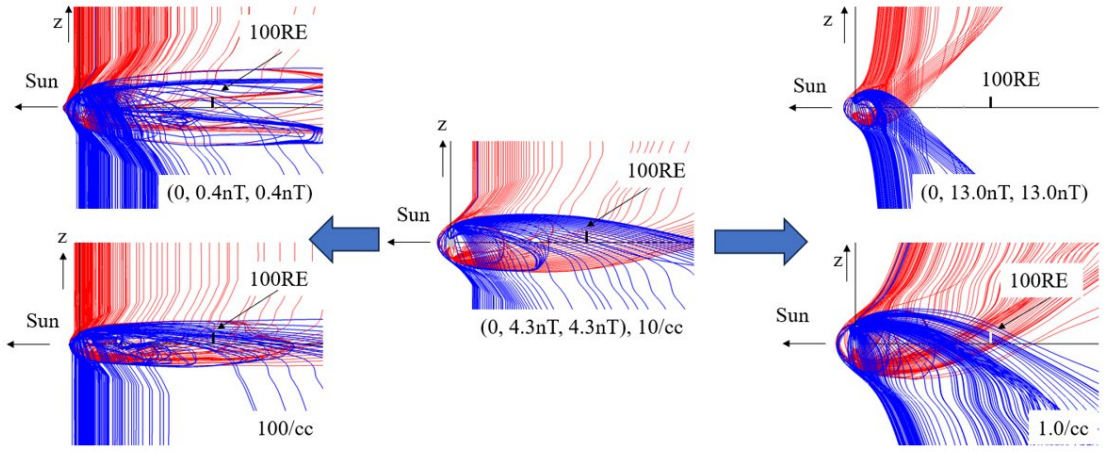


Figure 3. Changes in the cylindrical parts of Σ_A and Σ_B with IMF intensity and solar wind plasma number density. The Σ_A cylinder connects the Northern Hemisphere near Earth to the Southern Hemisphere farther downtail, whereas the Σ_B cylinder connects the Southern Hemisphere near Earth to the Northern Hemisphere farther downtail. The red and blue bundles in each panel represent the magnetic field lines forming the cylindrical parts of Σ_A and Σ_B, respectively, viewed from 18 MLT. The center panel shows the reference state (Fig. 2D). The top panels show results for the reference IMF intensity and varying solar wind plasma number density, whereas the bottom panels show results for the reference solar wind plasma number density and varying IMF intensity. The IMF intensity and solar wind plasma number density used in each case are indicated

in the figure. The cylinders bend more strongly toward the IMF direction as the IMF intensity increases or the solar wind plasma number density decreases, and less strongly as the IMF intensity decreases or the solar wind plasma number density increases.

④ The slit (window) structure

(4.1.3 Slit Generation as an Effect of Both the Mechanical Principle and the Topology Conservation Property)

In Section 4.1.3, we explained the formation of the slit as a consequence of the interaction between the mechanical principle and the topology conservation property. First, according to the mechanical principle, the field lines on the nightside Σ surface bend toward the IMF direction in the distant tail as a result of the competition between magnetic-field deformation by the solar wind and the restoring tendency toward the skeleton magnetic field. On the other hand, according to the topology conservation property, the γ line (spine) extending from the null point that forms the endpoint of the dayside separator maintains its connection with the solar-wind magnetic field. Therefore, it is not simply convected downstream by the solar wind in the same manner as ordinary open field lines. As a result, the opening of the cylinder in the original skeleton field, which separates the solar-wind field lines from the open field lines, is deformed into an elongated and narrow slit. Thus, the slit is a structure formed through the simultaneous action of the mechanical principle, which determines the deformation of the magnetic field, and the topology conservation property, which constrains the connectivity of the magnetic field.

In the revised manuscript, we will retain this explanation and more clearly emphasize the role of the γ line and the influence of the original magnetic-field structure of the skeleton field on slit formation. We will also consolidate the discussion of previous studies at the end of this section. Previous studies [Cowley, 1973; Sibeck et al., 1985a,b; Kaymaz et al., 1994; Kaymaz and Siscoe, 1998] reported a window structure on the flank of the magnetotail and interpreted it as a region where open field lines in the twisted magnetotail become connected to the IMF. We acknowledge that this structure has already been reported and that our results do not contradict these previous findings. However, the present study provides a physical interpretation of its formation by explaining how plasma-driven magnetic-field deformation acts in conjunction with the

global magnetic topology inherited from the skeleton field. In particular, we emphasize that the γ line constrains magnetic-field connectivity and that the original magnetic-field structure of the skeleton field is reflected in the formation of the slit, even though the field is deformed by plasma dynamics. Thus, although the slit examined in the present study corresponds to the previously reported window structure, our contribution is to explain its formation within a unified framework that integrates the topological constraints imposed by the skeleton field with plasma-driven magnetic-field deformation.

⑤ The plasma sheet

(4.2 Deformation of the Torus)

Section 4.2 examined the formation of the plasma sheet within the unified framework developed in this study. According to the topology conservation property, the null points and separator structures that characterize magnetic-field connectivity do not deviate substantially from the global structures prescribed by the skeleton magnetic field. Therefore, the boundary structures of the open-field-line regions are also constrained by the null–separator topology of the skeleton magnetic field. On the other hand, according to the mechanical principle, the two open-field-line regions on the nightside twist in different directions, resulting in a structure in which nearly antiparallel field lines become adjacent at their interface. For the system to remain in a quasi-steady state, these two open-field-line regions cannot be directly connected because of the topology conservation property, and a closed-field-line region must exist between them. In the present paper, we consider this closed-field-line region formed between the two open-field-line regions to correspond to the plasma sheet. Thus, the plasma sheet is formed through the interaction between the mechanical deformation of the open-field-line regions and the global magnetic-field topology that constrains this deformation.

The existence of the plasma sheet as a closed-field-line region surrounded by lobes consisting of open field lines, as well as the distinction of this region from the surrounding magnetic-field regions by separatrices, has been discussed previously [Dungey, 1961; Fedder and Lyon, 1995; Song et al., 1999; Petrukovich et al., 2003]. From the perspective of magnetic-field topology, it has also been discussed that, under northward IMF conditions, open field lines formed by high-latitude reconnection and closed field lines subsequently formed by reconnection of these open field lines contribute to the formation of the plasma sheet and boundary layer [Petrukovich et al., 2003; Tanaka et al., 2024]. Therefore, the present study does not newly propose that the plasma sheet is a closed-

field-line region or introduce new magnetic-field topology associated with the formation of the plasma sheet. On the other hand, in the present study, we explain the formation of the plasma sheet between the two open-field-line regions by simultaneously considering the mechanical process by which the two open-field-line regions constituting the magnetotail twist toward the IMF direction and the constraint on magnetic-field connectivity imposed by the topology conservation property. To our knowledge, such a formation process of the plasma sheet, linking the large-scale deformation of the magnetotail with the null–separator topology, has not been sufficiently discussed in previous studies. In the revised manuscript, we will discuss these previous studies in greater detail at the end of this section.

The fact that the plasma sheet extends far into the nightside is not essential to the plasma-sheet formation mechanism proposed in the present paper. On the other hand, the existence of the plasma sheet over a broad nightside region in the actual magnetotail is well established observationally. Therefore, we cite Mooney et al. (2024) to demonstrate that the results of our calculations reproduce a realistic large-scale structure of the magnetotail.

⑥ Conclusion

In response to the referee's comment, "By reading these papers, one will reach the same conclusions as the authors, so it is difficult to identify any advance made by the present paper," we would like to clarify that the purpose of the present paper is neither to discover new magnetospheric structures nor to rediscover individual, previously known magnetospheric structures. Rather, the purpose of this paper is to propose a unified physical framework for understanding the large-scale structure of the solar wind–magnetosphere system in terms of the interaction between magnetic-field topology and plasma dynamics.

As concrete examples of this framework, we consider the magnetotail twist, the slit (window), and the plasma sheet, whose structures have already been identified through observations and numerical simulations. We then explain how these structures are formed in a unified manner based on common fundamental concepts.

Therefore, the primary advance of the present paper is not the discovery of individual magnetospheric structures themselves, but the placement of these known structures within a unified physical framework based on the interaction between magnetic-field

topology and plasma dynamics, and the proposal of common physical principles for understanding their formation processes.