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Key Points:

- Conditions are less magnetopause reconnection favorable than closer to the Sun
- Reconnection site locations on Uranus' magnetopause are highly dynamic
- Coupling to the solar wind via reconnection may be more efficient at solstice

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Magnetic reconnection at Uranus' magnetopause

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Abstract The magnetosphere of Uranus has barely been explored by spacecraft but is distinct from other solar system magnetospheres in many respects. Determining how this magnetosphere is coupled to the solar wind is central to understanding energy flow through the system. Here we assess how the solar wind interacts with the Uranian magnetosphere via magnetic reconnection. Analytical models of conditions at the magnetopause are combined with current understanding of reconnection onset to predict where reconnection may occur on the boundary. The results suggest that conditions at Uranus' magnetopause are generally less favorable for reconnection than those at the magnetopause of any planet closer to the Sun, as a result of how typical solar wind parameters vary with heliocentric distance. The location of reconnection sites on the Uranian magnetopause is likely to be highly dependent on not only the interplanetary magnetic field orientation but also planetary longitude and season. Solar wind–magnetosphere coupling via magnetic reconnection may be stronger under near-solstice conditions than under near-equinox conditions. We discuss the typical reconnection electric field strength at Uranus' magnetopause and suggest that the typical reconnection voltage is considerably less than 40 kV. Complimentary assessments of other means of coupling to the solar wind (e.g., via a “viscous-like” interaction) are needed to establish the overall nature of solar wind–magnetosphere coupling at Uranus.

1. Introduction

The Uranus planetary system has only been explored by the Voyager 2 spacecraft to date, which flew by in 1986. Like all planets in our solar system, Uranus is unique in many respects. For example, Uranus has the largest obliquity of any of the planets (97.8°, the angle between the rotation axis and the orbital axis), which is expected to produce dramatic seasonal variations.

Uranus has a complex magnetic field, with an angle of 58.6° between the dipole moment axis and the rotation axis, and a significant quadrupole moment [Ness *et al.*, 1986; Connerney *et al.*, 1987; Herbert, 2009]. This large dipole tilt leads to strong variation of the planet's magnetic environment during a planetary rotation period of 17.24 h [Desch *et al.*, 1986]. Like all the magnetized planets, Uranus' magnetic field presents an obstacle to the solar wind plasma and its associated interplanetary magnetic field (IMF), producing a flow cavity within which the planetary magnetic field is essentially confined—a planetary magnetosphere [Bagenal, 1986, 1992]. Figure 1 illustrates Uranus' magnetosphere and its interaction with the solar wind at the time of the Voyager 2 flyby in 1986. Diagrams of the magnetosphere separated by half a planetary rotation period are shown to highlight the dynamic nature of this asymmetric magnetosphere.

Despite Uranus' distance from the Sun (~19 times the mean Sun–Earth distance) during the Voyager era it was proposed that the solar wind was a major driver of the planetary magnetosphere [Vasyliunas, 1986; Selesnick and Richardson, 1986; Mauk *et al.*, 1987; Selesnick, 1988]. The Voyager flyby took place under solstice conditions when the planet's rotation axis was close to the sunward direction (see Figure 1). Under such conditions it was argued that solar wind-driven plasma convection would pervade the magnetosphere, with little impedance offered by the presence of plasma corotating with the planet [Vasyliunas, 1986; Selesnick and Richardson, 1986]. The low plasma β (ratio of plasma to magnetic pressure) measured by Voyager 2 inside the magnetosphere [Bridge *et al.*, 1986; Krimigis *et al.*, 1986; Ness *et al.*, 1986; Mauk *et al.*, 1987] suggests weak internal plasma sources, and thus, that the solar wind may remain a major driver of the system even away from near-solstice conditions.

The process underpinning this proposed solar wind driving of Uranus' magnetosphere is magnetic reconnection [Dungey, 1961]. Reconnection occurs at current sheets like the magnetopause boundary of a planetary magnetosphere, changing the topology of the magnetic field and converting magnetic energy into particle kinetic energy. Plasma and associated magnetic field lines from the adjacent environments move toward the reconnection site, where the field lines are effectively “cut” and “reconnected,” before moving

Figure 1. Diagrams illustrating Uranus' dynamic magnetosphere at the time of the Voyager 2 flyby in 1986 (near-solstice conditions). (a and b) Configurations of the system separated by half a planetary rotation, for the special case of southward IMF and no magnetic connection across the magnetopause boundary. In both panels the solar wind plasma flow is indicated by block arrows, the IMF is shown in blue, the Uranian bow shock and magnetopause are shown as (outer and inner) gray curves, the planetary magnetic field is shown in red, and the planetary rotation axis is shown in black.

away from the reconnection site along the current sheet with the outflow of accelerated plasma. The aim of this paper is to shed further light on the operation of this key process at the magnetopause boundary of Uranus' magnetosphere.

The extensive spacecraft observations of reconnection in near-Earth space provide an important reference point for understanding reconnection at Uranus' magnetopause (see the recent reviews by *Fuselier and Lewis* [2011], *Gosling* [2012], and *Paschmann et al.* [2013]). The onset of reconnection is thought to require a thin current sheet (of order one ion inertial length [e.g., *Sanny et al.*, 1994; *Phan et al.*, 2011]), a sub-Alfvénic relative diamagnetic drift between ions and electrons within the current sheet in the direction of reconnection outflow [Swisdak et al., 2003, 2010; *Phan et al.*, 2010, 2013], and a sub-Alfvénic flow shear across the current sheet in the direction of reconnection outflow (in the rest frame of the reconnection site) [Cassak and Otto, 2011]. While conditions are generally more favorable for onset when the magnetic shear across the current sheet (the angle between the adjacent magnetic fields) is high, onset appears to also be possible at far lower magnetic shears [e.g., *Trattner et al.*, 2007; *Phan et al.*, 2010]. Once onset has occurred, the rates of open magnetic flux production and energy release increase with increasing strength of the reconnecting magnetic fields and decrease with increasing plasma mass density in the adjacent regimes [e.g., *Cassak and Shay*, 2007; *Mozar and Hull*, 2010]. It has also been suggested that the efficiency of reconnection may be parameter dependent [Sonnerup, 1970; *Slavin and Holzer*, 1979; *Anderson et al.*, 1997; *DiBraccio et al.*, 2013].

The limited in situ observations made by Voyager 2 alone cannot form the basis of a global assessment of magnetic reconnection occurring at Uranus' magnetopause current sheet. However, they do reveal the expected high plasma β in the planetary magnetosheath (the shock-processed solar wind between the planetary bow shock and the magnetopause) that results from the high-Mach number Uranian bow shock [Bagenal et al., 1987], and they indicate a magnetopause standoff distance (the shortest distance between the magnetopause and the center of the planet) of ~ 18 Uranus radii (R_U , $1 R_U = 25,559$ km) [Ness et al., 1986]. The signatures of the inbound and outbound magnetopause crossings potentially show evidence for magnetosheath mirror mode structures, partial magnetopause crossings possibly caused by

surface wave activity, and magnetic reconnection at the dayside magnetopause [Lepping *et al.*, 1987; Richardson *et al.*, 1988; Russell *et al.*, 1989; Huddleston *et al.*, 1997; Richardson, 2002]. A parallel has been drawn between the Uranian magnetopause and the terrestrial magnetopause under high- β conditions [Russell *et al.*, 1989].

Since the Voyager era the Uranian season has progressed from solstice conditions to equinox conditions, and improvements in our understanding of the planetary system have been based on remote observations. For example, in 2011 the Hubble Space Telescope (HST) observed Uranus in the far ultraviolet when solar wind pressure fronts were expected to impact the magnetosphere, leading to positive detection of auroral signatures [Lamy *et al.*, 2012]. Cowley [2013] suggested that the difference between the observed signatures and the more pronounced “compression-enhanced” auroras observed at other planets is a seasonal effect. They considered the opening and closing of magnetic flux in the system (where open flux is produced during reconnection at the magnetopause) and argued that the amount of open flux in the system is lower during equinox conditions than during solstice conditions, providing an explanation for the HST observations.

Here we assess the operation of magnetic reconnection at Uranus’ magnetopause under both solstice and equinox conditions using a combination of analytical models. The modeling results imply that conditions are less favorable for reconnection at Uranus’ magnetopause than at any planetary magnetopause closer to the Sun and that the location of reconnection sites is highly dynamic. The equinox results support the dayside reconnection scenarios proposed by Cowley [2013].

2. Approach

The coordinate system used throughout this paper is the Uranian Solar Orbital (USO) system, which is Uranus centered with the x axis pointing toward the Sun. The y axis is chosen such that the xy plane contains Uranus’ orbital plane, with the y axis antiparallel to the orbital velocity vector. The z axis completes the right-handed orthogonal set, pointing north of the ecliptic. Wherever the terms “northward” and “southward” are used they refer to the directions parallel and antiparallel to the z axis, respectively. The USO coordinate system is the Uranian equivalent of the geocentric solar ecliptic (GSE) coordinate system often used in the case of Earth. However, unlike the GSE system, no aberration of the USO system is needed because of Uranus’ small orbital speed with respect to that of the near-Uranus solar wind.

The foundation of our approach is the combination of different analytical descriptions of parameters immediately adjacent to the Uranian magnetopause current sheet (both external magnetosheath and internal magnetospheric), described in the following subsection. Similar assessments of the operation of reconnection at Mercury’s magnetopause [Slavin *et al.*, 2012], Earth’s magnetopause [e.g., Cooling *et al.*, 2001; Petrinec *et al.*, 2003], Jupiter’s magnetopause [Desroche *et al.*, 2012], and Saturn’s magnetopause [Desroche *et al.*, 2013] have been previously reported.

2.1. Treatment of Near-Magnetopause Parameters

Our treatment of magnetosheath conditions is fundamentally the same as that employed by Petrinec *et al.* [2003] for the case of Earth. Our fixed near-Uranus solar wind inputs are as follows: antisunward plasma flow at 450 km s^{-1} , proton number density of 0.05 cm^{-3} , plasma pressure of $4.5 \times 10^{-5} \text{ nPa}$, sonic Mach number of 27, and IMF strength of 0.19 nT. We set the orientation of the IMF as a free parameter but constrain the vector to lie in the yz plane. This constrained set of possible IMF orientations contains the expected prevailing IMF orientations at Uranus (see section 3) and considerably simplifies our magnetosheath modeling [e.g., Petrinec *et al.*, 2003]. To calculate solar wind mass densities we assume a neutral solar wind plasma with an ion composition of 96% protons and 4% He^{++} by number.

The fixed solar wind input values stated above are based on Voyager 2 observations made upstream of the Uranian bow shock [Bagenal *et al.*, 1987] and are all similar to estimated values based on solar wind scaling laws [e.g., Slavin and Holzer, 1981]. In particular, the implied near-Uranus solar wind Mach numbers (sonic Mach number of ~ 27 , Alfvén Mach number of ~ 23 , fast magnetosonic Mach number of ~ 17) are all higher than typical solar wind Mach numbers closer to the Sun, as also expected (see discussion in section 4.1).

We assume that the Uranian bow shock and magnetopause surfaces are parabolic conic sections, with standoff distances of 23 and $18 R_U$, respectively [Ness *et al.*, 1986]. The focus of both conic sections is located

on the x axis, halfway between the center of the planet and the magnetopause subsolar point. Both surfaces have rotational symmetry about the x axis, which is antiparallel to the solar wind flow direction. We consider the dayside region only.

The initial magnetosheath flow velocity, the magnetosheath mass density, and the magnetosheath plasma pressure immediately adjacent to the magnetopause are given by the following expressions, which were derived by *Petrinec and Russell* [1997] for the hydrodynamic case. The initial magnetosheath flow speed, v_{msh} , at any point on the magnetopause surface is given as

$$v_{\text{msh}} = v_u \sqrt{\frac{(M_s^2 + 3)}{M_s^2} \left(1 - \left(\cos^2 \psi + \frac{3^{3/2}}{4} \frac{(5M_s^2 - 1)^{3/2}}{M_s^5} \sin^2 \psi \right)^{2/5} \right)} \quad (1)$$

where v_u is the solar wind flow speed upstream of the bow shock, M_s is the sonic Mach number of the upstream solar wind, and ψ is the flaring angle (the angle between the local normal to the magnetopause surface and the x axis). This initial flow velocity field points away from the subsolar point and parallel to the magnetopause surface at all points on the boundary. Later, this initial flow field is modified to account for magnetic tension forces. The magnetosheath mass density, ρ_{msh} , at any point on the magnetopause surface is given as

$$\rho_{\text{msh}} = \rho_u \frac{4^{8/5} M_s^2}{(M_s^2 + 3)(5M_s^2 - 1)^{3/2}} \left[\frac{4^4}{3^{3/2}} M_s^5 \cos^2 \psi + (5M_s^2 - 1)^{3/2} \sin^2 \psi \right]^{3/5} \quad (2)$$

where ρ_u is the solar wind mass density upstream of the bow shock. The magnetosheath plasma pressure, P_{msh} , at any point on the magnetopause surface is given as

$$P_{\text{msh}} = P_u \left[\frac{4^4}{3^{3/2}} \frac{M_s^5}{(5M_s^2 - 1)^{3/2}} \cos^2 \psi + \sin^2 \psi \right] \quad (3)$$

where P_u is the solar wind plasma pressure upstream of the bow shock. For the magnetosheath magnetic field (the draped IMF) we use the *Kobel and Flückiger* [1994] analytical model (note that this dictates our choice of boundary geometries). More specifically, we use the expressions presented by *Petrinec et al.* [2003] (or equivalently *Cooling et al.* [2001]) that give the magnetosheath magnetic field vector immediately adjacent to any point on the magnetopause surface (derived from the *Kobel and Flückiger* [1994] model), which are defined by the IMF upstream of the bow shock and the boundary standoff distances. The high Alfvén Mach number of the near-Uranus solar wind (~ 23) [*Bagenal et al.*, 1987] means that we expect the hydrodynamic treatment of the magnetosheath plasma environment employed here in the case of Uranus to be more appropriate than in the case of planetary magnetosheaths closer to the Sun.

Plasma depletion layers (PDLs) of reduced plasma density and enhanced magnetic field strength [e.g., *Zwan and Wolf*, 1976] have been encountered by spacecraft immediately adjacent to a number of planetary magnetopauses closer to the Sun [*Anderson et al.*, 1997; *Gershman et al.*, 2013; *Masters et al.*, 2014a]. Although highly variable, in the case of each planet the typical observed “level” of the PDL appears to be roughly similar, indicated by a similar typical reduction in the local plasma β by $\sim 85\%$ (the median reduction reported by *Masters et al.* [2014a] in the case of Saturn’s magnetosheath). We account for a Uranian PDL of the same level by decreasing the magnetosheath mass density and increasing the magnetosheath magnetic field strength adjacent to each point on the magnetopause surface to produce an 85% reduction in the local plasma β , while maintaining a constant sum of plasma and magnetic pressures [*Anderson et al.*, 1997]. Following this, we account for the magnetic tension forces associated with the draped IMF by modifying our initial magnetosheath flow velocity, as outlined by *Petrinec et al.* [1997].

For magnetospheric conditions, we take the orientation of the planetary rotation axis (related to seasonal variations) and the orientation of the planetary dipole moment axis (related to diurnal variations) as free parameters. We assume that the near-magnetopause magnetosphere is a perfect vacuum, based on the low plasma β measured by Voyager 2 in Uranus’ outer magnetosphere [*Bridge et al.*, 1986; *Krimigis et al.*, 1986; *Ness et al.*, 1986; *Mauk et al.*, 1987]. To describe the direction of the magnetospheric magnetic field immediately inside the magnetopause at any point we compute the planetary magnetic field given by the *Herbert* [2009] model and then set the component in the direction that is locally normal to the boundary equal to zero.

The treatment of external magnetosheath and internal magnetospheric parameters outlined in this subsection form the foundation of our approach. After specifying the IMF orientation, planetary rotation axis orientation, and planetary dipole moment axis orientation, we can derive further near-magnetopause parameters and then assess the operation of magnetopause reconnection.

2.2. Example Near-Magnetopause Parameters

To give an example of modeled near-magnetopause parameters and the subsequent magnetopause reconnection assessment, we can use the Voyager 2 inbound pass. The Voyager flyby occurred close to solstice, when the planetary rotation axis was within 10° of the x axis. During approach to the magnetopause the spacecraft measured an approximately southward IMF in Uranus' magnetosheath, and after the magnetopause crossing(s) the measured magnetospheric magnetic field was also approximately southward [e.g., *Lepping et al.*, 1987]. Based on this, let us set the IMF orientation as perfectly southward. Let us set the planetary rotation axis as lying in the xz plane, with a positive projection on the x axis, and making an angle of 97.8° with the z axis. Finally, let us set the planetary dipole moment axis as also lying in the xz plane, with a positive projection on the z axis and making an angle of 58.6° with the planetary rotation axis. This scenario is illustrated in Figure 1a.

Figures 2a–2e show the near-magnetopause parameters discussed in section 2.1 for this example case. Figures 2a–2h show Uranus' dayside magnetopause surface as viewed along the upstream solar wind flow direction (antiparallel to the x axis). The magnetosheath flow velocity field shown in Figure 2a is not axis symmetric about the x axis because we have addressed the influence of magnetic tension forces associated with the draped IMF (see section 2.1). Figure 2d shows “cusp-like” magnetospheric magnetic field features (points of divergent and convergent magnetic field) in locations similar to those illustrated in Figure 1a. Figure 2d also shows the first of the near-magnetopause parameters that we derive from our initial parameter set: The magnetospheric magnetic field strength. We calculate this based on the assumption of total pressure balance at the magnetopause boundary. Since we are assuming the magnetosphere is a perfect vacuum, the magnetospheric magnetic pressure adjacent to each point on the magnetopause surface must equal the sum of the local magnetosheath plasma and magnetic pressures, resulting in a local magnetospheric magnetic field strength. Note that the magnetosheath and magnetospheric magnetic field strengths at the boundary are in reasonable agreement with Voyager 2 observations [e.g., *Lepping et al.*, 1987].

Figures 2f to 2h show further parameters. Figure 2f shows the magnetosheath plasma β . Figure 2g shows the cross-magnetopause magnetic shear (the angle between the magnetosheath and magnetospheric magnetic fields) for the present case of southward IMF. Note that reversing the direction of the IMF from southward to northward has no effect on all other parameters shown in Figures 2a–2f. For this reason, we can also consider the case of northward IMF here, which produces a map of cross-magnetopause magnetic shear shown in Figure 2h. The northward IMF scenario is illustrated in Figure 1b.

2.3. Example Magnetopause Reconnection Assessments

Figure 3 shows results of magnetopause reconnection assessments for the present example based on the inbound pass of the Voyager 2 flyby. In all assessments we assume that there is initially no open magnetic flux in the system, that the current sheet thickness is 1 ion inertial length, and that this thickness is sufficiently thin for reconnection onset (based on the investigation of Earth's magnetopause reported by *Phan et al.* [2013]). In the following, for a specific IMF orientation we consider each point on the model magnetopause surface and consider the hypothetical situation where reconnection onset has occurred. We then separately assess two effects that can suppress the reconnection process. If the condition for reconnection imposed by either effect is not satisfied then we conclude that reconnection onset cannot occur at that location. See section 4.1 for a justification of the independent application of these reconnection onset conditions.

Figures 3a–3c show the assessment results for our southward IMF example. In Figure 3a the diamagnetic drift condition for reconnection onset is applied [*Swisdak et al.*, 2003, 2010; *Phan et al.*, 2010, 2013], which is given as

$$\theta_B > 2 \arctan\left(\frac{d_i \Delta\beta}{2L}\right) \quad (4)$$

where θ_B is the magnetic shear, d_i is an ion inertial length, L is the thickness of the current sheet, and $\Delta\beta$ is the absolute difference between the magnetosheath and magnetospheric plasma β . In the present case, $\Delta\beta$ is

Figure 2. An example of model-predicted conditions at Uranus' magnetopause: Voyager 2 inbound. (a) Magnetosheath plasma flow velocity. (b) Magnetosheath proton number density. (c) Magnetosheath magnetic field. (d) Magnetospheric magnetic field. (e) Magnetosheath plasma pressure. (f) Magnetosheath plasma β . (g) Cross-magnetopause magnetic shear for southward IMF. (h) Cross-magnetopause magnetic shear for northward IMF. Arrows give only the direction of vector fields (no arrow heads are shown in Figure 2c since both southward and northward IMFs are considered). In all panels the dayside magnetopause surface is viewed from along the upstream solar wind flow direction, and the circle centered on the origin represents the planet.

equal to the magnetosheath plasma β , and $L = 1 d_i$. If this condition is satisfied, then reconnection onset is not prohibited by this effect. The modeling suggests that the regions of highest magnetic shear are located at high latitudes with respect to the xy plane (Figure 2g) and that only in these regions of close to antiparallel magnetic fields ($\theta_B > 170^\circ$) the diamagnetic drift condition is satisfied, and thus, this effect does not prohibit reconnection.

In Figure 3b we apply the condition for reconnection onset related to the flow shear across the current sheet. The dashed contour in each panel of Figure 3 bounds the region where the local magnetosheath flow is sub-Alfvénic. Since we assume that the outer magnetosphere is a vacuum, the flow shear across the boundary is

Figure 3. Example assessments of magnetic reconnection at Uranus' magnetopause: Voyager 2 inbound. Panels in the same row correspond to the same IMF orientation, indicated by the far left circles that show the upstream IMF vector (with length $2 R_U$) projected onto the planet, as viewed from along the upstream solar wind flow direction. (a, e, i, and m) Applications of the diamagnetic drift condition for reconnection onset. (b, c, f, g, j, k, n, and o) Applications of the flow shear condition for reconnection onset. (d, h, l, and p) Applications of both onset conditions (requiring both conditions to be satisfied for reconnection to not be prohibited). In all panels the dayside magnetopause surface is viewed from along the upstream solar wind flow direction, the circle centered on the origin represents the planet, and the dashed contour bounds the region where the local magnetosheath flow is sub-Alfvénic. Regions of the surface shown in green indicate where the applied reconnection onset condition(s) is satisfied, and thus, reconnection is not prohibited by the considered effect(s), whereas regions shown in red indicate where the condition(s) is not satisfied, and thus, reconnection is prohibited by the considered effect(s).

controlled by the magnetosheath flow. The flow shear onset condition (relevant for our modeling) can be expressed as

$$\Delta v_B < \left(\frac{B_{msh}^2 + B_{msh} B_{msp}}{\rho_{msh} \mu_0} \right)^{1/2} \quad (5)$$

where Δv_B is the flow shear in the direction of the reconnecting magnetic fields (the direction of reconnection outflow), B_{msh} and B_{msp} are the components of the magnetosheath and magnetospheric magnetic fields that reconnect (respectively), and ρ_{msh} is the magnetosheath plasma mass density [Cassak and Shay, 2007; Cassak and Otto, 2011]. The right-hand side of equation (4) is the reconnection outflow ("hybrid" Alfvén) speed. To determine the direction parallel to the reconnecting fields at each point we consider a line that bisects the shear angle between the adjacent magnetic fields and then use the direction perpendicular to this line that also lies parallel to the local magnetopause surface. The reconnecting field components are then the absolute field components in this (outflow) direction [Swisdak and Drake, 2007; Desroche et al., 2012]. If this condition is satisfied then reconnection onset is not prohibited by this effect. Note that when applying this condition we assume that reconnection site motion has no projection onto the outflow direction (see justification in section 4.1).

In this example the flow shear onset condition is not satisfied at any point on the boundary, and thus, the model predicts that dayside reconnection is entirely suppressed under the chosen combination of (southward) IMF, rotation axis, and dipole moment axis orientations. In other words, in the limited regions of high magnetic shear (where the diamagnetic drift effect does not prohibit reconnection onset) the local magnetosheath flow is super-Alfvénic and approximately aligned with the direction of reconnection outflow, leading to total suppression of dayside magnetopause reconnection. Figure 3b is mirrored in Figure 3c, where both conditions are applied, requiring both of them to be satisfied for reconnection to not be prohibited at any point.

Figures 3d–3f show the assessment results for our northward IMF example, applying the exact same conditions for onset. In this case the typically higher magnetic shear across the surface (see Figure 2h) leads

to a considerably greater region where the diamagnetic drift condition is satisfied, as shown in Figure 3d. Furthermore, even away from the sub-Alfvénic magnetosheath the expected directions of reconnection outflow tend to not be aligned with the direction of the locally super-Alfvénic magnetosheath flow, leading to the broad satisfaction of the flow shear condition for onset, as shown in Figure 3e. Note that the flow shear condition is not satisfied everywhere where the local magnetosheath flow is sub-Alfvénic because the flow shear condition concerns the expected hybrid Alfvén speed of reconnection outflow (see equation (5)). The overall assessment for our northward IMF example is shown in Figure 3f, where reconnection is not prohibited in three separate regions, in contrast to the total suppression of dayside magnetopause reconnection predicted in the case of our southward IMF example.

3. Results: Solstice and Equinox

The two example magnetopause reconnection assessments presented in section 2.3 correspond to a single combination of the two planetary free parameters in our modeling. Considering a range of IMF orientations, phases of Uranus' orbit and phases of planetary rotation produce a broad parameter space within which we can carry out further assessments. In this section we constrain the parameter space by first considering only the near-solstice conditions that prevailed during the Voyager 2 flyby in 1986, and then only the near-equinox conditions that prevailed during the 2011 HST campaign.

If we define the North Pole of a planet as pointing above the invariable plane of the solar system then Uranus is classified as a retrograde rotator, and the Voyager 2 flyby occurred in the year of northern winter solstice. All of the magnetopause reconnection assessments under solstice conditions presented in this section correspond to this phase of Uranus' ~84 year orbit of the Sun (i.e., they use the same planetary rotation axis orientation as the examples in section 2). In the interests of article length, only the cross-magnetopause magnetic shear and the combined application of reconnection onset conditions are shown for each assessment (the equivalents of Figures 2g and 3c).

Figure 4 shows the cross-magnetopause magnetic shear for reconnection assessments based on 16 different combinations of IMF orientation and planetary rotation phase, under solstice conditions. The format of each panel is similar to those in Figures 2 and 3. The planetary rotation axis points out of the page and slightly below the xy plane in all panels. Panels in the same row correspond to the same IMF orientation. Figures 4a–4d correspond to perfectly southward IMF, Figures 4e–4h correspond to an IMF parallel to the y axis, Figures 4i–4l correspond to an IMF antiparallel to the y axis, and Figures 4m–4p correspond to perfectly northward IMF. Panels in the same column correspond to the same phase of planetary rotation. Those in the first column correspond to a planetary dipole moment axis that lies in the xz plane and has a positive projection on the z axis. The panels in the second, third, and fourth columns (from left to right) correspond to planetary dipole orientations that are progressively rotated about the planetary rotation axis in 90° increments, in the sense of planetary rotation. The examples presented in section 2.2 are shown in Figures 4a and 4m.

The *Parker* [1958] prediction of the prevailing IMF orientation throughout the heliosphere is in good agreement with present spacecraft observations [e.g., *Forsyth et al.*, 2002] and suggests that an IMF that is parallel/antiparallel to the y axis (depending on the location of the heliospheric current sheet) is the dominant IMF orientation at Uranus' orbit. IMF variability makes strongly southward and northward IMF possible (as suggested by the Voyager 2 observations), although we expect such cases to be relatively rare. As a result, the modeled magnetic shear maps shown in Figures 4e–4l are expected to be the most common.

Unsurprisingly, the locations of high-magnetic shear regions on the model magnetopause surface vary considerably between the 16 points in free parameter space that are considered. This is controlled by not only IMF orientation (dominant in the case of Earth's magnetopause) but also Uranian longitude. Considering any single IMF orientation (i.e., the panels in any single row) highlights this. The time scale associated with variations in the IMF orientation at Uranus is unclear but would be comparable to Uranus' rotation period if it were typically a few hours. Also note that the adjacent magnetic fields in the sub-Alfvénic magnetosheath region are close to antiparallel for a number of the presented combinations.

Figure 5 shows the associated combined application of reconnection onset conditions for each assessment, presented in the same format as Figure 4. These modeling results suggest that reconnection is prohibited by

Figure 4. The variable magnetic shear across Uranus' magnetopause at northern winter solstice (the era of the 1986 flyby by Voyager 2). Panels in the same row correspond to the same IMF orientation, indicated by the far left circles that show the upstream IMF vector (with length $2 R_U$) projected onto the planet, as viewed from along the upstream solar wind flow direction. Panels in the same column correspond to the same orientation of planetary rotation and magnetic dipole axes, similarly shown in black and red (respectively) above each column. (a–p) The magnetic shear across the dayside magnetopause is shown as viewed from along the upstream solar wind flow direction, the circle centered on the origin represents the planet, and the dashed contour bounds the region where the local magnetosheath flow is sub-Alfvénic.

one or both of the considered effects over the majority of the magnetopause in all cases. In a number of cases (e.g., Figure 4a, the first example discussed in section 2) dayside reconnection is entirely prohibited. Regions where reconnection is not prohibited are exclusively those where the magnetic shear is greater than 170° (cf. Figure 4), which is always required for the satisfaction of the diamagnetic drift condition; however, in a number of such regions of almost antiparallel magnetic fields the flow shear condition prohibits reconnection (see section 2.3).

Figure 5. Assessments of magnetic reconnection at Uranus' magnetopause at northern winter solstice (the era of the 1986 flyby by Voyager 2). Panels in the same row correspond to the same IMF orientation, indicated by the far left circles that show the upstream IMF vector (with length $2 R_U$) projected onto the planet, as viewed from along the upstream solar wind flow direction. Panels in the same column correspond to the same orientation of planetary rotation and magnetic dipole axes, similarly shown in black and red (respectively) above each column. (a–p) The dayside magnetopause is shown as viewed from along the upstream solar wind flow direction, both the reconnection site drift and flow shear conditions for reconnection onset have been applied (green: reconnection not prohibited; red: reconnection prohibited), the circle centered on the origin represents the planet, and the dashed contour bounds the region where the local magnetosheath flow is sub-Alfvénic.

The 2011 HST campaign that provided remote observations of Uranus in the far ultraviolet occurred 25 years after the Voyager 2 flyby, close to northern spring equinox. As a result, the orientation of the planetary rotation axis and the related possible orientations of the planetary dipole moment axis are different from those considered in Figures 4 and 5 for the Voyager era. All of the magnetopause reconnection assessments under equinox conditions presented in this section correspond to a planetary rotation axis that lies in the yz plane, has a negative projection onto the y axis, but still makes an angle of 97.8° with the z axis.

Figure 6 shows the cross-magnetopause magnetic shear for reconnection assessments based on 16 different combinations of IMF orientation and planetary rotation phase, under equinox conditions. The format of

Figure 6. The variable magnetic shear across Uranus' magnetopause at northern spring equinox (the era of the 2011 Hubble Space Telescope campaign). Panels in the same row correspond to the same IMF orientation, indicated by the far left circles that show the upstream IMF vector (with length $2 R_U$) projected onto the planet, as viewed from along the upstream solar wind flow direction. Panels in the same column correspond to the same orientation of planetary rotation and magnetic dipole axes, similarly shown in black and red (respectively) above each column. In all panels the magnetic shear across the dayside magnetopause is shown as viewed from along the upstream solar wind flow direction, the circle centered on the origin represents the planet, and the dashed contour bounds the region where the local magnetosheath flow is sub-Alfvénic.

Figure 6 is the same as Figure 4, but with different rotation and dipole moment axis orientations. The panels in the first column correspond to a planetary dipole moment axis that appears to be aligned with the planetary rotation axis when viewed from along the solar wind flow direction but has a negative projection on the x axis. The panels in the second, third, and fourth columns (from left to right) correspond to planetary dipole orientations that are progressively rotated about the planetary rotation axis in 90° increments, in the sense of planetary rotation.

Like the solstice magnetic shear maps, these equinox magnetic shear maps show the expected highly variable nature of the location of high-magnetic shear regions on the model magnetopause surface.

Figure 7. Assessments of magnetic reconnection at Uranus' magnetopause at northern spring equinox (the era of the 2011 Hubble Space Telescope campaign). Panels in the same row correspond to the same IMF orientation, indicated by the far left circles that show the upstream IMF vector (with length $2 R_U$) projected onto the planet, as viewed from along the upstream solar wind flow direction. Panels in the same column correspond to the same orientation of planetary rotation and magnetic dipole axes, similarly shown in black and red (respectively) above each column. In all panels the dayside magnetopause is shown as viewed from along the upstream solar wind flow direction, both the reconnection site drift and flow shear conditions for reconnection onset have been applied (green: reconnection not prohibited; red: reconnection prohibited), the circle centered on the origin represents the planet, and the dashed contour bounds the region where the local magnetosheath flow is sub-Alfvénic.

However, in contrast, Figure 6 suggests that under equinox conditions there may be a range of planetary rotation phases when there is one (rather than two) dayside cusp-like magnetic features (e.g., Figure 6e). As a result, if we only consider the two dominant IMF orientations (Figures 6e–6l), there is generally a lower magnetic shear in the subsolar region in one case (IMF parallel to the y axis, Figures 6e–6h) compared to the other (IMF antiparallel to the y axis, Figures 6i–6l).

Figure 7 shows the associated combined application of reconnection onset conditions for each assessment, presented in the same format as Figure 5, but appropriate for northern spring equinox (cf. Figure 6). Similar to the solstice results (cf. Figure 5), these equinox results also suggest that reconnection is prohibited by one or

both of the considered effects over the majority of the magnetopause in all cases. However, the restriction of regions where dayside reconnection is not prohibited under these equinox conditions appears to be more severe than under solstice conditions. Also, unlike at solstice, the systematic difference between Parker spiral IMF polarities at equinox noted above manifests in Figure 7 as systematically smaller regions where reconnection is not prohibited in the case of one polarity (Figures 7e–7h) than the other (Figures 7i–7l).

4. Discussion

At this stage we remind the reader that our modeling approach is highly idealized and based on a number of assumptions (see section 2). However, nonetheless, such simple modeling does allow us to draw some important (generally qualitative) conclusions about reconnection at the boundary of the poorly understood Uranian magnetosphere.

Specific discussion themes are the subject of the following subsections, where the validity of some of the modeling assumptions and the likely impact of excluded physics is assessed. Separate from these discussion topics, we point out that a realistic treatment of parameters in the vicinity of the magnetospheric cusps and a more sophisticated description of the near-magnetopause magnetospheric magnetic field in future work would improve the accuracy of model predictions.

4.1. The Influence of Near-Uranus Solar Wind Conditions

Our modeling results suggest that reconnection at Uranus' magnetopause is generally restricted to regions where the adjacent magnetic fields are within 10° of antiparallel because of the diamagnetic drift suppression effect. The modeling also suggests that the magnetosheath flow is super-Alfvénic adjacent to the majority of the dayside Uranian magnetopause surface, and thus, that the flow shear suppression effect should also play an important role in controlling where reconnection takes place.

These predictions are in contrast with observational evidence for reconnection at Earth's magnetopause, which suggests that reconnection can occur for magnetic shears as low as $\sim 90^\circ$ at the terrestrial boundary [e.g., Pu et al., 2007; Trattner et al., 2007; Trenchi et al., 2008; Phan et al., 2013]. Comparing the present Uranus modeling with the equivalent modeling for Earth [Petrinec et al., 2003] is particularly revealing. Relative to the dayside magnetopause surface area, the region of sub-Alfvénic magnetosheath flow is predicted to be smaller at Uranus' magnetopause than at Earth's (compare Figure 3a with Figure 4 of Petrinec et al. [2003]). The only difference between magnetosheath modeling approaches is the treatment of the PDL. If we use the same PDL treatment as Petrinec et al. [2003] (double the magnetosheath magnetic field and halve the magnetosheath mass density) then the sub-Alfvénic magnetosheath flow area at Uranus' magnetopause contracts slightly, confirming the differing model predictions for Earth and Uranus.

This contrast with the terrestrial case is an expected consequence of the different solar wind conditions at Uranus. Spacecraft observations have so far confirmed predictions that the Mach numbers of the solar wind increase monotonically with heliocentric distance, due to decreasing wave speeds rather than an increasing solar wind flow speed [e.g., Slavin and Holzer, 1981; Russell et al., 1982, 1990; Bagenal et al., 1987; Masters et al., 2013]. Consequently, the bow shocks standing in front of planetary magnetospheres at greater distance from the Sun are stronger, and the upstream Alfvén speed is lower. The result of this is that the magnetosheath environments downstream of bow shocks at greater distance from the Sun become progressively higher plasma β and are associated with lower Alfvén speeds [Bagenal et al., 1987; Trenchi et al., 2008; Masters et al., 2012, 2014b].

This leads to the expectation that Uranus' magnetopause should be more asymmetric (defined as the difference in plasma β across the boundary) than Earth's and thus should suffer from more severe diamagnetic drift suppression, effectively constraining reconnection to almost antiparallel magnetic geometries [Swisdak et al., 2003]. This expectation is confirmed by the present modeling (note that the level of asymmetry of the modeled Uranian magnetopause is greater than the observed asymmetry of Saturn's magnetopause [Masters et al., 2012]; see Figure 2f). Differing solar wind conditions also lead to the expectation that the fraction of the dayside magnetopause surface where the adjacent magnetosheath flow is sub-Alfvénic should be smaller at Uranus than at Earth, which is also confirmed by the present modeling, and which should lead to more severe flow shear-related suppression of reconnection at Uranus. Another potential implication is the possibility that PDL level (see section 2.1) may be lower at such a high upstream Alfvén Mach number (~ 23) [Bagenal et al., 1987; Farrugia et al., 1995, 1997]. While we presently have

no observational evidence for this, we note that any reduction in PDL level would act to exaggerate the Earth-Uranus differences discussed here.

Related to the discussion in this subsection, we remind the reader that when applying the flow shear condition in all our Uranus reconnection assessments we assume that reconnection site motion has no projection onto the outflow direction. A nonzero projection could decrease the flow shear in the outflow direction in the reconnection site rest frame, potentially preventing flow shear suppression (e.g., see the discussion in *Petrinec et al.* [2003]). We make this assumption because the diamagnetic drift condition has passed observational tests at the time of writing [*Phan et al.*, 2010, 2013]. Since the physics underlying this condition involves the advection of the reconnection site at the local electron diamagnetic drift velocity [*Swisdak et al.*, 2003], the successful tests of the condition to date can also be regarded as successful tests of this expected reconnection site motion (under steady boundary conditions). In the case of Uranus' magnetopause, solar wind conditions mean that the diamagnetic drift condition is only satisfied where magnetic fields are close to antiparallel, and thus where the electron diamagnetic drift velocity is roughly perpendicular to reconnection outflow. Reconnection site motion is therefore not expected to significantly affect the flow shear in the outflow direction in the reconnection site rest frame, and so we apply the diamagnetic drift and flow shear conditions independently. However, it is important to point out that even if we consider the full range of potential reconnection site motion in our modeling (and all subsequent implications) this does not affect the high-level conclusions drawn in this paper.

Our modeling thus suggests that typical conditions at Uranus' magnetopause are likely to be less favorable for magnetic reconnection than those at any planetary magnetopause located closer to the Sun (e.g., Earth's magnetopause). Solar wind variability (e.g., related to the solar cycle) will perturb the nominal situation addressed in this paper, occasionally making conditions more favorable for magnetopause reconnection and occasionally making them less favorable.

4.2. Seasonal Effects

In section 3 we compared the magnetopause reconnection assessments at solstice and at equinox and noted that the regions on the modeled Uranian magnetopause where reconnection is not prohibited appear to be more restricted at equinox. We also noted that at solstice the regions of the magnetopause where reconnection is not prohibited appear to vary in a roughly similar fashion (over a planetary rotation) for both the dominant IMF orientations (Figures 5e–5l), whereas at equinox one of the polarities appears to be more favorable for dayside reconnection than the other (Figures 7e–7l).

Figure 8 shows the results of a more detailed examination of this apparent seasonal effect. Figures 8a and 8b apply to northern winter solstice (cf. Figures 4 and 5) and show how both the magnetic shear across the subsolar point on the model magnetopause surface and the percentage of the model (dayside) surface area where reconnection is not prohibited vary during a planetary rotation, for each of the dominant IMF orientations. Figures 8c and 8d show the equivalent plots for northern spring equinox (cf. Figures 6 and 7). At solstice there is no clear difference between the dominant IMF polarities. However, at equinox one polarity produces significantly lower magnetic shears in the subsolar region than the other and thus also produces a much lower percentage area where reconnection is not prohibited. Even in the case of the more reconnection-favorable dominant IMF polarity at equinox the percentage area where reconnection is not prohibited still does not reach the same maximum value as either of the dominant IMF polarities in the solstice case.

The physical origin of this predicted seasonal effect is the different ranges of possible dipole moment axis orientations. At solstice the cusp-like magnetospheric field features approximately cycle around the Uranus-Sun line, producing a 360° rotation of the magnetospheric magnetic field next to the subsolar magnetopause during one planetary rotation. Whereas at equinox the cusp-like magnetic features approximately rotate around the direction of Uranus' orbital velocity vector, likely often leading to only one dayside cusp, and making the magnetospheric magnetic field next to the subsolar magnetopause rotate over a more limited range during a planetary rotation (Figure 8c). This produces the apparent seasonal difference in the nature of magnetopause reconnection.

This examination implies that conditions at equinox are less favorable for dayside magnetopause reconnection than those at solstice. Assuming that both dominant IMF orientations are equally likely, we thus

Figure 8. An assessment of seasonal influences on reconnection at Uranus' magnetopause. (a) Variation of the magnetic shear across the magnetopause subsolar point over a Uranus day, at northern winter solstice. (b) Variation of the percentage of the dayside magnetopause surface area where reconnection onset is not prohibited over a Uranus day, at northern winter solstice. (c) Variation of the magnetic shear across the magnetopause subsolar point over a Uranus day, at northern spring equinox. (d) Variation of the percentage of the dayside magnetopause surface area where reconnection onset is not prohibited over a Uranus day, at northern spring equinox. Above Figures 8a and 8c the planetary rotation and magnetic dipole axes are shown (black and red respectively, both with length $2 R_U$), projected onto the planet as viewed from along the upstream solar wind flow direction. The axes are shown at 90° increments of planetary rotation phase. In all panels the variation for a fixed IMF parallel to the y axis is shown in pink and the variation for a fixed IMF antiparallel to the y axis is shown in green.

suggest that solar wind–magnetosphere coupling via reconnection may be more efficient under solstice conditions than under equinox conditions.

To explain the 2011 HST observations of Uranus' aurora, Cowley [2013] proposed a conceptual picture of open magnetic flux tube evolution in Uranus's magnetosphere under near-equinox conditions. We can test the magnetopause reconnection aspects of this concept with our model. Cowley [2013] invokes dayside magnetopause reconnection when the IMF is northward and the planet's dipole moment axis is approximately in the yz plane (of our model coordinate system) and pointing northward and also when the IMF is southward and the planet's dipole moment axis is approximately in the yz plane and pointing southward. These situations correspond to the reconnection assessments shown in Figures 7p and 7b, respectively, which support the magnetopause reconnection aspects of the concept, and suggest that reconnection occurs away from the subsolar region in both cases. We refer the reader to Cowley [2013] for a detailed discussion of open flux cycling through Uranus' magnetosphere at equinox.

4.3. Reconnection Electric Fields and the Reconnection Voltage

Constraining the component of the convective electric field tangential to Uranus' magnetopause current sheet that results from the onset of reconnection (the reconnection electric field, often referred to as the reconnection rate) is one of the keys to understanding how the solar wind interacts with the system, since this quantity tells us the rate at which magnetic flux enters the reconnection site, and is thus related to the overall rates of open magnetic flux production and energy release. In the case of our modeling, the strength of this tangential electric field, E , can be calculated as

$$E = 2k \left(\frac{B_{\text{msh}} B_{\text{msp}}}{B_{\text{msh}} + B_{\text{msp}}} \right) \left(\frac{B_{\text{msh}}^2 + B_{\text{msh}} B_{\text{msp}}}{\rho_{\text{msh}} \mu_0} \right)^{1/2} \quad (6)$$

where k is the dimensionless reconnection efficiency and the notation is otherwise the same as that used in equation (5) [Cassak and Shay, 2007]. For any of our reconnection assessments we can calculate this electric field strength at any point where reconnection is not prohibited, assuming that reconnection onset occurs at that point and assuming some value for the reconnection efficiency.

Figure 9. An assessment of the reconnection electric field strength at Uranus' magnetopause. A specific set of conditions is considered (shown in Figures 4c and 5c), corresponding to northern winter solstice. The circle to the left of the main panel shows the upstream IMF orientation, by projecting an IMF vector with length $2 R_U$ onto the planet, as viewed from along the upstream solar wind flow direction. The circle above the main panel similarly shows the orientation of the planetary rotation and magnetic dipole axes, in black and red, respectively. In the main panel the dayside magnetopause is shown as also viewed along the upstream solar wind flow direction, the circle centered on the origin represents the planet, and the dashed contour bounds the region where the local magnetosheath flow is sub-Alfvénic. The color scale indicates what the ratio of the reconnection electric field strength to the dimensionless reconnection efficiency would be if onset were to occur. Color is only applied to regions of the surface where both reconnection onset conditions are satisfied (see Figure 5c).

Figure 9 shows an assessment of the reconnection electric field strength at Uranus' magnetopause for conditions that correspond to northern winter solstice, southward IMF, and a planetary dipole moment axis that lies in the xz plane and also points southward. This case has already been presented in Figures 4c and 5c and is the combination of Uranus season, IMF orientation, and Uranus longitude when reconnection is not prohibited over the largest fraction of the model magnetopause surface, compared to all other parameter combinations considered in this study. The color scale shows the ratio of the reconnection electric field strength to the reconnection efficiency, given by a simple manipulation of equation (6).

The reconnection efficiency is difficult to measure in situ (see the recent reviews by *Fuselier and Lewis* [2011] and *Paschmann et al.* [2013]). A canonical value of 0.1 is often assumed for the case of reconnection in near-Earth space, but many authors have suggested, argued, and presented evidence that this efficiency is parameter dependent [Sonnerup, 1970; Slavin and Holzer, 1979; Anderson et al., 1997; DiBraccio et al., 2013]. The implication of this previous work is that the efficiency of reconnection at Uranus' magnetopause may be considerably lower than 0.1, because of the high magnetosheath plasma β and low magnetosheath Alfvén speed at Uranus compared to conditions at the terrestrial magnetopause. From Figure 9, we can see that the canonical efficiency of 0.1 would suggest a typical reconnection electric field strength at Uranus' magnetopause of 0.03 mV m^{-1} , whereas a lower value of 0.01 would suggest a typical value of 0.003 mV m^{-1} .

Magnetosheath variability, and particularly mirror mode structures, may have a significant effect on the typical reconnection electric field strength at Uranus' magnetopause. In the magnetosheath region adjacent to a planetary magnetopause mirror modes generally manifest as significant local reductions of the magnetic field strength and enhancements of the plasma density, and they are expected to be more prevalent in high- β planetary magnetosheaths, like that surrounding the Uranian magnetosphere [Bagenal et al., 1987; Soucek et al., 2008; Richardson, 2002; Masters et al., 2014a]. Note that even if the near-magnetopause magnetosheath is stable to the mirror instability, mirror mode structures can still form in the more distant (mirror unstable) magnetosheath and be convected by the flow to the (mirror stable) environment adjacent to the magnetopause [e.g., Soucek et al., 2008]. Parameter variations related to such magnetosheath phenomena can potentially cause significant reductions in the electric field strength associated with magnetopause reconnection [Phan et al., 2013; Masters et al., 2014b].

Our modeling allows us to make some statement about the reconnection voltage applied to Uranus' magnetosphere. This is the potential difference between the two ends of a line on the magnetopause surface where reconnection occurs at all points (a reconnection "X line"). To place an upper limit on the reconnection voltage applied to the system, we can consider the most favorable parameter combination for magnetopause reconnection, shown in Figure 9, and assume a $50 R_U$ long X line spanning the dayside magnetopause (through the colored region of Figure 9 where reconnection is not prohibited). If we take the

reconnection efficiency as 0.1 and then assume that a typical electric field strength of 0.03 mV m^{-1} applies to all points on the X line, then this results in an upper limit of $\sim 40 \text{ kV}$. The true, typical reconnection voltage applied to Uranus' magnetopause is likely to be considerably less than this. Note that reducing the reconnection efficiency to 0.01 lowers this voltage to $\sim 4 \text{ kV}$.

5. Summary

In this study we have used a combination of analytical models to assess the operation of magnetic reconnection at Uranus' magnetopause. Based on the modeling results we propose that conditions are generally less favorable for reconnection at Uranus' magnetopause than at the magnetopause boundary of any of the magnetized planets closer to the Sun, as a result of how typical solar wind conditions vary with heliocentric distance. This should lead to generally more severe suppression of reconnection onset due to a combination of diamagnetic drift and flow shear effects, and a weaker reconnection electric field when onset does occur. We also conclude that the location of reconnection sites on the Uranian magnetopause is highly dynamic and dependent on not only the IMF orientation but also planetary longitude and season. We suggest that the coupling between the solar wind and Uranus' magnetosphere via magnetic reconnection may be stronger under solstice conditions than under equinox conditions and that the typical reconnection voltage applied to the Uranian magnetosphere is likely to be considerably below an approximate upper limit of 40 kV .

Our understanding of magnetic reconnection at Uranus' magnetopause remains in its infancy. Advances in our understanding of how reconnection works under high plasma- β conditions in particular could have a significant impact on this topic and require us to question the conclusions drawn and suggestions made in the present study. Similar assessment of the viscous-like interaction between the solar wind and Uranus' magnetosphere, assessment of interactions mediated by other processes, and assessment of the impact of rapid changes in magnetospheric scale driven by the solar wind, all should also lead to further progress in understanding the coupling between the solar wind and the system. Establishing the relative importance of solar wind coupling via magnetic reconnection as a driver of Uranian magnetospheric dynamics requires such future work. Ultimately, further spacecraft exploration is needed to test our predictions and expectations about how this unique magnetosphere works [e.g., Arridge *et al.*, 2012].

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