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The role of magnetospheric plasma in solar wind-magnetosphere coupling: A review

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ABSTRACT

A variety of magnetospheric plasma populations have been proposed to impact solar wind-magnetosphere coupling. These magnetospheric populations could mass load the dayside magnetopause and include the plasmaspheric plume, plasma cloak, ion plasma sheet, and dayside ion outflow. Each has different densities, ion composition, and spatial/temporal occurrences at the dayside magnetopause which may coupling in different ways. These properties are reviewed as well as proposed mechanisms for impacting wave formation and magnetic reconnection. Broader discussion on control of solar wind-magnetosphere coupling governed by through local boundary physics or through the driving of the solar wind (local versus global control) is also considered.

1. Introduction

A central objective of heliophysics is understanding the connection between the Earth's magnetosphere and the Sun, specifically energy input and what causes geomagnetic disturbances. Initially a study primarily of correlations between the parameters in the solar wind and ground-based geomagnetic indices, a physical understanding gradually developed. Parameters in the solar wind go on to impact the conditions within the magnetosheath, which in turn contact the dayside magnetopause. The direction and strength of the magnetic field vector as well as plasma parameters in the magnetosheath can vary dramatically and have been demonstrated to impact the occurrence and efficiency of solar wind-magnetosphere coupling (Burton et al., 1975; Crooker et al., 1977; Perreault and Akasofu, 1978; Scurry and Russell, 1991; Newell et al., 2007; McPherron et al., 2015).

On the magnetosphere side of the magnetopause boundary the parameters can also vary. The magnetic field is dominated by the Earth's compressed dipole field (typical subsolar magnitude $\sim$ 45 nT) and can vary by a factor of 2 or 3 with the direction remaining relatively constant. The plasma populations contacting the dayside magnetopause however can change dramatically with number density varying orders of magnitude from 0.1 cm^{-3} to 100 cm^{-3}. Fig. 1 (panels (a) and (b)) presents the varying conditions on both sides of the magnetopause from 1184 dayside boundary crossings from the THEMIS mission and used in Walsh et al. (2013). These values correspond to a period near solar minimum (2008–2010). Although there is general consensus in the community that parameters in the solar wind will impact the occurrence and efficiency of solar wind-magnetosphere coupling, the role of the space environment on the magnetosphere-side in coupling is less clear. This paper reviews past studies investigating the role of the magnetosphere in solar wind-magnetosphere coupling and outlines paths forward.

2. Magnetospheric plasma

A variety of transport paths may bring dense plasma to the dayside magnetopause. These include the plasmaspheric plume (Elphic et al., 1996; Su et al., 2000; Borovsky and Denton, 2006; Moldwin et al., 2016; André, 2020), plasma cloak (Giles et al., 1994; Chappell et al., 2008; Borovsky et al., 2013), direct ion outflow from the ionosphere (Yau and André, 1997; Matsui et al., 1999; Lee et al., 2016), as well as plasma sheet ions that are transported to the dayside (Borovsky et al., 2013). A visual summary of these plasma populations, their energies, and their path ways is presented in Fig. 2. The transport mechanism will impact the plasma composition, density, and spatial extent at the magnetopause. Each of these in turn impact solar wind-magnetosphere coupling. It is noted that Fig. 2 is formed using simplified electric and magnetic fields. In reality turbulent and time-variable fields exist (Borovsky et al., 1997) which will cause more complicated and overlapping distributions. A summary of measurements from these populations distributed

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spatially at the dayside magnetopause is shown in Fig. 3. The measurements from the Cluster mission demonstrate large variation in number density with values up to 100 cm^{-3}. Two forms of coupling which have been proposed to be impacted by magnetospheric plasma are considered here, boundary waves, and magnetic reconnection.

3. Boundary waves

The primary wave that has been proposed to be influenced by magnetospheric plasma is Kelvin-Helmholtz (KH). KH waves occur at boundaries such as the Earth's magnetopause where a velocity shear is present. These waves have been commonly observed under a variety of magnetic field and plasma conditions in the solar wind (Li et al., 2012; Kavosi and Raeder, 2015; Henry et al., 2017). The non-linear instability drives dynamics on a variety of spatial scales, causing reconnection and plasma and mass transfer on the ion-gyroradius scale (Ma et al., 2014; Eriksson et al., 2016) as well as ULF waves launching from the magnetopause and propagating throughout much of the magnetosphere. Such ULF waves can drift resonate with energetic electrons within the Earth's radiation belt and cause acceleration (Claudepierre et al., 2008; Murphy et al., 2015).

In a magnetized plasma, the growth of the KH instability is favorable when the magnetic field vector is perpendicular to the flow direction and the difference in velocity between the two sides of the boundary is greater than the local Alfvén velocity (Chandrasekhar, 1961). Although there is typically little bulk flow on the magnetosphere-side of the magnetopause boundary in comparison to the magnetosheath, the mass density can vary significantly and therefore change the local Alfvén speed. If the local Alfvén speed decreases, the instability threshold can be met with a lower velocity shear. This means during periods of heavy magnetospheric mass loading, KH waves could occur closer to the nose of the magnetopause where magnetosheath bulk flows are lower. For nominal conditions in the magnetosheath and a typical density of 0.2 cm^{-3} in the magnetosphere, the boundary would be KH unstable where the velocity shear is $\sim$ 200 km/s or near the terminator. If magnetospheric mass loading brings the density up to 10 cm^{-3} during a geomagnetic storm the boundary would be KH unstable with a magnetosheath velocity of just 45 km/s which can commonly be observed near the nose of the magnetosphere (Dimmock and Nykyri, 2013; Walsh et al., 2012). In-situ spacecraft measurements as well as MHD modeling have shown this mass-loading effect (Walsh et al., 2015; Welling and Walsh, 2018).

4. Magnetic reconnection

Magnetic reconnection is the primary mechanism for the transport of energy from the solar wind into the Earth's magnetosphere. Parameters within the solar wind as well as the magnetosphere have been proposed to impact dayside magnetosphere coupling in a number of ways.

On small scales, mass loading a reconnecting boundary can impact plasma heating. Observations (Phan et al., 2013) as well as numerical simulations (Dargent et al., 2020) have reported heating to scale with the local hybrid Alfvén speed which is linked to the mass density and magnetic field strength on both sides of the boundary (Cassak and Shay, 2007). Increased mass density from magnetospheric mass loading would result in less heating. Ths introduction of a separate distribution with a new scale length (Toledo-Redondo et al., 2015; Divin et al., 2016) may also impact other features of reconnection such as current generation (André et al., 2016).

4.1. *Reconnection efficiency*

On large scales, mass loading a reconnecting boundary may also impact the global reconnection rate. Global reconnection integrated over the dayside magnetopause is a measure of the total energy being deposited into the magnetosphere. This may or may not be influenced by magnetospheric plasma. Although significant effort has been applied to understanding the role of magnetospheric plasma, observational and modeling challenges linked to the global nature of the problem and disparate plasma populations have limited progress.

The underpinnings of this problem come from theory (Cassak and Shay, 2007) and modeling (Borovsky and Hesse, 2007; Malakit et al., 2010) which have found the efficiency of reconnection to be dependent on the local hybrid Alfvén speed. In a simple view of the problem, as magnetospheric mass density can increase significantly along the dayside magnetopause, the increased density will decrease the local Alfvén speed and therefore decrease the integrated reconnection rate. On a broader scale the global nature of the problem and the associated feedback mechanisms within the interconnected magnetosphere/ionosphere system make the problem more challenging. Studies have concluded impact from the magnetosphere to span a wide spectrum of possibilities from playing a significant roll to none at all.

4.2. *Plasmaspheric plume*

The most commonly studied feature proposed to impact coupling is material from the plasmasphere or a plasmaspheric plume (Borovsky and Denton, 2006, 2008; McFadden et al., 2008; Walsh et al., 2014a; Wang et al., 2016). A plasmaspheric plume is composed of cold plasma ($\sim$ 5 eV and below) and has a number density at the magnetopause from 10's up to 100 cm^{-3} (Chandler and Moore, 2003; André and Cully, 2012). It is primarily composed of H+ with some He+ ($\sim$ 30%) and small amounts of O+ ($\sim$ 1%) (Horwitz et al., 1986; Berube et al., 2005). Spatially the structure is driven from the inner-magnetosphere by

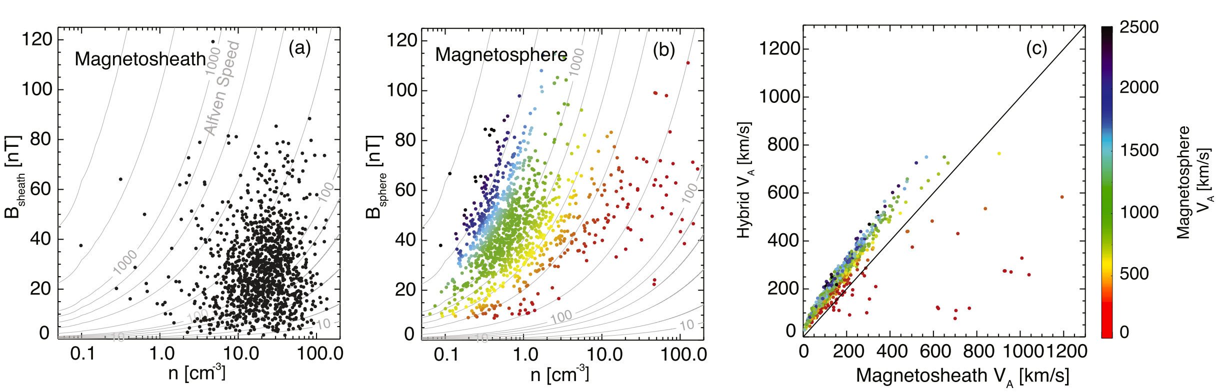

Fig. 1. Parameters just outside (left panel) and just inside (middle panel) the magnetopause for 1184 dayside boundary crossings by the THEMIS mission used in Walsh et al. (2013). In the middle panel and right panels the points are colored by the magnetosphere Alfvén speed. The gray contours on the left and middle panels present the local Alfvén speed. The right panel presents the hybrid Alfvén speed incorporating both sides of the boundary versus the Alfvén speed in just the magnetosheath.

magnetospheric convection and extends sunward from the plasmasphere through $E \times B$ drifts (Chappell, 1974; Lambour et al., 1997; Goldstein and Sandel, 2005). Early in a storm a plume can extend over a wide local time but then narrows and typically only exists over several hours in local time in the dusk sector at the magnetopause (Chen and Moore, 2006; Borovsky and Denton, 2008; Walsh et al., 2013).

With a significant increase in density over nominal conditions, the structure has been proposed to impact reconnection. Simultaneous multi-point measurements along the magnetopause, where one spacecraft probed reconnection in the presence of a dense plasmaspheric plume (n~ 50 cm^{-3}) while a second spacecraft measured reconnection with nominal magnetospheric conditions (n~ 0.4 cm^{-3}), found a clear reduction in local reconnection with the dense plume present (Walsh et al., 2014b). Consistent with this finding, MHD (Borovsky et al., 2008; Ouellette et al., 2016) as well as kinetic (Dargent et al., 2020) numerical simulations of reconnection with and without a plume present have also noted a reduction in the magnetopause reconnection rate due to the inclusion of the dense plume.

Although a number of studies have found the efficiency of reconnection to decrease locally in the presence of the plume, others have noted the reconnection rate will increase in adjacent areas where the plume is not present (Lopez et al., 2010; Ouellette et al., 2016). In such a scenario a field line in the magnetosheath that does not reconnect at the local time where the plume is present will simply flow to an adjacent part of the boundary where it can reconnect. In this model the net effect of a dense spatially localized plume on global solar wind-magnetosphere coupling would be minimal. Reconnection decreases at one place but increases elsewhere.

A challenge in understanding the actual role of a plasmaspheric plume is knowledge of the spatial extent and density of a plume at the magnetopause. Observationally, there are challenges in measuring cold densities accurately. Currently many of our measurements are inferred values rather than actual particle measurements. It is also challenging to accurately study structures with scale sizes of several Earth radii using just individual spacecraft. On the modeling front, although there has been progress in coupling a plasmasphere model into a global MHD model (Ouellette et al., 2016; Welling and Walsh, 2018), models are still limited in their ability to accurately predict plume and cold plasma dynamics. An additional feature that has not been fully considered is the clumpy nature of the density structures in a plume (Moldwin et al., 1995; Darrouzet et al., 2004; Borovsky and Denton, 2008) which will introduce a time variable feature and may or may not impact coupling.

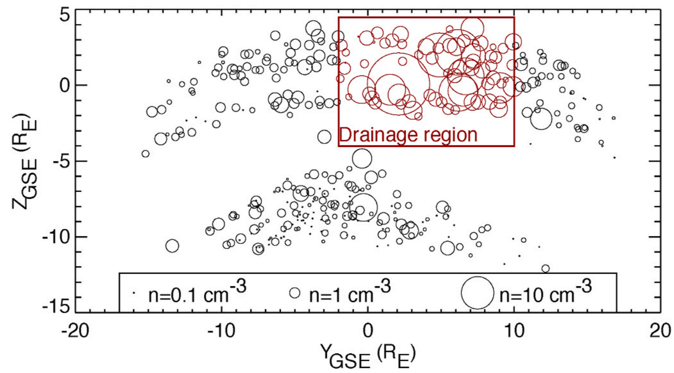

Fig. 3. Plasma density measured at the dayside magnetopause from the Cluster spacecraft from December 2006 through July 2009 (370 crossings). The drainage region highlighted corresponds the typical spatial region of the plasmaspheric plume. Adapted from André and Cully (2012).

4.3. Plasma cloak

Outflowing ions from the high-latitude ionosphere into the nightside plasma sheet that $E \times B$ drift to the dayside form the plasma cloak population. This population has typical energies of 10's to 100's of eV and densities in the outer-magnetosphere of 1–3 cm^{-3} (Chappell et al., 2008). Although the number density is lower than that in a plasmaspheric plume, the population has a rich contribution of heavy ions with O+ and H+ comprising roughly 50% each (Nosé et al., 2011). Similar to a plasmaspheric plume, the density is enhanced during periods of geomagnetic disturbances. The population can extend over a wide local time across the dayside magnetopause outside the plume (Nagai et al., 1983; Walsh et al., 2020).

The plasma cloak has also been proposed to impact reconnection. Global MHD modeling with inclusion of ion outflow into the tail and features of a plasma cloak found significant reduction in the polar cap potential linked to a reduction of dayside reconnection (Winglee et al., 2002). Winglee et al. (2002) found with the additional mass from the ionosphere input through ion outflow, and a fixed amount of momentum input to the magnetosphere, global convection and therefore dayside reconnection would be reduced. In-situ measurements (Wang et al., 2015) and modeling based on scaling arguments (Borovsky et al., 2013) predict this population could play the largest role of any magnetospheric populations. By contrast Fuselier et al. (2016) surveyed a number of magnetopause crossings in the dusk sector and found the density

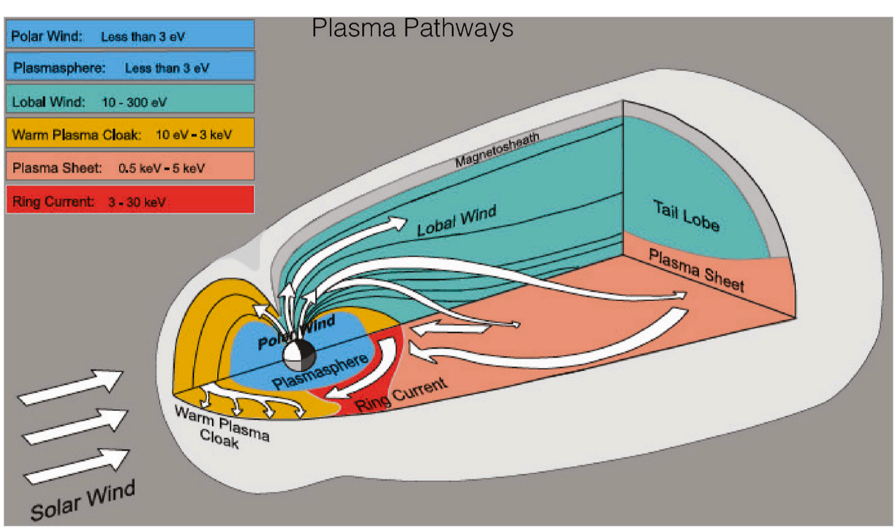

Fig. 2. Pathways of plasma through the magnetosphere and to the dayside magnetopause. Figure adapted from Chappell et al. (2008).

including heavy ions at the dayside magnetopause was not large enough to impact reconnection significantly. More measurements are needed to understand the global properties of this population in the outer-magnetosphere.

4.4. Ion outflow and ion plasma sheet

Direct ion outflow to the dayside magnetosphere can also mass load the magnetopause. Similar to the plasma cloak, this population is typically rich in O+ ions with a number density ~ 1 cm^{-3} and can occur along the entire dayside magnetopause (Lee et al., 2016). Temporally the population is often observed after periods of northward IMF (Fuselier et al., 2019). Global MHD modeling has found the role of dayside ion outflow to be highly dependant on the amount of outflow (Zhang et al., 2016, 2017). Similar to the plasma cloak, more measurements are needed to provide realistic bounds for modeling.

Lastly the ion plasma sheet has been proposed as a source of mass loading on the dayside magnetosphere. Ions from the plasma sheet drift to the dayside and can populate a wide local time with typical densities of 0.6 cm^{-3} (Korth et al., 1999; Denton et al., 2005, 2019). During quiet periods the plasma sheet is typically primarily H+ but during disturbed periods O+ can be an important constituent (Denton et al., 2005; Mouikis et al., 2010). This population has also been proposed to play a role in mass loading the magnetopause (Borovsky et al., 2008). Once again, the presence of the population is enhanced during periods of geomagnetic disturbances (Denton et al., 2019).

A comparison of many of the plasma populations described above is made by Borovsky et al. (2013). The study combined spacecraft measurements and scaling laws to estimate the role different magnetospheric populations may have on solar wind-magnetosphere coupling under different driving conditions. Values from Borovsky et al. (2013) are presented here in Table 1. During geomagnetic disturbances the different populations are predicted to reduce coupling by $\sim$ 10's of percent, a non-negligible amount.

4.5. Timing

One feature that must be considered in deciding on the role of magnetospheric plasma is timing. The most common state of the magnetosphere is quiet. When summing up all Kp over the past solar cycle or 11 years (2009–2020) the magnetosphere was in an excited state (Kp > 3) 11% of the time. A wealth of observations have shown that enhanced driving that will bring dense magnetospheric plasma to the dayside magnetopause occurs during geomagnetic disturbances (e.g. Chen and Moore, 2006; Darrouzet et al., 2008). During quiet times, it is less common to observe dense magnetospheric material at the magnetopause. Armed with this point, the argument has been made that at most, magnetospheric plasma can only play a minor role in solar wind magnetosphere coupling since it is commonly absent at the magnetopause. The counter-argument to this idea is to weigh time periods by a measure of importance. Although the most commonly occurring state of the magnetosphere and ionosphere is quiet, the most common time periods for space weather relevance and study system are disturbed times. During geomagnetic disturbances it is common to observe dense plasma at the magnetosphere, therefore it can play a more significant role.

Table 1
Estimated reduction in local and global magnetopause reconnection from different magnetosphere populations. Values reproduced from Borovsky et al. (2013). The bottom two rows correspond to the plasma cloak described in the current paper.

	Fractional Reduction of Local Reconnection Rate	Fractional Reduction of Length of X-line	Fractional Reduction of the total Dayside Reconnection Rate
Dayside ion plasmasheet	3.5%–15%	3.5%–15%	6.9%–28%
Plasmaspheric Plume	3%–45%	N/A	1%–22%
Ionospheric outflows into electron plasma sheet: low F10.7	2%–10%	2%–10%	5%–20%
Ionospheric outflows into electron plasma sheet: high F10.7	10%–40%	10%–40%	20%–60%

Recently work has also shown mass loading can occur for prolonged periods of time. If the magnetosphere remains in a disturbed state from prolonged driving a plasmaspheric plume can last for up to 15 days (Borovsky et al., 2014; Krall et al., 2018). In these studies the end of a plume is due to a decrease in magnetospheric convection rather than running out of plasma. Such an observation provides context for our models of refilling from the ionosphere and indicates plasma sources within the magnetosphere do not appear to “run dry.”

5. Local versus global control

Discussion of the role of magnetospheric plasma and local conditions in magnetopause reconnection is linked closely to the debate of local versus global control of solar wind-magnetosphere coupling. The global model is often referred to as the “Axford Conjecture” (Axford, 1984) (recently reviewed by Dorelli (2019)) and states that the rate of magnetic reconnection is determined by the external boundary conditions, and plasma conditions local to the diffusion region will adjust to accommodate the imposed rate. This means features inside the magnetosphere or in the diffusion region do not matter in determining the rate of solar wind-magnetosphere coupling. The Earth’s magnetosphere and its response are at the mercy of the solar wind’s motional electric field. Vasyliunas (1975) provided an early argument for a globally controlled system. The paper considered a system where a plasma flow was approaching a boundary faster than local conditions would allow the reconnection to proceed. If the magnetic field lines could not reconnect, they would pile up at the boundary and increase the local Alfvén speed. With an increased Alfvén speed, the reconnection rate would then increase and accommodate the driving of the global system, or solar wind in the case of the Earth’s magnetosphere. In a 2D system, this model works well, but the flow patterns in a 3D magnetosheath make the problem more complicated where similar pile up may or may not occur.

In contrast to the global control model, the local plasma conditions may control coupling. In 3D, magnetic field lines in the magnetosheath and incident on the magnetopause may not pile up sufficiently. Magnetosheath flow patterns could sweep the magnetic flux downtail without reconnecting, thus prohibiting the plasma conditions from adjusting to accommodate the solar wind electric field. Borovsky and Birn (2014) extended the work of Borovsky et al. (2008) and provided a model that argued the local conditions at the magnetopause boundary are what determine the rate of solar wind-magnetosphere coupling (local control). One piece of evidence used in the paper is a comparison of different parameters to predict coupling. Coupling functions which included the magnetospheric state and plasma did a better job predicting solar wind-magnetosphere coupling than functions which only included solar wind parameters. The argument is also made that the 3D flow in the magnetosheath changes the system and the electric field incident at the magnetopause is not linked to the motional electric field in the solar wind. The mismatch of electric field at the boundary has also been shown in simulations (Birn and Hesse, 2007) as well as experimentally through comparisons of statistical measurements of the electric field in the magnetosheath and solar wind (Pulkkinen et al., 2016).

Lopez (2016) analyzed flow in the Earth’s magnetohseath through global MHD simulations and found the geoeffectic length or the length of the reconnecting region to be a critical element in this problem. The study provided a modified version of the Axford Conjecture stating "At the Earth, the integrated dayside merging rate is controlled primarily by the solar wind conditions that determine how much magnetic flux per unit time is brought to and transferred across the dayside merging line by the magnetosheath flow." Here the flow pattern is the element emphasized. The flow controls the spatial extent of the solar wind which maps to the magnetopause separator in order to reconnect. This length in the solar wind is the geoeffective length and is the critical element in determining coupling rather than simply the length of the separator at the dayside magnetopause. Although modifying the Axford Conjecture to some extent, the model still under most conditions supports a global control of solar wind magnetosphere coupling.

The approach from Lopez (2016) also provides an explanation for periods of strong driving when the magnetosphere appears to saturate in response to solar wind driving. When the magnetic field in the magnetosheath is large, such as during a coronal mass ejection, the $\vec{J} x \vec{B}$ force dominates and controls the flow pattern as opposed to typical solar wind conditions when gradient forces ($\vec{\nabla} P$) dominate (Lopez et al., 2010). This modified flow pattern limits the amount of magnetic flux that reaches the magnetopause to reconnect and results in an apparent saturation.

Global MHD simulations by Zhang et al. (2016) and Zhang et al. (2017) used variable ion outflow to probe the problem of global versus local control. The studies found both global and local models to be active. With small amounts of mass loading at the dayside magnetopause, the magnetosheath adjusts to accommodate and the increased mass density does not change the solar wind-magnetosphere coupling (global control). As the mass density is increased further, the magnetosheath adjustments can not keep up, and the integrated reconnection rate decreases (local control). Fig. 4 presents a measure of the total reconnection potential as a function of mass loading. The left panel presents outflow over the full dayside while the right side models outflow only in the dusk sector, similar to a plume. The authors argue for a bimodel system where the solar wind electric field and global driving control the system for small amounts of magnetospheric plasma, but the local parameters control the system for significant amounts of plasma inside the Earth's magnetosphere.

The right panel (panel (c)) of Fig. 1 presents spacecraft measurements from the THEMIS mission which may support this bimodal approach. The figure compares the hybrid Alfvén speed with the Alfvén speed in the magnetosheath just outside the boundary. The points are colored by the Alfvén speed inside the magnetosphere. Since the magnetic field inside the magnetosphere verys little in comparison to the density, the density is a significant driver of the magnetospheric Alfvén speed. For a broad range of magnetospheric Alfvén speeds, the hybrid Alfvén speed scales well with the Alfvén speed in the magnetosheath, indicating the magnetosheath parameters may be adjusting to accommodate the solar wind driving and state of the magnetosphere (global control). During magnetopause crossing with significant magnetospheric mass loading ($\sim >$10 cm^{-3}), the hybrid Alfvén speed is significantly less than the Alfvén speed in the magnetosheath. In this cluster of boundary crossings the magnetospheric plasma is dominating the hybrid Alfvén speed (local control).

6. Pressure balance

Another form of coupling between the solar wind and the magnetosphere is the position of the magnetopause boundary. The outer envelope of the magnetosphere is a discontinuity formed through a pressure balance between the shocked solar wind in the magnetosheath and the outer-magnetosphere. The pressure balance at the interface can be monitored by carefully calibrated spacecraft instrumentation (McFadden et al., 2008; Znatkova et al., 2011). A typical total pressure on both sides of the boundary is 1 nPa however this can vary by an order of magnitude due to driving on either side of the boundary. Statics from Shue and Chao (2013) present the average components contributing to the total pressure on the two sides of the boundary for more than 900 in-situ spacecraft crossings. Just outside the magnetopause, in the magnetosheath, the average ram, thermal, and magnetic pressures are 0.05, 0.68, and 0.32 nPa respectively. Just inside the magnetopause, within the magnetosphere, the ram pressure is negligible while the thermal and magnetic pressures are 0.89 and 0.11 nPa respectively.

The different magnetospheric particle populations will provide different contributions to the thermal pressure component. A plume contacting the boundary could introduce a population with a number density ranging from 1 to 100 cm^{-3}, and a typically temperature of 0.2–2 eV. The thermal pressure contribution from this feature is 3×10^{-5} - 0.03 nPa. A similar calculation can be done for the warm plasma cloak which can have similar mass densities as the plume but extend across a wide region. The cloak population has a typical density from 1 to 3 cm^{-3} and temperatures of 10–100 eV, resulting in a thermal pressure contribution of 2×10^{-3} - 0.05 nPa. Lastly, plasma from the ion plasma sheet has typical densities 1 - 3 cm^{-3} and temperatures of 500 eV - 3 keV (Wang et al., 2012). These values result in thermal pressures ranging from 0.08 to 1.4 nPa. In the case of plume and cloak populations, the thermal pressure contribution is small in relation to the typical magnetic pressure (0.89 nPa). In the magnetopause crossings with plasmaspheric plumes presented in Fig. 1 the maximum

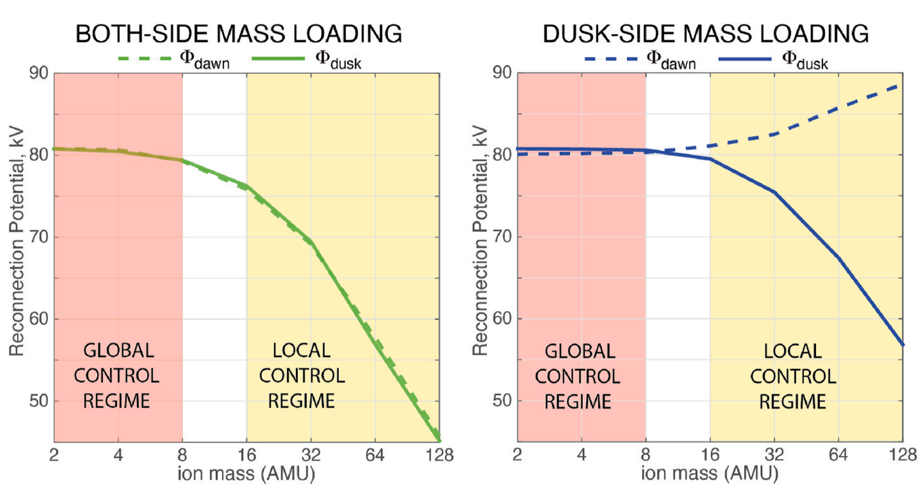

Fig. 4. Integrated reconnection as a function of mass loading from global MHD simulations. For small amounts of mass loading global parameters dominate coupling while local parameters at the reconnection site dominate for large amounts of mass loading. *Left* - Massloading on both the dawn and dusk sides of the magnetopause. *Right* - Mass loading only on the dusk side of the magnetopause (simulating a plume). Figure adapted from Zhang et al. (2016).

contribution a plume provided to the total pressure is just 6%. At some times, the thermal pressure from a population originating from the ion plasma sheet however can have significant contributions to the total pressure.

7. Looking forward

Several areas of progress could significantly advance our understanding and predictive ability. These include improved instrumentation for cold plasma measurements, global imaging, and multipoint measurements. Due to the challenges of a charged sunlit spacecraft, very few measurement systems have flown in space with the ability to make reliable cold plasma and composition measurements. Inferred measurements of electron density show that there is a significant amount of mass and momentum below several eV in the outer-magnetosphere (Escoubet et al., 1997; André and Cully, 2012; Lee and Angelopoulos, 2014) that is being missed from current particle detectors. As most charged particle detectors do not have the ability to observe these populations under most conditions, we are unable to measure their impact.

Questions such as how does magnetosheath flow develop during a geomagnetic storm or how wide is a plasmaspheric plume at the magnetopause are macroscale problems that can not be answered by single or small constellations of in-situ measurements. Adopting broader imaging systems and analysis techniques, similar to other research communities, has significant potential. Techniques such as EUV imaging of the plasmasphere (Sandel et al., 2001) have been shown to map global dynamics in ways unobtainable from individual spacecraft measurements. Use of soft X-ray imaging to map the shape and dynamics of the dayside magnetopause in response to varying magnetospheric plasma populations and magnetosheath flow could also provide major progress (Kuntz et al., 2015; Sibeck et al., 2018; Walsh et al., 2016).

Lastly, larger spacecraft constellations with broader spatial coverage could significantly advance our understanding. Although focused constellations of several spacecraft have flown such as MMS (Burch et al., 2016), THEMIS (Angelopoulos, 2009), and Cluster (Escoubet et al., 2001), the spatial separations have not permitted study of global properties. With the development of lower cost small spacecraft platforms, larger constellations can be adopted to provide global context (Fennell et al., 2000; Kepko, 2018). The path for such a mission has been paved by commercial companies that have decreased production costs in implementing large constellations over the past several years (Parham et al., 2019).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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