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Outstanding questions in magnetospheric plasma physics: The pollenzo view

Joseph E. Borovsky[a,*], Gian Luca Delzanno[c], Juan Alejandro Valdivia[b], Pablo S. Moya[b], Marina Stepanova[d], Joachim Birn[a], Lauren W. Blum[e], William Lotko[f], Michael Hesse[g,h]

[a] Center for Space Plasma Physics, Space Science Institute, Boulder, CO, USA
[b] Departmento de Fisica, Facultad de Ciencias, Universidad de Chile, Santiago, Chile
[c] Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM, USA
[d] Departmento de Fisica, Universidad de Santiago de Chile, Santiago, Chile
[e] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[f] High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, USA
[g] Space Plasma Physics Group, University of Bergen, Bergen, Norway
[h] Southwest Research Institute, San Antonio, TX, USA

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ABSTRACT

Based on discussions held at a workshop in Bra-Pollenzo, Italy, this paper elaborates upon 19 outstanding questions of plasma physics in the Earth's magnetosphere. The questions are grouped according to (a) driving processes, (b) radiation belt and ring current issues, (c) auroral physics, (d) internal plasma processes, and (e) magnetosphere-ionosphere mapping issues. Future needs for magnetospheric plasma physics (measurements, techniques, simulations, theories, studies) are outlined.

1. Introduction

The Earth's magnetosphere is a system of multiple, co-located particle populations interacting via plasma waves (Valdivia et al., 2005, 2013; Usanova and Shprits, 2017; Borovsky and Valdivia, 2018). The particle populations show great diversity from the ~0.5-eV H^+, He^+, and O^+ ions of the plasmasphere to the multi-MeV relativistic electrons of the high-energy tail of the radiation-belt distribution. A plot of the typical ranges of number densities and temperatures of some of these particle populations in and around the magnetosphere appear in Fig. 1. The magnetospheric plasmas show diverse spatial scales, from a Debye length of ~15 cm in the dense cold plasmasphere to the 1×10^8 cm gyroradii of MeV protons at geosynchronous orbit to a system size of greater than 1×10^{11} cm.

Ongoing plasma-physics processes in the Earth's magnetosphere include wave generation, wave dissipation, wave-particle interactions, the generation of field-aligned currents, Alfven-wave transmission-line processes, energy conversion, parallel electric fields, magnetic reconnection, time domain structures (double layers), transport, pitch-angle diffusion, energy diffusion, spatial diffusion, Coulomb collisions, radio-wave emission, kinetic instabilities, MHD instabilities, and MHD turbulence. These plasma-physics processes enable the Earth's magnetosphere to evolve in response to temporal changes in the solar wind and they underlie the phenomena of space weather, which impacts spacecraft systems, astronauts, radio communications, and ground based electric-power grids.

A 5-day workshop entitled "The Plasma Physics of the Magnetosphere" comprised of oral presentations and audience-participation discussions was held at Bra-Pollenzo, Italy June 2–7, 2019. A summary audience discussion on June 7 focused on the outstanding plasma-physics questions for the Earth's magnetosphere. This report is a summation of the outstanding questions of magnetospheric plasma physics arising during the 5-day workshop and summarized on June 7. The 19 outstanding questions addressed appear in Table 1.

In Section 2 of this paper 19 outstanding questions are discussed. Specific needs for the future to answer the 19 questions are summarized in Section 3. For similar writeups of outstanding questions in solar-wind plasma physics see Goldstein (2001) and Viall and Borovsky (2020).

* Corresponding author.
E-mail address: jborovsky@spacescience.org (J.E. Borovsky).

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2. The outstanding questions

Below, the 19 outstanding questions identified in the Bra-Pollenzo workshop are each briefly discussed. They are not ordered in terms of importance, rather they are grouped according to (a) driving processes (Questions 1–4), (b) radiation belt and ring current issues (Questions 5 and 6), (c) aurora (Questions 7–10), (d) internal plasma processes (Questions 11–17), and (e) magnetosphere-ionosphere-atmosphere issues (Questions 18 and 19).

2.1. How does the viscous interaction between the solar wind and the magnetosphere work?

The viscous interaction between the solar wind and the Earth's magnetosphere has been discussed for decades (e.g. Piddington, 1960; Axford and Hines, 1961), yet it is neither quantified nor understood, nor are its controlling factors known. The viscous interaction is believed to transport momentum and plasma across the magnetopause from the flowing magnetosheath into the magnetosphere. Evidence for the viscous interaction becomes clearest when the solar-wind magnetic field has very northward clock angles (when dayside reconnection should be very weak or nonexistent): that evidence is a residual geomagnetic activity when dayside reconnection should not be operating (Tsurutani and Gonzalez, 1995). This residual activity is shown in Fig. 2, where the 1-h-lagged AE index is plotted as a function of the clock angle of the solar-wind magnetic field with respect to the Earth's dipole field. Clock angles near 0° are northward and clock angles near 180° are southward. The residual activity of about 80 nT in AE seen in the 2000-pt running average (red points) for northward IMF is attributed to the viscous interaction, although that residual could be caused in part by reconnection between the solar wind and the magnetotail lobes (cf. Lockwood

Table 1
The 19 outstanding plasma-physics questions addressed in the Pollenzo workshop discussion.

#	Question
1	How does the viscous interaction between the solar wind and the magnetosphere work?
2	What determines when and where reconnection occurs? Under what conditions does it start? What causes it to stop?
3	Is magnetotail large-event reconnection a collection of small bursts?
4	How do we identify reconnection sites and separatrices in magnetotail spacecraft data and in auroral images?
5	What are the mechanisms and controlling factors for the loss of the radiation belts?
6	What is the spatial structure of the keV population of the ring current and what effects does this structuring have?
7	What is the cause of auroral arcs?
8	How is electromagnetic energy converted to particle energy in the aurora?
9	What plasma-physics processes are acting in the nightside downward-current regions when auroral signatures are not produced?
10	What determines the local-time distribution and the structuring of the diffuse and pulsating aurora?
11	What are the roles of Alfven waves in magnetospheric physics?
12	How does magnetotail turbulence affect the magnetosphere?
13	What is the impact of cold ions and electrons on the magnetospheric system?
14	How can we obtain more-accurate ion outflow rates?
15	What are the effects of time domain structures (double layers, etc.) on the particle populations of the magnetosphere?
16	What is the role of nonlinear wave-particle interactions?
17	Do we need a non-Maxwellian plasma physics?
18	How can the magnetic-field mapping be established so that magnetospheric plasma mechanisms and phenomena can be connected to ionospheric mechanisms and phenomena?
19	What is the impact of radiation-belt precipitation on atmospheric physics?

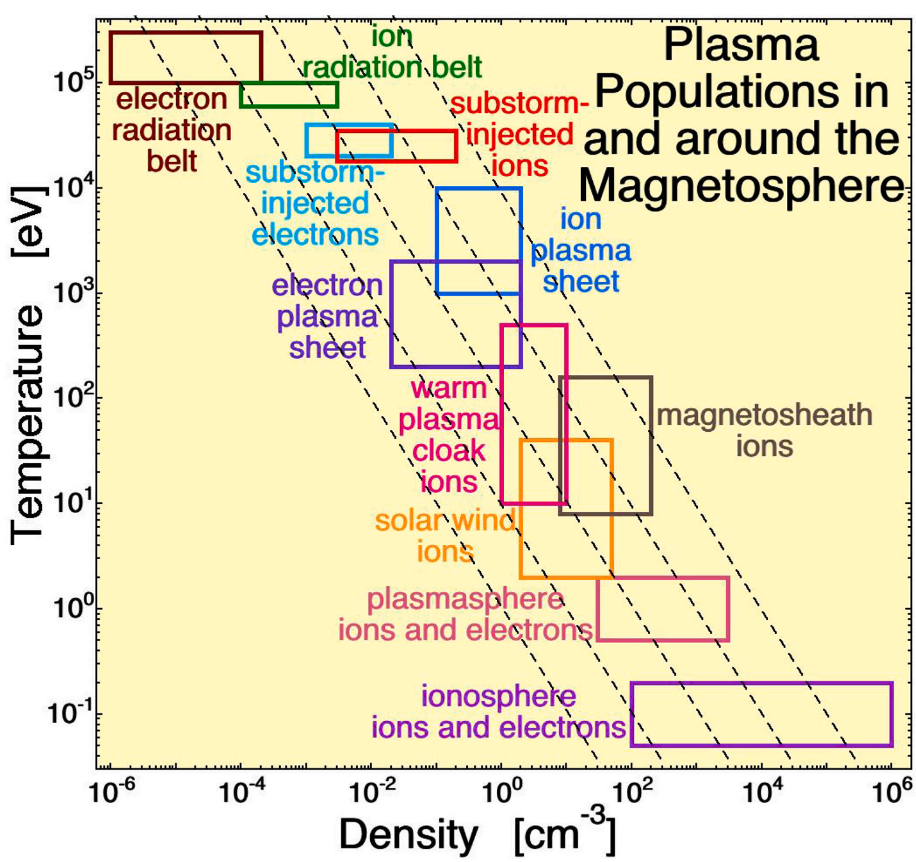

Fig. 1. A density-temperature map of some of the particle populations inside and around the Earth's magnetosphere. The black dashed curves are contours of equal energy density (pressure), with the curves being a factor of 10 apart.

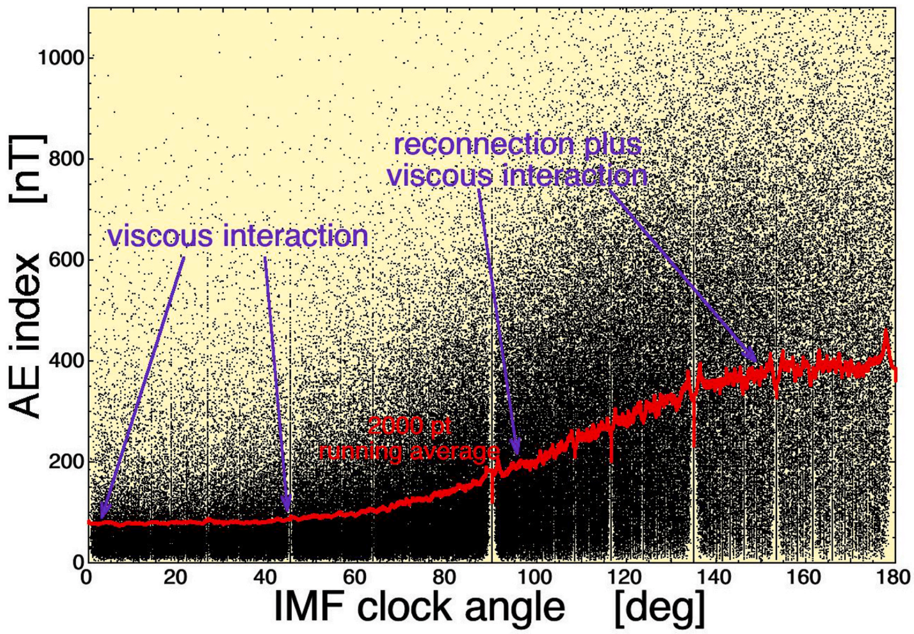

Fig. 2. Using 1-h-averaged values from the OMNI2 data set (King and Papitashvili, 2005), the 1-h-lagged AE index is plotted as a function of the (GSM) solar-wind clock angle for the years 1963–2014. Each black point represents 1-hr of data and the red points are 2000-pt running averages of the black points.

and Moen, 1999). There is also evidence for the viscous interaction in a measured electrical potential across the low-latitude boundary layer (LLBL) (Mozer, 1984; Lundin et al., 1995) and ionospheric signatures of this LLBL electrical potential (Drake et al., 2009). It is certain that the viscous contributions to geomagnetic activity and magnetospheric convection are small, however the viscous interaction may be important for the transport of solar-wind plasma into the magnetosphere.

For the mechanism of viscosity in a magnetized plasma, possibilities include Coulomb collisions (Braginskii, 1965), Bohm diffusion (Eviatar and Wolf, 1968; Borovsky, 2006), Landau damping (Borovsky and Gary, 2009), mass diffusion by plasma waves (Johnson and Cheng, 1997), and Kelvin-Helmholtz interactions (Nykyri and Otto, 2001). The two mechanisms most considered for the Earth are (1) plasma diffusion across the magnetopause mediated by plasma waves (Vasyliunas et al., 1982; Borovsky, 2013) and (2) large-scale Kelvin-Helmholtz waves on the magnetopause that exchange plasma parcels and that may lead to reconnection in the LLBL (Masson and Nykyri, 2018).

One phenomenon that seems to be part of the viscous interaction is the "freestream-turbulence effect" that the Earth exhibits, with geomagnetic activity increasing as the amplitude of fluctuations in the upstream solar wind increases, even under purely northward IMF (Borovsky and Funsten, 2003a; D'Amicis et al., 2007, 2011; Jankovicova et al., 2008; Osmane et al., 2015). For Navier-Stokes fluids the effect is explained as an enhanced eddy viscosity (Volino et al., 2003). For the solar wind, where the fluctuations do not seem to be evolving in time (Borovsky, 2020), this explanation might fail. Another possibility is the rippling of the pliant magnetopause by the solar wind fluctuations, enhancing the momentum transfer (cf. Nykyri et al., 2017).

For progress on discerning the underlying mechanisms and quantifying the strength of the interaction, large-scale kinetic simulation codes are needed. At the magnetopause where the viscous interaction operates global MHD codes are dominated by numerical diffusion (Raeder et al., 2020), yielding a false viscous interaction that differs in strength and has different controlling factors than the true viscous interaction. Further statistical studies comparing upstream-solar-wind conditions with strengths of low-latitude-boundary-layer potentials (e.g. Drake et al., 2009) are needed to quantify the strength and controlling factors of the viscous interaction.

2.2. What determines when and where reconnection occurs? Under what conditions does it start? What causes it to stop?

It is generally believed that magnetic reconnection in the magnetotail is initiated by a generalized tearing instability in the tail current sheet. An important stabilizing factor, however, is the presence of the normal magnetic field component B_z; even a small B_z can stabilize the tearing mode (Pellat et al., 1991; Brittnacher et al., 1995; Schindler, 2007). Another important factor is the thickness of a current sheet. Simulations (e.g, Birn et al., 2001) and observations (e.g., Baumjohann et al., 2007) suggest that the instability requires thicknesses comparable to, or less than, a typical ion inertial length or ion gyroradius. The fact that the local thickness and magnitude of B_z play a crucial role was originally suggested by Schindler (1974). A thorough analysis of the onset conditions require studying the transition from stability to instability. There are relatively few investigations that model this transition in the magnetotail, assessing the possibility of onset of tearing modes (e.g., Pritchett and Coroniti, 1994; Hesse and Schindler, 2001; Pritchett, 2005; Birn et al., 2014; Liu et al., 2014; Sitnov et al., 2019). (There are practically none for other possible instabilities.) These simulations typically are based on external driving, continuous or temporally limited, to cause a local reduction of current sheet thickness or magnitude of B_z or both. Further, these are typically based on smooth laminar initial configurations and only one (Liu et al., 2014) has explored the actual onset parameters. It is less clear what happens in less well-ordered, three-dimensional, or even turbulent fields.

At the magnetopause, reconnection occurs in current sheets without a normal component, but often with magnetic shear angles of less than 180°, implying a finite tangential magnetic field within the magnetopause current layer. While the lack of normal component should render reconnection more likely, the apparent lack of ubiquitous reconnection regions indicates that other effects limit reconnection occurrence. Among those are the magnetizing effects of the finite magnetic field within the current layers, which need to thin down to electron gyroradius scales in the diffusion region (Hesse et al., 2005a). Another effect is the diamagnetic drift generated by the pressure gradient across the current layer and the magnetic field within it: if this drift gets too large, reconnection is suppressed (Swisdak et al., 2003). A recent investigation shows that this suppression is reduced if the pressure gradient is primarily due to a temperature variation, rather than due to a temperature variation (Liu and Hesse, 2016). Finally, suppression mechanisms also include shear flows, such as expected on the magnetospheric flank, which can also create conditions unsuitable for reconnection (Cassak and Otto, 2011).

What stops reconnection is still not known. This is an important question for near-Earth reconnection in the magnetotail since substorm reconnection eventually ceases. One possibility is a change in the properties of the inflow plasma (Hesse and Birn, 2004). For example, if near-Earth reconnection proceeds through the entire plasma sheet into the lobes, the high-density mantle plasma being drawn into the reconnection region may sufficiently lower the Alfven speed at the reconnection site to greatly lower the reconnection rate. Further, the downtail momentum of the dense mantle plasma may carry the near-Earth reconnection site downtail. A related possibility is that the magnetic field in the inflowing plasma somehow gains an unfavorable geometry for reconnection. The effects on the magnetotail reconnection rate of ionospheric outflows (Oullette et al., 2013) and of ionospheric conductivity (Lotko et al., 2014) have also been explored. Another possibility for near-Earth reconnection is that the Earthward reconnection outflow becomes impeded by running into the dipolar magnetic field of the Earth, causing bouncing and return flow (e.g., Panov et al., 2010; Nakamura et al., 2013). MHD simulations (e.g., Birn et al., 2009) indeed have shown that this can greatly reduce energy conversion and transfer by reconnection, even without significant change in the properties of the inflow plasma. However, none of these mechanisms have been demonstrated to fully turn off reconnection.

2.3. Is magnetotail large-event reconnection a collection of small bursts?

There is evidence that multiple flow bursts in the tail may contribute to the flux accumulation in the wider substorm current wedge (SCW) (Liu et al., 2013; Birn et al., 2014, 2019; Kepko et al., 2015; Merkin et al., 2019). There is also evidence that flow bursts in the magnetotail are closely related to auroral streamers (e.g., Henderson et al., 1998; Lyons et al., 1999; Nakamura et al., 2001a,b; Sergeev et al., 1996, 1999, 2004; Zesta et al., 2006), such that multiple streamers may indicate multiple flow bursts in the tail. Flow bursts are generally believed to be exhausts from a magnetotail reconnection site. They may occur repeatedly at the same location (Gabrielse et al., 2017) (original definition of a bursty bulk flow) or (nearly) simultaneously or successively at different locations. It is not clear whether each burst is the result of an individual localized reconnection event (cf. Wiltberger et al., 2015), in time as well as in space, whether the bursts are coming from a single reconnection site (x-line) as a wide flow and subsequently break up as suggested by Sergeev et al. (1996, 2000), or whether a modulation of a single site takes place that causes flows to be localized in the cross-tail direction despite coming from a single x-line as suggested by some simulations (Birn et al., 2015, 2019). In either case, an additional cross-tail mode, such as a ballooning/interchange instability may play a role in the localization. However, the roles are not clear yet. THEMIS/ARTEMIS observations find tailward fast flows at 60 R_E downtail to have similar spatio-temporal localization as the earthward BBFs in the near-Earth tail, with spatial scales of 1–5 R_E (Li et al., 2014a, 2014b), with similar magnetic and energy flux transport properties (Runov et al., 2018), and with predominant localization in the pre-midnight sector (Kiehas et al., 2018). This is an argument against the picture of a global cross-tail reconnection line and the subsequent flow canalization by the interchange and/or ballooning instability.

To fully answer this question, multispacecraft observations across the tail are needed, perhaps with a dozen or so spacecraft to guarantee the needed coverage and resolution. Future higher-resolution global or magnetotail simulations are also needed, particularly simulations that include the correct reconnection-onset physics.

2.4. How do we identify reconnection sites and separatrices in magnetotail spacecraft data and in auroral images?

Identifying reconnection sites from spacecraft data is a crucial element in the success of the MMS mission. However, in three dimensions defining the reconnection site (which is no longer a simple X-line) can be ambiguous due to the absence of magnetic neutral lines. Furthermore, while measuring the critical $E_{||}$ (Hesse and Schindler, 1988; Schindler et al., 1988) is possible with modern spacecraft instrumentation, determining its integral (e.g. Hesse et al., 2005b) cannot be performed by local observations. Fortunately, major features of the 2D models still apply in 3 dimensions, such as the ejection of plasma from the reconnection site and the identification of topologically different plasma regimes separated by boundaries called separatrices. A definition provided by Vasyliunas (1975) is based on the plasma transport across a magnetic separatrix. This works, even remotely, for magnetotail reconnection (and similarly for solar reconnection) when it has proceeded to involve lobe magnetic fields, provided the separatrices can be uniquely identified. Thus, there is interest in determining what the remote signatures of the nightside reconnection site are, in particular determining the signatures of the separatrices and locating the signatures of reconnection in auroral images.

Innocenti et al. (2015, 2017) and Lapenta et al. (2015) have extensively explored the signatures that a spacecraft with high-time-resolution instrumentation should see at the separatrices, focusing on currents and ion and electron distribution functions. However, it is unclear how or whether these signatures relate to auroral structures. For the concept of using auroral images as a window on magnetospheric processes (Mende, 2016a), there has been a long desire to image the onset and evolution of near-Earth reconnection. Probably, there is only an indirect relation between the aurora and tail reconnection – via the currents that are set up by the reconnection flows. In fact, it is conceivable that reconnection may, for some time, not set up any significant field-aligned currents that reach the ionosphere. In such a situation, the ionosphere cannot “know” that reconnection has started, and there is also no associated auroral acceleration. Even electron heat flux from heating in the diffusion region and at the separatrices is likely to be too weak to be detected at low altitudes. Therefore, there is some doubt that an immediate relation between auroral phenomenology and magnetic reconnection in the tail can be identified – something, which likely contributed to the confusion in determining the relative timing of various substorm onset signatures.

2.5. What are the mechanisms and controlling factors for the loss of the radiation belts?

Earth’s radiation belts exhibit dramatic variations in time, space, and energy content. The outer electron radiation belt in particular can be highly dynamic, with often-unpredictable variations in intensity and spatial extent on timescales ranging from minutes to solar cycles. A number of competing acceleration and loss processes combine to produce net enhancements or depletions of the belts, and characterization and quantification of each of these processes is needed to understand overall dynamics and ultimately predict relativistic electron variations. Quantification of loss mechanisms in particular has remained elusive (Denton et al., 2016a), and both the rapid losses, or sudden dropouts, during storm main phases as well as losses contributing to the suppression of outer belt fluxes during recovery phases present challenges both observationally and for modelers. The sudden dropout of the electron radiation belt is depicted in Fig. 3, where the superposed-epoch average of the flux of ~1-MeV electrons is plotted in the dayside (blue) and nightside (green) at geosynchronous orbit for 24 dropout events; as can be seen, the electron flux drops by about a factor of 10 in the course of a few hours.

The two primary loss mechanisms for radiation-belt electrons are out through the magnetopause (magnetopause shadowing) or into Earth’s atmosphere (precipitation) (See Freidel et al. (2002) and Millan and Thorne (2007) for reviews.). Losses to the magnetopause often cannot fully account for the depletions observed across the outer radiation belt, and radiation belt models often have difficulty reproducing the observed losses (e.g. Hudson et al., 2014; Turner et al., 2014; Tu et al., 2014; Ozeke et al., 2017). Recent advances in understanding magnetopause and atmospheric loss have helped better identify the physical mechanisms and drivers of these processes. Recent studies have demonstrated the importance of ULF wave-driven outward radial diffusion, event-specific diffusion coefficients, last closed drift shell representation, and storm-time ring current adiabatic effects for magnetopause loss (e.g. Turner et al., 2012; Ukhorskiy et al., 2015; Tu et al., 2019; Sorathia et al., 2017; Olifer et al., 2018; Ripoll et al., 2019). Additionally, advances in directly tying observations of electron pitch-angle scattering and precipitation to various different wave modes have been made (e.g. Li et al., 2014a, 2014b; Blum et al., 2015a; Breneman et al., 2017; Mozer et al., 2018; Zhu et al., 2020); however, simulations have shown that the nature of these interactions (e.g. quasilinear vs nonlinear, resonant vs non-resonant) can have important consequences for what energies and pitch angles are affected (e.g. Chen et al., 2016; Albert and Bortnik, 2009; Osmane et al., 2016).

Despite these advances, a number of open questions remain, including when, where, and how much loss is driven by these different processes and wave modes, as well as what energies and particle species are affected. One mystery is an absence of stormtime sudden dropouts of the proton radiation belt when there are stormtime sudden dropouts of the electron radiation belt. At geosynchronous orbit there is a clear population of ~MeV protons that are distinct from the ion plasma sheet population and the substorm-injected ion populations (Fritz and Spjeldvik, 1979; Stevens et al., 1970), with the ion-plasma-sheet and substorm-injected populations feeding the "ring current". Global (all local time) dropouts of the outer electron radiation belt at geosynchronous orbit are common during high-speed-stream-driven storms, with the electron dropouts lasting ~0.5 day. However, for high-speed-stream-driven storms Borovsky et al. (2016) find systematically that 1-MeV protons of the ion radiation belt do not drop out when 1-MeV electrons do, a finding that holds for a wide range of energies (Note that an examination of a CME-driven storm by Turner et al. (2014) does find a proton dropout accompanying an electron dropout.). The absence of proton dropouts when there are electron dropouts casts doubt on the picture of electron-radiation-belt loss to the magnetopause caused by an Earthward displacement of the dayside magnetopause accompanied by enhanced radial diffusion (e.g. Shprits et al., 2006; Yu et al., 2013; Ozeke et al., 2014). Since the azimuthal drift speeds and drift periods of 1-MeV protons and 1-MeV electrons at geosynchronous orbit are very similar, it is anticipated that the radial-diffusion coefficients D_{LL} for the electron and proton radiation belts should have similar values for both protons and electrons. Hence radial diffusion loss to the magnetopause should have similar timescales for protons and electrons; if you see loss of electrons, it is expected to be accompanied by loss of protons, but it's not.

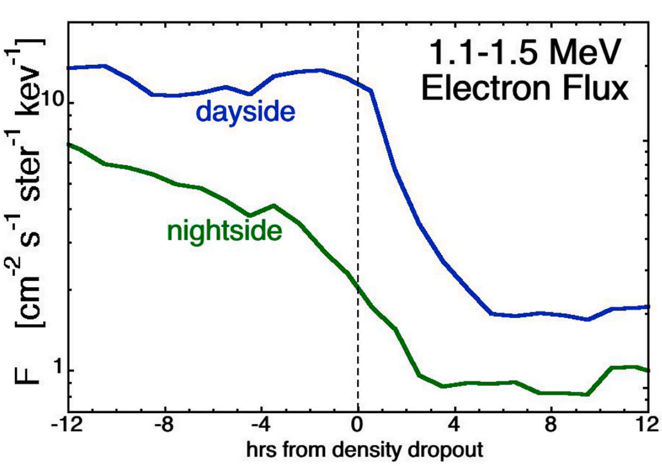

Fig. 3. For 24 high-speed-stream-driven storms with well-defined well-measured relativistic-electron dropouts, the superposed logarithmic average of the 1.1–1.5 MeV flux in the dayside (9–15 LT) and in the nightside (21-3 LT) in geosynchronous orbit are plotted in blue and green respectively. The zero epoch is the time at which the radiation-belt number density drops in the dayside at geosynchronous orbit.

Future improvements in the quantification of losses through the magnetopause and into the atmosphere will require multipoint observations and/or imaging techniques to better constrain the spatial and temporal scales of these processes. Global modeling of the system and incorporation of the effects of localized wave particle interactions, both quasilinear and nonlinear, into these models is also needed to achieve a more complete picture of these competing radiation-belt processes.

2.6. What is the spatial structure of the keV population of the ring current (ion plasma sheet) and what effects does this structuring have?

In the nightside and duskside dipolar regions of the magnetosphere there is a spatial structuring of partial ring current plasma (i.e. the ion plasma sheet) wherein localized ion-pressure peaks and localized ion-pressure troughs form (Liemohn and Brandt, 2005). This spatial pressure pattern in the magnetosphere drives localized field-aligned currents into and out of the ionosphere, resulting in a pattern of perpendicular currents in the ionosphere and a pattern of perpendicular resistive electric fields in the ionosphere (cf. Fig. 1 and Plate 3c of Liemohn and Brandt, 2005). The structured pattern of perpendicular electric fields mapping outward from the ionosphere results in a structured convection pattern in the partial ring current, altering the transport of the hot ions in the dipolar magnetosphere. Because this structuring is in the large-scale Region-II downward-field-aligned current region, it is not highlighted by producing structured aurora. Some of this pressure structuring in the magnetosphere could result in the subauroral ion drift (SAID) and subauroral polarization stream (SAPS), a channel of rapid magnetospheric convection from the nightside to the dayside (Spiro et al., 1979; Foster and Burke, 2002). This ion-plasma-sheet pressure structuring could be caused by magnetosphere-ionosphere feedback (e.g. Liemohn et al., 2005) or could be the result of multiple substorm injections of ions (Liemohn and Jazowski, 2008).

In the dayside dipolar regions of the magnetosphere there is a spatial dependence of the three-dimensional velocity distribution functions of the ion plasma sheet caused by a combination of (1) temporal source populations on the nightside, (2) time-dependent magnetospheric convection, and (3) charge-exchange with the neutral-hydrogen geocorona (Mauk and Meng, 1983; Kaye and Kivelson, 1979; Kistler et al., 1989; Korth et al., 2002; Denton et al., 2016b; Thomsen et al., 2017). In particular, as ions advect and gradient-and-curvature drift from the nightside dipolar region to the dayside, ions with different kinetic energies and different equatorial pitch angles have different paths and pass through different depths of the geocorona and suffer different rates of charge exchange, producing losses in the three-dimensional velocity distribution functions that depend on energy and pitch angle (denoted the "deep proton minimum" by MacIlwain and Whipple (1986)). Additionally, in the dayside magnetosphere some parts of the ion energy/pitch-angle distribution came around the duskside of the Earth and some parts came around the dawnside of the Earth to meet on the dayside, forming a "Frankenstein" distribution function assembled from different plasmas. With its mismatches and missing pieces, these ion velocity distribution functions can have complex regions where $\partial f/\partial v_\perp > 0$ that could be involved in wave growth: electromagnetic ion-cyclotron (EMIC) waves (Cornwall, 1977; Kaye et al., 1979; Solomon and Picon, 1981; Borovsky and Denton, 2009; Runov et al., 2016) and magnetosonic (ion-Bernstein) waves (Thomsen et al., 2011; Gary et al., 2011; Chen et al., 2011; Min and Liu, 2016). EMIC and magnetosonic waves are of importance for their roles in the evolution of the outer electron radiation belt (Horne et al., 2007; Shprits et al., 2008a).

To better understand (a) the spatial structuring of the nightside-duskside plasma sheet in the dipolar regions, (b) the associated magnetosphere-ionosphere coupling, and (c) the impact of this structuring on the magnetospheric system, higher-resolution simulations of the dipolar regions are needed. Also needed are more case studies with magnetospheric data analysis accompanied by high-resolution simulations. To better understand the three-dimensional ion distribution functions in the dayside magnetosphere and their role in the production of plasma waves, substantial surveys of ion measurements are needed with the observed distribution functions in the surveys connected to the time history of magnetospheric activity, in particular the overall magnetospheric convection strength and the occurrence times and strengths of substorms.

2.7. What is the cause of auroral arcs?

Auroral arcs are east-west-aligned curtain-shaped regions of airglow in the upper atmosphere, connected with a sheet-shaped field-aligned current between the nightside magnetosphere and the nightside ionosphere (Lessard et al., 2007; Karlsson et al., 2020). The airglow is produced by the impact of keV field-aligned electrons onto the atmosphere. The magnetic connection of an auroral arc into the magnetosphere is sketched in Fig. 4: in the equatorial magnetosphere a generator region supplies power and field-aligned electrical current to the arc and near the earth an acceleration region (parallel electric field) accelerates electrons into the atmosphere. The energy of the arc is dissipated in ionospheric and atmospheric heating (Vickrey et al., 1982). Auroral arcs extract energy from the nightside magnetosphere (Xi et al., 2016) and modify the conductivity of the ionosphere, thereby influencing the magnetosphere-ionosphere interaction (Lotko et al., 2014): since growth-phase arcs brighten dramatically at the time of substorm onset (Henderson, 2012), they may also be a key to understanding the onset mechanisms for magnetospheric substorms. Determining the sources of energy that power arcs and how the energy is converted to form arcs is essential if we are to fully understand magnetospheric evolution and dynamics (Denton et al., 2016a; Karlsson et al., 2020).

It is surprising, after decades of research and many hundreds of publications, that the plasma-physics mechanisms in the magnetosphere that generate auroral arcs are not known (cf. generator-mechanism reviews by Swift (1978), Atkinson (1978), Borovsky (1993), Haerendel (2011), and Borovsky et al. (2020a)). This might involve separate mechanisms for the supply of energy and for the supply of field-aligned current (e.g. Birn et al., 2020). Further, the type of energy conversion that powers the arcs is not known: flow kinetic energy, ion thermal energy, electron thermal energy, magnetic energy, etc. Outstanding issues remain regarding where in the nightside magnetosphere the auroral-arc magnetic-field lines connect to; i.e. where in the nightside magnetosphere do the generator mechanisms operate. One school argues that it is in the dipolar region (e.g. McIlwain, 1975; Meng et al., 1979; Kremser et al., 1988; Elphinstone et al., 1991; Mauk and Meng, 1991; Lu et al., 2000; Antonova et al., 2015, 2018; Motoba et al., 2015) and another school argues that it is in the stretched magnetotail (Yahnin et al., 1997, 1999; Birn et al., 2004a,b, 2012; Sergeev et al., 2012; Hsieh and Otto, 2014). It is in large part the uncertainty in the mapping that has hindered the answer of this auroral-arc-generator question (Borovsky et al., 2020b).

The major problem in solving the auroral-arc-generator question arises from the fact that magnetic-field-line mapping in the nightside magnetosphere is very uncertain (cf. Subsection 2.18), so connecting observed auroral arcs to spacecraft measurements in the equatorial magnetosphere is completely ambiguous. Unless breakthroughs are made with kinetic simulations of the entire magnetotail, a method of tracing nightside magnetic fields from a magnetospheric spacecraft to the ionosphere will be essential to solve this outstanding question.

2.8. How is electromagnetic power converted to particle energy in the aurora?

Despite extensive research into the microphysics of auroral particle acceleration, we still do not know how the electromagnetic power that flows into auroral acceleration regions is converted to charged-particle energy. When or how does the system decide to form a distributed potential drop, Debye-scale double layers, ion gyro-scale electrostatic shocks, or turbulent resistivity (Falthammar, 1978; Swift, 1978; Borovsky, 1993; Andersson and Ergun, 2012); and what are the implications of one process or the other on particle acceleration? How are transversely accelerated ions, dominantly O^+, produced (Chang et al., 1986; Maggiolo, 2016), and what determines the altitude distribution of acceleration? We also lack a basic understanding of how the effects of auroral acceleration, and the particular processes and structures they exhibit, feedback on the dynamo processes that sustain them. Answering such questions is essential in explaining the observed features and dynamics of a scale-interactive system like geospace – the coupled solar wind-magnetosphere-ionosphere-thermosphere.

These issues are not easily addressed by observations alone. Many observational studies have reported local correlations between various

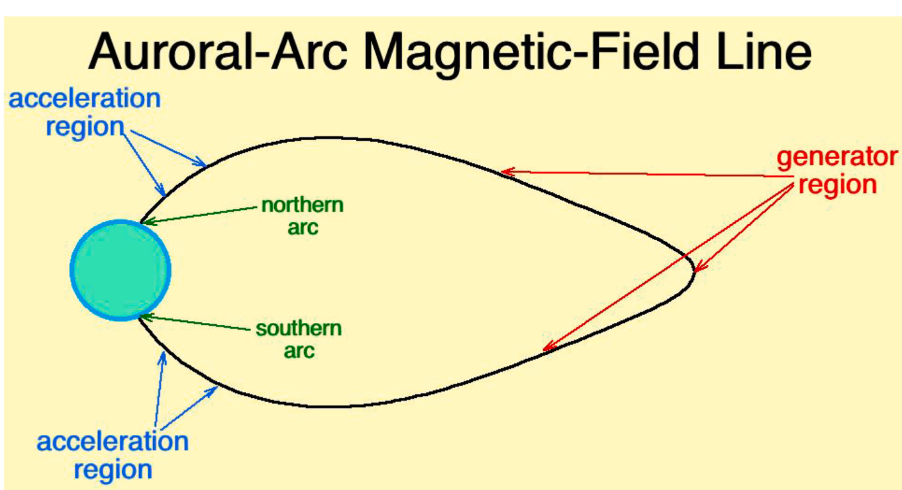

Fig. 4. A sketch of a magnetic field line connecting to an auroral arc in the atmosphere: near the Earth there is an acceleration region and in the equatorial regions there is a generator region.

types of charged-particle acceleration and electric fields implicated in the energization. But the causality often remains elusive. The most successful such relation is the so-called "Knight relation" (Knight, 1973; Antonova and Tverskoy, 1975; Lyons et al., 1979; Fridman and Lemaire, 1980), which relates the field-aligned potential drop responsible for parallel electron acceleration in "inverted-V" acceleration regions, to the field-aligned current carried by the electrons. However, later studies depict a more complicated current-voltage relation (Lotko, 1986; Marooka et al., 2004; Dombeck et al., 2013). Empirical transport relations between observed Poynting flux and precipitating electron energy flux (Chaston et al., 2003; Keiling et al., 2003; Zhang et al., 2015a) and outflowing ion flux (Strangeway et al., 2005; Zheng et al., 2005) have also been developed from local observations, and such relations have been embedded in global geospace models (Brambles et al., 2011; Zhang et al., 2015b; Varney et al., 2016) to assess the effects of the implied energy conversion on the system dynamics. The large scatter in the reported relationships suggests that hidden variables are influencing the energization – a not surprising conclusion given the manifold ways in which auroral acceleration occurs. Consequently, the fidelity of global predictions derived from such relations is uncertain at best.

Observational progress will require multi-point, multi-instrument measurements in space and on the ground. For example, major advances might be expected if two or more spacecraft separated along a single flux tube could resolve the energy conversion in progress, as demonstrated by a few conjunction studies for Polar-Fast (Dombeck et al., 2005) and Cluster auroral campaigns (Marklund et al., 2011; Sadeghi et al., 2011; Forsyth and Fazakerley, 2012). If such measurements were combined with conjugate optical measurements, the final disposition of the energized particles precipitating in the atmosphere could be determined and the implied cross-scale coupling (Chaston et al., 2011). Such in situ measurements would address the "when and how" of charged-particle energization while the visual outcomes could be used to infer how the large-scale processes powering the acceleration are influenced by it. Multi-point measurements across and along flux tubes are needed to resolve the complicated interplay between transverse (convective) and parallel transport in heavy-ion acceleration. Application of theory and simulations with increasing physical detail are needed to deconvolve the relationships between the products of auroral acceleration and the enabling processes, and their feedback on the geospace system.

2.9. What plasma-physics processes are acting in the nightside downward-current regions when auroral signatures are not produced?

Much attention has been paid to the processes that occur in the upward-field-aligned (downward electrons) current regions that give rise to dynamic auroral displays. Less is known about the plasma processes ongoing in the downward-field-aligned (upward electrons) current regions. Not understanding these processes impedes our understanding of magnetosphere-ionosphere coupling in the nightside magnetosphere, particularly in regions where there is transport of plasma from the magnetotail into the dipolar region. Since the downward field-aligned currents are often thought of as the return currents for the aurora, this lack of understanding also hinders our full understanding of the aurora.

Like the upward-current regions, the downward-current regions exhibit parallel and perpendicular electric fields (Carlson et al., 1998; Hwang et al., 2006; Marklund, 2010), accelerated electron beams (Carlson et al., 1998; Cran-McGreehin and Wright, 2005a), plasma-wave activity (Jasperse et al., 2010; Lynch et al., 2002), ionospheric modification (Streltsov and Lotko, 2003; Marklund, 2010), and a current-Voltage relationship (Temerin and Carlson, 1998; Cran-McGreehin and Wright, 2005b).

Reviews of the known plasma-physics processes operating in the downward-current regions can be found in Section 4.2 of Paschmann et al. (2002) and in Marklund (2009). Significant advances in the understanding of downward-current plasma processes could be made by revisiting existing spacecraft data and by advancements of large-scale (magnetotail-dipole) kinetic simulation codes. Future multi-point spacecraft measurements at auroral-acceleration altitudes and below (cf. Fig. 4), as suggested in Subsection 2.8, would also help to advance the understanding.

2.10. What determines the local-time distribution and the structuring of the diffuse and pulsating aurora?

Most of the global energy of electron precipitation into the atmosphere comes via the diffuse and pulsating aurora (Newell et al., 2009), caused as the electron plasma sheet and substorm-injected electrons scatter into the atmospheric loss cone and are lost from the magnetosphere. Diffuse and pulsating aurora are associated with chorus waves in the magnetosphere that pitch-angle scatter electrons with a wide variety of kinetic energies (Thorne et al., 2010) and with electrostatic-electron-cyclotron waves that pitch-angle scatter electrons with energies of a few keV (Fukizawa et al., 2018). One reason why it is important to understand the diffuse and pulsating aurora is because these chorus waves also energize the electron radiation belt and produce relativistic-electron microbursts. The unexplained patch behavior of pulsating aurora means we don't understand chorus waves in the magnetosphere, and as a consequence we don't fully understand the physics of the evolution of the electron radiation belt.

It is probably safe to assume that the local-time distribution of diffuse and pulsating aurora maps to the local-time distribution of where chorus and electron-cyclotron waves occur. The waves occur where wave-driving conditions occur. Diffuse and pulsating aurora occur most frequently in the postmidnight sector of the dipolar magnetosphere, lasting for a few hours after a substorm occurs. It is commonly thought that the chorus waves are driven by anisotropies in eastward-drifting (dawnward drifting) substorm-injected electrons. *A question is whether cold electrons are necessary.* As the electrons of the plasma sheet advect from the nightside through the dawnside to the dayside, they are largely lost to the atmosphere in supplying the diffuse aurora (Gkioulidou et al., 2012), transforming the nightside electron plasma sheet into the dayside "electron trough" (Thomsen et al., 1998). To ensure charge neutrality in the magnetosphere as the electron plasma sheet rains out, lower-energy electrons from the ionosphere must be upflowing. The dawnside electron plasma sheet also hosts the oxygen-rich warm plasma cloak (Chappell et al., 2008), which might have its origin as cool-ion outflows associated with the diffuse and pulsating aurora. The ions of the plasma cloak impact EMIC and ULF waves (Takahashi et al., 2014), and the cloak mass loads the dayside reconnection rate (Borovsky et al., 2013) and, with a mass-density dependence to the Kelvin-Helmholtz onset threshold (Otto and Fairfield, 2000), may alter magnetopause Kelvin-Helmholtz waves (Delzanno et al., 2020); hence understanding the ionospheric physics (e.g. the ion-outflow physics) of the diffuse and pulsating auroras is again important for understanding how the magnetospheric system works.

The origin of the temporal and spatial structuring of the diffuse pulsating aurora is a longstanding mystery (Nishimura et al., 2020). This structuring has been described as an emergent phenomenon in the complex magnetosphere-ionosphere system (Borovsky and Valdivia, 2018). The E-cross-B like motion of the pulsating patches implies that they are associated with structured cold plasma in the magnetosphere (Scourfield et al., 1983; Grono et al., 2017), with cold electrons in particular since chorus and electron-cyclotron waves are not affected by ions. The pulsating patches evolve in shape and intensity (Partamies et al., 2019) raising the question of whether there is an evolution of cold-electron structure in the magnetosphere, and raising the question of what could be causing that evolution. Another possibility suggested is that there is a structured ionospheric outflow that feeds back with patchy electron precipitation (Nishimura et al., 2015). There are also arguments that lower-frequency plasma waves are involved in temporally modulating the chorus-wave activity, i.e. compressional ULF waves

(Coroniti and Kennel, 1970; Johnstone, 1978; Li et al., 2011); these ULF waves might be guided by structured cold-ion populations in the magnetosphere. There are also indications that chorus waves can be modulated by EMIC waves (e.g. Colpitts et al., 2016; Usanova et al., 2018).

It will be difficult to fully understand the physics of the structuring and evolution of diffuse and pulsating aurora without having future cold-electron measurements in the equatorial magnetosphere. Cold-electron density measurements can often be obtained from a wave-electric-field instrument in conjunction with a hot-electron particle instrument. However, cold-electron temperatures, cold-electron temperature anisotropies, and cold-electron outflows are also of interest and those measurements may require the development of a new-generation of instrumentation. Simulations will be critical to understand the processes that drive structuring but are extremely challenging. Kinetic modeling of chorus wave generation driven by low-density, tens-of-keV electrons in the equatorial plane over a large domain relevant to structuring (roughly a cube of a thousand electron skin depths) is at the limit of what is doable with traditional explicit Particle-In-Cell techniques. Adding a cold electron component complicates things tremendously since it lowers the electron Debye length and hence requires even more resolution. A lot of understanding could be gained by 'hybrid-type' simulations, where cold electrons are treated like a fluid while the warm/hot electrons are treated kinetically. However, some recent works suggest that chorus waves could couple efficiently to the cold electrons by kinetic drift instabilities, hence also requiring a kinetic treatment for the cold electrons (Roytershteyn and Delzanno, 2020). While a fully-kinetic treatment of both cold and warm/hot regions over a large enough volume of space to be interesting for structuring questions appears not feasible with traditional explicit techniques, reduced-kinetic techniques (Delzanno, 2015; Roytershteyn and Delzanno, 2018) might be able to tackle this problem.

2.11. What are the roles of Alfven waves in magnetospheric physics?

Alfven waves are one of the fundamental normal modes of oscillation of magnetized plasmas. Ranging from the ULF (Ultra Low Frequency) global-scale shear Alfven waves with periods of minutes to kinetic Alfven waves (KAW) at ion and electron perpendicular scales, Alfven waves are ubiquitous throughout the magnetosphere (e.g. Keiling, 2009; Hartinger et al., 2013; Pilipenko et al., 2017). Global-scale ULF waves in the dipolar regions of the magnetosphere are of great interest for producing a radial diffusion of radiation-belt electrons that (a) spatially redistributes the radiation belts (Lanzerotti et al., 1978; Shprits et al., 2008b), (b) energizes radiation-belt electrons (Elkington et al., 1999; Sauvaud et al., 2013), and (c) leads to the loss of the radiation-belt electrons to the magnetopause (Shprits et al., 2006; Ozeke et al., 2014). Large amplitude KAW and have been observed in the inner magnetosphere during storms (Moya et al., 2015; Chaston et al., 2020). In the nightside magnetosphere Alfven waves act as transmission-line transients (Goertz and Boswell, 1979; Vogt, 2002; Gjerloev et al., 2007) to switch on and off the field-aligned electrical currents that mediate magnetosphere-ionosphere coupling (Lysak, 1990; Keiling, 2009). Aurora are one result of these currents (Birn et al., 2004a,b; Wu et al., 2017). Auroral arcs at the high-latitude edge of the auroral zone exhibit continuous Alfven-wave activity and Poynting flux to the ionosphere (Burke et al., 1994; Keiling et al., 2006). Alfven-wave dynamics impact the dynamical aurora during magnetospheric substorms (Lessard et al., 2011; Forsyth et al., 2020). Some of this dynamic substorm aurora may be associated with the magnetosphere-ionosphere coupling of bursty bulk flows in the magnetotail (Liu et al., 2008; Ergun et al., 2014). In the polar regions Alfven waves act to establish coupling between the magnetosheath and the polar-cap ionosphere (Wright, 1996) and for lower-Mach-number solar-wind conditions Alfven-wave effects become fundamental for global solar-wind/magnetosphere coupling (Kivelson and Ridley, 2008).

Alfven-wave effects play subtle roles in most theoretical models for auroral arcs (e.g. Knudsen, 1996; Haerendel et al., 2012; Watanabe, 2014). It is well known that the cause of auroral arcs is not understood (cf. Subsection 2.7; Borovsky et al., 2020a) and, needless to say, the role of Alfven waves in auroral-arc generation and evolution is as yet unsolved. Many studies have shown that wave-particle interactions between Alfvenic fluctuations and plasma particles play important roles in several magnetospheric processes. However, some of the details of these processes are still to be investigated, particularly at kinetic scales in which new fast- and small-scale observations have revealed more details regarding the plasma distributions and composition, magnetic-field gradients, and density inhomogeneity that should be relevant for questions such as: How is the energy cascade transferred from large-scale fluctuations to electrons? What is the relevance of KAW? How relevant are the non-Maxwellian properties of the plasma for the excitation and relaxation processes of the mainly collisionless magnetospheric plasma? Can we account for these and other phenomena in a non-linear self-consistent way?

As noted in Subsection 2.7, understanding the role of Alfven waves in the creation and evolution of aurora will require (1) a methodology to unambiguously connect equatorial magnetospheric measurements with auroral images and/or (2) kinetic simulations of the magnetotail and ionosphere.

Depending on energy, charge-to-mass ratio, and pitch angle, different kinds of Alfven waves can interact with plasma particles and transfer energy from fields to the particles, accelerating and heating the plasma, or also be an effective channel for unstable particle distributions to relax towards more stable states, especially when collisions are scarce. Understanding the details of non-linear wave-particle interactions for Alfvenic waves in multi-species non-Maxwellian plasmas is a key step to unravel some of the long-standing open questions in our community. To tackle these issues we need (1) to develop a better understanding of wave-mode determination, wave properties, and wave propagation in different regions of the magnetosphere; (2) a more comprehensive linear theory accounting for the effect of non-Maxwellian particle distributions, plasma composition, and temperature on the properties of Alfvenic waves (ULF, KAW, etc.); and (3) a better understanding of the role of Kinetic Alfven waves as a channel to deposit energy from large scale to electrons.

2.12. How does magnetotail turbulence affect the magnetosphere?

The high-beta portions of the Earth's plasma sheet exhibit large fluctuations in the vector magnetic field and vector flow velocity. The characteristic scale sizes of the field and flow fluctuations within the magnetotail are on the order of 1 R_E (R_E is Earth's radius), which is about 10 ion gyroradii r_{gi}. Several studies of these magnetotail fluctuations have been based on the assumption that they are manifestations of an MHD turbulence (e.g. Borovsky et al., 1997; Borovsky and Funsten, 2003b; Voros et al., 2004; Stepanova et al., 2005, 2009; Petrukovich, 2005; Consolini and Kretzschmar, 2005; Weygand et al., 2005; Arancibia Riveros et al., 2008; Pinto et al., 2011; Zelenyi et al., 2015). Turbulent fluctuations and magnetic-field distortions are also observed in the magnetotails of high-resolution (high-Reynolds-number) global-MHD simulations (White et al., 2001; El-Alaoui et al., 2010, 2012, 2013). Whereas the solar-wind magnetic-field structure (which is assumed by some to be governed by MHD turbulence) is dominated by strong current sheets, no such current sheets are found in the Earth's plasma sheet (Li et al., 2008). A hypothetical sketch of the "spaghetti" magnetic structure of the Earth's turbulent magnetotail appears in Fig. 5. Other depictions can be seen in Fig. 4 of Hruska (1973), Fig. 1 of Borovsky et al. (1997), or Fig. 1 of Borovsky and Funsten (2003b). Calculating the large-eddy Reynolds number R of the turbulence is somwhat ambiguous (cf. Table I of Borovsky and Gary, 2009): for the viscosity one could use Coulomb scattering ($R \sim 10^{12}$), the Alfven-wave emission of momentum ($R \sim 1000$), or Bohm diffusion ($R \sim 25$). The plasma sheet also has dissipation of vorticity to the ionosphere (Borovsky and Bonnell, 2001) which makes R very small, but (a) with a time delay (viscoelasticity) due to the Alfven-speed transit time from the magnetotail to the ionosphere and (b) with a magnitude that depends on the sign of $(\nabla \times \underline{\mathbf{v}})\bullet\underline{\mathbf{B}}$ (cf. Table 1 of Borovsky and Funsten, 2003b). There are many ideas about the origin (driving) of the plasma-sheet turbulence: cf. Section 5.2 of Borovsky and Funsten (2003b), Section 1 of Hoshino and Higashimori (2015), and Section 3.1 of Stepanova and Valdivia (2016). Two of the most plausible origins of the turbulence are (1) small-scale reconnection events producing bursty bulk flows (Hoshino, 2000; Voros et al., 2006; El Alaoui et al., 2016; Ergun et al., 2018) or (2) MHD instabilities (Lakhina et al., 1990; Antonova, 2008; Hoshino and Higashimori, 2015). Two properties of the turbulence in the magnetotail that make it rather unique are (1) a small dynamic range constrained between kinetic scales ($r_{gi} \sim 0.1\ R_E$) and the north-south thickness of the plasma sheet ($\sim$6 R_E) and (2) dissipation at all spatial scales (Borovsky and Funsten, 2003b) owing to the coupling of magnetotail vortices to the ionosphere.

With an active MHD turbulence in the plasma sheet, eddy diffusion and the eddy transport of plasma is expected (Borovsky et al., 1997; Ovchinnikov et al., 2000; Stepanova et al., 2011; Stepanova and Antonova, 2011, 2015; Ovchinnikov and Antonova, 2017). Associated with the eddy transport, there is also a mixing of the plasma (Antonova, 2000, 2005). MHD turbulence in the plasma sheet should result in a large-scale turbulent (eddy) viscosity owing to the eddy diffusion of momentum (Borovsky, 2006); the impact of turbulent viscosity in the Earth's plasma sheet is discussed in Borovsky and Funsten (2003b) for global convection, magnetotail dynamics, and magnetotail stability. Eddy diffusion across the magnetotail plays a fundamental role in the formation of a stable plasma sheet. Southward IMF leads to the formation of a large-scale dawn-dusk electric field; this field makes plasma advect towards the center of the tail. Antonova and Ovchinnikov (1997, 1998, 1999a,b, 2000, 2001) and Antonova (2002) proposed that turbulent transport can compensate this advection, thereby forming a stable plasma sheet. This turbulent-transport model explains (a) why the dynamics of the plasma sheet is sensitive to the IMF orientation, (b) how plasma sheet compresses (thins) during substorm growth phase, and (c) how the plasma sheet expands after substorm onset. The model predicts the value of the eddy-diffusion coefficient necessary for the plasma sheet stabilization to be on the order of 10^5 km^2/s. Early data analysis (Borovsky at al., 1997; 1998a) finds the value of the eddy diffusion coefficient to be $\sim 2.6 \times 10^5$ km^2/s and subsequent data studies find eddy diffusion coefficients that range between 10^4 and 10^6 km^2/s, depending on the location within the magnetotail and geomagnetic activity, with the intensity of eddy diffusion increasing going tailward and being stronger during geomagnetic substorms (Stepanova et al., 2005, 2009, 2011; Wang et al., 2010; Pinto et al., 2011). Stepanova and Antonova (2011) analyzed all parameters involved in the stability of the turbulent plasma sheet and showed that they are in agreement with the model proposed by Antonova and Ovchinnikov (1997, 1999a,b). Earthward advection from the magnetotail seems to be the main mechanism for delivering plasma into the dipolar magnetosphere (Angelopoulos et al., 1994; Borovsky et al., 1998b), however the turbulent transport in the X (Earthward-tailward) and Y (dawn-dusk) directions can also play an important role for plasma transport. By examining the spatial evolution of ion and electron distribution functions and assuming that acceleration of particles occurs in the inner magnetosphere, Stepanova and Antonova (2015) showed that eddy diffusion might also produce a tailward transport of plasma. If there is kinetic dissipation of the magnetotail turbulence (Landau damping, cyclotron damping, or reconnection) then there should be heating of the plasma-sheet ions and/or electrons. The spaghetti structure of the turbulent magnetic field in the plasma sheet may produce localized regions with geometries favorable for driven reconnection (Matthaeus and Lamkin, 1986; Dmitruk et al., 2004). Certainly, the disordered magnetic field and disordered electric field (Cattell et al., 1986; Borovsky et al., 1997) in the turbulent plasma sheet invalidates magnetotail-transport calculations based on test-particle orbits in a smooth magnetotail magnetic field with a uniform cross-tail electric field. (cf. Zimbardo et al. (2003) and Taktakishvili et al. (2003) who do test particle simulations with a disordered magnetic field but a uniform electric field.)

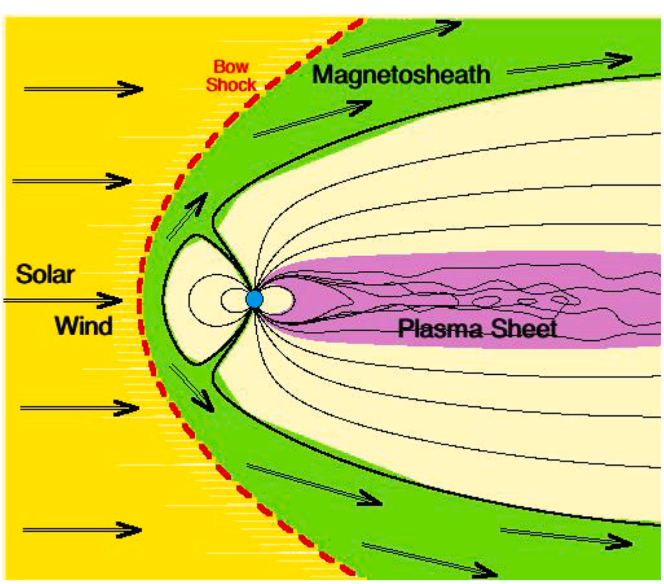

Fig. 5. A sketch of the magnetotail magnetic-field structure (black lines) obtained by adding magnetic fluctuations with observed amplitudes and correlation lengths have been added to the plasma-sheet region of a T96 (Tsyganenko, 1996) magnetic-field model.

Goals for the future are to determine the dynamics (nature of the fluctuations and physics of the energy transfer), the driving (origin mechanisms of the turbulence, when and where the driving occurs, and what controls the driving), and the dissipation mechanisms acting (kinetic processes, reconnection processes, and nature of magnetosphere-ionosphere coupling). Once those are understood, the question of the impact of the turbulence on the global magnetosphere-ionosphere system may be answerable. In the near future, higher resolution (and higher Reynolds number) computer simulations of the magnetotail resolving kinetic scales and including kinetic physics are needed. In the far future, a constellation mission of multiple spacecraft covering multiple scales of separation in the magnetotail is needed to produce a global picture of the plasma sheet, its turbulence, and the dynamics of the magnetotail.

2.13. What is the impact of cold ions and electrons on the magnetospheric system?

The cold-ion and cold-electron populations have multiple known impacts on the magnetospheric system (cf. Table 2). However, in general those impacts are not quantified and the factors (e.g. solar-wind conditions, time history of geomagnetic activity) that control the cold populations are not known. Until the cold populations of the magnetosphere are understood and their impacts quantified, the magnetosphere-ionosphere system will not be fully understood (Denton et al., 2016a; Denton, 2020).

The cold-particle populations that exist in the magnetosphere (cf. Table 2) are (1) plasmaspheric ions (including the plume), (2) plasmaspheric electrons (including the plume), (3) cloak ions (including the oxygen torus), (4) cloak electrons, (5) outflowing cold electrons, and (6) charge-exchange-byproduct cold protons (CHEX protons). Some cold populations are inferred, but not seen. Outflowing (from the ionosphere) cold electrons (cf. Mozer et al., 2017a) are anticipated for the maintenance of charge neutrality in the magnetosphere: two places where they should occur are (a) in the post-midnight to dawn region where the electron plasma sheet precipitates away to make diffuse aurora and (b) at the inner edge of the electron plasma sheet where (owing to gradient-curvature drift effects) the ion plasma sheet flows radially Earthward while the flow of the electron plasma sheet turns eastward. There are also plasmaspheric-refilling cold-ion and cold-electron outflows into open-drift-trajectory flux tubes on the dayside. The reaction of the plasmasphere to the solar-wind driving of the magnetosphere is well known, but the evolutions of the other cold populations in reaction to the solar-wind driving of the magnetosphere are mostly unknown.

Yet, the cold ~ eV plasma plays multiple major roles in magnetospheric dynamics. A list of their impacts in the magnetosphere-ionosphere system appears in Table 2. All of the magnetosphere's cold ions flow to the dayside magnetopause, where the cold ions can reduce solar-wind/magnetosphere coupling by mass-loading dayside reconnection (Borovsky and Denton, 2006; Borovsky et al., 2013; Walsh et al., 2014; Zhang et al., 2017; Fuselier et al., 2019). Cold ions (particularly CHEX protons) with their small gyroradii further alter reconnection by impeding the Hall current (Toledo-Redondo et al., 2015; Andre et al., 2016; Dargent et al., 2017). The presence of cold ions when magnetospheric convection slows down can increase the early-time refilling rate of the plasmasphere. Cold ions and cold electrons can affect waves and wave-particle interactions by changing (1) the resonant conditions between particles and waves, (2) the wave growth rates, (3) the saturation level of the waves, and (4) wave-particle diffusion coefficients, all with strong implications on the dynamics of plasma sheet, ring current, and radiation belts. The cold-dense ions of the plasmasphere significantly alter the patterns of ULF wave activity in the dipolar regions of the magnetosphere (Claudepierre et al., 2016) and the cold oxygen (and probably nitrogen (Ilie and Liemohn, 2016)) of the cloak changes ULF frequencies drastically (Takahashi et al., 2010; Denton et al., 2014). The high mass densities of the cloak and the plasmaspheric drainage plume lower the threshold for Kelvin-Helmholtz instability on the magnetopause (Walsh et al., 2015). Cold electrons have repeatedly been implicated for the spatial structuring of diffuse and pulsating aurora (Demekhov and Trakhtengerts, 1994; Nishimura et al., 2015; Grono et al., 2017), which is also the spatial structuring of chorus-wave activity.

Table 2
The cold ion and electron populations of the Earth's magnetosphere and their known or probable effects on the magnetosphere-ionosphere system (from Delzanno et al., 2020).

Cold Population	Impact on the Magnetosphere
Plasmasphere ions	Alter ULF frequency and radial diffusion of energetic electrons and ions
	Alter EMIC scattering of electron radiation belt
Plasmasphere electrons	Alter HISS decay of radiation-belt electrons
	Create whistler ducts
Plasmapause	HISS-chorus boundary
	Site of enhanced ULF activity
Plasmaspheric plume ions	Reduce the dayside reconnection rate
	Alter EMIC scattering of outer electron radiation belt
Cloak ions	Alter ULF frequency and radial diffusion of energetic electrons and ions
	Reduce the dayside reconnection rate
	Alter EMIC scattering of electron radiation belt
	Reduce electron-plasma-sheet-driven spacecraft charging
	Reduce threshold for Kelvin-Helmholtz on magnetopause
Cloak electrons	Alter chorus and affect electron-radiation-belt energization
Structured dawnside cold electrons	Produce spatial structure of (a) chorus-wave amplitudes and (b) the pulsating aurora
Charge-exchange-byproduct protons	Alter Hall-microphysics of dayside reconnection
	May increase early-time plasmaspheric refilling rate
	Alter EMIC scattering of electron radiation belt
Ionospheric ion outflows in magnetotail	Alter Hall microphysics of magnetotail reconnection
	Mass loading of magnetotail reconnection; altering magnetotail tearing instability
Ionospheric electron outflows	Alter chorus properties

We cannot understand the full complexity of the magnetospheric system until we can (1) reliably measure the full properties of the cold ions and electrons, (2) learn what controls these properties, and (3) learn all of the impacts of the cold populations. While the hot (ring current/plasma sheet) and energetic (radiation belts) populations have received a lot of attention because of their potential harm to space infrastructure, the cold-plasma populations are the least studied so that in some cases they have been referred to as the "hidden populations". Cool ions are difficult to measure because spacecraft in the magnetosphere are almost always positively charged preventing low-energy magnetospheric ions from reaching their instruments. (Two exceptions are (1) the geosynchronous-orbit spacecraft that charge negatively and see the total cold-ion populations (e.g. Thomsen et al., 2013) and (2) ion instruments that are biased negatively to see the total cold-ion populations (e.g. Chappell, 1982); otherwise, if there are sufficient spacecraft measurements, indirect techniques can be used to interpret the presence of cool populations (e.g. Haaland et al., 2012).) Cool electrons are almost impossible to measure because spacecraft surfaces exposed to sunlight and bombarded by energetic particles emit copious amounts of low-energy secondary and photoelectrons that overwhelm the fluxes of ambient magnetospheric low-energy electrons. While some success in measuring cold-ion properties was obtained by the Dynamics Explorer mission in the plasmasphere (Chappell et al., 1981) and THEMIS-D was run for 200 days in a special mode that allowed measuring the properties of some cold-electron outflows (Mozer et al., 2017a), there is a strong need to provide robust and systematic measurements of the cold plasma populations down to sub-eV energies throughout the magnetosphere, including in regions outside the plasmasphere where the cold-plasma density is low. Future spacecraft instrumentation is needed to survey the properties of the cold particle populations of the magnetosphere and the information gathered needs to be statistically analyzed to determine the origins and controlling factors for the various populations. Ion instruments that are negatively biased (e.g. Dynamics Explorer Retarding Ion Mass Spectrometer (Chappell, 1982; Fields et al., 1982) and Los Alamos Magnetospheric Plasma Analyzer (Thomsen et al., 2013)) and perhaps located on a boom are needed in future for studies of cold (0.1 eV–10's of eV) ions in the magnetosphere. Designs of new cold-electron instruments are needed accompanied with the development of techniques to suppress photoelectron and secondary-electron emission from the spacecraft.

After there is understanding of (1) the full properties of the cold ions and electrons in the magnetosphere, (2) what controls these properties, and (3) the impacts of the cold populations, we need to include all of the related cold-particle interactions into global models.

2.14. How can we obtain more-accurate ion outflow rates?

The issue was raised about the need to obtain better ion-outflow rates from the ionosphere into the magnetosphere (Giles et al., 1994; Gkioulidou et al., 2019), to better understand the plasma processes that produce the outflows, and to better understand the controlling factors for the outflows. This includes a recently expanded interest in nitrogen ions N^+ (Chappell et al., 1982; Ilie and Liemohn, 2016). These outflows from the ionosphere deliver almost all of the cold plasma to the magnetosphere (cf. Subsection 2.13), the exception being the byproduct cold protons from charge exchange processes and cold ions and cold electrons have multiple impacts on the solar-wind-driven magnetosphere-ionosphere system (cf. Sect. 2.13). Ion outflows also deliver keV ions into the plasma sheet, which have several impacts on the magnetosphere-ionosphere system such as reducing dayside reconnection and changing the properties of ULF and plasma waves. Various plasma processes act to produce the ion outflows from the various regions of the ionosphere: at the cusps (Valek et al., 2002), in the polar cap ionosphere (Schunk, 2007), from the sunlit dayside ionosphere (cf.

Fig. 1 of Denton et al., 2012), and from the auroral zone both for diffuse aurora (Gorney et al., 1985) and for auroral arcs (Fernandes et al., 2016). Ionospheric outflow issues in general have been reviewed by Welling et al. (2015). Electron outflows from the ionosphere into the magnetosphere (Subsection 2.13; Denton et al., 2012) have been less studied and less is known about them. The electron outflows have diverse, but less understood, impacts on the magnetosphere.

In the Pollenzo discussions, particular attention was focused on the large discrepancy between observations of strong plasmaspheric proton refilling rates and theoretical calculations of proton-outflow rates that are much weaker (Denton and Borovsky, 2014; Krall et al., 2018). The authors speculate here that accounting for charge exchange between neutral hydrogen H and nitrogen ions N^+ in the upper atmosphere, which may be a key missing factor in theoretical calculations, will boost proton-outflow rates in theoretical (numerical) calculations.

2.15. What are the effects of time domain structures (double layers, etc.) on the particle populations of the magnetosphere?

The name "time domain structures" is used to describe a variety of small-scale, moving electric-field structures seen in electric-field measurements onboard spacecraft. Time domain structures include (cf. Mozer et al., 2015) small-amplitude electrostatic and electromagnetic double layers, electrostatic and electromagnetic electron holes, and nonlinear whistlers. Electric-field instruments find time domain structures to be ubiquitous throughout the Earth's magnetosphere: in the plasma sheet (Ergun et al., 2009), the plasma sheet boundary layer (Matsumoto et al., 1994), at the magnetopause (Cattell et al., 2002), in the cusps (Franz et al., 1998), at injection fronts (Vasko et al., 2017), and in the radiation belt (Mozer et al., 2013). They are also seen in the solar wind (Salem et al., 2003). Various plasma-physics mechanisms can give rise to the various types of time domain structures (cf. Goldman et al., 2007; Mozer et al., 2015).

The various electron populations of the magnetosphere can interact with the intense electric fields of the time domain structures: as noted in Mozer et al. (2015) different types of time domain structures are characterized by different particle interactions. Through the years it has been argued that time domain structures are important for the evolution of particle distribution function in the magnetosphere. Early discussion focused on the acceleration of auroral electrons into the atmosphere by multiple weak double layers (e.g. Temerin et al., 1982; Hudson et al., 1983). Subsequent discussion focused on the possibility of the heating of keV electrons to 10's of keV to supply a seed population of electrons for the electron radiation belt (Artemyev et al., 2014; Mozer et al., 2016), or even on the acceleration of electrons toward the MeV range of energies to explain the energization of the electron radiation belt (Mozer et al., 2013, 2014; Zimbardo, 2013). The pitch-angle scattering of electrons by time domain structures to form the pulsating aurora has also been explored (Mozer et al., 2017b; Nishimura et al., 2018).

These impacts remain controversial. Malaspina et al. (2013, 2014) make the argument that time domain structures are mostly confined to current sheets and plasma boundaries and would therefore have difficulty affecting the bulk of the plasma, which is not in sheets or boundaries. Of course in the dipolar regions of the magnetosphere energetic electrons and hot ions will gradient-and-curvature drift through sheets and boundaries, thereby sampling the region where the time domain structures reside. Radiation-belt electrons in fact would periodically sample such a region as they drift around the Earth.

2.16. What is the role of nonlinear wave-particle interactions?

The interaction between particles and waves has long been identified as a major player in magnetospheric dynamics (Kennel and Petschek, 1966; Thorne, 2010), with whistler (hiss and chorus) and electromagnetic-ion-cyclotron (EMIC) waves being extremely important. The fluxes of moderate-to-high-energy electrons in the outer dipolar magnetosphere are highly time variable, with wave-particle interactions (WPI) playing key roles in acceleration, transport and losses of these electrons (Friedel et al., 2002; Chen et al., 2007; Shprits et al., 2008a,b). Spacecraft measurements have provided critical evidence of gyro-resonant WPI as a dominant mechanism for the energization of magnetospheric electrons to relativistic energies (Chen et al., 2007; Reeves et al., 2013; Thorne et al., 2013).

Gyro-resonant WPI are understood via the Doppler-shifted resonance condition

$$\omega - n\Omega_c/\gamma = k_{||}V_{||},$$

where ω and $k_{||}$ are frequency and parallel (relative to the magnetic field) wave number of the waves, $V_{||}$ is the parallel velocity of a particle, γ is the relativistic factor, Ω_c is the (signed) cyclotron frequency, and n is the harmonic number. Under resonance conditions, particles can experience a quasi-static electric field (in the particle's reference frame) from the wave and efficient energy exchange can take place. Modeling the plasma physics of WPI from first principles from microscopic scales to the full spatial and temporal scales of interest for the radiation belts in not feasible with present-day computational capabilities. For this reason the governing paradigm for modeling WPI is based on quasi-linear theory wherein the evolution of particle phase-space densities is described by a bounce-averaged Fokker-Planck diffusion equation (Schulz and Lanzerotti, 1974) where WPI enter through a diffusion tensor and the properties of the waves are parameterized empirically by spacecraft observations (Xiao et al., 2009; Subbotin et al., 2010; Camporeale et al., 2013a,b; Tu et al., 2014; Jordanova et al., 2010).

Quasi-linear theory is based on the assumption of small amplitude and broadband, incoherent (randomly-phased) waves (Kennel and Engelmann, 1966). While quasi-linear theory has been successful in modeling geomagnetic storms (Albert et al., 2009; Thorne et al., 2013; Li et al., 2014a, 2014b; Tu et al., 2014), the underlying assumptions are not always valid. For instance, chorus waves are coherent whistler emissions coming in discrete, quasi-monochromatic rising or falling tones. There is evidence that chorus waves can reach very large amplitudes, of the order of a few percent of the background magnetic field (Cattell et al., 2008; Cully et al., 2008; Wilson et al., 2011; Santolík et al., 2014; Tyler et al., 2019). Similarly, EMIC waves can also reach very large amplitudes and can occur as rising tones (Pickett et al., 2010; Nakamura et al., 2019). Chorus and EMIC waves therefore break the assumptions of quasi-linear theory, requiring a full non-linear treatment.

Several investigations have identified the importance of non-linear WPI effects such as phase bunching and phase trapping in the interaction of chorus waves with electrons (Matsumoto et al., 1974; Albert, 2000, 2002; Omura et al., 2007). An important aspect is the particle interaction with rising or falling tones and, more generally, with triggered emissions. Theory and modeling have identified the "inhomogeneity parameter", which depends on the wave amplitude as well as on gradients in the background plasma density and magnetic field, as a controlling factor of the interaction (Nunn, 1974; Omura and Matsumoto, 1982; Omura et al., 2007; see also the review paper by Golkowski et al., 2019). Following an initial linear phase where chorus waves grow from a temperature-anisotropy instability (Kennel and Petschek, 1966) driven by freshly injected plasma-sheet electrons with 10–100 keV energy, the waves reach amplitudes where non-linear trapping occurs. For chorus rising tones, the frequency and amplitude of the waves increases while resonant electrons trapped by the wave create a phase-space hole and are accelerated non-adiabatically (Omura et al., 2012, 2015). These non-linear effects are associated with specific sign changes of pitch angle and energy of the resonant particles implying an advective transport in energy-pitch-angle space, as opposed to stochastic, random-walk-like motion typical of diffusive transport (Albert, 2002; Bortnik et al., 2008). These interactions require therefore an advection-diffusion modeling paradigm (Albert, 2002). Note that the non-linear diffusion coefficients can be significantly smaller than the quasi-linear diffusion coefficients (Tao et al., 2012a), with strong implications on transport. Additionally, phase trapping can produce large changes in pitch angle and energy for a small number of particles, occurring on time scales that are much faster than those typical of the quasi-linear interaction (Albert, 2002; Summers and Omura, 2007; Bortnik et al., 2008; Artemyev et al., 2014; Mourenas et al., 2018). Observations have confirmed very fast electron acceleration associated with chorus waves that have been attributed to non-linear effects (Foster et al., 2017; Kurita et al., 2018). Landau resonance can also be very important for the non-linear acceleration of electrons by oblique whistler waves (Agapitov et al., 2015). Zhang et al. (2019) have analyzed data from the Van Allen Probes and the THEMIS spacecraft to show that non-linearly interacting chorus wave packets occur 5–30% of the times.

Several non-linear WPI effects have also been examined for EMIC waves in the magnetosphere. These effects produce rapid transport of electrons in pitch-angle space, including nonlinear resonance for EMIC waves and phase trapping in rising-tone EMIC waves (Kubota et al., 2015; Nakamura et al., 2019). When quasi-linear theory is used, the pitch-angle scattering into the loss cone by EMIC waves is typically limited to electrons with energies above an MeV or so (Ukhorskiy et al., 2010). That energy limit is lowered when non-resonant scattering of electrons with the EMIC waves is accounted for (Chen et al., 2016) or non-linear bounce resonances between electrons and the EMIC waves are accounted for (Blum et al., 2019). Liu et al. (2012) have studied the effect of phase bunching and phase trapping caused by large-amplitude EMIC waves, computing the advection and diffusion coefficients as a function of wave amplitude and concluding that these effects can significantly change the non-linear diffusion coefficients relative to the quasi-linear ones.

Non-linear WPI has been implicated in localized microburst losses to the atmosphere. Relativistic-electron microbursts are short-lived, spatially localized patches of relativistic-electron precipitation from the outer electron radiation belt (Blake et al., 1996; Thorne et al., 2005). Microbursts are associated with large-amplitude chorus waves (Lorentzen et al., 2001; Kersten et al., 2011; Breneman et al., 2017) and have been argued to be caused by electron interactions with whistler mode rising tones (Saito et al., 2012) or by the nonlinear trapping of electrons in coherent EMIC waves (Omura and Zhao, 2013). There are also lower-energy (nonrelativistic) electron microbursts (Lee et al., 2012; Tsurutani et al., 2013), which have been argued to be caused by rapid electron transport in pitch-angle space caused by electron interactions with coherent (chorus element) waves (Tsurutani et al., 2009) or electron phase trapping in chorus rising tones (Hikishima et al., 2010).

Non-linear WPI is an active topic in magnetospheric physics. The relative importance of non-linear and quasi-linear WPI in determining the dynamics of the radiation belts remains poorly understood. Zhang et al. (2019) argued that with a 5–30% occurrence rate non-linear WPI should be dominant, but other effects such as amplitude modulation (Tao et al., 2012b; Gan et al., 2020) might play a role in decreasing the efficiency of non-linear WPI and must be quantified and accounted for. Similarly, the nature of the WPI causing microbursts remains an open question. The importance of non-linear WPI for radiation belt remediation also remains to be assessed. Radiation-belt-remediation schemes aim to reduce harmful fluxes of relativistic electrons, such as those generated from a high-altitude nuclear explosion, to levels that are tolerable for spacecraft as fast as possible (Inan et al., 2003): currently a number of schemes based on artificial injection of plasma waves are under examination (Ganguli et al., 2015; Carlsten et al., 2019) but whether non-linear WPI are detrimental or favorable remains to be seen. Models and methods to include non-linear WPI into the evolution of particle phase-space densities are beginning to appear (Vainchtein et al., 2018) but are not yet the norm in radiation belt modeling.

2.17. *Do we need a non-Maxwellian plasma physics?*

Plasmas in many regions of the magnetosphere seem to be in a state that is out of thermal equilibrium displaying non-Maxwellian distribution functions for the particle velocities (e.g. Christon et al., 1989; Runov et al., 2015; Thomsen et al., 2017). In the particular case of magnetized nearly collisionless plasmas, once a particle velocity distribution function (PVDF) is perturbed, its subsequent evolution can be very complex and there is no reason for it to rapidly relax to a Maxwellian distribution due to the lack of collisions or faster than relaxation transport. Although the way this process occurs is still open for debate, there is evidence that these PVDF appear in a nonlinear quasi-stable state, coexisting with a finite level of electromagnetic fluctuations even in the presence of temperature anisotropy (Navarro et al., 2014). The understanding of these non-Maxwellian quasi-stable states, with their underlying PVDFs, is fundamental for (a) the transport coefficients that may be relevant in global kinetic/hybrid modeling of the magnetotail and the magnetosphere, the solar wind-magnetosphere interactions, the evolution of geomagnetic storms and substorms; (b) the regulation of the range of possible states that the macroscopic system may display; (c) the control of the kinetic nature and types of waves that can propagate in the environment, which are relevant for precipitation of particles into the ionosphere and auroral signatures; and (d) determining electromagnetic and density fluctuations that define specific plasma dissipation levels.

Under certain conditions the PVDFs that appear in these quasi-stable states seem to be well described by kappa-distributions (Livadiotis, 2017), a PVDF with a thermal core and enhanced power-law tails for higher energies (that may also include temperature anisotropy, beams, etc), such that for large values of the kappa parameter the PVDF usually approaches a Maxwellian distribution function. In the magnetosphere it is indeed difficult to find electron or ion PVDFs that resemble Maxwellian distributions. For instance, in the particular case of the magnetotail plasma sheet, the description of both electron and ion PVDFs as kappa-distributions provides an excellent agreement with data in a large number of observations (Espinoza et al., 2018). The obtained kappa values are relatively small, i.e., 2–5 for electrons and 5–7 for ions, with spatial variations along the magnetotail and during the phases of substorms. There are also spatial and substorm phase variations of the temperatures of electrons and ions. The fact that ions seem to display a consistent kappa value larger than that for electrons, with varying relative temperatures, suggests a robust nonlinear process that preserves the shape of the PVDFs as the particles are accelerated or lose energy in their motion within the magnetotail and during the different phases of substorms (Viñas et al., 2005; Benson et al., 2013; Stepanova and Antonova, 2015; Espinoza et al., 2018).

To resolve these open issues, there is a primary need to study, through simulations and theoretical efforts, the kinetic processes of the generation and relaxation of these PVDFs and there is a need to characterize the quasi-stable state that the plasma reaches after perturbation in the different magnetospheric environments. We need to resolve whether the kappa-distribution becomes a general asymptotic form of the PVDFs, as is common in the magnetotail plasma sheet, or whether there are other shapes that may be relevant. Global kinetic/hybrid simulations should consider the effects produced by transport coefficients and PVDFs that are based on these non-Maxwellian distributions. The existence of non-Maxwellian distributions may also affect the generation and propagation of waves and related kinetic instabilities. Similarly, non-Maxwellian distributions should produce a considerable level of electromagnetic and density fluctuations that may seed instabilities, help excite turbulent magnetic reconnection, contribute to the electron precipitation into the ionosphere, etc. These are just a few examples of the effects associated with non-Maxwellian PVDFs and that would certainly introduce some new exciting physics into magnetospheric plasma physics. In terms of data, it is important to provide, in a regular and easily accessible fashion, estimates of non-Maxwellian distribution coefficients beyond the usual densities, temperatures, and heat flux: quantities such as estimated kappa value, and hopefully other higher moments that could provide information about the type of distribution function that is observed. All of these in conjunction with magnetic-field and electric-field measurements at the proper electron and ion time scales (e.g. Kletzing et al., 2017).

These open questions may become even more interesting as the spatial/temporal variation of the background magnetic field, plasma density, or other plasma parameters become of the same order of the relevant particle spatial/temporal scales such as the Larmour radius or gyrofrequency, which is expected to affect the kinetic dynamics of the plasma considerably.

2.18. How can the magnetic-field mapping be established so that magnetospheric plasma phenomena can be connected to ionospheric phenomena?

One of the long-standing scientific problems in magnetospheric science concerns the coupling between the ionosphere and the magnetosphere (Denton et al., 2016a). Extensive sets of global ionospheric measurements exist associated, for instance, with dynamic auroral displays and a variety of auroral forms. These displays are manifestations of processes occurring in the equatorial magnetosphere, where extensive data sets of spacecraft measurements also exist. However, linking magnetospheric measurements with ionospheric measurements unambiguously is not possible. The inability to determine the magnetospheric location of discrete aurora (cf. Fig. 4) hinders the understanding of the impact of the aurora on magnetospheric dynamics (Borovsky et al., 2020a; Forsyth et al., 2020). The inability to determine the magnetospheric location of the growth-phase auroral arcs hinders our understanding of magnetospheric processes at work prior to and during substorm onset. Not knowing the magnetospheric location of ionospheric flows such as sub-auroral polarization stream (SAPS) (Foster and Burke, 2002) or substorm sub-auroral ion drifts (SAID) (Spiro et al., 1979) prevents us from understanding the true impact of these phenomena on the magnetospheric system. Thus, many of the fundamental connections, essential physics, and drivers of the coupling between ionosphere and magnetosphere remain poorly understood. This also implies that the long-standing quest of using auroral observations as a TV screen of magnetospheric activity (Akasofu, 1965; Mende, 2016a, 2016b) cannot be realized.

Since charged particles are constrained by the magnetic field, the problem of linking ionospheric and magnetospheric measurements is associated with the accuracy of the magnetic-field-line mapping. Magnetic-field models based on spacecraft data (Tsyganenko and Usmanov, 1982; Tsyganenko, 1989; Tsyganenko and Sitnov, 2007) are normally used for this task, but they can be very inaccurate, particularly when geomagnetic activity is high (Thomsen et al., 1996; Hones et al., 1996; Weiss et al., 1997; Ober et al., 2000; Shevchenko et al., 2010; Nishimura et al., 2011). In special cases the magnetosphere-ionosphere connection can be established unambiguously: (1) using “natural tracers” (Antonova et al., 2015) that can be seen above the ionosphere and in the magnetosphere such as particle-isotropy boundaries (Sergeev et al., 1993; Shevchenko et al., 2010), pressure gradients (Antonova et al., 2018), particle boundaries (Moretto and Yahnin, 1998), or particle distribution functions (Hones et al., 1996) or (2) by comparing the timing of chorus-mode modulation in the magnetosphere with the timing of optical auroral pulsation patches in the upper atmosphere (Nishimura et al., 2010; Jaynes et al., 2015). But in general the magnetosphere-ionosphere connection is poorly established.

The most robust solution the magnetic-mapping problem involves firing a high-power electron beam from a magnetospheric spacecraft into the atmospheric loss cone to create a beam spot in the atmosphere that can be imaged optically or with radar (Borovsky, 2002; Delzanno et al., 2016; Borovsky and Delzanno, 2019; Sanchez et al., 2019; Borovsky et al., 2020b). The use of electron beams for magnetic-field-line mapping has never been attempted for fear of catastrophic spacecraft charging induced by the electron beam: this aspect was identified as an outstanding technology problem in the most-recent decadal survey for space physics (National Research Council, 2012). A beam spot detectable from the ground in the presence of aurora requires ~10 kW of power: assuming a beam energy between 10 keV and 1 MeV, the corresponding beam current is between 10 mA and 1 A. This current is significantly larger than the thermal electron current of 10’s μA associated with the tenuous magnetospheric environment (plasma density $\sim 1\ cm^{-3}$), implying that the spacecraft would charge substantially. Indeed, simple spacecraft charging models estimate the resulting spacecraft potential above 100 kV for an electron beam experiment targeting magnetosphere-ionosphere coupling (Delzanno et al., 2015a).

Recent work has made significant progress on several plasma-physics fronts towards establishing the feasibility of high-power electron-beam active experiments in the low-density magnetospheric environment. Recent theory and modeling work has identified a suitable spacecraft-charging mitigation scheme based on the plasma-contactor technology (Delzanno et al., 2015a,b; Lucco Castello et al., 2018). The idea is for the spacecraft to emit a high-density, charge-neutral plasma prior to and during the emission of the electron beam. Modeling work shows that the plasma contactor can mitigate spacecraft charging by emitting substantial ion currents, instead of enhancing the collection of background electrons from the spacecraft as commonly believed. These ideas have been confirmed by recent laboratory experiments (Miars et al., 2020). Thus, the once-overwhelming spacecraft charging problem can be substantially reduced and current model predictions indicate that the spacecraft potential induced by the electron beam can be kept of the order of a 1 kV or less for parameters relevant to a magnetosphere-ionosphere active mapping experiment (Lucco Castello et al., 2018). The recent development of compact, radio-frequency electron accelerators (Lewellen et al., 2019) opens the possibility of using relativistic electron beams for space applications. As discussed above, a higher beam energy implies a lower beam current (for the same beam power) and lowers the spacecraft-charging risk. Furthermore, an electron beam rocket experiment based on this new technology is planned for 2021 (Reeves et al., 2020) and it will raise its technology readiness level for future space applications. Another line of work has focused on the transport of the beam to the atmosphere. Theory and modeling have shown that high electron-beam energies result in a shift of the atmospheric loss cone away from the magnetic-field direction (Mozer, 1966; Il’ina et al., 1993; Porazik et al., 2014). This loss-cone shift is due to a curvature-drift correction to the electron’s gyromotion. Test-particle simulations of beam electrons in suitable magnetic field models have studied the accessibility of the atmosphere to the beam electrons (Willard et al., 2019) and provided the boundary conditions for Monte-Carlo models that determine the atmospheric signatures for beam detection (Powis et al., 2019). Marshall et al. (2019) studied the atmospheric signatures of a 1-MeV electron beam with total injected energy of 100 J or 1 kJ to determine the detectability of the beam spot optically or by radars: they show that, when the beam spot is directly over the camera, the beam optical emissions are sufficiently strong to be seen even against a fairly bright auroral background. The use of on-off blinking technology will further facilitate the detection against auroral emissions. The analysis also predicts detectability of the beam by the incoherent scatter radar.

2.19. What is the impact of radiation-belt precipitation on atmospheric physics?

Discussion at Pollenzo emphasized an outstanding and important issue that is not fully understood: the impact of radiation-belt precipitation on the physics and chemistry of the atmosphere. This is not so much a plasma-physics question as it is an Earth-system-science question. The radiation-belt precipitation can take the form of relativistic-electron microbursts (Blum et al., 2015b; Douma et al., 2019), which are temporally and spatially isolated patches of intense precipitation into the atmosphere caused, presumably, by intense patches of large-amplitude chorus-wave activity (Saito et al., 2012; Osmane et al., 2016). Radiation-belt relativistic electrons deposit their energy (and produce the most ionizations) at altitudes of about 50 km. The atmospheric-chemistry impacts of auroral electron precipitation at altitudes of about 100 km have also been considered (Weimer et al., 2011), as have the impacts of substorm-injected electrons at altitudes of 60–90 km (Seppala et al., 2015) and the impacts of solar energetic protons at altitudes of 30–70 km (Denton et al., 2018).

The known atmospheric impacts of energetic-particle precipitation include the production of NO_x, HO_x, and ozone in the middle atmosphere (Sinnhuber et al., 2012; Andersson et al., 2012; Seppala et al., 2018) and increases in the atmospheric electrical conductivity (Rodger et al., 2007; Borovsky, 2017). Changes in the concentration of NO_x, HO_x, and ozone can affect atmospheric radiative cooling with impact on the climate (Hunt et al., 2011); the changes in the conductivity of the atmosphere could impact the current driven by the fair-weather electric field (Borovsky, 2017), the Schumann resonances in the Earth-ionosphere waveguide (Salinas et al., 2016), the scattering of VLF radio waves (Rodger, 2003), and perhaps atmospheric cloud physics (Tinsley, 2000).

In Borovsky and Valdivia (2018) the concept was developed of a magnetospheric system comprised of multiple interacting ion and electron populations. The obvious integration of this magnetospheric systems science into the broader Earth systems science (Lawton, 2001; Reid et al., 2010; Kasting, 2013) is via the connection between magnetospheric energetic particles and atmospheric physics.

3. Conclusions and future needs

Specific needs to answer each of the specific questions were called out in Subsections 2.1 - 2.19. An overview of the future needs for magnetospheric plasma physics are the following.

Measurements: Developing new techniques to measure cold ions and cold electrons in the dipolar regions of the Earth's magnetosphere was emphasized in Subsections 2.10 and 2.16 as an important advancement needed for magnetospheric plasma physics. The cold-plasma populations strongly affect many phenomena that are critical to the dynamics of the near-Earth environment such as solar-wind/magnetosphere coupling, substorm dynamics, waves and wave-particle interaction physics. Multispacecraft missions across the magnetotail (Subsection 2.3), in the dipolar region (Subsection 2.5), and in the auroral acceleration region (Subsections 2.8 and 2.9) were called for. A magnetotail constellation mission is envisioned in Subsection 2.12. The need to routinely providing non-Maxwellian measurement parameters for ions and electrons was highlighted in Subsection 2.17. Subsection 2.17 also pointed out future needs for measurements of the dynamics of particle velocity distribution functions in conjunction with electromagnetic field and density perturbations at the electron and ion time scales, since these interactions regulate the plasma parameters and electromagnetic fluctuation levels in the magnetosphere (Viñas et al., 2015; Valdivia et al., 2016).

Global models and new physics: There is an increasing need to construct new theoretical models, as well as global kinetic/hybrid simulation frameworks, that include some of the new physics discussed in this manuscript, with particular emphasis on the correct generation of more realistic particle velocity distribution functions and their evolution in space and time, wave propagation at the ion and electron scales and their instability thresholds, electromagnetic and density fluctuations with the associated dissipation levels, etc. The questions in Section 2 specifically called for (a) higher-resolution and higher-Reynolds-number global simulations (Subsections 2.3 and 2.12), (b) global and magnetotail kinetic simulations (Subsections 2.3, 2.9, and 2.12), (c) higher-resolution simulations of the dipolar regions of the magnetosphere (Subsection 2.6), (d) modeling of the dipolar region with better wave-particle physics (Subsection 2.5), (e) simulations based on reduced-kinetics techniques (Subsection 2.10), (f) kinetic simulations of time domain structures (Subsection 2.15), and (g) an additional chemistry term in plasmaspheric refilling numerical simulations (Subsection 2.14). While fully-kinetic global codes appear unfeasible because of the dramatic scale separation between microscopic and system scales, the development of the next generation global models that deal with microscopic/macroscopic coupling is an active research area and various technologies (embedding kinetic models locally into large-scale MHD frameworks (Sugiyama and Kusano, 2007; Daldorff et al., 2014), hybrid (Karimabadi et al., 2014; Palmroth et al., 2018), fluid-kinetic (Markidis et al., 2014; Lin et al., 2014), and reduced-kinetic approaches (Delzanno, 2015; Roytershteyn and Delzanno, 2018)) are being explored and show promise.

Field-line-tracing techniques: As noted in Subsections 2.7, 2.11, and 2.18, there is a need to improve field-line-tracing techniques to study important problems such as (a) the auroral-arc-generator question, (b) the impact of the ring current and pressure balance on the structure of the inner magnetosphere, (c) the mechanisms underlying SAIDs and SAPs, etc. For example an ensemble of cubesats, combined with nonlinear reconstruction and/or machine learning techniques, may provide useful and reliable information about how the magnetic field provides a connection to different regions of the complex magnetosphere. In Subsection 2.18 an electron-beam technique for connecting magnetospheric measurements to ionospheric phenomena was outlined.

System science and nonlinear/linear models: There is a need to continue developing system science approaches to study the highly connected magnetospheric system (Valdivia et al., 2005, 2013; Usanova and Shprits, 2017; Borovsky and Valdivia, 2018): to construct data-derived models to advance our understanding of the physics involved in the magnetospheric dynamics, in essence helping to advance and complement the development of physics-based models. Particularly relevant for the future is a need to ascertain the relevance of the linear and nonlinear coupling of the magnetosphere's subsystems to each other and to the Sun and solar-wind driver. In this respect, it is important to continue developing nonlinear system science techniques to determine these nonlinear connections, discarding irrelevant variables, and providing dynamical models that can improve our physical understanding of this highly complex system and help to develop space-weather applications.

Better solar wind monitors: At Pollenzo, the question arose about how to obtain better solar-wind measurements for magnetospheric physics. For more-accurate system science studies and for more-realistic upstream boundary conditions for global simulations, there is an increasing interest to have simultaneous and continuous monitoring of the solar-wind plasma and field parameters at as many different positions in the near-Earth region as possible (Sandahl et al., 1996; Viall and Borovsky, 2020; Burkholder et al., 2020). This will provide much improved accuracy of parameters of the solar wind that actually hits the magnetosphere and will provide improved understanding of the spatial variability of the solar wind plasma and magnetic-field structure impinging on the magnetosphere.

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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