Core-Plasma Refilling and Erosion: Science Justification

Jerry Goldstein[1] (jgoldstein@swri.edu); Dennis L. Gallagher[2], Philippa Molyneux[1], Geoffrey D. Reeves[3]
[1]Southwest Research Institute; [2]NASA Marshall Space Flight Center; [3] Los Alamos National Laboratory

Overview Global geospace circulation models do not currently couple dynamic plasmaspheric simulations due to computational limitations that will be overcome by 2050. A true GGCM will need to include a dynamic plasmasphere for both physics and space weather prediction. Such inclusion requires that we answer longstanding, fundamental questions about the life cycle of core (<10 eV, plasmaspheric) plasma: how it gets into the inner magnetosphere, and how it is eroded.

Erosion and refilling are processes controlling a fundamental space plasma population. During every geomagnetic disturbance, tens of metric tons of plasma are rapidly eroded away, then slowly and unevenly replenished. After several decades we still do not understand the cross-scale mechanisms proposed to be responsible for these 2 processes. Removal and replacement of this enormous plasma mass is as important to the dynamics of the magnetosphere as solar-wind driving. Our community must dedicate the resources and effort needed to solve this enduring puzzle.

Other HP2050 white papers are discussing cold plasma and ionospheric outflow in more general contexts. This white paper deals specifically with the science justification for studying refilling and erosion.

1 Scientific Background, Goal, Objectives

A long term strategic goal is to understand how the core plasma of the inner magnetosphere erodes and refills (Table 1). The goal comprises two major targets: (1) Refilling, and (2) Erosion.

Earth's Plasmasphere. The plasmasphere is the region of cold (<10 eV), dense (10–10^4 cm^{-3}) plasma extending several Earth radii (R_E) into space [*Lemaire & Gringauz* 1998; *Darrouzet et al* 2009] (Fig 1a). There remain major unsolved puzzles about this region and its boundary layer, the plasmapause [*Carpenter* 1963; *Carpenter et al* 1993], including the basic processes of refilling [*Gallagher &Comfort* 2016], and erosion [*Carpenter* 1995; *Carpenter & Lemaire* 1997; 2004]. Also still unknown are the mechanisms creating oxygen-rich ion structures such as the cold dense O^+ torus [*Roberts et al* 1987; *Fraser et al.* 2005; *Nosé et al* 2011, 2015, 2018]. All these unknowns are captured by the 2 major objectives and 5 major questions in Table 1. It is noteworthy that these 2 objectives map directly to 2major SWMI Goals of the last Decadal Survey [cf. §9-1].

Importance of Core Plasma. Core plasma's enormous mass argues for its central importance. At 10^2 - 10^3 metric tons (cf. Fig 1b), the plasmasphere's vast inertia affects time dependent behavior of multiple geospace plasmas [cf. *Goldstein et al.* 2018, many references therein]: (a) Alfvén waves responsible for magnetosphere-ionosphere coupling; (b) wave properties controlling energetic radiation belt electrons; (c) scattering and energy degradation of ring current ions drifting through cool plasma. Ion composition is of particular importance. For ≥5% O^+ concentration, the mass contribution from heavier O^+ ions compares with that of H^+ [*Goldstein et al.* 2019b; Fig 1b]. Mass loading governs the propagation speed of Alfvénic waves & affects the growth of electromagnetic ion cyclotron (EMIC) waves that scatter energetic electrons. Plasmaspheric mass density at large L values may slow dayside reconnection. Erosion and refilling—the episodic recycling of metric tons of space plasma—control the majority of magnetospheric mass and inertia.

Cross-Scale Measurements. The cold ion population (down to 0 eV) is rarely a primary observing target—but it should be. Basic questions remain in part because of an enduring lack of knowledge of fundamental attributes of the coldest plasma: density, convection, ion species composition, and pitch angle distributions. A true GGCM for the entire magnetosphere must include plasmaspheric dynamics, but a lack of primary cold plasma measurements to compare with models has hindered progress in this area. New core plasma measurements are sorely needed, and they must be cross-scale—spanning global, regioonal, and local. The most important outstanding questions about core plasma involve multiple spatial scales: macroscale (several R_E), mesoscale (0.2–1R_E), & microscale (single flux tubes). Tracking density of moving flux tubes on global/regional scales (e.g., via global imaging) captures how plasma is added, eroded, or redistributed. Measuring full cold (down to 0 eV) ion distribution functions captures the microphysics of individual flux tubes: ion trapping, heating, and transport.

2 Science Discussion

2.1 Determine how core plasma fills the plasmasphere

Plasmaspheric refilling is how ionospheric plasma repopulates magnetic flux tubes that have been emptied by erosion. As depleted flux tubes convect across the dayside in contact with the ionosphere, they fill with ionospheric plasma, reaching saturated levels on day-to-week timescales [*Carpenter and Anderson* 1992]. That refilling occurs is well established by decades of work [*Gringauz et al.* 1962; *Singh and Horwitz* 1992; *Gallagher and Comfort* 2016]. Despite this long history, there remain 3 major questions about the supply of cold plasma.

(1A) How is the plasmasphere replenished?

Refilling is a large-scale phenomenon of plasma flows from a nonuniform ionosphere—along entire field lines, over a range of L & magnetic local time

Table 1 Science Goal, Objectives, and Questions

Science Goal	Science Objectives	Science Questions
Understand how the core plasma of the inner magnetosphere erodes and refills	(1) **Refilling:** Determine how core plasma fills the plasmasphere	*1A* How is the plasmasphere replenished?
		1B How are ions trapped during refilling?
		1C What causes the dense oxygen torus?
	(2) **Erosion:** Understand how the plasmasphere is eroded and redistributed during disturbances	*2A* How does convection redistribute core plasma?
		2B What role does interchange play in erosion?

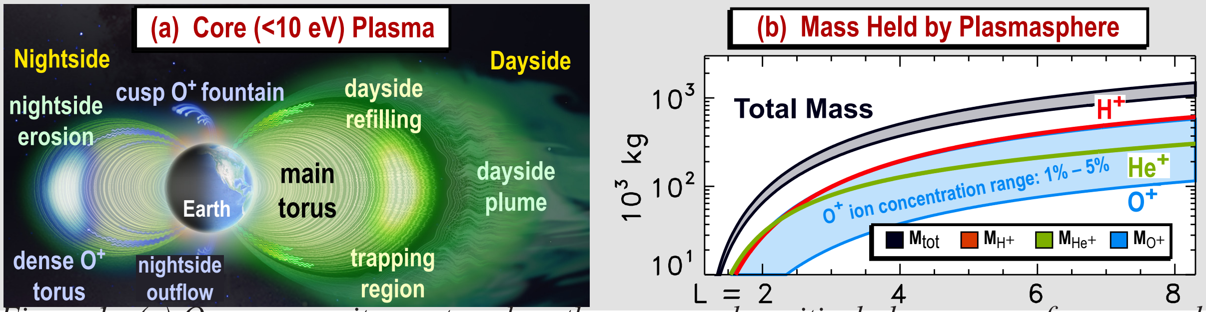

Figure 1 (a) Our community must explore the cross-scale, critical phenomena of source and loss of core (<10 eV) plasma. (b) Plasmaspheric core plasma composes the majority ($10^2 – 10^3$ metric tons) of the mass of the magnetosphere [adapted, *Goldstein et al.* 2019b].

(MLT). Observational studies of refilling have relied mostly on statistical analysis of in situ densities, to yield average refilling rates of a few to several hundred (cm^{-3} day^{-1}) [*Denton et al.* 2012]. Orbiting spacecraft cannot follow the drift paths of convecting/refilling flux tubes, so ground-based and geostationary studies have imperfectly addressed this limitation by assuming strict corotation [e.g., *Park* 1970; *Higel & Lei* 1984; *Sojka & Wren* 1985; *Su et al.* 2001]. The He^+ refilling rates estimated from IMAGE EUV images [*Sandel and Denton* 2007] were a first system-level view of this process, but with coverage gaps and assuming strict corotation. Tracking refilling along convection drift paths [*Nakano et al.* 2014a, b] to determine true field-line refilling is sorely needed. Local ion pitch angle distributions (PADs) are a refilling diagnostic; the transition from trapped ion PADs (inside the diffusive plasmasphere) to field-aligned (FA) beams (from ionospheric outflow) is observed even in the absence of a plasmapause gradient, and for warmer ion energies [*Sojka et al.* 1983, 1984, *Olsen et al.* 1985, *Menietti et al.* 1988, *Yue et al.* 2017]. We need to connect global density increases to local refilling ion beams for a definitive picture of refilling

(1B) How are ions trapped during refilling?

Another very basic question about refilling remains unanswered: how are ions trapped? During refilling cold ion beams emerge from the ionosphere in each hemisphere and flow upward along the magnetic field [*Sojka et al.* 1983, 1984]. For these streams to be effective at refilling requires trapping, i.e., conversion of field-aligned PADs to trapped distributions [*Singh and Horwitz* 1992]. Without ion trapping, refilling cannot happen—ion beams would simply re-enter the conjugate ionosphere. There are 3 candidate mechanisms responsible for ion trapping, all of which predict 2 stages of refilling (early & late): (1) *Shock thermalization (early-stage)* of bi-directional supersonic field aligned (FA) flows [*Banks et al* 1971; *Sojka et al* 1983; *Singh and Horwitz* 1992]; (2) *Scattering by waves (early stage)* [ion acoustic, ion cyclotron, equatorial noise; *Schulz & Koons* 1972; *Singh & Horwitz* 1992; *Young et al* 1981; *Omura et al* 1985; *Singh et al* 1982]; (3) *Coulomb collisions (late stage)* after density accumulates to 10–20 cm^{-3} or so [*Schulz and Koons* 1972; *Lemaire* 1989, 1990]. Models have advanced considerably, but we have lacked the observations to distinguish these trapping mechanisms. Cold ion moments would help diagnose supersonic flows/shocks and estimate Coulomb collision timescales and compare with observed PAD evolution. Local wave measurements would help determine which mechanisms correlate with ion PAD isotropization. We need system-level measurements of the global refilling rate time to determine if refilling occurs in 2 stages as predicted, and what the timescales are.

(1C) What causes the dense oxygen torus?

A major question has remained unsolved for 3 decades: what causes the dense oxygen torus [*Goldstein et al.* 2018]? Observations show factor-of-10 to 100 enhancements in O^+ (& O^{++}) density during/after geomagnetic disturbances—inside or just outside the plasmapause at any MLT [*Horwitz et al* 1984, *Roberts et al* 1987; *Fraser et al* 2005; *Nosé et al* 2011, 2015, 2018; *Goldstein et al* 2019b]. These enhancements are large compared to the quiescent O^+ concentration of ≤1% in the plasmasphere. If the torus is asymmetric in MLT, it is not known where the peak occurs or what controls that location. The dense torus strongly affects mass loading. E.g., at >5% concentration the O^+ mass contribution (tens to hundreds of metric tons) can equal that of the dominant ion H^+ [*Goldstein et al*. 2019b, Fig 1]. O^+ has properties (density, temperature), spatial and PA distributions that are very different from light ions [*Goldstein et al* 2019b]. Enhanced O^+ ion densities are seldom observed during light ion refilling, and field-aligned (FA) beams of O^+ and H^+ occur at different *L* shells [*Singh &Horwitz* 1992]. These differences imply different source mechanisms.

How are these ions supplied from the ionosphere? Three main pathways are proposed, with different timescales [*Goldstein et al*. 2018; *Hull et al.* 2019]: (1) cusp O^+ outflow over the polar cap (~1 h timescale), (2) convected from the dayside (several hours), or (3) directly from the auroral zone (>90 min). System-level observations of the global morphology (local time and latitude extent) and timing of formation of the dense O^+ torus can indicate source mechanisms and global pathways of O^+ [*Goldstein et al*. 2018]. Simultaneous in situ ion data (combined with models as needed) provide essential microphysics information, elucidate heating mechanisms, and can indicate cross-*L* or oblique transport [*Nagai et al* 1983; 1985; *Giles et al* 1994].

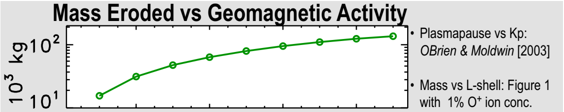

Fig 2. Erosion removes tens of metric tons of mass in several hours. Stronger disturbances (measured by Kp index) remove more mass.

2.2 Understand how the plasmasphere is eroded and redistributed during disturbances

During disturbances the outer layers of the plasmasphere are eroded [*Carpenter* 1970; *Chappell et al.* 1970a; *Goldstein et al*. 2019a], creating plumes of plasma reaching the magnetopause [*Grebowsky* 1970; *Elphic et al.* 1996; *Goldstein and Sandel* 2005; *Thaller et al.* 2015, 2019]. Whereas refilling takes days, erosion removes tens of metric tons of plasma in several hours [*Goldstein et al.* 2003a; *Goldstein et al*. 2019a, b; cf. Fig 2]—a rapid & immense reduction of inner magnetospheric inertia. Erosion occurs over a broad range of disturbance levels, from mild [*Goldstein et al* 2003a] to severe [*Baker et al* 2004].

Erosion informs us about both the plasma and the stormtime electric fields in the inner magnetosphere. The convection E-field is not simply a superposition of cross-tail and corotating components. The real field includes a host of mesoscale E-field structures—e.g., shielding, overshielding, contributions from ionospheric and thermospheric coupling, and many others uknown—few of which are even crudely captured by existing statistical/empirical models. Likewise, MHD convection fields are insufficient, and are difficult to test for lack of observations. There remain 2 major questions about the erosion and redistribution of cold plasma.

(2A) How does convection redistribute core plasma? According to the prevailing convection hypothesis, sunward convection erodes cold plasma—creating a steep nightside plasmapause gradient and a dayside plume [*Grebowsky* 1970; *De Pascuale et al.* 2018]. Convection models are successful at reproducing important system-level features (e.g., plasmapause & plumes) within 0.2–0.7R_E [*Goldstein* 2006; *Goldstein et al.* 2014a, b]. This level of agreement is insufficient to describe accurately severe stormtime erosion [e.g., *Baker et al.* 2004], or the large variety of mesoscale (0.2–1R_E) density structures observed at all activity levels, such as shoulders, notches, crenulations, and fingers [*Goldstein et al.* 2002, *Sandel et al.* 2003; *Gallagher* 2002; *Adrian et al.* 2004; *Goldstein and Sandel* 2005]. Despite decades of study, the stormtime convection field is not known or understood well enough to explain most of these features.

IMAGE EUV images have been used to deduce the full cross-*L* convection field at the plasmapause using the simple technique of *Goldstein et al.* [2004]. Recent development of more sophisticated Kalman-filter inversions has advanced significantly the ability to extract density and convection (E-field) from EUV images, and thus track the transport of He^+ density [*Nakano et al.* 2014a, b]. Measuring global density and convection versus location and time enables a long-awaited view of inner magnetospheric convection, and a true accounting of transport and loss of plasmaspheric mass during erosion.

(2B) What role does interchange play in erosion? For decades, the convection paradigm [*Nishida*,1966; *Brice* 1967; *Goldstein et al.* 2019a] has dominated the study of core plasma. The inability of convection models to reproduce many observed mesoscale features (noted above) suggests a basic gap in understanding. An alternate hypothesis is that centrifugally-driven flux tube interchange plays a major role in formation of a new plasmapause [*Lemaire* 1975; *Lemaire and Kowalkowski* 1981]. Centrifugal interchange is very important in the rapidly-rotating magnetospheres of giant outer planets [*Pontius et al.* 1997; *Burch et al.* 2005]. At Earth the role of interchange in plasmaspheric erosion is still an open question. Our community must finally answer this question. Each of the 2 physical processes (convection or interchange) makes measurably different predictions for global erosion dynamics [*Lemaire and Pierrard* 2008]. In the convection model the eroding plasmapause follows field lines. In the interchange model, the new plasmapause follows the zero-parallel force (ZPF) surface, where field-aligned components of centrifugal and gravitational forces cancel [Fig 3; *Lemaire and Gringauz* 1998]. The ZPF shape is very different from that of the field line, and would be clearly observable in global images. Local ion and e⁻ densities could be tested for the presence of nightside plasma blobs moving radially outward during erosion, as uniquely predicted by the interchange hypothesis.

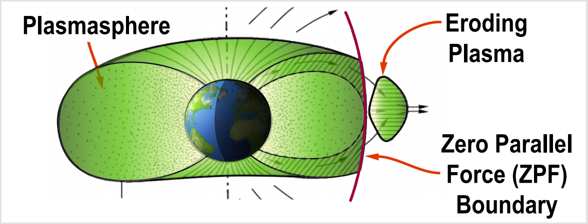

Fig 3. The interchange hypothesis predicts that during erosion events the new plasmapause forms along the Zero-Parallel Force (ZPF) surface [Lemaire and Gringauz 1998]

3 Conclusion

The plasmasphere must be a dedicated focus of the next few decades' effort. Core plasma mass controls Alfvén wave propagation and the loss rates of other space plasmas. Every time a storm or disturbance occurs, this important plasmaspheric plasma gets rapidly eroded away, then slowly and unevenly replenished. Episodic removal and replacement of tens of metric tons of plasma is as fundamentally important to the dynamics of the magnetosphere as solar-wind driving. It is time we devote the resources to finally understand how the erosion and refilling of this core plasma truly happens.

4 References

A list of references is found at: http://enarc.space.swri.edu/HP2050/ or http://plasmasphere.nasa.gov/HP2050/