Geospace Core Plasma Supply and Refillling (CPSR): Science and Observations for the Next Decade

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Synopsis

Geospace core plasma supply and refilling (CPSR) are fundamentally important to geospace dynamics, yet these processes fall within a major knowledge gap. The ionospheric supply of core (initially cold, <10 eV) plasma maintains and creates several fundamental geospace populations that carry tens to hundreds of metric tons of plasma mass: plasmasphere, dense oxygen torus, and plasma sheet and ring current (RC). These CPSR processes have a much wider impact than just supplying cold plasma regions; core plasma is initially cold but is energized (by tens of eV to keV) as it is transported, to provide a major contribution to the content and dynamics of the plasma sheet and RC. Beyond the significance to understanding the supply and refilling of the majority of magnetospheric plasma mass, this gap also has even greater importance because core plasma exerts such strong control over numerous basic geospace processes including Alfvén waves, M-I coupling, wave/scattering properties affecting radiation belt electrons and ring current ions, mass loading of magnetic reconnection, and the atmospheric H escape rate. It is essential that we answer longstanding, fundamental questions about the supply and replenishment of an enormous plasma mass whose cycle is as important to the dynamics of the magnetosphere as solar-wind driving. Our community must dedicate the resources and effort to finally understand it.

Progress in this area has been hindered—and basic questions have gone unanswered—because of an enduring absence of primary cold plasma measurements. These measurements are essential not only to compare with ever-evolving predictive models, but also to obtain basic and complete knowledge of fundamental attributes of magnetospheric plasma: density, convection, ion species composition, and pitch angle distributions. The cold ion population (down to 0 eV) is rarely a primary observing target, but it should be. New core plasma measurements must be cross-scale, and cross-energy. The most important outstanding questions about core plasma involve multiple spatial scales: macroscale (several R_E), mesoscale (0.2–1R_E), and microscale (single flux tubes). Tracking density of moving flux tubes on global and regional scales (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. Because transport and energization of core plasma may help create the plasma sheet and ring current, new measurements must also span a broad energy range, from 0 eV to at least a few tens of keV.

The needed new observations are herein discussed, grouped into two elements: in situ, and imaging. The majority of the proposed required technology is already mature and high heritage, requiring no additional development. The few exceptions either have an already-developed (and costed) technology maturation plan to get from TRL 5 to 6, or are high TRL technologies that merely require on-orbit demonstration for the novel application to geospace CPSR science observations.

Table 1.1 *Geospace Core Plasma Supply and Refilling (CPSR)*: Science Objective and Questions	
CPSR Science Objective	**CPSR Science Questions**
(1) Determine how core plasma is supplied and replenished	*1A* How is the plasmasphere replenished? *1B* How are ions trapped during refilling? *1C* What causes the dense oxygen torus?

0 Overview

The ionospheric supply of core (initially cold, <10 eV) plasma maintains and creates several fundamental geospace populations.

Plasmasphere. Ionospheric refilling directly creates the plasmasphere that makes up the vast majority of magnetospheric plasma mass [*Gringauz et al* 1962; *Singh & Horwitz* 1992; *Gallagher & Comfort* 2016; *Goldstein et al* 2019b]. Tens of metric tons of plasma are rapidly eroded away during every geomagnetic storm, then slowly and unevenly replenished in the post-storm recovery. After several decades we still do not understand the cross-scale mechanisms proposed to be responsible for refilling; major questions remain unanswered (***1A***, ***1B***, Table 1.1).

Dense Oxygen Torus. Mediated by energy-input, energized ionospheric outflow is responsible for the creation of the dense oxygen torus and warm plasma cloak [*Roberts et al* 1987; *Goldstein et al* 2018; *Hull et al* 2019; *Chappell et al* 2008]. After several decades we still do not know the pathways for heated ions to supply the dense oxygen torus (***1C***, Table 1.1). The dense torus can have a huge effect; for ≥5% O^+ concentration, the mass contribution from heavier O^+ ions compares with that of H^+ [*Goldstein et al* 2019b].

Plasma Sheet and Ring Current. These processes have a much wider impact than just supplying cold plasma regions. Core plasma is initially cold but is energized (by tens of eV to keV) as it is transported, to provide a major contribution to the content and dynamics of the plasma sheet and ring current [*Shelley et al* 1972; *Chappell et al* 1987; *Seki et al* 2003; *Huddleston et al* 2005; *André & Cully* 2012; *Glocer et al* 2020].

Geospace core plasma supply and refilling (CPSR) thus are fundamentally important to geospace dynamics, yet these processes fall within a major knowledge gap. This gap also has even greater importance because core plasma exerts such strong control over numerous basic geospace processes: (a) Alfvén waves, energy propagation, electrodynamic M-I coupling; (b) wave properties affecting radiation belt electrons; (c) scattering and energy degradation of ring current ions in cool plasma; (d) mass loading of magnetic reconnection that slows solar wind energy coupling; and (e) charge exchange reactions that can double the atmospheric H escape rate [*Goldstein et al* 2018 & citations therein, *Krall & Huba* 2019b, *Nass & Fahr* 1984]. It is essential that we answer long-standing, fundamental questions about the supply and replenishment of core plasma (Table 1), an enormous plasma mass whose cycle is as important to the dynamics of the magnetosphere as solar-wind driving. Our community must dedicate the resources and effort to finally understand it.

GPSR study advances multiple goals of the last *Decadal Survey* (Table 1.2). The core plasma component of these goals remains a knowledge gap, a decade later, on the eve of the next Decadal Survey. The perceived importance of this topic has only grown during the past decade (e.g., multiple core plasma-focused white papers submitted for the 2023 Decadal Survey). After decades of focus on almost every other element of geospace, core plasma is a knowledge gap that must be closed.

Table 1.2 Science contributions to Last Heliophysics Decadal Survey Goals

Decadal Survey Panel [c]	Goals [c]	CPSR Science Questions & Major Contributions
SWMI Solar-Wind-Magnetosphere Interactions	***S1*** How global & mesoscale structures in the magnetosphere respond to variable SW forcing	**1A, 1C.** Global and mesoscale core plama structures caused by variable SW forcing.
	S2 Factors that control the dominant sources of magnetospheric plasma	**1A, 1B, 1C.** Core plasma source of dominant magnetospheric plasma mass.
AIMI Atmosphere-Ionosphere-Magnetosphere Inter.	***A1*** How IT system responds to & regulates magnetospheric forcing	**1A, 1B, 1C.** Ionosphere and neutral H exosphere respond to & regulate magnetospheric forcing
	A3 Origins of plasma & neutrals within geospace	**1A, 1B, 1C.** Origins of core ions & exospheric neutrals

[c] *NRC Heliophysics Decadal Survey* [2013]

1 Still Unanswered CPSR Science Questions

Despite many decades of study of core plasma supply and refilling [*Gringauz et al* 1962; *Singh and Horwitz* 1992; *Lemaire & Gringauz* 1998; *Darrouzet et al* 2009; *Gallagher and Comfort* 2016], there still remain 3 major questions.

1A How is the plasmasphere replenished?

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; *Lemaire & Gringauz* 1998]. Observational studies 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. Ground-based and geostationary studies have assumed strict corotation, which also does not follow drift paths [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.

Another critical element is that the escape of major ion species (H^+, He^+, O^+, N^+) depends critically on ion/neutral distributions in the refilling source region [*Hultqvist et al* 1999, *Welling et al* 2015, *Krall & Huba* 2019b]. However, we lack measurements of these low-altitude distributions, and consequently, models are not well calibrated to reproduce observed refilling rates. Though it is known that the neutral H density <4,000 km is a major regulator of upward ionospheric light ion (H^+, He^+) escape flux [*Geisler* 1967, *Richards & Torr* 1985, *Krall et al* 2018b], we lack critical source-region measurements of neutral H variability that has been estimated to be as high as 40% [*Zoennchen et al* 2017, *Qin et al* 2017, *Cucho-Padin & Waldrop* 2019].

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]. Models have advanced considerably [*Pierrard et al* 2021], 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, what the timescales are, and whether or not early-stage refilling causes local density peaks near the magnetic equator.

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]. 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 high-altitude 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].

As with light-ion refilling (cf. **§1A** above) a critical aspect of the supply of oxygen ions is the dynamics within the low-altitude (<1200 km) source, the exobase transition region (ETR). Heavier ions such as O^+ must be heated from above to escape [*Roberts et al* 1987, *Strangeway et al* 2005]. Measurements throughout the ETR are needed to capture evolving cold ion distribution functions subject to two main acceleration processes: (a) charged particle kinetic energy input, such as magnetospheric electron precipitation and photoelectrons, and (b) electromagnetic energy input, such as magnetospheric Poynting flux, waves, and field-aligned currents. Proper study of this region requires multi-point synchronized probing to track variations of ion distributions and energy inputs vs. altitude and time.

2 Observational Needs

A complete description of the magnetospheric "system of systems" [*Claudepierre et al* 2022] must include core plasma dynamics. However, progress in this area has been hindered—and basic questions have gone unanswered—because of an enduring absence of primary cold plasma measurements. These measurements are essential not only to compare with ever-evolving models, but also to obtain basic knowledge of fundamental plasma attributes: density, convection, ion composition, and pitch angle. The cold ion population (down to 0 eV) is rarely a primary observing target—but it should be. The lack of a comprehensive, cross-scale (local regional and global), cross-energy observatory dedicated to finally understanding this continuously transformed plasma source is holding back crucial advances to understanding and predicting the basic dynamics of geospace.

New core plasma measurements must be cross-scale, and cross-energy. The most important outstanding questions about core plasma involve multiple spatial scales: macroscale (several R_E), mesoscale (0.2–1R_E), and microscale (single flux tubes). Tracking density of moving flux tubes on global and regional scales (via global imaging) captures how plasma is added, eroded, or redistributed. Measuring full cold (≥ 0 eV) ion distribution functions captures the microphysics of individual flux tubes: ion trapping, heating, and transport. Because transport and energization of core plasma may help create the plasma sheet and ring current, new measurements must also span a broad energy range, from 0 eV to at least a few tens of keV.

The needed new observations are herein grouped into two elements: in situ, and imaging.

2.1 In Situ Element Table 2.1

In situ measurements required for geospace CPSR science are summarized in Table 2.1.

2.1.1 Plasma / Particles

In situ particle measurements (Table 2.1a, c) are a primary measurement for CPSR science. Solving light-ion refilling and heavy-ion outflow requires capturing full ion distributions down to 0 eV to see the coldest ions (§2.1.2), and ≥ 20 keV to see core ion energization. Ion spectra and pitch angle distributions (PADs) characterize heating, trapping, and transport pathways. Ion moments are used to diagnose shocks, if they occur. Because

Table 2.1 In Situ Observations for Geospace CPSR Science			
Element	**Measurement or Capability**	**Description**	**Heritage Examples**
In Situ	**(a) Particles:** Ions	• Full ion distributions (spectra, PADs) for H^+, He^+, O^+ (minimum) and N^+, He^{++}, O^{++} (optimum). Energy 0 eV–20 keV, with $\Delta E/E \leq 20\%$. • Spacecraft Potential Control (SCPC) is required to access the coldest (≥ 0 eV) ions. High altitude: SPB (minimum required) with optional addition of IEM. Low altitude: BMS and IEM. • Spacecraft spin must sample full angular distribution with cadence ≤ 60 s (for spacecraft speed ≤ 3.2 km-s^{-1}, i.e. L ≥ 3 for GTO, need $\Delta t \leq 60$ s to get 3.3 points per 0.1 R_E.)	RBSP HOPE, MMS HPCA
	(b) Particles: Spacecraft Potential Control (SCPC)	Ion Emitter Method (IEM): Emits 5–9 keV indium ions to reduce positive SC potential. Use: ions	Cluster, MMS ASPOC
		Sensor-Panel Bias (SPB): instrument and adjacent SC panel are biased negative (≥3 on-orbit programmable voltage steps) relative to SC ground. Use: high altitude ions	DE-1 RIMS, Cassiope/e-POP SEI, Freja F3C
		Boom Mounted Sensor (BMS): Sensor of instrument mounted on boom to mitigate SC sheath effects. Use: low altitude ions	MAVEN / STATIC
		Electron Gun System (EGS): Emits 1 keV e^- to raise positive SC potential & separate cold electrons from photoelectrons. Use: electrons	N/A
	(c) Particles: Electrons	• Electron distributions (spectra, PADs), 0.6 eV–20 keV. EGS required to access cold electrons	RBSP HOPE
	(d) Fields	Measures Electric and Magnetic fields and waves.	RBSP EMFISIS, MMS FIELDS
	Fields: Magnetic Low Frequency	Fluxgate Magnetometer: Background B-field vector (for ion PADs), DC–20Hz waves, ±65,535nT, accurate to 1nT	
	Fields: Magnetic Waves	Waves 5Hz–10kHz, Δt=10s, 90dB, triaxial search coil assembly	
	Fields: Electric Waves	Waves & upper hybrid resonance (UHR): 5Hz–1MHz, Δt=10s, 90dB	
	Fields: Electric Low Frequency	Quasistatic (DC E-field, low-frequency waves <10Hz, SC potential. Δt=10s, 90kB, ±15V, ±0.5μV. Require two orthogonal spin-plane double probes, 100m tip-to-tip (minimum), spin-axis boom (optimum)	
	Radio Plasma Sounder (RPS)	Hosted on in-situ spacecraft because RPS requires use of dipole antennas. See Table 2.2	IMAGE RPI

LEGEND Particles Fields Radio

the mechanisms for light-ion refilling and heavy-ion outflow differ, composition information must at least distinguish H^+, He^+, and O^+ (and ideally should also resolve N^+, O^{++}, and He^{++}). The instantaneous field of view plus spacecraft spin must sample the full ion angular distribution every ≤ 60 s, with angular resolution ≤ 36º, sufficient to capture field-aligned ion outflow beams [*Olsen et al* 1985]. Cold electron distributions reveal field-aligned temperature gradients and scale heights that affect the strength of light-ion outflow [*Banks and Holzer* 1968, 1969]. Energetic electron distributions (up to 20 keV) reveal charged particle kinetic energy inputs driving heavy-ion outflow.

2.1.2 Spacecraft Potential Control (SCPC)

Sunlit, electrically conducting spacecraft (SC) charge positive relative to the ambient plasma. This SC potential barrier prevents the coldest ions from reaching particle instruments. Measurement of cold ions (§2.1.1, Table 2.1a) requires effective methods for spacecraft potential control (SCPC, Table 2.1b).

Ions, high altitude. For $r > 2\ R_E$, the positive SC potential can be up to +1V (in the dense plasmasphere), ≤ +5V (in the plasmatrough) [*Sarno-Smith et al* 2016a], and an order of magnitude higher in the more tenuous outer magnetosphere region. One effective mitigation method is negative electrostatic biasing (NEB) of instruments or sensor apertures to provide a pathway for cold ions through the SC sheath and into the sensor [*Knudsen et al* 2015; *Whalen et al* 1994; *Chappell et al*

1981; *Giles et al* 1994].

The Sensor-Panel Bias (SPB) method builds on previous NEB implementations by biasing the entire ion instrument and its adjacent SC panel negative relative to SC ground (i.e., the SC floating potential, V_{SC}), allowing cold ions to reach the sensor while minimizing angular deflection of incoming ions. Ideally, the sensor aperture should be close to the center of the SC panel. Measuring cold ions in the plasmasphere and trough requires at least 3 steps in bias voltage (V_B), and a ≥ 30V stepping power supply. Bias steps should be on-orbit programmable to optimize performance. V_B steps can occur once per SC spin, with a plasma equilibrium timescale of few µs. The SPB method incidentally obtains a measurement of V_{SC}, by comparing ion distributions at different V_B steps. Within the plasmasphere and trough, the SPB system is necessary and sufficient.

To optimize this performance and also extend it to more tenuous regions, it is recommended to include a secondary SCPC system, the Ion Emitter Method (IEM), which emits 5–9 keV indium ions to reduce positive SC potential to a nominal maximum value [e.g., ≤ +4V; *Torkar et al* 2016]. The IEM limits the SC potential so the SPB can do the best job of providing cold ion access.

Ions, low altitude. At ionospheric altitudes where density is higher, the Boom Mounted Sensor (BMS) method places the sensor on a boom whose length is scaled by the maximum expected Debye length, to mitigate SC sheath effects. As with the SPB system, BMS performance can be optimized by including a secondary IEM system.

Electrons. Positive SC potential does not impede cold electrons. However, cold photoelectrons generally obscure the ambient cold electron signal. An Electron Gun System (EGS) can emit 1 keV electrons to raise positive SC potential and separate cold electrons from photoelectrons.

2.1.3 Fields

Fields measurements are necessary to measure the local wave environment and the background geomagnetic field (to support particle PAD determination and wave identification). Driving requirements are obtained from the physically important frequency and spectral power ranges of three waves: ion cyclotron waves (ICW), equatorial noise (EQN), and the upper hybrid (UH) noise band. ICW and EQN are candidates for ion heating and trapping (cf. **§1B**), and the UH signature is needed to determine ambient total electron density. The various wave characteristics are well known [e.g., Figs 12 and 13 of *Kletzing et al* 2013]. Given existing technology, meeting these requirements possible with four instruments (Table 2.1d): two magnetic and two electric, each pair covering its required frequency range in 2 steps ("low-frequency", and "waves"). The notional Electric Low Frequency instrument also measures SC potential, which can be used to estimate plasma density, and complements estimates of SC potential from ion distribution functions during nonzero SPB bias steps (§2.1.2).

2.2 Imaging Element Table 2.2

Imaging measurements required for geospace CPSR science are summarized in Table 2.2.

2.2.1 Optical Imaging

Extreme ultraviolet (EUV) imaging (Table 2.2a) is a primary measurement for CPSR science. Two wavelengths of EUV imaging are needed to capture the distinct dynamics of light ions and heavy ions. EUV-304 and EUV-834 respectively image He^+ and O^+/O^{++} ions. The notional shared optical/mechanical design is based on that of IMAGE EUV; these 2 nearly identical cameras would differ only in their choice of front-end filter material and multilayer mirror coating formula [*Davis et al* 2013; *Goldstein et al*. 2018].

EUV-304 inversions (He^+ densities and convective flows) track moving flux tubes to determine true field line refilling as a funtion of time, location, and activity. Global and mesoscale refilling dynamics can be compared with 2-stage refilling models, and the field-aligned density dependence can be tested for an equatorial trapping peak. Simultaneous in situ particle moments and fields-derived densities can validate EUV-304 inversions, and in situ PADs confirm trapped versus refilling regions.

EUV-834 images distinguish pathways for O^+ torus formation by morphology and timescale: cusp outflow (~1h), convected from dayside (several h), auroral upflow (>90 min). Combined with simultaneous in situ O^+ distributions and models, EUV-834 field-aligned distributions help elucidate heating mechanisms. EUVHe-derived cconvection determines which drift paths feed into the

Table 2.2 Imaging Observations for Geospace CPSR Science

Element	Measurement	Description	Heritage Examples
Imaging	**(a)** Extreme Ultraviolet (EUV)	Extreme Ultraviolet imagers measure resonant scattering photons. • EUV-304: 30.4 nm light, He^+ ions, sensitivity ≥ 0.31 (R s pix)$^{-1}$ to capture 50 mR at ≤ 11 min cadence. • EUV-834: 83.4 nm light, O^+ & O^{++} ions, sensitivity ≥ 0.14 (R s pix)$^{-1}$ to capture 20 mR at ≤ 60 min cadence. • From notional 20 R_E circular orbit, require ≥ 30° field of view (FOV), 0.6° resolution to capture region $r \leq 6$ R_E and resolve 0.2 R_E.	IMAGE EUV
	(b) Radio Tomography (RT)	Measure total electron content (TEC) along LOS between receiver-transmitter pairs. Multiple LOS through plasmasphere/ionosphere e^- density provide tomographic measurement to complement EUV. • Limited Tomography: GPS receiver measures TEC between SC and multiple existing GNSS assets. • Full Tomography: Radio transmitters and receivers deployed on dedicated constellation of >20 microsatellites.	MMS Navigator
	(c) Energetic Neutral Atom (ENA)	Measure ENAs from 10eV–50keV with ΔE/E=100%, distinguish H, O. Global imaging of heated core ions supplied or transported to stormtime plasma sheet and ring current (RC)	BepiColombo LENA, JUICE JNA, TWINS
	(d) Geocoronal Imaging (GCI)	Measure variability of neutral H exosphere to determine effect on H^+ escape flux during refilling, estimate neutral H escape from charge exchange in plasmasphere, quantify charge exchange loss in RC	TWINS, ICON, GLIDE
	(e) Radio Plasma Sounder (RPS)	Remote sensing instrument (hosted on in-situ spacecraft; cf. Table 2.1). Scans 10kHz–1MHz, active sounding obtains electron density profile along the magnetic field, between spacecraft and ionosphere	IMAGE RPI
	(f) Thomson Scattering	Measure visible light scattered by electrons [*Englert et al* 2009] to obtain images of LOS-integrated total plasma density.	SOHO LASCO

LEGEND Optical ENA Radio

dense torus, and whether penetration E-fields are correlated with heavy ion outflow.

Geocoronal Imaging (GCI) (Table 2.2d) provides critical system-level, source-region measurements of neutral H variability that is a major regulator of upward ionospheric light ion (H^+, He^+) escape flux (**§1A**). Coordinated neutral-H and plasmaspheric (EUV, RT, and/or in-situ observations) are needed to determine how H variability affects light-ion refilling. GCI is also useful to quantify important ion-neutral interactions in the plasmasphere [*Nass & Fahr* 1984], and charge exchange losses in the RC [*Ilie et al* 2013].

Thomson Scattering (Table 2.2f) measures visible light scattered by electrons to obtain images of LOS-integrated total e^- density [*Englert et al* 2009]. Thomson scattering has long been used to image the solar corona; adaptation of this technique to imaging core plasma (the densest population, and thus the brightest magnetospheric signal, ~0.5–5 R) requires subtraction of in-band background light from zodiacal light (a bright ~1 kR source, but smoothly distributed and with dynamic timescale much longer than that of core plasma) and solar wind (a more time-variable source, 10–50 R). This technique complements EUV imaging with a LOS-integrated e^- density to calibrate He^+ and O^+/O^{++} ion fractions, validate inversions, and enable determination of total mass.

2.2.2 Radio Imaging

Radio tomography (RT) (Table 2.2b) uses space-based radio receivers and transmitters to obtain a tomographic determination of total electron density. Each receiver-transmitter pair obtains a measurement of total electron content (TEC) along their shared line of sight (LOS). A network of such pairs means multiple LOS through the plasmaspheric and ionospheric e^- density to enable tomographic reconstruction of density to complement EUV, and as a standalone capability.

Two categories of implementation are possible:

- Limited Tomography: On each SC, an onboard Global Positioning System (GPS) receiver measures TEC between the SC and multiple existing Global Navigation Satellite System (GNSS) SC. This implementation category is a cost-effective way to leverage existing assets. This capability could, for example, "light up" a finite number (12–20) of pixels in an EUV image with an absolute TEC calibration to scale He^{+} and O^{+}/O^{++} ion fractions, validate inversions, and enable limited determination of total mass.
- Full Tomography: In this option, radio transmitters and receivers are deployed on a dedicated constellation of 20–30 microsatellites and/or smallsats. This implementation yields a high-quality, rapidly-refreshing global tomographic reconstruction of density. More details are in the PILOT mission concept white paper [*Malaspina et al* 2022a, 2022b, 2022c, 2022d].

A ***Radio Plasma Sounder (RPS)*** (Table 2.2e) is an important addition to CPSR measurements. Based on IMAGE RPI [*Reinisch et al* 2000], the notional instrument scans within 10 kHz – 1 MHz, and 3-axis dipole antennas perform active sounding (transmitting radio pulses, observing echoes) of free-space and Z/whistler modes to get rapid field-aligned electron density [*Fung et al* 2003, 2008; *Sonwalker et al* 2014, 2011a, b, *Reinisch et al* 2004]. Because RPS needs dipole antennas on a spinning SC, it is probably best accommodated on an in situ observatory (Table 2.1).

2.2.3 Neutral-Particle Imaging

Energetic Neutral Atom (ENA) imaging (Table 2.2c) is needed for a system-level measurement of the core ion contribution to the content and dynamics of the plasma sheet and ring current (RC). As discussed (§0), initially cold core plasma is energized (by tens of eV to keV) as it is supplied or transported to become an integral part of these regions. Global measurements are complemented by ground-truth energetic particle observations (Table 2.1a, c). Assuming existing ENA technology, the required energy range (10 eV – 50 keV with $\Delta E/E$ = 100%) can be covered with two separate cameras: low-energy (10 eV – 3 keV) and medium/high-energy (1 keV – 50 keV). To distinguish light-ion and heavy-ion contributions, it is necessary to (at least) resolve H versus O ENAs.

2.3 Possible Mission Architectures

This white paper has focused on the types of measurements needed to study Geospace CPSR science. Mission designs are beyond our scope. Nonetheless, it is useful to consider generally where/how to deploy in situ (§2.1) and imaging (§2.2) elements. In situ measurements on spinning spacecraft must ideally be made at both low altitude (i.e., in the refilling source region) and at high altitude (where trapping and heating/transport occur). Imaging observations are best made from a high-altitude circular polar orbit on nadir-pointing 3-axis stabilized SC [*Goldstein et al* 2022], but are also useful from a near equatorial vantage point. Some possible mission architectures are suggested in other white papers, e.g., the PILOT [*Malaspina et al* 2022b, 2022c] and SOURCE mission concepts [*Goldstein et al* 2022wp].

3 Technology development

The majority of the proposed technology (Tables 2.1 and 2.2) is already mature and high heritage, requiring no additional development.

One exception is EUV-304/834 (Table 2.2a), currently TRL 5. A detailed EUV technology development plan (with schedule and cost for full prototype testing to TRL 6) was already developed for the 2019 TREO MIDEX proposal.

The other three exceptions involve a mixture of technology and technique demonstration:

- Radio tomography (Table 2.2b): A space-based demonstration of radio tomography is necessary to prove the capability to measure the expected signal (~0.1–10 TECU).
- Thomson Scattering (Table 2.2f): As noted, this technology is already used for solar corona imaging, but on-orbit demonstration for core plasma imaging must prove the capability to subtract the dominant in-band background light.
- Spacecraft Potential Control (Table 2.1b): On-orbit demonstration of existing and ever-improving SCPC technology elements is necessary to prove them effective for CPSR science.

4 Closing Remarks

In the coming decade, core plasma (down to 0 eV) must be a primary observing target. We need a comprehensive, cross-scale, cross-energy observatory dedicated to finally understanding this continuously transformed plasma source.

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