# ‘Follow the mass’: the Science Case for Transformational Multi-scale Observations of Mass and Energy Flow Dynamics in Earth’s Magnetosphere

A White Paper to the 2024-2033 Decadal Survey for Solar and Space Physics

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**A Massive Problem**: We have not yet determined the fundamental processes that govern plasma mass and energy flow through the terrestrial magnetosphere, nor the degree to which these flows regulate key magnetospheric subsystems.

**This Problem is Critical in Heliophysics and Beyond**: Hundreds of metric tons of ionized atmospheric gases pass into and through Earth's magnetic field. This mass accumulates in inner magnetospheric reservoirs, is transported through the magnetosphere, where it profoundly regulates magnetospheric subsystems, and can eventually be lost to the solar wind. Cold plasma ($< 1$ eV to 100 eV) carries the overwhelming majority of this mass, and tracking its flow is the weakest link in our chain of understanding for magnetospheric physics [23]. Currently, we understand more about atmospheric mass loss physics at planets with no intrinsic magnetic field, such as Mars and Venus, than we do at Earth [56, 114]. Understanding magnetospheric mass and energy flow is critical to understanding the mass loss rate of Earth's atmosphere, as well as to determining the importance of a planetary magnetic field for atmospheric retention [91], and therefore habitability, for Earth-like planets beyond the solar system.

**Persistent Knowledge Gaps**: Knowledge gaps related to the processes that govern plasma mass and energy flow through the magnetosphere have persisted through decades of magnetospheric measurements due to three primary limitations. First, the Earth's planetary magnetic field creates a complex 'system of systems' composed of interdependent plasma populations and overlapping spatial regions that perpetually exchange mass and energy. Because of this complexity, measurements that span a broad range of temporal and spatial scales are required to disentangle the coupled processes that drive mass and energy flow. Second, most cold plasma is not directly detectable by most space-borne particle instruments in the magnetosphere, because its thermal energy is well below the floating potential of spacecraft surfaces [23]. To make new progress, instrumentation specifically designed to detect cold plasma is required. Third, prior observations of mass flow and its impact on magnetospheric subsystems are limited to either single-spacecraft local measurements of total plasma density with limited composition data and no contextual mass spatial distribution information [5, 32, 65], or to single-view line-of-sight integrated measurements of minor ion species without in-situ measurements embedded in the imaged plasma [101]. New progress requires combining measurements of the plasma mass spatial distribution in the inner magnetosphere with simultaneous embedded in-situ measurements.

**The PILOT Mission Concept**: A mission concept study was recently conducted to define a space mission capable of making the observations needed to resolve this critical heliophysics problem, and close these persistent knowledge gaps. The mission concept is called PILOT (Plasma Imaging LOcal and Tomographic experiment), it combines local in-situ, global remote-sensing, and tomographic imaging to provide comprehensive multi-scale observations of mass flow in geospace. The PILOT concept was selected for study through a competitive open solicitation (NASA grant #80NSSCK0110). PILOT study results are fully described in a mission concept study report to be delivered to NASA in 2022, and summarized in this white paper and a companion one describing mission implementation, as well as in Malaspina et al. 2022, Frontiers in Astronomy and Space Sciences.

PILOT is defined as a Solar Terrestrial Probes (STP) mission. Table 1 shows how PILOT addresses all three STP objectives and advances the broader field of heliophysics, opening new paths of investigation while closing key knowledge gaps in geospace. Key science objectives were identified as part of the PILOT study. These objectives, described below, motivate transformational multi-scale observations of mass and energy flow dynamics in Earth's magnetosphere. Figure 2 shows the flow from STP objectives to PILOT science objectives.

| **STP Objectives** | **PILOT** |
|---|---|
| **STP #1:** "Understand the fundamental physical processes of the complex space environment throughout our solar system, … as well as a dynamic system of magnetic and electric fields." | PILOT 'follows the mass' through geospace, to close a critical knowledge gap about the fundamental physical processes that govern the flow of mass and energy in a planetary magnetic field |
| **STP #2:** "Understand how … the habitability of planets are affected by solar variability and planetary magnetic fields." | PILOT discovers mechanisms that enable planetary magnetic fields to regulate atmospheric mass loss, a key part of habitability. |
| **STP #3:** "Develop the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers." | PILOT determines how, when, and where plasma mass density profoundly regulates the magnetospheric subsystems that directly impact safety and productivity, including the radiation belts. |
| **Broader Heliophysics** | **PILOT** |
| **Science 2020-2024, a Vision for Scientific Excellence:** "Heliophysics incorporates studies of the interconnected elements into a single system … that evolves in response to solar, planetary, and interstellar conditions" | PILOT opens new paths of scientific investigation into magnetospheric system science by providing an essential missing piece to knowledge of the magnetospheric 'system of systems': plasma mass transport |
| **NASA SMD Science Plan 2014, Heliophysics Objective:** "Understand the Sun and its interactions with Earth and the solar system, including space weather" | PILOT advances Heliophysics broadly by obtaining a long overdue, multi-scale view of plasma mass flow's critical contribution to how planetary space environments respond to dynamic space weather |

Table 1: *PILOT STP and Heliophysics Objective Coverage*

**Science Objectives**: A focused science goal is necessary to close this persistent knowledge gap and bringing closure to the problem of mass dynamics in the Earth's magnetosphere. That goal is: **determine the primary pathways of mass and energy flow through the coupled systems of the terrestrial magnetosphere.** This goal motivates three science objectives, arranged to 'follow the mass' as ionized gases exit the ionosphere, enter and are transported through and out of the inner magnetosphere, and profoundly modify magnetospheric systems and energy transport along their journey (Figure 1).

Science Objectives (Ob)

**Ob1** Identify and quantify the key processes that govern mass and energy exchange between the ionosphere and the magnetosphere.

**Ob2** Discover the pathways and processes governing cold plasma mass transport through and out of the inner magnetosphere.

**Ob3** Determine how, where, and when cold plasma mass acts most efficiently to regulate coupling between magnetospheric regions and between plasma populations.

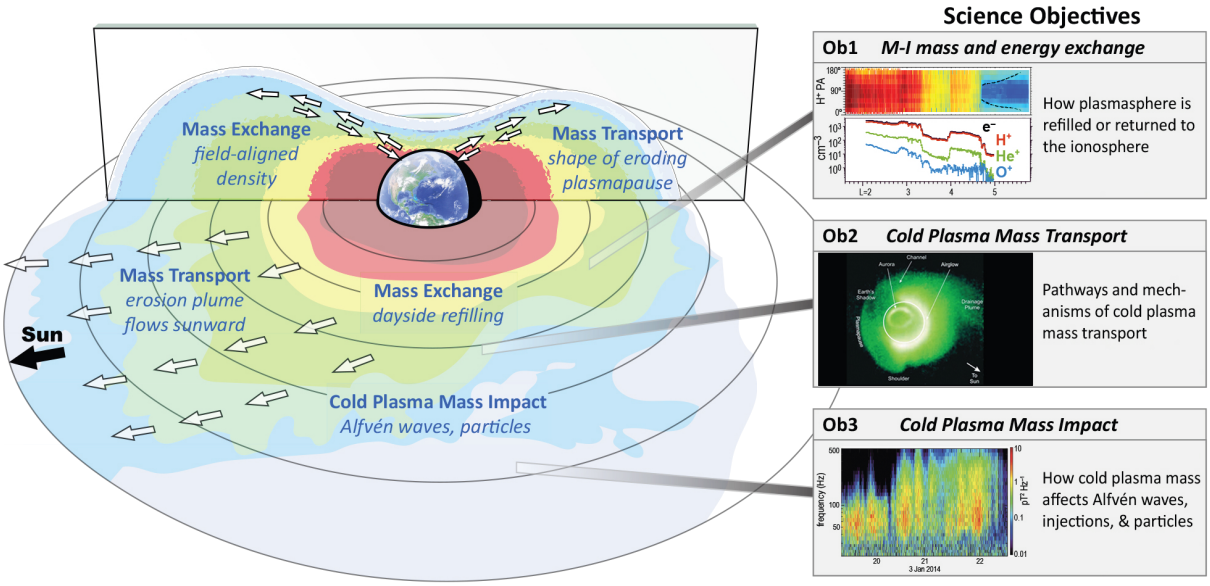


Figure 1: *Schematic of the current state of knowledge for mass transport through, and impacts on, the magnetosphere, highlighting the three science objectives. The sub-figures are from [44], [100] and [16].*

**Science Questions**: Achieving closure on each objective requires addressing specific science questions (SQ).

**Ob1 – SQ 1a:** How is the plasmasphere refilled from ionospheric sources?

When atmospheric gases are ionized, by solar radiation or electron bombardment, electromagnetic interaction with the solar wind causes them to flow out of the ionosphere (e.g. [9, 10, 105]). Earth's magnetic field traps much of this plasma in the plasmasphere, preventing it from escaping directly to the solar wind. During geomagnetic storms, some of the mass in this reservoir is forced into the solar wind and lost. Ionospheric outflow then refills the plasmaspheric reservoir and the process repeats.

After decades of research, fundamental questions concerning the physics of refilling remain unanswered. The observations required to address these questions do not yet exist [39]. In this observational void, gaps in our basic knowledge persist: What causes refilling rates to vary by orders of magnitude (4 to 800 $cm^{-3}$ $day^{-1}$ [14, 17, 24, 34, 39, 66, 88, 89, 93, 99])? Why is the amount of mass trapped by the magnetosphere only weakly correlated with the polar outflow rates [26]? What fundamental plasma processes are responsible for trapping new ions in the plasmasphere torus [45, 46]? What is the origin of the dense $O^+$ torus in the outer plasmasphere [4, 18, 43, 52, 54, 94]?

Closure on this science question can be achieved by comparing multi-scale measurements of cold plasma mass flow and variability over a broad swath of the inner magnetosphere against theories for ion trapping [53], refilling variability [39], refilling mass dependence [98], and O+ torus formation [43].

**Ob1 – SQ 1b:** By what processes, and to what extent, does plasmaspheric mass return to the ionosphere or neutral exosphere?

A full accounting of mass flow between the ionosphere and plasmasphere must include flow from the plasmasphere back into the ionosphere or neutral exosphere. There is a large knowledge gap related to this mass flow pathway. In the absence of sunlight, low-altitude recombination reduces ion pressure gradients, which is expected to cause downward transport [39, 68], allowing nightside flux tubes to return plasmaspheric mass to the ionosphere. This mechanism may explain the anomalous mass loss reported on L-shells far from the eroded plasmapause boundary [39]. However, the cross-scale measurements required to test this hypothesis, or to identify a new one, currently do not exist.

Closure can be reached on this science question by comparing existing predictions for downward ion transport of plasmaspheric mass [39] with direct multi-scale measurements of cold plasma mass content and its variability.

**Ob2 – SQ 2a:**What are the key pathways for transport of plasma mass through and out of the inner magnetosphere?

After cold plasma mass reaches the plasmasphere, it is distributed and transported to other magnetospheric regions. Known and speculated mass transport pathways include sunward plasmaspheric plume flows [22], interchange instability [90], and the warm plasma cloak [13, 38]. Limited existing measurements prevent us from knowing which mass flow pathways are most important under which geomagnetic conditions, what feedback exists among transport mechanisms, and how they combine to produce the observed magnetospheric mass distribution.

In particular, the physics that drive refilling rates necessary to sustain plasmaspheric plumes remain poorly determined [25, 38], especially considering that plumes can form in minutes, and persist for weeks [15, 64]. Many key questions persist about role of the warm plasma cloak (a population transported in from the magnetotail [18, 55, 84]) in cold mass transport. What mechanism heats the cloak plasma [50]? How does the cloak impact dayside magnetosphere mass loading [13]? Is the cloak a candidate for nightside plasmasphere refilling [38]?

Closure on this science question is achieved by comparing the observed morphology of cold plasma flows in the near-equatorial magnetosphere, and signatures of cold ion heating or cooling, against theoretical expectations for each pathway.

**Ob2 – SQ 2b:** What are the mechanisms of plasma mass transport and their drivers?

Once in plasmasphere, plasma mass may go sunward to the dayside magnetopause and participate in reconnection, or it may be diverted to the flanks and travel anti-sunward to load the plasmasheet. Dynamic electric fields (E) in the magnetosphere regulate this transport. Because of limited existing measurements, it is unknown the extent to which

plasmaspheric mass transport is governed by global vs local E-fields.

Statistical empirical models from single-point in-situ E-field measurements [76] obscure the role of intense small-scale E-field features such sub-auroral polarization streams (SAPS) [36] and sub-auroral ion drifts (SAID) [3]. As a result, their impact on plasma mass transport is unclear [31, 37, 70]. Further, IMAGE EUV observations show that the plasmapause is highly structured, with notches, crenulations, fingers and shoulders [40]. Yet statistical E-field models seldom reproduce such features [47], indicating that existing observations cannot resolve critical transport mechanisms.

Closure on this science question is achieved by comparing electric field drivers and magnetic field context with the resulting plasma mass motion, allowing key transport mechanisms to be identified.

**Ob3 – SQ 3a:** To what degree does the dynamic distribution of plasma mass regulate the expression of Alfvén waves?

Propagating at the Alfvén speed, Ultra Low Frequency (ULF) waves carry information via magnetic field fluctuations that enable magnetosphere-ionosphere coupling [71], magnetosphere-solar wind coupling [119], as well as radiation belt energization and particle transport via radial diffusion [30].

ULF waves carry energy Earthward from the magnetotail and magnetopause [112], driving either propagating waves or drive field line resonances and cavity modes [28, 62, 67, 96, 97]. The spatial distribution of ULF power, the energy flux transport via these modes, and the energy exchange between these modes are all critically sensitive to the Alfvén speed [21], itself determined by the cold plasma density spatial distribution.

PILOT achieves closure on this science question by measuring the dynamic spatial distribution of Alfvén speed, across scale sizes, over a broad region of the inner magnetosphere, while simultaneously quantifying the degree to which this distribution regulates ULF plasma wave properties.

**Ob3 – SQ 3b:** By what mechanisms and to what extent does the distribution of plasma mass govern the dynamics of meso-scale plasma flows that reach the inner magnetosphere?

The Dungey cycle [29] return flow of magnetic field and plasma sunward from the magnetotail takes the form of structured Bursty Bulk Flows (BBFs) [7, 8, 11, 95, 118]. BBFs originate in the magnetotail ($>\sim 15R_E$) [85, 95, 106]. They are accompanied by dipolarization of the Earth's magnetic field [6]. BBFs are responsible for much of the energy transport from the Earth's magnetotail to the inner magnetosphere (e.g. [109, 115]) and are known to drive ionospheric energy deposition [81, 102, 103, 108]. BBF velocities slow to $\sim$ 100 km/s between $\sim 12R_E$ and $\sim 8R_E$ [33, 77]. The fate of BBFs is not well understood Earthward of $\sim 8R_E$, where their flow speed is dramatically reduced [72, 92]. Mounting evidence indicates that the distribution of plasmaspheric mass determines the final deceleration of Earthward plasma flows [2, 42, 61, 69], thereby regulating the deposition of their remaining flow energy, and their ability to transport plasmasheet particles into the

inner magnetosphere [27, 41, 107, 111, 115]. Further, the Poynting flux generated during BBF breaking is implicated in the energization of the ionosphere and subsequent low-energy ion outflow that contributes to re-population of the outer plasmasphere [19].

PILOT achieves closure on this SQ by determining the extent to which cold plasma regulates plasma flow evolution in the inner magnetosphere, including particle injection physics and energy transfer from flows to plasma waves.

**Ob3 – SQ 3c:** To what extent does the dynamic distribution of plasma mass in the magnetosphere determine the expression of wave-particle interactions that energize, de-energize, and precipitate energetic plasma?

Plasma waves drive particle energization and loss in the inner magnetosphere [51, 58, 113], including Very Low Frequency (VLF) waves such as chorus and hiss [1, 73, 74, 83, 110] and electromagnetic ion cyclotron (EMIC) waves [63, 120]. Ambient cold plasma density and magnetic field strongly determine the efficiency of relevant wave-particle interactions on kinetic scales [20, 59, 60, 63, 87, 110, 120].

However, our knowledge of the spatial extent and dynamic behavior of wave growth and subsequent wave-particle interactions currently relies on an elaborate chain of complex modeling and statistical inference [23, 49, 75, 78, 79, 82, 121]. Predictions resulting from this chain often sharply disagree with any individual geomagnetic event [57, 117], especially for extreme driving cases. Because the distribution of cold plasma mass profoundly regulates the growth/damping of plasma waves, this disagreement demonstrates that the role of cold plasma dynamics is not yet understood [16, 49].

Closure on this science question is achieved using spatial distributions of cold plasma mass and magnetic field to determine the instantaneous expression (growth, damping) of plasma waves over broad regions of the inner magnetosphere.

**Traceability**: Figure 2 shows the flow from science goals, through objectives and questions, to required measurements. The companion PILOT mission concept white paper describes an implementation capable of generating the observations required to close the fundamental science knowledge gaps described here.

Fully addressing this science requires novel, simultaneous measurements, including: (i) images of total plasma density in equatorial plane (L-shell / magnetic local time (MLT)), (ii) images of ions ($He^+$ and $O^+$) in the meridional plane (L-shell / latitude), (iii) in-situ cold ($\sim$0.1 eV to $\sim$100 eV), warm ($\sim$100 eV to $\sim$50 keV) and hot particle distribution functions ($\sim$100 keV to 1 MeV), with cold and warm mass-resolved ions, and (iv) in-situ electric and magnetic field observations.

Plasma density images must span a broad region of the equatorial inner magnetosphere ($3 <$ L-shell $< 6$, $\geq 3$ hrs MLT) to capture the mass-dynamic L-shells (SQ 1a) and those with weak transport (SQ 1b), as well as injection fronts (SQ 3c). Spatial resolution of $\leq 0.5 R_E$ is needed to resolve refilling flux tubes (SQ 1a) mass convection patterns (SQ 2a, 2b), injections (SQ 3b), and wave distributions (SQ 3c). Meridional coverage is needed to $\pm 4.8$ $R_E$ equatorially and $\pm 4.8$ $R_E$ for $He^+$ and $\pm 2.2$ $R_E$ for $O^+$ out of plane (SQ 1a, 1b). In-situ observations must be embedded within the imaged regions to resolve small-scale

electric field structures (SQ 2b), plasma waves that facilitate ion trapping (SQ 1a [12, 48, 53, 86, 104]) and particle energization (SQ 3b), ULF waves (SQ 3a), and mass-resolved ion distribution functions (all SQ). A distributed network of magnetic field measurements is needed to define Alfvén speed and ULF spatial distributions (SQ 3a), and injection flow breaking (SQ 3c [61, 92, 118]). A network of trapped electron flux measurements is needed to capture particle injection processes (SQ 3b [2, 42, 61, 69, 80, 115, 116]).

Images and in-situ data with cadences of $< 20$ s are needed to fully resolve mass-dynamic timescales (SQ 1a, 1b, 2a, 2b, 3b), and injection front motion (SQ 3c [35, 92, 95]).

**Table STM-1**: Science Traceability, STP to Required Measurements

| Solar Terrestrial Probes (STP) Science Objectives | PILOT Science Goal | PILOT Science Objectives | PILOT Science Questions | Target Physical Processes | Required Measurements: Network | | | | Required Measurements: Embedded In Situ and EUV | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| **STP #1**: Understand the fundamental physical processes of the complex space environment throughout our solar system, which includes the flow of energy and charged material, known as plasma, as well as a dynamic system of magnetic and electric fields. **STP #2:** Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields. **STP #3:** Develop the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers. | Determine the primary pathways of mass and energy flow through the coupled systems of the terrestrial magnetosphere | [Ob1] Identify and quantify the key processes that govern mass and energy exchange between the ionosphere and the magnetosphere. | [SQ1a] How is the plasmasphere refilled from ionospheric sources? | Ionospheric outflow | ● | ● | ● | | ● | ● | | | | ● | | | ● | | ● | | | | ● |
| | | | | Plasmasphere refilling | ● | ● | ● | | ● | ● | | | | ● | | | ● | | ● | ● | ● | ● | ● |
| | | | | O+ torus evolution | ● | ● | ● | | | ● | | | | ● | ● | | ● | ● | ● | | ● | | |
| | | | [SQ1b] By what processes, and to what extent, does plasmaspheric mass return to the ionosphere or neutral exosphere? | Ionosphere return flow | ● | ● | ● | | ● | ● | ● | ● | | ● | ● | | ● | ● | ● | | | | |
| | | [Ob2] Discover the pathways and processes governing cold plasma mass transport through and out of the inner magnetosphere. | [SQ2a] What are the key pathways for transport of plasma mass through and out of the inner magnetosphere? | Plume evolution | ● | ● | ● | | ● | ● | | | | ● | ● | | ● | ● | ● | | ● | | ● |
| | | | | Interchange instability | ● | ● | ● | | ● | ● | | | | ● | | | ● | | ● | | | | ● |
| | | | | Plasma cloak | ● | ● | ● | | ● | | ● | ● | | ● | ● | | ● | ● | ● | | | | ● |
| | | | [SQ2b] What are the mechanisms of plasma mass transport in the inner magnetosphere and their drivers? | Mass transport | ● | ● | ● | | ● | ● | ● | | | ● | | | | | ● | | ● | | ● |
| | | | | Micro/meso E-fields | ● | ● | ● | | ● | ● | ● | ● | | ● | ● | | | | ● | | ● | | ● |
| | | [Ob3] Determine how, where, and when cold plasma mass acts most efficiently to regulate coupling between magnetospheric regions and between plasma populations. | [SQ3a] To what degree does the dynamic distribution of plasma mass regulate the expression of Alfvén waves? | Alfvén speed and ULF waves | ● | ● | ● | | ● | ● | | | | ● | | | ● | | ● | | ● | | ● |
| | | | [SQ3b] By what mechanisms and to what extent does the distribution of plasma mass govern the dynamics of meso-scale plasma flows that reach the inner magnetosphere? | Injection flow dynamics | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| | | | [SQ3c] To what extent does the dynamic distribution of plasma mass in the magnetosphere determine the expression of wave-particle interactions that energize, de-energize, and precipitate energetic plasma? | VLF and EMIC plasma waves | ● | ● | ● | | | | | | | | | | | | ● | ● | ● | ● | ● |
| | | | | Warm / hot e-, i+ wave growth contributions | ● | ● | ● | ● | | | | ● | ● | | ● | ● | | ● | ● | | | | ● |

| | Network | | | | Embedded In Situ and EUV | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | 1 | 2,19 | 3,15 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 18 |
| Class | Density | | EM Fields | Electrons | Photons | | Electrons | | | Protons | | | Heavy Ions | | EM Fields | | |
| Type | Total Plasma Density | | Magnetic Field | Energetic e- | He+ | O+ | Cold e- | Warm e- | Energetic e- | Cold p+ | Warm p+ | Energetic p+ | Cold He+, O+ | Warm He+, O+ | Magnetic Field | Electric field | |
| Detail | Equatorial 2D | In situ | DC-coupled, In situ | Trapped Flux | Meridional Profile | | Pitch Angle Distributions | | | Pitch Angle Distributions | | | Pitch Angle Distributions | | AC-coupled | DC-coupled | AC-coupled |

Measurement # Key

Figure 2: *Flow from science goals to required measurements.*

**Why Now?** The next decade is the ideal time to answer the science questions posed here. The last decade saw ground-breaking studies of individual magnetospheric subsystems (e.g. radiation belts, magnetopause). The next decade's greatest leap in magnetospheric physics will be to 'follow the mass', determining how mass and energy flow between these systems binding them together into an interconnected 'system of systems'. This leap is enabled by coordinated system-scale context and embedded in-situ observations.

The last decade saw advances in spacecraft manufacturing capability, instrument miniaturization, as well as in the launch and deployment of large spacecraft constellations. In the next decade, we will leverage these new capabilities to produce transformational constellation observations capable of resolving one of Heliophysics's most massive problems: determining the fundamental physics of mass and energy flow through a planetary magnetosphere and the degree to which these flows regulate magnetospheric subsystems.

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