# Magnetospheric Plasma Systems Science and Solar Wind Plasma Systems Science: The Plasma-Wave Interactions of Multiple Particle Populations

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Building upon the research legacies of Peter Gary and Richard Thorne, this perspective discusses a plasma-system picture wherein multiple ion and electron populations interact with each other *via* multiple types of plasma waves. The two cases discussed are 1) the Earth's magnetosphere with ion and electron populations trapped in the closed flux tubes of the magnetic dipole and 2) the solar wind with ion and electron populations expanding away from the Sun in open magnetic flux tubes. For the magnetosphere, internal convection drives particle populations into stronger magnetic fields, leading to particle anisotropies; for the solar wind the expansion of the plasma away from the Sun results in the particle populations moving into weaker magnetic fields, leading also to particle anisotropies. In both cases, the anisotropies of the diverse ion and electron populations produce kinetic instabilities resulting in the production of diverse types of plasma waves and wave-particle interactions. Following the extensive research of Richard Thorne, web diagrams of plasma-wave interactions are laid out for the multiple ion and electron populations of the magnetosphere and following the extensive research of Peter Gary web diagrams of plasma-wave interactions are laid out for the multiple ion and electron populations of the solar wind. The advantages of a systems-analysis approach to these two plasma systems is discussed.

Keywords: magnetosphere, solar wind, system science, plasma waves, plasma instabilities

## INTRODUCTION

The Earth's magnetosphere and the solar wind provide two valuable opportunities to bring systems science into the field of plasma physics. Both the magnetospheric system and the solar-wind system are comprised of multiple electron and ion populations with interactions between the populations occurring largely via plasma waves. Many of the plasma-wave interactions of the magnetosphere were uncovered and quantified by Richard Thorne in over 4 decades of research (e.g. Thorne, 1968; Thorne et al., 2017) and many of the plasma-wave interactions of the solar wind were uncovered and quantified by Peter Gary in over 4 decades of research (e.g. Gary, 1974; Gary et al., 2020). Without theses two visionary researchers, these two coherent plasma-systems pictures could not be created.

   Both the magnetosphere and the solar wind exhibit multiple populations of ions and electrons that are co-located (i.e. that reside on the same magnetic-field lines) so that the multiple populations

easily interact with each other. The evolution of magnetized plasmas often leads to anisotropies giving rise to instabilities and wave-particle interactions: for the magnetosphere the particle anisotropies arise from solar-wind-driven magnetospheric internal convection pushing particle populations into the strong magnetic field of the dipolar regions and for the solar wind the particle anisotropies arise from the solar-wind expansion into weaker magnetic fields away from the Sun. For every plasma-wave instability, wave-particle interactions act in two fashions: in driving the waves and in dissipating the waves. In this manner two diverse particle populations can interact with each other.

In this perspective article the plasma system science of the magnetosphere and the plasma system science of the solar wind will be briefly outlined. The magnetosphere is a driven closed system (more or less), with the multiple particle populations trapped in dipolar (or stretched) magnetic flux tubes. The solar wind is an open system with multiple particle populations born in the solar corona and moving outward at different speeds from the Sun in open magnetic flux tubes.

This paper is organized as follows. In *The Magnetospheric System* Section the magnetospheric plasma system is described. In *The Solar-Wind System* Section the solar-wind plasma system is described. *Discussion* Section contains discussions of 1) previous system-science analysis that has been done for the magnetosphere and the solar wind, 1) the availability of data for future studies, and 3) some advantages that systems analysis may provide.
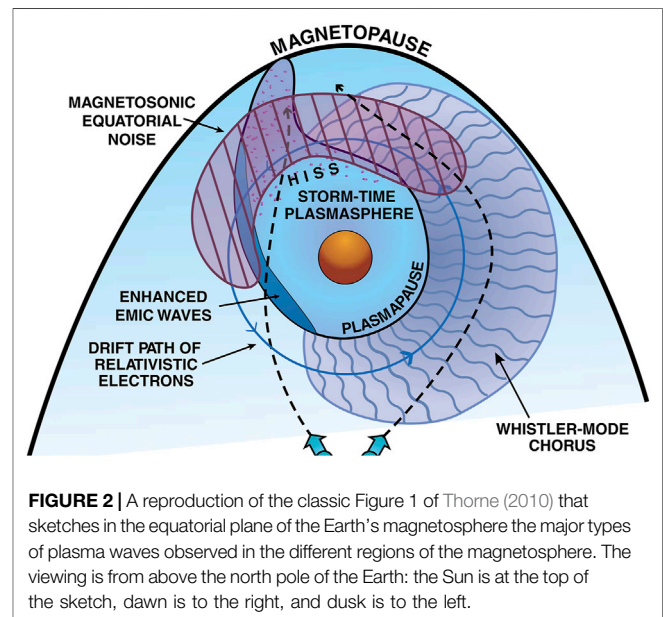
## THE MAGNETOSPHERIC SYSTEM

The Earth's magnetosphere is a system of multiple trapped particle populations with free energy added from the solar wind, which drives internal convection. Convection of particle populations into the stronger field of Earth's dipole drives particle anisotropies and free energy for plasma waves. The resulting multiple plasma instabilities gives rise to multiple couplings between the diverse particle populations, resulting in a complex evolution of those diverse particle populations. A thorough review of the Earth's magnetosphere as a system wherein the multiple ion and electron populations interact *via* plasma waves appears in Borovsky and Valdivia (2018).

The key to the interaction of the different particle populations is the fact that they are co-located on the same magnetic field lines. There are three major regions in the Earth's magnetosphere and the three regions contain differing particle populations. The first region is the stretched-field "magnetotail" on the nightside of the Earth. The major particle populations of the magnetotail are the ion plasma sheet, the electron plasma sheet, the cusp-mantle (ions and electrons), and the polar wind (ions and electrons). The second region is the "outer dipole": this region contains the ion plasma sheet (ions), the electron plasma sheet (electrons), substorm-injected ions, substorm-injected electrons, the electron radiation belt, the ion radiation belt, cloak ions, cloak electrons, and polar-wind ions and electrons. The third region is the "inner dipole" closest to the Earth: this region contains the plasmasphere (ions and electrons), the ion plasma sheet, substorm-injected ions, the electron radiation belt, and the ion
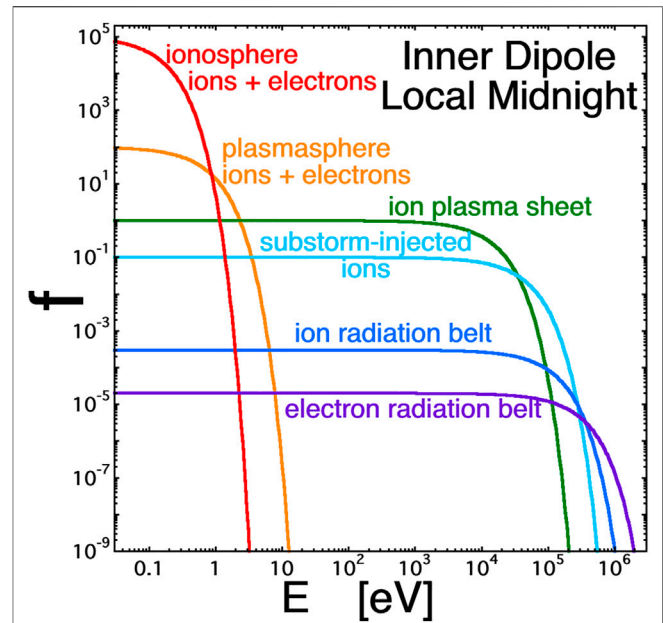


**FIGURE 1 |** A sketch of the distribution functions of 5 ion populations and 3 electron populations on the same magnetic field line in the inner-dipole region of the nightside magnetosphere.



**FIGURE 2 |** A reproduction of the classic Figure 1 of Thorne (2010) that sketches in the equatorial plane of the Earth's magnetosphere the major types of plasma waves observed in the different regions of the magnetosphere. The viewing is from above the north pole of the Earth: the Sun is at the top of the sketch, dawn is to the right, and dusk is to the left.

radiation belt. The boundary between the inner and outer dipole regions is the plasmapause, which is the outer boundary of the dense, cold plasmasphere.

As an example of the co-location of multiple particle populations, **Figure 1** provides a sketch of the distribution functions of the ions and electrons in the inner dipolar region at local midnight. The plot is a log-log plot, sketching each particle distribution as a Maxwellian, which in general they are not. (The hotter populations often have anisotropies and
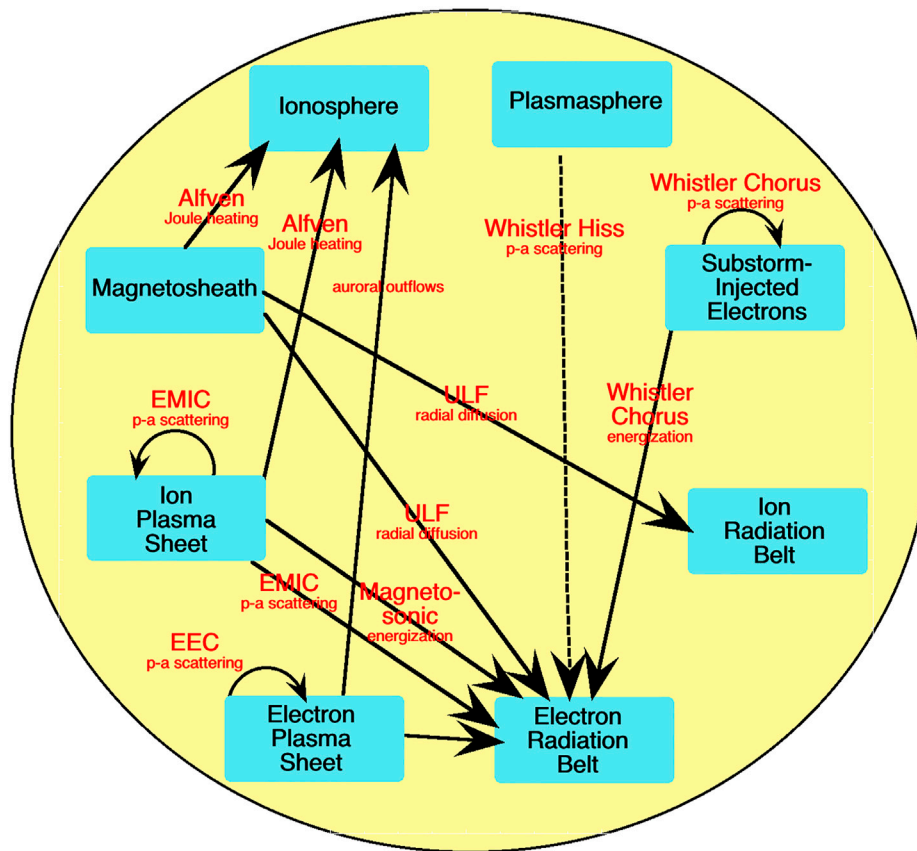
**FIGURE 3 |** A sketch of the web of plasma-wave interactions between the major ion and electron populations of the Earth's magnetosphere.

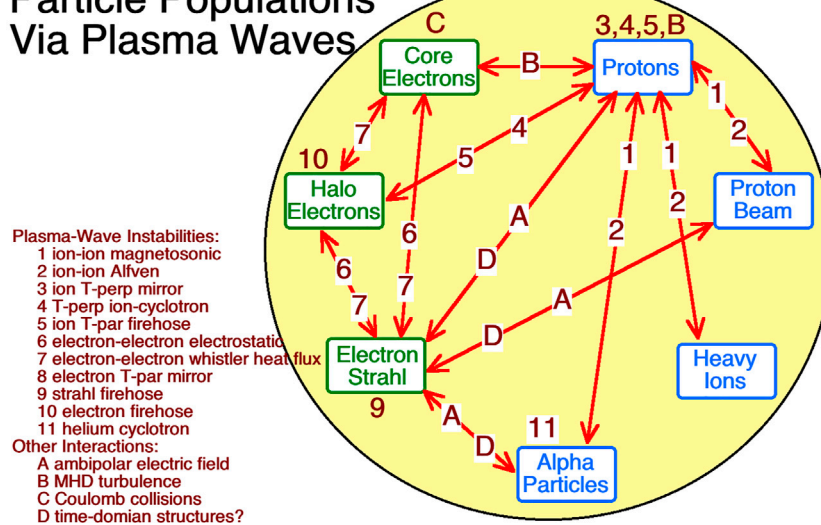biteouts). The populations range in energy from the ionosphere ($T_i \approx T_e \sim 0.1$ eV) and plasmasphere ($T_i \approx T_e \sim 0.5$ eV) to the ion radiation belt (which has a tail of particles in the 1-MeV range of energies) and the electron radiation belt (which has a tail of particles in the 10-MeV range).

The plasma populations of the magnetosphere interact *via* plasma waves. The typical types of plasma waves observed depend on the region of the magnetosphere and the ion and electron populations in that region that can drive the waves. **Figure 2** is a classic sketch from Thorne (2010) that has been reproduced in numerous scientific publications: the sketch depicts the equatorial plane of the Earth's magnetosphere and the major types of plasma waves that impact the electron radiation belt observed in the various regions. The types of plasma waves seen inside the plasmapause (inner dipole) differ from the types seen outside the plasmapause (outer dipole), with drastically different consequences for the particle populations in those two regions. Critical to the evolution of the electron radiation belt, **Figure 2** depicts that whistler-mode chorus waves exist outside of the plasmasphere (outer dipole), whistler-mode hiss waves exist inside of the plasmasphere (inner dipole), and electromagnetic ion-cyclotron (EMIC) waves tend to exist inside the plasmasphere (inner dipole).

In the interactions of co-located particle populations *via* plasma waves in the Earth's magnetosphere, typically a warm (keV) population of particles with medium density is the driver for the waves and typically a very-energetic populations (100's of keV) with a very-low-density is the absorber of the wave energy. And often there is a high-density cold population of ions or electrons that regulates the plasma-wave dispersion relation, determining what waves can be driven and determining the resonance conditions for those waves (cf. Delzanno et al., 2021).

In **Figure 3** a map is displayed of the basic web of interactions between the multiple electron and ion populations of the Earth's magnetosphere and the type of plasma wave that mediates each interaction. (The various plasma waves in **Figure 3** are elaborated upon in Section 6 of Borovsky and Valdivia (2018).). In the map of **Figure 3** the direction of each arrow indicates the transfer of wave action: from the driving population to the receiving population. For the receiving population, the waves can lead to energization and/or to pitch-angle scattering, with pitch-angle scattering often leading to scattering into the atmospheric loss cone where the scattered ions or electrons are lost from the magnetospheric system into the atmosphere. Note in **Figure 3** that a number of "circular" wave interactions are indicated: here one portion of a single population will drive waves that affect another portion of the same population. This often produces

**FIGURE 4 |** A sketch of the web of plasma-wave interactions between the major ion and electron populations of the solar wind. (This interaction map is an update of Figure 8 of Viall and Borovsky (2020), which was assembled by the author with critical guidance from Peter Gary).

pitch-angle scattering into the atmospheric loss cone, resulting in a loss from the magnetospheric system and perhaps producing aurora in the upper atmosphere.

The complicated system of instability-driven wave-particle interactions that drive the evolution of the multiple ion and electron populations of the Earth's magnetosphere were largely worked out by Richard Thorne. Focused review articles on these various interactions can be found in Thorne and Kennel (1971), Thorne et al., (1973, 1979, 2010, 2013, 2017), Thorne (1974, 2010), Thorne and Summers (1991), and Thorne and Horne (1992, 1994).

One hallmark of a "complex system" is that the system exhibits "emergence", new things "emerge", i.e. the system creates something from nothing. Examples of emergence are given in Borovsky and Valdivia (2018). On example of emergence in the Earths magnetospheric system is the electron radiation belt: here the system takes medium-energy short-lifetime substorm-injected electrons and, via a complex web of interactions, creates a population of high-energy long-lifetime relativistic electrons.

## THE SOLAR-WIND SYSTEM

The magnetic structure of the solar-wind plasma resembles a spaghetti of magnetic flux tubes with strong current sheets forming the boundaries between adjacent flux tubes (Michel, 1967; Bruno et al., 2001; Borovsky, 2008; Greco et al., 2008; Pecora et al., 2019). The field of most of the solar wind is "open", with field lines magnetically connecting the Sun to the distant heliosphere. The multiple solar-wind particle populations are born in the solar corona and move outward (at different speeds) along the magnetic field in the open flux tubes. Note, however, that many of the details of the physical processes in the corona that are acting in the birth of the solar wind are not known (cf. Cranmer et al., 2017).

The solar-wind plasma in the inner heliosphere has 7 major particle populations: protons, alpha particles, highly charged heavy ions, an antisunward proton beam, core electrons, halo electrons, and a field-aligned energetic electron strahl. Minor populations can include a sunward streaming proton beam.

As the fast energetic strahl electrons move outward from the Sun they produce an ambipolar electric field that pulls ions outward from the Sun against the Sun's gravity (Jockers, 1970; Lemaire, 2010). This magnetic-field-aligned electrostatic "interplanetary electric field", in part, accelerates the solar wind to high velocities. (A similar process occurs on the sunlit ionosphere of Earth where multi-eV photoelectrons from the atmosphere produce an ambipolar electric field that pulls sub-eV ions out against the Earth's gravity: this is the "polar wind" (Schunk, 2007).) The field-aligned potential drop from the Sun to infinity is on the order of 1 kV, with most of that drop occurring between the Sun and the orbit of Mercury. As the ion and electron populations of the solar wind move outward from the Sun (at different speeds), they interact and evolve. Some of the plasma-wave interactions between the major particle populations are mapped out in **Figure 4**.

Free energy sources for the system evolution are (cf. Borovsky and Gary, 2014; Smith and Vasquez, 2021) 1) electron heat flux, 2) large-amplitude Alfvén waves, 3) the relative drift between alpha particles and protons, and 4) anisotropies driven by the

changing magnetic-field strength. Well beyond 1 AU other sources are interplanetary shocks (Smith et al., 1985) and interstellar pickup ions (Lee, 2018).

It is thought that whistle-mode scattering of the field-aligned strahl electrons gives rise to the quasi-isotropic energetic electron halo population (Gary and Saito, 2007): as evidence, with distance from the Sun the strahl population becomes fractionally less dense and the halo population becomes fractionally more dense (Stverak et al., 2009).

A key source of energy in the solar wind resides in outward propagating Alfvénic fluctuations from the corona. About half of the solar wind at 1 AU is Alfvénic, with strong correlations between the vector changes in the magnetic field and the vector changes in the proton flow velocity. In the Alfvénic solar wind, it is observed that the magnetic structure moves en masse relative to the proton plasma at a speed of about $0.7\, v_A$ (Borovsky, 2020a; Nemecek et al., 2020), where $v_A$ is the measured Alfvén speed. In the reference frame of the magnetic structure, to within measurement error all proton flows **v** are parallel to the local magnetic-field direction **B**; with $v_\perp = 0$ there is (to within measurement error) no time evolution of the magnetic structure as it moves outward through the inner heliosphere. This is an example of the Chadrasekhar dynamic equilibrium ("CDE") (cf. Fig. 7.1 of Parker (1979)) where a nonlinear tangle (spaghetti) of magnetic field will propagate en masse without evolution provided that the flow is everywhere parallel to the local field. The alpha particles of the solar wind (and perhaps also the heavy ions) reside nearly at rest in the reference frame of the magnetic structure (Nemecek et al., 2020): it is not known why. The outward-propagating Alfvénic structure interacts with the particle populations 1) via parametric instabilities (e.g. Malara et al., 2001; Vasquez and Hollweg, 1996) and 2) *via* an MHD-turbulence cascade where the Alfvén waves transfer energy into electrons and ions via mode conversion (Gary and Smith, 2009; Gary et al., 2020) followed by kinetic (cyclotron or Landau) damping (Leamon et al., 1998; Gary and Borovsky, 2004, 2008).

Because of the relative motion of the alpha particles with respect to the proton population, ion-ion streaming instabilities can couple the two populations (Gary, 1991; Gary et al., 2000a). In particular, the alpha-proton magnetosonic instability acts to heat both populations in a fashion such that the protons and alpha particles both have the same thermal speed (Gary et al., 2000b), which is observed in the solar wind (Feynman, 1975).

As the particle populations move outward from the Sun into weaker magnetic fields, conservation of the particle first adiabatic invariants $v_{perp}^2/B$ decreases the perpendicular temperatures of the populations and leads to anisotropy. For the protons the firehose instability driven by $T_{parallel} > T_{perp}$ acts to return the proton population toward isotropy (Gary et al., 1998, 2001). Similar instabilities act on the alpha-particle anisotropy (Gary et al., 2003) and on the electron anisotropy (Gary and Nishimura, 2003).

Core electrons originate from the low-energy portion of the strahl population (e.g. Boldyrev et al., 2020). The core electrons are locally trapped along the magnetic field (Marsch, 2006): 1) moving toward the Sun the core electrons mirror as the interplanetary magnetic field gets stronger nearer to the Sun

and 2) moving away from the Sun the interplanetary electric field pulls them back. The core-electron temperature reflects the local potential of the plasma with respect to infinity (away from the Sun) (Feldman et al., 1975).

Review articles on the diverse types of solar-wind plasma waves and their impact on the solar-wind particle populations can be found in Gary (1991, 1992, 1999), Gary et al. (1975a,b, 1976, 1984, 1994, 1999, 2000a), and Gary and Karimabadi (2006) and in the monograph Gary (1993).

Here we see the system, with the strahl driving the interplanetary potential that drives the solar wind outward. As the populations move through each other at different speeds (all moving outward), they interact *via* plasma waves (cf. Figure FF03).

The magnetic-field structure of the solar wind resembles a spaghetti of magnetic flux tubes separated by current sheets. The diameters of the flux tubes vary, but a typical flux tube at 1 AU has a diameter of about $4 \times 10^5$ km, and a spacecraft crosses from one flux tube to the next every 10 or 20 min. From tube to tube there can be differences in the plasma properties: proton specific entropy, ion composition, magnetic-field strength, plasma beta, etc. Important for this system-science picture, the strahl intensity (Borovsky, 2020b) and the electron temperature (Borovsky et al., 2021) can vary from tube to tube with sudden jumps in the values as the current-sheet wall between flux tubes is crossed. The electron-temperature jumps indicate that the interplanetary electric potential differs from flux tube to flux tube. This implies that each flux tube is an independent evolving system, and that as a solar-wind spacecraft crosses from tube to tube it is measuring different realizations of system evolution. This opens the possibility of statistical plasma system science.

## DISCUSSION

This section discusses previous system-science analysis that has been done for the magnetosphere and the solar wind, the availability of quality data for future studies, and the advantages that systems analysis may provide.

## Plasma Systems Science and Data Availability

Reviews of magnetospheric system-science work can be found in Valdivia et al., [2005, 2013], Vassiliadis (2006), Stepanova and Valdivia, 2016, and Borovsky and Valdivia (2018). Early magnetospheric system science began with two-variable correlation studies between near-Earth solar-wind measurements and measures of the strength of magnetospheric activity (Snyder et al., 1963; Clauer et al., 1981; McPherron et al., 2015): those studies yielded critical information about the processes by which the solar wind drives magnetospheric activity and important information about the multiple reaction times of the magnetospheric system to changes in the solar wind. Later, vector-vector correlation studies (Borovsky and Osmane, 2019) yielded information about multiple modes of reaction of the magnetospheric system to the solar wind. Information-

transfer studies (Wing and Johnson, 2019) have further refined our knowledge about solar-wind driving and in future can be used to examine the causality pathways through the multiple ion and electron populations of the magnetosphere as they undergo the web of interactions (cf. **Figure 3**). Toy mathematical models (Smith et al., 1986; Goertz et al., 1993; Vassiliadis et al., 1993; Klimas et al., 1997; Freeman and Morley 2004; Spencer et al., 2018) have also been constructed and used to gain understandings of the dynamical behaviors of the solar-wind-driven magnetospheric system. In contrast, for the solar-wind plasma system very little system analysis has been performed. Most of the data analytics applied to the solar wind has focused on investigating the nature of the MHD fluctuations in the wind (e.g. Burlaga and Klein, 1986; Marsch and Tu, 1997; Wawrzaszek et al., 2019), not on the particle-population evolution. Here again, information-transfer analysis may be helpful for uncovering and gauging the importance of the various intercouplings of the particle populations with distance from the Sun.

For magnetospheric systems science diverse measurements of the magnetosphere-ionosphere system have been available for over 5 decades, as are measurements of the solar wind at Earth that drives the system. For solar wind system science quality spacecraft data throughout the inner heliosphere from about 15 solar radii to 1 AU (215 solar radii) and beyond are available from multiple spacecraft. For the most part this spacecraft data is centralized and publically available, but with effort more plasma data from the spacecraft of diverse government agencies could be made publically available for scientific purposes.

## Advances That Could be Made With a Systems Science Approach

For the Earth's magnetosphere, global simulations codes cannot build in all of the diverse ion and electron populations, all of the kinetic wave processes, and the huge span of important spatial scales. Ring-current-subsystem codes (Jordanova et al., 2001, 2012; Gamayunov et al., 2009) and radiation-belt-subsystem codes (Varotsou et al., 2005; Shprits et al., 2008a,b; Jordanova et al., 2018) resort to using diffusion coefficients or particle lifetimes to represent the action of waves (energization, pitch-angle scattering, and radial diffusion) acting upon the particle populations, typically with diffusion coefficients based on statistical pictures of plasma-wave observations parameterized by magnetospheric-activity levels. Systems analysis examines the behavior of the actual measured system that includes all of these attributes, extracting information about the behavior of the true, fully realized system. This perspective article encourages the development of systems science methodologies specifically for the critical science challenge of understanding the time-evolving solar-wind-driven magnetosphere-ionosphere system, where physics-based simulations are a long way from containing the physics necessary to simulate the coupled system. The situation is similarly difficult for the evolving solar wind: in the near future simulation codes will not be able to capture all of the diverse ion and electron populations and kinetic wave-particle processes that act as the solar wind evolves from the solar corona outward into the heliosphere. System science analysis of the actual system will be needed.

A systems science analysis can yield unique information about the behavior of a system, including the uncovering of hidden or unnoticed modes of behavior. Systems science analysis works even before all of the physics is identified or understood. It can find couplings and feedback loops in the operation of a system. This information has the potential to guide reductionist data analysis, to guide the development of simulation techniques, and to guide the design of new instruments and new measurement techniques. Systems analysis can be used to test the veracity of simulation codes: performing the same systems analysis on simulation data as on the actual system can compare the statistical behavior of the simulations and the actual system.

Systems science tools that may be developed specifically for the multiple interacting plasmas of the magnetospheric system or the solar-wind system may be generalizable to other problems: laboratory plasma experiments, fusion machines, solar physics, and plasma astrophysics. The tools developed for the solar-wind-driven magnetospheric system may also be useful for other driven systems, such as biological organisms and economic systems.

An integration of magnetospheric systems science into the broader research field of "Earth systems science" could enhance the scientific and societal impact of plasma physics (Thorne, 1977, 1980; Tinsley 2000; Georgieva et al., 2005; Rycroft et al., 2012; Sinnhuber et al., 2012; Clilverd et al., 2016; Lam and Tinsley 2016).

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

JB initiated this project, performed the analysis, and wrote the manuscript.

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