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Advances in Space Research 73 (2024) 5383–5405

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Heliophysics Great Observatories and international cooperation in Heliophysics: An orchestrated framework for scientific advancement and discovery

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Received 5 October 2023; received in revised form 2 January 2024; accepted 5 January 2024
Available online 9 January 2024

Abstract

We suggest that the next era of Heliophysics should focus on the Sun–Heliosphere and Geospace as each a system-of-systems, and recommend a coordinated, deliberate, worldwide scientific effort to answer long-standing questions that will remain unanswered without a unified program. Many of the biggest unanswered science questions that remain across Heliophysics center around the interconnectivity of the

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https://doi.org/10.1016/j.asr.2024.01.011
0273-1177/Published by Elsevier B.V. on behalf of COSPAR.

different physical systems and the role of mesoscale dynamics in modulating, regulating, and controlling that interconnected behavior. Heliophysics has made key progress understanding both the large-scale dynamics and the microphysical processes that occur in these dynamic systems. Such understanding grew out of a systematic approach to study both limits of the system, from global, with the coordinated missions of the International Solar Terrestrial Physics (ISTP) program, to micro, with largely uncoordinated (albeit coincident) missions such as Cluster, Time History of Events and Macroscale Interactions during Substorms (THEMIS), Van Allen Probes, Magnetospheric Multiscale (MMS), Parker Solar Probe, and Solar Orbiter. We suggest that the international Heliophysics community should embark on a grand program to study these system-of-systems holistically, with coordinated, multipoint measurements. We particularly recommend an emphasis on resolving the mesoscale dynamics that links micro to global, and a whole-of-science approach that includes ground-based measurements and advanced numerical modeling. In effect, we propose a mesoscale ISTP type program that would consist of a system of Great Observatories capable of revealing the connections among systems from the solar interior to the top of Earth's atmosphere. The paradigm and specific approaches outlined in this paper could serve as a strategic imperative and overarching theme that binds our Solar and Space Physics communities together under a common scientific objective. By its very nature, the type of program we argue for would be large, with several coordinated elements, and international in scope. It would include space-borne missions and coordinated ground-based observatories, artificial intelligence/machine learning (AI/ML) methods of analyzing large and complex datasets, and next-generation numerical modeling. The need to coordinate and integrate these different elements is independent of any specific mission implementation. Hence, we suggest the Heliophysics community organize around an ISTP-type program, ISTPNext, with associated Heliophysics "Great Observatories".

Keywords: Heliophysics; ISTP; System science

1. Introduction

Heliophysics, née Solar and Space Physics, studies the influences of the Sun on life and technology on the "shore of our cosmic ocean", to borrow from Carl Sagan. Although these studies began before our ability to launch satellites (e.g. Birkeland, 1913; Chapman and Ferraro, 1930; Biermann and Lüst, 1958; Appleton and Barnett, 1925), the space age ushered in a scientific revolution of our understanding of Earth's magnetosphere and upper atmosphere and the interaction with the Sun and its dynamics. In response to the new ability to launch spacecraft across the solar system, nations around the world established space agencies to fully leverage spaceborne observatories for scientific research and exploration.

In the decades that followed, our ever-increasing understanding of the Sun–Heliosphere system led to the unification of Solar and Space Physics into a new scientific discipline: Heliophysics, the study of the Sun and its effects throughout the solar system. The term Heliophysics was adopted by NASA in 2005 to describe what were previously separate fields of research. The name is based directly on the existence of four clearly distinct physical domains. Although these domains share many common physical processes, their individual studies are so different that the studies constitute distinct science disciplines. "Helio"-physics is the study of the physical domain defined by the Sun — the heliosphere — just like "astro"-physics is the study of the physical domain defined by stars — the rest of the universe. Note that by the term "heliosphere" we refer to the whole volume carved out of the Milky Way by our Sun, not just to the solar wind. This physical domain includes the Sun itself, the solar system, and stretches out to the start of interstellar matter. In principle, Heliophysics studies everything inside the Sun's domain of influence, but the planets and other solid bodies are so physically different from the rest of the heliosphere and so special to humanity that they define a separate physical domain and discipline, Planetary Science. One of the planets, in turn, is of such extreme importance and its study so unique that it defines the fourth discipline, Earth Science.

The science of Heliophysics extends over an incredible range of scales, from fundamental plasma physics at the electron scale to the boundary that separates our solar system from interstellar space. As a result, Heliophysics covers a staggering array of sub-disciplines and expertise, with measurements spanning in situ particles and fields from the ionosphere out to the Sun's corona, to remote sensing of the Sun, Heliosphere, and near-Earth environment at multiple wavelengths and in energetic neutral atom (ENA) observations.

Heliophysics is a science of connections and fundamentally cross-disciplinary: coupled with Earth sciences at the boundary between the stratosphere and the mesosphere; enabling comparative planetary magnetospheric physics at Jupiter, Saturn, Uranus, Venus, and Mercury, and comparative aeronomy at Venus and Mars; and with crucial applications to exoplanets and astrophysics. Additionally, Heliophysics enjoys a strong societal relevance through the dominant impact of solar variability on the terrestrial environment and human space exploration (Pulkkinen, 2007). The effects of those impacts, referred to as 'Space Weather', drive increasing attention to Heliophysics research from government and private industry stakeholders across the world (National Academies of Sciences et al., 2022).

1.1. Success in Heliophysics is built upon system approaches and international collaborations

The evolution of Heliophysics from nascent discipline to the mature field we have today occurred over a remarkably brief timeframe. We can roughly divide space exploration in Heliophysics during this timeframe into 4 eras:

1. Discovery-Regions (1958–1973)
2. Discovery-Dynamics (1973–1990)
3. Coarse system science/International Solar Terrestrial Physics (ISTP) (1990–2005)
4. Microscales (2005-present)

Each era was approximately 15 years in duration, roughly the time needed to implement missions and/or space flight programs, extract scientific understanding from those data, and plan the next set of investigations.

The Era of Discovery-Regions began with the International Geophysical Year (IGY) of 1957–1958 and the launches of Sputnik 2 and Explorer I, both of which carried Geiger-Müller tubes and separately discovered Earth's radiation belt (Van Allen, 1957; Vernov and Chudakov, 1960). An ambitious program of exploration followed as spacecraft were launched into unexplored areas of space carrying increasingly capable, though still primitive compared to the modern era, in situ and remote sensing instrumentation. By its very nature of exploring a new region of space to make measurements no one had ever before made, each launch carried the potential for discovery: Explorer 10 discovered the magnetopause in 1961 (Heppner et al., 1962), followed by Explorer 12 that provided 4 months of detailed data (Cahill and Amazeen, 1963); Explorer 18 (Interplanetary Monitoring Platform (IMP)-1) discovered the bow shock in 1963 (Ness et al., 1964); Orbiting Solar Observatory (OSO)-7 discovered "coronal transients", now known as Coronal Mass Ejections (CMEs) in 1971 (Tousey, 1973). The plasmapause was discovered with Antarctic VLF receivers placed during the IGY Carpenter et al. (1969) and separately by space-based observations Gringauz et al. (1960). By the early 1970's, we had a reasonable understanding of the key regions of Earth's magnetosphere and the solar wind, and understood at a basic level the contours of the solar wind-magnetosphere interaction (for an in-depth history of this era, see Gillmor and Spreiter (1997)).

These early years of Heliophysics also saw the creation of international organizations that grew out of the cooperative mechanisms established during the IGY. A major legacy of the IGY are the World Data Centers (WDCs) (https://wdc.kugi.kyoto-u.ac.jp/wdc/whatis.html). These centers, originally organized as WDC-A, -B, and -C, and created by the International Council of Science (ICSU), made observational data readily available to scientific workers in all disciplines related to the Earth, its environment, and the Sun, and continue to this day in much expanded form. In addition, international organizations such as the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) and the Committee on Space Research (COSPAR) grew out of the cooperative mechanisms established during the IGY, highlighting that international coordination can lead to relevant long-lasting programs.

Having identified critical regions and boundaries, we set out to discover the dynamics of those regions in the second era of exploration. Through multi-spacecraft missions such as Dynamics Explorer (DE) (Hoffman, 1988), Atmosphere Explorers (AE) (Dalgarno et al., 1973; Spencer et al., 1973), International Sun Earth Explorers (ISEE) (Pedersen, 1988), Active Magnetospheric Particle Tracer Explorers (AMPTE) (McEntire, 1987), Helios (Burlaga, 2001; Cane et al., 1997; Jackson et al., 1994; Neubauer et al., 1984; Schwenn and Rosenbauer, 1984; Porsche, 1981), Solwind (Sheeley et al., 1980), the Solar Maximum Misson (SMM) (Bohlin et al., 1980), and platforms such as Skylab (Eddy and Ise, 1979), scientists were able to start to disentangle temporal and spatial variations within localized regions in pursuit of understanding fundamental dynamical processes, such as coronal mass ejections, geomagnetic storms, and magnetospheric substorms. These were focused exploratory missions that yielded enormous scientific results well beyond their focus areas. This era also saw the development of the first global MHD models Leboeuf et al. (1978). Even at this early stage of exploration, the need for multi-spacecraft missions, often with international participation, with a mixture of remote and in situ instrumentation, and physics-based numerical models enabled by computers, was recognized as necessary to study the pieces of the dynamical system.

By the 1980s scientists knew that the global system needed to be studied in a coordinated fashion and developed a detailed implementation plan. In the United States, the Global Geospace Science (GGS) program was designed to study the system at multiple points simultaneously and would form the foundation for the InterAgency Solar-Terrestrial Physics (IASTP) Program, coordinated by the InterAgency Consultative Group (IACG) (Baker and Carovillano, 1997). The ambitious GGS program was eventually cut to only Polar and Wind (Acuña et al., 1995) then augmented by Geotail (ISAS/Japan), Equator-S (MPE/Germany), the Solar and Heliospheric Observatory (SOHO, ESA), and Cluster (ESA), which together formed the satellite components of the International Solar-Terrestrial Physics (ISTP) Program. Additional spacecraft such as IMAGE (Imager for Magnetopause-to-Aurora Global Exploration), which provided auroral and inner magnetospheric imaging, contributed to the space-based fleet. Significant ground-based systems were also established during this era, including SuperDARN Greenwald et al. (1995) and the Sondrestrom incoherent scatter radar (ISR) with modes specifically designed to complement the ISTP spacecraft Kelly (1999). ISTP was designed to provide a global, system-level understanding of the Earth's magnetosphere driven by the Sun and its dynamics. The ISTP program explicitly included, for the first time, theory and global numerical modeling efforts as an integral part of the program, and a central data repository and data standards (which exist to this day) for universal access of ISTP data. Similarly to IGY, the ISTP era also led to the establishment of important scientific organizations that facilitate scientific progress and help train the next generation of scientists. The National Science Foundation (NSF) established the Geospace Environment Modeling (GEM), the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR), and the Solar, Heliospheric, and INterplanetary Environment (SHINE) communities, which remain to this day critical focal points for broad community engagement, scientific discussion and coordination, and development of early career researchers.

It was also during this era that the term "space weather" entered broad usage. Although coined many years earlier (Lanzerotti, 2017; Cade and Chan-Park, 2015), the term became entrenched in the late 1990s, as our society became increasingly reliant on technology susceptible to damaging effects of the Sun's interaction with Geospace. Gradually, space weather has become the applied science branch of the Heliophysics discipline, working in tandem with the research branch to map the pathways of space weather impacts, improve forecast models, and identify observational and modeling gaps. The United States government published its first National Space Weather Program Implementation Plan in 1997, highlighting the importance of what we now call Heliophysics for the economy and national security. Research-grade models and observations became operational, used by national agencies such as NOAA to forecast and predict harmful space weather impacts. The ISTP-era Wind and ACE spacecraft, which provided an early warning system for incoming solar wind conditions, and SOHO, which continues to monitor CMEs, demonstrated both the necessity of continuous monitoring of the sun and solar wind and our ability to predict these impacts.

The ISTP era led to three major achievements. First, the coarse system-level ISTP era results exposed gaps in our understanding of plasma physics, such as the electron-scale physics of reconnection, and whether radiation belt electrons were accelerated locally by waves or accelerated remotely and then diffused, that led to the next generation of highly successful, but very specifically targeted missions. This fourth era of Heliophysics, the era of Microsales, followed naturally from the coarse system science ISTP era, with missions targeting substorms (Time History of Events and Macroscale Interactions during Substorms, THEMIS), radiation belts (Van Allen Probes), magnetic reconnection (Magnetospheric Multiscale, MMS), and solar wind heating and acceleration (Parker Solar Probe and Solar Orbiter). These missions sought to elucidate the microphysical processes that ultimately aggregate to large-scale behavior. Second, ISTP broke the long-standing paradigm in which data "belonged" to the instrument principal investigator (PI) and could only be obtained by request. Finally, ISTP started the long journey to FAIR (Findable, Accessible, Interoperable, Reusable) standards for data, models, and analysis codes. In the United States, the White House Office of Science and Technology Policy (OSTP) declared 2023 the year of open science, "to advance national open science policy, provide access to the results of the nation's taxpayer-supported research, accelerate discovery and innovation, promote public trust, and drive more equitable outcomes."[1]

The results of the international, coordinated ISTP program revolutionized Heliophysics, and brought in a new generation of outstanding scientists that have become the leaders of today. The ISTP program led to quantum leaps forward in our understanding of Earth's dynamic magnetosphere and its response to solar wind driving, and altered for the better how our community performs scientific research. It is a shining example of how coordinated worldwide efforts can be brought to bear on otherwise intractable problems.

1.2. The fifth era of Heliophysics - system of systems and mesoscales

These four eras of Heliophysics show a natural progression starting with discovery through qualitative then to quantitative understanding. Today, we have studied both ends of the physical systems extensively — at the microscales, with numerous in situ observations, remote sensing, and sophisticated kinetic-scale modeling, and at the large scales through statistical studies, chance multipoint event studies, fluid-scale and kinetic-scale modeling, and remote imaging. Based on the scientific results of the ISTP and Microscales eras, we suggest that the 5th era of Heliophysics should focus on Geospace and the Sun–Heliosphere as each a system of systems. This refocused effort would integrate the concept of 'messenger dynamics' (2.2), wherein the mesoscales — the messengers and connectors of dynamical change across the system and across spatial and temporal scales — are a primary focus. This emphasis is crucial considering that many of the outstanding questions of our day relate to the inter-connectivity of the systems, intricately connected via underexplored mesoscale connectors and messengers. The mesoscales cover an enormous spatial and temporal range, extending from the motion of individual particles up to the system size. This middle scale is difficult to observe in any systematic fashion, and also difficult to simulate given that it straddles boundaries with micro and macro. Hence, resolving the inter-connectivity of these system-of-systems and the inherent cross-scale coupling will require a large undertaking and new approaches.

In the sections that follow, we lay out the case that many of the unanswered questions for both Solar-Inner Heliosphere (SIH) and Geospace (Geo) require a coordinated scientific program. Such coordinated programs have been implemented in the past, as briefly discussed above, with tremendous scientific return. Additionally, as with the highly successful ISTP era, the Heliophysics community

[1] https://www.whitehouse.gov/ostp/news-updates/2023/01/11/fact-sheet-biden-harris-administration-announces-new-actions-to-advance-open-and-equitable-research/

could benefit from the establishment of an international scientific framework with well-defined strategic science goals and objectives around which worldwide efforts could coalesce. At the same time, we must marshal all tools at our disposal, including space- and ground-based observations, next-generation numerical modeling, and artificial intelligence/machine learning (AI/ML) methods.

In this paper we first discuss how both the Sun-inner heliosphere (SIH) and Geospace (Geo) operate as system-of-systems, highlighting the critical role of mesoscale connectors in coupling those systems (Section 2). We then discuss the inadequacy of the current, largely uncoordinated, ad hoc approach towards understanding these systems, and introduce the concept of the Heliophysics Great Observatories 3. Heliophysics Great Obersatories would harness all available data, including space- and ground-based assets, and combine them with next-generation numerical simulations and theory, and advanced analysis techniques and tools, into well-coordinated, holistic studies of these complex systems. Such Great Observatories would necessarily involve worldwide coordination, and in order to move forward with such an ambitious program, we would require a refinement of the current inter-agency approaches and a better-coordinated international scientific roadmap. We discuss such considerations in Section 4. Although beyond the scope of this paper, this approach also would require revamping our graduate training programs, the structure of funding opportunities, and our evaluation and recognition processes from individual investigator to trans-interdisciplinary team science. Finally, we make specific recommendations and conclude in Section 5.

2. The Solar-Heliosphere and Geospace systems

2.1. System of Systems

A system-of-systems refers to a complex system composed of multiple independent components that can operate independently but, when integrated together, yields a more complex, coupled system and sometimes unexpected (emergent) behavior. A familiar example of a system-of-systems that exhibits emergent behavior is the human body, which consists of 11 major systems. Specialists often study the components of human anatomy separately, such as details of the endocrine or immune systems, for example. Yet unexpected, emergent behavior arises when the different components are coupled together. For example, the connection between heart disease and gum disease was not initially understood until it was observed that bacteria in the gums could enter the bloodstream and damage the heart (Tonetti et al., 2013; Lockhart et al., 2012). No one studying those systems in isolation would have imagined that such a link existed; it is only when studying the system holistically that such relationships between components and emergent behavior are discovered.

It is well established that both Geospace and the Sun–Heliosphere operate as a system of systems (Borovsky and Valdivia, 2018; Wedemeyer-Böhm et al., 2009; Viall and Borovsky, 2020). Geospace is composed of several distinct components, each with its own dynamics and characteristics that can be, and typically are, studied in isolation from the other systems. Geospace is often split into two systems, comprising the magnetospheric system (Mag), which includes the magnetotail, inner magnetosphere, magnetopause + magnetosheath + bow shock/foreshock, and ionosphere-thermosphere-mesosphere (ITM) system. Similarly, the Sun–Heliosphere (SH) is also a system-of-systems with cross-scale feedback and cross-regional coupling between regions of the Sun and the extended solar atmosphere. The SH system includes the solar interior, the photosphere, chromosphere, transition region, inner and outer corona, and inner and outer heliosphere. The solar dynamo generates the magnetic field that connects this system-of-systems. Despite the distinct nature of each subsystem, they are all governed by a set of fundamental principles that govern the behavior of magnetized plasmas. Physical processes, such as magnetic reconnection, at the boundaries of the system or its components can inject energy into the system. Complexity arises when the system components are coupled, through internal processes driven by external coupling, leading to the emergence of novel behaviors that cannot be predicted by studying each subsystem in isolation. Often, this emergent behavior leads to emergent length scales. Magnetic reconnection, which occurs on electron-kinetic scales but yields reproducible mesoscales of 1–3 RE - flux transfer events (FTEs) and bursty bulk flows (BBFs) - for reasons we do not fully understand, is one magnetospheric example. Therefore, a holistic approach that considers the interactions between components is necessary.

Fig. 1 illustrates the complexity of the Sun-Earth system and the many components that comprise them. At the Sun, magnetic fields are generated at the base of the convection zone and break thorough the solar surface as Sunspots and active regions, emerging into the corona as bright features (plages in the He II 304 Å filter image in Fig. 1). These bright features can be the source of large-scale coronal mass ejections and solar wind that travels throughout the solar system and interacts with all the planets. The base of the corona is highly structured and dynamic, where mesoscale structures mediate small-scale structures coming up from below to form the solar wind. Within a few solar radii, the solar wind becomes structured with radial flow. Each of the different components that together comprise the Sun-inner heliosphere (SIH) is complex and studied intensively in their own right in an attempt to answer fundamental physical questions. For example: How is the magnetic field created? How does it emerge? How is the solar wind created? How are solar eruptions triggered? How are transients and solar wind transported through the Heliosphere? To address each of these questions

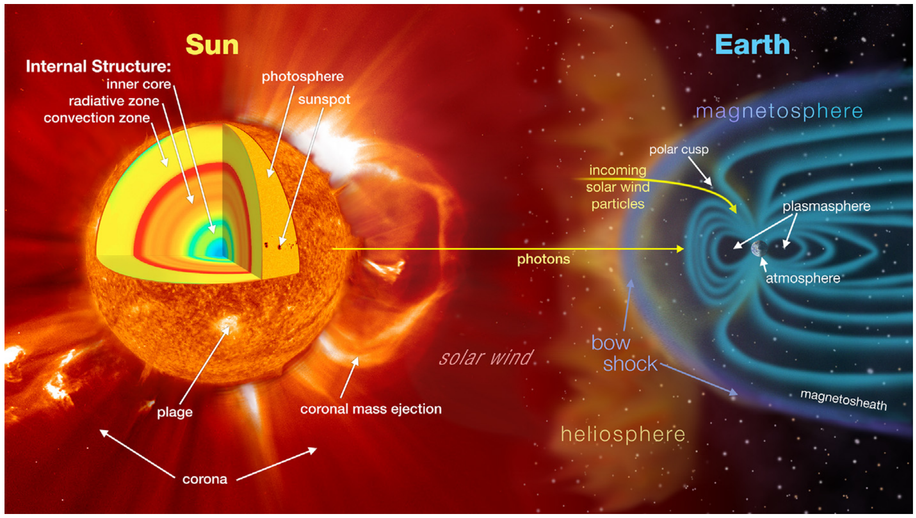

Fig. 1. The Sun-Earth system-of-systems. The various solar and terrestrial atmospheric layers are studied by specialized communities yet they are all connected by the solar magnetic field and radiative output. Image Credit: NASA GSFC.

requires knowledge and modeling of physics in widely different domains where temperatures, densities, and opacities change by huge amounts from region to region. Because of this, different instruments and expertise are needed to probe each domain, and modeling throughout the different solar domains is challenging.

The magnetosphere is also a structured and dynamic system composed of several distinct components, each with its own unique characteristics and dynamics. Although these components can be studied independently in response to imposed boundary or input conditions and the responses parameterized as functions of geomagnetic activity indices or solar wind measurements, this approach has its limitations and fails to capture the dynamical features that arise due to internal cross-component coupling. For example, the energization of the ring current in the inner magnetosphere is believed to depend on the spatial extent and temporal evolution of magnetotail flow bursts (Sorathia et al., 2021). Measuring this inner magnetospheric particle population without concurrent measurements of magnetotail mesoscale plasma flows misses a critical piece of the energization puzzle. Moreover, determining whether a geomagnetic storm produces a radiation belt enhancement requires an understanding of the balance between particle diffusion, loss, and acceleration, which are functions of loss to the ionosphere and out to the magnetopause, enhancements due to injection of fresh particles from the magnetotail, and the state and structure of the cold plasma (dependent on the time history of ionospheric outflow) and large-scale wave activity (see review by Li and Hudson (2019)). Therefore, a complete understanding of the particle acceleration question requires concurrent measurements across the system. Similarly, recent studies have proposed a direct link between magnetopause reconnection events on the dayside and subsequent tail reconnection and magnetospheric substorms on the nightside (Nishimura et al., 2014). Even reconnection at the dayside magnetopause may be subject to mesoscale structures created at the bow shock and foreshock (Zhang et al., 2022), invisible to L1 solar wind monitors. These cross-scale and coupled-system dynamics are poorly captured with our limited suite of remote and in situ measurements and are just now being captured in coupled system numerical models (Palmroth et al., 2023, Sorathia et al., 2021, e.g.

Geospace and the solar atmosphere are similar in that there is clear need to study the way the components comprising those large-scale systems interact with each other. As we detail in the next section, a key component of cross-component and cross-scale coupling, and of the emergent dynamics that naturally arise, is that they depend heavily on mesoscale dynamics, where enormous observational and numerical gaps exist. These mesoscale processes play a crucial role in the exchange of mass, momentum, and energy between different components, as well as in the emergence of complex behavior that is not easily predictable from the behavior of individual components.

2.2. Mesoscales: The gap between micro and macro

The cross-component coupling that occurs within the Heliospheric systems is further complicated by the fundamental nature of magnetized plasma dynamics. This universal physics of multi-scale feedback results from dynamical plasma physics occurring over temporal and spatial scales that span many orders of magnitude. We can broadly categorize these regimes into three scales: microscale (kinetic), mesoscale, and macroscale (global). Though each regime encompasses vastly different temporal and spatial scales, and these temporal and spatial scales vary depending on the system, the bidirectional feedback across the scales is crucial to physical understanding and, ultimately, prediction. This is true of all of the physical systems that comprise the sub-disciplines of Heliophysics.

Characteristics		Regime: Microscale/Kinetic	Regime: Mesoscale	Regime: Macroscale/Global
Temporal Scale	Solar surface	<0.1 s	Hours to days	Days to decades
	Solar wind	seconds	10s of seconds to hours	Days to weeks
	Magnetosphere	<seconds	10s of seconds to minutes	10s of minutes to days
	ITM	seconds	Few minutes to hours	Hours to days
Spatial Scale	Solar surface	<10s of km	10s km – 30 Mm (granular scale)	100 Mm-Solar radius (700 Mm)
	Solar wind	<1 Mm	10 Mm-thousands of Mm	1 AU (150,000 Mm)
	Magnetosphere	<hundreds of km	Up to few RE	>few RE
	ITM	<meters	<100s km	<1000s km
Simulation		PIC	MHD, hybrid, mixed models, plug-ins	MHD, hybrid, mixed
Example		Wave particle interactions, ohmic heating, magnetic reconnection, plasma instabilities, small-scale gravity waves	Bursty bulk flows, FTEs, streamer blobs, granular scale, solar bright points, ionosphere polar cap patches, gravity waves	Solar dynamo, CMEs, CIRs, substorms, planetary waves, atmospheric tides

Fig. 2. The primary systems within Heliophysics straddles a large range of temporal and spatial scales, spanning from the kinetic/microscale up through global/macroscale, summarized here. Note that these ballpark scales are simple guidelines, and do not even account for additional scale changes that occur, e.g., with solar cycle, or within sub-regions.

Table 2 summarizes the temporal and spatial scales associated with different Heliophysics regimes. The smallest scale is the kinetic regime, which deals with the motions and effects of individual particles. The dynamics in this regime include thin current sheets and magnetic reconnection, wave-particle interactions, kinetic plasma instabilities, and particle acceleration. The temporal and spatial scales in this regime are dictated by particle gyromotion. At the opposite end of the spectrum, macroscales are defined as significant fractional sizes of the system under consideration, and the timescales associated with macroscale spatial scales are generally determined by the timescale it takes to significantly alter the large-scale structure. Examples of macroscale structures and dynamics include the overall morphology of the magnetosphere, coronal mass ejections, planetary waves and tides, and the heliospheric current sheet.

Mesoscales exist in the space and time regime that lies between the microscale/kinetic and the macroscale/global scales, and is where many important cross-scale interactions and emergent dynamics take place. The mesoscale begins around the ion scale and ends at a significant fraction of the system under consideration. However, the boundaries at both ends of the mesoscale, between micro and meso, and between meso and macro, are fuzzy, and the transitions are not sharp; one cannot put an absolute number on either end. Indeed, it is this fuzziness in the cross-scale coupling that makes the boundaries so interesting and difficult to study, as it indicates regions of energy conversion.

Earth's magnetosphere offers striking examples of how a system-of-systems is connected by mesoscale 'connectors' and 'messengers' (Fig. 3). These mesoscale connectors are fundamental units of transport, and play a vital role in the transfer of mass, momentum, and energy throughout and across systems, and to and from micro and global. In effect, they are the commuter rails of the magnetosphere, shuttling mass and flux from one region to another, from the tail to the inner magnetosphere (via BBFs), and from the dayside to nightside (via FTEs), for example.

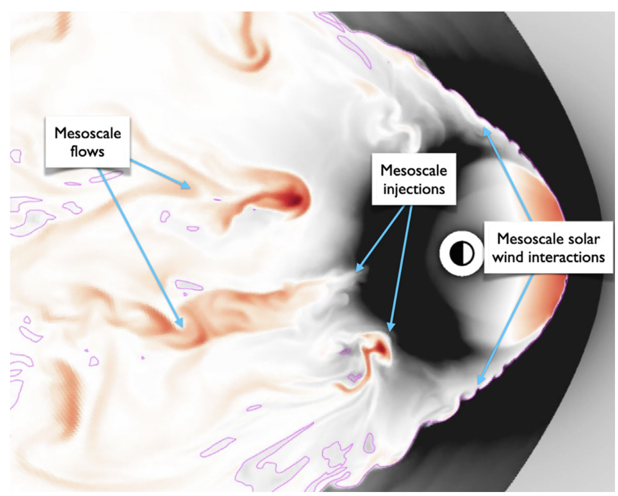

Fig. 3. Global numerical simulations show ubiquitous mesocale connectors that couple the magnetosphere system of system together, from dayside solar wind interactions, through nightside tail reconnection, to inner magnetospheric injections. Figure produced with the GAMERA magnetosphere simulation, adapted from Sorathia et al. (2020).

In addition to their role in mass and energy transport, mesoscale connectors also facilitate cross-scale coupling between micro and macro scales in the inter-regional space. These interactions are bidirectional, with microscale processes impacting global structures, and vice versa. For example, the thinning of the nightside current sheet down to a microscale thickness during substorm growth phase is driven by the global pressure buildup in the magnetotail as a result of the solar wind driving. The eventual reconfiguration of the magnetosphere during substorms is then initiated by microscale reconnection in the tail region, which generates mesoscale flows that can lead to global reconfiguration. At the dayside, global solar wind forcing can trigger microscale thin current sheets and reconnection on a recurrent scale of 1–2 RE. Solar wind discontinuities can also change the magnetic field orientation over kinetic scales at the bow shock leading to large mesoscale structures called Hot Flow Anomalies (HFAs), which are not well understood (Zhang et al., 2022). At the Sun, there is increasing evidence that the structure of solar granular and supergranular scales at the solar surface leaves imprints upon the solar wind (Fargette et al., 2021). However, the mechanism of this coupling through through the highly dynamic and complex middle corona is a topic of considerable debate.

In addition to serving as transport connectors, mesoscales also play a critical role as information messengers. In the solar chromosphere and corona messengers, such as waves (e.g., magnetoacoustic and Alfvén waves) and field-aligned currents (whose dissipation occurs at mesoscales) are the main contributors to coronal heating. Similarly, in the magnetosphere messengers include Alfvén waves and field-aligned energetic particles. However, the bulk of configuration changes in the magnetosphere are communicated through the mesoscales. For instance, when the interplanetary magnetic field (IMF) turns southward, the nightside magnetosphere knows about this due to magnetic flux transfer events (mesoscale connectors) that transmit flux from the dayside to nightside. During a substorm, when reconnection occurs in the tail, the resulting reconfiguration change is transmitted to the inner magnetosphere and ionosphere-thermosphere-mesosphere (ITM) system through mesoscale flow bursts. These flow bursts act as messengers that carry critical information about the reconfiguration change from the tail to the inner magnetosphere and ITM system.

Recent studies of the Sun with higher spatial and temporal resolutions reveal a growing level of dynamics, indicating that energy transfer and release occur at small scales. However, we are also discovering that the imprint of mesoscale structures in the solar atmosphere is manifested in the near-Sun solar wind, altering our understanding of how solar wind forms. The magnetic field in the larger scales emerges in large-scale coherent structures on the solar surface, such as sunspots and active regions, and eventually disperses and drifts towards the poles due to an interplay between the magnetic field and the convective motions of the plasma. Small-scale fragmentation is responsible for the transfer of energy upwards and downwards, and it is detected as radiation, plasma motion, or nonthermal particles. However, the fundamental scale of energy release and the corresponding elemental flux tubes in the solar corona is well below current observing capabilities. The energy accumulated in the corona above active regions or within sheared coronal loop systems in the quiet Sun is eventually released as flares and coronal mass ejections (CMEs). Despite our knowledge that small-scale changes lead to big eruptions, we still have only a vague idea of how and when this occurs. The reason is our inability to access the relevant spatial and temporal mesoscales of energy accumulation and release, as well as the relevant mesoscale connectors at work between them.

Solar wind formation involves cross-regional and cross-scale coupling and can be broken down into three steps: the source (heating in the lower corona), the release in the middle corona (escape through reconnection or already open field lines), and the acceleration that occurs through the upper end of the extended corona (Viall and Borovsky, 2020). The solar wind subsequently observed in the heliosphere, typically in near-Earth space, but more recently in the inner heliosphere thanks to Parker Solar Probe and Solar Orbiter, displays a structure that results from both the near-Sun boundary conditions and transport effects, as a result of micro-stream interaction and turbulence (Viall et al., 2021; Owens et al., 2011).

Despite the importance of mesoscale dynamics in cross-regional and cross-scale coupling, there are significant gaps in our understanding of these processes, both in terms of observational data and numerical models. The gap exists because understanding the mesoscales requires simultaneous observations at multiple locations and scales. Yet, today, this cross-scale, system science currently relies on ad hoc and chance alignments of uncoordinated missions, which hinders substantial progress in understanding the system dynamics. In the next section, we briefly summarize this knowledge gap, and then recommend a path forward.

2.3. The system-of-systems and mesoscale knowledge gaps

The field of Heliophysics faces significant challenges in accurately modeling and observing physical systems due to observational undersampling and limitations in technological and computational capabilities. The temporal and spatial gaps between the kinetic and global scales are orders of magnitude apart (see Table 2), which hampers our ability to implement a comprehensive modeling and observing program. As a result, researchers are compelled to focus on restricted regions of parameter space, and modeling must simplify the complexity of the phenomena it mimics, by simplifying boundary conditions, reducing the dimensionality, or approximating the physical interactions.

Kinetic physics is modeled with particle-in-cell (PIC) and Vlasov simulations, while large systems have earlier employed the MHD (fluid) description. Recent breakthroughs in modeling efforts and supercomputing resources have also enabled kinetic description of global systems that complement the earlier MHD simulations (Ganse et al., 2023; Palmroth et al., 2023). Observations of kinetic-scale phenomena require rapid, in situ measurements sufficient to capture kinetic temporal and spatial scales (like Parker

Solar Probe, Magnetospheric Multiscale, Cluster, and the Fast Auroral SnapshoT Explorer (FAST)), or spectroscopy (the Daniel K. Inouye Solar Telescope (DKIST), the Interface Region Imaging Spectrograph (IRIS)), while global studies require widely separated spacecraft working together – such as STEREO in situ + L1 in situ, THEMIS radial conjunctions, solar and heliospheric imagers such as STEREO/SECCHI, SDO/AIA, and SOHO, and magnetospheric EUV and ENA imagers. Global scales are studied with the ad hoc Heliophysics System Observatory (HSO) that acts like a "system science" observatory.

The middle, or mesoscales, are observationally undersampled. Yet, there are still critical aspects of the solar-inner heliosphere, ITM, and magnetospheric systems that remain unanswered and rely on knowledge of this understudied regime. Broadly speaking, we can summarize these top-level science questions as follows:

- (SIH) What is the nature of magnetic energy flow from the photosphere, through the layers of the corona, and out into the solar wind?
- (Mag) What is the temporal and spatial extent and cross-system impacts of mesoscale and cross-scale energy input, dissipation, and transport in Earth's magnetosphere?
- (ITM) How is multi-scale and multi-directional forcing processed and redistributed by internal dynamics and chemistry, and how does the ITM form a tightly coupled two-way feedback loop with the magnetosphere?

In the sections that follow, we dive a bit more deeply into these top-level science questions. Each of these strategic science goals is associated with understanding the system-of-systems aspect of the regions, connecting the microphysical processes to the macroscale structure and topologies, and the nonlinear, emergent dynamics that often result. The answer to these top-level Heliophysics science questions flows through the mesoscales.

2.3.1. Solar-inner heliosphere system knowledge gap

As the seat of the Heliosphere, the Sun's magnetized plasma and radiation output establishes the conditions through which all solar system objects must respond and therefore sets many of the primary relevant temporal and spatial scales. The details of the magnetic energy flow from the convection zone, through the solar atmosphere and into the solar wind impose the original spatio-temporal scales on the Solar-Heliosphere and Geospace systems (2.1). Understanding how these original scales evolve through the solar atmosphere and into the Heliosphere will go a long way toward understanding how the Sun — and by extension, a star — affects the planetary environment around it.

The Sun is an immensely complex system that can only be studied remotely through a limited number of observing windows of spectral, temporal, and spatial coverage. The highly structured solar atmosphere can be visualized as a series of physical interfaces across which the plasma and magnetic properties, and hence the relevant physical processes, change drastically. This inherent property makes the tracking of energy flow and structures extremely difficult. A particularly vital interface is the transition from the closed field, collisionally-dominated corona to the outward flowing collisional plasma that forms the seed of the solar wind. Much of this transition takes place in the middle corona (roughly 1 to 4 Rs), a difficult to access region due to its close proximity to the bright solar disk and its structural complexity. It can be thought of as a processing filter that allows some structures/frequencies to go through, reflects others, and creates new spatio-temporal scales on its own. Some examples, below, from recent observations help illuminate the problem.

The Sun has continuous and dynamic solar winds, both slow and fast. The recent results from the Parker Solar Probe have revealed magnetic switchbacks in the solar wind that are frequent when the measurements are made closer to the Sun (Bale et al., 2019). There has been much debate about the sources of these switchbacks, but these fall into two regimes. In the first, the switchbacks are created low in the solar atmosphere (e.g., Tripathi et al., 2021; Upendran and Tripathi, 2022) and in the second, they are created in the solar wind (see Fig. 4). For the former option, there is evidence that the switchbacks may be associated with supergranulation scales, which correspond to their longitudinal separation. The source is the diverging magnetic field that funnels into the network magnetic field.

At these spatial scales, it is critical to differentiate between coronal remnant structures and structures forming en route (Viall et al., 2021). This is complicated by the fact that the solar wind evolves as it flows outward and consists of a mixture of injected and evolved structure by the time it is measured at Earth. Solar wind switchbacks are one such example, observed ubiquitously by Parker but less frequently further out (Neugebauer et al., 1995), as are magnetic discontinuities in general. Ion composition and

Fig. 4. There are a number of explanations of magnetic switchbacks which are illustrated here. Courtesy of NASA.

charge states can be particularly useful for differentiating injected vs. evolved structures (Kepko et al., 2016), but almost no such multi-point observations exist at mesoscales.

UV and EUV solar observations, e.g., from SDO/AIA, GOES-R/SUVI, Hinode/EIS, IRIS, show evidence of the omnipresence of small-scale activity in the form of transient brightenings and minor jetting (see e.g., Raouafi et al., 2023; Berghmans et al., 2021; Madjarska, 2019; Mulay et al., 2016; Peter et al., 2014; Harra et al., 2008). The origin of these phenomena is most probably magnetic reconnection at the base of the solar corona, which occurs at the lower end of the mesoscale and is not readily observable and with no clear predominant output in the form of waves and/or particle acceleration. This ubiquitous physical mechanism could heat the corona. Similarly, the discrete nature of these events leads to intermittent outflows, which become homogeneous as they propagate away from the Sun and would be the source of the solar wind. Higher spatial and temporal resolution imaging spectroscopy, as well as in situ measurements (e.g., of plasma composition) to confirm the link with the remote observations, would be required to disentangle the real nature and characteristics of the mesoscale mechanism.

Even large-scale structures, such as CMEs and shocks, are highly structured on the mesoscale. The WISPR observations from Parker Solar Probe (Howard et al., 2022) indicate a highly complex internal CME structure that apparently remains at 1 A.U., complicating in situ reconstructions (Lugaz et al., 2018) and severely limiting our ability to predict the orientation and strength of the CME magnetic field (Riley et al., 2017). Smaller-scale structure in the ambient solar wind is expected to have an increasing influence with distance from the Sun, as both expansion and the decrease in characteristic wave speeds mean that large-scale structures lose their coherence (Owens, 2020). Resolving the mesoscale structures of solar transients, across the vast inner heliosphere from the solar surface through the layers of the corona, requires a carefully designed architecture of simultaneous remote sensing and in situ measurements of the transients en route to Earth. The architecture would involve in situ spacecraft constellations at L1, or preferably upstream of L1, with sufficiently dense spacing to resolve the internal structure of transients, assisted by high-sensitivity heliospheric imaging from outside the Sun-Earth line, either from 1 A.U orbits or better inside of 1 A.U., through the exploitation of quasi-stable orbits, for example. Similar architectures have been presented in the recent NASA Living With a Star (LWS) architecture report Cohen et al. (2022).

2.3.2. Magnetosphere system knowledge gap

There still remain major outstanding questions of how Earth's magnetosphere responds to solar wind driving. It is abundantly clear that the major science questions of our time are related to how mass, momentum, and energy flow from system to system within Earth's magnetosphere and across its boundaries, and how rapid, emergent phenomena are triggered. The key to answer these questions is through the mesoscales, the vast region between the microscales that can be studied with our fleet of in situ spacecraft, and the global, which are studied through statistical or average observational studies. Recent advances in numerical modeling with global kinetic simulations and high-resolution MHD simulations coupled with kinetic codes are continuously bringing new and exciting proposals on how the system works, but await observational verification (Palmroth et al., 2023; Sorathia et al., 2020).

Each system within Earth's magnetosphere requires understanding of the cross-scale (micro $<->$ meso $<->$ global) and cross-system coupling. As recent discoveries in both observations (Gabrielse et al., 2023) and global kinetic (Palmroth et al., 2023) and fluid (Sorathia et al., 2021) simulations demonstrate, it is insufficient to study these domains in isolation. One cannot simply study or model each piece independently, then plug the pieces together and expect to produce a realistic result or understanding. A coherent, systematic, "system of systems" observational and modeling approach is required.

On the nightside magnetosphere, there is a concerted effort to understand the degree to which mesoscale transport in the magnetotail contributes to the global dynamics of magnetic flux transport and dipolarization, particle transport, and injections contributing to the storm-time ring current development and impacts on auroral precipitation and the global ionospheric system response. It is necessary to understand how Earth's inner magnetosphere is connected to the greater magnetosphere beyond it (and to itself, through the various collocated particle populations) and the ionosphere and neutral atmosphere below it. Finally, an understanding of cross-scale physics of the solar wind-magnetosphere interaction would vastly develop our understanding of magnetic reconnection, broad-scale magnetospheric responses, and shock and foreshock phenomena.

Multipoint magnetospheric missions like Cluster and MMS provided insight into the structure of and energy transformation at plasma boundaries, current sheets, and coherent dynamic structures in the magnetosphere and near-Earth solar wind at ion and electron scales. However, these missions did not observe the spatial structure and evolution of these dynamical processes at mesoscales (greater than a few 1000 km) or their impact on other remote plasma regions. The THEMIS mission was designed to study the energy and plasma transport and evolution of plasma structures at mesoscales. However, it was designed for a narrowly defined 1-dimensional science question and lacks the capability to simultaneously reveal 3D structure at kinetic scales. As a result, we either know the local structure of plasma objects at kinetic scales or we have information on energy and plasma transport at larger scales. Specifically, it is still unclear how the plasma instabilities excited at kinetic scales (for example, magnetic reconnection) in the magnetotail create mesoscale structures and how important they are in affecting the inner magnetosphere. Similar relationships on the 3D evolution of plasma systems and the related energy transport from kinetic to meso- and macroscales (and vice versa) are of interest for other magnetospheric regions.

To achieve further advancements with these challenges, we need to combine the underlying ideas of Cluster/MMS and the THEMIS missions. A perfect tool could be a launch of several constellations of satellites forming specific configurations in space to observe simultaneously the 3D pattern at kinetic (like Cluster and/or MMS) and mesoscales (like THEMIS), combined with remote imaging of the inner magnetospheric plasma environment. Conjunctive measurements of such spacecraft fleet will provide broad monitoring of the region(s) of interest and its coupling with the ionosphere.

2.3.3. ITM system knowledge gap

The Ionosphere-Thermosphere-Mesosphere (ITM) represents the transition layer between the neutral atmosphere and the ionized magnetosphere, extending from the stratosphere ($\sim$ 50 km) up to several 1000 km above Earth's surface. The field-aligned currents (FACs) that link the ionosphere and magnetosphere close across a thin conducting layer near 120 km altitude. The region's variability is driven both from above by solar EUV and UV radiation, magnetospheric forcing through electric fields, Joule heating, and particle precipitation, and from below by atmospheric tides and gravity waves. The resulting global thermospheric circulation redistributes mass and composition changes and heat throughout the system. Planetary waves, tides, and gravity waves propagate upward from the lower atmosphere and deposit momentum across various spatial scales. The neutrals and ions are driven by separate processes but linked through collisions, momentum, and ionization exchange, resulting in a complex, multifluid environment.

Fig. 5 summarizes the complex, cross-scale, and cross-regional coupling within the ITM system, which is driven by solar, magnetospheric, and lower atmospheric drivers. Short-wavelength (EUV and UV) solar radiation heats the neutral atmosphere and ionizes the dayside atmosphere, and this ionized plasma is carried to the nightside via corotation. Earth's magnetic field leads to mesoscale features, such as the equatorial anomaly and ionospheric irregularities and bubbles. The solar wind and IMF input energy into the auroral zones and cusps, while magnetospheric convection imposes the two-cell ionospheric convection pattern on the polar cap. Finally, large geomagnetic disturbances produce regional composition changes and nightside plasma irregularities.

The ITM system's responses to these drivers are determined by interacting dynamical, chemical, and electrodynamic processes across a wide range of spatial and temporal scales. These processes often involve nonlinearity and feedback, leading to emergent behavior that affects systems beyond the ITM. For example, during strong solar wind driving, the ionospheric outflow of heavy ions can alter the reconnection efficiency in the tail. In some cases, an $\sim$ 3 hour planetary scale oscillation, so-called sawtooth oscillations, are observed to emerge from this nonlinear coupling between the ITM and magnetospheric system in numerical simulations (Brambles et al., 2011), but await observational confirmation.

The next NASA Living With a Star mission, Geospace Dynamics Constellation (GDC), aims to study the ITM system's dynamics at all spatial scales, by measuring the energy input from above and the ionspheric and neutral response, and includes local, regional, and global phases. Combined with NASA's proposed DYNAMIC mission, which would measure momentum input from the lower atmosphere, the two missions together will provide comprehensive measurements of the ITM system's behavior. These two strategic missions, when combined with other current and planned ITM missions, as well as extensive ground-based observatories and advanced numerical models, would fundamentally alter our understanding of this critical transition region just above Earth's surface. This concept of leveraging the full suite of available tools and assets towards a larger strategic science objective forms the foundation for the concept of the Heliophysics Great Observatories, described in the next Section.

3. Heliophysics Great Observatories

3.1. Inadequacy of the current approach

As discussed earlier, the inter-connectivity of the Geospace and Sun–Heliosphere system-of-systems and the role of mesoscale dynamics are central to many key science questions. Although the ISTP program provided the first systematic insight into the functioning of various systems within Earth's magnetosphere in response to solar and solar wind driving, it had some significant limitations. The measurements were restricted to single-point measurements in specific regions with limited auroral imagery and off-Sun-Earth-line solar observations. The inner magnetosphere and ITM systems were not included in the ISTP program, which was a rudimentary system observatory for its time.

Since then, we have relied on infrequent, serendipitous alignments of largely uncoordinated missions of the Heliophysics System Observatory (HSO) and other agency missions to bootstrap a system-level observatory to answer system-of-systems questions. However, the HSO has two significant inadequacies. First, the sparse measurements, even if coordinated, are insufficient to fully capture the system of systems because of observational gaps. For example, Fig. 6a illustrates the significant knowledge gaps in the base state of the solar surface and coronal magnetic field due to the unobserved backside of the Sun and poles. Second, the sparse measurements, even if coordinated, are inadequate to fully capture the mesoscales. For instance, the locations of MMS, THEMIS, and ARASE, as shown

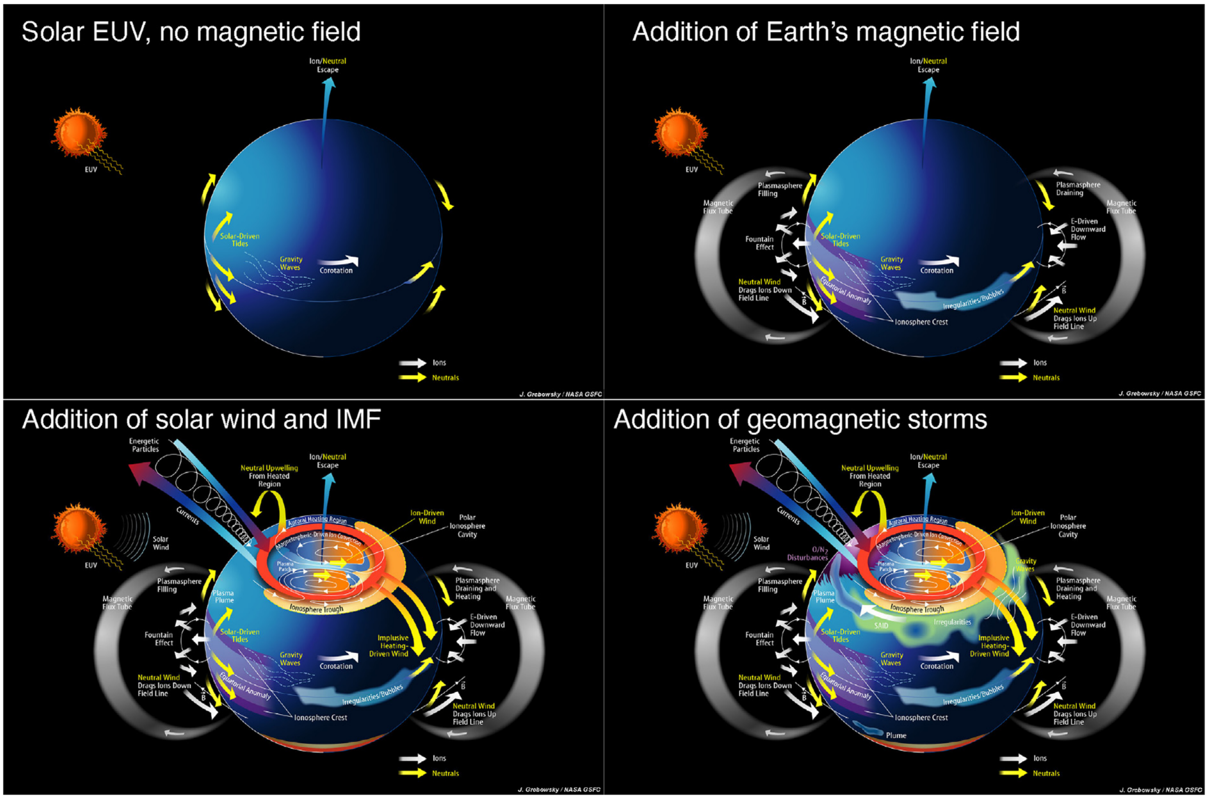

Fig. 5. Earth's ITM system is structured by input from a variety of sources, as indicated here. The solar EUV produces ionization in the dayside, creating gradients that propagate through the sytem. Earth's magnetic field provides equatorial structuring, such as the equatorial anomaly. Finally, energy derived from the magnetosphere-solar wind interaction leads to tremendous energy input at high latitudes, which redistributes to all latitudes and local times. Figure Courtesy J. Grebowsky/NASA.

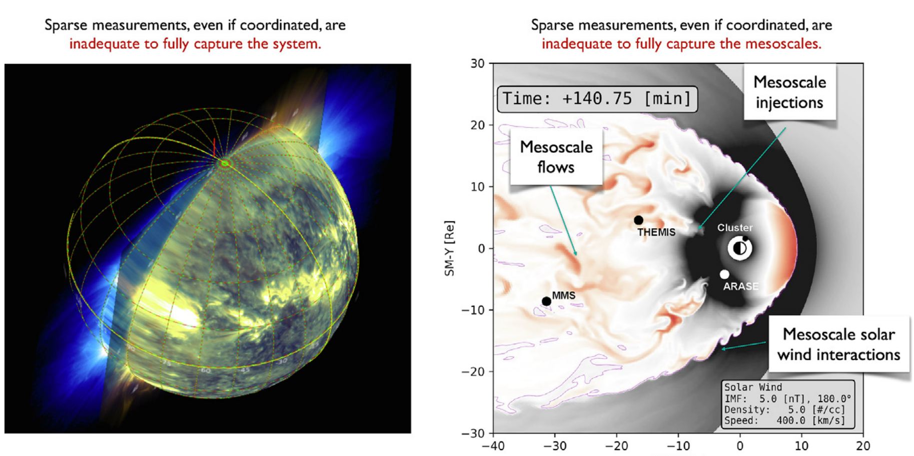

Fig. 6. Sparse measurements, even if coordinated, fail to capture the system-of-system, and fail to capture the mesoscales. The figure at left shows concurrent STEREO and SOHO images from the same time, overlaid on each other. The backside of the Sun is unobserved, and the polar regions are not resolved. The simulation snapshot at right shows that the sparse network of in situ magnetospheric missions, even if well-coordinated, are inadequate to capture the mesoscale dynamics thought to be occurring.

in Fig. 6b for a simulated moment in time, are limited and wholly inadequate to capture the mesoscale dynamics thought to be occurring within Earth's magnetosphere. The HSO's limitations are due to the fact that HSO elements are standalone missions with their specific science objectives to accomplish. In recent years, these missions have focused on microscales, and the systems aspect has been an afterthought. Furthermore, upfront coordination with ground-based facilities is not always considered, except in a few cases such as THEMIS, which highlights the potential for tremendous science returns when coordination is incorporated into a program.

Although Geo and SIH have different observational strengths and limitations, both communities are converging on the need to understand the cross-scale (micro < – > macro) and cross-regional coupling that are inherent to a system-of-systems approach. By definition, this flows through the mesoscales. Therefore, there is a need for a comprehensive, system-level observatory that can fully capture the interconnected behavior and mesoscale dynamics of the Geospace and Sun–Heliosphere system-of-systems. The NASA GDC mission, as described earlier, is a significant step in this direction, as it is a multi-spacecraft mission designed to study the ITM's behavior and includes local, regional, and global phases to capture the spatial and temporal scales of these dynamics. Furthermore, the DYNAMIC mission, which will provide measurements of momentum input from the lower atmosphere, is designed to operate simultaneously with GDC. The pair of missions will provide an unprecedented opportunity to study the interconnected behavior of the Geospace and Sun–Heliosphere system-of-systems comprehensively. This strategic NASA mission pair also provides an opportunity to develop a reimagined holistic scientific program, called ISTPNext, which is described below and based on a concept called the Heliophysics Great Observatories.

3.2. An alternative approach: ISTPNext and Heliophysics Great Observatories

To address the mesoscale and system-of-systems knowledge gap, we propose an orchestrated, international effort in a coordinated, global Heliospheric observation system that includes ground- and space-based observations, numerical modeling, advanced analysis techniques, and new data archiving and accessibility programs. This program would contain the key elements outlined below and would necessarily link the ground-based and modeling communities, along with data science and advanced analysis techniques and archiving to deal with the logistics of the volumes of data to be inter-compared and calibrated. To achieve this vision, we need to establish new international coordination mechanisms that promote data sharing, modeling, and coordinated analysis that would form the basis of a next generation ISTP program, ISTPNext.

To achieve the objectives of the coordinated global Heliospheric observation system, the program must resolve the mesoscales simultaneously across the system of systems. For Geospace, this would require a mesoscale/fluid backbone of multiple constellations of in situ spacecraft and/or imagers in key regions. For the Sun–Heliosphere, deployments of mesoscale-sized grids of in situ spacecraft in tight coordination with imaging of the same areas for the global context would be required. Second, we must continue to monitor the state variables of the Sun-Earth system, which include, but is not limited to, global solar magnetic field and coronal activity observations, in situ solar wind measurements, auroral and solar EUV imagery, cross polar cap potential, and radiation belt content. There is also a need to coordinate space-weather observational assets across NASA, NOAA, and international partners. Operational space weather missions are often treated separately than the science missions; however, with careful forethought, it may be possible to combine science instrumentation with space weather monitoring on a single platform. Third, the initiative must invest in next-generation numerical modeling, a key component of modern space physics. Fourth, ground-based assets must be integrated directly and early into flight programs. Finally, embracing and using 'big data' and ML/ AI techniques would be crucial for the success of the program.

All these activities and initiatives would work in concert to study Geospace and the inner Heliosphere holistically, as systems, at the scale sizes — mesoscales — that we now know are driving the overall dynamics. Overall, this international effort would fundamentally alter our understanding of Geospace and the inner Heliosphere, help us address the knowledge gap in the mesoscale and system-of-systems, and answer the strategic science goals listed in Section 2.3.

Fig. 7 provides a summary of the approach. ISTPNext combines all available tools, including space- and ground-based measurements, integrated theory and modeling programs, and small, low-cost missions (sounding rockets, balloons, and cubesats) under a common scientific umbrella for comprehensive, coordinated system-of-systems science. Advanced analysis techniques, including data assimilation, AI/ ML, and open source analysis tools, are used alongside a future research infrastructure that enables the use of large and diverse data sets and cloud computing to facilitate international data sharing and collaboration. The Heliophysics disciplines of Geospace (ITM + Magnetospheric) and Solar-Inner Heliosphere (SIH) organize into "Great Observatoriers", described in more detail in the next section. Together, these Great Observatories, along with the inter-agency collaborations and international coordination that bind them together, would form the suggested ISTPNext program.

3.3. The Geospace Great Observatory

Geospace is a highly coupled system, consisting of the ionosphere-thermosphere-mesosphere (ITM) and magnetosphere. NASA is planning to launch its next Living With a Star mission, the Geospace Dynamics Observatory, in the coming decade. It is designed to study how the high latitude ionosphere-thermosphere (IT) system responds to variable solar wind and magnetospheric forcing, and how internal processes in the global IT system redistribute mass, momentum and energy. GDC is managed out of NASA's Goddard Space Flight Center and will consist of 6 spacecraft, orbiting near 400 km, with three distinct mission phases that study the local, regional and global IT system. It is expected to launch concurrently with DYNAMIC, nominally a 2-spacecraft mission to study ITM forcing from below. Together, GDC + DYNAMIC would yield

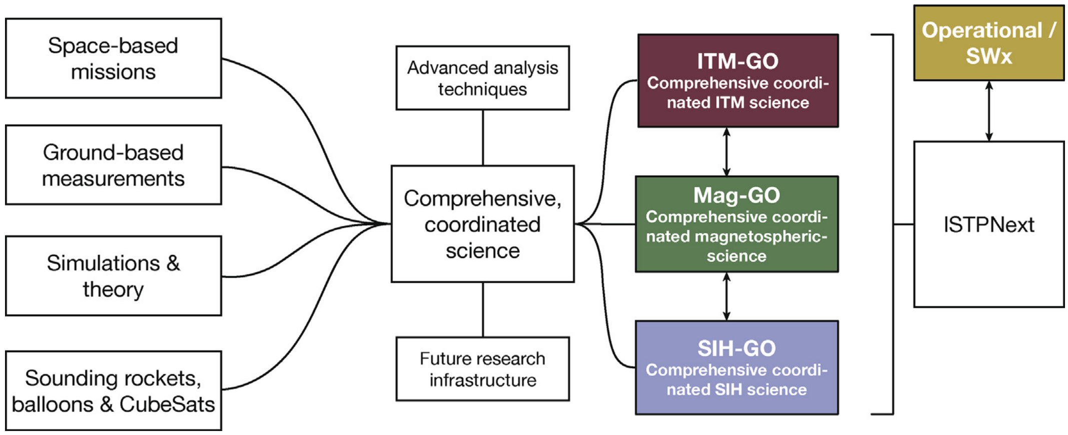

Fig. 7. ISTPNext would consist of 3 Great Observatories, each producing comprehensive, coordinate science of their respective system-of-systems. The Great Observatories integrate observations and theory with advanced analysis techniques and an advanced research infrastructure to yield more overall science return than the individual components. ISTPNext would have tight coordination with the operational space weather component of Heliophysics.

tremendous scientific insight into the multiscale (micro, macro and global) dynamics of the ITM system-of-systems.

The launch of NASA's GDC + DYNAMIC mission complement will represent a significant strategic hub for ITM science and an opportunity to establish the principles outlined in this document. Fig. 8 summarizes the ITM Great Observatory (ITM-GO) as currently envisioned. Boxes in light pink represent resources under the auspices and control of the GDC program. DYNAMIC will be a PI-led mission and is explicitly designed to operate concurrently with GDC while assuming use of certain key GDC measurements. Once selected, the DYNAMIC PI and their team will coordinate closely with GDC, and participate in the GDC science team meetings with an ex officio status. This explicit linkage of GDC and DYNAMIC so early in the development phase of both missions offers an exciting opportunity for the ITM community.

Although GDC and DYNAMIC are linked per the NASA announcement of opportunity for DYNAMIC, each mission still maintains an independent set of science

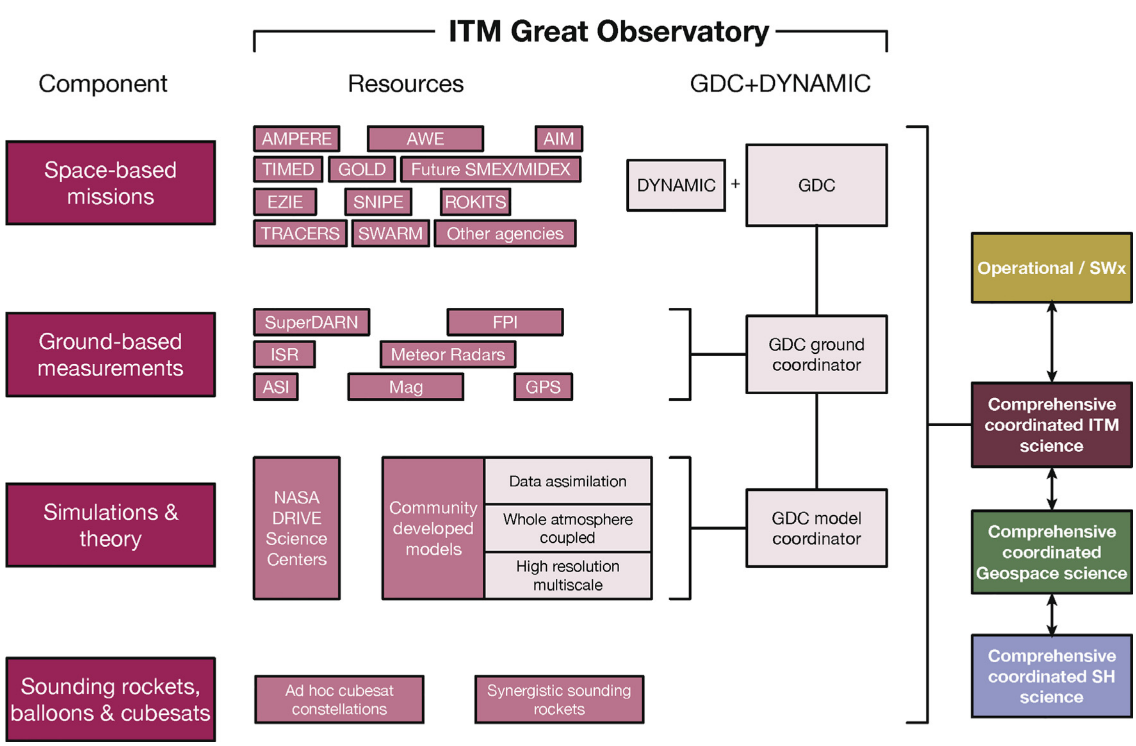

Fig. 8. The ITM Great Observatory (ITM-GO) would combine current and future space- and ground-based assets, simulations and theory, and sounding rockets, balloons, and cubesats into a coordinated, holistic observatory for studying the ITM system. It leverages NASA's planned investment in the strategic missions Geospace Dynamics Constellation (GDC) and DYNAMIC to serve as strategic hubs for a worldwide, coordinated science program.

objectives for which each mission will be responsible. A traditional mission approach would be to assemble research and observational components needed to answer the science objectives of that particular mission. For GDC, this would be the six spacecraft and associated instruments, ground measurements as needed for science closure or calibration/validation, and numerical modeling. The approach of DYNAMIC remains to be determined. Since missions have specific science questions they are expected to answer, and often quite constrained resources with which to do so, the science scope is often constrained to these local boxes, and limits the system aspects, as discussed previously in the context of the HSO.

However, there are enormous existing and planned scientific resources beyond the GDC + DYNAMIC missions that could be brought to bear on broader scientific questions of the ITM system. These additional resources are highlighted in medium pink and include other space-based missions, an enormous collection of ground-based instruments and facilities, and numerical tools that are not formally part of the GDC team. The only thing lacking is an organizational structure and the infrastructure (data standards, open source software, observation planning) to allow for those collaborations. Since GDC + DYNAMIC represents a significant investment in ITM science, it can serve as a strategic hub to bring together worldwide ITM resources under a common science architecture, thereby producing science beyond what would be obtained individually.

Ideally, ITM-GO would be part of a larger Geospace Great Observatory with the addition of a magnetospheric component. However, the space-based observational program for magnetospheric physics is quite limited at this moment. A Magnetosphere Great Observatory (Mag-GO) would likely have to wait for new mission elements but should include the ability to:

- Resolve mesoscale dynamics across the system (flow bursts, magnetopause FTEs, foreshock/magnetosheath transients impact on magnetosphere/ionosphere, etc.)
- Resolve mesoscales in the inner magnetosphere and coupling to tail/transition region mesoscale dynamics
- Resolve ionospheric/auroral mesoscales, magnetospheric coupling, and the auroral acceleration region
- Resolve kinetic < – > mesoscale (cross-scale) coupling

It is possible that some of these objectives could be partially met through strategic coordination of existing mission elements of the NASA’s Heliophysics System Observatory. However, as noted by the 2023 Heliophysics Senior Review, no such coordination mechanism currently exists. Were such a coordination mechanism available, it might then be possible to identify critical missing elements or observational gaps and insert ad hoc missions of opportunity. This would represent a significantly different approach than currently implemented within ESA or NASA.

3.4. The sun-inner heliosphere Great Observatory

Like Geospace, the Solar-Inner Heliosphere (SIH) is a system of systems, bounded by key physical interfaces. The SIH can be roughly organized into the solar interior; the plasma-dominated solar surface and low atmosphere; the magnetized corona; and the super-Alfvénic inner heliosphere, which ends at the Martian orbit for the purposes of the present discussion. The outer Heliosphere engulfs the outer solar system to the edge of interplanetary space. It lies, however, outside the scope of this paper.

The study of the various SIH systems requires different techniques and science approaches leading to fragmentation of SIH science into sub-disciplines, focusing variously on solar or coronal or space physics investigations. This fragmentation began to change after the deployment of the STEREO mission that provided the first multi-view imaging of the near-Sun space and the first-ever imaging of the inner heliosphere. It continues with the Parker Solar Probe and SolO missions that provide joint imaging/in situ measurements from a wide range of heliocentric distances and angular separations from the Sun-Earth line and the deployment of radio arrays that expand an under-utilized spectral window for the study of solar wind and solar transients (Carley et al., 2020; Vourlidas et al., 2020; Chhetri et al., 2022; Morgan et al., 2023). The recent addition of the ground-based Daniel K. Inouye Solar Telescope (DKIST) observatory adds a powerful micro-scale capability in the existing, quite diverse, but aging, SIH component of the HSO (Fig. 9). The increasing attention to measurements for space weather research and operations is bringing additional measuring platforms into the system, such as the Deep Space Climate ObserVatoRy (DSCOVR), Geostationary Operational Environmental Satellite-R and -U (GOES-R/U) and Space Weather Follow On - Lagrange-1 (SWFO-L1), which provide both research-grade and state-variable observations. GOES-R/U and SWFO-L1 will also contribute to Mag-GO and ITM-GO, highlighting how NASA/NOAA collaborations and space weather observations can facilitate heliophysics science. Missions under development will provide some continuity in studying both small-scale (via high-resolution spectroscopy) and large-scale (via higher-sensitivity heliospheric imaging from the Sun-Earth line).

Although the current state of the SIH-GO (Fig. 9) provides a healthy mix of diverse and distributed measurements, at least within the near-future, critical observational elements remain elusive, as indicated by dotted boxes in Fig. 9:

- Global coverage of the photospheric and chromospheric magnetic field, including the farside and the unexplored polar regions
- Resolution and tracking of the mesoscale flow of energy from the solar interior to the solar wind, particularly through the corona

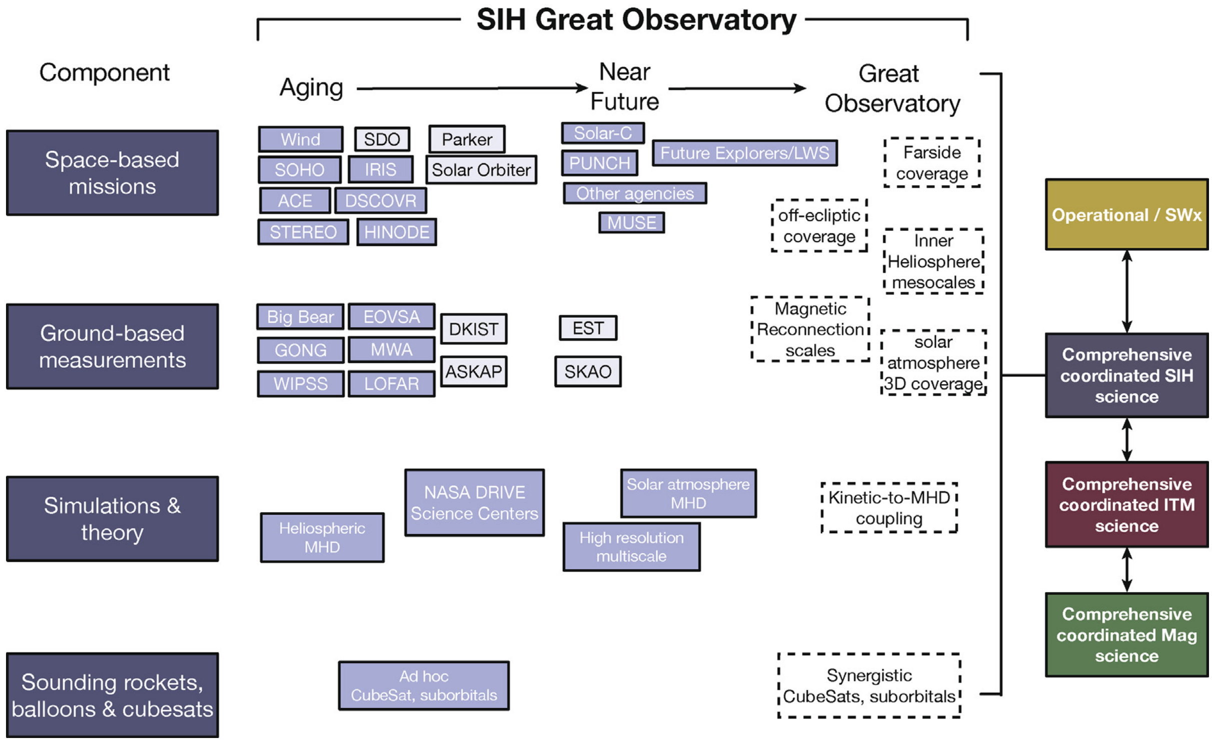

Fig. 9. Conceptual diagram of the SIH Great Observatory. Light blue boxes indicate flagship-scale projects. Dotted boxes indicate missing capabilities required for an effective SIH Great Observatory.

- Resolution of the scales of energy accumulation and release in the corona
- Coupling between kinetic and mesoscales

Modeling and simulations have grown in sophistication and realism due to the impressive progress in computing power and algorithms, but they cannot substitute for missing observational information. Enormous gaps remain, such as the magnitude and evolution of the magnetic fields around the solar poles ($\gtrsim 60^\circ$); modeling of the sub-Alfvénic corona and the generation of the solar wind; the initiation of CMEs, particularly fast ones, from first principles; the acceleration of particles in 3D configuration, and several others. Many of the gaps trace their origins to the complexity and immense scales involved in solar/heliospheric regimes combined with limited viewpoints, but progress is stymied because of the lack of critical measurements outlined above. A carefully planned and executed SIH-GO is required to close these gaps.

4. Considerations for moving forward

Some portions of the suggested program of ISTPNext could be implemented today. For example, the Heliophysics scientific community could coordinate from the grassroots up on issues involving data-sharing and access, coordinated observation campaigns, and analysis tools. Indeed, these types of activities (pySPEDAS, WHPI, SolarSoft, WHPI) have been occurring over the past decade. However, some aspects of the proposed program, such as large-scale data infrastructure (e.g., SPDF and the Cluster Science Archive), universal data standards, and coordinated observational campaigns, require higher-level coordination and, in some cases, agency funding. Activities such as the International Heliophysics Data Environment Alliance (https://ihdea.net) are an example of a path forward.

Although these community-led activities are necessary for a tightly integrated Heliophysics community, they alone are not sufficient to achieve our science objectives. Two of the largest, and slightly related, obstacles, are: 1) the misalignment of agency schedules and priorities, and 2) the lack of an overarching organization or structure to help guide the agencies and global Heliophysics community.

4.1. Agency priorities, timelines, and observational gaps

Despite being a worldwide community with shared scientific objectives, the national space agencies have vastly different implementation approaches, timelines, and processes for setting their Heliophysics scientific priorities. NASA, for example, has a dedicated Heliophysics science division that is guided by the Decadal Survey in Solar and Space Physics, the next of which is expected in mid-2024. These Decadal Surveys provide 10-year scientific priorities and guide NASA, NSF and NOAA in their implementation strategies for Heliophysics. At ESA, the Directorate of Science (D/SCI) has historically been most visibly involved in the area of Heliophysics, with missions such as SOHO, Cluster, Double Star (with the Chinese National Space Administration), Solar Orbiter, and Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) (with the Chinese Academy of Sciences). More recently, other ESA directorates have initiated missions or activities with components relevant to Heliophysics, such as: the Earth Observation Program's Swarm mission, the Directorate of Human and Robotic Exploration supporting instrumentation flying on the ISS and also planned Lunar Gateway payloads, the Directorate of Operations Space Weather program's Vigil mission, and distributed space weather sensor system. However, each directorate has its own strategy or road map. In the case of D/SCI, this was outlined most recently in the Voyage 2050 exercise (https://www.cosmos.esa.int/web/voyage-2050/), which mapped priorities across astronomy, planetary, heliophysics, and fundamental physics for D/SCI for the next 2–3 decades. Ultimately, three top priorities for large class missions were selected: Moons of giant planets, temperate exoplanets or the galactic ecosystem, and new physical probes of the early Universe. Heliophysics related science only appears within the medium class category of themes, which are subject to competitive open calls against the entire breadth of space science within D/SCI. While this could be a potential route for ESA participation in an international partner's flagship mission, similar to the ESA contribution to JWST, it would require strong European community and ESA member state support. Even across just these two space agencies, ESA and NASA, making such connections is highly complex. Larger coordination across different space agencies is currently unwieldy and lacks an overall scientific or implementation strategy. We discuss this issue more deeply in the next Section.

Both Geospace and solar-inner heliosphere have substantial observational gaps, but missions for each have been studied extensively and the implementation approaches well established. While focused science will still occur via small-to medium-class mission elements, such as via the NASA SMEX or MIDEX, JAXA medium class missions, and ESA F- and M-class and Earth Explorer missions, answering the larger system-of-systems question would require larger missions than afforded by the current national agency PI-led mission lines. These larger strategic mission elements include currently operating missions such as SDO, Parker Solar Probe, and SolO, and future missions such as GDC + DYNAMIC and Solar-C. Additionally, these larger missions would need to be concurrent and well-coordinated to be most effective in addressing system-of-systems science questions.

For example, as shown in Fig. 9, a global view of the Sun is a critically missing observational element. Even the most simplistic implementation of such a system, involving a backside mission combined with a polar imager and existing L1 assets, is unlikely to fit within a single Agency's program and would require coordination across national agencies to ensure concurrent observations. Similarly, a magnetospheric fluid backbone mission consisting of a large constellation of in situ satellites, combined with a smaller constellation to simultaneously study electron and ion scales and a high inclination mission to remotely study the inner magnetosphere and auroral zone would answer the majority of system-level and cross-scale science questions related to solar wind driving and the magnetospheric response. This architecture, too, is too large for any single space agency given the current Heliophysics budget profiles.

The key driver is that the observations need to occur simultaneously. Such a large and coordinated undertaking is not unprecedented. The original ISTP program was designed to provide multipoint, simultaneous observations, but was, in the context of our current understanding, exploratory, and unable to answer the outstanding cross-scale and cross-system science questions of our era. NASA's Living With a Star (LWS) program element was originally envisioned to operate several key mission elements simultaneously, but budgetary constraints within NASA limited mission overlap, and the ITM component (IT Storm Probes) was never realized. Within NASA, NASA's Earth System Observatory, growing out of the 2017 Earth Science Decadal Survey, is quite similar in approach to what we are advocating here, and is designed to provide a "3-dimensional, holistic view of Earth, from bedrock to atmosphere", and recommends that "NASA, NOAA, and USGS, in collaboration with other interested U.S. agencies, should ensure efficient and effective use of U. S. resources by strategically coordinating and advancing this program at the national level".

To address the science questions discussed in Section 2.3 requires a program of coordinated, worldwide efforts across agencies. Ideally, members of ISTPNext would develop top-level science objectives for Heliophysics, and would agree to a long-term strategy to provide specific components of the ISTPNext fleet in a disaggregated fashion but with a well-defined timeline. This collaboration could take several forms. For example, each agency could provide the specific platforms and the necessary launch capability needed to access complementary regions of space, similar to the original ISTP program. For larger components of the program needing many spacecraft, a generic platform and instrument suite could be defined and mass produced, perhaps with industry support, as a joint agency effort. However, given the current structures of the different space agencies, including differing, unsynchronized schedules, and the fact that only one space agency has a dedicated Heliophysics division, building a 'bottom up' synergistic program remains a major challenge.

In the short term, one could look to take advantage of fortuitous alignment of the separate agency schedules, utilizing potential opportunities and ensuring sufficient coordination and collaboration. In particular, the 2030s provides such an opportunity for ESA, JAXA and NASA, but only if key missions that address the Heliophysics system-of-system objectives are selected. Such selections are not guaranteed, and we would be concerned that such a limited coordination approach would not address the major outstanding questions.

4.2. Historical and current international coordination

International coordination amongst space agencies has taken on several forms over the years. Bodies such as COSPAR (Committee on SpAce Research) and the International Association of Geomagnetism and Aeronomy (IAGA), part of the International Union of Geodesy and Geophyiscs (IUGG), are dedicated to the international promotion and coordination of scientific research and studies. But they have limited influence on agency directions. The Inter-Agency Consultative Group (IACG) for Space Science, active from the 1980s-90s, had as its main objective to coordinate research activities among the four main space science programs at the time, Europe (ESA), USA (NASA), Russia (Rosaviakosmos) and Japan (ISAS). The IACG served as a focal point for the exchange of information, discussion on common problems, and mutual support to enhance the overall scientific return of space missions. At the first meeting held at the University of Padua in September, 1981, Professor Giuseppe (Bepi) Colombo said during his speech, "If you will be able to find an agreement beyond national interests and within the domain of a fruitful cooperation, you will demonstrate how good-willed people have an intrinsic capability to work together in their search for truth, the augmentation of human knowledge and the promotion of a peaceful and better society." During the height of the cold war, this sentiment echoed across space science; although today's geopolitical environment is different, the words still resonate.

IACG coordinated the unified observations of Comet Halley in 1986 by the "Halley Armada", which included spacecraft from the Soviet Union (Vega 1 and Vega 2), ESA (Giotto), and ISAS (Suisei and Sakigake), which were wildly successful (Münch et al., 1986). Following this successful effort, the IACG selected solar-terrestrial science as the next major science discipline for coordinated efforts. In 1993, the IACG recommended that the membership of the IACG science group be expanded to include the study of the 3-dimensional Heliosphere, in recognition of the unique opportunity presented with the coordination of 11 solar and heliospheric missions, including Ulysses. This activity of course led to the ISTP program.

Following on from NASA's establishment of the Living With a Star (LWS) program in 2000, the IACG just prior to disbanding itself identified that there was potential to stimulate new international efforts and established a task group to form a new international program of cooperation focusing on solar-terrestrial science. This International Living With a Star (ILWS) task group consists of 14 agencies and institutes from around the globe, and ostensibly provides an umbrella for forging such collaborations. However, lacking interagency agreements, ILWS does not have the charter to guide or influence agency direction in the way that IACG did, and cross-agency collaborations are now less impactful than when IACG was active.

At the same time that IACG was dissolving, the Heliophysics program within NASA began to be guided by regular decadal surveys. These decadal surveys are products of community input and guided by the US National Academies of Science, Engineering and Math (NASEM). They provide recommendations for science implementation and science objectives for a 10-year period; the first heliophysics decadal survey was released in 2003. Decadal surveys represent a consensus priority list for the US solar and space physics community. They do not necessarily reflect global scientific priorities, and carry no weight on the priorities of agencies outside of the US. Since decadal surveys are representative of the US scientific community, and since NASA (and NSF and NOAA) are bound to them, this means that NASA flight and research thrusts are directly representative of the US scientific community. However, this also means that it may not necessarily reflect the scientific priorities of other nations or institutions outside the US, and the 10-year cadence of the US decadals is not often aligned with other agency roadmapping activities (e.g. ESA), complicating coordination efforts.

In parallel with these efforts in the US, European stakeholders and in particular the European Space Agency (ESA) were keen to avoid duplication of effort, given the financial context in Europe and the possible misalignment with the "better, faster, cheaper" doctrine used by NASA at the time. Hence, ESA pushed towards creating a truly global endeavor in the broader space sciences. In 2000, the ESA Director of Science commissioned a study to the European Science Foundation's European Space Sciences Committee (ESSC-ESF) for the purpose of defining a roadmap for each theme of ESA's Science Program. In particular, the study would ensure that Europe's space science priorities could be incorporated in roadmaps and/or international programs such as ISTP. The study was led by an international ad hoc group and its findings reviewed by a separate international assessor group, supported by a group of auditors from ESSC-ESF and SSB-NAS. The outcome was published (European Science Foundation, 2000) and presented in June 2000 to ESA's Science Programme Committee. It analyzed and reviewed all major space science programs and the respective priorities in ESA, NASA, Japan, Russia, etc. The study extracted from these programs main themes or potential international programs (astronomy, fundamental physics, planetary exploration, heliosphere and Sun), and proposed processes to establish international roadmaps in which the different proposed projects could find their place in a complementary way. It presented specific disciplinary findings, including for the heliospheric section, for which efficient long-term planning and flexible coordination was recommended.

Apart from those thematic findings, the study proposed an operational structure to pilot this coordination, dubbed the Inter-Agency Scientific Collaboration Working Group"

(IA-SCWG) that would include space agency executives as well as scientists, whose selection could be decided after consultation with and advice from SSB and ESSC, as well as similar bodies world-wide when they existed, e.g. SRC-JSC (Japan). Modelled on the successful IACG but extending its participation to scientists, the idea was that the necessary input to the IA-SCWG would be grassroots rather than top-down, enabling a better ensuing coordination at agency level that was reflective of the scientific conensus. This recommendation for coordination was not adopted by the agencies at the time nor since, but its need and obvious relevance to a better use of resources was advocated several times since 2000, including in a recent workshop jointly organized on 25 August 2022 by COSPAR and the Chinese Space Science Centre of the Chinese Academy of Sciences.

International coordination is complicated by the fact that Heliophysics as a scientific division currently exists only at NASA, within the Science Mission Directorate (SMD), where the division of space science into studies of physical domains is both scientifically rational and administratively effective. Yet this administrative approach is not universally applied. At the National Science Foundation (NSF), Heliophysics is split between the Division of Atmospheric and Geospace Sciences and the Division of Astronomical Sciences. Within ESA, Heliophysics is part of the Science Directorate (D-SCI), joint with Astrophysics and Planetary Sciences. In addition, nature does not provide a clean boundary defining where one domain ends and another begins. At NASA, that region of the Earth's (or other planet's) atmosphere that is clearly dominated by planetary effects, such as the Troposphere, is included within Earth (or Planetary) Science. Everything above, such as the mesosphere, thermosphere, and ionosphere, is included within Heliophysics. Solar effects generally dominate this middle and upper atmospheric region, but again, there is no hard boundary between the Earth and heliosphere. Energetic particles and electromagnetic fields from above, and gravity waves from below all interpenetrate the interface region between the physical domains of Heliophysics and Earth (or Planetary) Science. Understanding this interface region, therefore, involves both disciplines.

Today, inter-agency interactions are most frequently carried out on an opportunity-based and a case-by-case basis (e.g., Solar-C, Solar Orbiter) and are complicated by the internal structure, budgeting and priorities of the agencies themselves (for example NASA Heliophysics interacting separately with the various directorates within ESA and JAXA). However, a dedicated large-scale, world-wide endorsed scientific effort under an ISTPNext program, with unified strategic science goals and objectives, when accompanied by interagency agreements, could enhance both the science return and facilitate interagency cooperation. It is worth exploring whether an IACG type group, perhaps modeled after the proposed IA-SCWG, should be reconstituted to correct deficiencies in the current system.

5. Recommendations and conclusions

Heliophysics in the space age began with the launches of primitive Geiger counters in the near-Earth space environment. It is now flying sophisticated sensors deep into the solar atmosphere. The field has expanded into the study of both fundamental plasma physics in the natural plasma laboratory of our cosmic backyard and the space weather that impacts our technological society. Heliophysics research and model development underpins the protection of vital technological infrastructure and humanity's journey into space.

Yet, the field is far from reaching its limits. The discoveries of large numbers of planetary systems in our Galaxy are casting Sun-Planet relations — the core of Heliophysics — into the center of Star-Exoplanet research. As the only truly accessible system that harbors life, the Sun-Earth system is the natural laboratory to test and validate research on exoplanet habitability. Closer to home, the increasing instability of (even short-term) climate patterns raises the importance of 'tipping points' within the highly non-linear system of the terrestrial atmosphere. This in turns point to an increasing societal need for deeper understanding of the effects of fluctuating solar inputs into our atmosphere. The developments in Astrophysics and Earth science along with Heliophysics' own successes in the space age are pointing the direction of the field into the nexus of the future space age. Heliophysics is a science of connections. Heliophysics can, and should, become the connecting point among Astrophysics, Planetary, and Earth sciences. ISTPNext, or a similarly structured approach, could lead us there. As a start, the next phase of space exploration should be the era of Mesoscales and the S-IH and Geospace and systems-of-systems, focused on the cross-scale and cross-regional coupling that occurs between the two spatial and temporal extremes.

With the US Decadal Survey, the evolution of the ESA directorate of science Voyage 2050 program via F- and M-class competitions, and JAXA's medium mission competitions all occurring in the near-term, in addition to active programs among other national agencies such as the Korea Astronomy and Space Science Institute (KASI) and the Indian Space Research Organization (ISRO), the next decade provides an opportunity to take the first steps toward addressing mesoscale, system-of-systems dynamics while simultaneously establishing an ISTPNext program. If missions stemming from these competitions and activities recognize a common scientific priority, there is a very good chance of coordinating them organically under the umbrella of an internationally coordinated strategic science program. However, such an approach should be considered as a bare minimum and would only be marginally better than the current (wholly inadequate) coordination approach. It would be far better to make investments of the type listed above so that the missions selected and recommended over the decade + could achieve ground-breaking science across the overall system-of-systems, extending discoveries beyond their narrower design space. Heliophysics should articulate a strong strategic science vision for the discipline, and the common System-of-Systems at mesoscales theme can be used to unify Heliophysics across discipline and national boundaries.

GDC + DYNAMIC is a test-case for what a different approach may look like. It could be used as a strategic focal point mission for ITM science, a true community "Great" observatory that pulls in not only space-based missions from other agencies but tightly integrates the worldwide ground-based and modeling communities under a common scientific objective. With GDC + DYNAMIC not launching until the early 2030s, there is some time to put the pieces in place to ensure that it becomes an ITM 'Great Observatory' with broad worldwide community involvement, answering questions beyond those for which it was designed because of this synergy. GDC, however, is a mission, not a program. It has specific science questions it is designed to answer, and other agencies may decide to leverage it for their own aims. Or they may not. To obtain the type of investment that is needed to answer the mesoscale system-of-system science questions the community has identified requires a large, sustained, worldwide effort as outlined in this paper. We need a program — an ISTPNext — with grand ambitions, world-wide scientific buy-in on a set of strategic science goals, and interagency agreements, to enable the sustained, large investment required to address the science questions of our era, and drive our field towards more amazing discoveries.

Findings:

1. All the major systems within Heliophysics, ITM, SIH, Mag, operate as a system of systems;
2. Mesoscales are critically under measured;
3. Both space- and ground-based assets could benefit from tighter coordination;
4. The lack of an international coordinating body for research priorities and coordination has led to a fractured Heliophysics landscape.

We require both a new intentional, forward-thinking coordination mechanism and a new worldwide effort that should include the following initiatives:

- Resolve the mesoscales, simultaneously, across the Sun-Geospace System of Systems;
- Monitor the Heliophysics state variables;
- Invest in next-generation numerical modeling;
- Organize the ground-based community and integrate directly and early into flight programs;
- Embrace and utilize 'big data' and ML/AI techniques;
- Establish unified data formats, metadata, accessibility and discovery via cloud-based computing, and code repositories;

All these activities and initiatives would be globally coordinated and working in concert to study Geospace and the inner Heliosphere holistically, each as a system, at the scale sizes — mesoscales — that we now know are driving the overall dynamics. Only thus we will overcome the current roadblocks and thrust Heliophyics science into its prominent role as the 'essential' systems science for discovery and society service.

Humanity has now extended from the physical domain of our birthplace, the Earth, to the neighboring domain of the Heliosphere. Space-based commercial and government infrastructure has grown so explosively in the past half-century that space is increasingly crowded. Furthermore, humans have been living continuously in the heliosphere for the past three decades, and this human presence will only increase. Now that we have moved into this physical domain, our requirements on its study have changed to the point that this study is truly a new science discipline. We are no longer simply observing some domain beyond our reach, we now must gain that level of understanding required to develop and inhabit a new environment. The past decades have brought us to this point now, where we must understand the cross-scale and cross-regional coupling within the Heliophysics domain. Such a large effort requires a unified and coordinated scientific discipline and scientific program, if we are to continue our progress from the domain of our birth, Earth, to the domain of the stars.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

L. Kepko was funded by the NASA competed Internal Scientist Funding Model (ISFM). A. Vourlidas was funded by NASA grants 80NSSC22K0970, 80NSSC22K1028, and Parker Solar Probe/WISPR phase-E funds. CHM acknowledges grants PICT-2020-SERIEA-03214 and PIP 11220200100985. CHM is a Senior Researcher at Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). MP thanks the Academy of Finland project numbers 339327, 335554, 347795, 345701. The work of DC is supported by the Department of Space, Government of India. Work at Laboratoire d'astrophysique de Bordeaux was performed with the support of CNRS, CNES and the University of Bordeaux.

Appendix A. Appendix

AE - Atmospheric Explorers
AI - Artificial Intelligence
AIA - Atmospheric Imaging Assembly
AMPTE - Active Magnetospheric Particle Tracer Explorers
BBF - Bursty Bulk Flow
CEDAR - Coupling, Energetics, and Dynamics of Atmospheric Regions
COSPAR - Committee on Space Research
CME - Coronal Mass Ejection
DE - Dynamics Explorer
DKIST - Daniel K. Inouye Solar Telescope
DSCOVR - Deep Space Climate Observatory
DYNAMIC - Dynamical Neutral Atmosphere Ionosphere Coupling
EIS - Extreme-ultraviolet Imaging Spectrometer
ENA - Energetic Neutral Atom
ESA - European Space Agency
ESF - European Science Foundation
ESSC - European Space Sciences Committee
FAIR - Findable, Accesssible, Interoperable, Reusable
FTE - Flux Transfer Event
GDC - Geospace Dynamics Observatory
GEM - Geospace Environment Modeling
GOES - Geostationary Operational Environmental Satellite
GGS - Global Geospace Science
HSO - Heliophysics System Observatory
IA-SCWG - Inter-Agency Scientific Collaboration Working Group IACG - InterAgency Consultative Group
IAGA - International Association of Geomagnetism and Aeronomy// IASTP - InterAgency Solar-Terrestrial Physics
IGY - International Geophysical Year
IMF - Interplanetary Magnetic Field
IMP -Interplanetary Monitoring Platform
IRIS - Interface Region Imaging Spectrograph
ISAS - Institute of Space and Astronautical Science
ISEE - International Sun Earth Explorer
ISRO - Indian Space Research Organisation
ISTP - International Solar Terrestrial Physics
ITM - Ionosphere-Thermosphere-Mesosphere
IUGG - International Union of Geodesy and Geophyiscs
JAXA - Japan Aerospace Exploration Agency
JSC - Science Council of Japan
KASI - Korea Astronomy and Space Science Institute
MHD - MagnetoHydroDynamics
MIDEX - Medium-class Explorers
ML - Machine Learning
MMS - Magnetospheric Multiscale
NASA - National Aeronautics and Space Administration
NASEM - National Academies of Science, Engineering and Math
NOAA - National Oceanographic and Atmospheric Administration
NSF - National Science Foundation
OSTP - Office of Science and Technology Policy
PIC - Particle-In-Cell
PSP - Parker Solar Probe
SCOSTEP - Scientific Committee on Solar-Terrestrial Physics
Committee on Solar-Terrestrial Physics
SDO - Solar Dynamics Observatory
SHINE - Solar, Heliospheric, and INterplanetary Environment
SIH - Solar-Inner Heliosphere
SMEX - SMall EXplorers
SMILE - Solar wind Magnetosphere Ionosphere Link Explorer
SMM - Solar Maxiumum Mission
SO or SolO - Solar Orbiter
SOHO - Solar and Heliospheric Observatory
SRC - Science Research Committee (Japan)
SSB - Space Studies Board
STEREO - Solar TErrestrial RElations Observatory
SUVI - Solar Ultraviolet Imager
SWFO-L1 - Space Weather Follow On - Lagrange 1
THEMIS - Time History of Events and Macroscale Interactions during Substorms
WDC - World Data Center
WHPI - Whole Heliosphere and Planetary Interactions
WISPR - Wide-field Imager for Parker Solar Probe

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