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On the need for International Solar Terrestrial Program Next (ISTPNext)

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Synopsis: We suggest that the next era of Heliophysics should focus on the Sun-Heliosphere and Geospace as 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 different 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 missions such as MMS, Parker Solar Probe, and Cluster. We believe that Heliophysics should embark on a grand program to study these system-of-systems holistically, with coordinated, multipoint measurements, with particular emphasis on resolving mesoscale dynamics, and a whole-of-science approach that includes integrated ground-based measurements and advanced numerical modeling. By its very nature, the type of program we argue is needed would be large, with many 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. In effect, a mesoscale ISTP type program, which we call ISTPNext. The ***paradigm and specific approaches outlined in this white paper could serve as an imperative and overarching theme that binds our Solar and Space Physics community together under a common scientific objective.***

1. Background and motivation

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. While these studies began prior to our ability to launch satellites, the space age ushered in a scientific revolution of our understanding of Earth's magnetosphere and the interaction with the sun and its dynamics. We can roughly divide space exploration into 4 eras: Discovery-Regions (1958-1973), Discovery-Dynamics (1973-1990), coarse system science/International Solar Terrestrial Physics (ISTP) (1990-2005), and Microscales (2005-present). These 4 eras show a natural progression from discovery through qualitative then to quantitative understanding. Based on the results of the ISTP and Microscales eras, we suggest that the 5th era should focus on 'messenger dynamics' - Geospace and the Sun-Heliosphere as System of Systems, wherein mesoscales - the messengers and connectors of dynamical change - are a primary focus.

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. One of the many legacies of the IGY are the World Data Centers and the spirit of international data sharing that continues to this day. In the years that followed, spacecraft were launched into unexplored areas of space carrying increasingly capable, though still primitive compared to modern era, in situ and remote sensing instrumentation. By their 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. By the early 1970's, we had a reasonable understanding of the key regions of Earth's magnetosphere, the solar wind, and the sun (active regions, quiet sun, coronal holes), and understood at a basic level the contours of the solar wind-magnetosphere interaction.

Having identified critical regions and boundaries, we set out to discover the dynamics of those regions. Through multi-spacecraft missions such as Dynamics Explorer (DE), Atmospheric Explorer (AE), International Sun Earth Explorers (ISEE), AMPTE, Helios, etc., and platforms such as Skylab and SMM, scientists were able to start to disentangle temporal and spatial variations in pursuit of understanding fundamental dynamical processes, such as coronal mass ejections, storms, and substorms. These were focused, exploratory missions that yielded enormous scientific results well beyond their focus areas. Even at this early stage of exploration, the need for multi-spacecraft missions, with a mixture of remote and in situ instrumentation, 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 developed to study the system at multiple points, simultaneously. The ambitious GGS program was eventually cut to just Polar and Wind then augmented by Geotail (ISAS), Equator-S (Germany), SOHO (ESA), and Cluster (ESA), all of which were coordinated under the (ISTP) Program[1]. ISTP was designed to provide a global, system-level understanding of Earth's magnetosphere driven by the sun and its dynamics. The results of the ISTP program, which included not just space-based in situ and remote observations but a robust theory and modeling program, ground-based infrastructure, and data standards, revolutionized space physics, and brought in a new generation of outstanding scientists that have become the leaders of today.

The coarse system-level ISTP era results highlighted that we had major 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 remotely and diffused. The Era of Microscales that followed the ISTP era, with missions such as Van Allen Probes, MMS, and Parker Solar Probe, sought to elucidate the

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[1] Space Sci. Rev., Volume 71, Issue 1-4, February 1995.

microphysical processes that ultimately aggregate to large-scale behavior.

Today, we have studied both ends of the system extensively – at the microscales, with in situ observations, and at the large scales through statistical studies, chance multipoint event studies, and remote imaging. ***The next era of space exploration should be the Era of Mesoscales, focused on the coupling that occurs between the two extremes***. This necessity flows from the fact that the Sun-Heliosphere and Geospace are both a system-of-systems, and many of the outstanding questions of our day relate to the interconnectivity of the systems – systems that are connected via underexplored mesoscale connectors and messengers.

2. System of Systems

It is widely recognized that both Geospace and the Sun-Heliosphere operate as a "System of Systems". Each system that comprises Geospace – the magnetotail, inner magnetosphere, magnetopause+ magnetosheath+bow shock/foreshock, and ionosphere-thermosphere-mesosphere, has its own dynamics and characteristics that can be, and often are, studied in isolation from the other systems. Within these systems, plasmas operate under a set of governing principles, and we have flown missions to study these physical processes at the kinetic scales (e.g., MMS, Cluster, and Parker Solar Probe). The Sun-Heliosphere is also a system-of-systems, comprised of the solar interior, the photosphere, chromosphere, transition region, low, middle, and upper corona, and the solar wind and heliosphere, with cross-scale feedback and cross-regional coupling between the systems. The solar dynamo generates a magnetic field which connects this system-of-systems.

By system-of-systems we mean that each system can operate independently, or at very least can be understood by knowing just the input conditions, but when integrated together they yield more complex, and sometimes unexpected (or emergent), behavior. A familiar example is the human body. Specialists study the pieces of human anatomy, and the different bodily systems. Yet unexpected behavior arises when the different systems are coupled together. The classic example is the link between heart and gum disease. 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 are discovered.

Earth's magnetosphere and the solar atmosphere are similar, in that there is clear need to study the way the systems within the larger Geospace and Sun-Heliosphere system interface and interchange mass, momentum, and energy with one another. For example, how does magnetotail and nightside transition region dynamics lead to ring current and radiation belt enhancements? Solar wind formation involves cross-regional coupling and can be broken down into 3 steps – heating in lower corona (source), release in the middle corona (e.g. reconnection), and acceleration that happens through the high end of the extended corona. Addressing these types of cross-scale, cross-system science questions requires multipoint and/or multi-wavelength, coordinated observations.

3. Mesoscales

Mesoscales exist in the space and time regime between the microscale/kinetic and the global. The mesoscale begins around the ion scale and ends at a significant fraction of the system under consideration. However, the boundaries at both ends are fuzzy, and the transitions are not sharp; one cannot (and should not) put an absolute number on either end. Indeed, it is this fuzziness 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'. Mesoscale connectors are fundamental units of transport, and carry mass, momentum, and energy throughout and across systems, and to and from micro and global. They are basic, elemental units of mass and momentum transport (Figure 1). In effect, they are the commuter rails of the magnetosphere, connecting the different regions together, transferring mass and flux from the tail to the inner magnetosphere, and from the dayside to nightside, for example. Cross-scale coupling between micro and macro also occurs in the inter-regional space of the mesoscales, and this cross-scale coupling is bidirectional. An example of micro to global is microscale reconnection > mesoscale flows > global reconfiguration, and an example of global to local is solar wind forcing leading to microscale thin current sheets and reconnection of recurrent scale sizes of 1-2 RE.

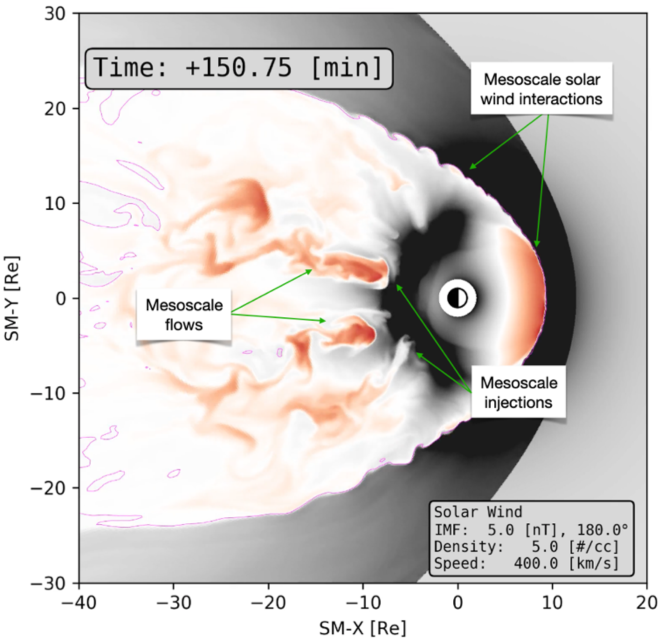

Figure 1. High resolution global simulations, such as from GAMERA above, highlight how mass, momentum and energy flow through Earth's magnetosphere is dominated by mesoscale dynamics.

Mesoscales are more than just units of transport ("connectors") – they also carry information ("messengers") about configuration changes. Magnetospheric messengers include Alfvén waves and field-aligned energetic particles, but the bulk of configuration change is communicated via the mesoscales. When the IMF turns southward, the nightside knows about this because flux transfer events (mesoscale connectors) transmit flux from the dayside to nightside. When reconnection occurs in the tail during a substorm, this reconfiguration change is transmitted to the inner magnetosphere and ITM system by mesoscale flow bursts.

If one studies the subsystems in isolation, and attempts to stitch them together, key dynamical features are missed. For example, we know the plasmasheet thins when IMF turns southward. It is possible to study dynamical changes in the plasmasheet knowing only the IMF value. Yet, there is evidence that patchy, time-dependent coupling processes at the dayside impacts the evolution of the plasmasheet. Similarly, one could study the inner magnetospheric particle populations solely as functions of solar wind driving, yet we also know that the magnetotail input into the inner magnetosphere is impulsive and patchy. In the Sun-Heliosphere, we are observing new types of mesoscale structures that are imprinting on the solar wind and changing the way we think about solar wind formation. For example, how do supergranules, created in the convection zone, leave their imprint in the solar wind through, e.g., patches of switchbacks?

4. Inadequacy of the current approach

For both Geospace and the Sun-Heliosphere system-of-systems, many of our key science questions revolve around the interconnectivity of the systems, and the role of mesoscale dynamics in modulating, regulating, and controlling that interconnected behavior. The ISTP program was tremendously successful in providing the first systematic insight into how the various systems within Earth's magnetosphere operate in response to solar wind driving. The measurements were limited to single point measurements (Wind, Geotail, Equator-S, Polar in situ), in very particular regions, with some auroral imagery (Polar) and significant solar imaging and spectroscopy (SOHO). Yet, ISTP lacked measurements in critical regions of Geospace and Sun-Heliosphere. The inner magnetosphere and the ionosphere-thermosphere-mesosphere (ITM) systems were noticeable missing elements of this rudimentary - yet revolutionary for its time – system observatory. Off-Sun-Earth-line solar observations were completely lacking at this point, later partly remedied by STEREO, but out-of-the-ecliptic remote sensing remain a crucial observational gap. We have since then relied on the ad-hoc Heliophysics System Observatory (HSO) along with other agency missions to bootstrap a system observatory, in an attempt to answer these system-of-systems questions. Since the HSO elements are standalone missions, with their own specific science objectives they are responsible for, the systems aspect arises as an afterthought. For example, MMS was launched into an opposite local time than THEMIS, which precluded coordinated measurements. In addition, upfront coordination with ground-based facilities is not always considered (THEMIS is a notable counterexample and highlights the tremendous science return possible when coordination is built into a program). Additionally, the HSO cannot resolve the mesoscales in any systematic fashion.

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[2,3]. Oftentimes this flow is through the mesoscales, the vast spatial scale that lies between the ion-kinetic scales, observable with single spacecraft, and the global scale, studied through statistics, averaging, or remote sensing. Mesoscales lie in an observational gap, where single or even a few in situ points are incapable of providing the measurement density necessary to resolve them. At the same time, while remote imaging of, for example, the magnetotail with ENAs and of the magnetopause with soft x-rays is possible, remote imaging of Geospace has inherent limitations, such as the inability to provide the magnetic field. In situ and remote measurements are required to work simultaneously to provide the complete mesoscale picture. We note that this is a similar problem faced by solar physics and white light imagers. The mesoscales also fall in the zone of modeling space between kinetic models and MHD approximations and approaches. ***To understand this system-of-system, mesoscale flow of mass, momentum, and energy, requires a reimagination of our measurement and research approach***.

5. The ISTPNext program

We envision that resolving the Geospace and Sun-Heliosphere system-of-systems will require spacecraft covering the key regions and scales simultaneously and over sufficiently long timescales. This would likely involve a combination of constellations of in situ measurements combined with remote sensing in a coordinated, global Heliospheric mesoscale observation system. The combined NASA and NOAA observatories in the current HSO already offer some glimpse of what is possible, but the HSO is incapable of answering the critical scientific questions of this era. ***What we propose moving forward is a more orchestrated, international effort, designed to address the mesoscale knowledge gap***. While several space agencies today have the capability to realize multi-satellite missions, the wide scope of resolving both the Geospace and Sun-Heliosphere system-of-systems calls for international collaboration and coordination. The suggested program, containing the key elements outlined below, would form the basis of a next generation ISTP type program. A critical point is that, like the original ISTP program, the holistic approach outlined below must contain elements beyond just space-based missions. It would necessarily include the ground-based and modeling communities, along with data science and archiving to deal with the logistics of the volumes of data to be inter-compared and calibrated. We require both a ***new intentional, forward-thinking coordination mechanism*** and a ***new worldwide effort*** that includes the following initiatives:

- Resolve the mesoscales, simultaneously, across the System of Systems
  - For the magnetosphere, this likely requires a mesoscale/fluid backbone of multiple constellations of in situ spacecraft and/or imagers in key regions. Sun-Heliosphere requires

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[2] Kepko et al. WP, "Geospace as a System of Systems", and links therein

[3] Ho et al., WP, "Perspectives on NASA Heliophysics Mission Porgrams for Addressing Systems Investigations"

connecting remote sensing and in situ observations with 4π steradian coverage.

- Monitor the state variables
  - The 'vital signs' of the magnetosphere and the Sun, which include 4π solar magnetic field and flow measurements, solar wind observations, auroral imagery, EUV imagery, cross polar cap potential, radiation belt content, etc. There is an additional need to coordinate space-weather observational assets across NASA, NOAA, and international partners, similar to what we are describing here from the research perspective[4].
- Invest in next generation numerical modeling
  - In 30 years, our models are unlikely to resemble what we have today[5]. The time is now to substantially invest in new approaches, such as through a Mission of Opportunity (MoO) or SMEX equivalent for next generations models.
- Organize the ground-based community & integrate directly and early into flight programs.
- Embrace & utilize 'big data' & ML/AI techniques.

All these activities and initiatives are globally coordinated and working in concert to study the Heliosphere holistically, as a system, at the scale sizes - mesoscales - that we now know are driving the overall dynamics. To provide a sense of the type of mesoscale system science objectives involved that would form the basis of an ISTPNext program, below we list the Geospace objectives, and examples of the types of observations (planned missions in blue) that are likely required, simultaneously, across the system of systems:

- Resolve mesoscale dynamics across the system (flow bursts, magnetopause FTEs, foreshock/ magnetosheath transients, impact on magnetosphere/ionosphere, etc.)
  - Dense multipoint in situ mesoscale measurements
  - Soft x-ray imaging of dayside magnetopause (SMILE)
  - Ground-based imagers, riometers, magnetometer, radars
- Resolve dynamical mesoscale coupling between the tail/transition region and the inner magnetosphere
  - Remote sensing of the inner magnetosphere (plasmasphere and ring current)
  - Multipoint in situ ground truth, simultaneous with remote
  - Determine the core plasma distribution & variability
  - Ground-based radars and imagers
- Resolve ionospheric/auroral mesoscales, magnetospheric coupling, and the auroral acceleration region
  - Mesoscale ionospheric and neutral wind driving (GDC)
  - Auroral imagery (e.g. SMILE)
  - Lower atmospheric forcing (DYNAMIC)
  - Low-altitude electrodynamics (ENLoTIS/ESA-EOP & NASA)
  - Energy coupling between magnetosphere & ionosphere (FACTORS/JAXA) and multipoint in situ auroral acceleration region
  - Ground-based radars, imagers, riometers, magnetometers
- Quantify ion outflow and the effect on magnetosphere
  - Low altitude missions to measure outflow and composition measurements in the magnetosphere
  - Ground-based radars
- Resolve kinetic <-> mesoscale (cross-scale) coupling
  - Small constellation with high temporal resolution measurements (e.g. Plasma Observatory/ESA M Competition) inserted into mesoscale/fluid backbone

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[4] Vourlidas et al. WP; also NASEM Space Weather Operations & Research Infrastructure report

[5] Sorathia et al. WP "First-Principles Geospace Modeling in the Next Decade"

6. Considerations for Moving Forward

This list of Geospace science objectives above, which is not meant to be exhaustive across all of Geospace, has substantial observational gaps, but missions for each have been studied extensively and the implementation approaches well established. A similar list of objectives for Sun-Heliosphere is well described in other white papers. Some objectives could be achieved via a SMEX or MIDEX mission, but others would require a larger budget than offered in the current Explorer line[6]. The key, however, is that the observations need to occur simultaneously. This undertaking is currently too large for any single space agency, particularly if the current budget profile remains. ***However, such a large undertaking is not unprecedented within NASA***. NASA's Earth System Observatory, growing out of the 2017 Earth Science Decadal, is quite similar in approach to what we are advocating here, for analogous reasons, and is designed to provide a "3-dimensional, holistic view of Earth, from bedrock to atmosphere".

To address these next generation science questions requires a program of coordinated, worldwide effort across agencies. Ideally, members of ISTPNext 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. 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[7]. 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-systems 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.

These new observations and resultant science output will also be of great importance to space weather research, monitoring, and forecasting. There are well known knowledge gaps in space weather prediction and forecasting, which require new observations of how the systems in Heliophysics couple and interact.

7. International coordination

Historically, international coordination amongst agencies has taken several forms. Bodies such as COSPAR (Committee on SpAce Research) and International Association of Geomagnetism and Aeronomy (IAGA), part of the International Union of Geodesy and Geophysics (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 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). 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

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[6] Kepko et al. WP, "Heliophysics Needs a Mission Element Between MIDEX and Flagship"

[7] E.g. NASEM report, "Agile Responses to Short-Notice Rideshare Opportunities for NASA HPD"

of Comet Halley in 1986, which were wildly successful. 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 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 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.

Inter-agency interactions are most frequently carried out on a case-by-case basis (e.g., Solar-C), and complicated by the internal structure of agencies themselves (for example NASA Heliophysics interacting separately with the various directorates within ESA and JAXA). A dedicated large-scale, worldwide endorsed scientific effort under an ISTPNext program, when accompanied by interagency agreements, could enhance both the science return and facilitate interagency cooperation. It is worth exploring whether an IACG type group should be reconstituted to correct deficiencies in the current system.

8. Conclusions

The next decade provides an opportunity to take the first steps toward an ISTPNext program, with the US Decadal Survey, the ESA M class competition, and JAXA's medium mission competitions all occurring in the near-term. If missions stemming from these competitions and activities recognize a common scientific priority, there is a very good chance to coordinate them organically under the umbrella of an internationally coordinated science program. However, such an approach should be considered as a bare minimum and would be only 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 next decade+ could achieve ground-breaking science of the holistic systems, extending science discoveries beyond that for which they are narrowly designed. ***The common System-of-Systems at mesoscales theme can be used to unify Heliophysics across discipline boundaries.***

GDC is a test-case for what a different approach may look like. It could be used as an anchor mission for ITM science, a true community observatory that pulls in not only space-based missions from other agencies (such as FACTORS/JAXA), but tightly integrates the worldwide ground-based and modeling communities under a common scientific objective. With GDC not launching until the end of the decade, there is some time to put the pieces in place to ensure that it becomes an ITM 'Great Observatory' with broad 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 above. ***We need a program – an ISTPNext – with grand ambitions, world-wide scientific buy-in, 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***.