Plasma physics and the 2013–2022 decadal survey in solar and space physics

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Abstract
The U.S. National Academies established in 2011 a steering committee to develop a comprehensive strategy for solar and space physics research. This updated and extended the first (2003) solar and space physics decadal survey. The latest decadal study implemented a 2008 Congressional directive to NASA for the fields of solar and space physics, but also addressed research in other federal agencies. The new survey broadly canvassed the fields of research to determine the current state of the discipline, identified the most important open scientific questions, and proposed the measurements and means to obtain them so as to advance the state of knowledge during the years 2013–2022. Research in this field has sought to understand:

- dynamical behaviour of the Sun and its heliosphere;
- properties of the space environments of the Earth and other solar system bodies;
- multiscale interaction between solar system plasmas and the interstellar medium; and
- energy transport throughout the solar system and its impact on the Earth and other solar system bodies.

Research in solar and space plasma processes using observation, theory, laboratory studies, and numerical models has offered the prospect of understanding this interconnected system well enough to develop a predictive capability for operational support of civil and military space systems. We here describe the recommendations and strategic plans laid out in the 2013–2022 decadal survey as they relate to measurement capabilities and plasma physical research. We assess progress to date. We also identify further steps to achieve the Survey goals with an emphasis on plasma physical aspects of the program.

Keywords: plasma physics, magnetosphere, astrophysics

(Some figures may appear in colour only in the online journal)

Introduction
The astrophysics community in the United States has prepared so-called ‘Decadal Surveys’ under the aegis of the U.S. National Academies going back to the 1960s (see National Academies 2015). In recent times each of the discipline areas of astrophysics, planetary science, Earth science, and space physics have carried out similar community-wide assessments of where each field stands in terms of research and in terms of what programs and projects must next be pursued to make significant progress in the field. The specific requirement for the National Aeronautics and Space Administration (NASA) to carry out such studies every 10 years was enacted into U.S. law by Congressional action in 2008. However, each of the science disciplines listed above also have tended to broaden the examination of the various fields by including other such federal agencies as the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy (DOE), and the Department of Defense (DoD) in whatever ways are deemed appropriate. The Decadal Surveys are carried out under the leadership of the U.S. National Research Council, which is the operational
arm of the U.S. National Academies of Sciences, Engineering, and Medicine (NASEM).

The solar and space physics community carried out its first decadal survey in the period 2001–2002 and the report was published in 2003 (National Research Council 2003). The second and most recent space physics decadal survey was initiated with NASEM in 2010 and was published after an intensive 18 month study period (National Research Council 2013). This paper describes some of the salient features of the decadal survey process and it lays out the goals of the effort. Research progress in the prior decade—with a special eye toward plasma physical issues—is briefly described and then recommendations of the 2013–2022 Survey are described. The paper concludes with an assessment of progress and prospects for achieving the Decadal goals outlined.

The decadal survey process

The Office of Science and Technology Policy (OSTP) in the Executive Office of the President (U.S.) has long endorsed the use of Decadal Surveys for the nation’s space programs. It has been argued (Morse 2006) that Decadal Surveys provide a community-based document that offers a consensus view of science opportunities to promote advanced research and to maintain a competitive national posture. It is widely recognized that these Surveys provide a well-respected source for establishing program priorities and for defining scientific goals of various federal agencies, for the Office of Management and Budget (OMB), and for the U.S. Congress.

In laying out the preferred Survey approach, OSTP recommended that the discussion be framed by identifying key science questions to be addressed (Morse 2006). It was clearly recommended that the focus of each Survey be on what to do, not on a particular spacecraft or ground facility to build. The specific guidance for Surveys has been to provide broad, in-depth arguments as to what a particular recommended element could have as far an impact on understanding fundamentals in a given science area. It also was urged to place recommendations in the context of interdisciplinary research and related fields of inquiry.

As laid out for the solar and space physics (SSP) community for the decade 2013–2022, the objectives of the Survey were to provide an overview of the science and to assess the then current state of knowledge in the field. A key goal was to identify the most compelling science challenges. Central to the Survey objectives was to determine the highest priority research targets for the decadal interval, not only for NASA, but also for NSF, NOAA, the U.S. Air Force and other possible sponsoring agencies. A key overarching goal was to develop an integrated research strategy for the nation and the SSP community.

The 2013–2022 decadal planning process was initiated in the Fall of 2010 with the formal request by NASA to NASEM to undertake the study. A task statement and charter for the effort was negotiated. It was determined that the study should be national (and in some ways, international) in scope and should consider NASA, NSF, NOAA, and DoD investments in solar and space physics. A chair of the study was appointed (D N Baker, U. of Colorado) as was a vice-chair (T Zurbuchen, U. of Michigan). Thereafter, a further 16 steering committee members were appointed, representing all areas of solar, interplanetary, magnetospheric, ionospheric, and atmospheric science. Under the steering committee were emplaced three disciplinary panels covering: (1) Solar and heliospheric physics; (2) Solar wind-magnetosphere interactions, and (3) Atmosphere–ionosphere–magnetosphere interactions. In a cross-cutting matrix of study efforts, there were five ‘National Capabilities’ working groups. These covered: (1) theory, modeling, and data exploitation; (2) Novel orbital and suborbital observing platforms; (3) Innovative advanced technologies and data systems; (4) Research to operations (and operations to research) issues; and (5) education and workforce development themes.

Under the steering committee leadership and over an 18 month period, some 300 community white papers were received and assessed. These represented new ideas and mission concepts ranging from small research efforts to major spacecraft constellations. Dozens of town-hall meetings and workshops were held throughout the U.S. (and, in some instances, at meetings held outside the U.S.). For the most attractive and compelling ideas for missions exceeding several hundred million U.S. dollars in total mission costs, a cost and technical evaluation (CATE) process was carried out of ‘reference’ NASA mission concepts. In August 2012, the 2013–2022 Decadal Survey was rolled out (see figure 1) at NASEM (National Research Council 2013). It was briefed to OMB, OSTP, NASA, NSF, NOAA, DOD, and to Congressional staff over a period of just a few weeks.

Understanding the Sun–Earth connection: recent progress

Since the publication of the 2003 decadal survey (National Research Council 2003), tremendous progress has been made in understanding the Sun–Earth system. Much of this progress has been the result of successful new NASA spacecraft missions. Initiation, for example, of the NASA Living With a Star (LWS) flight program by launching the Solar Dynamics Observatory (SDO) in February 2010 has returned a treasure trove of new observations of the solar corona and solar interior properties (Pesnell et al 2012). The successes of SDO have been followed up with the launch in June 2013 of the IRIS (Interface Region Imaging Spectrograph) mission under the aegis of the NASA Small Explorer (SMEX) program. As illustrated in figure 2, IRIS was placed into a low-Earth orbit and has provided fascinating new data about the plasmas in the transition region between the solar photosphere and the solar corona (e.g. Tian et al 2014).

The future also looks very bright for ground-based observations of plasma processes on the Sun. A major new telescope, the Daniel K Inouye Solar Telescope (DKIST), is under construction at the top of Haleakala volcano on the Hawaiian island of Maui (see figure 3). This 4 m class off-axis telescope will provide exquisite spatial resolution of features on the...
One of the most novel and long-sought in situ observational platforms for studying the Sun is the Solar Probe Plus (SPP) mission of NASA being readied for launch in July 2018. The instrument complement for SPP is shown in figure 4. As noted in the diagram, SPP will fly within 6 million km of the solar ‘surface’ (photosphere) and will make multiple passes through the solar corona over its several year lifetime. By measuring the local plasmas, magnetic fields, and plasma waves, SPP should give unprecedented insights into how the solar wind is accelerated and how energetic particles are produced in the million K solar atmosphere (Clark 2015). SPP represents the first mission ever to fly into the region just outside of where solar plasmas accelerate from subsonic to highly supersonic speeds.

Studies of the Earthward end of the solar-terrestrial system have also led to tremendous progress in the past decade. Figure 5 provides a broad schematic representation of the Earth’s space environment. As shown in the diagram, the supersonic, super-Alfvenic solar wind flow past the Earth’s strong dipolar magnetic field leads to fascinating plasma physical interactions. The fast solar wind flow means that a standing (collisionless) bow shock forms in front of the obstacle presented by the Earth. The shocked and slowed solar wind with its embedded interplanetary magnetic field (IMF) can interact with the Earth’s field through dayside reconnection. Such interconnection of the IMF and the Earth’s field can lead to a strong dynamo action and can impart huge amounts of energy into the ‘magnetospheric’ cavity surrounding the Earth. This energy can be temporarily stored in the elongated magnetic tail of the magnetosphere and then this energy can be suddenly by magnetic reconnection in an episodic release process known as a magnetospheric ‘substorm’ (Baker et al 1996). Such substorms can transport and greatly energize...
plasma particles in the highly coupled inner part of the magnetosphere and in the ionosphere. The very innermost part of the magnetosphere comprises the Van Allen radiation belts (Baker 2014) and electrons and protons trapped in the Van Allen zones can reach relativistic and ultra-relativistic energies.

Despite the fact that discovery of the Van Allen belts was the first major scientific achievement of the Space Age (Van Allen et al 1958), many mysteries have remained about how the Van Allen radiation belt particles are accelerated, transported, and lost. For this reason, in August 2012 NASA launched the dual-spacecraft radiation belt storm probes (RBSP) mission into elliptical Earth-orbits (Mauk et al 2012). The RBSP mission was renamed by NASA as the ‘Van Allen Probes’ mission in November 2012. Just a few days after the successful launch of the RBSP spacecraft, it was discovered (Baker et al 2013) that under some circumstances there are really three Van Allen radiation zones, not two as originally reported by Van Allen and coworkers (see figure 6).

The work with the remarkably sensitive and highly capable RBSP (Van Allen Probe) instrumentation showed that relativistic electrons in the Earth’s magnetosphere can be accelerated on very short (minutes to hours) timescales under strong forcing conditions. But in a similar vein—and as shown in figure 6 for the period in October 2012—these megaelectron volt (MeV) electrons can also be lost from the magnetosphere almost instantaneously. Prior to the Van Allen Probes program (and the new instrumentation afforded in that mission), researchers had no idea how efficiently and effectively particles were accelerated and lost in the radiation belts.

The data displayed in figure 6 come from the REPT instruments on board the Van Allen Probes spacecraft (see Baker 2014). As shown by the plotted data, the electrons produced in major acceleration events can ‘diffuse’ inward from larger radial distances (‘L’ values) but they never seem to penetrate closer to Earth than about $r = 2.8R_E$ (Earth radii). This fascinating feature has suggested that there is an ‘impenetrable
barrier to inward transport of megaelectron volt electrons in the Earth’s magnetosphere (Baker et al 2014). Thus, while electrons can be effectively accelerated to immense energies and can be transported freely over radial ranges of $r = 6R_E$ to $r \sim 3R_E$ geocentric distances, there is an almost immutable barrier to electrons making their way inside of $r \sim 2.8R_E$.

This amazingly sharp boundary for ultrarelativistic electron transport has very recently (Foster et al 2016) been examined in greater detail. This new work suggests the inward transport of relativistic electrons corresponds almost precisely to the outward extent of manmade very low frequency (VLF) radio waves produced by powerful Navy transmitters (used for submarine communication). Figure 7 illustrates that the outward extent of the VLF ‘bubble’ corresponds closely to the inward extent of the impenetrable barrier.

Perhaps the most pervasive and fundamental plasma physical process operating in astrophysical systems is magnetic reconnection (Burch and Drake 2009). As shown in figure 5 above, reconnection is the mechanism by which magnetized plasmas reconfigure themselves and is a principal mechanism for converting stored magnetic energy into heated plasmas. Ultimately, reconnection is responsible for such phenomena
as solar flares and coronal mass ejections from the Sun and for powerful auroral displays in the Earth’s magnetosphere.

Understanding in physical detail how reconnection works in a collisionless plasma has been one of the longstanding problems in both solar physics and in magnetospheric research. Figure 8(a) shows in a schematic way how magnetic field lines (shown as the dashed lines with black arrowheads) can be broken and then reconnected in a very confined volume of space. Plasmas can be accelerated in such a reconnection site (see figure 5) to large fractions of the local Alfvén speed due to the ‘slingshot’ kind of reconfiguration of magnetic field lines. This jetting action can occur in the rather broad region shown as the light blue box in figure 8(a). This is known as the ‘ion diffusion’ region and is the volume in which plasma ions become demagnetized and their orderly gyromotion breaks down (Burch and Drake 2009). However, active ongoing space research in recent years has shown that the actual breaking of magnetic flux tubes must involve effects on the electron gyroscale (shown by the pink box in figure 8(a)). This is the so-called ‘electron diffusion’ region and it can be a volume of just a few tens of kilometers in scale size in typical magnetospheric plasmas. As indicated schematically in figure 8(a), to probe reconnection at the electron gyroscale, a constellation of spacecraft must fly just a few tens of kilometers apart in an orderly and prescribed formation (Burch et al 2015).

In March 2015, NASA launched the Magnetospheric Multiscale (MMS) mission into Earth orbit. This spacecraft mission is comprised of four identical satellites with a full suite of particle, wave, and fields experiments (Burch et al 2015). As shown in the artist’s concept of figure 8(b), the four satellites can fly in a tetrahedral arrangement so as to encompass the actual reconnection ‘neutral line’ and can examine...
the magnetic reconnection precisely on the electron scales required (both spatially and temporally). The data from MMS are capable of providing deep insight into magnetic reconnection phenomena and are already shedding new light on this key plasma process. The launch of MMS by NASA fulfills the highest priority of the 2003 Decadal Survey (National Research Council 2003).

To complete our very brief summary of recent progress in space physics research, it is useful to note that one of the least studied parts of the Sun–Earth system has been the region just a few hundred kilometers above our heads. This understudied region is the upper part of Earth’s atmosphere known as the ionosphere. It is a key region where the neutral atmosphere of Earth wanes and where the magnetospheric domain of the Earth holds sway. Recent research has shown that forcing of the ionosphere by solar influences (from above), as well as terrestrial forcing from below due to terrestrial weather effects, can produce huge effects on the ionosphere.

Figure 9 shows a schematic diagram that illustrates the possibilities of studying solar influences as well as the meteorological driving of the ionosphere system. The goal of this research is to measure the composition, temperature, and winds across the ionospheric domain. This will permit deeper understanding of the relative roles of plasma upwelling, advection, and thermal expansion in determining the latitudinal and temporal evolution of the ionosphere. A NASA small explorer (SMEX) mission dubbed ICON (ionospheric connection explorer) is presently under development for launch in 2017 (see Rider et al. 2015). This program should take some key initial steps (as outlined in figure 9) to assess ionospheric spatial and temporal forcings.

Another NASA mission in development is called GOLD (global-scale observations of the limb and disk). It will provide a very capable Earth-viewing instrument flying on a geostationary-orbit communication satellite (see Eastes et al. 2008). The implementation approach for GOLD is shown in figure 10. This diagram in the center shows the key ultraviolet spectrometer instrument at the heart of the GOLD mission concept. This will be mounted on the operational communication platform and provide essentially continuous Earth-viewing. The GEO spacecraft is illustrated in the upper left of figure 10. As shown in the lower portion of the figure, the GOLD measurements will provide unprecedented images of thermospheric properties of the Earth. The five disks in the figure show modeled expectations for thermospheric temperature evolution near 160 km altitude during a geomagnetic storm. The five images show a possible pattern of heating at 1 h intervals during a storm main phase. GOLD, like ICON, will launch in 2017 and will revolutionize our understanding of what has heretofore been known somewhat disparagingly as the ‘ignorosphere’ of the Earth.

The decadal survey: recommendations for the future

Based on awareness of the many accomplishments of the solar and space physics communities over the past decade, the Decadal Steering Committee encouraged a broad assessment of key next steps in the decade 2013–2022. Armed with community inputs (as described previously) and recognizing that many space programs were already underway, a plan was laid out to optimize science return for decadal investments. Based on guidance from OMB and Congressional sources, it was judged that developing a program plan to fit within a relatively flat budgetary profile over the decade was the right strategy to adopt.
The basic ‘zeroth order’ recommendation of the Decadal plan (National Research Council 2013) was to complete the ongoing program. As indicated in the last section of this paper, many exciting projects, programs, and NASA flight missions were brought to fruition in the period 2003–2012. Many other programs and flight missions were also already initiated and were on the verge of reaching their active science phases. Examples of this, as discussed above, were the Van Allen Probes and the MMS missions of NASA. The 2013–2022 Decadal Survey strongly renewed its endorsement for carrying such underway programs to their natural culmination.

The Decadal plan was released at a time of very considerable federal budgetary stress. Thus, the Steering Committee took the view that advocating for relatively small-impact budgetary items could be the wisest approach for the early years of the decade. Thus the highest priority new recommendation in the Decadal plan was for a program called DRIVE. As shown in figure 11, DRIVE stands for Diversify, Realize, Integrate, Venture, and Educate. Each of these elements of the overall initiative have specific meaning to NASA, NSF, and the other federal agencies. A key feature of DRIVE was (and is) that it strives to place substantial new resources directly into the research community and it does so at a modest new cost to each of the federal agencies.

The ‘Diversify’ element of DRIVE urges use of new observing platforms for the solar and space physics discipline. This was intended to motivate much greater use of micro- and nano-satellites, for example, and use of mid-scale ground-based assets. Given the spectacular increase in the number and diversity of so-called ‘Cubesat’ missions being flown now by NSF, NASA, and DOD, this Diversity element of DRIVE has already been wildly successful.

The ‘Realize’ part of DRIVE urges full exploitation and utilization of operating space and ground systems and it advocates infusion of adequate funds to better carry out data analysis from these already deployed systems. This aspect of DRIVE seems to have been warmly embraced by NASA and NSF so that more resources for operations and analysis are being added to existing budgets.

The ‘Integrate’ component of DRIVE urges strengthening of ties between the ‘sister’ disciplines closely related to solar and space physics. This means, for example, encouraging more active cooperation between SSP and astrophysics as well as exploiting synergies with planetary research and with...
Earth science. This also extends to collaboration between space physics and, for example, laboratory plasma research. This integration concept seems to have resonated strongly with, and amongst, agency leaders.

‘Venture’ in the DRIVE initiative means making greater investment in new instrument designs and space system technologies. It also means development of science centers with joint funding from NASA, NSF, DOE, NOAA, and other agencies. Evidence of support for this DRIVE element has already been seen in the fiscal year (FY) 2014 and FY 2015 budgets of the agencies.

To round out DRIVE, ‘Educate’ means focusing on training, empowering, and inspiring the next generation of space researchers. Study of the Sun and its interaction with the Earth has always greatly inspired young students. It is of paramount importance to continue—and, indeed, to redouble—the federal support for educating the next generation of scientists and engineers.

While the DRIVE initiative calls out specific activities and recommendations for NASA and NSF, there are also broad guidelines for the Survey for other agencies as well. It is well appreciated in the NASA space physics community that basic plasma physics, laboratory plasma experiments, and numerical simulations of all sorts have fundamental importance to the space exploration program. This intimate relationship was illustrated very well, for example, by the 'Frontiers of Plasma Science' Workshops held under the aegis of the U.S. Department of Energy in 2015 (see www.orau.gov/plasmawks2015/). Themes examined in these workshops included: particle acceleration in shocks; wave-particle interactions in dusty plasmas; magnetic reconnection-driven particle acceleration; Alfvén wave heating in laboratory and space systems; and numerous other forefront issues. The attention focused on such topics in DOE-sponsored meetings makes clear that plasma physics—whether in the laboratory, in near-Earth space, or in remote astrophysical systems—is of fundamental national (and international) importance.

As noted above, virtually every relevant agency of the U.S. government seems to have embraced the DRIVE concept in some ways. One would have liked to see more new resources already devoted to this top priority, but progress is clearly being made. The second priority of the Survey (National Research Council 2013) was to reinvigorate the Explorer program of NASA. As shown in figure 12, the Explorer program has been one of the most singularly successful parts of the U.S. space program. Explorer I, for example, was the first U.S. satellite that discovered the Van Allen radiation belts. As shown in figure 12, just since about 1990 there have been some two dozen Explorer missions in SSP as well as astrophysics. The Decadal Survey urged that some $70M per year be restored to the Explorer line for space physics in order to increase the launch cadence of SMEX and so-called ‘MIDEX’ missions to a rate of new flights every year or year-and-a-half. Such a boost for smallish space missions would be one of the best conceivable steps for NASA (National Research Council 2013).

The traditional focus of decadal surveys in the past has been on the large or very large (‘flagship’) missions of NASA. The 2013–2022 Survey turned things on their head a bit by making DRIVE and Explorer augmentation a higher priority than new Solar-Terrestrial Probes or Living With a Star missions (National Research Council 2013). However, the Decadal plan put considerable emphasis on getting new interplanetary, magnetospheric, ionospheric, and solar missions underway. In particular, there was strong recognition that a mission provisionally dubbed ‘IMAP’ (interstellar mapping and acceleration probes) should be the highest priority new $0.5B-class mission for NASA. As shown in figure 13, we are at a unique time in scientific history where the Voyager spacecraft (Stone et al 2013) are now exploring in situ the termination shock, heliopause, and perhaps the nearest portions of our local interstellar medium. The IMAP spacecraft concept would be to use remote sensing technologies on a relatively near-Earth spacecraft to view the outer part of the heliosphere while the Voyager spacecraft make concurrent and direct measurements some hundreds of astronomical units (AU) from the Sun (National Research Council 2013).

In addition to IMAP, the Decadal Survey advocated for using pairs or constellations of new Solar-Terrestrial Probes spacecraft to explore coupling from the Earth’s atmosphere to the magnetosphere (‘MIDEC’) or from the magnetosphere to the lower atmosphere (‘DYNAMIC’). Each of these notional missions (see figure 14) would measure plasmas in situ while also making remote sensing observations in order to gain a more global view of the Earth system (National Research Council 2013).
A key recognition of the Decadal Survey was how practically important solar and space physics is in the daily lives of citizens in our technological society. Thus, the theme of ‘space weather’ pervaded the Survey plan (National Research Council 2013). It was strongly urged that NASA (through LWS) and NOAA, especially, invest much more heavily in the new decade in operational space weather observing systems as well as improved modeling and forecasting techniques (National Research Council 2013). A roadmap for addressing space weather needs has recently been presented by Schrijver et al (2015) in a study sponsored by COSPAR (Committee on Space Research).

Figure 11. A relatively small, low-cost initiative, DRIVE, provides high leverage to current and future space science research investments with a diverse set of science-enabling capabilities. The five DRIVE components are as follows:

- Diversify observing platforms with microsatellites and midscale ground-based assets.
- Realize scientific potential by sufficiently funding operations and data analysis.
- Integrate observing platforms and strengthen ties between agency disciplines.
- Venture forward with science centers and instrument and technology development.
- Educate, empower, and inspire the next generation of space researchers.

This is the highest priority recommendation of the National Research Council 2013–2022 Decadal Survey (National Research Council 2013).

Figure 12. A diagram showing the Explorer-class missions launched by NASA since ~1990. (Courtesy of NASA).
Summary and conclusions

The consensus of the 2013–2022 Decadal Survey study has been that solar and space physics has a bright future with immense opportunities for breakthrough research in solar, space plasmas, local astrophysics, and many other domains. There is a committed and highly capable community ready to explore the solar-terrestrial (and, more broadly, solar-planetary) system all the way from the Sun’s interior to the outermost fringes of the heliosphere. The record of the last decade is one that shows that the space physics (or ‘heliophysics’ as it is called in NASA) practitioners are very good stewards of the

Figure 13. The solar system and its nearby galactic neighborhood are illustrated here on a logarithmic scale extending from <1 to 1 million AU. The Sun and its planets are shielded by a bubble of solar wind—the heliosphere—and the boundary between the solar wind and interstellar plasma is called the heliopause. Beyond this bubble is a largely unknown region—interstellar space. NOTE: The G cloud is a cloud of interstellar gas near the Local Interstellar Cloud in which the solar system is embedded. (Source: Image and text adapted from NASA and available at http://interstellar.jpl.nasa.gov/interstellar/probe/introduction/scale.html).

Figure 14. MEDICI targets complex, coupled, and interconnected multiscale behavior of the magnetosphere–ionosphere system by providing high-resolution, global, continuous 3D images of the ring current (orange), plasmasphere (green), aurora, and ionospheric–thermospheric dynamics and flows as well as multipoint in situ measurements. (Courtesy of Jerry Goldstein, Southwest Research Institute).
resources made available to the community. Whether through major spaceflight missions, through small sounding rockets and cubesat, or through innovative modeling approaches, solar and space physics research has demonstrated remarkable progress in the recent decade with relatively modest budgetary resources. There is every reason to presume that infusion of new resources into solar and space physics by NASA, NSF, NOAA, DoE, DoD, and other federal agencies will pay similar, or indeed larger, dividends in the decade now extending into the early 2020’s (National Research Council 2013).

As noted previously, from an overall U.S. perspective, space physics really does involve all the federal agencies listed in the last paragraph. In fact, when one considers the full ranges of observations and models relevant to space research and space weather, there are many other agencies that are also key to ultimate success. This includes the U.S. Geological Survey (USGS), the Federal Emergency Management Administration (FEMA), the Federal Aviation Administration (FAA), the Department of Homeland Security (DHS) and a host of other organizations that have deep and abiding concerns about the space and near-Earth environment, which is so much a part of our modern technological society (see National Research Council 2008).

From the perspective of this paper, a principal issue is how basic plasma science research can be effectively prosecuted over the ensuing decade and beyond. That the SSP Decadal plan is well-founded and affordable is illustrated by the budgetary ‘waterfall’ chart for NASA shown in figure 15. The horizontal axis of this figure (from National Research Council 2013) shows time measured in U.S. fiscal years. The time span shown is for FY 2013 to FY 2024. The vertical axis of the figure shows annual budgetary expenditures in millions of (real year, RY) U.S. dollars. The diagram then shows by different coloured shapes the expenditures recommended by the Decadal plan for each of the key areas of NASA heliophysics program. As shown, this proposed spending plan is highly responsible in a fiscal sense. Since almost everything proposed for NASA falls under the FY 2012 budget plan projection that the U.S. government issued as the Decadal Survey was being prepared. With a slightly more robust spending plan (labeled ‘Enabling Budget’) shown by the red dashed curve, everything proposed in the Decadal plan could effectively be carried out by ~2025.

The research carried out by NASA, NSF, and other space-faring agencies has immense relevance to the broad theme of plasma physics. This includes plasma heating mechanisms, particle acceleration, loss processes, wave-particle interactions and a host of other fascinating topics than can be examined in very productive ways in the space arena. As described above, much progress has been made in the past decade or so on many of these topics by using NASA-sponsored space missions. Moreover, the next decade and beyond look very promising as Van Allen Probes, Magnetospheric Multiscale, Solar Probe Plus, and other NASA missions reach their full fruition.

It is important to note, however, that progress in the research domain does not by any means come exclusively...
from the large spaceflight missions. Much of the success of NASA, NSF, NOAA, DOE, and other programs comes from very basic theory and modeling research. This fact was clearly recognized in the 2013–2022 Decadal Survey. It was a fundamental component of the Survey to recommend that space plasma physics should ever more strongly ally itself with both laboratory plasma research, on the one hand, and with astrophysical research on the other hand. Both theory and modeling of plasmas in the laboratory setting and in remote astrophysical systems were viewed as crucially important to space plasma physics.

It seems particularly important to note that the Decadal Survey placed special emphasis on laboratory experiments and upon numerical modeling work. In Chapter 4 of the Survey (p 84), it was recommended that ‘NASA should join with NSF and DOE in a multiagency program on laboratory plasma astrophysics and spectroscopy…’. It was noted that such a program would ‘obtain unique insights into fundamental physical processes’. Furthermore, the Survey recommended (p 87) that federal agencies, ‘…together create heliophysics science centers to tackle the key problems of solar and space physics that require multi-disciplinary teams of theorists, observers, modelers, and computer scientists…’. Indeed, the record of recent space plasma research shows that numerical modeling of both solar and magnetosphere–ionosphere processes has been indispensable for understanding these complex systems.

In this brief summary of the National Academies’ report, it is not possible to convey anything like the breadth and depth of space physics progress in recent times. Nor is it possible to convey fully the potential of future programs to advance our understanding of basic plasma processes. Suffice it to say that continued close cooperation between laboratory and space-oriented researchers has immense potential to increase our basic understanding and to also produce practical improvements in the space weather that can benefit all of human society. At its core, this is what the 2013–2022 Decadal plan sought to endorse.

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