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Instigators of Future Change in Magnetospheric Research

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ABSTRACT

This chapter focuses on emerging methods and capabilities enabling future breakthroughs in magnetospheric research. That is, it does not focus on magnetospheric research regions and science issues, but on how new trends in the scientific research is conducted. We specifically cover four topics emerging as techniques/issues that will likely cause a major upheaval in our approach to magnetospheric physics. The four topics are: the miniaturization of spacecraft systems and scientific instrumentation; high-end computing and advanced techniques in code coupling methodologies; storage and handling of large data sets, along with awareness of advanced statistical techniques; and diversity within the magnetospheric physics workforce. We think they are paradigm-shifting breakthroughs that will revolutionize many research areas within the science, technology, engineering, and mathematics umbrella.

47.1. INTRODUCTION

As discussed in all of the previous chapters of this book, the magnetosphere, not only that around Earth but also those around every other planet with an intrinsic magnetic field, are natural laboratories rich in fundamental physical processes of universal application to many other scientific disciplines. Magnetospheric volumes are vast, yet some of the relevant physics occurs on a tiny scale. Topics range from the microscopic processes of magnetic reconnection and wave–particle interactions to the macroscopic phenomena like plasma circulation through the system and pressure balance and magnetic topological distortion during strong active times.

This final chapter of the book is about the future of magnetospheric research. That is an extremely broad topic and one that cannot be covered in just a few pages. Indeed, earlier chapters in this section cover specific aspects of this topic, and many recent reviews and commentaries have addressed the open questions in the field. For instance, there is an entire special section of a journal on "unsolved problems of magnetospheric physics" (Denton et al., 2016), covering the topics of the future of plasmaspheric investigations (Gallagher and Comfort, 2016), current system analysis (Dunlop et al., 2016; Liemohn et al., 2016), magnetic reconnection (Milan et al. 2016), and radiation belt physics (Kessel, 2012). Other works have covered the future of magnetosphere–ionosphere coupling, noting the nonlinear physics and feedback inherent in the geospace system (Burch, 2016; Moore et al., 2016) and the difficulty in knowing even the spatial connectivity between different parts of geospace (Delzanno et al., 2015, 2016). The substorm problem, of course, is still a point of contention and ambiguity that requires additional attention (Lui, 2018).

Therefore, this chapter will not focus on magnetospheric research *regions and science issues* but rather on the emerging *methods and capabilities* enabling future breakthroughs in magnetospheric research. Here, we

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specifically cover four topics emerging as techniques that will probably cause a major upheaval in our approach to magnetospheric physics. Indeed, we think they are paradigm-shifting breakthroughs that will revolutionize many research areas within the science, technology, engineering, and mathematics (STEM) umbrella.

47.2. TECHNIQUES TO WATCH AND ADOPT

While there are other items that could be in this list, we will focus on just these four emerging trends in magnetospheric physics. The first is the miniaturization of spacecraft systems and scientific instrumentation, allowing for microsatellites and nanosatellites to become robust and reliable contributors to the scientific endeavor. The second is high-end computing and advanced techniques in code coupling methodologies. This is mostly covered in an earlier chapter but we wanted to emphasize this point here. The third is recent developments in data storage and handling, along with awareness of advanced statistical techniques (i.e., data science and machine learning). The fourth topic that we will focus on here is diversity in the workforce, and the burgeoning mindfulness that different perspectives in the research community lead to more creative solutions to problems.

47.2.1. Spacecraft System and Instrumentation Miniaturization

Both scientific instruments and satellite subsystems have seen a revolution in the reduction of size, weight, and power plus cost (SWaP+C) requirements in recent years. A workshop on Small Satellites for Space Weather Research and Forecasting was recently held to discuss the current progress and future opportunities for harnessing these improvements for research in our field as well as applications for space weather operations.

The magnetosphere is a large region consisting of interconnected pathways of energy and mass transport occurring at multiple concurrent scales. As such, it has long been recognized that constellations are needed to resolve spatial and temporal ambiguities, and provide the simultaneous, global measurements required to resolve questions of cross-scale coupling. Yet despite the recognized need, large constellations have been out of reach, primarily due cost concerns.

There are three key emergent areas that finally enable these long sought after magnetospheric constellation missions: (1) instrument miniaturization, for which heliophysics in situ instruments are particularly well suited; (2) commoditization of spacecraft subsystems components; and (3) new avenues for access to space. These developments enable increased usage of small satellites, such as CubeSats, for small, focused missions accessible to a broad population in the field, a large mission based on many small satellites, such as the Magnetospheric Constellation (MagCon) mission concept (Angelopoulos and Spence, 1999), to make significant progress on unanswered questions, and the use of small instruments to be flown on nondedicated satellites for additional research and space weather monitoring at greatly reduced costs when compared to dedicated missions.

As concluded in a National Academies of Sciences study (National Academies, 2016), CubeSats have demonstrated their ability to deliver compelling science on small and economic platforms. Since the publication of that report, CubeSat technologies, particularly with respect to instrumentation, have continued to mature, through such programs as the In-Space Validation of Earth Science Technologies (INVeST) in Earth Sciences and the Heliophysics Technology and Instrument Development for Science (H-TIDeS) in heliophysics. As noted by Posner et al. (2014), NASA leadership recognizes the importance of small spacecraft mission contributions to our understanding of the Sun–Earth space environment, most notably for their ability to provide low-cost magnetospheric constellations. Note that CubeSat missions are delivering exceptional science for magnetospheric physics. For example, the Focused Investigations of Relativistic Electron Bursts: Intensity, Range, and Dynamics (FIREBIRD) CubeSats provided new information about electron microbursts, including their spatial scale and evidence that discrete whistler mode chorus packets are their source (Breneman et al., 2017; Crew et al., 2016), and the Colorado Student Space Weather Experiment (CSSWE) CubeSat mission, which demonstrated that galactic cosmic rays are responsible for inner radiation belt electrons (Li et al., 2017).

The SmallSat commercial industry is growing in leaps and bounds. There now exist multiple, low-cost solutions for spacecraft subsystems, at a fraction of previous costs. A key enabler for high quality yet cost effective science missions is to utilize subsystem development efforts and instrument miniaturization and scale up from CubeSat platforms to larger small satellites (SmallSats). The reliability of such systems has increased as well, due in part to government and industry initiatives aimed at reliability, and the natural progression of the marketplace. Commercial constellations of hundreds to thousands of spacecraft are now being proposed and built, with per spacecraft reproduction costs in the range of a few $M (see, e.g., OneWeb Satellites (https://onewebsatellites.com/) or Blue Canyon Technologies (https://bluecanyontech.com/)). This is one or two orders of magnitude below the cost for large spacecraft bus designs, making small satellite technology affordable for everyone. The reliability of the mission is increased because the loss of any one spacecraft does not doom the mission. An example of such an approach is the Cyclone Global Navigation Satellite System (CYGNSS) mission that consists of eight identical spacecraft flying in low-Earth orbit (Ruf et al., 2013), making breakthrough measurements of ocean winds (Ruf et al., 2016) and soil moisture content (Kim and Lakshmi, 2018). Under the hood, the spacecraft bus looks like a CubeSat, and it was developed for NASA with a higher acceptance of risk than larger, more traditional missions.

Designs for several constellation missions have been studied over the past few decades. In the last Solar and Space Physics Decadal Survey (NRC, 2013), Magnetospheric Constellation (MagCon), and a similar mission, Magnetospheric Tomography (MagCat), were studied but deemed too expensive. It is worth quoting directly from that document (NRC, 2013, pp. 9–42):

> "To implement such a constellation (36, 30 kg s/c) requires development of small satellite systems and instruments that can be more cheaply manufactured and tested in a reasonable time frame (2–3 years) with acceptable reliability levels."

It is fair to state that both reliability and spacecraft manufacturing capability have since increased to the point that such relatively simple spacecraft can be manufactured for such a constellation, with reasonable costs.

Previous approaches to constellation formation relied on a single, dedicated launch vehicle, and a dispenser ship. The availability of large launch vehicles with excess launch capacity, and the potential for smaller launch vehicles (LVs), such as from Electron and Virgin Galactic, offer an alternative path to constellation formation. It is no longer necessary to have a dedicated LV; rather, a smallsat constellation could get to orbit as a rideshare on an ESPA (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter) beneath a primary payload, greatly reducing the cost of the mission to NASA or other government agency. For a mission such as MagCon, a commercially available propulsive ESPA could rideshare to geosynchronous transfer orbit, then act as the dispenser ship to move the spacecraft to the final location (Kepko, 2018). For low-Earth orbit (LEO) missions, the ability to directly launch into LEO is a true game-changer, as it economically allows multiple spacecraft in multiple orbit planes, with reduced cost and complexity compared to a single launch.

Instruments are getting smaller, too, fitting within the SWaP+C requirements of nanosat form factors. For instance, miniaturization is possible for particle detectors (Scime et al., 2016; Clark et al., 2016; Zurbuchen and Gershman, 2016; Skoug et al., 2016; Desai et al., 2016; Wieser and Barabash, 2016; Michell et al, 2016), magnetic and electric field probes (Korth et al., 2016; Miles et al., 2016; Sheinker and Moldwin, 2016; Regoli et al., 2018), and even auroral imagers are getting close to fitting CubeSat specifications (Unick et al., 2016; Paxton et al., 2017). Fennell et al. (2016) conclude that CubeSat versions of most particle sensors nearly match the performance of full-sized spaceflight instruments. In addition, the use of engineering-grade sensors for scientific data products, such as the magnetometers on the Iridium satellite constellation (Coxon et al., 2018), has significant potential for rapid growth in space-based instrumentation.

Ground-based sensors have also come a long way too, enabling distributed arrays of small instruments. Several new miniaturized and low-power sensors have been developed recently, for example, for magnetometry (Engebretson and Zesta, 2017), for geocoronal measurements (Gardner et al., 2017), and galactic cosmic ray monitoring via their byproduct fast neutrons (Caballero-Lopez, 2016). In addition, the compilation of ground-based magnetometers from across the globe into the SuperMAG network (Gjerloev, 2012), with unified processing and easy accessibility, has provided a key breakthrough in science studies with these data sets.

47.2.2. High-End Computing and Code Coupling Advancements

Summit was the world's fastest supercomputer, brought online in the summer of 2018. At 200 petaflops, it outpaced the previously fastest machine by a factor of three. Are we still on track with Moore's Law, the observation that electronic transistor density on a computer chip doubles approximately every two years? Of particular relevance for magnetospheric physics, however, is not transistor density but rather total computing speed, as quantified by floating point operations per second (FLOPS). Figure 47.1 shows the history of FLOPS increase in the top computers from near the beginning of the supercomputing age through to the announcement of the Summit machine. The three curves show the fastest machine (dotted curve), the 500th fastest machine (dashed curve), and the sum of computing power for the top-500 machines (solid curve). The growth is a factor of roughly one million times speed-up (that is, roughly 20 "doublings" of FLOPS) over the past 25 years. Note that yet another new machine, Fugaku, came online in the summer of 2020, with a performance 2.8 times faster than Summit. The amazing speed of Fugaku will surely also be surpassed some day.

For space physics, this fact of continually-increasing computational resources means that codes must be designed to take advantage of efficient parallel processing algorithms. New codes need to be written with this in mind and legacy codes need to be updated to exploit this fact of modern computing. For example, the

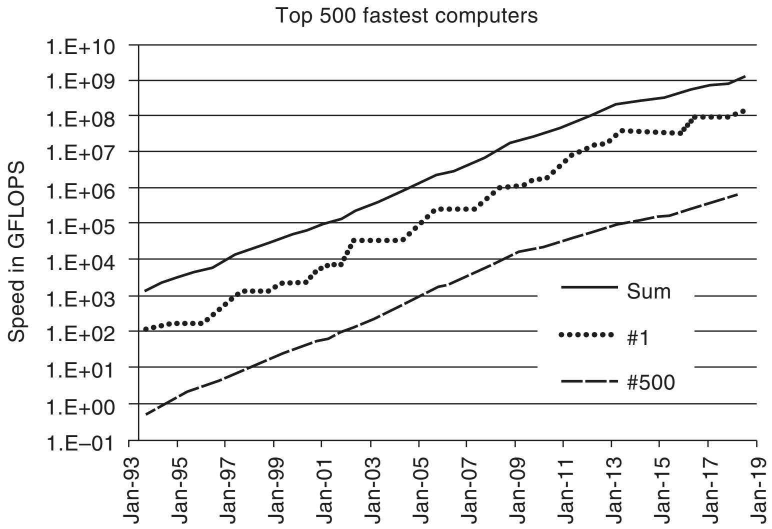

Figure 47.1 Peak computing speed in giga-floating-point operations per second (GFLOPS) as a function of time, from the advent of supercomputers to summer 2018.

Block-Adaptive-Tree Roe-type Solar wind Upwind Scheme (BATS-R-US) magnetohydrodynamic model (Gombosi et al., 2002; Toth et al., 2012) was written with parallel processing as a cornerstone of its design. Conversely, the Rice Convection Model (Harel et al., 1981), originally written well before the highly-networked supercomputing age, needed to be adapted for parallel calculation many years after its creation (De Zeeuw et al., 2004). Some modeling techniques, like test particle codes, are embarrassingly parallel in that the particle solutions do not depend on each other, but load balancing becomes an issue and smart algorithms need to be applied for efficient use of computational resources (Fang et al., 2008).

Code coupling algorithms are also getting better. We are no longer at the stage of requiring files to be written by one program and then read by another to transfer numerical results between codes. While this works well for one-way coupling, it is inefficient for two-way coupling, in which the codes are run simultaneously on the same machine. Goodrich et al. (2004) provide a plan for the code coupling within the Center for Integrated Space Weather Modeling, detailing the complexity of this task. Toth et al. (2005, 2012) describe the algorithms behind the Space Weather Modeling Framework, in particular the methodology of synchronizing many disparate code styles into a unified whole. Wiltberger (2015) gives a review of global magnetospheric modeling capabilities, many of which are coupled code suites. Such coupled code algorithms are needed for going beyond the magnetopause, too, especially space weather simulations from Sun to the Earth (Merkin et al., 2007; Toth et al., 2007). This will be especially true as magnetospheric physics ties in with magnetotelluric modeling to predict geomagnetic induced currents (Liemohn et al., 2018b).

The standardization of code input–output will help tremendously with the code-coupling issue. The adoption of the Space Physics Archive Search and Extract (SPASE) convention (http://www.spase-group.org/), for both observational and numerical data sets, provides a protocol for information transfer. Development of SPASE-compliant code requires an initial investment of effort, but the future payoff will be highly beneficial for eventual coupling with other models or allowing SPASE-enabled websites to find your model results and display them, such as the Virtual Model Repository (http://vmr.engin.umich.edu/) and the Community Coordinated Modeling Center's Integrated Space Weather Analysis (iSWA) tool (https://ccmc.gsfc.nasa.gov/iswa/).

The idea of quantum computing, first put forward by Feynman (1986), has been around for a few decades (see review by Steane, 1998). The idea is that the information is stored in the excited states of single atoms, allowing an enormous increase in capacity regarding both storage and processing. A quantum computer is still beyond our grasp (King, 2018; Yung, 2018). If realized, it will usher in a new reality of Moore's Law growth in computing capabilities. This is something to watch for in the coming years that will revolutionize the way we conduct computational space physics.

47.2.3. Big Data Storage, Handling, and Data Mining Techniques

There are several topics that fit within the broad category of "big data." The first is the storage, handling, and transfer of these large files. While transfers of gigabytes are possible across networks, terabyte transfers are slow, perhaps taking days to complete, and moving larger data sets on the petabyte or exabyte scale through network connections are, at the moment, impractical. It is often easier to load the data onto a hard drive and ship it to its destination than wait for bandwidth on the Internet. Figure 47.2 shows a network of 100 Gb s^{-1} nodes developed by the Department of Energy, the Energy Sciences Network (Guok et al., 2008). A regional version of this network is being created within California and eventually up the coast (https://prp.ucsd.edu/), and an effort is underway to create a national big data superhighway (NRP, 2017). NASA is considering these efforts to increase connectivity to this high-end network, allowing space physics data to flow more rapidly across the country from the data storage facilities to the researchers analyzing it.

A second aspect of big data is data assimilation – ingesting observations into model results, changing the values for the next time step in a simulation. Data assimilation in magnetospheric models has been an elusive goal. One of the first was Garner et al. (1999), with direct replacement of values within the Rice Convection Model. Because of the high flow speeds and correlation between neighboring locations, this method is not the optimal choice for magnetospheric physics studies. When only one or two satellites are used, assimilation in this manner does not make for a better, more realistic solution. Better success has been found with ensemble Kalman filters, particularly for the radiation belts, when the underlying model is drift-averaged, so a data stream from a single spacecraft can influence all local times. This has been done with several models, like the Versatile Electron Radiation Belt model (Kondrachev et al., 2011; Shprits et al., 2013; Kellerman et al., 2014), the Dynamic Radiation Environment Assimilation Model (Reeves et al., 2012; Schiller et al., 2012), the Salammbo code (Maget et al., 2015), and the relativistic electron extension of the ring current–atmosphere interaction model (Godinez et al., 2016; Jordanova et al., 2017). Ensemble Kalman filters have also been used to nudge the high-latitude electrodynamics solution for global magnetospheric models, as done by Merkin et al. (2016). Another approach that has gained some traction for magnetospheric data assimilation is 3DVAR, the three-dimensional variational assimilation method, which has been used for plasmaspheric modeling (Nikoukar et al., 2015).

The new developments mentioned in the earlier sections will enable data assimilation to become a regular part of other magnetospheric studies. A constellation of satellites

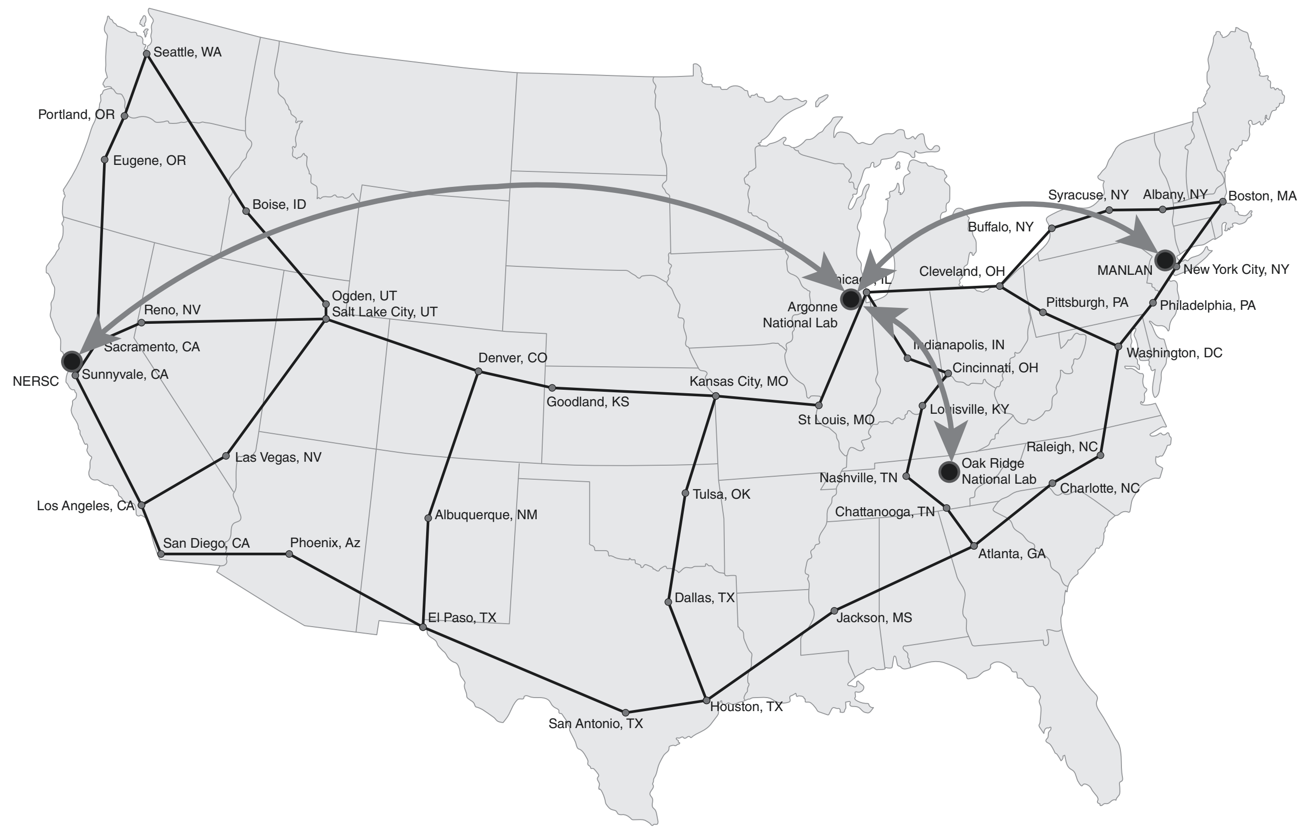

Figure 47.2 Department of Energy ESnet data superhighway nodes with ~100 Gb s^{-1} throughput. NASA is proposing to join this effort and expand connections to the system. From the ESnet policy board.

sprinkled throughout the magnetosphere would be ideal, providing observations across the vast spatial extent of geospace for a more uniform nudge of the model results. Similarly, an extensive array of ground-based sensors throughout the high-latitude regions in both hemispheres would be a tremendous data resource for magnetospheric physics.

The third component of this issue is robustness in data model comparisons. It is not enough just to do a correlation coefficient or a data model root-mean-square error; while those are starting calculations that should be done, there are many more metrics of fit performance and event detection performance that should be included when comparing model output to observations. For instance, Vanhamäki and Juusola (2018) discuss data methods for ionospheric electrodynamics, Morley et al. (2018) describe a method for assessing model results against particle flux data, which can fluctuate over orders of magnitude, and Liemohn et al. (2018a) describe a baseline set for geomagnetic index model assessment. There is much that magnetospheric physicists can learn from our counterparts in meteorology (see, for example, the many metrics techniques discussed in Jolliffe and Stephenson, 2011).

A fourth and final topic within the "big data" umbrella is the adoption of advanced statistical techniques, known as data science, in particular the idea of machine learning. McGranaghan et al. (2017) give an excellent overview of how these new techniques could be used for space physics, providing examples of how other disciplines have embraced these methods and offering a strategy for future research directions that optimize magnetospheric physics engagement with these tools. Employment of neural networks has long been used for geomagnetic index prediction (Lundstedt and Wintoft, 1994; Takalo and Timonen, 1997; Boberg et al., 2000), but they have only relatively recently been used for magnetospheric quantities (Bortnik et al., 2016; Chu et al., 2017a, 2017b). A workshop entitled "Space Weather: A Multidisciplinary Approach" was held to bring together researchers from the space physics and big data communities (Camporeale et al., 2018a). This workshop resulted in a book describing efforts to date and an introduction to relevant techniques (Camporeale et al., 2018b).

Note that the national Science Foundation (NSF) has recognized "big data" and the various topics mentioned above related to it as an area of special attention. In fact, the NSF is launching a "Ten Big Ideas" initiative, of which "Harnessing the Data Revolution" is one (https://www.nsf.gov/news/special_reports/big_ideas/harnessing.jsp). The NSF intends to heavily invest in this topic over the next decade; the magnetospheric research community is poised to be part of this national effort, allowing for unprecedented advancements in our understanding of geospace.

47.2.4. Increased Workforce Diversity

At this 2018 Triennial Earth–Sun Summit (TESS) meeting, a plenary session was held on the topic of "Unconscious Bias in Space Physics." The kick-off presentation outlined the problem (Richey and Rodgers, 2018), followed by a lengthy panel discussion and question period. This is just one of several conversations taking place in the space physics community on the topic of creating an inclusive workplace for all scientists. The journal *Scientific American* had an entire edition devoted to diversity, equity, and inclusion, explaining the demographics of diversity in the scientific workplace (Guterl, 2014a), the fact that different backgrounds leads to different approaches towards a problem (Medin et al., 2014), and how a diverse workforce leads to excellence (Guterl, 2014b). That is, a diverse research community leads to more creative and open-minded thinking about the problems being addressed. It is, therefore, good to promote a diverse workforce, taking this issue into account in the recruitment of new researchers into the field as well as helping to make the work environment a more equitable and inclusive place, so that the diverse population will feel welcome to fully participate.

There is a long way to go on this topic, however. Several studies have examined this issue. For example, our community's demographics are changing, albeit very slowly. A survey of American Geophysical Union (AGU) membership shows that women comprise only 20% of the Space Physics and Aeronomy (SPA) section, while a study by Moldwin and Morrow (2016) of solar and space physics PhD recipients between 2001 and 2009 showed that 25% were female (of those for whom gender could be identified, which was 344 of the 416 PhDs). King et al. (2017) discuss the difficulties in ensuring diversity in the geosciences, Rosen (2017) describes the myriad obstacles that women face in overcoming sexism to advance their careers, and Lerback and Hanson (2017) presented data on how Earth and Space Science journal editors systematically and disproportionately ask fewer women than men to review manuscripts. The workplace is not equitable; there is still work to do to make our research community fully inclusive and inviting to all people. Even more insidious and damaging towards diversity, equity, and inclusion is the existence of sexual harassment. A National Academies report (National Academies, 2018) publicly exposed the prevalence of sexual harassment in academia.

Several key allies in leadership within our field have responded by drafting updated Code of Conduct statements for conferences and providing relevant keynote speakers and training sessions, particularly at the AGU (https://ethics.agu.org/) and GEM (https://gem.epss.ucla.edu/mediawiki/index.php/Main_Page#Anti-Harassment_Policy_for_GEM_Meetings_and_Activities). This is an important step to ensuring an inclusive environment. Recognition of the achievements of all people in the field is also important, but has historically not been representative of the population of the field. Women currently make up 13% of AGU Fellows within SPA, while being 20% of the membership. Low numbers of nominations of women and other underrepresented groups perpetuates this. In the years 2015–2017, only one of 16, two of 14, and zero of 15 SPA nominations were for women in each of those years, respectively. In 2016, members of the Earth Science Women's Network (ESWN) worked to increase the nominations of women for AGU Fellow (including the one SPA nomination mentioned, which was successful). In 2018, SPA supported a Nomination Task Force (NTF) to deliberately address this problem within the section (Jaynes et al., 2019). Members of the NTF supported the submission of five nominations for AGU Fellow and one nomination for AMS Fellow for women and one nomination for an AGU medal for a member of an underrepresented group. The AMS Fellow, AGU medal, and one of the AGU Fellow nominations were successful. The NTF is continuing this work to sustain the effort.

It should also be noted that magnetospheric physics is a fundamentally international endeavor. Greenwald (2017) presents a compelling case that this field has been inherently international from its very beginnings, and details several of the big initiatives to increase global cooperation in space research. This cross-border collaboration should continue, as it is part of the diverse perspective collection that makes for better and more creative solutions to the challenges that face the community. Moldwin and Liemohn (2018) also demonstrated that papers with international co-authors had higher impact as measured by citations. It should be noted, however, that there are obstacles to international collaboration, including visa policy, travel costs, and technology transfer restrictions. The increased availability and ease of remote communication methods can overcome some of these obstacles, but others will be more difficult to address.

47.3. CLOSING COMMENTS

This is an exciting time to be carrying out magnetospheric research. We are on the edge of accurate and meaningful forecasting of space weather and these new techniques allow for revolutionary advancements in our understanding of how the magnetosphere works. Furthermore, the demographics of those working in magnetospheric research is shifting, bringing new ideas to how to answer the tough questions we face.

Where will the magnetospheric physics community be in 10, 20, or 30 years? We foresee that, at some point in the distance future, it will resemble today's atmospheric sciences research community in terms of research initiatives yet be something completely different in terms of workforce interactions. We imagine a robust and distributed array of measurements contributing to accurate multiday forecasting of the space environment. We envision having large-scale community modeling tools open for all researchers to examine output, conduct their own simulations, and make code improvements that get checked back in to the community model. We expect that there will be full-scale merging of observational and numerical approaches that allow researchers to probe not only the microphysical processes but also the system-level nonlinearities and large-scale emergent phenomena. We hope that the research community will look like the general population, that we will be fully aware of and respectful towards different perspectives and differing opinions, and that we will embrace this mixture of ideas as the path to the best solutions.

Cassak et al. (2017) and Robinson et al. (2018) note the importance of the research community in shaping the future direction of the field. The research community should be engaged in the planning and implementation of strategic documents, setting priorities for the research directions and helping make the plan into reality. The goals of the National Space Weather Strategy (OSTP, 2015a) and the Space Weather Action Plan (OSTP, 2015b) are within reach, achieving space weather prediction and forecasting on the level of terrestrial weather reporting and accuracy. The topics discussed above will have tremendous impact in helping us achieve that objective.

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