

# Laboratory Space Physics: Investigating the Physics of Space Plasmas in the Laboratory

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Laboratory experiments provide a valuable complement to explore the fundamental physics of space plasmas without the limitations inherent to spacecraft measurements. Specifically, experiments overcome the restriction that spacecraft measurements are made at only one (or a few) points in space, enable greater control of the plasma conditions and applied perturbations, can be reproducible, and are orders of magnitude less expensive than launching spacecraft. Here I highlight key open questions about the physics of space plasmas and identify the aspects of these problems that can potentially be tackled in laboratory experiments. Several past successes in laboratory space physics provide concrete examples of how complementary experiments can contribute to our understanding of physical processes at play in the solar corona, solar wind, planetary magnetospheres, and outer boundary of the heliosphere. I present developments on the horizon of laboratory space physics, identifying velocity space as a key new frontier, highlighting new and enhanced experimental facilities, and showcasing anticipated developments to produce improved diagnostics and innovative analysis methods. A strategy for future laboratory space physics investigations will be outlined, with explicit connections to specific fundamental plasma phenomena of interest.

## I. INTRODUCTION

On January 31, 1958, the United States entered the space age with the launch of *Explorer I*, the first U.S. satellite to orbit the Earth. This historic event also marked the birth of an entirely new field of science: experimental space physics. *In situ* measurements of high-energy particles by James Van Allen's Geiger counter instrument on *Explorer I* led to the first major scientific discovery of the space age—that the Earth's magnetic field traps high-energy particles in regions encircling the Earth,<sup>1</sup> now known as the Van Allen Radiation Belts.

The ability to launch spacecraft to make direct measurements of the plasma and electromagnetic fields beyond the Earth's atmosphere has stimulated tremendous progress in our understanding of the heliosphere, our home in the universe. The heliosphere is the realm of influence of the Sun, within which the planets of our solar system orbit. Heliophysics, more commonly known as space physics, is dedicated to the study of the physical mechanisms that govern the dynamics and evolution of the space environment from the Sun to outer boundary of the heliosphere, beyond which the field of astrophysics takes over.

The international space physics community tackles major open questions about the flow of matter and energy from the Sun, to the Earth and other planets, and out to the edge of the heliosphere, where the heliosphere interacts with the surrounding interstellar medium. At the heart of heliophysics are fundamental questions about how the solar magnetic dynamo draws on the energy released by fusion reactions in the Sun's core to generate

strong magnetic fields. As these magnetic fields intensify, they become buoyant, rising through the solar interior and emerging through the photosphere into the atmosphere of the sun, driving the frenzied and occasionally explosive dynamics that occur in active regions on the Sun. How magnetic reconnection governs the eruptions of coronal mass ejections into space, and how plasma physics processes determine whether such explosive activity is accompanied by a solar flare or by the acceleration of solar energetic particles, remain poorly understood at present. Another long-standing open question in heliophysics is what role plasma turbulence and magnetic reconnection play in the heating of the solar corona to more than a million Kelvin—nearly a thousand times hotter than the approximately six thousand Kelvin temperature of the solar photosphere below.

Extreme space weather is caused by these violent events on the Sun—solar flares, coronal mass ejections, and the acceleration of solar energetic particles—and can impact the technological infrastructure upon which our society depends daily, such as satellite communication and navigation, radar and radio communication, air travel, and even the electrical power grid. Predicting how coronal mass ejections and solar energetic particles propagate through the turbulent interplanetary medium is critical to our ability to predict their detrimental effect at Earth, and to unravel how the Earth's magnetosphere responds to forcing by the variable solar wind and by these sporadic outbursts from the Sun. The conditions in the near-Earth space environment, including the Van Allen Radiation Belts, react to this external forcing in complicated ways that are not well understood. Challenges at the forefront of space physics include discovering the processes responsible for the acceleration of high-energy particles trapped in the radiation belts and for the eventual loss of those confined particles. Furthermore, unrav-

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eling the complicated interactions and feedback mechanisms that couple the ionosphere and thermosphere to the magnetosphere will require an improved understanding of ion-neutral coupling and of the physics of multi-ion plasmas.

The solar wind carries the influence of the Sun beyond the orbit of the planets in our solar system, where its supersonic and super-Alfvénic flow is abruptly slowed at the collisionless termination shock. The shocked heliosheath plasma beyond this point slows further until it finally halts at the heliopause, the final boundary separating the heliosphere from the surrounding interstellar medium. Numerous new questions have arisen as we obtain new information about the interaction of the heliosphere with the interstellar medium through remote sampling by energetic neutral atoms<sup>2,3</sup> and direct measurements by *Voyager 1*.<sup>4</sup> Although distant stellar systems and galaxies almost certainly lie beyond the reach of *in situ* measurement in our lifetimes, the lessons learned about the fundamental physical mechanisms that govern the evolution of the plasmas that fill the heliosphere can be applied to better interpret remote measurements of these distant and fascinating astrophysical systems.

Being able to understand, and ultimately to predict, the evolution of the heliosphere requires not only learning how different regions of the system—such as the sun, the solar wind, the planetary magnetospheres, and the interface with the surrounding interstellar medium—interact and feedback upon each other, but also discovering how the fundamental dynamics of the heliospheric plasma mediates those interactions. In other words, it requires a “systems-science” study of the heliosphere as a coupled system of different interacting elements complemented by detailed investigations of the underlying plasma physics that governs those interactions.<sup>5</sup> The Heliosysics System Observatory (HSO) comprises the current fleet of thirty-three spacecraft<sup>6</sup> that simultaneously sample many different regions of the heliosphere, enabling the complex interplay of the different elements to be observed. Individual missions return, from each spacecraft’s location, direct measurements of the plasma and electromagnetic field fluctuations that are critical to unravel the fundamental plasma mechanisms at play in the heliosphere. In many cases, the macroscopic evolution of the heliosphere depends upon the physical processes at play in the plasma on microscopic scales. For example, the heating of the solar corona is widely believed to depend on the dissipation of plasma turbulence at small scales.

The ability to make direct measurements of the plasma dynamics using the spacecraft of the HSO, however, does not guarantee that we will understand the physical processes governing what we observe. In particular, the HSO spacecraft missions make measurements of the plasma at a single point—or, for multi-spacecraft missions, a few points—in space. But to unravel the complicated evolution of fundamental plasma mechanisms, such as magnetic reconnection, the restriction to single-point or

few-point measurements significantly limits our ability to discern the underlying plasma physics. It is here that laboratory experiments can provide an invaluable complement in the effort to understand the physics of space plasmas, motivating an approach denoted here as *laboratory space physics*.

In particular, laboratory experiments enable detailed investigations of the fundamental physical mechanisms that govern the transport of mass and energy within heliospheric environments of interest. Plasma turbulence, magnetic reconnection, particle acceleration, and kinetic instabilities are four physical processes that play key roles in the evolution of the plasmas that fill the heliosphere, constituting four grand challenge problems at the frontier of heliophysics. Terrestrial experiments enable us to measure in the laboratory what is often difficult or impossible to measure in space, facilitating our study of these mechanisms to gain much deeper insight into the fundamental plasma physics that governs the dynamics of the heliosphere.

The natural synergy between spacecraft observations and laboratory experiments has only become stronger as improved capabilities in both arenas are leading to a convergence of their regimes of applicability. In particular, the cadence of measurements by modern spacecraft instruments has finally decreased to a point that the kinetic length and time scales of the plasma can be directly probed. For example, the *Magnetospheric Multiscale (MMS)* mission<sup>7,8</sup> measures the three-dimensional proton distribution function at a sampling rate of 150 ms, shorter than the typical timescales of 1 s associated with ion cyclotron motion and with the Doppler shift of fluctuations on the kinetic scale of the ion Larmor radius. The three-dimensional electron distribution function is sampled by *MMS* at 30 ms, nearing the typical timescales of 25 ms for the Doppler-shifted electron Larmor radius.

In contrast, laboratory experiments have generally suffered from the inability to model the large scales (relative to kinetic length scales) characteristic of many physical processes at play in space plasmas. But intermediate-scale experiments now, often operated as national user facilities, can generate sufficiently large plasmas that there exists a substantial dynamic range above the typical kinetic length scales. For example, the *Large Plasma Device (LAPD)*<sup>9</sup> at UCLA produces a 17 m long, 60 cm diameter cylindrical plasma confined radially by a strong axial magnetic field around 1 kG; with an ion Larmor radius around 0.2 cm and a long-enough parallel length to contain MHD waves with frequencies below the ion cyclotron frequency, the *LAPD* enables exploration of the large-scale, MHD dynamics of magnetospheric and heliospheric plasmas. Another example is newly constructed *Facility for Laboratory Reconnection Experiments (FLARE)*, which can produce plasmas with a Lundquist number above  $10^5$  and a current sheet length relative to the ion inertial length or ion Larmor radius of around  $10^3$ , enabling studies of the plasmoid instability in the both the collisional and collisionless regimes of

magnetic reconnection.<sup>10</sup>

This convergence of the regimes accessible to spacecraft measurements and laboratory experiments is a key reason why the study of space physics in the laboratory is now particularly timely, with the potential to make a transformative contribution to the study of fundamental plasma mechanisms in the heliosphere.

Previous works by Fälthammar<sup>11</sup> in 1974 and Koepke<sup>12</sup> in 2008 have reviewed the use of laboratory experiments to investigate space plasma physics. In this review, I discuss the application of appropriately scaled laboratory experiments to study space and astrophysical phenomena and emphasize the advantages of laboratory experiments in §II. In §III, I identify key questions in space physics and astrophysics and discuss aspects of these questions that can be tackled in the laboratory, briefly reviewing previous successful laboratory investigations. Next, I outline in §IV developments on the horizon of laboratory investigations of space physics, identifying velocity space as a key new frontier, highlighting new and enhanced experimental facilities, and showcasing anticipated developments to produce improved diagnostics and innovative analysis methods. Finally, in §V, I wrap up the discussion with a perspective on why laboratory experiments are likely to play an increasingly important role in the study of space physics, with a call for the strategic alignment of experimental efforts with upcoming spacecraft missions.

## II. HOW DO YOU STUDY THE PHYSICS OF SPACE PLASMAS IN THE LABORATORY?

Laboratory experiments provide a valuable complement to the observational, theoretical, and numerical study of the physics of space plasmas because they make possible the study of fundamental plasma physics processes in a controlled and well-diagnosed environment. Here I discuss how to design experiments relevant to space or astrophysical environments of interest. I also highlight the key advantages that laboratory experiments have over measurements by spacecraft, arguing that they provide a unique complement to observational studies of space plasmas.

### A. Scaling

In the effort to explore the physics of space and astrophysical plasmas in the laboratory, an obvious question arises: how can one reconcile the enormous discrepancy in the length and time scales of astrophysical phenomena with what can be achieved in a terrestrial laboratory? The answer is that the physical equations governing the evolution of a system of interest remain invariant through a careful scaling of the length scales, time scales, and other dimensional parameters of the system. Through dimensional analysis, the physical behavior of

a given system can be found to depend on a minimal number of dimensionless parameters, as shown by Buckingham in 1914, commonly known as the Buckingham “Pi Theorem.”<sup>13</sup> This type of similarity analysis<sup>14</sup> represents a powerful approach to understand the fundamental physical behavior of a system which remains invariant upon appropriate scaling of dimensional quantities.

One of the most famous applications of similarity analysis occurred in 1950 when G. I. Taylor used declassified photos of the first atomic explosion in New Mexico to estimate accurately the yield of that atomic weapon test.<sup>15,16</sup> Similarity analysis has been applied successfully to a wide variety of physical systems, from turbulent fluids<sup>17</sup> to avalanching systems that exhibit self-organized criticality.<sup>18</sup>

In the effort to employ laboratory experiments to explore the physics of space and astrophysical plasmas, the high-energy density physics community has taken full advantage of similarity analysis to design experiments using laser-generated plasmas to explore the physics of supernova explosions and the nonlinear evolution of their remnants.<sup>19–23</sup> Specifically, a careful analysis has been carried out to identify the “Euler similarity” for compressible hydrodynamic fluids<sup>19</sup> and ideal compressible magnetohydrodynamic fluids,<sup>21</sup> with significant attention to the limits of validity of such a mathematical description<sup>19,21,22</sup> and to the constraints inherent to the laboratory environment.<sup>20</sup> A thorough review of the application of similarity analysis to produce appropriately scaled high-energy density physics laboratory experiments can be found in Remington, Drake, and Ryutov.<sup>23</sup>

In this review, I focus not on the high-energy density environments relevant to supernova explosions that can be explored using facility-class laser plasmas, typically denoted using the term *laboratory astrophysics*, but rather on scaled laboratory experiments at the lower energy densities that are typical of many heliospheric and less extreme astrophysical environments. Here I choose to refer to the experimental study of those moderate-energy density plasma environments as *laboratory space physics*, although many such studies indeed may be applicable to processes occurring beyond the limits of the heliosphere. A wide range of cutting-edge experiments in laboratory space physics can be successfully conducted at universities on small-scale to moderate-scale laboratory devices.

### B. Advantages of Laboratory Experiments

Laboratory experiments enjoy a number of significant advantages over the spacecraft exploration of the physics of space plasmas: (i) many-point measurements, (ii) reproducibility, (iii) controlled conditions, and (iv) much lower cost. On the other hand, spacecraft missions can probe the plasma dynamics without perturbing the plasma substantially, three-dimensional velocity distributions are much easier to measure in space than in the

laboratory, and it is often not possible, even with appropriately scaled experiments, to reproduce the large dynamic range of time and length scales found in space.

One of the most restrictive limitations of spacecraft measurements is that they are limited to a single point in space for the majority of missions which consist of only one spacecraft, or a few points in space for multi-spacecraft missions. Since heliospheric plasmas are often moving at a large velocity relative to the sampling spacecraft, the spacecraft obtains a time series of measurements along a trajectory slicing through the plasma being studied. For single-point measurements made in the spacecraft frame, in relative motion with respect to the plasma rest frame of reference, it is not possible to definitively separate temporal variations in the plasma frame from spatial variations that are being advected past the spacecraft at the plasma flow velocity. If the plasma flow is much faster than typical wave velocities in the plasma, as is generally the case in the solar wind, observers often adopt the Taylor hypothesis,<sup>24</sup> assuming that the temporal fluctuations in the spacecraft frame are solely due to the spatial fluctuations in the plasma frame sweeping over the spacecraft with the plasma flow.<sup>25,26</sup> But if the condition of fast plasma flow is not satisfied, such as in the solar corona or planetary magnetospheres, detailed calculations must be used to estimate when the Taylor hypothesis is violated.<sup>27–29</sup>

In contrast to the case with spacecraft, an array of diagnostic probes can relatively easily be inserted into a laboratory experiment to sample the plasma at many points simultaneously, for example in the *Magnetic Reconnection Experiment (MRX)*<sup>30</sup> for studies of magnetic reconnection or in the *Swarthmore Spheromak Experiment (SSX)* MHD wind tunnel for studies of plasma turbulence.<sup>31,32</sup> Such diagnostic access makes possible the sampling across a region of interest in the plasma, enabling a more complete characterization of the dynamics that is extremely valuable for the illumination of the underlying plasma physical processes.

A second key advantage of many laboratory investigations over spacecraft measurements is the ability to design experiments that are reproducible. At the Basic Plasma Science Facility (BAPSF) at UCLA, the *Large Plasma Device (LAPD)*<sup>9</sup> takes reproducibility to new limits, with experimental shots in the machine fired at a cadence of 1 Hz, meaning 86,400 separate experiments can be performed in a single day. In typical *LAPD* experiments, this enables a single probe (rather than a probe array, which may interfere with the plasma dynamics under investigation) to be moved throughout the plasma, making possible the measurement of the evolution of the plasma throughout the plasma volume. Furthermore, for such reproducible experiments, measurements may be made at the same location for many independent shots, allowing the signal-to-noise ratio to be improved through averaging.

Another major advantage of laboratory experiments over spacecraft measurements is the ability to exert some

measure of control over the plasma conditions and dynamics. For example, in the *Space Physics Simulation Chamber (SPSC)* at that Naval Research Laboratory and in the *Auburn Linear Experiment for Instability Studies (ALEXIS)* at Auburn University,<sup>33–35</sup> studies of the relaxation of stressed plasma boundary layers measured unstable fluctuations with a frequency that varied over five orders of magnitude as the ratio of the boundary layer width to the ion gyroradius was varied over nearly an order of magnitude.<sup>36,37</sup>

A final major advantage is that laboratory experiments can be orders of magnitude less costly than spacecraft missions. For example, expenses for five years of operation at the Basic Plasma Science Facility (BAPSF) at UCLA, a national user facility supported jointly by the National Science Foundation and the Department of Energy, total approximately \$14M. For comparison, the life-cycle cost of the twin *Van Allen Probes* spacecraft mission totals \$686M.<sup>38</sup> The cost for the launch vehicle for the *Van Allen Probes* was approximately \$135M, so just getting the instruments into space represents a major investment of research funding. The life-cycle cost of the upcoming *Parker Solar Probe* mission, the first spacecraft to visit the Sun, is \$1,553M,<sup>39</sup> more than 100 times the operating expenses of the BAPSF. Naturally, if we want to understand in detail the physics of space plasmas, then the sampling of those plasmas directly with spacecraft is an essential endeavor. But to develop a complete understanding of the plasma physics mechanisms at play in space plasmas, laboratory experiments represent a cost-effective means of complementing spacecraft missions.

It is worthwhile mentioning, however, that spacecraft observations do enjoy some specific advantages over laboratory measurements, besides the obvious fact that spacecraft are directly sampling the space plasma of interest. First, the size of the spacecraft, typically on the order of meters, is typically much smaller than the characteristic length scales in a plasma: in the near-Earth solar wind, the proton gyroradius is around 100 km, the electron gyroradius is around 1 km, and the Debye length is around 10 m. Therefore, the plasma dynamics can be sampled without perturbing the plasma substantially, although near-spacecraft effects generally need to be taken into account to calibrate measurements. Second, although the measurement of particle velocity distribution functions—a key measurement to probe the kinetic plasma physics—is rather difficult to achieve in the laboratory, spacecraft instruments have been capable of measuring three-dimensional velocity distributions for decades, although the cadence of these measurements has only recently improved to the point that kinetic timescales are accessible. Finally, even with appropriately scaled laboratory experiments, it is not always possible to reproduce the dynamic range of time and length scales occurring in the space environment. Notwithstanding these limitations in the laboratory, terrestrial experiments are likely to play an increasingly important

role in illuminating the physics of space and astrophysical plasmas.

### III. KEY QUESTIONS IN SPACE PHYSICS AND PAST SUCCESSES IN LABORATORY SPACE PHYSICS

Plasma physics governs the fundamental interactions that influence the evolution of plasmas throughout the heliosphere, from the depths of the solar interior to the far reaches of the heliosphere, where the solar wind slows and ultimately comes to a halt at the heliopause, marking the boundary between the heliosphere and the surrounding galactic interstellar medium. Appropriately scaled laboratory experiments provide a uniquely accessible platform to explore in detail the same physical processes that are believed to control the dynamics of space plasmas. Here I review these fundamental mechanisms of plasma physics and identify the space environments in which they arise, briefly highlighting existing experimental facilities where these problems can be studied and reviewing previous successful studies of the physics of space plasmas in the laboratory.

#### A. Plasma Turbulence

Turbulence arises in nearly every plasma environment throughout the heliosphere: the solar convection zone, chromosphere, transition zone, and corona; the solar wind; the planetary magnetospheres and their interaction with their underlying thermospheres and ionospheres; and the heliospheric termination shock and heliosheath. Fundamentally, turbulence influences the transport of plasma particles, momentum, and energy. Specifically, turbulence governs the interpenetration of distinct plasmas, affects the propagation of energetic particles, and mediates the conversion of the energy of large-scale plasma flows and electromagnetic fields into plasma heat or other non-thermal forms of particle energization. In many space and astrophysical environments, the micro-physics of turbulence and its dissipation at small scales can strongly influence the macroscopic evolution of the system.

In the solar convection zone, turbulent magnetoconvection is widely believed to play a key role in the magnetic dynamo that drives the solar cycle.<sup>40,41</sup> As dynamo activity enhances the magnetic field strength, strong magnetic flux tubes buoyantly rise through the solar convection zone and emerge through the solar photosphere into the sun's atmosphere, generating sunspots that often gather together in areas of intense magnetic activity called Active Regions. The granular and supergranular networks of the convecting photosphere buffet the solar magnetic fields that pass through the surface, leading to a persistently turbulent state of the solar chromosphere; high resolution imaging by *Hinode* satellite has shown that even the quiescent regions of the solar atmosphere

abound with turbulent motion.<sup>42,43</sup>

As you move up through the sun's atmosphere from the chromosphere, the narrow transition region marks a drastic increase in temperature and decrease in density from the cool, dense, partially ionized, and collisional conditions of the chromosphere to the hot, diffuse, fully ionized, and collisionless conditions of the lower solar corona. Ever since coronal emission lines were used to demonstrate in the 1940s that the temperature of the coronal plasma is more than a million Kelvin,<sup>44,45</sup> the question of how the solar corona is heated to a temperature nearly three orders of magnitude higher than the photosphere below has persisted as a major unanswered question in heliophysics. Although the detailed mechanism by which the coronal plasma is heated remains poorly understood, plasma turbulence plays a crucial role in many of the proposed mechanisms.<sup>46–51</sup>

A major problem at the forefront of heliophysics research is to determine the detailed plasma physics governing the removal of energy from turbulent fluctuations and the consequent heating of the plasma particles. Under the weakly collisional conditions relevant to most heliospheric environments, such as the solar corona, solar wind, and planetary magnetospheres, the proposed collisionless energy transfer mechanisms fall into three broad categories: (i) resonant wave-particle interactions, such as Landau damping, transit-time damping, or cyclotron damping;<sup>52–72</sup> (ii) nonresonant wave-particle interactions, primarily leading to stochastic ion heating;<sup>51,73–81</sup> and (iii) dissipation in coherent structures, such as collisionless magnetic reconnection occurring in small-scale current sheets.<sup>82–97</sup>

Which of these mechanisms dominates in a given turbulent plasma likely depends on the character of the turbulence and on the plasma parameters. For example, the strength of resonant wave-particle interactions depends on where the phase velocity of a given wave falls within the particle velocity distribution, and the location of this resonant velocity for both ions and electrons depends on the ion plasma beta,  $\beta_i = 8\pi n_i T_i / B^2$ , and the ion-to-electron temperature ratio,  $T_i / T_e$ . Thus, to understand fully the mechanisms that govern how turbulent energy is converted into energy of the plasma particles, it is important to study turbulence under a wide range of turbulent and plasma conditions: in the solar chromosphere, the plasma is partially ionized and strongly collisional, so the impact of ion-neutral collisions will have a significant impact on how the turbulent energy is dissipated; in the solar corona, the turbulent dynamics are weakly collisional and the plasma beta is low,  $\beta_i \ll 1$ ; in the solar wind near the Earth, the plasma beta increases to unity,  $\beta_i \sim 1$ ; much further out in the heliosphere, the magnetic field magnitude decreases with the radially expanding solar wind, but *in situ* heating of the plasma leads to a slower radial decline in plasma temperature, leading to high beta conditions,  $\beta_i \gg 1$ .<sup>98,99</sup> A key motivation for the upcoming *Parker Solar Probe* mission<sup>100</sup> is to explore the energization of the plasma in the un-

explored inner heliosphere within the orbit of Mercury, sampling the turbulent conditions down to low beta values,  $\beta_i \ll 1$ , so that we can discover how the solar corona is heated and how the solar wind is accelerated.

The interplanetary medium, which is dominated by the radially outward flow of the supersonic and super-Alfvénic solar wind, is always observed to be in a turbulent state. This turbulence naturally leads to a very tangled interplanetary magnetic field,<sup>101–104</sup> and this tangled magnetic field has important implications for the transport of energetic particles through the heliosphere to the Earth,<sup>105,106</sup> including solar energetic particles generated by violent activity at the Sun,<sup>107</sup> anomalous cosmic rays generated through poorly understood mechanisms in the outer reaches of our heliosphere,<sup>108,109</sup> and galactic cosmic rays.<sup>110,111</sup> For particularly extreme space weather events, the copious solar energetic particles that are often generated represent a significant hazard for robotic and human assets in space, so accurate prediction of their propagation through the turbulent solar wind toward the Earth is critical to prevent damage to spaceborne technology and harm to astronauts.

Turbulence plays a role in a number of other important physical processes that occur in various regions of the heliosphere. Turbulence arises as a response of the Earth's coupled magnetosphere-ionosphere-thermosphere (MIT) system to forcing by the variable solar wind and to major impulses during extreme space weather events. For example, ionospheric turbulence driven by the MIT system response to variations in the solar wind can drive density irregularities that scatter radio waves, causing amplitude and phase scintillations in radio signals and thereby affecting satellite communication and GPS navigation systems.<sup>112</sup> In addition, many proposed mechanisms for particle acceleration at collisionless shocks, such as diffusive shock acceleration, require turbulent fluctuations upstream of the shock to scatter particles back toward the shock.<sup>113,114</sup>

Laboratory experiments open up valuable new avenues to explore the dynamics of plasma turbulence over a wide range of turbulence and plasma parameters. In the *Large Plasma Device (LAPD)* at UCLA,<sup>9</sup> experiments have been conducted to understand the nonlinear evolution of Alfvén wave collisions<sup>115</sup>—the nonlinear interactions among counterpropagating Alfvén waves, proposed as the fundamental mechanism mediating turbulent energy transfer to small scales in early studies of MHD turbulence.<sup>116,117</sup> Asymptotic analytical solutions for the evolution of Alfvén wave collisions in the weakly nonlinear limit<sup>115</sup> have been confirmed numerically with gyrokinetic numerical simulations in the MHD regime<sup>118</sup> and verified experimentally in the laboratory,<sup>119–123</sup> establishing Alfvén wave collisions as the fundamental building block of astrophysical plasma turbulence. The success of this experimental investigation of Alfvén wave collisions has laid the foundation for subsequent advances in our theoretical understanding of how current sheets arise self-consistently in plasma turbulence,<sup>70,124</sup> the role

played by resonant wave-particle interactions in the dissipation of these current sheets,<sup>72</sup> and how collisions between localized Alfvén wavepackets in the strongly nonlinear limit mediate the turbulent cascade of energy to small scales.<sup>125,126</sup>

Observations of enhanced perpendicular ion temperatures in the solar corona<sup>127</sup> have lead to the important question of how ions are energized perpendicular to the magnetic field under low plasma beta conditions. Under similar low plasma beta and weakly collisional conditions, a broadband spectrum of anisotropic magnetic turbulence has been observed to arise during magnetic relaxation events in the *Madison Symmetric Torus (MST)* experiment;<sup>128</sup> application of a Rutherford scattering diagnostic<sup>129</sup> has shown there to be anomalous ion heating coincident with this turbulence.<sup>130</sup> Such laboratory experiments, using devices that have primarily been used to explore magnetic confinement fusion, provide an alternative path to understand the physics underlying ion heating mechanisms in the low beta, collisionless plasma turbulence relevant to the solar corona.

In the near-Earth solar wind, in the outer heliosphere, and in many astrophysical systems such as accretion disks around black holes, turbulence occurs in plasmas with plasma beta of unity or higher. Experimental facilities capable of generating plasma turbulence with beta of order unity or higher enable uniquely detailed investigations. The *Swarthmore Spheromak Experiment (SSX)* MHD plasma wind tunnel<sup>31,32</sup> is used to launch a spheromak which immediately relaxes its magnetic configuration, generating broadband plasma turbulence with  $0.1 \lesssim \beta_i \lesssim 1$ , enabling studies of intermittency<sup>131</sup> and statistical complexity<sup>132</sup> in the resulting turbulence. In the *Big Red Plasma Ball*<sup>133</sup> at the Wisconsin Plasma Astrophysics Laboratory (WiPAL),<sup>134</sup> a new national user facility for frontier plasma science, a multi-cusp magnetic field configuration using a spherical array of permanent magnets can be used to confine a turbulent plasma at high plasma beta,  $\beta_i \gg 1$ . The *Plasma Liner Experiment*<sup>135</sup> at Los Alamos National Laboratory uses coaxial plasma guns mounted to a spherical chamber to launch colliding plasma jets that can generate flow-dominated turbulence with target plasma beta conditions over the range  $0.01 \lesssim \beta_i \lesssim 10$ .

Together, these unique facilities make possible laboratory experiments that can overcome the limitations of spacecraft measurements to understand in more detail how plasma turbulence influences the evolution of the space environment.

## B. Magnetic Reconnection

Another fundamental phenomenon of plasma physics that influences the evolution of many diverse environments in space and astrophysical plasmas is magnetic reconnection, mediating the rapid release of magnetic energy through the topological rearrangement of mag-

netic field lines. Although the field lines reconnect in spatially localized places, the process often causes fundamental changes in macroscopic configurations, such as in the evolution of solar flares or in the dynamics of the Earth's magnetosphere during geomagnetic storms and substorms. Over the years, numerous reviews have thoroughly explored the implications of magnetic reconnection for heliospheric, astrophysical, and laboratory plasmas.<sup>136–141</sup> Here I highlight the different space environments in which magnetic reconnection plays a key role, with an emphasis on experimental efforts in the laboratory that are helping to illuminate the properties of this fundamental physical mechanism under various conditions.

Magnetic reconnection under the collisional plasma conditions within the solar convection zone plays an essential role in the incompletely understood dynamo mechanism<sup>40,41</sup> that generates the Sun's magnetic field and dictates the 22-year magnetic solar cycle. The magnetic flux generated by the solar dynamo emerges through the photosphere into the solar atmosphere, generating sunspots and driving intense activity that can lead to stress in the configuration of the magnetic field that pervades the solar chromosphere and solar corona, ultimately building up energy in the magnetic field. In this stressed magnetic field topology, the sudden onset of magnetic reconnection can trigger explosive activity by tapping the magnetic energy to power intense solar flares<sup>142</sup> or cause the eruption of a coronal mass ejection.<sup>143,144</sup> Unraveling the complex evolution of these poorly understood events that drive extreme space weather is a major goal of the heliophysics community. Beyond the lower solar atmosphere, the plasma conditions become collisionless, where kinetic effects rather than resistivity lead to the breaking of the magnetic field lines. A key frontier in heliophysics and astrophysics is to understand the details of collisionless magnetic reconnection.<sup>10,145–148</sup> In the solar corona, for example, the collective effect of many magnetic small magnetic reconnection events, known as nanoflares, has been suggested to be a candidate process for the heating of the coronal plasma to more than a million Kelvin.<sup>48</sup>

Near the Earth, if the interplanetary magnetic field carried by the solar wind or by a coronal mass ejection has a significant southward component, asymmetric magnetic reconnection can occur at the dayside magnetopause,<sup>149</sup> leading to a sweeping of the reconnected magnetic field toward the tail of the Earth's magnetosphere, driving magnetic substorms or geomagnetic storms, as first proposed by Dungey in the 1960s.<sup>150</sup> This dayside magnetic reconnection drives a two-cell convective pattern at the polar caps<sup>151</sup> and sweeps magnetic flux into the magnetotail. Symmetric magnetic reconnection in the magnetotail leads to a shift in the topology of the magnetospheric field which is transmitted to Earth via Alfvénic fluctuations that propagate along the magnetic field line to the polar ionosphere, triggering a magnetic substorm<sup>152</sup> and leading to the glowing of discrete

auroral arcs.<sup>153</sup> Furthermore, the ionosphere and thermosphere respond to shifts in the Earth's magnetosphere caused by magnetic reconnection, and this coupling of the magnetosphere-ionosphere-thermosphere (MIT) system represents an important aspect of how the Earth reacts to forcing by the variable solar wind and extreme space weather events.

Of course, these same collisional and collisionless magnetic reconnection processes play an important role in a wide range of plasma systems throughout the Universe.<sup>139</sup> In addition, magnetic reconnection also occurs in partially ionized plasmas, where it impacts the evolution of a number of important astrophysical systems, such as in the interstellar medium, protostellar and protoplanetary disks, and the outer envelopes of cool stars.<sup>154</sup>

The inherent geometry of the magnetic reconnection process—with spatially separated inflow, x-point, and outflow regions—presents severe a challenge to develop a full understanding of the mechanism using observations in space plasmas due to the limitation to single-point or few-point measurements that are possible with spacecraft missions. The laboratory provides an ideal complement to observational studies, enabling multi-point measurements along with some measure of control over the plasma conditions and the driving of the reconnection process. A number of experimental facilities have pursued studies of magnetic reconnection, including the *Large Plasma Device (LAPD)* at UCLA,<sup>9</sup> the *Magnetic Reconnection Experiment (MRX)* at Princeton University,<sup>30</sup> the *Swarthmore Spheromak Experiment (SSX)*,<sup>155</sup> the *Versatile Toroidal Facility*<sup>156</sup> at the Massachusetts Institute of Technology, and the recently completed *Facility for Laboratory Reconnection Experiments (FLARE)*<sup>10</sup> at Princeton University. There have also been studies of magnetic reconnection in plasmas generated by facility-class lasers,<sup>157,158</sup> but the broad range of laboratory astrophysical studies of high-energy density plasmas using these facility-class lasers—such as the *National Ignition Facility* at Lawrence Livermore National Laboratory, the *Omega* laser at the University of Rochester, and the *Vulcan* laser Rutherford Laboratory in the UK—is beyond the scope of this review.

By enabling some measure of control over plasma conditions, laboratory experiments make possible studies of how magnetic reconnection influences the plasma evolution across the broad range of space and astrophysical environments discussed above. Although recent reviews<sup>139–141</sup> provide a more thorough discussion of past successes in the laboratory, I showcase here the flexibility of laboratory experiments with the range of reconnection problems examined on *MRX*, from collisional<sup>159–161</sup> to collisionless reconnection,<sup>162,163</sup> from electron-scale<sup>164,165</sup> to ion-scale physics,<sup>166</sup> from periodic to line-tied boundary conditions,<sup>167,168</sup> from zero-guide-field to finite-guide-field reconnection,<sup>169,170</sup> from two-dimensional to three-dimensional physics,<sup>171–173</sup> from fully ionized to partially ionized plasmas,<sup>174</sup> from

symmetric<sup>175,176</sup> to asymmetric reconnection,<sup>177,178</sup> and from single X-line to multiple X-line geometries.<sup>161,173</sup>

A current frontier in the study of magnetic reconnection is to understand how the plasmoid instability arises under high Lundquist number conditions, leading to breakup of a thin current sheet with a single x-point into multiple x-points.<sup>179–184</sup> To access in the laboratory the parameter regime in which the plasmoid instability arises,<sup>10,185</sup> new experimental facilities must be developed that can achieve a larger dynamic range of plasma size relative to current sheet thickness. The recently completed *Facility for Laboratory Reconnection Experiments (FLARE)*<sup>10</sup> at Princeton has been constructed specifically to provide an experimental platform for understanding in detail how the plasmoid instability influences the microscopic dynamics and macroscopic structure of magnetic reconnection that governs the evolution of the space environments enumerated above. Another new experimental facility for magnetic reconnection operates at the Wisconsin Plasma Astrophysics Laboratory (WiPAL), where the *Terrestrial Reconnection Experiment (TREX)* is a set of coils that can be inserted into the *Big Red Ball* to drive reconnection,<sup>134</sup> with sufficient flexibility to access numerous key regimes, including the collisionless plasmoid instability,<sup>186</sup> anti-parallel reconnection, strong guide-field reconnection, and 3D reconnection.

### C. Particle Acceleration

Another poorly understood fundamental process in plasmas is how a small fraction of particles in weakly collisional plasmas can be accelerated to very high energies, seemingly defying the laws of thermodynamics. The acceleration of particles arises in many different space and astrophysical plasma environments, creating populations of energetic particles that impact regions far beyond the region of acceleration. Unknown particle acceleration mechanisms lead to a spectrum of galactic cosmic rays up to more than  $10^{20}$  eV per particle, and anomalous cosmic rays up to about 100 MeV/nucleon are believed to be accelerated in the outer regions of our heliosphere.<sup>108,109</sup> Near the sun, both impulsive and gradual solar energetic particle events<sup>107</sup> shower near-Earth space with high-energy particles that pose a threat to manned space exploration and spaceborne assets for communication and navigation by satellite. The upcoming *Interstellar Mapping and Acceleration Probe (IMAP)* mission, recommended by the National Research Council’s (NRC) 2013 Decadal Strategy for Solar and Space Physics,<sup>5</sup> is intended to make observations needed to tackle the problem of particle acceleration throughout the heliosphere.

Within the Earth’s magnetosphere, protons and electrons trapped in Earth’s dipolar magnetic field can be accelerated to high energies, populating the Earth’s Van Allen radiation belts. Particle acceleration also plays a part in the coupling of the magnetosphere-ionosphere

(MI) system,<sup>187</sup> where shifts in the magnetic field in the distant magnetotail—due to magnetic reconnection driven by substorms or geomagnetic storms—are transmitted down towards the Earth by propagating Alfvén waves. Under the very low plasma  $\beta$  conditions of the polar magnetosphere, these downward traveling Alfvén waves are believed to accelerate electrons which precipitate into the ionosphere and cause the glowing of discrete auroral arcs.<sup>153,188–191</sup> Finally, turbulent electromagnetic fluctuations driven in the inner magnetosphere by geomagnetic storms have been proposed to accelerate ionospheric ions and drive ion outflows.<sup>192–194</sup>

In these various space environments, acceleration is believed to be caused either by the interaction of particles with collisionless shocks, as a consequence of collisionless magnetic reconnection, or via resonant wave-particle interactions. Common shock acceleration mechanisms include shock surfing acceleration (SSA),<sup>195–197</sup> shock drift acceleration (SDA),<sup>198,199</sup> diffusive shock acceleration (DSA),<sup>113,114</sup> and the single-bounce “fast Fermi” mechanism.<sup>200,201</sup> Magnetic reconnection has also been proposed as an effective acceleration mechanism for ions<sup>202</sup> and electrons<sup>203–206</sup> and for the generation of anomalous cosmic rays.<sup>207</sup> Resonant wave-particle interactions can also lead to the acceleration of a small number of particles if the resonant velocity occurs in the tail of the velocity distribution, thus enabling a small fraction of the total distribution of particles to gain significant energy, as is believed to occur in the case of auroral electron acceleration.<sup>153,190</sup>

The observational study of particle acceleration in space is hampered by the frequent case that we measure the accelerated particles away from the region of acceleration, such as the cases of impulsive solar energetic particles associated with solar flares<sup>107,142,208,209</sup> and anomalous cosmic rays accelerated in the outer heliosphere.<sup>108,109</sup> Although reproducing in the laboratory the highly energetic conditions of acceleration regions in space is a major challenge, the ability to control the location and properties of shock interactions and magnetic reconnection in experiments provides exciting new possibilities for illuminating the fundamental plasma physics of particle acceleration.

The capability to collide multiple plasma jets to generate shocks in the *Plasma Liner Experiment*<sup>135,210</sup> at Los Alamos National Laboratory makes possible a new path to study the fundamental particle energization and acceleration processes that occur in space plasmas, with ongoing work pushing from the collisional<sup>211,212</sup> to the collisionless regime.<sup>213</sup> Laboratory experiments may also provide a new avenue for exploring the acceleration of particles due to magnetic reconnection, for example recent measurements of the generation of an anisotropic non-thermal tail in the electron velocity distribution during magnetic reconnection events occurring in the *Madison Symmetric Torus (MST)* experiment at the University of Wisconsin.<sup>214</sup> Furthermore, expanding plasmas generated by moderate-power lasers in a pre-existing plasma

environment make possible the investigation of magnetized shocks, and recent work in the *Large Plasma Device (LAPD)*<sup>9</sup> at UCLA has made possible the first experimental creation in the laboratory of sub-critical<sup>215</sup> and super-critical<sup>216</sup> perpendicular shocks, as well as the first observation of collisionless Larmor coupling.<sup>217</sup> Future experiments will be able to explore also the formation of quasi-parallel shocks,<sup>218</sup> and possibly the physics of diffusive particle acceleration and injection.<sup>219</sup>

The *LAPD* has also been used to explore two proposed mechanisms for the downward acceleration of the magnetospheric electrons that precipitate into the ionosphere and lead to the glowing of discrete auroral arcs.<sup>220</sup> Long-lived discrete auroral arcs have been proposed to be caused by stationary inertial Alfvén waves on the Earth's magnetic field,<sup>221,222</sup> and recent *LAPD* experiments have successfully generated a stationary inertial Alfvén wave in the laboratory frame.<sup>223</sup> An alternative idea is that propagating inertial Alfvén waves, generated along the plasma sheet boundary layer by magnetotail reconnection, propagate downward along the Earth's magnetic field toward the high-latitude ionosphere and accelerate auroral electrons along their way.<sup>153,188–191</sup> To test this hypothesis, recent experiments on the *LAPD* have launched inertial Alfvén waves down the 16 m cylindrical plasma column and measured the resulting perturbations of the parallel electron velocity distribution function using a novel whistler wave absorption diagnostic.<sup>224</sup> These auroral electron acceleration experiments have found good agreement with the predicted linear perturbation of the parallel electron distribution function,<sup>225–227</sup> establishing the critical foundation for future experiments to directly measure the acceleration of the electrons by inertial Alfvén waves. With enhanced capabilities, laboratory experiments are likely to contribute increasingly to our understanding of the mechanisms for particle acceleration in space and astrophysical plasmas.

#### D. Collisional and Collisionless Shocks

In addition to their role in particle acceleration, collisionless shocks in space plasmas establish the macroscopic boundaries separating distinct regions of the heliosphere, decelerating super-magnetosonic flows while heating and compressing the downstream plasma.<sup>228</sup> Such important heliospheric boundaries include planetary bowshocks,<sup>229</sup> shocks associated with solar flares and coronal mass ejections,<sup>230</sup> and the heliospheric termination shock that abruptly slows the outward flow of the solar wind.<sup>231</sup> In these rarefied environments, the Coulomb collisional mean free paths exceed the observed interaction length scales by many orders of magnitude, signifying that the shocked plasma exchanges momentum and energy with the ambient plasma via collisionless, collective, electromagnetic effects.

Achieving astrophysically relevant collisionless shocks in the laboratory is extremely challenging, but it can be

achieved using scaled experiments, as shown in a detailed analysis by Drake.<sup>20</sup> Unlike in space shocks, important dimensionless parameters in laboratory experiments are of order unity and only marginally satisfy the shock formation criteria.<sup>232</sup> But laboratory experiments enable a detailed study of the poorly understood physics of the collisionless coupling between the shocked and ambient plasma that mediates the acceleration and heating of the upstream plasma, including micro-instabilities and ion reflection.

In addition to the studies of shocks in high-energy density plasmas relevant to extreme astrophysical environments that are generated by facility-class lasers or imploding theta-pinch or Z-pinch experiments, a number of facilities are tackling shock conditions relevant to the lower-energy-density environment of the heliosphere. The *Plasma Liner Experiment*<sup>135,210</sup> at Los Alamos National Laboratory uses colliding supersonic plasma jets, providing a unique experimental platform to explore key issues in space plasma shock physics, including the identification of the two-scale structure and ambipolar electric fields predicted by two-fluid plasma theory<sup>233</sup> as well as the subtle effects of interspecies ion separation arising in plasmas consisting of multiple ion species.<sup>234,235</sup> In the strongly magnetized plasma of the *LAPD*,<sup>9</sup> magnetized plasma shocks relevant to the heliosphere can be studied by generating expanding laser-produced plasmas in the pre-existing plasma environment. Successful experiments have studied perpendicular shocks, where the magnetic field is perpendicular to the shock normal, observing both sub-critical<sup>215</sup> and super-critical cases,<sup>216</sup> and future experiments will tackle fundamental questions about the formation of quasi-parallel shocks.<sup>218</sup>

#### E. Kinetic and Fluid Instabilities

Kinetic and fluid instabilities arise in a wide variety of space and astrophysical plasma environments, regulating the thermodynamic state of the plasma by limiting temperature anisotropies, differential drift among species, and heat flux; governing eruptive behavior driven by magnetic buoyancy that drives the solar dynamo and triggers extreme space weather events; impacting the relaxation of stressed boundary layers; and controlling the linear and nonlinear response of space plasmas to applied perturbations.

Temperature anisotropy instabilities are a critical class of kinetic instabilities that both regulate the thermodynamic state of space plasmas and lead to the generation of unstable fluctuations that can significantly impact the evolution of different space environments. For a plasma with a bi-Maxwellian proton distribution, there exist four potential proton temperature anisotropy instabilities: the parallel (or whistler) firehose instability,<sup>236,237</sup> the Alfvén (or oblique) firehose instability,<sup>238</sup> the mirror instability,<sup>53,239–242</sup> and the proton cyclotron instability.<sup>236,237,243,244</sup> Spacecraft mea-

surements in the near-Earth solar wind demonstrate that the observed proton temperature anisotropy  $T_{\perp p}/T_{\parallel p}$  is constrained, as a function of the parallel proton beta  $\beta_{\parallel p}$ , by the marginal stability boundaries of kinetic proton temperature anisotropy instabilities,<sup>245–249</sup> and these instabilities are likely to affect the dynamics and dissipation of turbulent fluctuations in space plasmas.<sup>250–252</sup> For example, for sufficiently large plasma  $\beta$ , the anisotropic velocity distributions self-consistently generated by Alfvén waves of sufficiently large amplitude can trigger the parallel firehose instability, effectively eliminating the magnetic tension that serves as the restoring force for the wave, thereby interrupting the Alfvén wave dynamics.<sup>253–255</sup>

Experimental validation of the instability predictions for  $\beta_{\parallel p} > 1$  plasmas is an area of active research. At West Virginia University, laboratory studies of instability growth and the limits of ion temperature anisotropy in  $\beta_i \sim 1$ , space-relevant plasmas were conducted in the *Large Experiment on Instabilities and Anisotropies (LEIA)* facility. Those experiments demonstrated an upper bound on the ion temperature anisotropy  $T_{\perp i}/T_{\parallel i}$  that scales inversely with the parallel ion beta in low collisionality plasmas.<sup>256,257</sup> Additional measurements provided direct evidence of enhanced electromagnetic, ion-cyclotron-like, fluctuations for the same plasma conditions.<sup>256,257</sup> Current experiments in the *Large Plasma Device* at UCLA aim to measure the parallel firehose instability by generating a plasma with  $T_{\perp i}/T_{\parallel i} < 1$  and  $\beta_{\parallel i} \sim 1$ .

Of course, more general non-Maxwellian velocity distributions, such as loss-cone or ring distributions, can also lead to instabilities that generate electromagnetic fluctuations. In the Earth's magnetosphere and Van Allen radiation belts, the acceleration and loss of energetic particles trapped in the Earth's dipolar magnetic field<sup>258,259</sup> is affected by different instability-driven waves: whistler-mode chorus,<sup>260–262</sup> electromagnetic ion cyclotron (EMIC) waves,<sup>263–267</sup> extremely low frequency (ELF) magnetosonic equatorial noise,<sup>268–271</sup> and plasmaspheric hiss.<sup>272–279</sup> Laboratory investigations are a unique tool that can be used to improve our understanding of the instabilities that drive these different waves and their effect on the particles trapped in the magnetosphere.

At altitudes below 2,000 km in the auroral ionosphere, laboratory experiments have played a critical role in understanding a velocity-shear driven instability,<sup>280</sup> the Inhomogeneous Energy Density Driven Instability (IEDDI),<sup>281–283</sup> that leads to intense ion heating that drives the observed outflow of heavy oxygen ions to higher altitude.<sup>284</sup> Experiments in the *Q machine* at West Virginia University and in the *Space Plasma Simulation Chamber* at the Naval Research Laboratory (NRL) showed the generation of unstable modes,<sup>285,286</sup> and later experiments confirmed the broadband electrostatic emissions<sup>287</sup> and ion heating<sup>288</sup> as well as electromagnetic emission<sup>289</sup> of the IEDDI. This experimental pro-

gram verified key aspects of a comprehensive ionospheric heating model,<sup>290</sup> inspiring numerous sounding rocket missions to look for corroborating signatures in the ionosphere.<sup>291–294</sup>

Laboratory experiments have also made valuable contributions to our understanding of the Electron-Ion Hybrid Instability<sup>295–297</sup> that arises in the relaxation of stressed boundary layers in the Earth's magnetotail between the high-pressure plasma sheet and low-pressure lobe.<sup>298,299</sup> A clever means was devised to establish a scaled laboratory experiment of the plasma sheet-lobe boundary<sup>300</sup> in the *Space Physics Simulation Chamber* at the NRL, demonstrating the unstable generation of waves with similar properties to those observed in space. Subsequent experiments using the *Auburn Linear Experiment for Instability Studies (ALEXIS)*<sup>35</sup> at Auburn University characterized these broadband electrostatic emissions over five orders of magnitude in frequency,<sup>36,37</sup> providing an experimental confirmation of theoretical predictions.<sup>290</sup> Subsequent experiments at NRL have also measured electromagnetic emissions from a similar stressed boundary layer experiment,<sup>289,301</sup> but at a much smaller energy density than the electrostatic emission.

Parametric instabilities have long been suggested as a potential nonlinear mechanism underlying the turbulent transfer of energy from large-scale, large-amplitude unidirectional Alfvén waves into a turbulent cascade.<sup>302,303</sup> Recent experimental work in the *Large Plasma Device* at UCLA has focused on exploring the physics of parametric instabilities. Initial experiments demonstrated the resonant excitation of acoustic modes by large-amplitude Alfvén waves,<sup>304,305</sup> followed by the successful measurement of an Alfvén wave parametric instability in the laboratory.<sup>306</sup>

Finally, a number of other important instabilities in space and astrophysical plasmas are susceptible to investigation in the laboratory, including the magnetic buoyancy instabilities<sup>307</sup> that play a key role in the solar dynamo and drive space weather eruptions, the gradient drift coupling (GDC) instability that can potentially enhance magnetic reconnection in astrophysical plasmas,<sup>308,309</sup> and current-driven instabilities of coronal arches.<sup>310</sup> In summary, a host of kinetic and fluid instabilities are believed to significantly influence the evolution of space and astrophysical plasmas, and carefully devised laboratory experiments can be used to explore the physics of these instabilities in great detail and confirm their effect on the evolution of these plasmas.

## F. Self-Organization

An important fundamental process that occurs in heliospheric plasmas is the self-organization of turbulent motions to generate ordered magnetic fields through a dynamo mechanism, the details of which remain incompletely understood. Such turbulent magnetic dynamos dominate the evolution of the heliosphere, generating the

strong solar magnetic fields<sup>40,41</sup> that drive explosive dynamics on the Sun's surface and are eventually swept out with the supersonic solar wind to form the heliosphere. Furthermore, turbulent dynamos also operate in the liquid metal cores of the Earth<sup>40,311,312</sup> and other planets that generate their own protective magnetospheres.

To understand better the nature of magnetic dynamos, many laboratories around the world have performed magnetic dynamo experiments using liquid sodium, including constrained flows<sup>313,314</sup> and unconstrained turbulent flows.<sup>315–319</sup> More recently, a plasma dynamo experiment<sup>133</sup> has been designed in the *Big Red Ball* at the University of Wisconsin, employing a cusp magnetic field confinement scheme to make possible the investigation of the dynamo mechanism under high- $\beta$  (*i.e.*, weak magnetic field) conditions within the interior of the plasma.<sup>320</sup> Magnetic field generation by the Weibel instability<sup>321</sup> driven by interpenetrating plasma flows at collisionless shocks has also been studied successfully in facility-class laser plasmas.<sup>322</sup>

Another example of self-organization in space plasmas is the relaxation of a magnetized, low- $\beta$  plasma toward a minimum-energy state under the constraint of constant magnetic helicity, occurring due to the faster decay of magnetic energy compared to the decay of magnetic helicity in low- $\beta$ , MHD-unstable plasmas.<sup>323</sup> In the *Caltech Spheromak Experiment*, experiments using a simple, planar magnetized coaxial plasma gun<sup>324,325</sup> have revealed vivid details of the 3D, dynamical processes involved in magnetic relaxation, including the formation and collimation of a plasma jet, kink instability of the jet, and subsequent poloidal flux amplification associated with spheromak formation and evolution toward a minimum energy state.<sup>310,326</sup> The relationship of these experiments to jet formation and morphology in astrophysical environments has also been described in detail.<sup>327</sup> Such magnetic relaxation of a spheromak plasma injected into a larger plasma volume also generates vigorous plasma turbulence, an approach exploited in the *Swarthmore Spheromak Experiment (SSX)* wind tunnel to study MHD turbulence.<sup>31,32,131,132</sup>

Magnetic self-organization also underlies the development of collimated astrophysical jets, where laboratory experiments have been used to generate and explore the evolution of magnetized plasma jets both at Caltech<sup>310,326</sup> and at the University of Washington.<sup>328</sup> Laser plasmas at the *ELFIE* laser facility at Ecole Polytechnique in France have also been used to produce scaled experiments of a collimated plasma outflow relevant to the physics of young stellar objects.<sup>329–331</sup>

## G. Physics of Multi-Ion and Dusty Plasmas

Due to the inherent complexity of plasma physics, many studies of space and astrophysical plasmas treat the idealized case of a fully ionized, proton-electron plasma, ignoring the presence of neutrals, additional ion species,

or charged microparticles (dust). But the effects of these other species cannot always be treated as a higher order correction, and for some space and astrophysical environments the effects of neutrals, heavier ions, or dust fundamentally alters the macroscopic evolution. Early studies recognized the potentially important role played by charged dust in star formation,<sup>332</sup> the formation of planetary rings,<sup>333,334</sup> and other processes throughout the solar system.<sup>335</sup> In the ionosphere, ion-neutral interactions and the presence of a significant density of minority ions, such as oxygen, influence how the ionosphere responds to various impulses from the magnetosphere.<sup>336–338</sup>

The study of strongly coupled, dusty (complex) plasmas has emerged as a unique discipline within the larger community of the basic plasma physics. Beyond the fundamental investigation of strongly coupled plasma physics, applications to the dynamics of the solar system<sup>335,339</sup> and more distant astrophysical environments,<sup>340</sup> for example the study of waves and instabilities in dusty plasmas,<sup>341</sup> have defined a new frontier of space plasma physics. In addition to a number of small-scale laboratory experiments for the study of dusty plasmas at different universities, experimental facilities included experiments onboard the Mir space station<sup>342</sup> and the international space station<sup>343–345</sup> to explore the dynamics under microgravity conditions. Currently, the *Magnetized Dusty Plasma Experiment (MPDX)*<sup>346</sup> is a user facility at Auburn University devised to explore how the presence of a magnetic field alters the physics of a dusty plasma, applicable to many space and astrophysical environments. The *Caltech Water-Ice Dusty Plasma Experiment*<sup>347</sup> is dedicated to understanding the accretion and grain growth of ice crystals in a cold, magnetized dusty plasma environment relevant to protoplanetary disks and molecular clouds.<sup>348</sup>

In contrast to the wide range of laboratory experiments dedicated to the study of the physics of dusty plasmas, there have yet been relatively few experimental studies of the physics of multi-ion plasmas. But the partially ionized, multi-ion nature of plasmas in the Earth's ionosphere and magnetosphere significantly influences the topside current instabilities<sup>349</sup> that play a role in the dynamics of the magnetosphere-ionosphere coupling, the resonant acceleration and scattering of particles in the radiation belts,<sup>260,350–352</sup> the stability of ion-ring distributions in multi-ion plasmas,<sup>353</sup> the acceleration and heating of particles in the solar wind<sup>354,355</sup> including when ions are differentially streaming,<sup>356,357</sup> the physics of Alfvén waves in the multi-ion plasma of the chromosphere and lower solar corona,<sup>358</sup> and the impulsive acceleration of different ions in solar flares.<sup>359</sup>

Improving our understanding of the physics of multi-ion plasmas and ion-neutral coupling will take on an enhanced strategic importance with plans for NASA to launch a number of missions in the near future that will focus on probing magnetosphere-ionosphere-thermosphere (MIT) coupling. The *Global-Scale Observations of the Limb and Disk (GOLD)* mission<sup>360</sup>

was launched in January 2018 and the *Ionospheric Connection Explorer (ICON)* mission<sup>361</sup> is due for launch later in 2018. In addition, the National Research Council's (NRC) 2013 Decadal Strategy for Solar and Space Physics<sup>5</sup> proposes three upcoming missions: the *Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)* mission, the *Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)* mission, and the *Geospace Dynamics Coupling (GDC)* mission. Targeted laboratory experiments to elucidate the physics of multi-ion plasmas and ion-neutral coupling have the potential to complement these scientific missions, making a valuable contribution to our knowledge of MIT coupling.

## H. Astrophysical Connections

The physical mechanisms governing the evolution of the heliosphere are broadly expected to apply also to more distant astrophysical environments that are, for the foreseeable future, beyond the reach of measurement by *in situ* instrumentation. But the universe also harbors more extreme astrophysical environments without analogue in the heliosphere, with many open scientific questions about the physical processes governing the evolution of those systems. Appropriately scaled laboratory experiments can provide unique opportunities for detailed examination of the physics of these astrophysical plasmas.

A key question in supernova physics is the strong-shock-driven instabilities that generate turbulence and the impact of those effects on the supernova blast wave and the resulting supernova remnant.<sup>362</sup> Appropriately scaled laboratory experiments<sup>19–23</sup> using intense facility-class lasers provide unique opportunities to study the nonlinear evolution of instabilities, such as the Weibel instability,<sup>321</sup> that arise in these extreme environments.<sup>322</sup> Laser plasmas can also be used to create the hot, dense conditions of stellar interiors to enable improved measurements of iron opacity<sup>363</sup> that are needed to refine models of stellar structure.<sup>364</sup>

Exploring the interaction between plasma flows and magnetic fields remains a fundamental plasma physics problem necessary to understand the formation and stability of astrophysical jets.<sup>365–369</sup> Laser plasma experiments have been used to investigate the physics of radiative jets<sup>370</sup> and protostellar jets.<sup>331</sup> Some aspects of MHD models of the formation and collimation of astrophysical jets<sup>365–369</sup> can be tested in laboratory experiments,<sup>327</sup> where experiments at Caltech have generated a collimated plasma jet and observed its unstable evolution due to the kink instability.<sup>324,325</sup> At the University of Washington, the *MoCHI* device has been recently constructed with the aim to produce long, collimated, stable, magnetized plasma jets by mimicking an accretion disk threaded by a poloidal magnetic field with concentric planar electrodes in front of a solenoidal coil.<sup>328</sup>

The physics of astrophysical accretion disks<sup>371–374</sup> represents a major topic at the frontier of astrophysics, particularly the attempt to understand the generation of turbulence and its impact on the rate of accretion under the weakly collisional conditions typical of accretion disks around compact objects, such black holes and neutron stars. The magnetorotational instability<sup>375–377</sup> explains how MHD turbulence arises in a weakly magnetized disk with a Keplerian rotation profile, and numerous efforts are underway to understand the physics of the magnetorotational instability under the weakly collisional conditions of hot accretion disks<sup>63,378–387</sup> as well as under the poorly ionized conditions relevant to protoplanetary disks.<sup>388</sup> In particular, the shearing due to the differential rotation in the accretion disk can drive firehose and mirror instabilities in the collisionless plasma, significantly impacting the turbulence and thermodynamic evolution of the disk.<sup>389–392</sup> The ability to study the plasma turbulence under high plasma  $\beta_i$  conditions experimentally, possible in the *Big Red Ball*<sup>134</sup> at the University of Wisconsin, may provide new opportunities to illuminate the physics of turbulent astrophysical plasmas.

Furthermore, exploring the physics of kinetic temperature anisotropy instabilities, such as the firehose and mirror instabilities (see §III E), in the laboratory may contribute to a better understanding of how these instabilities affect the turbulent dynamics in astrophysical systems. For example, carefully devised laboratory experiments may be able to probe how Alfvén waves can be interrupted by these instabilities under sufficient high  $\beta_i$  plasma conditions.<sup>253–255</sup>

Another major topic at the frontier of astrophysical research is the plasma physics of the intracluster medium in galaxy clusters, including the generation of magnetic fields by a turbulent dynamo in the weakly collisional intracluster plasma<sup>393–398</sup> and the thermodynamics of cooling flows in galaxy clusters.<sup>399–401</sup> In particular, the dynamics and instabilities associated with thermal conduction in the turbulent intracluster medium<sup>402–405</sup> remains an active area of research, with a focus on recently discovered instabilities in the collisionless intracluster plasma, such as the magnetothermal instability<sup>406–408</sup> and the heat flux buoyancy instability.<sup>395,409</sup> Laboratory experiments in the *Large Plasma Device* are being designed to explore electron heat conduction through a series of magnetic mirrors, connecting to the frontier issue of thermal conduction in a mirror-unstable plasma.<sup>405</sup>

## IV. WHAT'S ON THE HORIZON FOR LABORATORY SPACE PHYSICS?

The value of complementary efforts between plasma physics experiments in the laboratory and satellite measurements in space is dramatically increasing as the accessible length and time scales of spacecraft observations and laboratory measurements are converging. In the past, limitations on the size of the vacuum chambers

and the magnitude of magnetic fields and other applied perturbations limited the experimental investigation of space-relevant plasma phenomena to length scales at or below the typical ion kinetic length scales. Similarly, the cadence of plasma and field measurements by older spacecraft missions limited the accessible length scales—when using Taylor hypothesis to use the plasma flow relative to the spacecraft to convert from the temporal sampling cadence to a spatial resolution<sup>24</sup>—to scales typically in the MHD regime, much larger than the ion kinetic length scales. Improved experimental facilities and modern spacecraft instrumentation have closed this gap, enabling the two complementary approaches to tackle the same plasma phenomena in an overlapping regime of applicability, exponentiating the impact of the synergy between laboratory investigations and spacecraft missions on our understanding of the physics of space and astrophysical plasmas.

In this section, I stress specific ways in which laboratory experiments can make unique contributions to potentially transformative progress in our knowledge of space plasmas. A valuable new frontier for developing an improved understanding of space plasmas using laboratory experiments is to exploit fully the vast store of information about the plasma dynamics stored within the fluctuations of the particle velocity distributions. New experimental facilities, improved diagnostic capabilities, and novel analysis methods will open new avenues of investigation and revitalize established approaches, with the promise to revolutionize our understanding of the physics of space plasmas, which can be sampled directly by spacecraft missions, and of astrophysical plasmas, which are presently beyond the reach of *in situ* probes.

### A. Velocity Space: A New Frontier

Although spacecraft missions have been able to measure three-dimensional particle velocity distributions since the 1970s (*e.g.*, the *Helios* missions provided unique measurements of 3D proton velocity distributions at 90 s cadence<sup>410–413</sup>), only with modern instrumentation are spacecraft now able to sample the fluctuations of the plasma particle velocity distributions at the kinetic time and length scales of the plasma dynamics. For example, the *Magnetospheric MultiScale* mission (*MMS*) provides 3D velocity distributions for protons at a cadence of 150 ms and for electrons at a cadence of 30 ms.<sup>8</sup> By comparison, in the solar wind, the period (Doppler-shifted by the solar wind flow relative to the spacecraft<sup>24</sup>) of fluctuations with typical ion kinetic length scales is approximately 0.4 s and with typical electron kinetic length scales is approximately 50 ms. Since the collisionless mechanisms of energy transfer between the electromagnetic fields and the particles dominantly operate on the corresponding particle kinetic length scales, only now with such recent improvements in instrumental capabilities is it possible to explore properly these important

dynamical processes in space plasmas.

Fundamentally, collisionless interactions among the electromagnetic fields and the individual plasma particles generate characteristic signatures in the particle velocity distributions,<sup>414</sup> although novel means of interpreting these velocity-space signatures are in their relative infancy. Nonetheless, the fluctuations of the particle velocity distributions provide a largely untapped potential source for discovery science in space physics. In the effort to diagnose and interpret the velocity-space dynamics of space plasmas, laboratory experiments provide an invaluable complement to spacecraft missions. Although three-dimensional velocity distributions are extremely challenging to measure in the laboratory (see §IV C for more detail), the combination of multi-point diagnostic access and reproducibility in experiments makes the conjunction of laboratory and spacecraft investigations a powerful tool for illuminating the fundamental physics governing space plasmas, in particular the kinetic plasma physics of turbulence, magnetic reconnection, particle acceleration, and kinetic instabilities. Improvements in experimental diagnostics (which, in some cases, may contribute to refinements of spacecraft instrumentation) and analysis methods will enable heliophysicists and astrophysicists to exploit fully the velocity-space dynamics to understand the plasma physics that governs the evolution of space and astrophysical environments.

### B. New and Enhanced Experimental Capabilities

The potential for discovery science using laboratory experiments is directly related to the accessibility of ground-breaking experimental facilities. The immediate future for space physics in the laboratory looks especially promising at present with number of new and enhanced experimental facilities that are available across the plasma physics community.

National user facilities for laboratory investigations provide a frontline for the collaborative investigation of fundamental space physics phenomena. The *Basic Plasma Science Facility (BAPSF)* at UCLA is an established national user facility for the experimental investigation of space plasma physics and fundamental plasma physics. Funded over its lifetime by multiple federal agencies, including the National Science Foundation, Department of Energy, and Office of Naval Research, this facility boasts as its primary experimental platform the unique *Large Plasma Device (LAPD)*,<sup>9</sup> a long cylindrical plasma chamber capable of generating a plasma of length 17 m and diameter 60 cm, with sufficient flexibility in axial magnetic field, plasma temperature, and density to access plasma betas over the range  $10^{-5} \lesssim \beta \lesssim 0.1$ . The shot repetition rate is 1 Hz, enabling up to 86,400 shots per day. The flexibility of the *LAPD* plasma has enabled a broad range of experiments, from Alfvénic space plasma turbulence to magnetized collisionless shocks to the interaction of energetic particles with plasma waves

to magnetic reconnection between flux ropes.

In 2017, the *Wisconsin Plasma Astrophysics Laboratory (WiPAL)*<sup>134</sup> was named a new national user facility, boasting the combined experimental capabilities of the *Madison Symmetric Torus (MST)*, the *Big Red Ball (BRB)*,<sup>133</sup> and the *Terrestrial Magnetic Reconnection Experiment (TREX)*. The *MST* device is reverse field pinch that can confine plasmas with  $0.03 \lesssim \beta \lesssim 0.15$  and, in addition to the numerous magnetic confinement fusion studies it has hosted, has also provided a unique platform for the investigation of anomalous ion<sup>128</sup> and electron<sup>214</sup> heating in broadband plasma turbulence. The *BRB* is a spherical, multi-cusp magnetic field confinement device that can be used to confine a turbulent plasma at high plasma beta,  $\beta \gg 1$ . By adjusting external magnetic field coils, it can access plasma beta over the range  $10^{-3} \lesssim \beta \lesssim \infty$ . *TREX* is a set of magnetic field control coils that can be inserted into the *BRB* to enable studies of magnetic reconnection under a wide variety of background plasma conditions, with an effective plasma beta range of  $10^{-4} \lesssim \beta \lesssim 4$ . Together, *MST*, *BRB*, and *TREX* provide a wide range of experimental platforms for the exploration of space and astrophysical plasma phenomena available to the national research community.

In 2014, the *Magnetized Dusty Plasma Experiment (MPDX)*<sup>346</sup> at Auburn University began operating as a user facility for the study of the physics of dusty, or complex, plasmas in the magnetized environment that is applicable to many space plasmas. Completed experiments have explored the physics particle motion<sup>415</sup> and ordering in different dimensionality<sup>416</sup> as well as the effect of the magnetic field on phase transitions in a dusty plasma.<sup>417</sup>

The recently constructed *Facility for Laboratory Reconnection Experiments (FLARE)* at Princeton University is intended to be a user facility open to worldwide users from multiple communities, with a focus on exploring new reconnection phases modified by the plasmoid instability.<sup>179–181</sup> Experimental studies of the plasmoid instability necessarily require a larger dynamic range of accessible Lundquist number and normalized plasma size.<sup>10</sup> The physics of the plasmoid instability may provide the much needed multi-scale solution to couple global MHD scales to local kinetic scales.<sup>10,185</sup>

In addition to these user-class experimental facilities, the collective capabilities of numerous moderate-scale experimental platforms at national laboratories and universities around the country provide a powerful complement to spacecraft missions to discover the fundamental plasma physics mechanisms that govern the evolution of space and astrophysical plasmas. The *Space Physics Simulation Chamber* at the Naval Research Laboratory is a laboratory device dedicated to the investigation of near-Earth space plasma phenomena, under scaled ionospheric and magnetospheric conditions. The large plasma size of approximately 150 ion gyro-radii across the plasma column enables a range of experimental studies, from exploring the plasma response

to strongly sheared flow<sup>287,418,419</sup> to understanding the triggering of the Electron-Ion Hybrid Instability<sup>295–297</sup> in stressed boundary layers,<sup>300</sup> such as that found in the plasma sheet boundary layer in the Earth's magnetotail. The physics of the relaxation of stressed boundary layers was further explored using the *Auburn Linear Experiment for Instability Studies (ALEXIS)*<sup>35</sup> at Auburn University, where varying the width of the boundary layer to the ion gyroradius lead to the generation of unstable electrostatic fluctuations which varied over five orders of magnitude in frequency.<sup>36,37</sup>

At Los Alamos National Laboratory, collisional plasma shocks are generated in the *Plasma Liner Experiment* using colliding plasma jets driven by pulsed-power-driven plasma guns,<sup>135,210</sup> with future experiments aiming to form collisionless shocks. At Swarthmore College, the *Swarthmore Spheromak Experiment (SSX)* MHD plasma wind tunnel<sup>31,32</sup> launches a spheromak which immediately relaxes to a lower energy magnetic configuration, enabling studies of magnetic reconnection<sup>155</sup> and plasma turbulence in the ion plasma beta parameter range  $0.1 \lesssim \beta_i \lesssim 1$ .<sup>131,132</sup> At Bryn Mawr College, the *Bryn Mawr Magnetohydrodynamic Experiment (BMX)* is a larger scale version of the *SSX* wind tunnel that is currently under construction, with the aim to produce a continuous injection of plasma and to allow extensive diagnostic access to the turbulent flowing plasma. In the *Caltech Spheromak Experiment*, experimental campaigns are conducted to explore the physics of magnetic relaxation<sup>323–325</sup> and magnetic self-organization related to solar coronal arches and astrophysical jets.<sup>310,326,420</sup> At West Virginia University, an experimental platform combining the *Hot Helicon Experiment* and the *Large Experiment on Instabilities and Anisotropies (HELIX-LEIA)* together enables studies of ion temperature anisotropy instabilities in space plasmas,<sup>250</sup> in particular the mirror instability<sup>53,239</sup> and the ion cyclotron instability<sup>236,243,244</sup> that both occur for ion temperature anisotropies  $T_{\perp i}/T_{\parallel i} > 1$ . For  $\beta_i \sim 1$  conditions relevant to the near-Earth solar wind, *HELIX-LEIA* experiments have demonstrated the theoretically predicted<sup>421</sup> inverse scaling of the ion temperature anisotropy with the parallel ion beta in low collisionality plasmas.<sup>256,257</sup> Finally, the *Colorado Solar Wind Experiment*<sup>422</sup> at the University of Colorado, Boulder explores the interaction of supersonic and super-Alfvénic plasma flow with small-scale magnetic anomalies at unmagnetized bodies, such as the Moon.

Even facilities that have been constructed for fusion energy research are beginning to make available a small fraction of runtime for science at the frontier of plasma physics, including the physics of space and astrophysical plasmas. The Department of Energy supports the Frontier Science Campaign on the *DIII-D* tokamak at General Atomics in San Diego, dedicating one week of runtime annually to non-fusion plasma physics experiments. During the initial year of the campaign in 2017, experiments observed whistler waves driven by runaway

electrons, relevant to the physics of the Van Allen radiation belts.<sup>423</sup>

Laboratory experiments also contribute to the investigation of other aspects of space and planetary environments beyond the physics of plasmas, including the study of the physics of ice under the cryogenic vacuum conditions of space,<sup>424,425</sup> investigation the formation of ice in dusty plasma environments,<sup>347,348</sup> the ablation of micrometeoroids in Earth's atmosphere,<sup>426</sup> the effect of micrometeoroid impact on icy surfaces,<sup>427</sup> and the determination of the surface chemistry of planets and moons, such as Titan.<sup>428–430</sup>

Viewed collectively as a national resource for the laboratory investigation of the physics of space plasmas, akin to the collection of spacecraft missions that comprise the Heliophysics System Observatory, these facilities have the capability to contribute uniquely to progress in our understanding of space physics. Increased coordination and collaboration among these distinct facilities, through an emerging organized *laboratory space physics* community, will enable us to maximize the scientific return from our investments in spacecraft missions and in these facilities and contribute to transformative progress in our knowledge of the physics of the heliosphere, as well as of more remote astrophysical systems.

### C. Improved Diagnostic Capabilities

One of the primary advantages of laboratory experiments is the ability to overcome the practical limitation that spacecraft missions can measure the plasma at only a single point (or a few points) in space. On the other hand, the measurement of three-dimensional particle velocity distributions is routinely performed by spacecraft but remains extremely difficult to accomplish in the laboratory. Thus, the development of enhanced diagnostic capabilities for laboratory experiments will increase their impact on our understanding of the physics of space and astrophysical plasmas.

One of the key challenges in the laboratory is to sample the plasma behavior without substantially perturbing its dynamics. In particular, obtaining three-dimensional particle velocity measurements in laboratory plasmas is challenging primarily due to the size of diagnostic instrumentation relative to the plasma kinetic length scales. In the solar wind, for example, the ion gyroradius is around 100 km, whereas the size of the spacecraft is on the order of magnitude of meters. In a laboratory plasma, such as the *Large Plasma Device (LAPD)*, the ion gyroradius is of order one centimeter, approximately the same size as physical probes inserted into the plasma. One approach used to overcome this problem is to exploit the reproducibility of experimental shots in the *LAPD* plasma, enabling a single small probe to sample the plasma at a different location during each repeated shot. But a more widely applicable approach is the develop miniaturized diagnostics for use in the laboratory.

Retarding potential analyzers have long been used in the laboratory to sample the velocity distribution of electrons<sup>431,432</sup> and ions,<sup>433–437</sup> and technological developments are continually improving the performance and robustness of such diagnostics.<sup>438</sup> At West Virginia University, researchers are working on the development of an ultra-compact plasma spectrometer (UCPS)<sup>439</sup> for the measurement of particle velocity distributions in both laboratory and space plasmas. Ongoing innovation will improve the ability to measure the particle velocity distributions, making possible the illumination of the weakly collisional dynamics and energy transfer mechanisms that govern the evolution of many space plasma environments.

Besides the miniaturization of diagnostics, another valuable approach is the application of advanced non-perturbative techniques, particularly for the measurement of particle velocity distributions. For example, laser induced fluorescence (LIF) is a sophisticated means of making spatially resolved measurements of ion velocity distributions in the laboratory.<sup>440–450</sup> Several studies have compared the performance of retarding field energy analyzers to that of LIF systems in measuring ion velocity distributions.<sup>451,452</sup> Note, however, that because LIF depends on the existence of suitable atomic emission lines, it cannot be used to probe the velocities of protons (in ionized hydrogen plasmas) or electrons. To circumvent this limitation, the wave absorption technique is an innovative approach that has been developed and refined in the laboratory relatively recently.<sup>224,453,454</sup> Whistler wave absorption, for example, has been used in *LAPD* experiments to study the physics of electron acceleration by Alfvén waves in the auroral regions.<sup>225–227</sup> A number of other non-perturbative approaches have also been applied in the laboratory to determine various aspects of the velocity space dynamics of plasmas, including Rutherford scattering diagnostics applied in the *Madison Symmetric Torus*,<sup>129</sup> charge-exchange recombination spectroscopy,<sup>455–459</sup> continuous wave cavity ring-down spectroscopy,<sup>460,461</sup> and nonlinear optical tagging.<sup>462,463</sup>

Improvements in conventional diagnostic techniques and the development and refinement of innovative ideas for the measurement of laboratory plasmas will no doubt boost the impact of laboratory experiments on studies at the frontier of heliophysics and astrophysics.

### D. Novel Analysis Methods

To make the most of the improved measurements of laboratory plasmas by innovative diagnostics, in particular detailed measurements of ion and electron velocity distributions, the development and refinement of novel analysis methods is essential. Most valuable are methods that can be applied to the analysis of both laboratory experiments and spacecraft observations, enabling the controlled nature of the laboratory to be exploited to interpret the dynamics of the uncontrolled space environment.

Nonlinear kinetic theory dictates that the collisionless interactions between the electromagnetic fields and charged particles in weakly collisional heliospheric plasmas necessarily lead to correlations between the fields and fluctuations in the particle velocity distributions. Based on this fundamental insight, a novel field-particle correlation technique<sup>464–466</sup> has been developed that employs single-point measurements of the electromagnetic fields and particle velocity distributions to determine the net energy transfer between the fields and particles. Furthermore, the technique can be used to identify which particles in velocity space take part in this energy transfer, enabling different kinetic physical mechanisms for particle energization to be distinguished. Previous applications of this technique have successfully explored particle energization by resonant collisionless wave-particle interactions,<sup>414,464,465</sup> by kinetic instabilities,<sup>467</sup> by the damping of strong plasma turbulence,<sup>466</sup> and in current sheets generated self-consistently in strong Alfvén wave collisions.<sup>468</sup>

To understand how energy is cascaded by turbulence through the six-dimensional phase-space of weakly collisional heliospheric plasmas, recent studies have employed a Hermite spectral representation of the structures in velocity space.<sup>469–481</sup> Such an optimal spectral representation of the deviations from equilibrium in the particle velocity distribution functions has lead to the discovery of an unanticipated process, called *anti-phase-mixing*, that may inhibit collisionless damping in a turbulent environment.<sup>477,478</sup> Such elegant spectral methods maximize the scientific return from the detailed measurements of fluctuations in velocity-space that can be made both in the laboratory and by modern spacecraft instrumentation.

Other innovative methods have been primarily developed for application to the study of the kinetic plasma physics of the heliosphere, but may also find use in the analysis of laboratory experiments. One such techniques is the determination of the wave vector  $\mathbf{k}$ , assuming a single dominant plane-wave mode, using single-point measurements of the magnetic field and current density fluctuations,<sup>482,483</sup> a technique recently used to analyze *MMS* measurements to show the collisionless transfer of energy between the electric field and plasma particles.<sup>484</sup> Another novel technique is the application of the Nyquist stability analysis to solar wind plasma measurements to make possible the determination of whether kinetic instabilities can tap free energy in observed non-thermal particle velocity distributions to drive turbulent fluctuations.<sup>485</sup>

## V. THE FUTURE OF LABORATORY SPACE PHYSICS

The convergence and overlap of the plasma length and time scales that can be accessed by spacecraft missions and by terrestrial laboratory experiments presents a new, unique opportunity for synergy in the study of the

physics of space and astrophysical plasmas. By overcoming the limitations of single-point or few-point measurements and affording reproducibility and control of conditions, laboratory experiments represent a powerful complementary approach to explore space plasma physics, here denoted by the term *laboratory space physics*. One particularly promising application is to determine the kinetic mechanisms responsible for particle energization and plasma heating in space plasmas. Being able to sample the fluctuations in velocity distributions at cadences associated with the time scales of kinetic dynamics and energy transfer processes in space plasmas provides a new opportunity to answer key questions definitively. Laboratory platforms enable a sufficient spatial sampling of the plasma, over a controllable range of parameters, that will help to facilitate the development of a predictive capability of the heliospheric plasma evolution, the ultimate goal of heliophysics. With space measurements alone, due to their inherently uncontrolled conditions, it would be very difficult to develop predictive theories and test them thoroughly over a range of parameters.

In the effort to employ laboratory studies to examine the mechanisms at play in the heliosphere, it is critical to initiate active collaborations between laboratory plasma physicists and space physicists. The effort to make direct contact between laboratory measurements and spacecraft observations, even when an appropriately scaled experiment has been devised, is decidedly non-trivial. Often, the work needed to connect laboratory measurements to spacecraft observations reveals unforeseen issues, the resolution of which ultimately leads to a more complete understanding of the underlying fundamental plasma physics, enriching both the observational and experimental perspectives on the problem at hand. Numerical simulations, which have intentionally not been reviewed here, can provide a critical bridge between spacecraft observations and experimental measurements and can establish a direct connection to idealized theoretical models.

How can laboratory space physics experiments make the biggest possible impact on the frontier of space physics and astrophysics? The laboratory space physics community can maximize their scientific contribution by strategically aligning their efforts to current and upcoming spacecraft missions. The current *Magnetospheric Multiscale (MMS)* mission<sup>7</sup> focuses primarily on exploring the physics of magnetic reconnection and aligns well with the recently completed *Facility for Laboratory Reconnection Experiments (FLARE)* at Princeton University.<sup>10</sup> Understanding turbulent heating and particle acceleration are key science targets of the upcoming *Parker Solar Probe*<sup>100,486,487</sup> and *Solar Orbiter*<sup>488</sup> missions as well as the proposed *Turbulent Heating ObserveR (THOR)*<sup>489</sup> and *Interstellar Mapping and Acceleration Probe (IMAP)*<sup>5</sup> missions. Designing well-diagnosed laboratory experiments to explore plasma turbulence and particle acceleration will complement the single-point measurements returned by each of these four spacecraft

missions. In addition, the development and refinement of novel analysis methods that make full use of particle velocity distribution data, a key goal advocated by this review, will enable us to maximize the scientific return from the costly investment in these strategic missions.

The physics of multi-ion plasmas and ion-neutral coupling, critical to improving our knowledge of magnetosphere-ionosphere-thermosphere (MIT) coupling, is a topic that has scarcely been investigated using laboratory experiments in the past. Presently, there is a significant need for synergistic laboratory experiments that can complement a host of upcoming missions aimed at developing a better understanding of the dynamics and feedback of the MIT system. The poorly understood processes controlling how the Earth responds to variable forcing from the Sun will be addressed by several new spacecraft missions, including the recently launched *Global-Scale Observations of the Limb and Disk (GOLD)* mission<sup>360</sup> and upcoming *Ionospheric Connection Explorer (ICON)* mission,<sup>361</sup> as well as the proposed *Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)*, *Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)*, and *Geospace Dynamics Coupling (GDC)* missions.<sup>5</sup> Timely experiments exploring multi-ion effects in plasmas and the impacts of ion-neutral coupling can make valuable contributions to our understanding of the MIT system.

Ultimately, laboratory space physics experiments present a cost effective means to complement spacecraft observations in our quest to better understand the physics of space and astrophysical plasmas. Collectively, the user-class experimental facilities and moderate-scale experimental platforms at national laboratories and universities around the country provide a powerful complement to spacecraft missions to discover the fundamental plasma physics mechanisms that govern the evolution of the heliosphere. Improved diagnostics and innovative analysis techniques, in particular those that make full use of the measured dynamics of the particle velocity distributions, are likely to spur a significant leap in our study of the physics of space plasmas. Ultimately, the convergence of the regimes accessible to spacecraft measurements and laboratory experiments makes the pursuit of laboratory space physics particularly timely, with the potential to make a transformative contribution to the study of fundamental plasma mechanisms in the heliosphere. All signs indicate a bright future for laboratory space physics.

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