Enabling Discoveries in Heliospheric Science through Laboratory Plasma Experiments

Synopsis: Resolving 3D physics occurring on multiple spatial and temporal scales is difficult with spacecraft and computer simulations alone, but can be studied much more easily with laboratory plasma experiments. This white paper proposes increasing funding for both human and physical infrastructure development in laboratory plasma facilities, as well as educating early career scientists on how to better utilize laboratory experiments in their own research.

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1. Introduction:

Recent results from today's most advanced multi-spacecraft missions (MMS, Cluster) suggest that the physics of reconnection, shocks, and turbulence are distinctly three-dimensional. While these and future missions such as HelioSwarm seek to understand the 3D and multiscale physics via a constellation of satellites, such spacecraft missions are limited: they only allow exploration of naturally occurring solar wind plasmas, lack control over the plasma parameters, are unable to track the evolution of the plasma, and can not distinguish whether the observations are due to local effects or variations in the initial conditions [17]. Similarly, tackling these 3D and multi-scale phenomena with simulations is a steep challenge. Even if computing capabilities continue advancing at the rate of the recent decades, simulations in 2050 will remain unable to fully resolve all naturally occurring heliophysics phenomena, particularly in three spatial dimensions.[1] The additional computational complexity of the appropriate model choice across this wide range of temporal and spatial scales, *e.g.*, the need for kinetic modeling of the collisionless solar wind only makes the limitations of computing more salient.

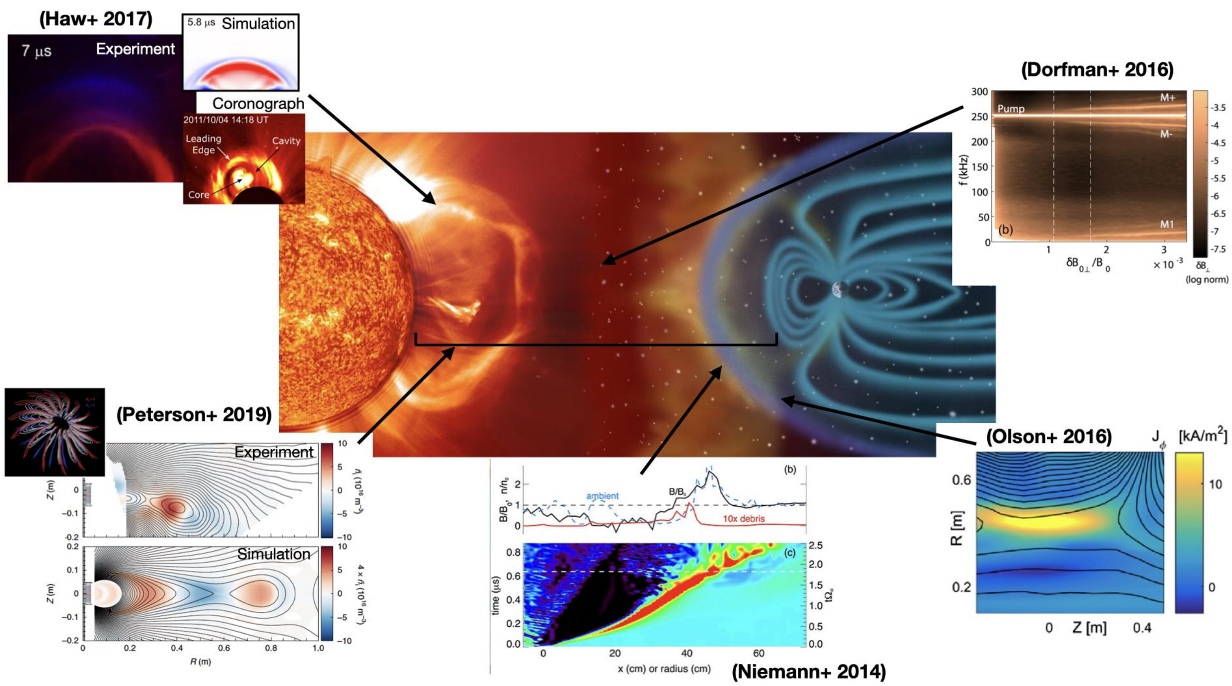

Fig. 1 Images from selected solar-wind-relevant laboratory experiments. Center image is a cartoon of the Sun-Earth system [12], surrounded by examples of heliospheric-relevant experiments. Counter-clockwise starting from the top left, the figures include a laboratory experiment of a flux rope [1], plasmoid formation in the heliospheric current sheet [2], collisionless shocks [9], magnetic reconnection [5], and the parametric instability [6].

[1] Continuing at the Moore's law pace of the past 40 years, by 2050 we would at most expect to have zetta-scale (1e21 flops/second) supercomputers, and have the capability of performing Reynolds number ~10^5-10^6 fluid calculations at uniform resolution. Even with algorithmic advances such as adaptive mesh refinement, the equivalent magnetohydrodynamic simulations would still be orders of magnitude off from the real resistivity of heliospheric systems such as the solar corona. Thus, we cannot expect direct numerical simulations of these plasma systems to completely supplant other means of advancing our understanding of the heliosphere.

Laboratory experiments have a demonstrated ability to investigate both the 3D and multi-scale nature of heliospheric phenomena, complementing the limitations of spacecraft and simulations. While laboratory experiments may have raw densities and temperatures that differ from those that arise naturally in space and astrophysical plasmas, when normalized to the appropriate plasma parameters, laboratory experiments operate well within the regimes relevant to space and astrophysical plasmas. While the raw collision rate in existing laboratory plasma experiments is much higher than in the solar wind and magnetosphere, the time between collisions can be much slower than the physics of interest, and still allow the study of kinetic physics in collisionless systems relevant to heliospheric science. The range of normalized plasma parameters accessible to laboratory plasma experiments also allow the study of fluid physics in relevant heliospheric regimes.

Laboratory experiments have a number of benefits - they can simulate regions inaccessible to spacecraft, such as coronal loops on the surface of the Sun [1]. They can take multi-point measurements of systems at scales beyond the capabilities of the spacecraft clusters, such as plasmoids in the heliospheric current sheet [2]. They can probe fundamental physics interactions relevant to the heliosphere, such as nonlinear interactions between counterpropagating Alfvén waves [3,4]. They can explore physical processes that are outside the range of current theoretical models, such as collisionless plasmoids observed below the ion kinetic scale. They can also uncover physical processes that were not originally expected from theoretical models [5]. They have even been used to investigate the reliability of spacecraft measurements [6, 7] and for investigating solar bursts [18, 19]. A successful community will take full advantage of laboratory experiments to address questions unresolvable by simulations or spacecraft measurements alone.

2. Recommendations for supporting existing laboratory experiments:

For a researcher looking to execute a heliophysics relevant experiment today, several collaborative facilities exist, including UCLA's LArge Plasma Device (LAPD), Wisconsin Plasma Physics Lab's (WiPPL's) Big Red Ball (BRB), and Auburn's Magnetized Plasma Research Laboratory (MPRL), as well as the DIII-D Frontier Science Campaign. In addition to these devices, there are a number of laser facilities that are dedicated user facilities, such as the University of Rochester's Laboratory for Laser Energetics (LLE) and others that are part of LaserNet (https://lasernetus.org/). Together, these platforms provide a reasonable coverage of space and astrophysical plasma parameters and produce a great deal of excellent research. These collaborative facilities dedicate a portion of their time for users outside the experimental group to propose and run experiments using the facility. Recently an organization called MagNetUS (www.magnetus.net) was formed; this organization aims to support the broader scientific community interested in magnetized plasma and facilitate the onboarding of potential new users [13]. However, even with the establishment of MagNetUS it is difficult for researchers without a background in experimental plasma physics to effectively use these tools. Improving facility accessibility means not only soliciting users with a wide variety of backgrounds, but also creating training opportunities and providing staff support to allow those users to succeed. For this reason, our vision for the state of the field in 2050 requires continued funding and improvement along two main channels:

- **Increased funding for both human and physical infrastructure development** so that these facilities can operate more effectively as user facilities, continually expand the explorable parameter space, and ensure equitable access for all potential users, particularly those from a diverse range of institutions
- **Creating an educated workforce** that optimizes use of laboratory experiments as a tool for investigating space and astrophysical plasma physics questions

Increased funding for both human and physical infrastructure development

Robust collaboration between laboratory, computation, and in-situ measurements happens with dedicated support and focus from the community.

Short term: Increased funding for the creation of dedicated scientist positions to broaden access to these facilities and specifically facilitate connections to NASA missions. A user facility requires investment both in the physical infrastructure (in the form of robust equipment and control processes, developing the ability to access data easily, etc.) as well as time on helping potential users design and run experiments on the machine. NASA has dozens of staff doing this for each spacecraft mission, and NIF and OMEGA similarly have a number of scientists in this role, whereas most laboratory plasma facilities only have a handful of dedicated staff. Adding additional dedicated scientist positions will allow more science to be done by a more diverse group of users, as well as allowing more time to be dedicated to improving the machine's physical infrastructure, benefiting all users. Bringing in additional scientists that can both improve infrastructure and devote time specifically to science relevant to NASA missions, will allow a deeper understanding of the phenomena observed by the spacecraft.

Long term: Dedicated funding sources to allow professors and graduate students to develop experiments at their home institutions to run on the user facilities. This has been the practice in laser facilities for many years, providing grants for specific experiments to bring to the user facility. Implemented broadly, this would open pathways for starting and maintaining experimental plasma physics laboratories at a diverse set of institutions, including small liberal arts colleges and historically black colleges and universities (HBCU). For example, designing and building one additional piece of equipment to simulate the Sun and the Parker Spiral (and support the ongoing missions of Parker Solar Probe and Solar Orbiter) using the existing diagnostics on a machine, is relatively inexpensive but can yield incredible scientific results. It is important to ensure that any dedicated pool of funds for approved users at these facilities include the option to apply for salary support for the personnel involved to conduct the work. In addition to funding the salaries of undergraduates, graduate students and postdocs, running an experimental lab requires money to purchase materials and equipment. By providing a dedicated funding source, this would encourage the growth of small plasma physics groups at diverse institutions. Along with continued support, an important part of maintaining the usefulness of laboratory experiments over the next thirty years will involve **the investment in new user facilities** to expand both the parameter regimes available and the range of scales that can be captured. For more information on investment in new user facilities, a discussion is provided in another white paper submitted to this call, [14].

Creating an educated workforce

Education is a vital part of ensuring that early career scientists are poised to take advantage of existing user facilities. Developing educational tools to teach students and postdocs about the potential of laboratory experiments, and training them to design their own experiments, is necessary to maximize their use. To this end, we recommend:

Creating a summer school to educate students and postdocs on how to implement their research question in laboratory experiments. This would educate graduate students and postdocs on the capabilities of the facilities and the process for designing an experiment, with the ultimate goal of running their own proposed experiments. In the **short term**, this would be for older graduate students and postdocs with specific research areas of interest. In the **long term**, this could be extended to younger graduate students and undergraduate students. This proposed summer school would involve scientists from LAPD, WiPPL, MPRL, and the laser facilities. These facilities together cover a range of parameters that includes questions of interest to most space and astrophysical scientists. It could also include training in basic plasma physics, an opportunity not available to students at smaller institutions with a limited plasma presence, and eventually be extended to available computational tools as well. These summer schools will ensure that students at all institutions have access to user facilities, training in diverse codes, and opportunities to innovatively collaborate with peers apart from their institutional advisors. These connections with peers will form the seed for future collaborations and research projects. The intentional professional development of the SHINE conference for young heliophysics scientists serves as an example of the significant benefits provided to early career scientists and the field from such an investment.

Creation of a summer lab program along the lines of the Office of Science Graduate Student Research (SCGSR) Program or Summer Undergraduate Laboratory Internship (SULI). This would be another channel to support students and professors at smaller institutions in creating and maintaining a robust laboratory experiment program. While the SULI program or the Plasma and Fusion Undergraduate Research Opportunities (PFURO) program give undergraduates the opportunity to get research experience for the first time, this program would provide target funding to allow a graduate student at a smaller university to complete the experimental component of their thesis work.

3. Community support

The laboratory plasma community is a diverse set of researchers, spanning a number of different fields, including the fusion community and the fundamental plasma physics community. Both of these communities recently completed their decadal reports in 2020, “Powering the Future Fusion & Plasmas” from the Fusion Energy Sciences Advisory Committee (FESAC) and “Plasma Science: Enabling Technology, Sustainability, Security, and Exploration (2021)” (referred to as Plasma 2020) respectively. Both reports strongly emphasize the importance of laboratory-based research relevant to astrophysical and space plasmas. In particular, the FESAC report contained recommendations to “Strengthen support of laboratory-based research relevant to astrophysical and space plasmas through increased programmatic and facility funding as well as expansion of partnership opportunities” as well as a recommendation to “Support networks to coordinate research and broaden access to state-of-the-art facilities, diagnostics, and computational tools”[15].

The Plasma 2020 decadal report contained similar recommendations. One of the major recommendations of the document is for “Federal agencies whose core missions include plasma science and engineering—for example, DOE, NSF, NASA, and DoD—should provide recurring and increased support for the continued development, upgrading, and operations of experimental facilities, and for fundamental and translational research in plasma science. A spectrum of facility scales should be supported, reflecting the requirements for addressing different problems at the frontiers of plasma science and Engineering” [16]. Later on in the document this was reinforced specifically with regards to space and astrophysical plasmas, stating that “Dedicated DOE and NSF programs are urgently sought to support the next-generation experimental facilities and diagnostic instrumentation in concert with SAP (space and astrophysical plasma) observations.”

3. Conclusion

Tackling the most pressing open questions in space physics requires resolving the multi-dimensional physical processes that operate on multi-scales. Laboratory experiments are well-suited to complement the limitations of simulations and spacecraft observations and resolve these multi-scale processes. There is support for increased investment in and collaboration with space and astrophysical plasma physicists from both the fundamental plasma and fusion communities. A small investment in funding for both human and physical infrastructure development as well as creating an educated workforce that optimizes use of laboratory experiments will lead to an enormous return on investment for both the space physics and plasma physics communities.

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