Roles, Current Status, Opportunities, Future Trends, and Funding Issues for Laboratory Plasma Astrophysics

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1. Scientific Background of Plasma Astrophysics

Most astrophysical objects are part of or immersed in an environment filled with plasmas, and every one of them is, as far as we can measure, permeated by magnetic fields. These fields are often dynamically important, sometimes introducing instabilities otherwise absent (e.g. kink instability, magnetorotational instability or MRI, and the Parker instability). These instabilities often lead to a self-sustained turbulence, which in turn generates a magnetic field via the dynamo mechanism. Thus, astrophysical plasmas and magnetic fields are often inseparable through magnetohydrodynamic (MHD) processes; one cannot be understood without the other. MHD effects govern not only the large-scale dynamics as in jet acceleration and collimation, magnetocentrifugal wind launching, magnetic breaking, and star spin-down; but also lead to small-scale turbulence that drastically affects transport properties such as angular momentum transport by MRI. When plasmas are dilute and hot, kinetic plasma physics becomes important. Such collisionless plasmas include the ISM, galaxy clusters, stellar and disk coronae, jets, and winds. The particle distribution functions are generally non-Maxwellian exemplified by cosmic rays.

Four key characteristic components, Thermal Plasma, Magnetic Fields, Turbulence, and Non-thermal Energetic Particles, are intricately connected and interact with each other through various plasma-astrophysics processes. The best example is the ISM in our Galaxy where all these components are roughly in equipartition, i.e. dynamically and energetically they are all equally important. Some example key processes include: (1) the magnetic dynamo which connects turbulent flows to the magnetic field; (2) magnetic reconnection which dissipates magnetic energy and converts it to thermal, non-thermal, and flow energy; (3) Non-thermal particle acceleration in collisionless shocks and reconnection events which converts either kinetic energy (shocks) or magnetic energy (reconnection) into non-thermal particles.

Amazingly, the four processes described above are important for plasmas ranging in size, density and temperature from relatively small and dense stars to enormous diffuse plasmas in galaxy clusters including compact objects, accretion disks, the ISM, and star-forming regions. Important plasma astrophysics problems are listed in our eight White Papers submitted to the five Astro2010 Science Frontier Panels. Astrophysical systems would be better understood by explaining the underlying universal plasma processes. Theory and computation have been the primary methods to study these processes, but in the physical sciences the ultimate measure of the truth is in physical realizations. And thus, it is imperative to study these astrophysically relevant plasma physics processes via laboratory experiments.

2. Roles of Laboratory Plasma Experiments in Astrophysics

The laboratory experiments designed to study these processes began with reproducing some dynamical astrophysical phenomena on a small scale. Examples include flow past magnetized bodies, magnetic dynamos, and collisionless shocks. During the last 10-15 years, laboratory plasma astrophysics has developed from the state of a few disparate experiments to a broad area of research with increased coordination of research efforts among groups.

If the dynamical scaling constraints are properly applied, one could reproduce astrophysical processes on some segment of their time-evolution. Unlike astrophysical observations, we can measure and control physical conditions in the laboratory with much greater confidence. Like numerical experiments, laboratory experiments can provide both local measurements of key physical quantities simultaneously at numerous places and global morphologies as in the remote-sensing observations. Experiments can sometime be used to study turbulence with a larger dynamic range than is possible in numerical simulations. Such experiments add a new dimension to the process of interpreting observational data and relating them to the existing theories.

Such experiments also play a very important role in the validation and verification of computer codes used to interpret astrophysical phenomena. If scaling constraints are observed, the ability to test code predictions in a controlled fashion makes the use of these codes for prediction and interpretation of astrophysical phenomena much more reliable. Real experiments are also irreplaceable in providing new insights into subtle physics issues and in stirring the creative imagination of scientists. Astrophysicists may find it quite helpful to take part in designing laboratory experiments as this process allows one to get a new and refreshing prospective of a real (astrophysical) problem.

While the laboratory provides a true realization of the physical processes under investigation, we point out that the goal of these laboratory experiments is not to directly simulate astrophysical phenomena. This is because the laboratory and astrophysical plasmas are vastly different in spatial and temporal scales, and are often driven by different energy sources. By carefully matching the dimensionless parameters where possible with appropriate initial and boundary conditions, some astrophysical processes can be studied on laboratory scales. This scalability of physical phenomena is fundamental to interpret laboratory results for astrophysical applications. However, we recognize that there exist large gaps in some dimensionless parameters and that these gaps will not likely disappear in the foreseeable future. The discrepancy is most severe between laboratory or numerical systems and astrophysical phenomena. It is less severe but still problematic between laboratory experiments and numerical experiments. Here, analytic theory, guided by but not limited to the regimes accessible to the laboratory and to the computer, help to close the gap in parameters and unify our understanding. Although powerful, useful theories do not appear overnight. Often they are born from many failed attempts and from the interplay between laboratory experiments, numerical experiments, and astronomical observations.

3. Status and Opportunities of Laboratory Plasma Astrophysics

In this section, four different platforms for laboratory plasma astrophysics are discussed focusing on their current status and opportunity followed by a brief discussion of future trends and funding issues in the next section.

3.1 Magnetically-driven Experiments [Table I]

In a magnetically-driven plasma, the energy source that generates the plasma is magnetic and the plasma dynamics are strongly influenced by the magnetic field which is produced by currents flowing either external or internal to the plasma**.** Typically, the magnetic energy is equal to or much greater than the kinetic energy associated with the plasma pressure or flow as in many astrophysical plasmas.

3.1.1 Study of Astrophysical Processes in Magnetically-driven Laboratory Plasmas

Many astrophysical processes are amenable to experimental study including magnetic reconnection, dynamo, ion and electron heating, momentum transport, magnetic turbulence, and energy transport in a chaotic magnetic field.

Table I. Major facilities for magnetically-driven experiments

Facility	*Location*	*Topics*
MRX	Princeton	Reconnection, ion heating
VTF	MIT	Reconnection
Caltech Spheromak	Caltech	Jets
SSX	Swarthmore	Reconnection, ion heating
RSX	LANL	Line-tied reconnection
RWE	Wisconsin	Line-tied reconnection
MST	Wisconsin	Dynamo, reconnection, ion heating, momentum transport
DIII-D, C-Mod, NSTX	GA, MIT, Princeton	Reconnection, momentum transport
TS-3/TS-4	Japan	Reconnection, ion heating

Magnetic reconnection, the breaking and re-organization of magnetic field lines, is essential to nearly all magnetically-dominated plasma phenomena. Without the breaking of the frozen flux constraint, a wide range of astrophysical phenomena would not be possible including stellar flares and mass ejections, jet formation, and aspects of particle energization. There have been a few experiments built to study magnetic reconnection [1]. Some of them use a toroidal geometry [2-4] where reconnecting current sheets are continuous while others use a linear geometry to study line-tying effects at the end [5,6]. In these devices significant progress has been made recently in understanding the reconnection rate. Hall effects [2,3] and microscopic kinetic physics [4] have been experimentally verified.

The Dynamo is the mechanism giving rise to magnetic fields in flow-dominated plasmas (Sec.3.3). Dynamo effects occur also in plasmas in which the field is already strong, and they are related to the general question of why the universe is magnetized. Recently a laboratory experiment has shown that the Hall dynamo can be dominant at small scales [7].

Ion and electron heating can occur from magnetic field dissipation. Reconnection can energize charged particles such as ions in the solar corona and high-energy cosmic rays. Significant ion heating was observed and attributed to reconnection in a toroidal plasma [8]. Experiments also display production of Alfvénic jets and turbulence by reconnection in addition to the mechanisms by plasma waves (Sec.3.4.1).

Momentum transport regulates accretion and possibly determines flow structures in magnetically-dominated jets. In addition to the flow-driven instabilities such as the MRI, current-driven instabilities are also considered as a candidate for momentum transport, particularly in jets with a strong magnetic field. The physics of this transport mechanism and its applicability to astrophysics is a current topic of research.

Magnetic chaos and turbulence are ubiquitous. Magnetic fields typically display a broad featureless wave number spectrum. This is observed directly in the solar wind and is inferred from density measurements in the ISM. The chaotic wander of a field line affects the transport of particles and energy in cooling flows of galaxy clusters. Experiments showed that magnetic chaos affects plasma transport and heating.

Jet formation Well-collimated high-velocity outflows or jets are observed in many protostars and quasars, but the generation mechanisms remain largely mysterious. Laboratory experiments have been performed to study magnetized jets and have demonstrated striking morphological similarities with observations [9].

3.1.2 Opportunities

Opportunities fall in two categories: upgrade of existing facilities and construction of facilities with new capabilities.

Existing facilities can be utilized more effectively in two ways. First, facilities built for dedicated studies relevant to plasma physics have typically relied upon a variety of insertable probe diagnostics as the dominant measurement approach. Understanding of such plasmas would benefit by using non-perturbing diagnostics that access new quantities. The fusion research program has developed a wide range of advanced diagnostics that can be applied to laboratory plasma astrophysics. Second, fusion experiments can be exploited for information relevant to astrophysics. For example, toroidal fusion experiments display strong reconnection events at temperatures much higher than most experiments dedicated to laboratory astrophysics. Thus, they offer information on reconnection scaling with resistivity and behavior at high temperature.

New facilities are needed that are either tailored to specific phenomena not sufficiently studied in existing facilities or that extend studies to dimensionless parameter regimes closer to astrophysical plasmas. Examples include experiments to study momentum transport and controlled reconnection experiments at lower resistivity.

3.2 High-Energy-Density (HED) Experiments [10,11, Table II]

3.2.1 Magnetically-driven HED Experiments

These experiments are performed mostly on moderate-scale pulsed-power machines operated as Z pinches. A great variety of jets have been created imitating such processes as the formation of tower jets and episodic outflows [12]. Interactions of plasma flows with a magnetic field, generation of shocks, and Kelvin-Helmholtz and Rayleigh-Taylor instabilities are also studied in astrophysics-relevant settings.

Larger-scale facilities are used as very intense sources of thermal (hohlraums) and non-thermal radiation which can then be applied to a variety of astrophysics-related experiments. In particular, measurements of opacities relevant to radiation-dominated astrophysical plasmas have been performed at these facilities.

3.2.2 Laser-driven HED Experiments

The Equation of state (EOS) for various materials at pressures exceeding 1 Mbar and opacities of plasmas containing high-Z impurities have been subjects of HED experiments. These measurements are performed with laser and pulsed-power facilities. Techniques for shockless compression have been developed. Opacities with respect to black-body radiation are obtained with the use of hohlraums.

Rayleigh-Taylor (RT) and Richtmyer-Meshkov instabilities are studied at their non-linear stage and transition to the turbulent stage for the verification of hydrodynamic codes. An example is that the spikes in a compressible material due to the 3D RT instability at the nonlinear stage can be compared with numerical predictions [13]. Generally, experiments of this type can be well characterized and can provide high-quality experimental information under conditions scalable to supernova problems.

Radiative shocks The effect of radiation on shock dynamics has been studied thus far in regimes where the radiation pressure was lower than the plasma pressure. The advent of NIF opens up a possibility of studying shocks where the radiative pressure will be dominant, and the opacity will be large enough to couple the radiation with matter. Such shocks and their stability are of a great interest for the physics of the most energetic phenomena in the Universe, in particular, accretion disks around massive black holes.

Blast waves and Vishniac instability Blast waves have been generated by focusing an intense laser on the gaseous cluster medium or on the surface of a thin needle. Trajectories of blast waves in various regimes were measured [14]. Development of pre-imposed perturbations has been studied and related to Vishniac instabilities. Effects of electron heat conduction were identified as an important factor in the wave evolution. This area is ripe for a meaningful comparison with astrophysical observations.

The Interaction of dense clumps with hypersonic flows is also a well-established area with connections to a variety of astrophysical phenomena. Several well-diagnosed experiments have been performed during the last decade. They provided a detailed characterization of the destruction of clumps via shear flows and instabilities together with entrainment of the clump material. The observed structures cover essentially the whole time-history of the process. Experiments were used to interpret the evolutionary stage of a structure observed in Puppis A by comparing observations with the experimental data [15]. More sophisticated experiments and quantitatively analyses have followed [16].

Plasma jets have been generated in a number of laser-driven experiments to observe structures similar to astrophysical jets. A variety of settings have been used, from conical targets to structured irradiation of a flat plate. A number of morphological structures observed in astrophysical jets have been reproduced including the shape of the working surface, clumps in the body of the jet, and curving of the jets. Sometimes these jets are scalable to astrophysical jets which may allow one to study more subtle effects associated with the turbulence and smaller-scale vortices.

Table II. Major facilities for HED experiments

Facility	*Location*	*Driver*	*Topics*
ZEBRA	Nevada	Z-pinch	Magnetic field
Saturn, ZR	Sandia	Z-pinch	Opacity, EOS
OMEGA, OMEGA-EP	Rochester	Laser	Instability, shocks, jets
NIF	LLNL	Laser	Shocks, photo-ionized flows
Z-beamlet	Sandia	Laser	Blast waves
NOVA	LLNL	Laser	Photo-ionized flows
COMET, Callisto	LLNL	Laser	Beams
TITAN	LLNL	Laser	Magnetic field, positrons
MAGPIE	UK	Z-pinch	Jets
LULI	France	Laser	Shocks, jets
VULCAN	UK	Laser	Shocks
PALS	Czech Rep.	Laser	Jets
GEKKO	Japan	Laser	Photo-ionized flows

Photo-ionization driven flows It is possible to emulate the dynamics of photoevaporated molecular clouds in star-forming regions. Significant theoretical and numerical analyses have been produced and experiments on NIF could study the relative role of various mechanisms giving rise to complex structures of photoevaporated clouds.

High-speed impact Significant contribution can be made to the study of hyper-velocity collisions of dust particles present in a number of astrophysical objects. Fast microparticles can be generated in laser experiments by a variety of techniques.

Particle beams When the quiver velocity is high, intense streams of relativistic electrons are formed. Their collisionless interaction with the ambient plasma via a variety of instabilities is of a direct interest for astrophysical phenomena associated with energetic events and cosmic ray acceleration. These electrons can generate ion beams accelerated by the ambipolar electric field. Interactions of such beams with a downstream plasma could yield experimental information of relevance to cosmic-ray physics.

Ultra-strong magnetic fields up to hundreds of Megagauss can be generated by interaction of the ultra-intense radiation with a plasma. Identification of the generation mechanisms is an active area of research. Using these fields for the studies of various magnetically-induced effects (like, e.g., "squeezing" of the atoms) is an untouched area.

Generation of positrons by relativistic electrons interacting with a target of a high-Z material have recently been detected experimentally [17]. This opens up the possibility of creating pair plasmas. If such plasmas are loaded with a small amount of ions, the latter can be very effectively accelerated to relativistic energies.

Collisionless shocks have been generated by irradiating a solid target situated in a pre-formed, magnetized plasma. An alternative would be to inject an intense ion beam (mentioned under "*Particle beams*") into a pre-existing plasma. Intense instabilities then may scatter the beam and drive a collisionless shock into the plasma. Both settings are relevant for simulating of astrophysical phenomena.

Table III. Major facilities for flow-driven experiments

Facility	*Location*	*Geometry*	*Liquid*	*Topics*
Madison Dynamo Exp.	Wisconsin	1m sphere	sodium	dynamo
Princeton MRI Exp.	Princeton	0.4m cylinder	gallium	MRI
Maryland Dynamo Exp.	Maryland	0.6m and 3m spheres	sodium	Dynamo, MRI
New Mexico Dyn. Exp.	New Mexico	0.3m cylinder	sodium	dynamo
PROMISE	Germany	0.2m cylinder	gallium	MRI
VKS	France	0.4m cylinder	sodium	dynamo
DTS	France	0.25m sphere	sodium	dynamo
Riga Dynamo Exp.	Latvia	0.8m helical	sodium	dynamo

3.3 Flow driven experiments [Table III]

Astrophysical plasmas are often characterized by much larger plasma flow energy than that of magnetic field. Examples include stellar interiors, accretion disks and the solar wind. Such plasmas are inherently difficult to generate by using magnetic confinement as described in Sec.3.1. Transiently, laser-driven plasmas can reach this regime, but most of their initial energy is carried by photons. Recently, conditions similar to these plasmas have been created in the laboratory using liquid metals, which approximate well their MHD properties.

Two important dimensionless parameters are magnetic Reynolds number $Rm=\mu_0\sigma UL$ and Alfvén (Mach) number $A=U/V_{Alfvén}$. For the astrophysical processes important to stellar interiors, galaxies, accretion disks and jets, Rm is usually enormous and A is also large. While experiments are unlikely to ever match the actual dimensionless numbers of astrophysical objects, the plasma processes can be accessed and investigated in a meaningful way if those numbers are sufficiently large.

3.3.1 Astrophysical Plasma Processes in Super Alfvénic and High Rm Flow

There are at least two common fundamental plasma processes in flowing plasmas. The first is the generation of a magnetic field of energy comparable to the flow from which it arises. Conversion of flow energy into magnetic energy is often referred to as the dynamo process. There exist many fundamental questions regarding the dynamo process: How is the small-scale magnetic field generated and maintained? How does the large-scale magnetic field grow out of the fast-growing small-scale fields without being overwhelmed? How does the growing magnetic field affect the original flow?

A second fundamental plasma process concerns how a weak magnetic field can act as a catalyst for transporting momentum, heat, etc. One prominent example of such processes is the MRI in weakly magnetized accretion disks. Without a magnetic field, it is difficult to generate turbulence while with a weak magnetic field, plasmas are rigorously unstable due to MRI. Active areas of research are identifying which processes control the saturation amplitude of the MRI (e.g. the role of microscopic diffusivities such as resistivity and viscosity), exactly how the turbulence is dissipated into heat at small scales, and how the turbulence behaves in very weakly collisional plasmas.

3.3.2 Current Status of Flow-driven Laboratory Experiment

Experiments have been carried out using flows of liquid metals (either sodium or gallium) to achieve sufficiently high conductivity to investigate the dynamo [e.g. 18,19]. Liquid metals are conducting fluids satisfying the MHD equations which require no magnetic field to provide initial confinement, hence they can easily satisfy the $A >> 1$ criteria. These experiments have been successful in observing magnetic field self-generation and are beginning to investigate the role of turbulence.

Laboratory investigations of the MRI using liquid metals are just beginning. These experiments use velocity fields similar to Keplerian flows in a Taylor-Couette geometry. An axial field is applied to the flows to induce MRI. Features resembling the MRI have been observed in a spherical Couette sodium flow [20]. A second experiment has reported observing the MRI in a cylindrical Couette gallium flow in which a helical field was applied [21]. Designed to detect the standard MRI in a cylindrical Couette flow with active boundary controls, the Princeton MRI experiment reported quiescent hydrodynamic flow at Reynolds numbers up to 2 million, effectively ending the debate whether nonlinear hydrodynamic instability can explain fast accretion [22].

3.3.3 Opportunities

Existence of essentially laminar flows at large Reynolds numbers has opened possibilities that the next generation of liquid metal experiments can be built at much larger *Rm* without prohibitive power. Such experiments can provide a platform to study the dynamo in interesting regimes where MHD turbulence can be generated with sufficient dynamic range. For the MRI problem, such experiments can study MRI saturation over a significant range of *Rm*, and at a sufficiently large speed that even the required magnetic field could be generated through the dynamo. Self-sustained MHD turbulence by the MRI-dynamo is a highly desired state to reach in the laboratory.

Another frontier for flow-driven experiments is to use a plasma as the working medium. Until now, magnetic instabilities have only been investigated in strongly magnetized plasmas in which $A < 1$. This is because the strong, externally imposed magnetic field is critical for providing the thermal insulation that allows the plasma to become hot and strongly conducting. To study the dynamo or MRI requires a large, sufficiently hot, and flowing plasma, simultaneously requiring that $A >> 1$ and $Rm >> 1$.

Another advantage for such experiments is the freedom to choose a different ratio of Reynolds number to magnetic Reynolds number, or magnetic Prandtl number, *Pm*. Both *Pm* >>1 or <<1 regimes have their counterpart in astrophysics. Compressibility, two-fluid effects, neutral collisions, as well as kinetic effects can be studied in such plasma experiments. Finally, a supersonic and possibly super Alfvénic plasma flow experiment can be used to study collisionless shocks widely observed in astrophysical plasmas.

3.4 Laboratory Studies of Plasma Waves and Dusty Plasmas [Table IV]

3.4.1 Plasma Wave Experiments

Waves and instabilities are of central importance in astrophysical plasmas. Radio emission from pulsars is thought to occur in Langmuir wave turbulence via mode conversion and decay instabilities. Alfvén waves are thought to play an important role in scattering and confinement of cosmic rays, stellar coronal heating, and in establishing the spectrum of turbulence observed in the ISM through scintillation in radio signals. The Weibel instability has been invoked as a critical mechanism in collisionless shocks, accelerating charged particles, and creating structure in relativistic jets. Particle acceleration by whistler waves and by solitary Langmuir waves during reconnection has also been proposed. Mirror and firehose instabilities are thought to establish the distribution of ion temperature anisotropy in the solar wind.

Our current understanding of the linear and nonlinear physics of a number of plasma waves and instabilities has been built in large part on decades of exploration in the laboratory, both in experiments dedicated to basic plasma physics research and in devices for fusion energy research. Recently, the properties of the astrophysically important Alfvén wave have been studied in great detail [23]. The dispersion and damping characteristics of the kinetic Alfvén wave was characterized [24]. Kinetic Alfvén waves are thought to play a role in electron acceleration in the near-Earth space environment and ion heating in high beta astrophysical plasmas. Studies of nonlinear interactions between Alfvén waves are being carried out [25]. Fast ions driven by neutral beam injection, ion cyclotron heating or fusion events have been shown to drive Alfvénic instabilities in tokamaks. The extensive dataset on this phenomenon may yield insight into the interaction between cosmic rays and Alfvén waves. The role of flow shear and temperature anisotropy in exciting instabilities has also been investigated, including an observation of a proton

Table IV. Major facilities for plasma wave and dust experiments

Facility	*Location*	*Topics*
Large Plasma Devices	UCLA	Alfvén wave, Whistler
LEIA/HELIX	West Virginia	Anisotropy-induced waves
HELCAT	New Mexico	Drift-wave, Alfvén wave
Space Physics Simulation Chamber	NRL	Whistler, ion cyclotron, lower hybrid wave
Dusty plasma device; IQ-3; RF dusty plasma	Iowa	Dust acoustic wave; ion acoustic, cyclotron wave
Smoky plasma device; Double plasma device	Colorado	Nano-scale dust, grain charging, lunar simulation
ALEXIS; 3DPX	Auburn	Ion cyclotron, dust acoustic wave, ion-dust interaction

cyclotron instability driven by parallel anisotropy [26]. Coupling with theory and simulation [e.g. 27] will be important for physics understanding.

Going forward, experiments in directly relevant parameter regimes are of great interest. One critically important but largely unexplored area is plasma waves and instabilities in high beta, magnetized laboratory plasmas. For example, in high beta plasmas, kinetic Alfvén waves damp through Landau or Barnes damping on ions, a process that has not been characterized in the laboratory but is important astrophysically. A high beta laboratory experiment could address the relative heating of ions and electrons by an MHD turbulent cascade, relevant to accretion disk plasmas. High beta plasma experiments also provide an opportunity to study important instabilities such as the mirror and firehose instabilities that are inaccessible in lower beta plasmas.

3.4.2 Dusty Plasma Experiments

Dust is a ubiquitous component of the universe and recent measurements indicate that it is even more pervasive than previously thought [28]. Observations of the reddening of quasars from intergalactic dust indicate that the reddening extends up to ten times beyond the apparent edges of galaxies [29]. The dust which litters intergalactic space may provide the reaction sites necessary for the formation of complex molecules and the basic materials out of which planets are formed. Examples of dust within the solar system include the circumsolar dust rings, cometary coma and tails, the asteroid belts, and of course the rings of the giant outer planets [30]. In almost all cases, dust is immersed in a plasma or a sea of photons both of which cause it to acquire an electric charge. This state of matter in which charged dust coexists with plasma is called a dusty plasma. It is now obvious that understanding dust must involve electromagnetic and gravitational forces.

There is little doubt that the growth of understanding of the dusty plasma has been driven largely by dedicated laboratory experiments. We can envision five areas where the basic studies of dusty plasmas can be applied to problems of astrophysical significance: Coagulation and growth, Dust transport, Self-organization of dust structures, Interaction of electromagnetic waves with dusty plasmas, and Magnetized dusty plasmas.

Underlying all of the problems listed above is the issue of dust charging mechanisms. Numerous laboratory experiments have been performed to measure the charge on dust grains in various plasma environments. Ongoing work in this area concentrates on the effects of electron-neutral and ion-neutral collisions on the dust charge. Very few laboratory studies have been performed on the effects of ionizing radiation, grain surface temperature, and magnetic field in determining the charge.

Investigation of dust transport mechanisms requires understanding the forces on dust grains in a plasma. The role of the ion drag force was demonstrated in the laboratory. Experiments have illustrated the formation of organized dust lattice structures when in the strongly coupled state. In the weakly coupled (gaseous) state another type of organization seems to occur with the formation of dust acoustic waves. The tendency of dusty plasmas to self-organize into these structured states will have important consequences for the ways in which electromagnetic waves scatter from dust clouds. The interaction of electromagnetic waves with a dusty plasma is an area of direct astrophysical importance that is amenable to laboratory experiment.

Astrophysical dusty plasmas are likely to be immersed in magnetic fields. This provides perhaps the biggest challenge for dusty plasma experimenters—to construct a device in which the dusts are magnetized, i.e., the gyroradius of the dust grains is significantly smaller than the plasma size. Dusty plasma researchers are now in the initial stages of a feasibility study for such a device. The physical size, complexity, and cost of designing and constructing such a device suggest that it would be a user facility available for the entire dusty plasma community. It would be of great value to develop partnerships with the astrophysics community to address scientific issues of common interest.

4. Future Trends and Funding Issues

In the next decade, this emerging field of laboratory plasma astrophysics is expected to mature significantly, and thus to contribute more to our understanding of astrophysical phenomena in the following three respects. First, the scope of the physics topics studied in the laboratory and their parameter ranges will continue to broaden as technology advances and interests grow. Second, increasingly sophisticated diagnostics will elevate the data quality from these experiments which will be especially important for experiments focusing on morphological comparisons to understand the underlying physics. Third, numerical and theoretical studies will play increasingly important roles in extracting physical insight from the laboratory and applying it to astrophysical regimes.

To support the healthy growth of this emerging field a sound funding strategy is required. Currently the support is sporadic and scattered in different programs from three agencies: DoE Office of Fusion Energy Sciences (OFES) Basic Plasma Physics Program, NSF-DoE Partnership in Basic Plasma Science and Engineering, DoE OFES-NNSA Joint Program on HED Laboratory Plasmas, with occasional support from NASA space and astrophysics programs, NSF Astronomical Sciences and Atmospheric Sciences programs. The majority of support is in single PI-based programs on the order of \$100K (occasionally larger but <\$1M) per year. For HED and wave experiments, some projects use as a user facility, sharing generic experimental setups. For magnetically or flow driven experiments, each project often uses a unique setup specific to the topics. In most cases, researchers are funded from the sources unrelated to astrophysics and spend only a small fraction of their time on astrophysics. This growing field deserves better support through a systematic funding strategy involving multiple agencies due to its interdisciplinary nature.

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