Topic 7: Dust in astrophysical plasmas

7.1 Introduction and current status

In the astrophysical environment, the fraction of the ionized particles varies widely from nearly no ionization in cold regions to fully ionized in regions of high temperature. This leads to a wide range of parameters where astrophysical plasmas can exist. While the astrophysical plasma environment is often dominated by the presence of the plasma, this plasma is often strongly influenced by and coupled to the presence of embedded particulates (i.e., dust). These dust grains – which range in size from a few nanometers to micron-sized objects – can become either positively or negatively charged due to interactions with the background plasma environment and/or ionizing radiation sources in the astrophysical environment. Understanding the processes that govern these plasma – particle interactions is critical to the study of astrophysics because it is the agglomeration and growth of larger particles from single atoms and dust grains that leads to the eventual formation of objects that are large enough for gravity to become the dominant force that controls their subsequent evolution.

In any plasma environment, the charged species can be dominated by or at least perturbed by electromagnetic forces. For most systems, it is the ion and electron dynamics that is dominated by these forces, while charged dust grains are perturbed by these forces. The uncharged species (i.e., neutral particles), will not be directly affected by these electromagnetic forces. However, the charged and uncharged particles interact through collisions, which transfer energy and momentum from one species to another.

Furthermore, larger particles (i.e., dust grains), can become both an important source and sink of charged particles. For example, in regions of space with ionizing radiation, photoionization processes at the surface of the grains can lead to the generation of electrons from the surface of the grains at the same time generating charged dust. Similarly, in regions where the grains are can become significantly heated through collisions with the background plasma particles or neutrals, the grains can become heated to the point of thermionic emission – again leading to the grains becoming a source of electrons for the plasma. At the other extreme, in very cold regions of space, atoms and molecules can become trapped on the surfaces of these dust grains leading to growth of the particles as well as becoming a sink for the background gas and plasma environment. The presence of dust can alter the density, energy distribution, and the composition of its plasma environment.

From this wide range of phenomena that can occur in astrophysical plasmas, it is important to consider those processes where it is possible to perform laboratory studies that will enable new insights and new understanding to be gained of the astrophysical plasma environment. Three topics have emerged as "grand challenges" for laboratory astrophysics in the area of plasma-particle interactions.

1) How do the dust grains become charged in astrophysical plasmas?
2) How does the plasma influence the growth and breakup of macroscopic particles in astrophysical environments?
3) What is the role of magnetic fields in influencing charged macroscopic particles?
4) How does the presence of neutrals atoms and/or charged or neutral macroscopic particles affect the evolution of the plasma environment?

7.2 **Key Scientific Challenges**

In the context of astrophysical plasmas, these three questions are part of a singular, overarching theme – *how are larger objects - comets, planets, stars - formed from clouds of gas and dust*? At the same time, these three questions also have a strong connection to very tangible issues in modern laboratory plasma science research in areas such as plasma manufacturing and fusion. Each of these challenges is discussed in the following section.

Topic 1: *How do dust grains become charged in astrophysical plasmas?*

Perhaps the dominating question for much of dusty plasma research – for laboratory, fusion, and astrophysical plasma environments – is defining the mechanisms that lead to the charging of the grains. In laboratory plasmas, the charging process is primarily due to the collection of ions and electrons from the background plasma. However, in astrophysical plasmas, the charging process will not only be driven by the collection of ions and electrons, but also will be influenced – and possibly dominated by – sources of ionizing radiation. Understanding the charging process, particularly in highly collisional environments or regions with large magnetic fields are areas of research in which much theoretical and experimental work remains to be done.

As a scientific problem, the determination of the charge of dust grains in an astrophysical plasma is quite challenging. First, the material composition of the dust grain is important because this determines the work function of the grain. Also, the charge distribution oon an individual grain is determined by whether the grain is insulating or conducting. Second, the shape of the grain can determine how much surface area is available for charge to be collected. And third, the size of the grain, with respect to the local Debye length, can have a significant influence on how free charges (ions and electrons) are captured by the grain. These are all issues for which significant theoretical and computational efforts are needed.

In terms of the astrophysical plasma environment, the dust grains can become charged either positively or negatively – depending upon the conditions of the local plasma and radiation environment. Once charged, the particles can be influenced by electromagnetic as well as gravitational forces. The formation of the radial spoke structures in Saturn's rings are often cited as an example of this competition between electromagnetic and gravitational forces on the transport of charged grains in the space environment. Ultimately, the dust grains can play an important role in the distribution of charge in astrophysical plasmas because they can transport substantial quantities of charge from one region to another. As such, these grains can be important sources and sinks of plasma.

Topic 2: *How does the plasma influence the growth and breakup of macroscopic particles in astrophysical environments?*

The growth and agglomeration of particles from clusters to atoms to the size of dust grains or larger is a long-standing problem in astrophysics. The matter that eventually forms the stars, planets, comets, and the other objects in solar systems begins its life as small grains of dust particles. These particles interact with and are influenced by the neutral and plasma particles in the space environment. However, because of the strength of the electromagnetic force is so much larger than the gravitational force – when considering small, nanometer and micron-sized grains – precisely how these small particles become charged, the sign of the charge, the number of charges on the particles, and the spatial distribution of charges on these particles all can have a significant influence on the processes that eventually lead to the building of stars and planets.

Initially, in the gas phase – as atoms are first combined to form molecules and then atomic clusters – the growth of particles is believed to be driven by a Brownian motion growth process for particles up to ~100 nm.[1,2,3] As particles grow to larger sizes, a number of environmental features begin to have a stronger influence on the growth process. These include the density and temperature of source materials (neutral atoms, plasma ions, and smaller agglomerates) as well as the thermal properties of the grains themselves. If these particles can be become charged, this can have a significant impact on the rate at which further particle growth can occur.

Of course, it is well known that the electrostatic force is many orders of magnitude stronger than the gravitational force. Therefore in the simplest approximation, two small dust grains that carry even a single, but opposite charge will experience an attractive force that is far greater than the gravitational attraction. Consequently, if those two same particles have the same sign of charge, the electrostatic repulsion will far exceed the gravitational attraction. Therefore it is immediately obvious that the presence of charged dust can have a significant influence on the evolution of a planetary nebula in an astrophysical environment by simply taking into account the charge state of the grains and how those charged grains are distributed in space.

However, it is not simply the fact that individual grains are charged, because these grains are generally not conductors nor are they uniformly shaped. Thus, the underlying physical phenomenon that influences all of the aforementioned issues is how the grains become charged. In the astrophysical environment, the charging of the grains is a complex process. Not only do the grains collect ions and electrons from the background plasma as occurs in laboratory experiments, but these grains are often in environments with ionizing radiation or strong heating processes. Furthermore, grains in space are subjected to high-energy particles that can lead to the production of secondary electrons. As a result of these different charging processes, dust grains in space can be found to carry either a net positive or net negative charges depending upon the details of the plasma environment.

Therefore, current experimental, theoretical, and numerical studies all point to the need to have a better understanding of the initial formation of large scale dust grains in astrophysical environments. And, because charged grains can have a profound impact on the coagulation of material into these larger grains, having detailed knowledge of the plasma environment and it coupling to the dust is vital.

Topic 3: *What is the role of magnetic fields in influencing charged macroscopic particles?*

Just as plasmas are ubiquitous in the universe, magnetic fields are just as pervasive. For much of the development of astrophysics, the role of the magnetic field has not been considered to play a significant role. However, as the importance of charged particle effects is becoming more evident, it has become increasingly necessary to determine if the presence of magnetic fields can also have an influence on plasma – particle interactions. In this context, it is not only vital to determine how the magnetic field may shape the properties of the background plasma, but also to determine how the magnetic field may have a *direct* influence on the charge macroscopic particles themselves.

Although the consideration of the influence of the magnetic fields on macroscopic particles in astrophysical plasmas has not always been a prominent topic, early works in the 1950's by Alfven[4] and Mestel and Spitzer[5] show that the idea of the coupling between the plasma, dust, and magnetic fields has been a topic of discussion for some time. More recent work by Goertz shows that – in the context of phenomena within a solar system, notably in planetary rings or particles in planetary magnetospheres – it is quite important to include magnetic field fields in order to properly reconstruct the dynamical behavior of these systems.[6] Magnetic field effects on the dust particles in astrophysical plasmas can be considered from two aspects. First, how does the presence of a magnetized plasma affect the coupling with the dust? And second, how does the presence of a magnetic field affect the dynamics of the charged grains?

As noted in Topics 1 and 2, the underlying phenomenon that connects the dust grains to the plasma is the charging process. Over the years, there have been many theoretical works that have modeled the charging processes in laboratory and astrophysical plasmas in the presence of magnetic fields. The magnetic field alters the ion and electron fluxes to the grains and can result in differences in the both the final charge of the grains and the distribution of charge on the grains. At the microscopic level, this could alter the agglomeration processes that lead to the growth in particle size.

In terms of direct magnetic field effects on the charged dust, at the present time it remains unclear under which regimes of the astrophysical environment that such observations could be made. While there are some theoretical works, there are few direct observations or experimental studies to validate these models. Thus, this is an area of research that is ripe for new scientific discoveries to be made.

7.3 Major opportunities

The three topical areas described in this section represent areas of scientific study that can each stand on their own merit. However, as a major thrust of this work is to make connections between laboratory studies and astrophysical processes, these three areas are particularly well-suited to be bridge the gap between the lab and space. The underlying issues of dust grain charging, dust grain growth and breakup, and the effect of the magnetic fields are all areas that have strong overlap with current and future research directions of the laboratory plasma community.

Particle charging: At the present time, there are a number of dusty plasma laboratory experiments in which the charging of the dust grains is a component of the research program. However, these studies are primarily focused on ion/electron collection from the background plasma. In order to extend this work to areas of relevance to astrophysical system, it would be necessary to have dedicated studies that are also focused on charging in intense radiation environments.

Particle growth and breakup: In the area of particle growth and breakup, there are important issues that relevant to the plasma astrophysics community that have a great deal in common with the industrial plasma processing and fusion research communities. In both of these applied areas, the formation of nanometer and micrometer sized particles from the gas phase in reactive plasma is often considered to be a major source of contamination. Nonetheless, the particles formed in these environments share a number of common features with their astrophysical counterparts – namely, the particles were charged while they were in the plasma and large particles are clearly shown to be formed from the coagulation of many smaller particles.[7,8] To date, there have only been few dedicated experiments on the formation of grain aggregation / coagulation processes.[9,10] To make progress in this area, experimental studies that can simulate specific aspects of the space plasma environment (e.g., choosing the ratio of ion, electron, dust and neutral gas densities to mirror a particular planetary nebula region) may provide a more complete representation of the processes that occur in nature. Additionally, studies performed in chemically active plasmas that can mimic processes that occur in space environments (e.g., star forming regions), may give insight into the material properties of the dust grains.

Magnetic field effects: If there is any aspect of dust-plasma interaction studies that remains essentially unexplored in the laboratory it is the role of magnetic field effects. Almost all studies to date have been performed without a magnetic field or at magnetic field strengths where only the electrons are magnetized. This is because there are significant technical challenges to building an experiment that can operate in a regime where the electrons, ions, and charged dust can be magnetized (e.g., typically requiring steady-state, multi-Tesla magnetic field strengths and the ability to detect nanometer-sized particles). There is currently one operating, 4-Tesla dusty plasma experiment and various groups in the community are planning up to 3 additional experiments to come online within the next 5 years.

These new experiments offer a unique opportunity to verify and validate which of the various numerical models have properly captured the role of the magnetic field. Moreover, studies with magnetic fields open up entirely new regimes of dust – plasma interactions that have not previously been considered. Experiments on dust transport parallel to the magnetic field, perpendicular to the magnetic field (e.g., Hall effects, $\boldsymbol{E} \times \boldsymbol{B}$), and parallel to electric fields and perpendicular to magnetic fields (e.g., Pedersen effects) can be investigated. Moreover, the study of fully magnetized plasmas with magnetized dust may allow the study of new wave modes such as dust cyclotron, dust magnetosonic, and dust Alfvén modes.

7.4 Impacts and Major Outcomes

Because the laboratory study of dusty plasmas is still in its infancy, there are many possible directions for the field to go and, subsequently, many areas of plasma physics research that could be impacted. Perhaps the most important impact of this work is gaining an understanding of a plasma in the most "general" state. Because plasmas, dust, and magnetic fields are found throughout the universe – often in combination with each other – the study of astrophysical plasmas should focus on understanding the various complex interactions among these three components. While it recognized that this is a difficult problem, a new generation of dusty plasma laboratory experiments are becoming available that may make it possible to explore aspects of this complex system.

7.5 Connections to Other Topics

The topic of dusty plasmas in astrophysical plasmas has connections to many other areas of plasma astrophysics research. In particular, studies of radiation from charged dust (Radiative Hydrodynamics group) is particularly important in interpreting data from star forming regions. Additionally, the presence of shocks (Collisionless Shock and Particle Acceleration group) can "process" dust grains leading to changes in their morphology, material characteristics, and charge state. Finally, there is already experimental evidence that the presence of charged dust grains can modify many existing plasma waves and give rise to new waves and instabilities (Waves and Turbulence group). Mapping these results to the astrophysical plasma environment represents a new area of research for the community.

[1] P. Meakin, Fractal Aggregates in Geophysics, Rev. Geophys., **29**, 317 (1991)
[2] S. Kempf, S. Pfalzner, and T. Henning, N-Particle-Simulations of Dust Growth: I. Growth Driven by Brownian Motion, Icarus, **141**, 388 (1999)
[3] J. Blum, G. Wurm, S. Kempf, et al., Growth and Form of Planetary Seedlings: Results from a Microgravity Aggregation Experiment, Phys. Rev. Lett., **85**, 2426 (2000).
[4] H. Alfvén, On the Origin of the Solar System , Oxford, Clarendon Press (1954).
[5] L. Mestel and L. Sptizer, Jr., Star formation in magnetic dust clouds, Mon. Not. Royal Astro. Soc., **116**, 503 (1956).
[6] C. Goertz, Dusty plasmas in the solar system, Rev. Geophys, **27**, 271 (1989).
[7] G. S. Selwyn, J. Singh, and R. S. Bennett, *In situ* laser diagnostic studies of plasma-generated particulate contamination, J. Vac. Sci. Technol. A, **7**, 2758 (1989)
[8] J. Winter, Dust: A new challenge in nuclear fusion research?, Phys. Plasmas, **7**, 3862 (2000).
[9] G. Praburam and J. Goree, Cosmic dust synthesis by accretion and coagulation, Astrophys. J., **441**, 830 (1995).
[10] G. Wurm, and J. Blum, Experiments on Preplanetary Dust Aggregation, Icarus, **132**, 125 (1998).