Plasma – dust interactions for astrophysical applications

While the astrophysical plasma environment is dominated by the presence of charged particles, the plasma is often strongly influenced by and coupled to other particles. This includes the background of neutral atoms that interact with the plasma ions and electron as well as larger particles such as nanometer- to micrometer-sized dust grains – which could either be neutral or charged. Understanding the processes that govern these plasma – particles interactions is critical to the study of astrophysics because it is the agglomeration and growth of larger particles from the 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, as a function of their charge-to-mass ratio, the charged species can be dominated by (e.g., electrons, ions) or at least perturbed by (e.g., dust) electromagnetic forces. The uncharged species, however, will not be directly affected by electromagnetic forces, but will be under the influence of other process present in the system. In astrophysical systems, this will primarily be the gravitational force. Nonetheless, the charged and uncharged particles interact through collisions, which transfer energy and momentum from one species to another while converting energy from one type to other types. Depending on the time scale of interest, the these two populations may be treated as moving together when the collision times are much shorter than the time of interest, or moving separately when the collision times are much longer than the time of interest. In the intermediate time scales, one species may accelerate or drag the other while the whole fluid is heated by frictional heating due to collisions among them.

The fraction of the ionized particles varies in space from nearly no ionization in cold regions to fully ionized in regions of high temperature. The densities of the neutral gas and the ionized portion may also vary in space, for instance, from highly collisional near an astronomical body to collisionless further away. The processes in one region will influence the processes in the other region through a transition region. For example, processes in highly-collisional low-ionization gas can be coupled to those in highly-ionized collisionless plasma. This is especially the case if there is a significant internal magnetic field near an astronomical or planetary body, which allows long-range coupling by electromagnetic forces in addition to short-range coupling by collisions.

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 does the plasma influence the agglomeration and growth of macroscopic particles in astrophysical environments?
2) What is the role of magnetic fields in influencing charged macroscopic particles?
3) How does the presence of neutrals atoms and/or charged or neutral macroscopic particles affect the evolution of the plasma environment?

At the heart of these three questions is a singular, overarching theme for astrophysical systems – *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. In the following sections, this report will briefly discuss each of these three topics. This will be followed by a short discussion of experimental and theoretical needs to make progress in this area.

Topic 1: How does the plasma influence the agglomeration and growth 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

---

[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).

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.

Additionally, it is found that small grains can maintain distributions of charges since they are often composed from agglomerates of even smaller particles which were themselves charged. Therefore, these aggregate particles could be modeled as dipoles or other higher order charge distributions. For example, recent simulations have shown that the arrangement of the charge on these small particles can enhance the overall growth of large dust grains.[4,5]

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 2: 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

---

[4] L. Matthews and T. W. Hyde, Charging and Growth of Fractal Dust Grains, IEEE Trans. Plasma Sci., **36**, 310 (2008).
[5] L. Matthews and T. W. Hyde, Effect of Dipole-Dipole Charge Interactions on Dust Coagulation, New J. Phys., **11**, 063030 (2009).

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[6] and Mestel and Spitzer[7] 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.[8] 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 Topic 1, 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.

Topic 3: How does the presence of neutrals atoms and/or charged or neutral macroscopic particles affect the evolution of the plasma environment?

Since the earliest days of research in plasma science, it has been recognized that the presence of neutral atoms in the plasma can have a significant dissipative effect on the plasma. Partially ionized plasma environments such as stellar chromospheres or planetary ionospheres are often the transition regions between highly ionized, collisionless regions (e.g., magnetospheres) and highly collisional, neutral-dominated regions (e.g., troposphere/stratosphere). Since the observational means and the theoretical framework for the neutrals and plasma are quite different, understanding the coupling processes between plasma and neutrals is extremely challenging, in particular in the transition region.

---

[6] H. Alfvén, On the Origin of the Solar System , Oxford, Clarendon Press (1954).
[7] L. Mestel and L. Sptizer, Jr., Star formation in magnetic dust clouds, Mon. Not. Royal Astro. Soc., **116**, 503 (1956).
[8] C. Goertz, Dusty plasmas in the solar system, Rev. Geophys, **27**, 271 (1989).

In addition to the neutrals, charged dust can also enable the modification of the background plasma. This is done through the fact the presence of charged dust grains can alter the threshold conditions for the triggering of plasma instabilities. In this way, the dust causes the modification of existing plasma modes as well as the allowing the generation of entirely new dust-driven plasma modes. A number of experiments have been performed that confirm both of these processes under laboratory conditions.[9] Moreover, there have been well over 100 papers as well as two monographs[10,11] that have discussed dust-driven wave modes and dust-modified plasma wave modes in the space environment. As with the studies of the neutrals, this is a topic of great interest that has great challenges. There remain many areas in which it remains unclear which of the competing models are indeed correct and so much work remains to be done.

Experimental and theoretical needs:

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 modification of the plasma, 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.

In the area of particle growth, this is an important issue to both the industrial plasma processing community as well as the fusion research community. In both 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.[12,13] To date, there have only been few dedicated experiments on the formation of grain aggregation / coagulation processes.[14,15] To make progress in this area, experimental studies – possibly under microgravity conditions – 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.

---

[9] R. L. Merlino, A. Barkan, C. Thompson, and N. D'Angelo, Laboratory studies of waves and instabilities in dusty plasmas, Phys. Plasmas, **5**, 1607 (1998).

[10] F. Verheest, Waves in dusty space plasmas, Kluwer Academic Press, Dordrecht, The Netherlands (2000).

[11] P. K. Shukla and A. A. Mamun, Introduction to dusty plasma physics, Institute of Physics Publishing, London (2002).

[12] 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)

[13] J. Winter, Dust: A new challenge in nuclear fusion research?, Phys. Plasmas, **7**, 3862 (2000).

[14] G. Praburam and J. Goree, Cosmic dust synthesis by accretion and coagulation, Astrophys. J., **441**, 830 (1995).

[15] G. Wurm, and J. Blum, Experiments on Preplanetary Dust Aggregation, Icarus, **132**, 125 (1998).

Beyond particle growth, much of the focus of laboratory studies of dust-plasma interactions has been on charging, transport, and instabilities. While this work is expected to continue for many years into the future, then emphasis of these studies has generally shifted away from astrophysical focus to more of an applications-based focus. Nonetheless, the fundamental studies of dust-plasma interactions in laboratory settings can provide important information to the astrophysics community – provided that new experiments can be performed that make use of appropriately scaled conditions. In particular, there needs to be a new generation of laboratory studies that can explore the full range of plasma environments that occur in nature – and many of these include magnetic fields.

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 astrophysically relevant wave modes such as dust cyclotron, dust magnetosonic, and dust Alfvén modes.

One final area in which much work remains to be done – both theoretically and experimentally – is the area of grain charging. This is of particular importance in regions with highly collisional environments or, at the other extreme, in regions with large magnetic fields. Research in laboratory dusty plasmas has given new theoretical insights into the charging mechanisms under those plasma conditions. It is important to be able to extrapolate, and then validate, those results as applied to astrophysical systems.