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Dusty Plasmas

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Introduction

Plasmas are a universal phenomenon. They are ionized gases, formed from a collection of electrons (negatively charged), ions (positively, and sometimes negatively, charged), and neutral atoms that can freely interact with each other. From the solar wind in space to bolts of lightning on Earth, plasmas can be found nearly everywhere.

Similarly, dust is all around us. On the Earth's surface, dust accumulates as tiny, solid clumps (aggregates) of material ranging anywhere in size from micrometers (about 10 times smaller than the thickness of a human hair) to millimeters (about the thickness of a fingernail). Many industrial applications have mechanical processes (for example, grinding or milling) or chemical processes (for example, the soot formed from burning hydrocarbons or microelectronic manufacturing processes with chemically active gas species) that can lead to the formation of solid nanometer to micrometer-sized dust particles.

Beyond the Earth, the presence of dust in space is a universal phenomenon. All of the solid bodies in the solar system, the planets, comets, meteorites, and even the planetary rings were formed from vast numbers of icy and rocky dust particles. Beyond our own solar system, vast structures known as planetary nebula that can be tens of light-years across are massive collections of dust and gas that will be the birthplaces of new solar systems. The physical, chemical, and thermal processes of *dusty plasmas* (sometimes called, *complex plasmas*) can connect these tiny specks of material to astrophysical objects and can link industrial processes on Earth to the formation of new planets. Figure 1 shows some examples of dusty plasma in astrophysical environments and the laboratory.

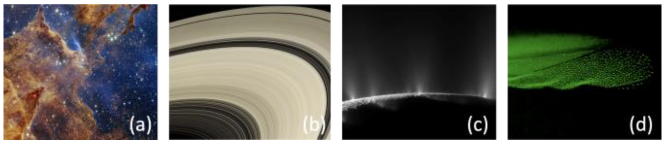

Fig. 1: Dusty plasmas can occur over a wide range of size scales in nature. (a) (*light years*) JWST image of the Eagle Nebula (); (b) (*thousands of kilometers*) Image of Saturn's Rings from the Cassini spacecraft; (c) (*hundreds of meters*) Image of charged ice volcanos on Saturn's moon Enceladus taken by the Cassini spacecraft (d) (*centimeters*) Image of a laboratory dusty plasma where 3-micron diameter silica particles are illuminated by a green laser.

Image sources: (a) https://www.nasa.gov/sites/default/files/thumbnails/image/stsci-01gfnn3pwjmy4rqxkz585bc4qh.png; (b) https://solarsystem.nasa.gov/resources/17849/translucent-arcs/; (c) https://solarsystem.nasa.gov/resources/14852/bursting-at-the-seams/; (d) E. Thomas, Auburn University

Dust particles can be introduced into a plasma through many different mechanisms:

Dust particle growth: If a plasma is made of chemically active gases (i.e., hydrogen, hydrocarbons, silicates, etc.), then the dust particles can be formed directly from chemical processes occurring in the plasma. These grown particles can come in a variety of shapes or sizes; particularly in the space environment.

Plasma-surface interactions: A variant of the particle growth process is when energetic particles from a plasma collide with a large surface (e.g., the walls of an experimental chamber, a silicon wafer, or the surface of a meteor or comet) and "knock off" atoms from the surface in a process called sputtering. These sputtered atoms can then come together to form new dust particles, again, often in a variety of shapes or sizes.

Dust injection: In many laboratory studies of dusty plasmas, researchers want to have detailed knowledge of the properties of the "dust" particles that are in the plasma. In these studies, powders of highly uniform plastic, silica, or metallic (gold, silver) spherical particles are injected into the plasma. These types of dusty plasmas made of highly uniform particles are sometimes referred to as "complex plasmas".

No matter how the dust is introduced into a plasma, the dust grains will become charged. The dust particles acquire this charge by collecting electrons and ions from the background plasma. In most laboratory experiments, the net charge is negative (due to the faster motion of the electrons than the ions) which leads to a dust particle acquiring a charge that can be tens of electrons, for nanometer-sized particles, up to thousands of electrons, for micrometer-sized particles.

In the space environment, where the dust particles not only collect charges from the plasma, but can also become charged due to radiative processes (e.g., due to ionizing radiation or ultraviolet light) this charge can either be positive or negative, depending upon the size of the particle. Regardless of the sign of the charge, it is the fundamental property that dust particles *are* charged that connects their behavior to the surrounding plasma and makes the system a "dusty plasma".

Why study dusty plasmas?

So, an obvious question is – why would anyone want to study dust in a plasma? Great question!

"Dust" particle in industry- contaminant or commodity: In the microelectronics industry, chemically active plasmas are used to perform plasma etching to form the millions of microscopic circuit elements (e.g. transistors) that are at the heart of all modern electronics. These are precisely the same conditions under which dust can be formed in a plasma! Since modern microelectronics use circuit elements that are often less than 10 nm in size, dust particles of that size can easily damage and contaminate the processed chips. However, the dust particles are not just simply a nuisance, they can be an important commodity. For example, nanoparticles are embedded in solar cells for greater light collection efficiency, can be used as anti-microbial agents, or even be used for improvements in computer memory.[1,2]

Advanced microelectronics are critical to virtually every industry – from AI to aviation to space and from healthcare to energy production– and the sale of semiconductors to those industries was over $500 billion in 2021.[3] Therefore, ensuring that nanoparticle dust contamination is minimized while selectively growing desirable nanoparticles that enhance the quality of microelectronics is of vital economic importance.

Dusty plasmas– a new way to study plasma physics: Once it was discovered that dust particles can be formed as a by-product of plasma manufacturing processes in the 1990's, a new community of plasma researchers was formed to study the properties of this new type of plasma system. The charge on the dust particles connects (or couples) the dynamics of the dust particles to the dynamics of the background plasma. But, the large mass of the dust particles (compared to the ions and electrons in the plasma) means that plasma phenomena associated with the dust are slowed down so that it is possible to directly image dusty plasma behavior using a laser to illuminate the particles and a video camera to capture movies of the particle motion.

Researchers can use the images to determine the position (from one image), the velocity (using two sequential images), and acceleration (using three sequential images) of the particles. From the velocity, quantities such as kinetic energy and thermal properties can be constructed. From the acceleration, the forces on the dust particles can be determined through Newton's second law which states that the sum of the forces that are acting on the dust particles is equal to the product of the mass and acceleration: $\sum \vec{F} = m\vec{a}$; this is illustrated in Fig. 2. Ultimately, observations of the dust particles can be turned into fundamental physical quantities that can be used to study many of the properties of the plasma such as their motion (transport), waves and instabilities, such as the dusty plasma wave seen in Fig. 1(d), or the electrical and thermodynamic processes that connect the charged dust particles to the plasma.

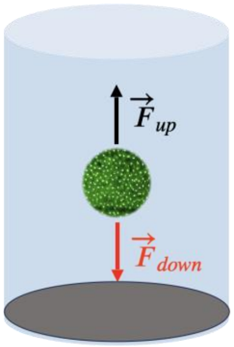

Fig. 2: A balance of forces dust particle in a laboratory dusty plasma. In order for the dust particles to be suspended in the plasma, there must be a balance between a downward gravitational force and all of the other forces acting on the particles. It is a complex balancing act between electric forces, drag forces, and interaction forces between the charged dust grains that ultimately establish this equilibrium.

Dusty plasmas– a new way to study other physical systems:

A truly amazing feature of the dusty plasmas is their ability to be used to study physical processes that can occur in other, very different, kinds of systems. In most plasmas, even though the electrons and ions want to attract each other, their motion is so fast that they only have weak interactions with each other. In many dusty plasmas, in spite of the fact that the charged dust particles are very large, they also only weakly interact with the electrons, ions, and other charged dust particles.

However, if the conditions in the dusty plasma are carefully adjusted, something remarkable happens. The dust particles can be forced to have stronger and stronger interactions with each other until, at a critical point, the dust particles can transition into a highly organized, solid-like, "strongly coupled" state known as a plasma crystal. An example of this is shown in Fig. 3. Using these plasma crystals, it is possible to study the transition of matter from solid-like to liquid-like behavior with extraordinary detail in a way that cannot be done using "normal" systems – all the while performing these studies in a plasma!

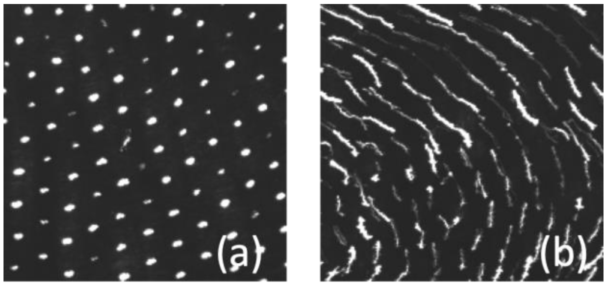

Fig. 3: Photos of a: (a) solid-like dusty plasma crystal and (b) liquid-like dusty plasma. Each photo is composed of a sum of 100 images. In (a), the particle positions are fixed over the 100 images and most particles are surrounded by 6, roughly equally spaced nearby particles. This is a indicative of a hexagonal crystal pattern that appears frequently in nature. In (b), the particles are no longer fixed and, instead, appear as streaks. This is the same set of particles as shown in (a), but the parameters in the plasma were adjusted to allow the dusty plasma crystal to "melt" and begin to flow as a liquid. [Auburn University]

Finally, recall that the dust particles are very large (compared to electrons and ions), so for experiments on Earth, gravity is an important force. What would happen without gravity? For several years, researchers have been able to carry out a series of experiments on the International Space Station called "Plasma Kristall" (now up to Plasma-Kristall-4 or PK-4) to study dusty plasmas under microgravity conditions.

Studies of both solid-like and liquid-like microgravity dusty plasmas have been performed.[4,5,6]

The future

The future for dusty plasma studies is very exciting. If we can use our knowledge of the dust – plasma interactions to select desirable plasma-grown particles, while rejecting unwanted particles, that would convert the formation of nanoparticles in plasmas into a valuable commodity that will open up new areas of plasma manufacturing.

For space-based studies, the need to understand dusty plasmas has never been greater. We know that dust particles can be transported even on airless bodies such as the moon, meteors, and comets, which means that some type of electromagnetic / plasma processes must be involved. As humans venture to the moon and beyond, understanding transport processes in dusty plasmas is not only a matter of scientific curiosity, it is necessary for the safety of future space explorers!

If you would like more technical information about dusty plasmas, consider the recent review article by R. Merlino, for an excellent technical overview of the state of the field.[7]

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References/suggested reading

[1] H.J. Jang, E.Y. Jung, T. Parsons, H.-S. Tae, and C.-S. Park, "A Review of Plasma Synthesis Methods for Polymer Films and Nanoparticles under Atmospheric Pressure Conditions," Polymers-Basel **13**(14), 2267 (2021).

[2] P.G. Jamkhande, N.W. Ghule, A.H. Bamer, and M.G. Kalaskar, "Metal nanoparticles synthesis: An overview on methods of preparation, advantages and disadvantages, and applications," J Drug Deliv Sci Tec **53**, 101174 (2019).

[3] Semiconductor Industry Association, "2022 State of the U. S. Semiconductor Industry", p. 16 (2022); https://www.semiconductors.org/wp-content/uploads/2022/11/SIA_State-of-Industry-Report_Nov-2022.pdf

[4] H.M. Thomas, G.E. Morfill, A.V. Ivlev, A.P. Nefedov, V.E. Fortov, H. Rothermel, M. Rubin-Zuzic, A.M. Lipaev, V.I. Molotkov, and O.F. Petrov, "PKE-Nefedov — Complex plasma research on the international space station," Microgravity- Sci Technology **16**(1–4), 317–321 (2005).

[5] H.M. Thomas, G.E. Morfill, V.E. Fortov, A.V. Ivlev, V.I. Molotkov, A.M. Lipaev, T. Hagl, H. Rothermel, S.A. Khrapak, R.K. Suetterlin, M. Rubin-Zuzic, O.F. Petrov, V.I. Tokarev, and S.K. Krikalev, "Complex plasma laboratory PK-3 Plus on the International Space Station," New J. Phys. **10**(3), 033036–15 (2008).

[6] M.Y. Pustylnik, M.A. Fink, V. Nosenko, T. Antonova, T. Hagl, H.M. Thomas, A.V. Zobnin, A.M. Lipaev, A.D. Usachev, V.I. Molotkov, O.F. Petrov, V.E. Fortov, C. Rau, C. Deysenroth, S. Albrecht, M. Kretschmer, M.H. Thoma, G.E. Morfill, R. Seurig, A. Stettner, V.A. Alyamovskaya, A. Orr, E. Kufner, E.G. Lavrenko, G.I. Padalka, E.O. Serova, A.M. Samokutyayev, and S. Christoforetti, "Plasmakristall-4: New complex (dusty) plasma laboratory on board the International Space Station," Rev. Sci. Instrum. **87**(9), 093505–17 (2016).

[7] R. Merlino, "Dusty plasmas: from Saturn's rings to semiconductor processing devices," Adv Phys X **6**(1), 1873859 (2021).

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Dr. Edward Thomas, Jr. is a Professor of Physics and Dean of the College of Sciences and Mathematics (COSAM) at Auburn University. He previously served as the Associate Dean for Research and Graduate Studies in COSAM. He earned his B.S. in Physics at Florida Tech, an M.S. in Physics at MIT, and Ph.D. in Physics from Auburn University. Dr. Thomas began his research career studying edge particle transport in fusion plasmas. Over the years, his work has become centered on fundamental plasma physics where his group conducts experimental, computational, and microgravity research on dusty (complex) plasmas, magnetized plasmas and plasma diagnostic development – with an emphasis on particle, wave, and energy transport in low temperature plasmas and laboratory simulations of the space environment. Prof. Thomas and his team have published over 100 scientific articles, have made over 400 invited and contributed presentations at scientific meetings, and have received research funding from the NSF, Dept. of Energy, NASA, and the Dept. of Defense. He is an elected member of the International Union of Radio Science (URSI) – Commission H, a Fellow of the American Physical Society and the National Society of Black Physicists and has served as a member of numerous advisory committees for the APS, NSF, DOE, National Academies of Sciences, and the European Space Agency. He is also currently serving as Chair-Elect of the American Physical Society - Division of Plasma Physics and is a member of IEEE.