Modeling of Voids in Colloidal Plasmas

M.R. Akdim and W.J. Goedheer
FOM-Institute for Plasmaphysics 'Rijnhuizen'
P.O.box 1207, 3430 BE Nieuwegein, the Netherlands
akdim@rijnh.nl and goedheer@rijnh.nl

Plasma crystal experiments under microgravity show that noble gas discharges often feature a stable void, i.e., a dust-free region inside a dust cloud produced by injection of dust particles. The void appears due to the balance between the forces acting on a dust particle. The most significant forces are the electrostatic, ion drag and thermophoretic force. In plasma crystal experiments two processes may generate the temperature gradient needed for the thermophoretic force. The ion flux towards the reactor walls can heat the surface and ion-neutral collisions can heat up the background gas. Modeling proves to be a powerful tool to get some understanding concerning the physics of these complex plasmas. Here we report on an investigation of these voids by means of a two dimensional model of a capacitively coupled dust containing rf plasma in which the particle balances, Poisson equation and the electron energy balance are solved self-consistently. The transport of dust is taken into account. Important mechanisms as well as charging of the dust and recombination of ions and electrons on the dust surface are included, the heating of the background gas due to ion-neutral collisions is included. Modeling results show that the thermophoretic force can not be used to give a full explanation of the appearance of the void. The ion drag appears to be small in the bulk of the plasma because of the small "linearized" Debye length, however replacement of the "linearized" Debye length by the electron Debye length or enhancement of the ion drag with a certain factor (of the order 15) results in an appearance of a void. [Fig.1.].

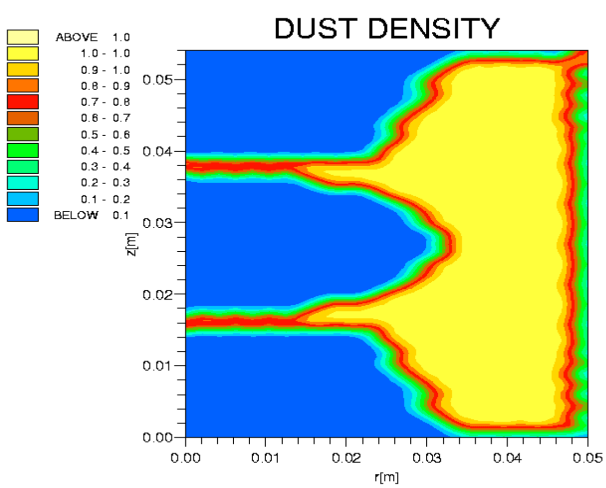

Fig.1. The dust density plotted as function of position. The dust density is normalized with a factor $2.2*10^9$. PKE geometry[1]. Electrodes are in the region (r < 2.4 cm and 1.2 > z > 4.2 cm).

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[1] G. E. Morfill et al, Phys. Rev. Lett. 83, 1598-1601 (1999).
[2] H. Thomas, G. E. Morfill, and V. Demmel, Phys. Rev. Lett. 73, 652-655 (1994).
[3] J. Goree et al, Phys. Rev. E 59, 7055-7067 (1999).

Anisotropic Dust Lattice Modes and Stability of Two-Dimensional Plasma Crystals

A. V. Ivlev and G. Morfill
Max-Planck-Institut für Extraterrestrische Physik
D-85740 Garching, Germany
ivlev@mpe.mpg.de, www.mpe.mpg.de/pke

We study longitudinal and transverse dust lattice (DL) waves in a horizontal monolayer of particles suspended in the plasma sheath. The ion flow in the sheath introduces an anisotropy, in particular "ion wakes" below the crystal particles. Using a simplified model of the wake[1] we demonstrate that the vertical transverse DL mode and the longitudinal DL mode are coupled due to the particle-wake interaction. The longitudinal wave has acoustic dispersion ($\partial\omega/\partial k>0$), whereas the transverse wave is described by inverse optical-like characteristics ($\partial\omega/\partial k<0$). Therefore, the branches $\omega(k)$ of these modes can intersect at a certain point, (ω_0, k_0), as shown in Fig. 1. The wake-induced coupling close to this point can drive an instability of the modes if the particle density in a monolayer is sufficiently high.[2] Analysis shows that for typical experimental conditions the growth rate of the wake-induced instability can exceed the damping due to neutral gas friction. Thus the instability might be responsible for observed melting of 2D plasma crystals.

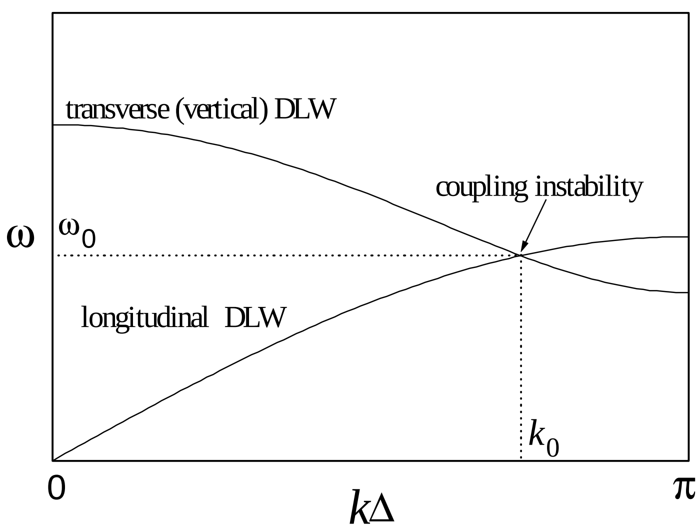

Figure 1. Dispersion relation, $\omega(k)$, of the longitudinal and transverse (vertical) dust lattice waves. The particle-wake interaction causes the coupling of the modes close to the intersection point, (ω_0, k_0), and can drive an instability (the first Brillouin zone for 1D particle string is shown, $0<k\Delta<\pi$, with Δ the particle separation).

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[1] V. Steinberg, R. Sütterlin, A. V. Ivlev, and G. Morfill. Vertical pairing of identical particles suspended in the plasma sheath (to be published in Phys. Rev. Lett., 2001)

[2] A. V. Ivlev and G. Morfill. Anisotropic dust lattice modes, Phys. Rev. E **63**, 016409 (2001)

Similarity of Microtubules in Tokamak Dust and Macrotubules in Tokamak Plasma

B.N. Kolbasov, A.B. Kukushkin, V.A. Rantsev-Kartinov, P.V. Romanov
INF RRC "Kurchatov Institute", Moscow, 123182, Russia
rank@nfi.kiae.ru

For verifying the hypothesis[1] for the presence, in the observed long-living filaments, of a microsolid skeleton assembled, during electric breakdown, from wildly formed (carbon) nanotubes, and for survivability of such skeletons in hot plasmas,[2(a,b)] an analysis of the database on the electron transmission and scanning micrography of various types of dust deposit in tokamak T-10 was carried out. This included (i) dust particles deposited at a glass filter while they were pumped out from a crimp in the tokamak vacuum chamber; (ii) dust particles extracted from the oil used in the tokamak vacuum pumping system; (iii) thin films deposited at the internal surface of the tokamak vacuum chamber; (iv) dust particles deposited at a collector mounted on a stock located in the vacuum chamber well outside the plasma column. Previous results [3] showed the presence of (i) tubules of the size typical for individual carbon multilayer nanotubes (from few nanometers to few tens of nanometers); (ii) tubular structures of diameter 50-100 nm, which are built from smaller tubules; (iii) on the surface of the films, tubular structures of micrometer diameter which, in turn, include tubules of smaller diameter as constituent blocks. The present analysis shows that tubular structures of diameter in nanometer range build up the skeletons of various topology and spatial dimensionality, namely fibers, spheres, balls, dendritic structures, etc.. For all types of skeletons, contrary to quasi-continuous amorphous media, a tubular structure seems to be a key building block.

The above results are compatible with hypothesis[1] in the sense that the trend of assembling bigger tubules from smaller ones, which is shown in the nanometer and micrometer ranges (in the dust deposits), may go to much larger length scales, the centimeter range, as it follows from the similarity of structures of easily distinguishable topology (namely, tubules and especially cartwheels often located in the edge cross-section of a tubule) in the dust deposits and in the visible light images[2(a,c)] of plasma in tokamaks TM-2, T-4, T-6 and T-10 (see Figs. 1 and 2 from Ref. [3]).

Fig. 1

Fig. 2

Fig. 1. The «cartwheel» structure in tokamak TM-2 plasma. Diameters of larger and smaller ring-shaped structures on a common axle are ~2.2 cm and ~1 cm, respectively. Diameter of the axle at the cartwheel's plane is ~ 2 mm. Image is taken in the visible light with the help of a strick camera.

Fig. 2. The TEM image of small fragment of dust particle (1.2 mcm diameter) extracted from the oil used in the vacuum pumping system of tokamak T-10 (magnification 34,000). The tubule whose edge with the distinct central rod is seen in the lower left part of the figure, is of ~70 nm diameter and ~140 nm long. Diameter of slightly inhomogeneous cylinder which is seen on the left side of the tubule and is a constituent part of the tubule, is ~10 nm. The radial bonds between the side-on cylinder and the central rod are of ~ 10 nm diameter.

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1 Kukushkin A.B., Rantsev-Kartinov V.A., (a) *Fusion Energy 1998* (IAEA, Vienna, 1999, IAEA-CSP-1/P, Vol. 3) pp. 1131-1134; (b) In: *Current Trends in Int. Fusion Research: Review and Assessment* (Proc. 3rd Symposium, Washington D.C., 1999, Ed. E. Panarella, NRC Research Press, Ottawa, Canada), pp. 107-136; (c) Proc. 26-th Eur. Phys. Soc. conf. on Plasma Phys. and Contr. Fusion, Maastricht, Netherlands, 1999, pp. 873-876 (http://epsppd.epfl.ch/cross/p2087.htm).

2 Kukushkin A.B. Rantsev-Kartinov V.A., (a) Preprint of Kurchatov Institute, IAE 6157/6, Moscow, October 1999; (b) Proc. 27-th Eur. Phys. Soc. conf. on Plasma Phys. and Contr. Fusion, Budapest, Hungary, June 2000 (http://sgi30.rmki.kfki.hu/EPS2000/P2_028.pdf); (c) Ibid., http://...P2_029.pdf.

3 Kolbasov B.N., Kukushkin A.B., Rantsev-Kartinov V.A., Romanov P.V., Phys. Lett. A269, 363-367 (2000).

Electrostatic Discharging of Dust near the Surface of Mars

C.E. Krauss, M. Horányi, S. Robertson
LASP, University of Colorado
Boulder, CO 80309
kraussc@colorado.edu

Due to the prevalence of Martian dust devils and dust storms, an understanding of the underlying physics of electrical discharges in Martian dust is critical to future Mars exploratory missions. When dust particles with different compositions come into contact, charge can be transferred between the grains. This effect is referred to as triboelectric charging. Wind driven dust studies show that in the case of particles with identical compositions, the particle with the larger radius in a collision preferentially becomes positively charged.[1] The stratification of particle sizes generated by upwinds within a dust cloud causes an electric dipole to form. When the electric potential within the cloud exceeds the breakdown voltage of the surrounding atmosphere, a discharge occurs.

Numerous environmental factors have led to the conclusion that dust near the surface of Mars is even more susceptible to triboelectric charging and subsequent electrical discharges than dust on Earth. The atmospheric breakdown electric field, E_b, is dependent on the atmospheric pressure and composition. Since the average atmospheric pressure on the surface of Mars is 4.5–6 Torr compared to Earth's 760 Torr, E_b on Mars is expected to be ≈ 20 kV/m while E_b on Earth is ≈ 3000 kV/m. This lower value for E_b implies that lightning discharges on Mars should occur more frequently but at lower intensities than those seen on Earth. In addition, the dry Martian environment is helpful in maintaining charge separation since low humidity decreases conductivity. Finally, if dust particles are to charge via contact with one another, sufficiently strong winds must be present to facilitate the dust motion. Based on laboratory experiments and *in situ* measurements, dust particles are expected to move on the surface of Mars with frictional wind velocities on the order of 1 m/sec.[2] Wind velocities greater than this were observed by Mars Pathfinder. Measurements done in our lab on the charging of single dust grains show that particles of JSC-Mars-1, a Martian regolith simulant, can have large electrical potentials due to triboelectric charging.[3] We have conducted experiments to determine the range of pressures and wind speeds over which discharges can be observed. When JSC-Mars-1 is agitated in a low-pressure CO_2 atmosphere, electrical discharges are electronically detected. Under extremely dark viewing conditions, these electrical discharges are visually observed in the laboratory at pressures between 0.1 and 50 Torr. Measurements of the frequency and intensity of these discharges as a function of pressure (from 0.5 to 7.3 Torr) and stirring speed (corresponding to wind speeds from 0.1 to 5 m/sec) show that discharges occur at pressure and wind speeds similar to those expected on the Martian surface.

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[1] C.D. Stow, Dust and sand storm electrification, Weather, 24, 134-140, 1969.

[2] B.R. White, B.M. Lacchia, R. Greeley, and R.N. Leach, Aeolian behavior of dust in a simulated martian environment, J. Geophys. Res., 102, 25629-25640, 1997.

[3] A.A. Sickafoose, J.E. Colwell, M. Horányi, and S. Robertson, Experimental investigations on photoelectric and triboelectric charging of dust, J. Geophys. Res., to appear, 2001.

Long-Lived Filaments in Plasmas and Hypothesis of Microdust-Assembled Skeletons

A.B. Kukushkin, V.A. Rantsev-Kartinov
INF RRC "Kurchatov Institute", Moscow, 123182, Russia
kuka@nfi.kiae.ru

A short review is given of (i) the progress in studying the long-lived filaments (LLFs) in fusion plasmas (tokamaks, Z-pinch, plasma focus) and (ii) verification of hypothesis[1] which suggested the LLFs to possess a microsolid skeleton which might be assembled during electric breakdown from wildly produced carbon nanotubes (or similar nanostructures of other chemical elements). This includes:

1. Evidences for straight tubular filaments, several centimeters long and longer, often directed nearly radially, are found in the databases of high-resolution visible light images of plasma in tokamaks TM-2, T-4, T-6, T-10 (time resolution $\Delta t\sim 1\text{-}15\ \mu s$),[2(a,b,f)] gaseous Z-pinch ($\Delta t\sim 2\text{-}60$ ns),[2(a,d)] and plasma focus ($\Delta t\sim 2$ ns).[2(d)] The pictures were taken by a strick camera, an electronic optical converter (EOC), and a fast-framing camera.

2. Evidences for tubular structures in the range from several nanometers to several micrometers in diameter are found in the electronic micrographs of various types of dust deposit (submicron and micron particles, and films, mostly carbon ones) in tokamak T-10.[3] The trend of assembling bigger tubules from smaller ones is found.[3] Also, the topological similarity of cartwheel-like structures (either located in the edge cross-section of a tubule or as a separate block) in the above dust and in the few centimeters-sized structures seen in the plasma images in small tokamaks,[2(a,b,f)] is found.[3]

3. The presence of skeletons (tubules and cartwheels of millimeter size) at initial, «dark» stage of electric discharges (in which long-lived filamentary structures form) was shown[4] via laser shadowgraphy of a vacuum spark (at the «dark» stage the plasma's self-emission is not yet detectable by an EOC). Similar structures at electric breakdown stage are found in the visible light images of plasma in tokamak T-6.[2(f)]

4. In developing the hypothesis,[1] the microsolid skeletons were suggested[2(a,c,e)] to be self-protected from an ambient high-temperature plasma by the thin vacuum channels sustained around the skeletons by the pressure of the skeleton-induced high-frequency (HF) electromagnetic waves of the TEM type (a «wild cable» model[2(a,c)]). This model was shown to be compatible with measurements of HF electric fields in tokamak T-10, both inside and outside plasma column, and in a gaseous Z-pinch.

The above data, and their predictability,[1] show that the presence of a condensed matter in plasmas may be extended to the case of (i) assembling of *skeletons*, (ii) their survivability in *hot* plasmas, (iii) essential contribution of *magnetic* coupling (i.e. far beyond the frames of strongly coupled *Coulomb* systems).

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[1] A.B. Kukushkin and V.A. Rantsev-Kartinov, *Fusion Energy 1998* (IAEA, Vienna, 1999, IAEA-CSP-1/P, Vol. 3) pp. 1131-1134; In: *Current Trends in Int. Fusion Research: Review and Assessment* (Proc. 3rd Symposium, Washington D.C., 1999, Ed. E. Panarella, NRC Research Press, Ottawa, Canada), pp.107-136; Proc. 26-th EPS PPCF (Maastricht, Netherlands, 1999) pp. 873-876 (http://epsppd.epfl.ch/cross/p2087.htm).

[2] A.B. Kukushkin and V.A. Rantsev-Kartinov, (a) Proc. Innovative Confinement Concepts Workshop (Lawrence Berkeley Lab., Berkeley, CA, USA, 2000; http://icc2000.lbl.gov/proceed.html...); (b) Proc. 27-th Eur. Phys. Soc. conf. on PPCF, Budapest, Hungary, June 2000, http://sgi30.rmki.kfki.hu/EPS2000/P2_029.pdf; (c) Ibid., http://...P2_028.pdf; (d) Ibid., http://...P2_051.pdf; (e) Rev. Sci. Instrum., 72 (#1, Part II), 506-507 (2001); (f) V.A. Krupin, V.A. Rantsev-Kartinov, A.B. Kukushkin, Abstracts XXVIII Zvenigorod Conf. on Plasma Phys. and Contr. Fusion (February 2001).

[3] B.N. Kolbasov, A.B. Kukushkin, V.A. Rantsev-Kartinov, P.V. Romanov, Phys. Lett. A269, 363-367 (2000).

[4] A.B. Kukushkin, V.A. Rantsev-Kartinov, D.E. Prokhorovich, P.A. Sivko, and A.S. Savjolov, Mat. 2nd Russian Symp. on Plasma Diagnostics (Moscow Engineering & Phys. Inst., Moscow, 2000) pp. 53-55 (in Russian).

Modified Stoermer Problem

C. J. Mitchell, M. Horanyi
Lasp, University of Colorado
Boulder, CO 80309
mitchelc@ucsub.colorado.edu

The motion of a charged particle moving in a dipole field was treated by Stoermer in his monograph *The Polar Aurora* (Stoermer, 1955)[1]. Though the Stoermer problem is a good description for highly charged particles in a planetary magnetosphere, it neglects both the planet's gravitational and electric fields. These have little effect upon ions and electrons due to their high charge to mass ratios and the fact that E x B drifts are the same for both ions and electrons. However, when dealing with highly charged dust grains the effects of these fields can no longer be ignored since upon varying the charge a point will be reached where the effects of gravity are comparable to those of electromagnetism.

A linearized theory[2] was used to predict the motions of particles of varying charge to mass ratios in the planet's equatorial plane. The particle was assumed to move in an ellipse in a frame which is rotating with the mean motion of the particle. The size and shape of this ellipse as well as the mean angular velocity of the particle is predicted and compared to the results of computer simulation. Particles with charges of both signs are considered as well as prograde and retrograde orbits. Cases are also considered where the orbits are both inside and outside of the corotation radius.

Since Cassini is due to arrive at Saturn in three years, The mass, rotation rate, and magnetic field of Saturn were used in these simulations. With these parameters it was found that only negatively charged, prograde particles have a smooth transition from Keplerian orbits to corotating ones. All other cases are either ejected from orbit or crash into the planet at some point as the charge to mass ratio varied.

Because linear theory was used, predictions for particles which undergo large radial excursions differ from those determined by the simulation. It was found that the shape of the ellipse varied considerably from predictions and that in some cases the trajectory was far from elliptical in the simulation.

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[1] Stoermer, C., 1955, *The Polar Aurora*, London: oxford University Press.

[2] Mendis, D. A., Houpis, L. F., Hill, J. R., The Gravito-Electrodynamics of Charged Dust in Planetary Magnetospheres, *J. Geophys. Res.*, 87, 3449, 1982.

Formation of Dust Ion Acoustic Shocks in Complex Plasmas

Sergey I. Popel[(a)], Anatoly P. Golub'[(a)], Tatiana V. Losseva[(a)], and Robert Bingham[(b)]
[(a)]Institute for Dynamics of Geospheres, Leninsky pr. 38-6, Moscow 117334, Russia
[(b)]Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX 11 OQX, UK
popel@idg1.chph.ras.ru

The non-stationary problem of the evolution of perturbation and its transformation into nonlinear wave structure in complex plasmas is considered. For this purpose the model based on a set of fluid equations, Poisson's equation, and a charging equation for dust is developed[1]. The model takes into account the variation of the ion density and the ion momentum dissipation due to dust particle charging as well as the source of plasma particles due to ionization process. We refer to this model as the ionization source model. The model is appropriate for the description of laboratory experiments in complex plasmas and contains the most important basic mechanisms responsible for the formation of a new kind of shock waves, which are related to the anomalous dissipation due to dust particle charging process. The numerical data obtained on the basis of the ionization source model and the simplified model (used[2] to show the possibility of the existence of the exact steady-state shock wave solutions related to the dissipation originating from the dust particle charging process) are compared.

The consideration on the basis of the ionization source model allows us to obtain shock structures as a result of evolution of an initial perturbation, and (for large enough dust densities) to explain the experimental value of the width of the ion acoustic shock wave front as well as the shock wave speed. In Fig. 1, which is constructed by analogy with Fig. 2b in Ref. 3, the dependence of ion density on time for different axial positions from the grid of the experimental installation[3] is shown. The parameters correspond to those of Ref. 3 ($\varepsilon Z \approx 0.75$). The profiles of the perturbations are shown by bold lines. The sets of thin lines indicate some steepening (shock formation).

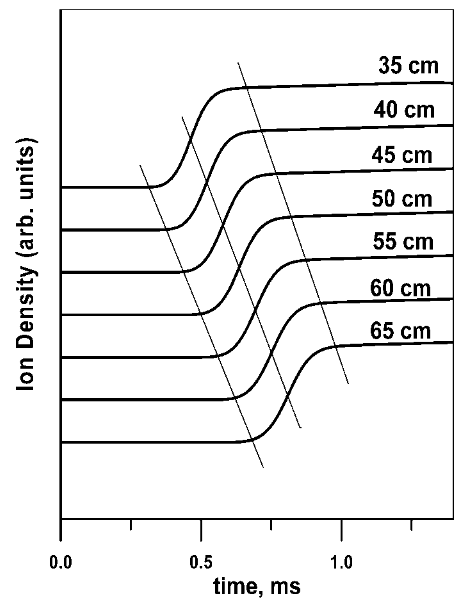

Fig. 1.

The solution of the problem of the evolution of perturbation and its transformation into shock wave in complex plasmas opens up possibilities for description of the real phenomena like supernova explosions as well as of the laboratory and active space and geophysical experiments.

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1 S.I. Popel, A.P. Golub', T.V. Losseva, and R. Bingham, *Formation of Shocks Related to Dust-Particle Charging in Complex Plasmas*, JETP Letters **73**, 223-227, 2001; S.I. Popel, A.P. Golub', T.V. Losseva, R. Bingham, and S. Benkadda, *Evolution of Perturbation in Charge-Varying Dusty Plasmas*, Phys. Plasmas **8**, No. 5, 2001, in press.

2 S.I. Popel, M.Y. Yu, and V.N. Tsytovich, *Shock Waves in Plasmas Containing Variable-Charge Impurities*, Phys. Plasmas **3**, 4313-4315, 1996.

3 Q.-Z. Luo, N. D'Angelo, and R. Merlino, *Experimental Study of Shock Formation in a Dusty Plasma*, Phys. Plasmas **6**, 3455-3458, 1999.

Coulomb coupling and screening parameters from wave dispersion in a stratified binary mixture

R. A. Quinn, A. Ivlev, H. Rothermel, G. E. Morfill
Max Planck Institute
85478 Garching, Germany
raq@mpe.mpg.de

Two of the key parameters in describing strongly coupled complex plasmas are the Coulomb coupling (Γ) and the screening (κ) parameters. Typically, wave experiments in complex plasmas only yield information about the relation between Γ and κ (through the dispersion relation), but cannot uniquely identify both in one experiment.

Here we present a wave experiment in a large-scale stratified binary mixture. Plane waves are propagated normal to the interface, and the resulting dispersion relations in the two regions are computed. From this information, and a relevant theory which includes information about the boundary conditions, Γ and κ are jointly determined in a single experiment.

Ion currents on droplets in plasma

Scott Robertson, Zoltán Sternovsky, and Mihály Horányi

Physics Department, University of Colorado, Boulder, Colorado 80309 – 0390

robertso@stripe.colorado.edu, http://debye.colorado.edu

Preliminary results are presented on charging of droplets by plasma ions. The droplets are made of vacuum pump oils and dropped from a ~ 200 μm i.d. metallic capillary. The flow of the oil is controlled by a fine syringe pump what allows the calculation of the droplet size from the frequency of dropping. Prior to the dropping the droplets are negatively charged by keeping the capillary negatively biased. The initial charge on the droplets can be measured and the corresponding surface potential can be calculated.

The charged droplets fall through a column of plasma that is created in argon gas by electron emission (up to 50 mA) from heated tungsten filaments. Because of the initial negative charge of the droplets, plasma electrons cannot reach the surface of the droplets and thus the ion current is the only charging mechanism. The plasma parameters are adjusted so that the final charge on the droplets (measured beneath in a Faraday cap) does not reach equilibrium and still much more negative than the charge corresponding to the floating potential.

Modeling of magneto-dynamics of dusty astrophysical plasmas in laboratory

L. I. Rudakov
MIT, Department of Physics
rudakovl@wam.umd.edu

It is well known that most astrophysical plasmas contain charged dust particles. To support the quasi-neutrality in dusty plasma strong Hall electric field arises. The Hall electric field in 2D geometry is not a potential one. As a result, magnetic field may penetrate even in motionless plasma as a magnetic shock wave. This phenomenon was investigated theoretically and experimentally for laboratory plasmas during last 15 years. The breaking of MHD "frozen-in" law may occur in such astrophysical objects as dense molecular clouds and dark circumstellar disks of young stars and may affect shock structure, efficiency of dynamo and magnetic field reconnection [1]. Hall physics take place if $M_d n_d >> M_i n_i$ and $(n_i/w_{ci})^2 << (n_d z_d/n_i)^2$. M_p, z_p, n_p, $w_{cp} = ez_pB/cM_p$, $w_{pp} = (4pe^2 z_p^2 n_p/M_p)^{1/2}$ are the mass and charge of particles ($p = i$ refer to ions, $p = d$ to dust), density, cyclotron and plasma frequencies. n_i is the rate of momentum exchange of the plasma ions with neutrals and dust particles.

As a result, in interstellar matter we have two very different ranges of plasma dynamics and turbulence where we should take into account Hall physics. Those are high frequency, $w >> w_{ci} > 10^{-1}s^{-1}$, short scale, $l < c/w_{pi} < 10^9 cm$, turbulence and low frequency, $w >> w_{cd} > 10^{-9}s^{-1}$, long scale, $l < c/w_{pd} < 10^{15} cm$, turbulence.

It is not simple to create magnetized dusty plasma inside a vacuum chamber of reasonable radius R with both ion and dust inertial scales c/w_{pi} and c/w_{pd} less then R. For the dust particles with radius $a = 0.03mm$ in a plasma with temperature $T = 30\ eV$ n_d must be larger than $10^{12}\ cm^{-3}$. But there is an option of a laboratory experiment with the mixture of hydrogen and xenon (atomic weight $A = 132$) gases. The inertial scales of xenon with charge z and protons are related as A/z for the same mass density. If $T = 30\ eV$ xenon will be ionized to $z = 4\text{-}5$ and A/z » 25.

Let us give an example of experimental device and plasma parameters. A dielectric plasma chamber has a radius of $50\ cm$ and is $100\ cm$ long. A steady state axial magnetic field of about $1000\ Gauss$ is created by a Helmholtz coil. A rising in time $\approx 10^{-5}s$ axial magnetic field, of about the same amplitude and opposite direction, is created by a single-turn current coil fed by an electrical capacitor battery. The width of the layer where the magnetic field reverses direction is about $30\ cm$. We suggest the set of plasma parameters: $n_i = 10^{14}\ cm^{-3}$, $n_{xe} = 3$´$10^{12}\ cm^{-3}$, $T = 30\text{-}100\ eV$, $z_{xe} = 5\text{-}8$, $n_i = (2\text{-}1)$´$10^5\ s^{-1}$. In such a plasma the scale of short wave turbulence are $l < c/w_{pi} = 3\ cm$. The scale of long wae turbulence are $l < c/w_{pxe} = 30\ cm$. Electrons and hydrogen ions are magnetized. Xenon ions are non-magnetized. They are captured in a Hall potential well $U = B^2/8pezn_{xe}$ having width of $c/w_{pxe} = 30\ cm$.

1. L.I. Rudakov, Physica Scripta, v. T89, 158-162 (2001).

Experimental Dust Levitation Near Surfaces

A.A. Sickafoose, J.E. Colwell, M. Horányi, and S. Robertson
LASP, University of Colorado
Boulder, Colorado 80309
amanda@casper.colorado.edu, http://debye.colorado.edu/

Dust grains suspended above the lunar surface have been observed on multiple occasions. A horizon glow roughly one meter above the surface of the Moon was detected by Surveyors 5, 6, and 7[1]. Apollo astronauts observed high altitude streaks due to scattered light from particles extending up to 100 km from the lunar surface, and a dim horizon glow 10 to 20 km above the lunar surface was observed by the Clementine spacecraft. In addition, the Lunar Ejecta and Meteorite Experiment (LEAM) deployed by Apollo 17 recorded evidence for horizontal dust transport on the surface of the Moon during terminator crossings. The interaction between charged dust particles and a photoelectron layer above the surface of the Moon is the most likely explanation for these observed dust dynamics.

Dust dynamics also occur in planetary ring systems, as confirmed by Voyager's discovery of spokes in Saturn's B-ring in 1981. These features are most likely clouds of particles electrostatically levitated off the surfaces of larger bodies in the ring and into a plasma cloud created by meteoritic impacts[2]. Virtually all small, airless bodies in the solar system are coated with a dusty regolith; therefore, charged dust particle levitation and transport may occur on Mars, Mercury, planetary satellites, asteroids, and comets[3]. Thus, dust charging and dynamics are important in interpreting observations of planetary bodies, analyzing the evolution of planetary ring systems, and preventing contamination of instruments on planetary surfaces.

We have conducted experiments to measure the charging of isolated dust grains from photoemission, from interaction with a photoelectron sheath, and from triboelectric charging[4]. The particles tested are 90-106 μm in diameter and composed of zinc, copper, graphite, glass, SiC, lunar regolith simulant (JSC-1), or martian regolith simulant (JSC Mars-1). We are currently performing experiments on the charging, levitation, and dynamics of glass microballoons < 45 μm in diameter. These particles rest on a flat plate surrounded by an Ar plasma sheath. Sheath characteristics are determined through Langmuir probe and floating potential probe sweeps. An agitator under the surface provides a disturbance to inject dust into the sheath. Dust particles levitating above the surface of the plate are illuminated by an Ar laser. Levitated dust particle dynamics are then observed and recorded by a video camera.

This work is supported by NASA Microgravity Fluid Physics Program and NASA Office of Space Sciences GSRP.

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[1] J.J. Rennilson and D.R. Criswell, Surveyor observations of lunar horizon glow, The Moon, 10, 121-142, 1974.
[2] C.K. Goertz, Dusty plasmas in the solar system, Reviews of Geophysics, 27 (2), 271-292, 1989; T. Nitter, O. Havnes, and F. Melandsø, Levitation and dynamics of charged dust in the photoelectron sheath above surfaces in space, J. Geophys. Res., 103, 6605-6620, 1998.
[3] R. Grard, Solar photon interaction with the martian surface and related electrical and chemical phenomena, Icarus, 114, 130-138, 1995; W.H. Ip, Electrostatic charging and dust transport at Mercury's surface, Geophys. Res. Lett., 13, 1133-1136, 1986; P. Lee, Dust levitation on asteroids, Icarus, 124, 181-194, 1996; D.A. Mendis, J.R. Hill, H.L.F. Houpis, and E.C. Whipple, Jr., On the electrostatic charging of the cometary nucleus, Astrophys. J., 249, 787-797, 1981.
[4] A.A. Sickafoose, J.E. Colwell, M. Horányi, and S. Robertson, Experimental investigations on photoelectric and triboelectric charging of dust, JGR, to appear, 2001.

Particle Formation and Growth in an Acetylene RF-Discharge

S. Stoykov, C. Eggs, U. Kortshagen
University of Minnesota, Dept. of Mechanical Engineering,
111 Church St. S.E., Minneapolis, MN 55455

A model describing the chemical clustering kinetics in a low-pressure acetylene RF discharge has been developed[1]. The model contains neutral chain and cyclic hydrocarbons, positive and negative ions, and electrons. The gas-phase chemistry includes neutral-neutral reactions, electron-induced H-abstraction, electron attachment, and ion-ion neutralization. In addition, diffusion losses to the reactor walls are considered. The model predicts the time evolution of species concentrations and chemical reaction rates, and reveals the preferred clustering pathways. We have found that after the initial phase of rapid chemical nucleation, a steady state is reached due to a balance between the species production by chemical reactions and diffusion losses to the walls. The steady state composition is affected by the plasma parameters − gas temperature, degree of ionization (RF power density), and pressure. Regimes with enhanced and inhibited coagulation are identified based on the ratio between neutral and charged particles[2] (Figure 1). The clustering occurs mainly through addition of growth species and formation of linear molecules. However, the amount of aromatic compounds is considerable even at room temperature and increases strongly with the gas temperature. The performed FTIR and NMR measurements indicate aromatic presence in the produced particles. We believe that the formation of cyclic structures is an underlying theme of particle generation in acetylene plasmas.

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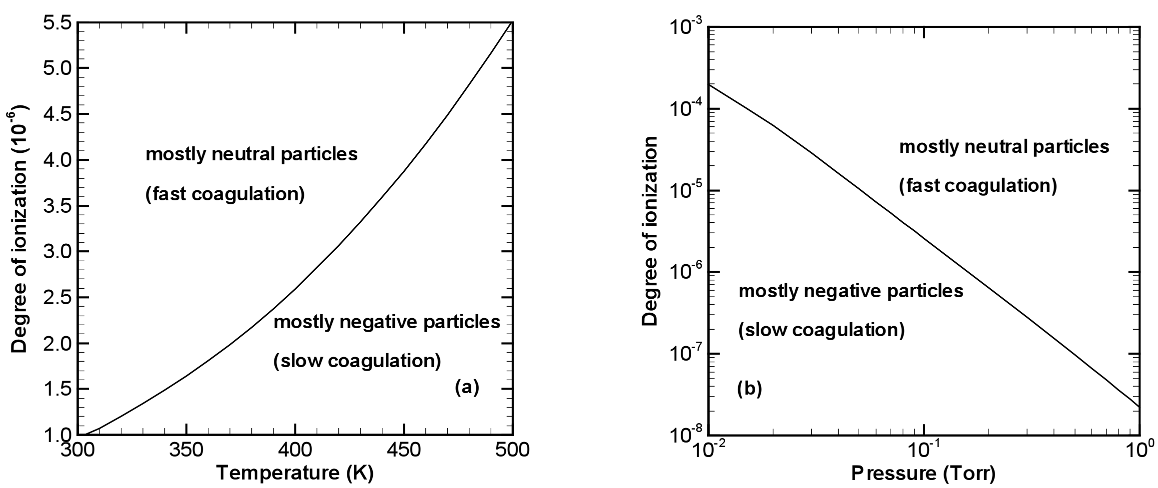

Fig.1. Degree of ionization for which the steady state concentrations of neutral and charged particles are equal; (a) for different gas temperatures at p = 100 mTorr, (b) for different pressures at T = 400 K.

[1] S. Stoykov, C. Eggs, U. Kortshagen, Plasma Chemistry and Growth of Nanosized Particles in a C_2H_2 RF-Discharge, submitted to *J. Phys. D: Appl. Phys.*
[2] U. Kortshagen and U. Bhandarkar, *Phys. Rev. E* 60(1): 887, 1999

The International Microgravity Facility (IMPF)
A Modular Platform for Advanced Plasma Experiments on ISS

Timo Stuffler, Jürgen Burfeindt, Roland Seurig, Roberta Castegini, Christian Schmidt
Kayser-Threde GmbH, Wolfratshauser Straße 48, 81379 München, Germany
su@kayser-threde.de, http://www.kayser-threde.de

The successful first ISS experiment PKE (Plasma Kristall Experiment) is the pre-cursor of the µG facility IMPF enabling plasma experiments on ISS with various key aspects. The facility is planned to be operational for the next 10 years.

IMPF consists of up to six mid-deck-locker-equivalent inserts, which can be accommodated in all possible areas on the space station. This approach was selected to have the highest planning flexibility and to provide fast and straight development capabilities.

The flight of IMPF is scheduled in the '04/'05 timeframe. Planning of facility inserts has already been started allowing for fundamental as well as applied plasma research. The actual development status of IMPF including pre-developments for critical H/W elements will be reported in this paper.

Measurements of the vertical Potential in the Pre-Sheath of a Radio-Frequency Plasma, using Non-Linear vertical Oscillations.

Robert Suetterlin
Max-Planck-Institut fuer extraterrestrische Physik

The vertical profile of the electric potential in the so called pre-sheath is measured using non-linear oscillations (see Ivlev, Suetterlin, Steinberg, non-linear vertical oscillations of dust particle in an rf plasma sheath, published in Phys. Rev. Lett.).

For high pressure (>10Pa) and dust particles deep in the sheath there is strong theoretical and experimental proof for the model of a parabolic vertical potential. Between the sheath with its linearly decreasing electric field and the main plasma with no electric field, there is a transitional region called pre-sheath. At low pressures (<10Pa), needed for example in wave or shock experiments, this pre-sheath is comparable in size to the sheath itself. For typical rf-power and particle sizes used, most experiments are conducted in the pre-sheath region. Good knowledge of the vertical potential is needed for example in simulations, charge calculation, etc.

Using particles of different sizes and densities, the vertical potential of the rf-pre-sheath, of Ar and Kr Plasmas at selected rf-powers, is measured over a large vertical extent. The limits of the applicability of the non-linear oscillations (due to neutral gas pressure, power, relative position of particle within (pre)sheath) are discussed.

Numerical models of dust particle transport and dust densities in the Auburn Dusty Plasma Experiment

Edward Thomas, Jr and Brian Christy
Auburn University
Physics Department, Auburn University, AL 36849-5311
etjr@physics.auburn.edu, http://narn.physics.auburn.edu

Studies of dusty plasmas in the Auburn Dusty Plasma Experiment have focused primarily on the transport of charged microparticles within clouds of suspended particles. In these experiments, the negatively charged particles are suspended below an anode in argon dc glow discharge plasmas.[1] Recent results have shown that the dust particles are in a fluid-like state and execute closed convective flows within well-defined dust cloud boundaries.[2] We have recently begun the development a one-dimensional numerical model that simulates the closed transport of the dust particles using realistic experimental conditions.

The model follows the trajectory of a charged dust particle by solving for the forces acting upon the particles. At each time step, the model self-consistently computes the dust grain charge. Additionally, the dust, ion and electron densities are spatially varied in a manner that is generally consistent with the experimental observations. The model also includes the reduction of the free electron density by the collection of negative charge by the dust particles. Consequently, the background electric field that suspends the particles is also computed self-consistently using Poisson's equation.

This presentation will show that this model does lead to a one-dimensional oscillation of the dust particles with time and can possibly form the basis for expanded two-dimensional and three-dimensional models of dust particle transport. Nonetheless, several questions remain regarding the details used to model the ion, electron, and dust densities. Many of these questions arise from a general lack of detailed experimental measurements of plasma conditions near sheath boundaries - the region in the plasma in which the microparticles are suspended.

Related to these investigations of dust particle transport, is the development of a generalized model for the dust cloud density. Choosing the correct dust density model is critical to correctly modeling the particle transport. The value of the dust density impacts the free electron density, the dust grain charge, and, ultimately, the strength of the local electric field. In our analysis of dust cloud structures from three years of experiments, we have identified three classes of dust cloud structures and are in the process of developing generalized density models for each one. This presentation will also show the preliminary results of this study.

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[1] E. Thomas, Jr. and M. Watson, Phys. Plasmas, **6**, 4111 (1999).
[2] E. Thomas, Jr., Physica Scripta, **T89**, 20, (2001).

Parametric Study of the Formation of Coulomb Crystals in the GEC Reference Cell*

Vivek Vyas[a)] and Mark J. Kushner[b)]

[a)]Department of Materials Science and Engr.
[b)]Department of Electrical and Computer Engr.
University of Illinois, 1406 W. Green Street,
Urbana , IL 61801 USA

Gregory A. Hebner, Merle Riley, Pauline Ho and Richard Buss

Sandia National Laboratories
Albuquerque, NM 87185 USA

Particles in low temperature, partially ionized plasmas exhibit collective behavior and form coulomb solids at moderate gas pressures (100s mTorr), smaller particle sizes (< 10s μm) and lower powers in capacitively coupled, radio frequency discharges. The regimes of plasma operating conditions in which these structures are formed are of interest as an indication of crystal formation mechanisms. In this paper, we present results from a computational study of the formation of coulomb crystals in a modified Gaseous Electronic Conference Reference Cell (GECRC). The plasma parameters in 2- and 3-dimensions are obtained from the Hybrid Plasma Equipment Model (HPEM), a comprehensive simulator of low temperature plasmas.[1] The plasma parameters obtained from the HPEM are exported to a 3-dimensional Dust Transport Simulation (DTS).[2] In the DTS, particle trajectories are integrated while including particle-particle coulomb interactions. In addition to the particle-particle forces we included electrostatic, ion-drag, thermophoretic, fluid-drag by neutrals and gravity in computed particle trajectories. In addition to particle locations, the DTS also produces the crystal Γ-factor (electrostatic potential energy/thermal energy) and g(r), the radial structure factor. The GECRC modifications include placement of a metal ring on the substrate to help confine the particles.

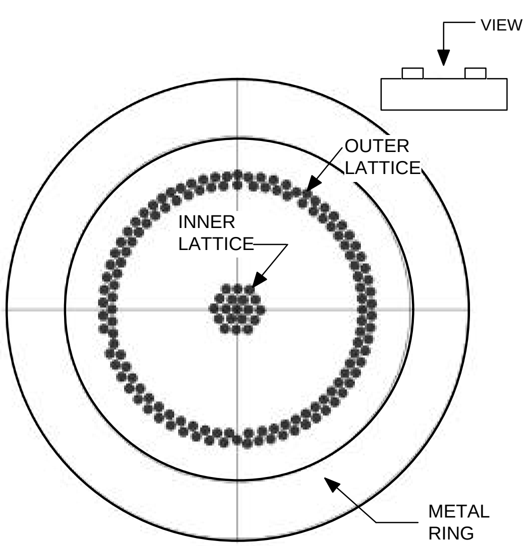

Fig 1 - Top view of 3.5 μm diameter particles that have abruptly separated into 2 lattices with increase of substrate bias to 250 V (Ar, 95 mTorr).

Results will be presented for the consequences of varying the bias voltage, gas pressure, particle diameter, and number of particles on the propensity for crystal formation, interparticle spacing in the coulomb solid, the Γ-factor and g(r). In particular, phase changes are observed as function of these parameters as the particle cloud transitions between liquid and solid. We also observe spontaneous breakup of a single, one layer lattice into separate lattices, a circle an ring, as the particle size or voltage is varied. For example, for typical conditions (Ar, 95 mTorr), an increase in bias voltage produces an abrupt splitting of a single hexagonal lattice into two separate sub-lattices, as shown in Fig. 1. The sub-lattices may be a different heights above the electrodes. Comparisons will be made to experiments.

[1] R. Kinder and M. J. Kushner, J. Vac. Sci. Technol. A **19**, 76 (2001)
[2] H. H. Hwang and M. J. Kushner, J. Appl. Phys. **82**, 2106 (1997)

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Electron and Ion Densities in SiH_4 HF Discharges

Y. Watanabe, M. Shiratani, and K. Koga
Graduate School of Information Science and Electrical Engineering,
Kyushu University, Fukuoka 812-8581, Japan
watanabe@ed.kyushu-u.ac.jp

In SiH_4 high frequency (HF) discharges, we have found Si clusters of 10^{10}-10^{11}cm^{-3} in density even under the so called "device quality" conditions.[1] The effective attachment rate of electrons to the clusters has been reported to increase drastically when they grow up to Si_nH_x (n=4~5).[2] Hence, temporal evolution of difference between ion density n_i and electron density n_e after the HF discharge initiation are closely related to the growth of clusters. Recently, a sophisticated computer simulation has been carried out regarding Si cluster growth in SiH_4 HF discharges[3]. In the result, n_e is low by about two orders of magnitude compared to n_i.

To study the decay of n_e due to electron attachment, we have observed temporal evolution of n_e and n_i using a microwave interferometer and Langmuir probe, together with that of density and size of clusters by the double pulse discharge method, [4] after the discharge initiation. The experiments have been carried out for excitation frequencies f =13.56, 28 and 60 MHz.

Figure 1 shows the time evolution of n_e and n_i under experimental conditions of pure SiH_4, 5sccm, 13.3Pa, 28 MHz and 20W. While n_i increases and n_e decreases with time t, a ratio R= n_e/n_i is about 0.4 even at t=1s. Our experimental results have shown that, while the difference increases with f, the ratio R > 0.1 even at 60 MHz. The smaller R for the higher f may be explained by the facts that the cluster density increases and the electron temperature decreases with increasing f. These results indicate that the ratio R is quite large compared to that obtained in the simulation, suggesting that the smaller electron attachment rate to Si_nH_x's must be employed or the electron detachment from them must be taken into account.

We have also studied effects of H_2 dilution on both time evolution of n_e and that of cluster growth for f=28 MHz. When increasing the concentration ratio of H_2 to SiH_4, the density of clusters does not so change and coagulations between them are largely suppressed, and further the density n_e closes to n_i.

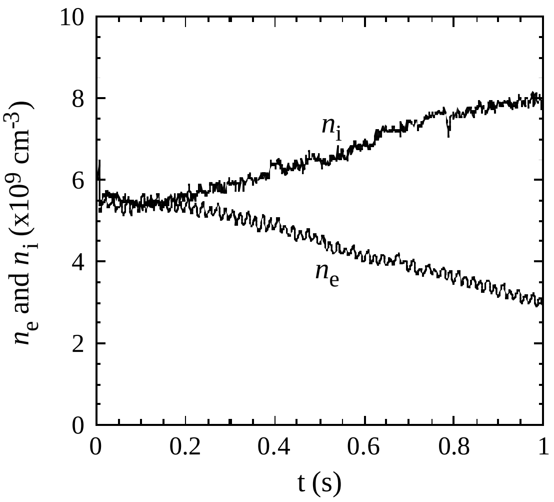

Fig. 1. Time evolution of n_e and n_i. 100% SiH_4, 5 sccm, 13.3 Pa, 28 MHz, 20 W, T_{GND}= R.T

1 Y. Watanabe, M. Shiratani, and K. Koga, Physica Scripta, **T89**, 29-32 (2001).
2 J. Perrin and Ch. Hollenstein, Dusty Plasma, edited by A. Bouchoul (John Wiley & Sons. Publ., 1999) Chap.2.
3 U. V. Bhandarkar, M. T. Swihart, S. L. Girshik, and U. R. Kortshagen, J. Phys. D, **33**, 2731-2746 (2000).
4 K. Koga, Y. Matsuoka, K. Tanaka, M. Shiratani, and Y. Watanabe, Appl. Phys. Lett. **77**, 77-79 (2000).

Plasma Crystal Structures on Earth under different Plasma Parameters

M. Zuzic, D. D. Goldbeck, A. Ivlev, U. Konopka, G. E. Morfill, R. A. Quinn, H. Rothermel, R. Sütterlin, and H. M. Thomas
Max-Planck-Institut für extraterrestrische Physik,
Giessenbachstrasse, 85740 Garching, Germany

Numerous experimental investigations have been published about the structural ordering of plasma crystals on Earth. In three dimensions fcc-, bcc-, hcp- and hexagonal aligned structures have been observed. The external gravitational pressure restricts the laboratory investigations to a limited vertical range above the lower electrode of a radio-frequency discharge, so that the crystals consist of only a few horizontal lattice planes. The usually observed vertical particle alignment is due to interaction between downward streaming ions and the dust particles. The interaction is stronger for heavier particles (at same mass density). If the particles become smaller they are levitated in regions with lower ion streaming velocities. In this case, lattice structures like those found in natural crystals can be obtained. In many experiments, the observed structures are a mixture of different crystal types with some transitional regions which are probably caused by lattice defects, vertical stress and small temperature variations.

A new plasma chamber design allows us to form plasma crystals consisting of up to 10^7 microparticles with typically 100 lattice planes in 3 dimensions. We have analyzed large scale crystal structures for different experimental conditions and present conclusions about the mechanisms which are responsible for the formation of the observed structures.