# GRAIN-GRAIN INTERACTION IN STATIONARY DUSTY PLASMA

Martin Lampe and Glenn Joyce
Dept. of Astronomy, University of Maryland

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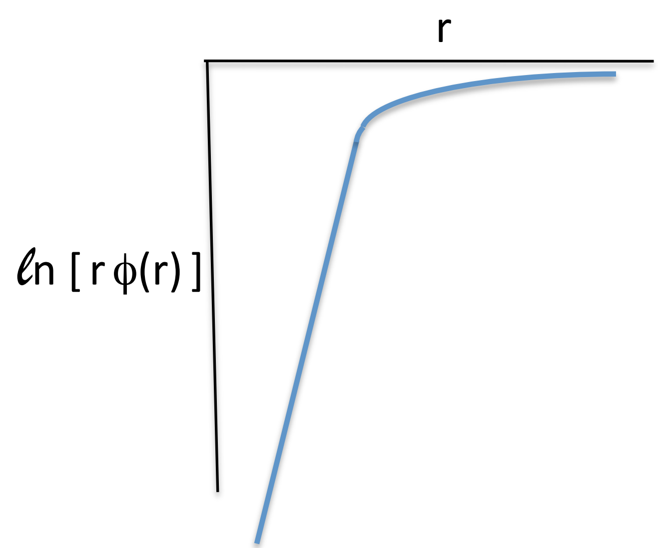
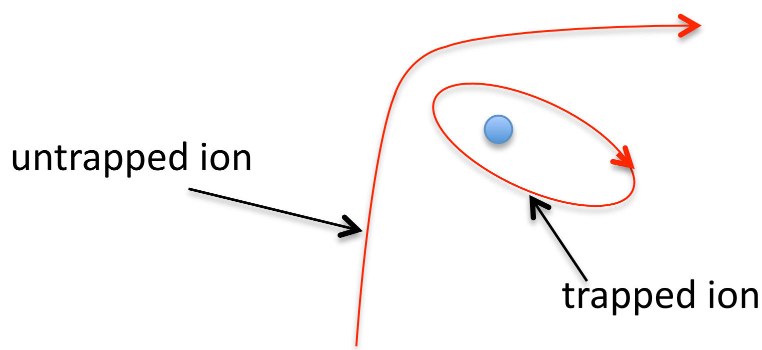
# SINGLE GRAIN POTENTIAL IN NON-FLOWING PLASMA: A SOLVED PROBLEM

- The potential $\phi(r)$ around an isolated grain in non-flowing plasma is well understood:
  - Debye-like out to $r \sim 4\lambda_D$
  - Falls off as $r^{-2}$ for $r > 4\lambda_D < r < \lambda_{mfp}$
  - Always repulsive to other negative grains
  - Shielding is mainly due to trapped ions



# BUT THERE ARE STILL PERSISTENT QUESTIONS ABOUT GRAIN-GRAIN INTERACTIONS

- Many authors have argued that the presence of a second grain changes things, i. e. the force on a second grain is not given simply by the one-grain potential.

- Can there even be an attractive force between two negatively-charged grains?

- Possible mechanisms for an attractive force:

  - Arguments based on “correlation energy” (Tsytovich; Resendes, Mendonca & Shukla)
  - Classical analogs to Van der Waals forces and chemical bonds (Lampe et al)
  - Shadowing force (Ignatov, Tsytovich, Lampe, Ivlev, Khrapak, et al)

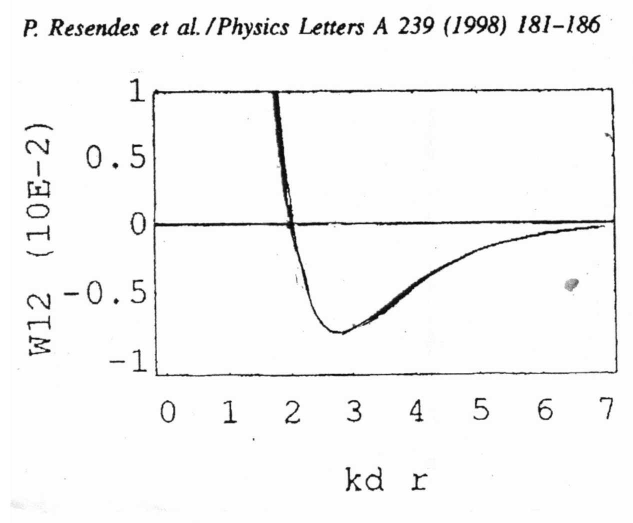
- A recent experiment by Usachev et al confirms existence of an attractive force: A large central grain confines a spherical shell of smaller grains with radius $9.5\lambda_D$.

# MINIMA IN ELECTROSTATIC ENERGY

- Many authors have noted that the electrostatic energy, as a function of grain separation d, has a minimum at $d \approx 2.7\lambda_D$, and have argued that this minimum represents a stable two-grain bound state due to "correlation energy."

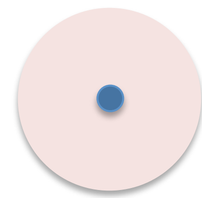
- Some authors have included kinetic as well as electrostatic energy, with similar conclusions.

- These arguments are incorrect, because the system is open, with ions and energy transported to the ambient plasma and to the grains. See Markes and Williams (2000), Fillipov et al (2006).

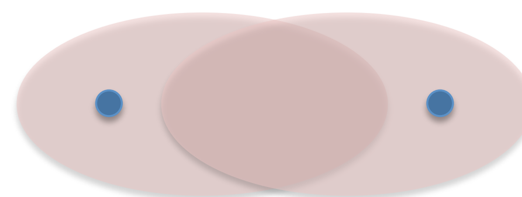


# VAN DER WAALS FORCES AND CHEMICAL BONDS

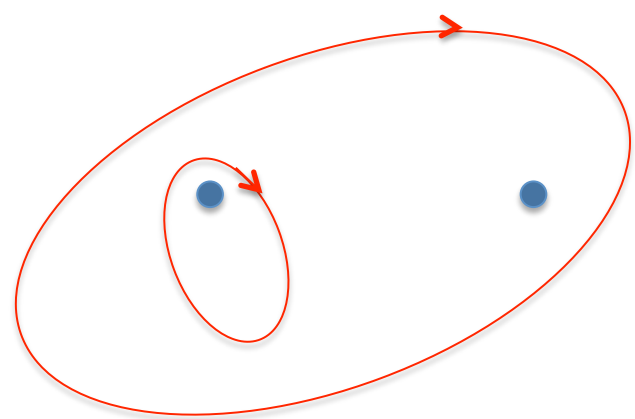
- A grain with its trapped ion cloud is much like a classical atom.



- Could a second grain polarize the trapped ion cloud, leading to Van der Waals forces?

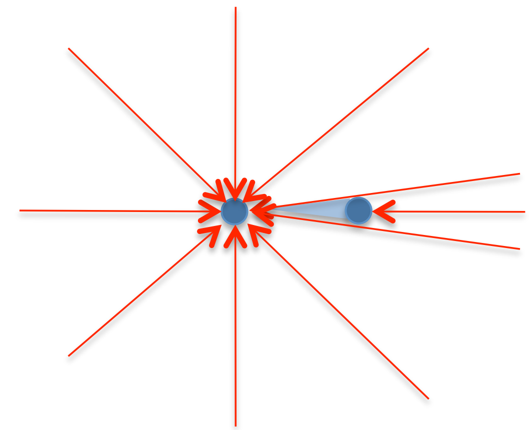


- Could the two grains be bound together by trapped ions with orbitals that encircle both grains, analogous to covalent bonds?



# SHADOWING FORCE

- A grain absorbs ions that hit it.
  So there must be an inward ion flow.
  If there is a second grain, this ion flow
  exerts an ion drag on the second grain.
  This is known as the shadowing force.

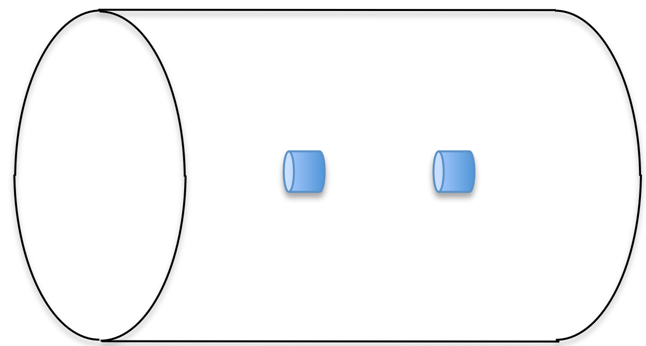


- In a dilute neutral gas,
  where molecule trajectories are straight lines,
  the shadowing force is an inverse square force.

- But in a dusty plasma, ion trajectories are curved,
  ions speed up as they approach grains,
  near-miss collisions result in Coulomb drag.
  Consequently, the shadow force is complicated.

- Khrapak, Ivlev et al have done approximate calculations,
  and have argued that the attractive shadowing force
  overwhelms the repulsive electrostatic force
  at large grain separations.

# SIMULATION STUDY OF TWO GRAINS: DUSTrz CODE



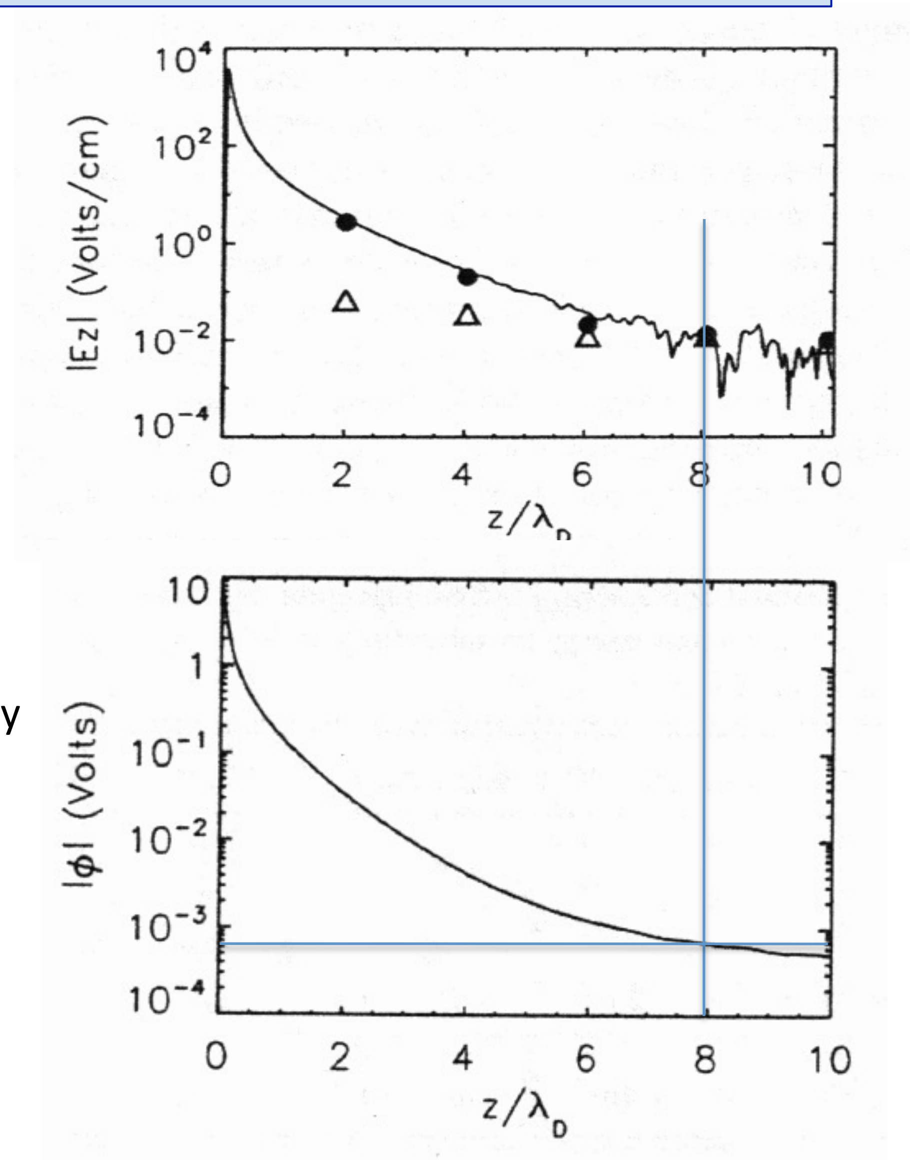
- 2-D cylindrical r-z grid
- 1, 2, or a string of cylindrical grains on axis
- Grains can have any aspect ratio (can be probes)
- Ions are PIC particles, with charge-exchange collisions
- Electrons are Boltzmann
- Grains don't move, but code calculates the electrostatic and ion-impact forces on the grains
- Outer boundary is porous, surrounded by ambient plasma
- Ambient plasma can be flowing, with a driving $E_z$ field
- Ions are absorbed if they hit a grain; ion charge and momentum are given to the grain
- Short time steps for the ion push; long time steps for Poisson solution

# METHOD FOR THE SIMULATION STUDY

- Run each simulation until steady state is reached,
  then run for a long time and time-average all steady state quantities.
- First do a one-grain simulation. Determine $\phi(r)$ and $E_r(r)$.
- Then do a series of 2-grain simulations with the same grain and plasma parameters, one simulation for each value of the grain separation d.
- From each 2-grain simulation, get the electrostatic force on a grain.
  Compare this to the force from the one-grain potential $\phi(r)$ at r=d.
  From each 2-grain simulation, get the shadowing force on a grain
  by adding up the ion momentum deposition on the grain.
- Typical runs take about an hour on a single-processor computer.
  Can get by with as few as 50,000 particles,
  because steady-state results are averaged over many time steps.
- The DUSTrz code is available to anyone who might want to use it.
  A listing is in the supplementary material for Phys. Plasmas **22**, 023704 (2015).

# RESULTS: TWO IDENTICAL GRAINS

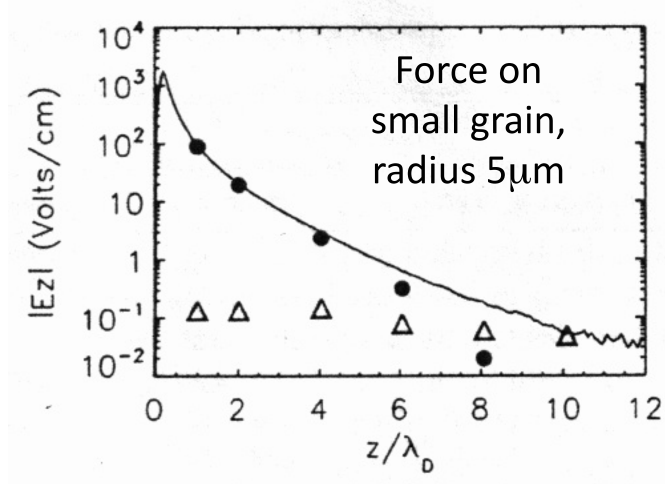
- The electrostatic force (dots) calculated in the 2-grain simulations is always repulsive, and nearly identical to the single-grain E-field (curve) acting on the bare grain charge.
- The attractive shadowing force (triangles) becomes larger than the repulsive ES force for grain separation $d_0$. In this simulation, $d_0 = 8\lambda_D$. We always find $6\lambda_D < d_0 < 9\lambda_D$.
- $E_z(z)$ is smooth for $z < 6\lambda_D$, noisy for larger z.
- $\phi(d_0) \approx 0.0007$ V << $T_i \approx 0.03$ V.
- Simulation cannot directly calculate binding energy $\Phi$ (ES + shadow) for a 2-grain "molecule," but if we assume $\phi(d) \sim 1/d^2$ and $\phi_{shadow} \sim 1/d$, then $\Phi \approx Qe\phi(d_0)$. $Q \approx 27{,}000$, giving $\Phi \approx 19$eV, probably sufficient to bind a stable "molecule."
- $\Phi$ is even stronger in most simulations, ranging from 19 eV to 900 eV. In general, this exceeds T, $T_e$ or the kinetic temperature of the dust grains, so 2-grain molecules should be stable.



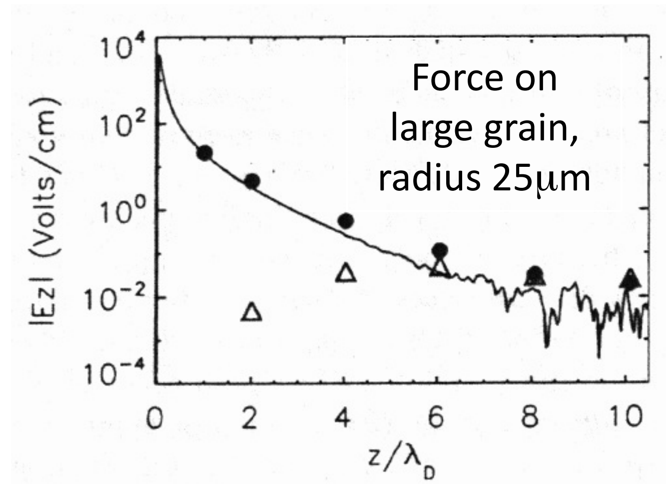

P= 2Pa, $n_i = 10^{14}$m$^{-3}$, $T_e$=3eV, T=0.03eV, a=5μm

# RESULTS: GRAINS OF UNEQUAL SIZE

- The grain-grain electrostatic force (dots) calculated in the 2-grain simulations
  is always repulsive, but
  - Force on the smaller grain is smaller than $Q_{small}$ × single-grain electric field.
  - Force on the larger grain is larger than $Q_{large}$ × single-grain electric field.




- The attractive shadowing force (triangles) becomes larger than the repulsive ES force for grain separation $d_0$. In this simulation, $d_0=7\lambda_D$. In all cases, we find $6\lambda_D < d_0 < 9\lambda_D$.



# WHY DOES THE 2-GRAIN ELECTROSTATIC FORCE DIFFER FROM THE SINGLE-GRAIN POTENTIAL?

- Imagine that the 2 grains are connected by a rigid massless rod.

- The 2-grain ensemble will accelerate if
  the sum of the forces on each of the 2 grains is non-zero,
  i.e. if the forces are not equal and opposite.

- But the grains are sitting in a uniform Maxwellian plasma.
  The Second Law of Thermodynamics says a body cannot accelerate
  by extracting energy from a uniform Maxwellian plasma.

- The single-grain potentials are not reciprocal
  if the grains are of unequal size.
  So the plasma space charge must rearrange itself
  so as to make the forces reciprocal.

- It is the total force (electrostatic + shadowing) that must be reciprocal.
  The electrostatic force alone is not reciprocal.
  This is found to be true in the simulations.

# CONCLUSIONS

- There is no attractive electrostatic force between negatively-charged dust grains.

- For two identical grains, the electrostatic interaction is given accurately by the single-grain potential.

- For two grains of different size,
  the force on the larger grain is larger than would be given by the single-grain potential,
  the force on the smaller grain is smaller than would be given by the single-grain potential.

- In all cases, the shadowing force dominates for separation $d > d_0$,
  where $d_0$ is between $6\lambda_D$ and $9\lambda_D$, giving net attraction for $d > d_0$.

- The binding energy for a 2-grain molecule varies from 19eV to 800eV for cases studied, strong enough to hold a two-grain molecule together in the face of Brownian motion.