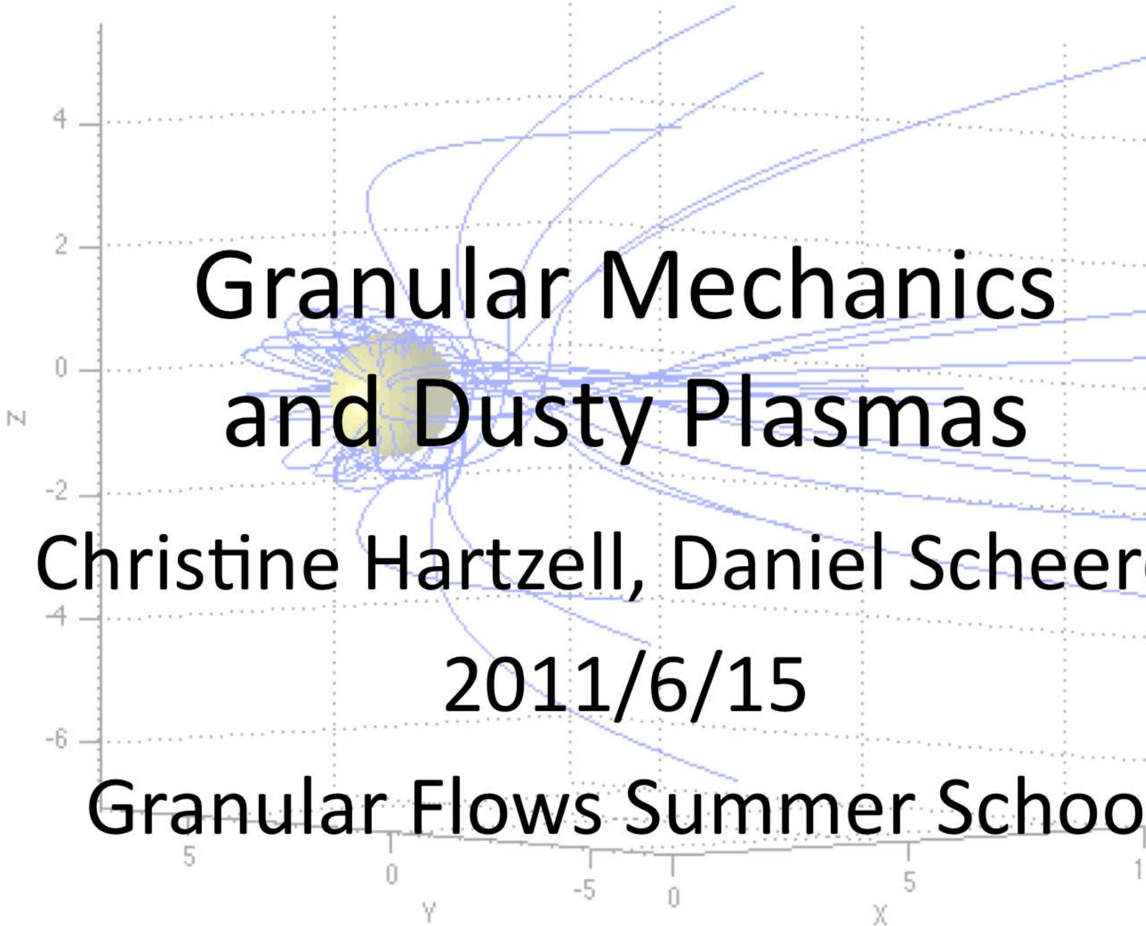

Granular Mechanics and Dusty Plasmas

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2011/6/15

Granular Flows Summer School

University of Colorado Boulder

Motivation: Dust

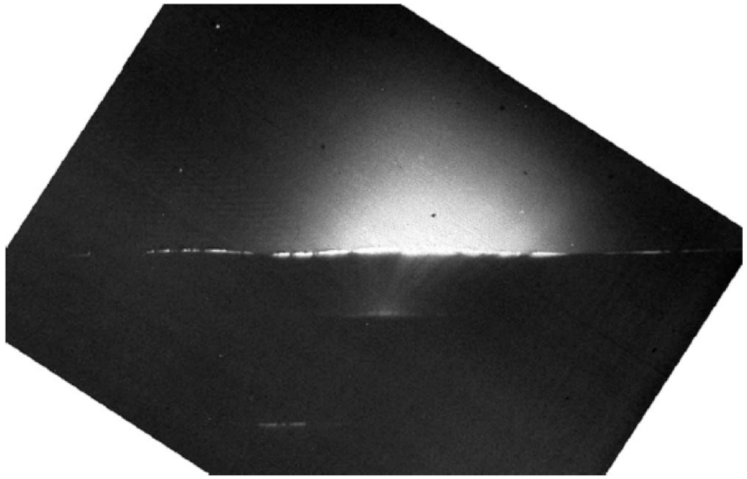


Figure Credit: Colwell et al. *J. Aerospace Engineering 2009.*

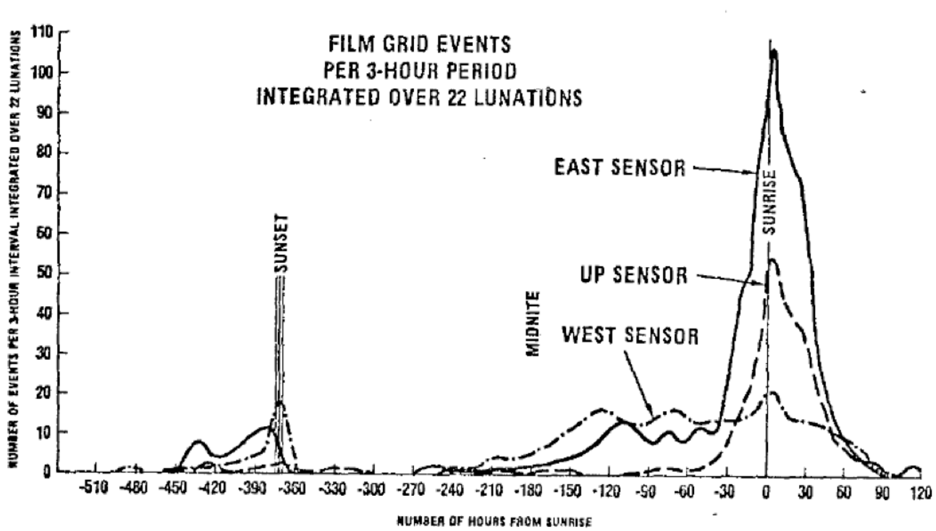


Figure Credit: Berg et al. *Interplanetary Dust and Zodiacal Light 1976.*

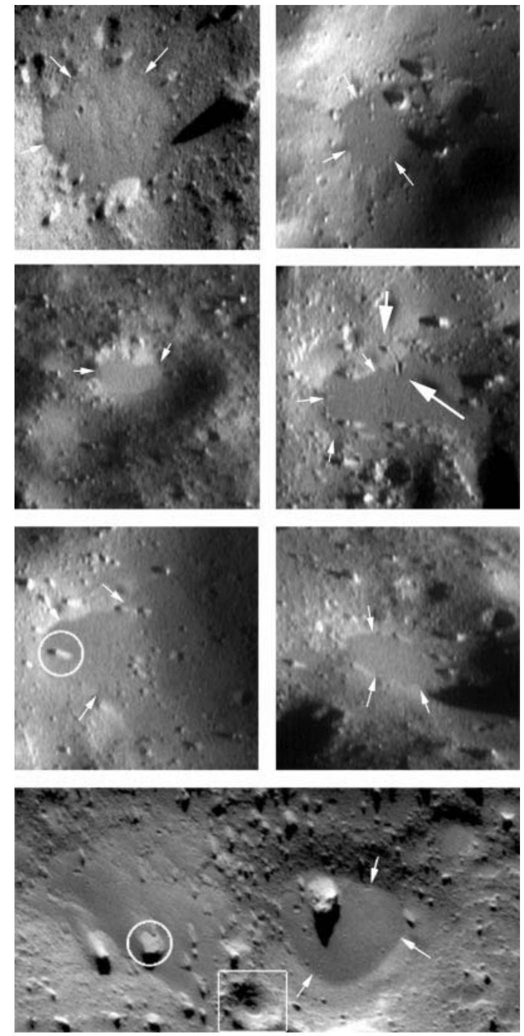
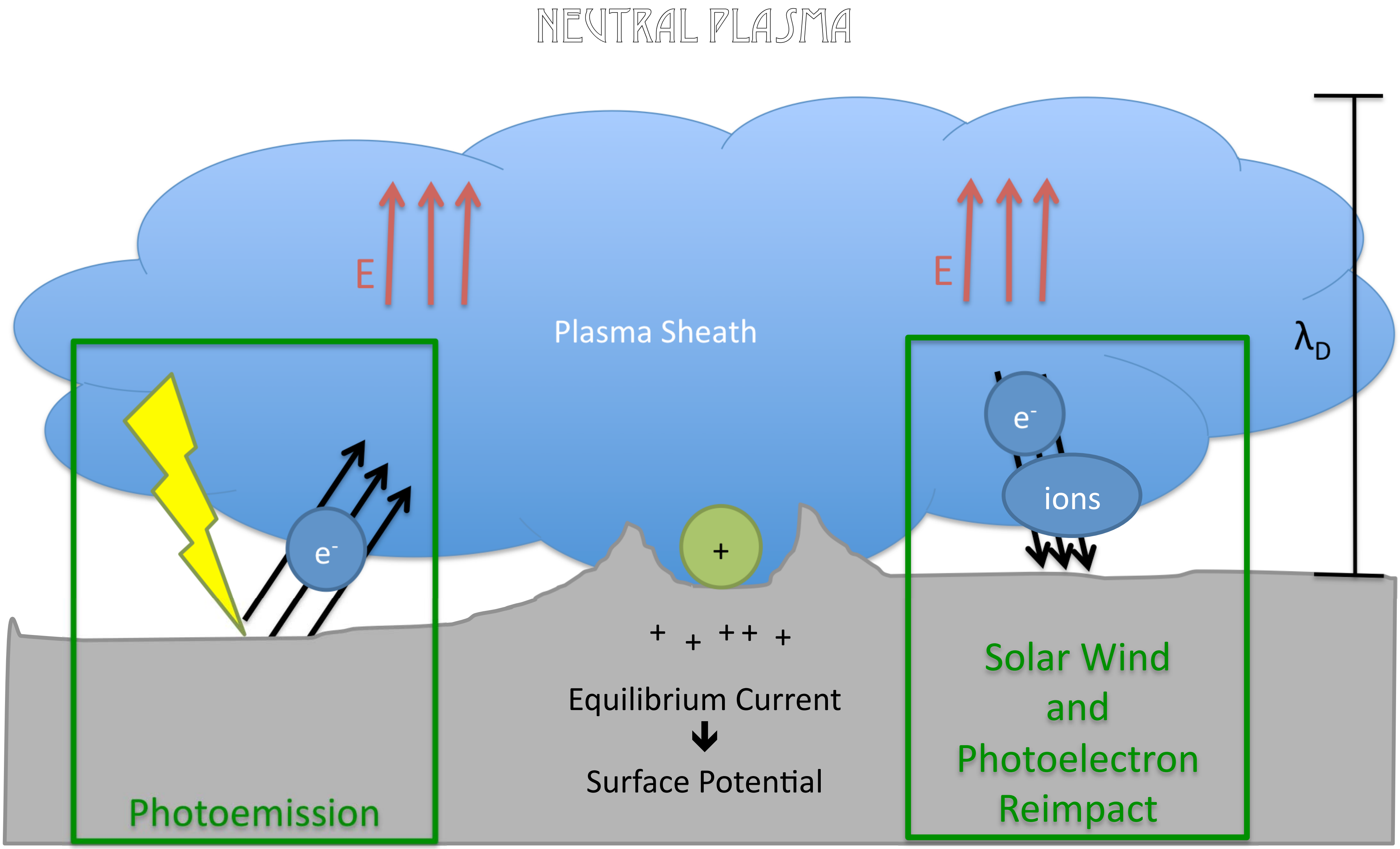


Figure Credit: Robinson et al. *Nature 2001.*

Intro to Electrostatic Levitation



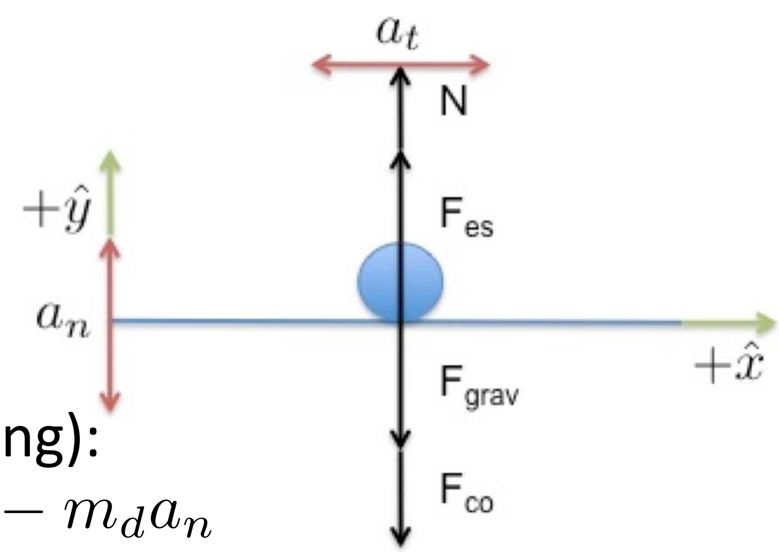
Outline

- Dust Particle Launching
- Experimental Problems
- Electrostatic Levitation

Equation of Motion

- Model of seismic shaking:

$$\mathbf{a} = A_t \sin(\Omega_t t)\hat{x} + A_n \sin(\Omega_n t)\hat{y}$$
$$a_t = A_t \sin(\Omega_t t)$$
$$a_n = A_n \sin(\Omega_n t)$$



- Equation of Motion (vertical shaking):

$$m_d \ddot{y}_{rel} = F_{es} + F_{grav} + F_{co} + N - m_d a_n$$

- Conditions:
  - If $\ddot{y}_{rel} \geq 0$, then the particle is said to be ***separated*** from the surface. The cohesive force disappears in subsequent motion.
  - If $\ddot{y}_i > 0$, the particle is said to be ***launched***. The cohesive force disappears in subsequent motion.
  - EOM is valid only until particle is no longer in contact with surface (gravity is assumed to be constant).

Force Models

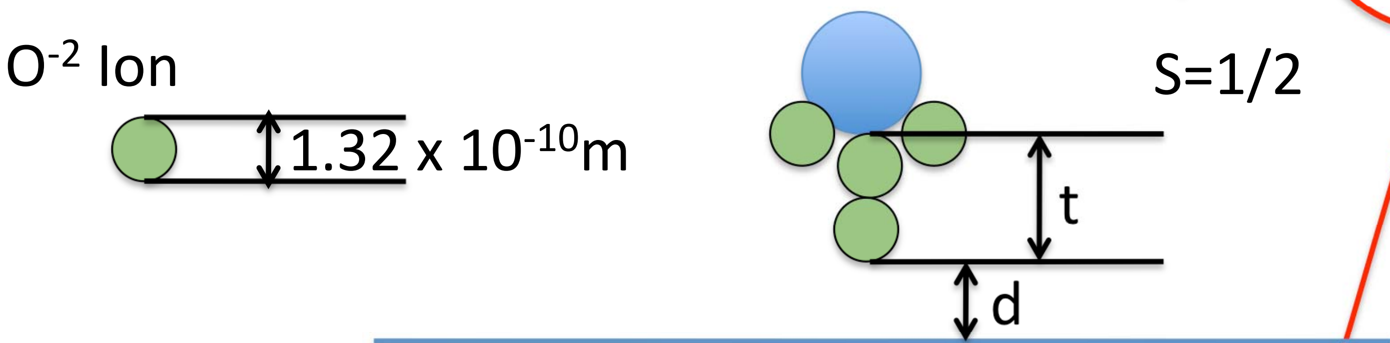
- Gravity: $F_{grav} = -\frac{4}{3}\pi r_d^3 \rho g_s$

- Electrostatic force: $F_{es,gen} = QE$
  - Assume: $Q = EA\epsilon_0$

$$F_{es} = E^2 \pi r_d^2 \epsilon_0$$

Force Models (Cohesion)

- Cohesion (Perko[23]): $F_{co} = \frac{B}{48\left(t + \cancel{d}\right)^2} \frac{r_1 r_2}{r_1 + r_2}$



– Assume:

$$S = 1.32 \times 10^{-10}/t$$

$$B = 4.3 \times 10^{-20} \text{ J}$$

$$F_{co} = -5.14 \times 10^{-2} S^2 r_d$$

Electric Field Required

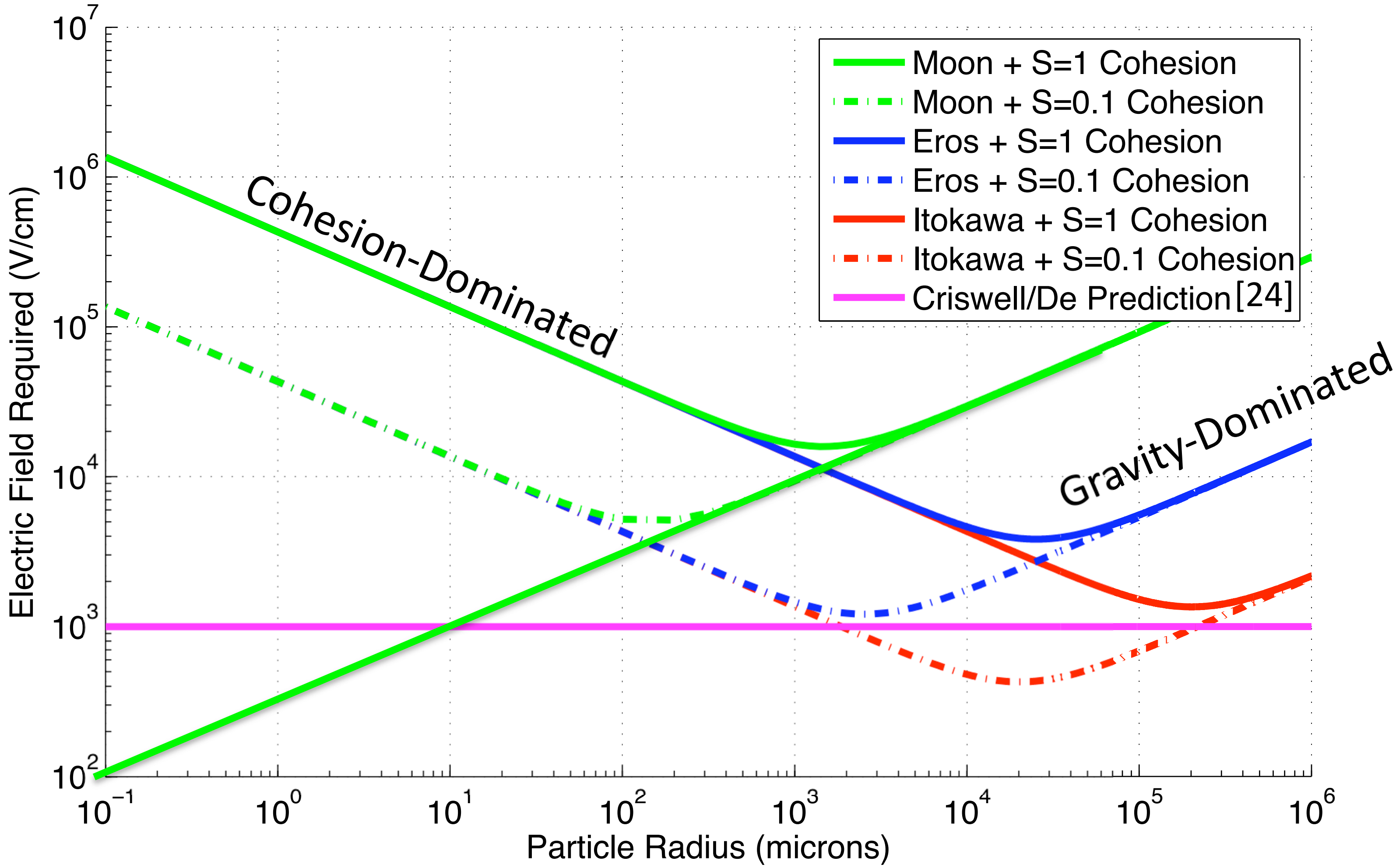
- What electric field strength is required to separate a particle from a surface ($\ddot{y}_{rel} > 0$)?

$$F_{es} \geq m_d a_n - F_{grav} - F_{co}$$

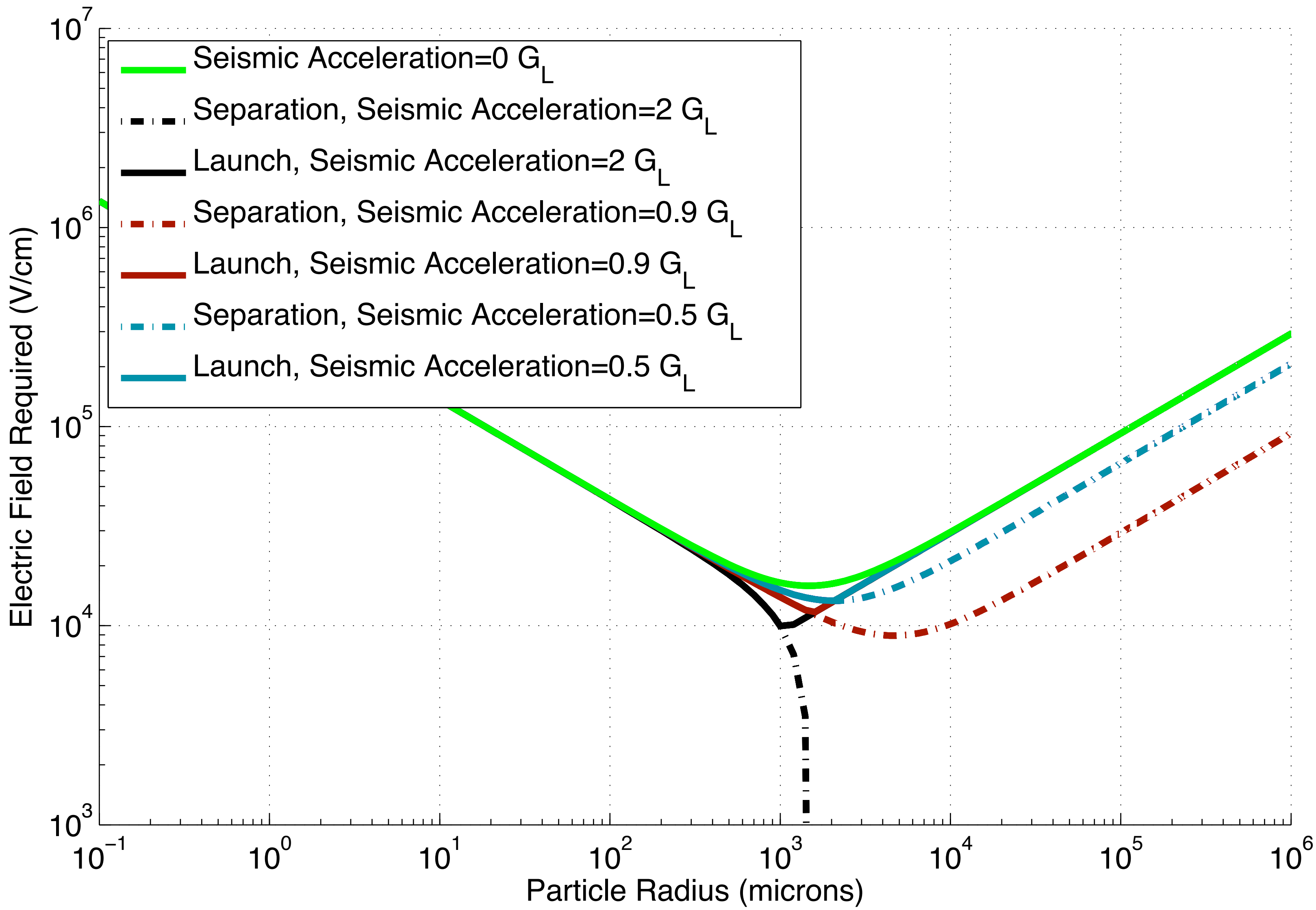
$$E_{req} \geq \left[\frac{4}{3\epsilon_0} r_d \rho \left(g_s + a_n \right) + \frac{5.14 \times 10^{-2} S^2}{\pi \epsilon_0 r_d} \right]^{1/2}$$

- If $a_n = 0$, then the electric field is that required to launch a particle.

	Moon	Eros	Itokawa
Gravity	1.622 m/s^2	0.0055 m/s^2	8.603x10^{-5} m/s^2
Radius	1737.1 x10^3 m	8420 m	165 m



- $E_{req} >> E_{criswell}$
- Curve minima at large particle sizes (even at S=0.1)
- Curve minima shifted right for asteroids
- See also: Hartzell and Scheeres. *The role of cohesive forces in particle launching on the Moon and asteroids.* Planetary and Space Science.



- Lunar gravity only
- Seismic accelerations do not significantly impact E_{req} for launching

Outline

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Experimental Dust Lofting

- Two main dust lofting experiments:
  - Xu Wang et al. 2009, spreading dust mound
  - Flanagan and Goree 2006, dust release from spinning sphere
- With Wang's values $F_{es} < F_{grav}$!!!

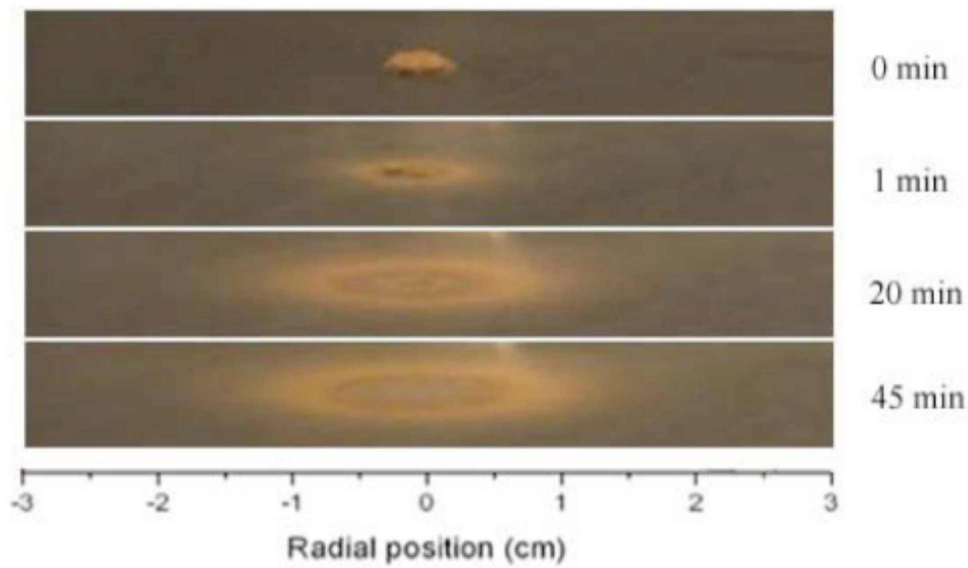
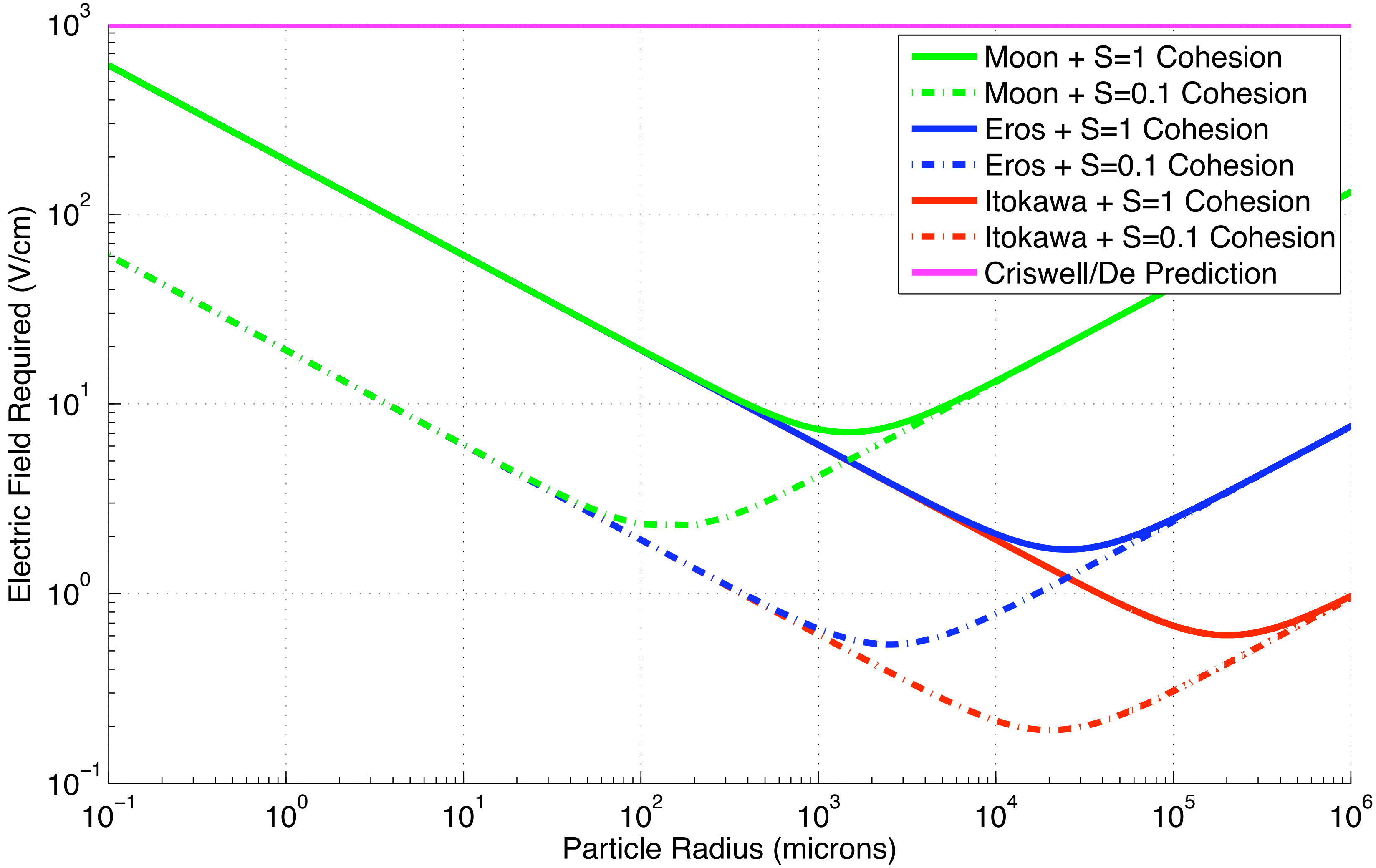


Figure Credit: Wang et al. *JGR 2009.*

Charge Amplification

- We calculate the amount charging level beyond that predicted by Gauss' law that is required to explain experimental results.
- $4.04 \times 10^4 < C_{amp} < 1.04 \times 10^9$
- Use $C_{amp} = 5.01 \times 10^6$
- Can this level of charge amplification occur in reality?



- Lofting possible in terminator
- Still not possible elsewhere (subsolar=10^{-1}V/cm)
- Easiest size to loft does not change

Outline

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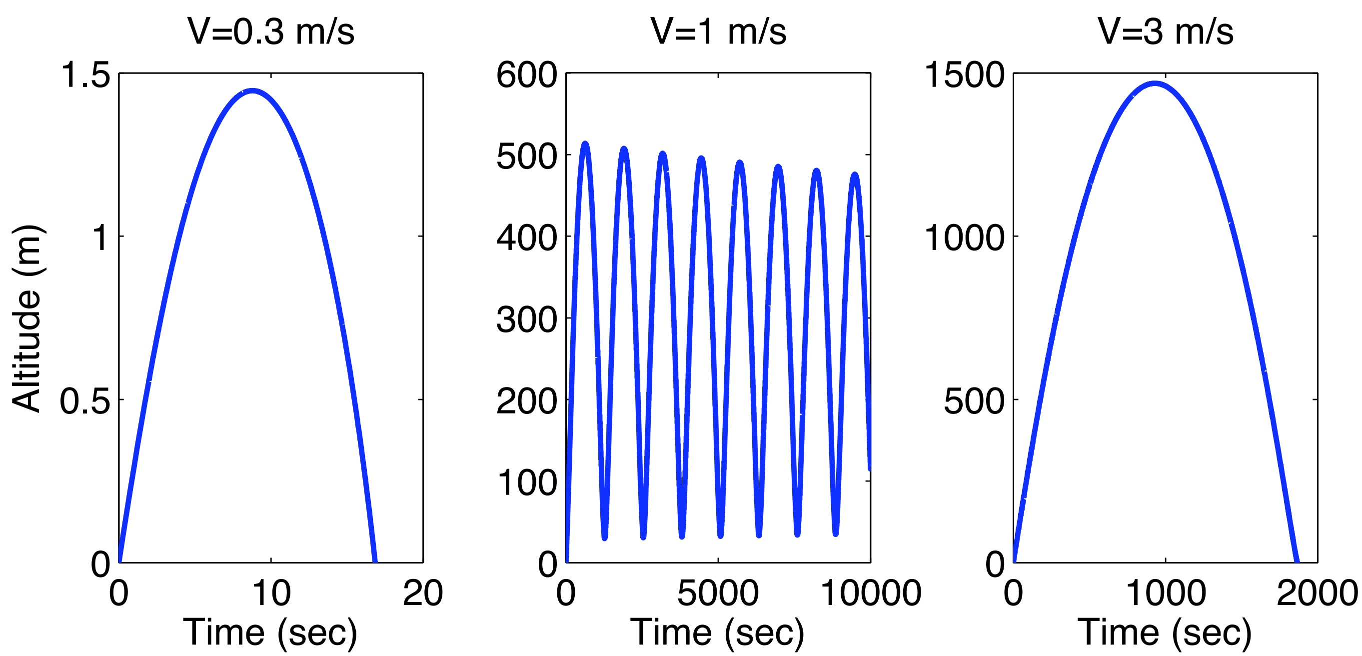
What is Particle Levitation?

- Lacking a feasible launching mechanism, arbitrary initial conditions are chosen.



Plasma Physics Disclaimer

Nitter et al. Model

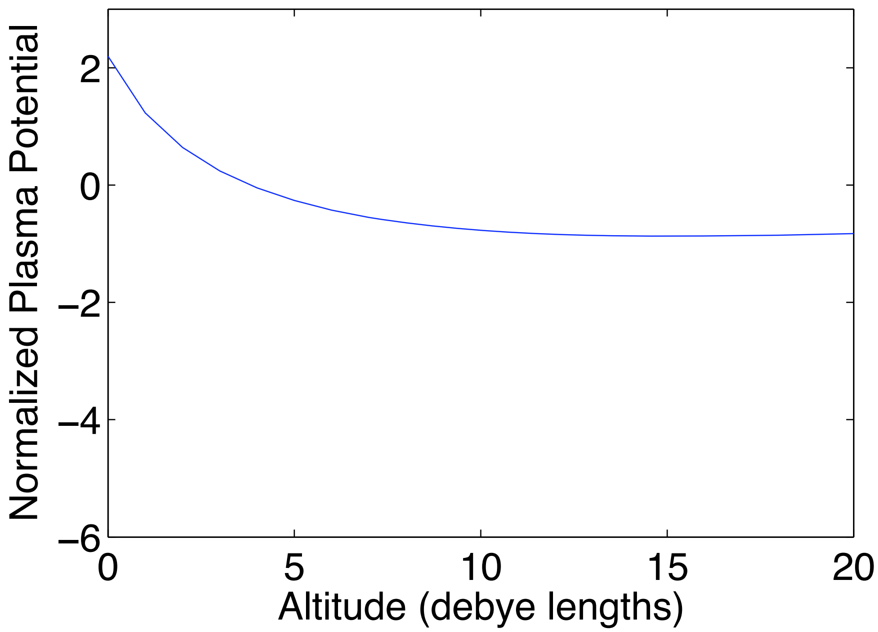
- Predicts two sheath types
- Non-monotonic sheath has been suggested as more energetically favorable.
- Presence of non-monotonic sheaths supported by PIC models and Lunar Prospector data.

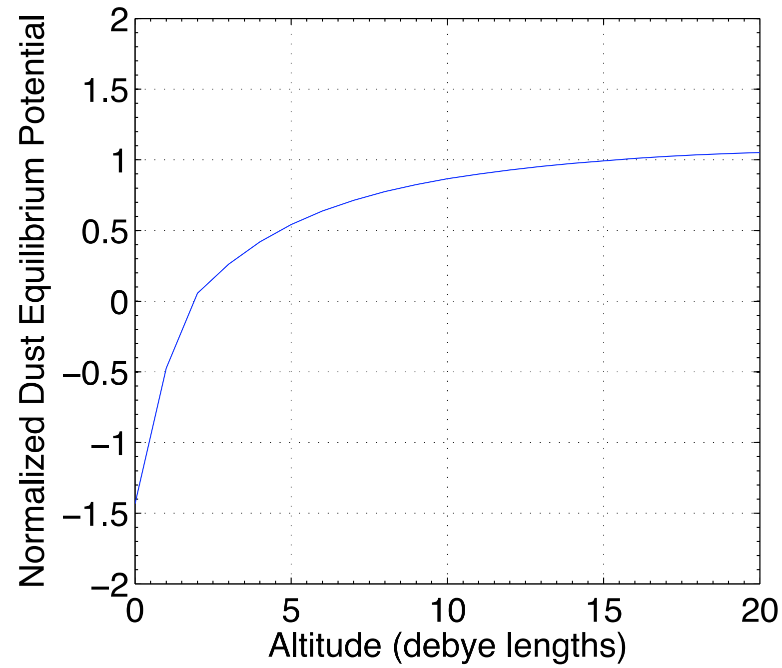
Non-Monotonic Sheath

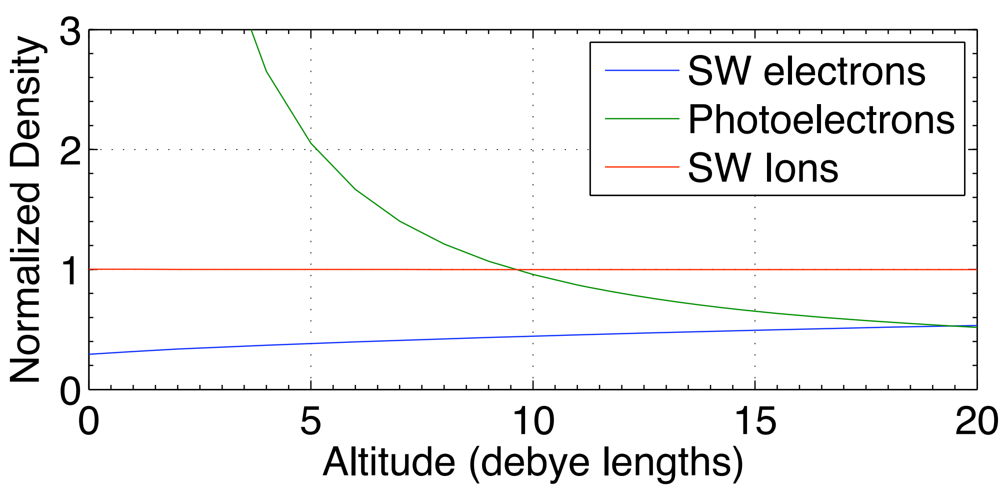
Colwell et al. Model

- Simpler, analytically-described sheath.
- Only photoelectron density varies with altitude.
- Has been used in previous dust motion studies by Colwell.

Description of Sheath







$$m_d \ddot{h} = qE - \frac{m_d g_s}{\left(\frac{h}{r_c} + 1\right)^2}$$

$$\dot{q} = \sum I(h, q)$$

Linear Stability Analysis

- Define: $F(q,h) = \dot{q}$ $G(q,h) = \ddot{h}$

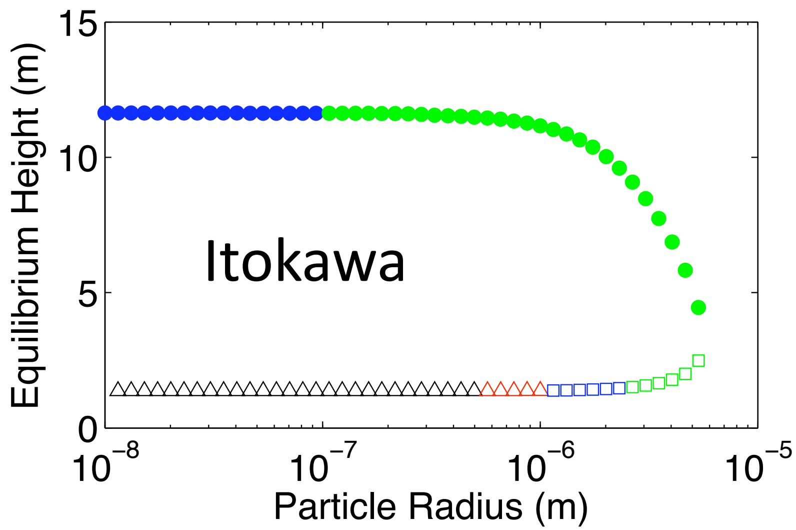
$$\begin{bmatrix} \delta\dot{q} \\ \delta\dot{h} \\ \delta\ddot{h} \end{bmatrix} = A \begin{bmatrix} \delta q \\ \delta h \\ \delta\dot{h} \end{bmatrix} \qquad A = \begin{bmatrix} \frac{\partial F}{\partial q} & \frac{\partial F}{\partial h} & 0 \\ 0 & 0 & 1 \\ \frac{\partial G}{\partial q} & \frac{\partial G}{\partial h} & 0 \end{bmatrix}$$

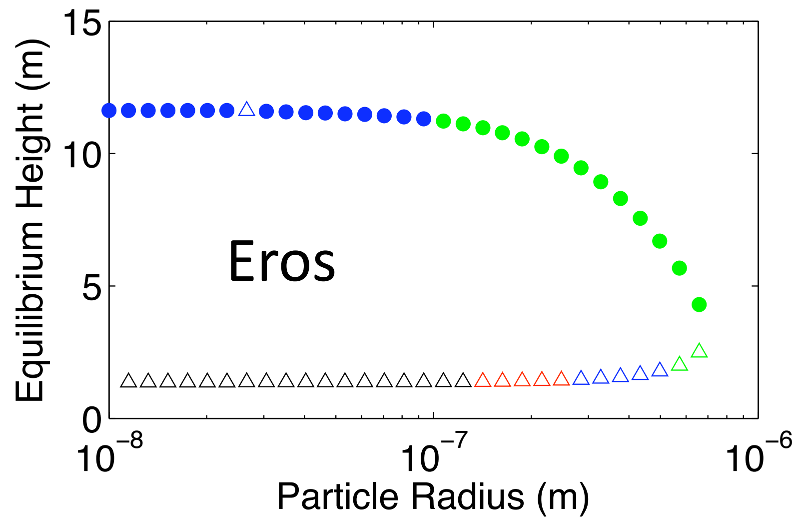
- From A, compute linearized stability by solving for eigenvalues (x):

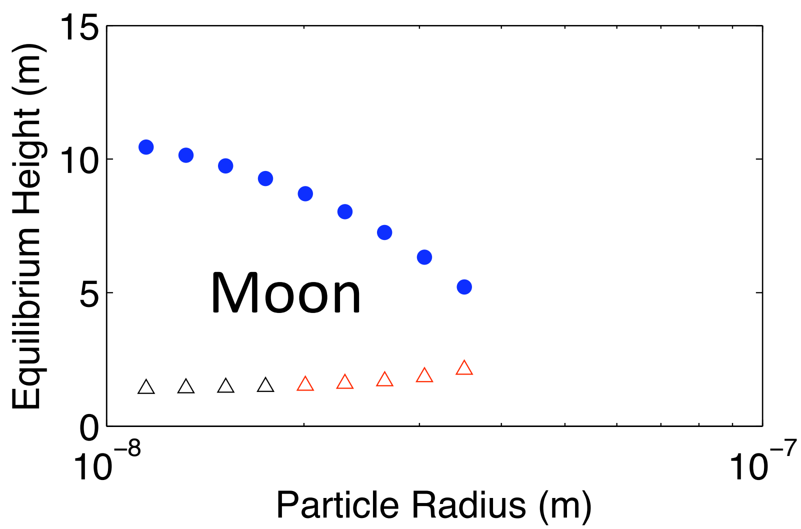
$$x^3 - F_q x^2 - G_h x + F_q G_h - F_h G_q = 0$$

- Eigenvalues give approximate oscillation frequency and decay constant
- Eigenvectors can be used in nonlinear stability analysis

Equilibria

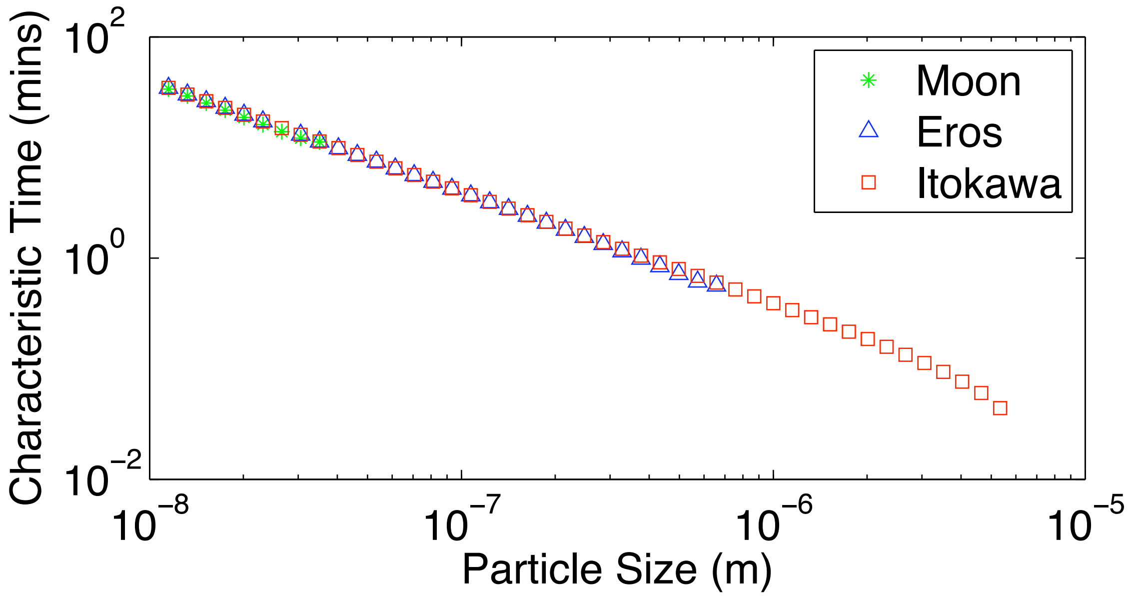






Black: [0,1) electrons
Red: [1, 10) electrons
Blue: [10, 100) electrons
Green: >100 electrons

Timescales of Motion

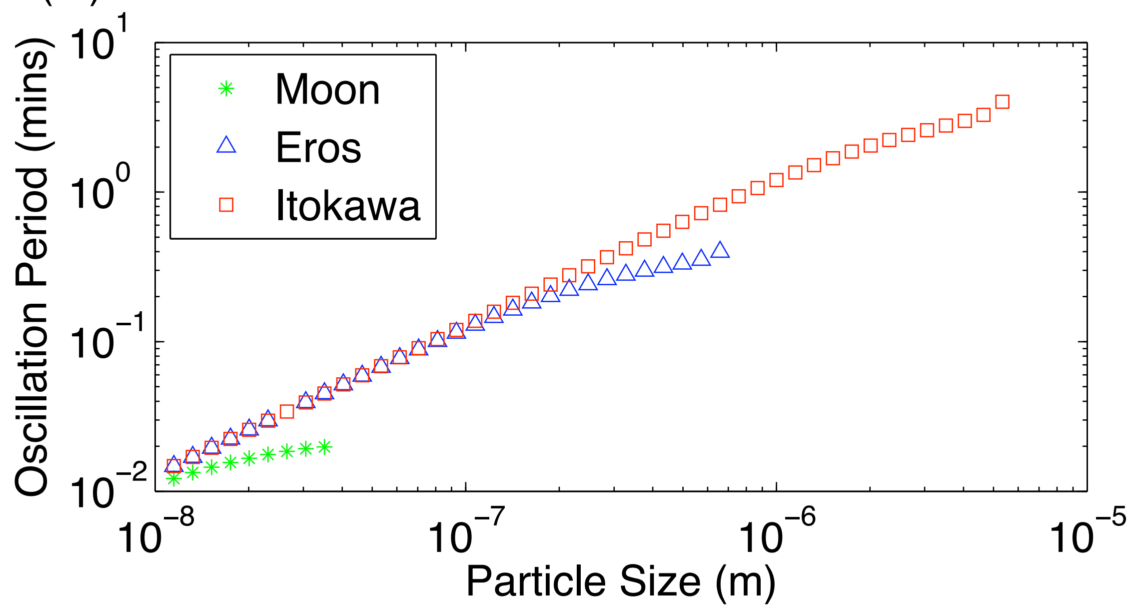


Rotation Periods:

Itokawa: 12hrs

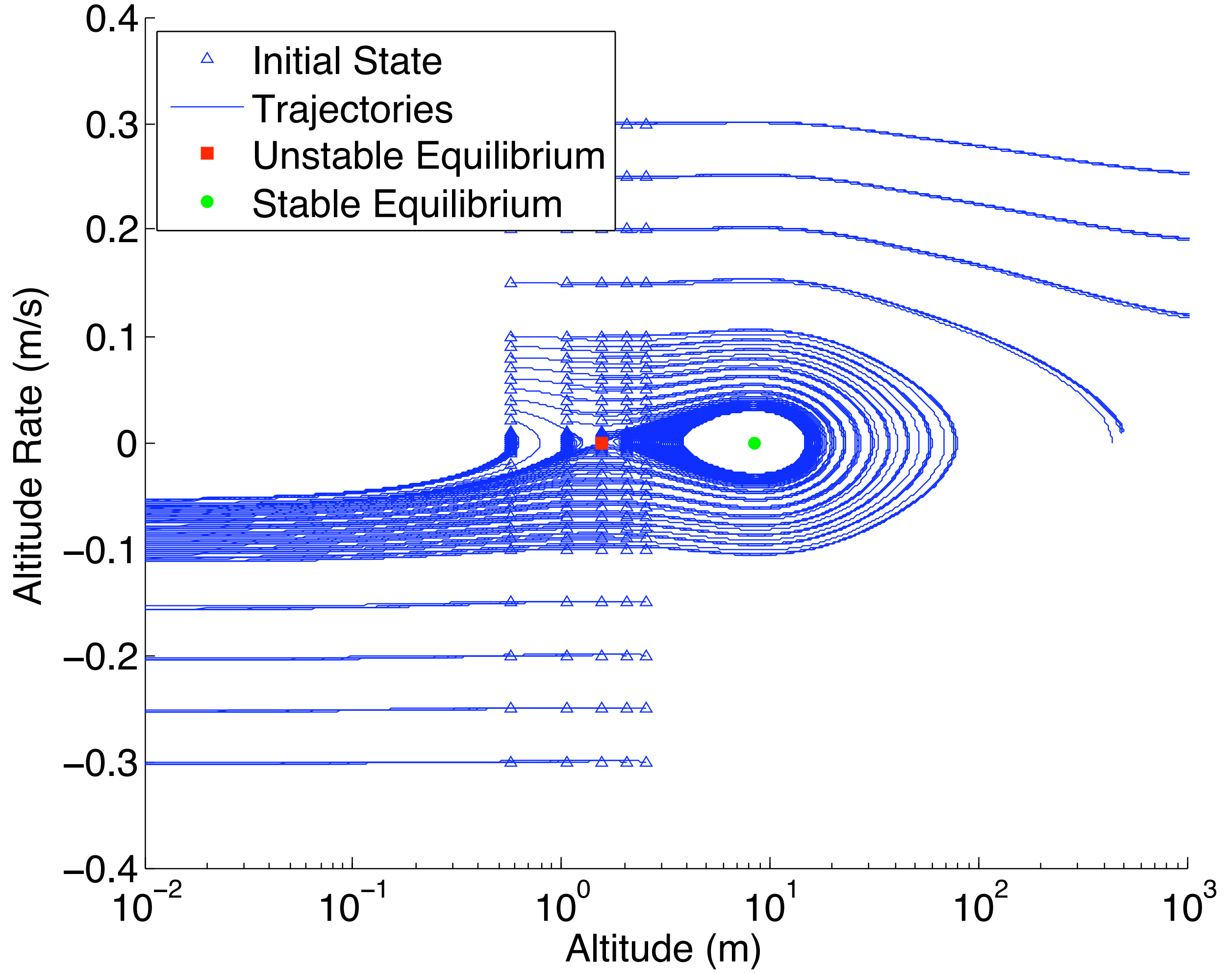
Eros: 5 hrs

Moon: 27 days

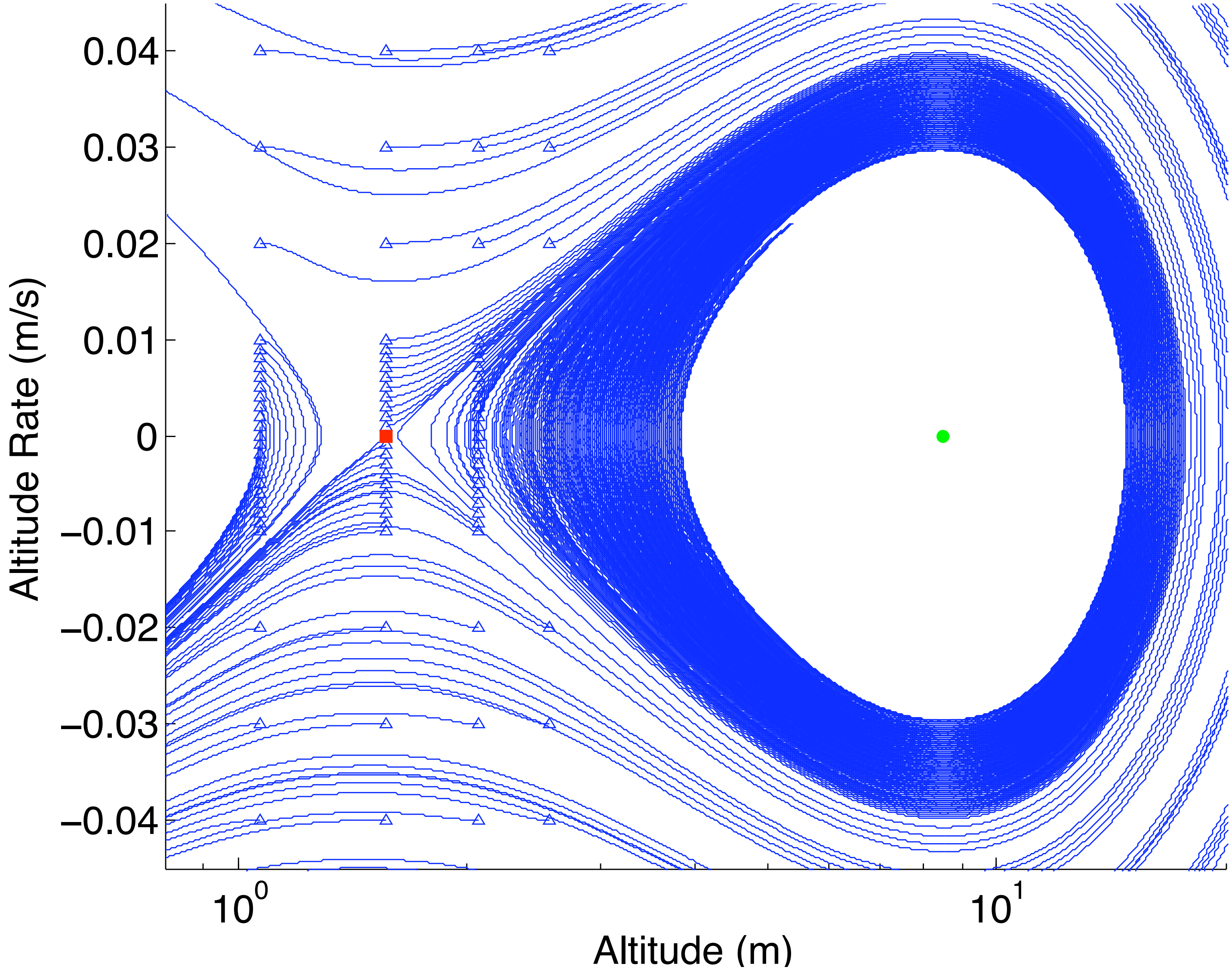


State Space

~3micron particle above Itokawa

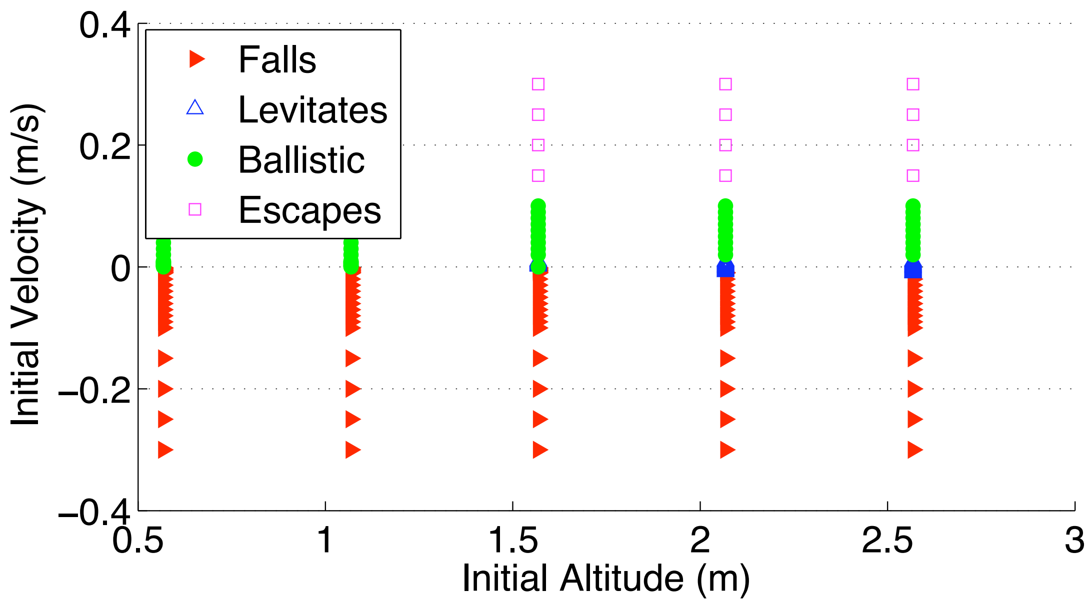


State Space



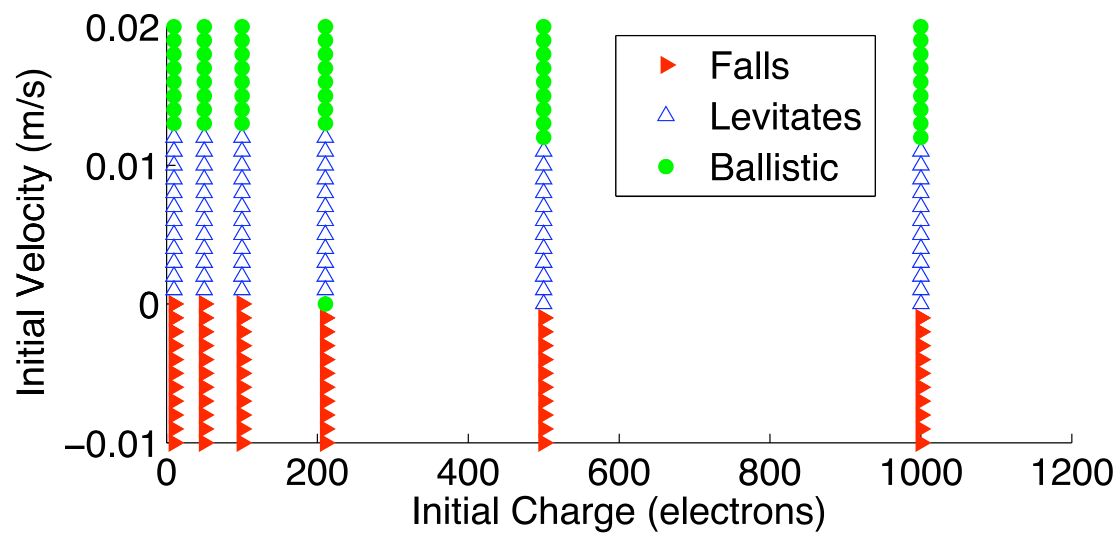
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
Altitude Rate (m/s)
10^0
10^1
Altitude (m)

Fate Plots



Initial Charge: 211 e

Initial Altitude: 1.57 m



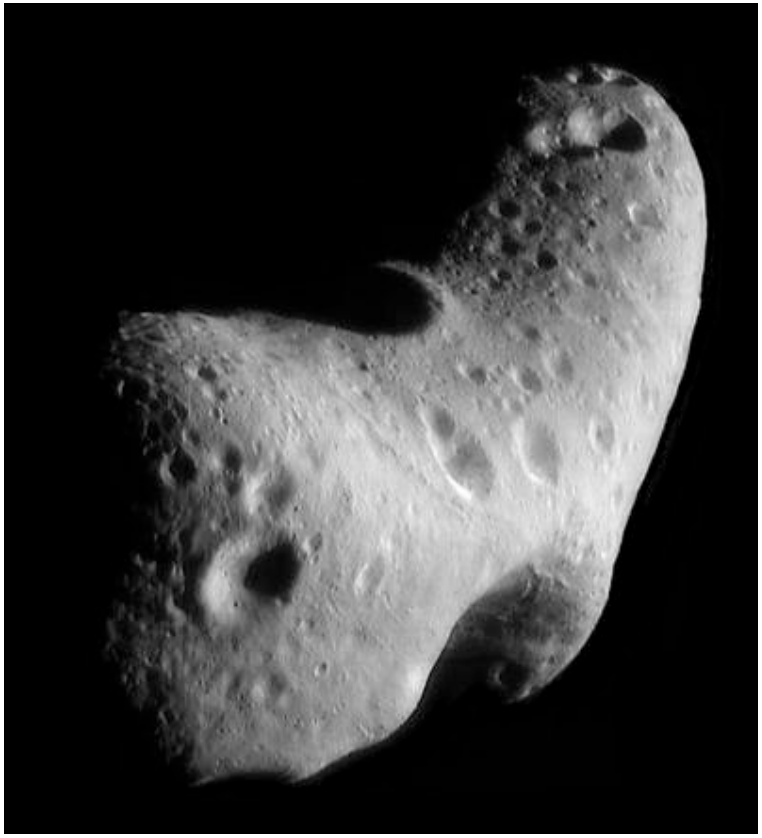
Conclusions

- Earlier work did not include cohesion when researching electrostatic dust lofting
  - Makes a big difference!
  - Experimental work is also lacking
- Have an increased understanding of levitation after doing dynamical systems analysis
  - Informs which particles will levitate in situ
  - Predictions of where to observe levitation

Future Work

- Complete state space exploration for electrostatic levitation
- Model dust motion about 3D asteroid (with accurate gravity)
- Experimental work on cohesion in plasma environment

Questions?



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