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# Simulating Small Body Formation Using Soft Sphere DEM with Induced Magnetic Dipoles

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## Abstract

We examine the effect that adding magnetic forces to SSDEM simulations of small body formation has on their resulting shape. For large objects, gravity maintains stability and creating spheroidal shapes. For small, low density objects, other forces become important. We simulate the aggregation of an asteroid from a cloud of magnetically susceptible grains with a permanently magnetized seed. We present a comparison of simulations with and without magnetism, and to the morphology of existing shape models.

## 1. Introduction

When studying the strength and shape of small bodies and the dynamics of regolith, gravity is insufficient to explain many phenomena. Asteroids are found to spin with angular velocities that would disrupt an object held together purely through self gravity [1], meteors remain intact longer than expected during entry into the atmosphere [2], and the interstellar object, 1I/2017 U1‘Oumuamua, has been observed as having a higher aspect ratio than would be expected through formation by spherically symmetric forces [3]. Van der Waals cohesion plays a significant role in maintaining asteroid strength, creating stable dynamics and shapes that cannot exist through just gravity [4, 5].

M-type asteroids are presumed to be made up mostly of nickel and iron [6]. These metals have high magnetic permeabilities. Additionally, magnetic fields have been observed on asteroids Gaspra and Braille, with an upper bound on the order of 100 μT [7].

## 2. Magnetic Forces

With magnetic fields strengths on the order of Braille and Gaspra’s, magnetic effects may have an impact in the formation and shape of metallic asteroids. Calculating the forces between two in-line particles in various background fields and comparing to the attractive force of various surface gravities, we find that the magnetic force exceeds the gravitational force (fig. 1).

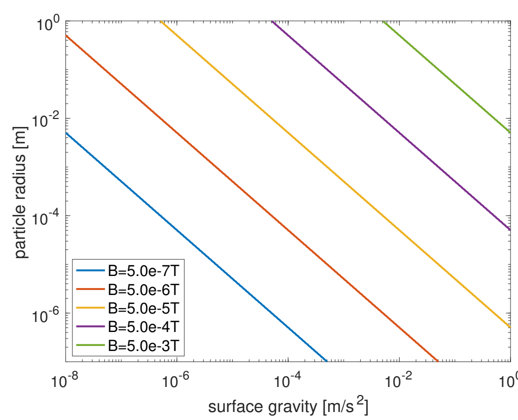


Figure 1: Lines of equal force between surface gravity and magnetic interaction. Magnetism dominates under the lines, for a given magnetic field strength.

## 3. Simulation

We simulate the formation of an M-type asteroid from a thermal cloud of iron particles. The cloud is initially given a random distribution of particle sizes, positions, and velocities. A large, permanently magnetized, “seed" particle is placed in the cloud to provide the initial background magnetic field. The system is then allowed to relax into a steady state configuration.

### 3.1. SSDEM Model

Our simulations run on the open source Soft Sphere Discrete Element Method (SSDEM) framework LIGGGHTS [8]. SSDEM models each grain in the system as a deformable sphere, which can interpenetrate with other grains, according to a Hertzian contact force. Also included in the LIGGGHTS framework, and used in this simulation, are cohesion, friction, and rolling resistance. Forces are summed at each time step, between each particle, within a cutoff distance. In addition, we have added models for magnetic dipoles and self gravity.

### 3.2. Magnetic Model

The force and torque on a magnetic dipole ($\vec{m}$) by an external magnetic field ($\vec{B}$) is given by [9]:

$$\vec{F}_m = \nabla(\vec{m} \cdot \vec{B}) \tag{1}$$

$$\vec{\tau}_m = \vec{m} \times \vec{B} \tag{2}$$

The total force on a magnetic grain with dipole moment ($\vec{m}_i$) due to the dipole field of its neighbors ($\vec{B}_j(\vec{r}_{ij})$) is therefore equal to:

$$\vec{F}_i = \nabla(\vec{m}_i \cdot \vec{B}_0) + \sum_{j=1,j\neq i}^{n} \nabla \left[\vec{m}_i \cdot \vec{B}_j(\vec{r}_{ij})\right] \tag{3}$$

The magnetic field and force drop off as $r^{-3}$ and $r^{-4}$, so the fields and forces can be approximated by summing over a short range, with acceptable accuracy. Using a cutoff distance of several particle diameters allows for high fidelity, while still maintaining efficient parallelization of the workload across processors.

Permanently magnetized grains have a constant value of $\vec{m}$ for the course of the simulation. When a soft magnetic grain is affected by a magnetic field (approximated as constant over the volume of the sphere), it has a dipole induced. The total dipole moment is the sum of the magnetic dipole induced by each of its neighbors. In order to solve this system numerically we use an iterative, mutual dipole method [10], which uses the dipole moments from the previous iteration to calculate the magnetic field at each grain, which, when multiplied by a constant ($C_i$) yields its dipole moment (eqn. 4). In three iterations, this converges to within $10^{-2}$ percent of the value at 1000 iterations.

$$\vec{m}_i^k = C_i \sum_{j=1,j\neq i}^{n} \vec{B}_j^{k-1} \tag{4}$$

The timestep for SSDEM simulations is constrained by particle size and hardness, such that the movement per timestep is small compared to the gradient of the magnetic field. Therefore, due to the rapid convergence, rather than iterating multiple times per timestep, we use the dipoles from the previous timestep to find the magnetic fields for magnetizing the current timestep. Our model for magnetic interactions and induced dipoles has been validated using simulations of magnetorheological fluids using >$10^5$ particles. The resulting yield stresses are within 10% of experimental data, indicating accurate bulk behavior of magnetic granular dynamics [11].

### 3.3. N-Body Gravity

Gravitational forces drop off proportional to $r^{-2}$, therefore, a range cutoff can add unacceptable error. The field does not, however, depend on the field from any other particles, simplifying the physics to solving Poisson's equation for N-bodies. Using a purely spectral solver limits the near field accuracy, instead we use a Particle-Particle Particle-Mesh PPPM solver. In PPPM solvers, the problem is decomposed into long range and short range terms [12]. The short range term is calculated exactly for near neighbors. The long range term is then calculated spectrally, using FFT.

## 4. Summary and Conclusions

Magnetism is found to dominate surface gravity for a range of possible magnetic field strengths, suggesting magnetism will have a significant effect during formation. We will present results comparing the coalescence of paramagnetic grains around a ferromagnetic seed particle to that of non-magnetic grains. We will also compare the simulated morphologies with existing asteroid shape models to evaluate whether observed features have magnetic origins.

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