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Final Report for LDRD Feasibility Study 11-FS-0015 Feasibility of Asteroid Deflection Investigations

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Feasibility of Asteroid Deflection Investigations
Written by Paul Miller, 8 November 2011, with input from the team members

Introduction

This report is a compilation of material generated in the course of the LDRD feasibility study 11-FS-0015, Feasibility of Asteroid Deflection Investigations. The descriptive material is from the web-based proposal for the project.

Plan

The NRC reported to Congress that nuclear explosives are the only current technology to defend Earth against large asteroids, or when time is short. This project aimed to develop a matrix of parameter variations to investigate, which includes a range of threat compositions, sizes, dynamics, and times to impact, optimizing with regard to parameters such as height of burst and yield. We also wanted to establish collaborations with expert material scientists to determine material models for of asteroids.

Expected Results

By the end of this feasibility study, we planned to have developed a matrix of important parameters to be varied to understand the dependence of energy coupling to Near Earth Objects (NEOs). We sought to establish a collaboration with material experts in this area, including members of the Computational Geophysics Group. These tasks were part of determining the feasibility of further investigations in this area.

Mission Relevance

This project sets the stage for further investigation into an important, exciting, and challenging application area that is beyond the traditional NNSA mission focus. The work will draw directly on LLNL secondary nuclear design capability for a mission of national interest. It will exercise our evaluation of outputs and their coupling to the materials of the Near Earth Objects (NEO). It expands upon our traditional role of stockpile stewardship. Several major national reports have identified nuclear energy coupling as an important NEO deflection strategy, and this work will help prepare LLNL and the NNSA complex for a role in a future threat situation.

Scope of Work

The study set out to establish a matrix of parameter variations that would be the starting point for our ER project on Asteroid Deflection. Further, it was to identify the key materials science issues for asteroid compositions. As part of the project we intended to hold team meetings, conduct planning for the initial period in the perspective of a three-year plan for a follow-on project, and work with our new postdoc to get her rapidly up to speed, in addition to working on our deliverables.

Accomplishments

This six-week feasibility study accomplished all of its proposed work, and more. A matrix of parameter variations was developed, material-science considerations were examined, and a preliminary set of impactor scenarios was constructed. Six weekly team meetings were held, involving over ten different participants. Two presentations were made to the Computational Geophysics Group, four members of which joined the project. Planning of future work was conducted and mentoring of the project postdoc began. Several group members ran modest calculations as part of the process of scoping out future simulations. We planned a computational problem, simply named Test Problem #1, although we did not begin calculations of it during the period.

Many of our deliberations were captured in a sequence of notes to the group. The notes on Preliminary Asteroid Models, Test Problem #1, and Key Parameters are included as Appendices 1, 2, and 3. Several examples of scoping simulation results are included in Appendix 4.

Follow-on Work

This feasibility study established the viability and potential for asteroid deflection as a topic for investigation, and it was followed by the approval of a full three-year LDRD project entitled "Asteroid Deflection" (LDRD 12-ERD-005) that began in October 2011.

Team members

Participants have included Dave Dearborn, Seran Gibbard, Kirsten Howley, Aaron Miles, Mike Owen, Rob Managan, Jim Elliott, Tarabay Antoun, Ilya Lomov, Eric Herbold, Oleg Vorobiev, Joe Wasem, and Paul Miller.

Appendix 1: Preliminary asteroid models

Compiled by Seran Gibbard.

The following models are chosen to be representative of observed asteroids. They are characterized by the following properties:

Porosity: There are basically three types:

1. "Monolith", density about equal to the grain density (porosity 0-5%). These tend to be the largest asteroids such as Ceres and Vesta. Note that large asteroids can also be rubble piles up to a point (~150 km radius). Above this size partial or full melting due to short-lived radioactive isotopes is possible. I do not include a large "monolith" in the suggested calculations since we are unlikely to be faced with a differentiated asteroid of these dimensions. A small monolith is included as a possible chunk from a larger body.
2. "Fractured", porosity typically 15-25%. Typically higher-albedo, S-type asteroids. Examples: Hermione, Ida, Eros. Large range of sizes from 100 meters (Eros) to 5 km (Sylvia) in radius.
3. "Rubble pile", porosity 30-80%. Range of sizes similar to fractured asteroids, but tend to be more dark, primitive-type asteroids (C-type).

Size: We can loosely characterize asteroids as "small", "medium", and "large". Here I will define "small" as <100 m in radius, "medium" as 100m-1km in radius, and "large" as > 1km radius. I am assuming here that we aren't worried about very large bodies that are monoliths such as Vesta and Ceres.

Density: I will assume here a density that corresponds to an average for the type of asteroid, scaled by the porosity as follows:

1. Fractured, density 2.7, porosity 20% (based on average S-type asteroid density)
2. Rubble pile, density 1.4, porosity 50% (based on average C-type asteroid density)
3. Monolith, density 3.44 (based on Vesta or chunks thereof)

From these considerations we can derive a starting point for the suite of models:

Asteroids:

1. Small, C-type, rubble
2. Medium, S-type, fractured
3. Large, rubble pile. Type C (primitive)
4. Medium, rubble pile, type C
5. Large, fractured, Type S
6. Medium, fractured, Type S
7. Binary, medium/small
8. Binary, small/small
9. Monolith, small (for the sake of completeness)

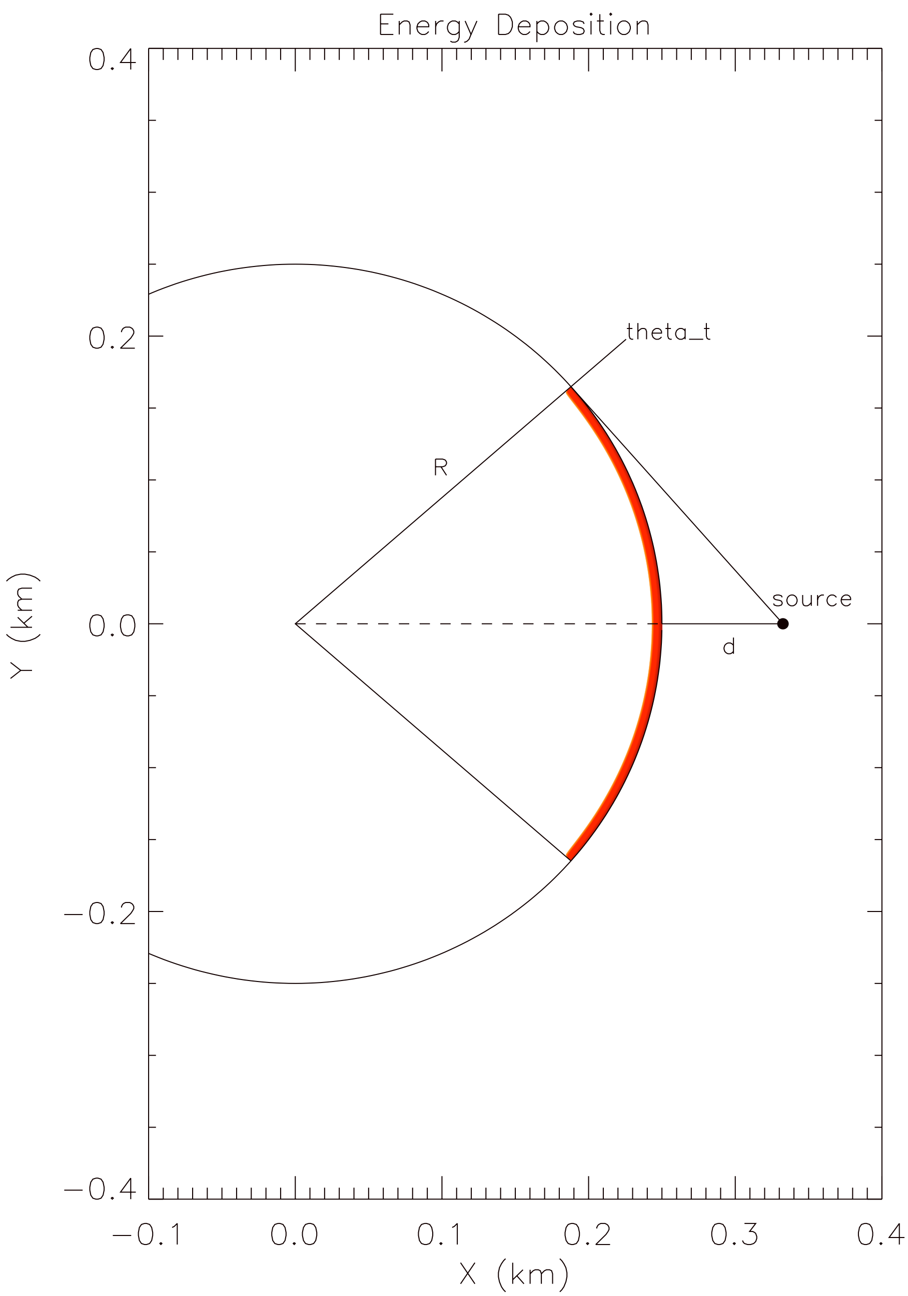
Comets:

10. Large (10 km radius) density 0.5 (?)
11. Medium (100 m radius) density 0.5 (?)

Other considerations: We haven't worried here about internal structure, except to call certain scenarios "rubble piles." To make the problems more specific we will need to come up with a rubble chunk size and something for the properties of the interstitial material (as well as surface material). Also the answer will also be dependent on how the chunks are distributed (concentrated in the center vs. scattered throughout). A single chunk size would be the easiest to represent; at this time it's not clear how you could derive a realistic distribution in any case. Two end-points would be a single "core" surrounded by strengthless material, and a uniform distribution of cores (size TBD) with strengthless material between them.

Appendix 2: Test Problem 1a, b, c:

Compiled by Kirsten Howley and Aaron Miles.



- Energy Deposition:
  - $\varepsilon_{dep}(r,\theta) = \varepsilon_0 e^{-(R-r)/\lambda_{eff}} \cos\left(\frac{\pi\theta}{2\theta_t}\right)$.
- Asteroid:
  - Material: SiO_2
  - ρ = 2.65 g/cc (density)
  - Porosity = 0
  - Tension:
    a. P_{min} = 0
    b. P_{min} = 10^{-4} Mbar
    c. P_{min} = 10^{-3} Mbar
  - R = 0.25 km (asteroid radius)
  - EOS: Mie-Gruneisen
    a. C_0 = 3.6839 x 10^5 cm/s
    b. S_1 = 1.8954
    c. S_2 = 0
    d. S_3 = 0
    e. γ_0 = 0.9
    f. A = 1.0
- Deflection:
  - Time to Impact: ~ decade
  - $\Delta v_z \approx 3$ cm/s (desired deflection velocity)
- Source: Fusion Weapon Neutrons
  - Y_{TOT} = 26.7 KT (source yield)
  - Y_{dep} = *5.4 KT (deposited yield)*
  - d = 0.33 R (stand off distance)
  - λ_{eff} = 30 cm (3 x 10^{-4} km, effective mean free path)
  - θ_t = 0.72 rad
  - ε_0 = 1.6512E10 erg/cc

Please report results in cgs units

Derivations:

$$\theta_t = \cos^{-1}\left(\frac{R}{R+d}\right)$$

$\eta_Y = 1.19$ (yield coupling, includes neutron caputure energy)

$\beta = 5.0\times10^{-3}$ (kinetic fraction of ε_{dep})

Define the problem in terms of device yield:

$$Y_{\text{int}} = \frac{1-\sin\theta_t}{2}Y_{TOT}$$

$$Y_{dep} = \eta_Y Y_{\text{int}}$$

$$Y_{dep} = \int \varepsilon_{dep}(\varepsilon_0, r, \theta)\,dV$$

$$Y_{dep} = \int_0^{2\pi}\int_0^{\theta_t}\int_0^{R} \varepsilon_0 e^{-(R-r)/\lambda_{eff}} \cos\left(\frac{\pi\theta}{2\theta_t}\right) r^2 \sin\theta\, dr\, d\theta\, d\phi$$

$$Y_{dep} = \left(2\pi\varepsilon_0\lambda_{eff}R^2\right)\left[1-2\frac{\lambda_{eff}}{R}+2\left(\frac{\lambda_{eff}}{R}\right)^2\left(1-e^{-R/\lambda_{eff}}\right)\right]\left(\frac{2\theta_t}{\pi}\right)\frac{\sin\theta_t - 2\theta_t/\pi}{1-\left(2\theta_t/\pi\right)^2}$$

$$\varepsilon_0 = \frac{\eta_Y Y_{TOT}}{\lambda_{eff}R^2 - 2\lambda_{eff}^2 R + 2\lambda_{eff}^3\left(1-e^{-R/\lambda_{eff}}\right)}\frac{\left(1-\sin\theta_t\right)}{8\theta_t}\left(\frac{1-\left(2\theta_t/\pi\right)^2}{\sin\theta_t - 2\theta_t/\pi}\right)$$

In the limit $\lambda_{eff} << R$:

$$Y_{dep} = 4\theta_t \frac{\sin\theta_t - 2\theta_t/\pi}{1-\left(2\theta_t/\pi\right)^2}\varepsilon_0\lambda_{eff}R^2$$

Substitue Y_{TOT} and solve for ε_0:

$$\varepsilon_0(R,\lambda_{eff},\theta_t,Y_{TOT})_{(erg/cc)} = \frac{1}{8\times10^{15}}\frac{\eta_Y Y_{TOT(erg)}}{\lambda_{eff(km)}R_{(km)}^2}\frac{\left(1-\sin\theta_t\right)}{\theta_t}\left(\frac{1-\left(2\theta_t/\pi\right)^2}{\sin\theta_t - 2\theta_t/\pi}\right)$$

$$\varepsilon_0(R,\lambda_{eff},\theta_t,Y_{TOT})_{(erg/cc)} = 5.23\times10^{11}\frac{\eta_Y Y_{TOT(MT)}}{\lambda_{eff(cm)}R_{(km)}^2}\frac{\left(1-\sin\theta_t\right)}{\theta_t}\left(\frac{1-\left(2\theta_t/\pi\right)^2}{\sin\theta_t - 2\theta_t/\pi}\right)$$

Or define the problem in terms of desired deflection velocity:

$$\Delta v_z \approx R_{\oplus}/t_{hit}$$

$$\Delta v_{z(cm/s)} = \frac{6.83\times10^{-9}}{R_{(km)}^2}\sqrt{\lambda_{eff(km)}\beta\eta_Y Y_{TOT(erg)}/\rho_{(g/cc)}}\,\frac{g(\theta_t)}{g_{\max}}$$

$$\Delta v_{z(cm/s)} = \frac{4.42}{R_{(km)}^2}\sqrt{\lambda_{eff(cm)}\beta\eta_Y Y_{TOT(MT)}/\rho_{(g/cc)}}\,\frac{g(\theta_t)}{g_{\max}}$$

$$Y_{TOT(MT)} = \frac{5.12\times10^{-2}}{\eta_Y\beta}\frac{R_{(km)}^4\rho_{(g/cc)}\Delta v_{z(cm/s)}^2}{\lambda_{eff(cm)}}\left(\frac{g_{\max}}{g(\theta_t)}\right)^2$$

$$\frac{g(0.72)}{g_{\max}} = 1$$

$$\eta_Y Y_{TOT} = \frac{2}{1-\sin\theta_t}\eta_Y Y_{\text{int}} = \frac{2}{1-\sin\theta_t}Y_{dep}$$

Substitute Y_{dep} for $\eta_Y Y_{TOT}$ in the v_z equation and solve for ε_0:

$$\varepsilon_0(R,\lambda_{eff},\theta_t,\Delta v_z)_{(erg/cc)} = \frac{2.56}{\beta}\left(\frac{R_{(km)}}{\lambda_{eff(km)}}\right)^2\frac{\left(1-\sin\theta_t\right)}{\theta_t}\frac{1-\left(2\theta_t/\pi\right)^2}{\sin\theta_t - 2\theta_t/\pi}\rho_{(g/cc)}\Delta v_{z(cm/s)}^2$$

$$\varepsilon_0(R,\lambda_{eff},\theta_t,\Delta v_z)_{(erg/cc)} = \frac{2.56\times10^{10}}{\beta}\left(\frac{R_{(km)}}{\lambda_{eff(cm)}}\right)^2\frac{1-\sin\theta_t}{\theta_t}\frac{1-\left(2\theta_t/\pi\right)^2}{\sin\theta_t - 2\theta_t/\pi}\rho_{(g/cc)}\Delta v_{z(cm/s)}^2$$

Appendix 3: Preliminary list of key parameters

Compiled by Seran Gibbard.

This list helped formulate the set of scenarios listed in Appendix 1.
Suggestions for range of asteroid/comet parameter space to be investigated:

1. Property: **Composition**
Reason: to determine EOS and bulk density
Members: C type, S type, M type, comet

2. Property: **Size**
Reason: Determines amount of energy needed, likelihood of occurrence
Members: 50 m, 100m, 300m, 1km

3. Property: **Porosity**
Reason: Determines strength/mass/other properties? of body. (I am assuming the bulk density will be set by the material)
Members: 0% (solid body), up to 30-80% (expected porosity of comets)

4. Property: **Internal Structure**
Reason: Affects propagation of shock waves, strength, behavior after shock
Members: solid body (monolith), rubble pile (large rubble), rubble pile (smaller rubble), central core (e.g. "peanut m&m")

Appendix 4: Results from several scoping simulations

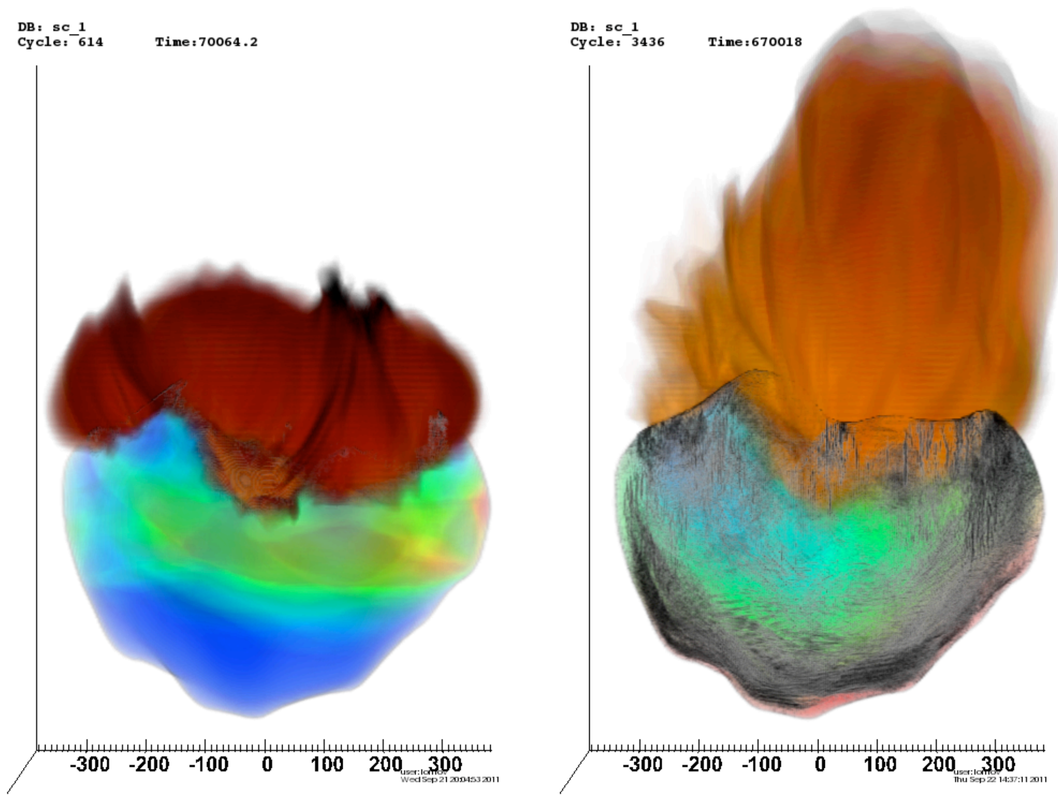


Figure 1 — Two visualizations are presented from the calculation of the response of a scaled version of the Geographos asteroid to a standoff 750kt nuclear explosion. The simulation represents 150kt of deposited energy acting upon an asteroid volume equivalent to a 500-meter-diameter sphere. Image times are 0.07s (left) and 0.67s (right). Each graphic combines volume rendering of three quantities: energy density in the ejecta (orange colorscale), velocity (RGB colorscale) and damage (grey scale). The resulting bulk deflection velocity is about 6cm/s. Work by Ilya Lomov.

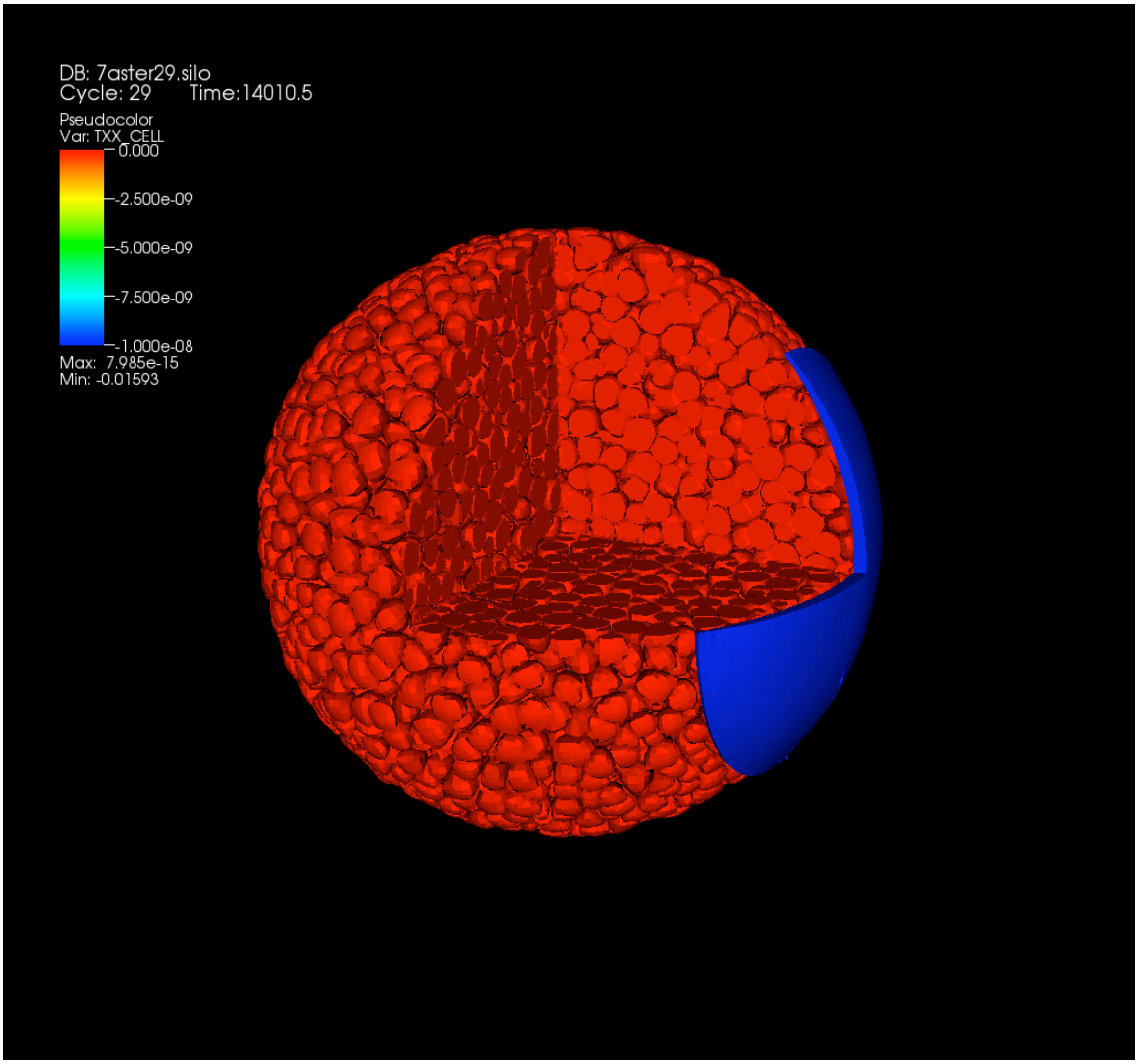


Figure 2 — The initial simulation configuration is shown of an asteroid comprised of 6250 discrete rocks. The blue cap on the right-hand side contains the energy imparted to the asteroid from a nuclear explosive, and will push the entire assembly as the simulation progresses. Variations of such a "rubble pile" structure are considered leading possibilities to describe many small-to-medium sized asteroids. Work by Eric Herbold.

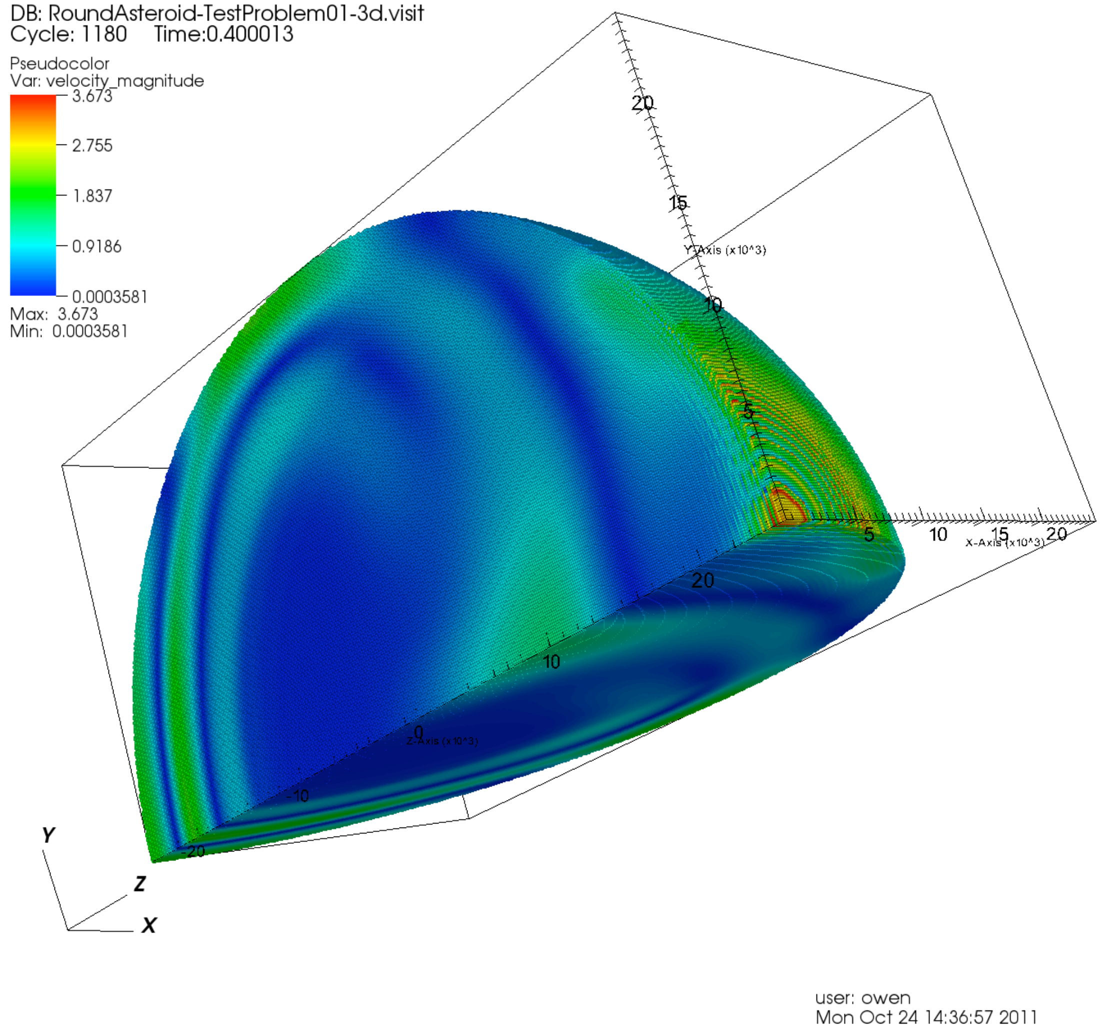


Figure 3 — Velocity magnitude (cm/sec) 0.4 sec after the simulated energy deposition from a nuclear device on an idealized 0.5 km diameter solid granite asteroid. The shock waves have traversed the asteroid and reflected back several times, resulting in the interacting waves and ringing evident in the image. A more realistic asteroid would likely have disrupted (come apart) by this time, due to an inability to support tension. Work by Mike Owen.