Simulating the Artificial Cratering on the Asteroid Ryugu

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LLNL-PRES-821487
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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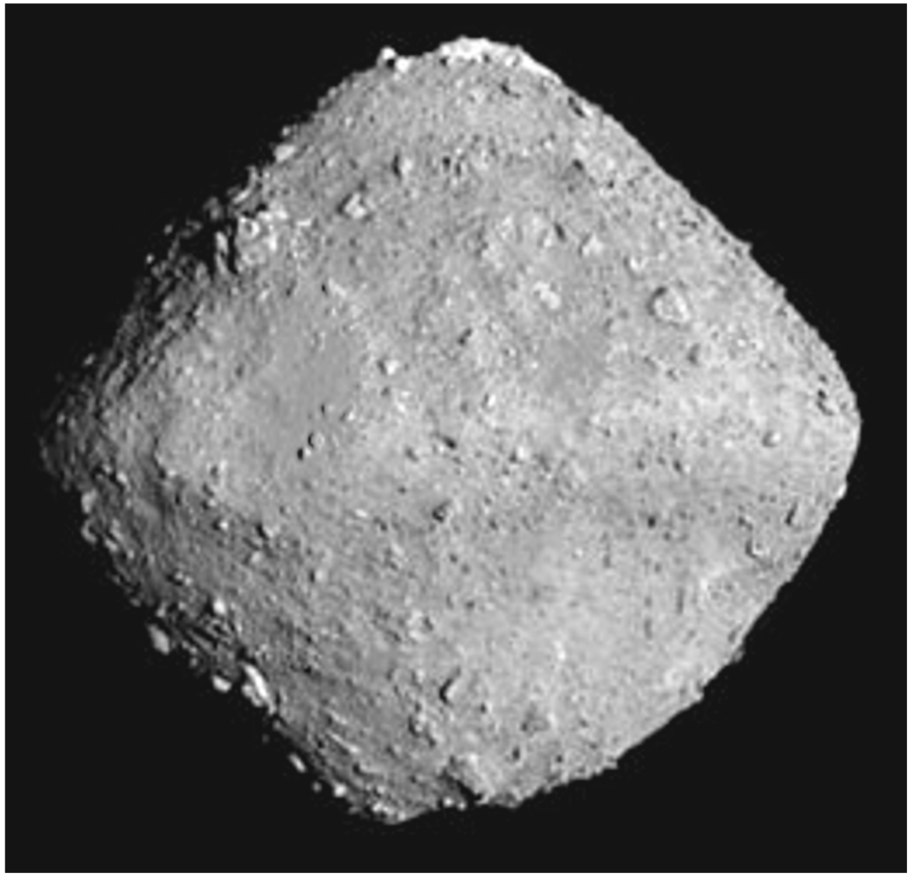
Background

- On June 27, 2018, the Japanese space agency's (JAXA) Hayabusa2 spacecraft arrived at the asteroid Ryugu. Their mission was to better understand the carbonaceous asteroid to understand the formation of extraterrestrial planets.



JAXA, Kobe University, Chiba Institute of Technology, The University of Occupational and Environmental Health, Kochi University, Aichi Toho University, The University of Aizu, and Tokyo University of Science

To study the composition of Ryugu, Hayabusa2 formed an artificial crater using an impactor (EFP)

- Copper Slug from explosively formed projectile (EFP)
  - ~2 kg
  - ~2 km/s
  - 300 m traveled
  - 30° off normal
- Resulting Crater
  - Semi-circle
  - ~14 m diameter

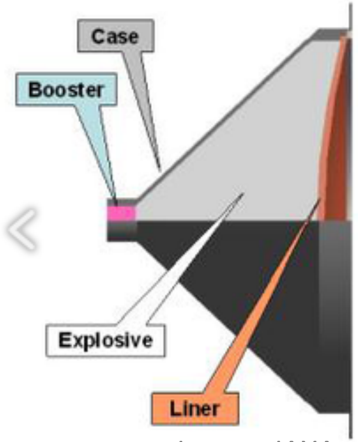
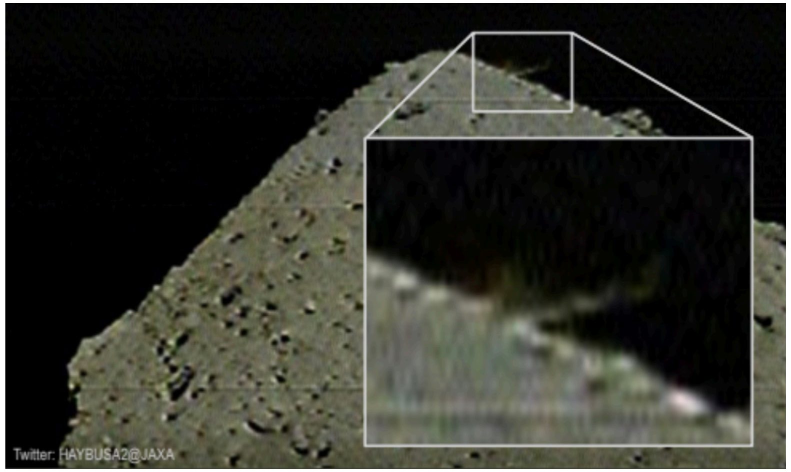
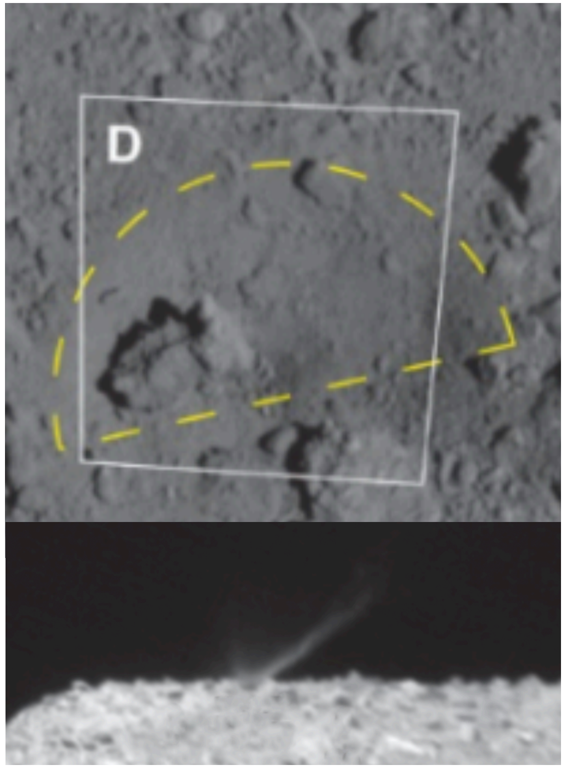


Image: JAXA



Twitter: HAYBUSA2@JAXA



Arakawa et al 2020

We seek a better understanding of Ryugu's composition through accurate simulation

- Understand asteroid composition better through hydrodynamic simulation of Ryugu impact
- The simulated composition of asteroid gives insight into subsurface layers
- We are simulating the EFP formation, propagation and impact into Asteroid 162173 Ryugu done by JAXA in 2020.
  - ~2 kg copper slug impacting the surface at ~2 km/s, 30° off normal
  - Resulted in a semi-circular crater approximately 14m in diameter
  - Images and impact analysis suggest Ryugu surface resembles sand

Crater Scaling Laws can help inform us about an asteroid's composition

- We can use crater scaling laws (*Holsapple and Housen 2007*) to gain some theoretical intuition for crater formation in different impacts
- Assuming a sandy surface these scaling laws predict the impact into Ryugu would result in a circular crater with a 9 m diameter.

$$R = a\,K_1\left(\frac{ga}{U^2}\left(\frac{\rho}{\delta}\right)^{2\upsilon/\mu} + \left(\frac{\bar{Y}}{\rho U^2}\right)^{2+\mu/2}\left(\frac{\rho}{\delta}\right)^{\upsilon(2+\mu)/\mu}\right)^{-\mu/2+\mu}$$

where a is projectile spherical radius; g is gravitational acceleration; ρ is asteroid bulk density; δ is projectile density; $\bar{Y}$ is tensile strength of asteroid; and U is normal projectile velocity

- Does not account for non-normal impact, surface boulders, subsurface composition

How we gain confidence in our simulations

- To ensure confidence in simulation of the impactor, we confirm the accuracy of our codes by comparing to known experiments of half-sized and full-sized EFP
- We compare simulations of ground-based explosively-formed projectile (EFP) to similar experiments (half and full-sized) done by JAXA
- We then run our projectile through vacuum and compare to JAXA's given projectile dimensions
- Using these results, we develop simplified projectile approximation for use in future 3D Spheral simulations for modeling impact scenarios

Copper slug impactor is formed using high explosives

- Considerable effort was put into properly modeling the materials, masses and behavior of the EFP:
  - Copper shell lining (2kg)
  - High explosive (4.7 kg HMX)
  - Aluminum casing

- High explosive deforms the copper liner into hemispherical-shell shape

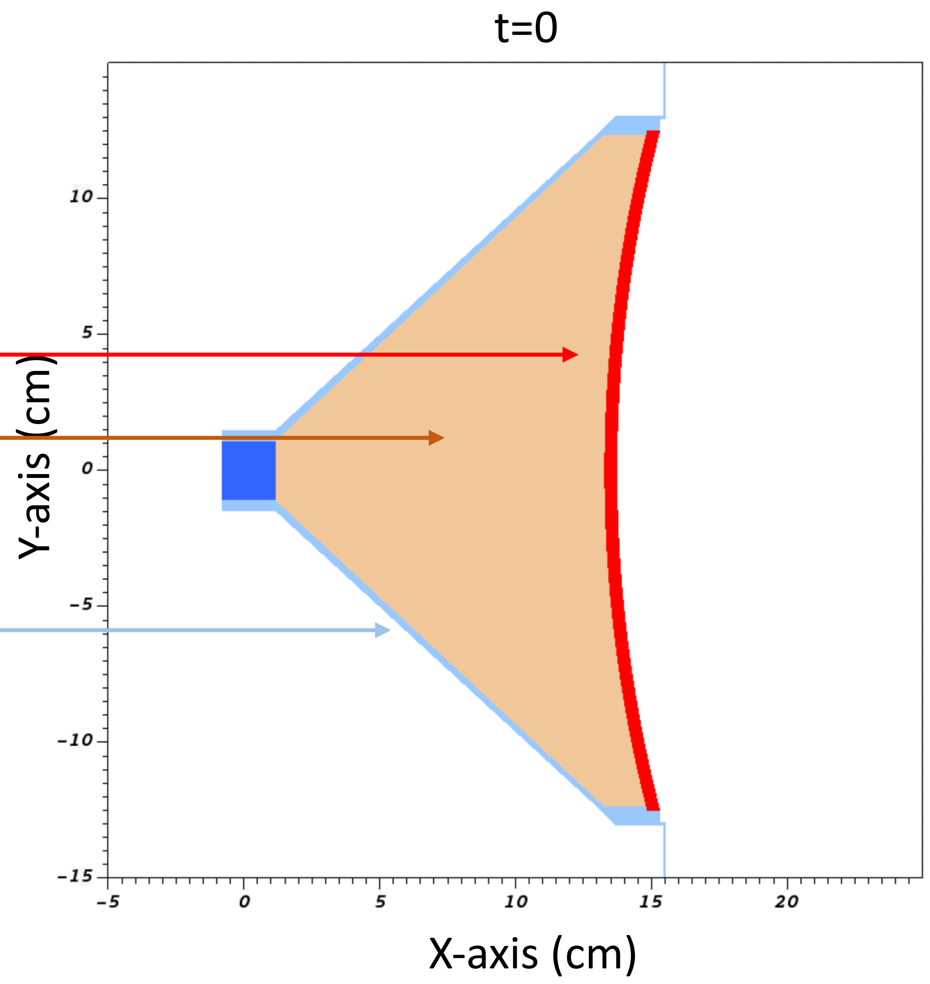


Image: T. Chang using ALE3D

Half-sized EFP: Simulation matches Ground-Based Experiment through Air

JAXA Data	Our Simulations (@t=150 us)
50 mm diameter shell → 20 mm diameter projectile	50 mm diameter shell → ~30 mm diameter projectile
Velocity exceeded 2 km/s	~2.4 km/s
~30 grams	~22.3 grams

- Mass from the 30 gram liner is lost as the EFP forms and propagates
- As EFP continues to travel through air the tails become more compressed

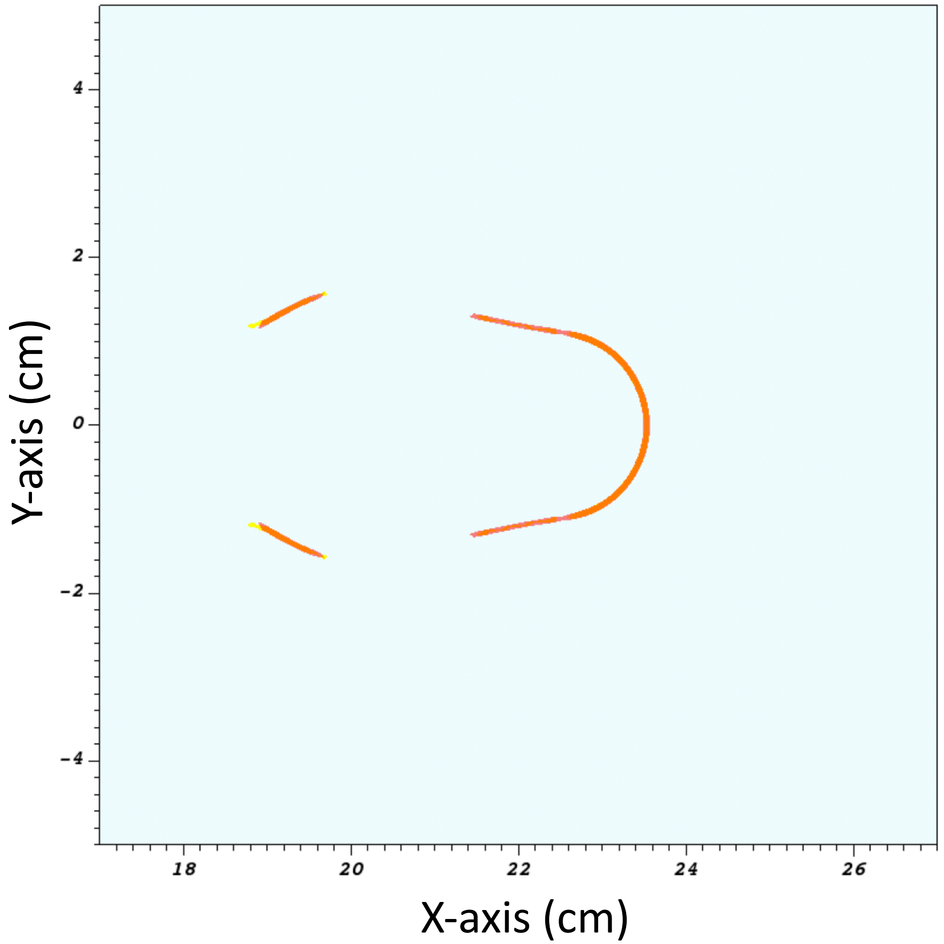


Image: T. Chang using ALE3D

Full-sized EFP: Simulation matches Ground-Based Experiment of through Air

JAXA Data	Our Simulations (@t=700 us)
25 cm diameter shell → 15 cm diameter projectile	25 cm diameter shell → ~13 cm diameter projectile
Velocity exceeded 2 km/s	~2.1 km/s
~2 kg before formation	~1.2 kg

- Mass from the 2 kg liner is lost as the EFP forms and propagates
- As EFP continues to travel through air the tails become more compressed

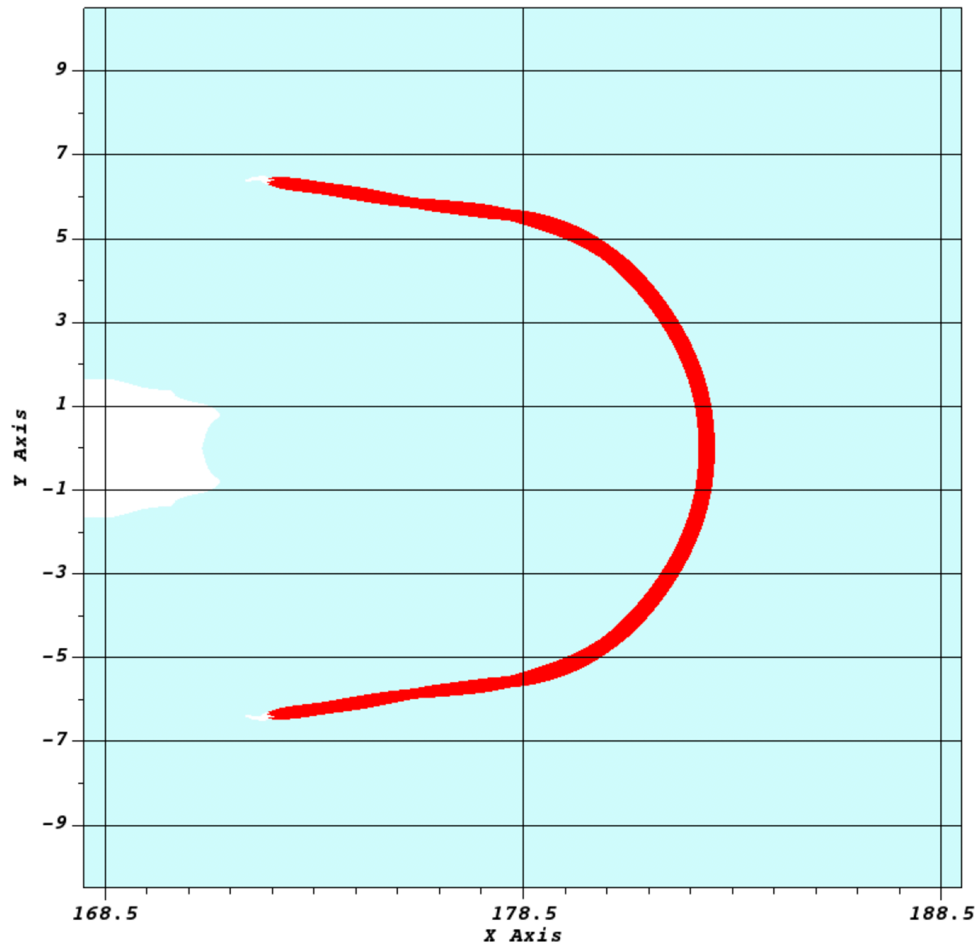


Image: T. Chang using ALE3D

Simulated EFP provides a good match Ground-based Experiment

high speed image of explosively formed projectile, similar to the one used to impact Ryugu, at 100 m (~50 milliseconds)

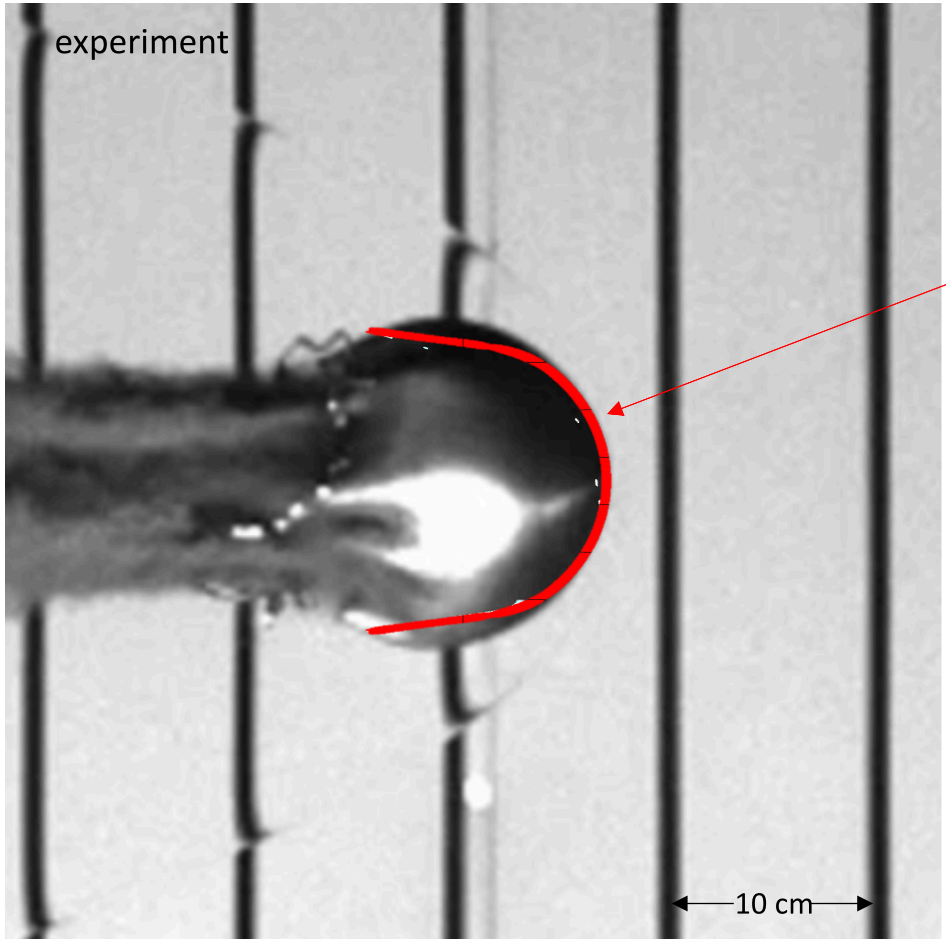


Image: Takagi et al 2014 with overlay by T. Chang using ALE3D

EFP through Vacuum results in a slightly faster velocity than EFP through air

Fully formed EFP

- Mass: 1.2 kg
- Velocity: 2.4 km/s

Ran projectile scan at multiple resolutions (density of elements in simulation) to find correct behavior for least computing power

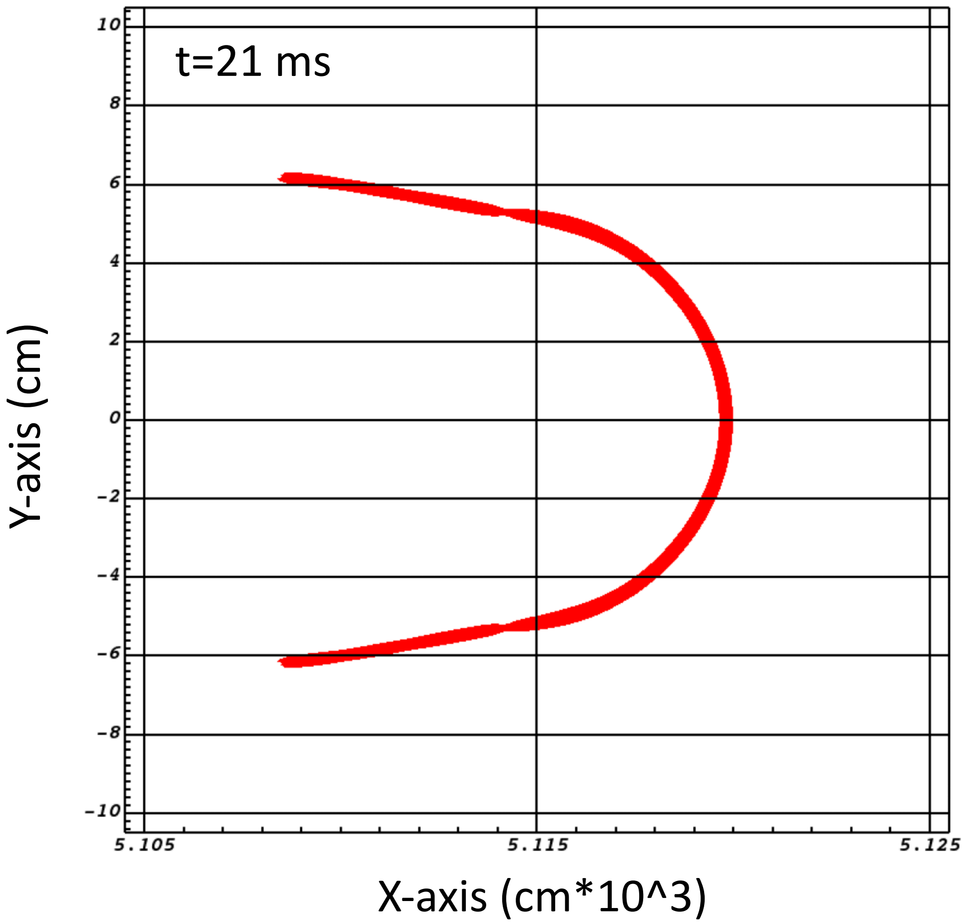


Image: T. Chang using ALE3D

We find a hemispherical shell of equivalent mass with 6.9 cm radius provides a good approximation to the EFP

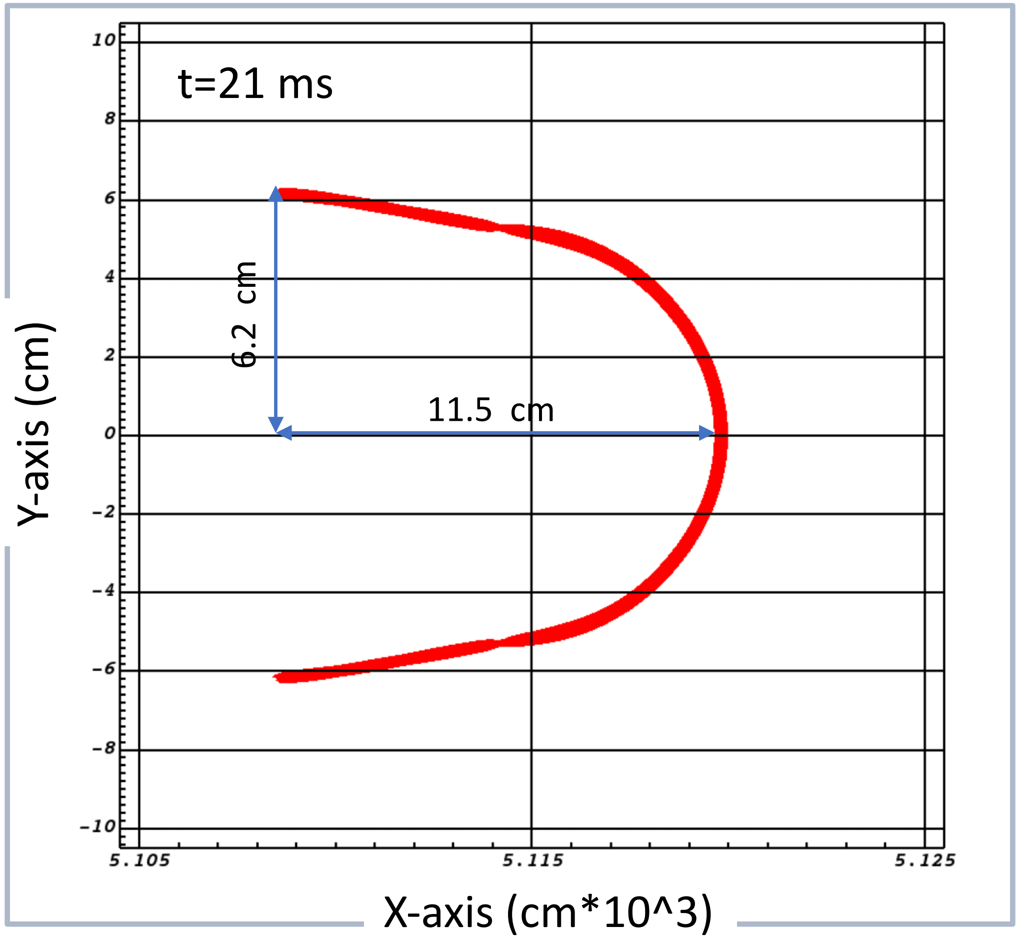


Image: T. Chang using ALE3D

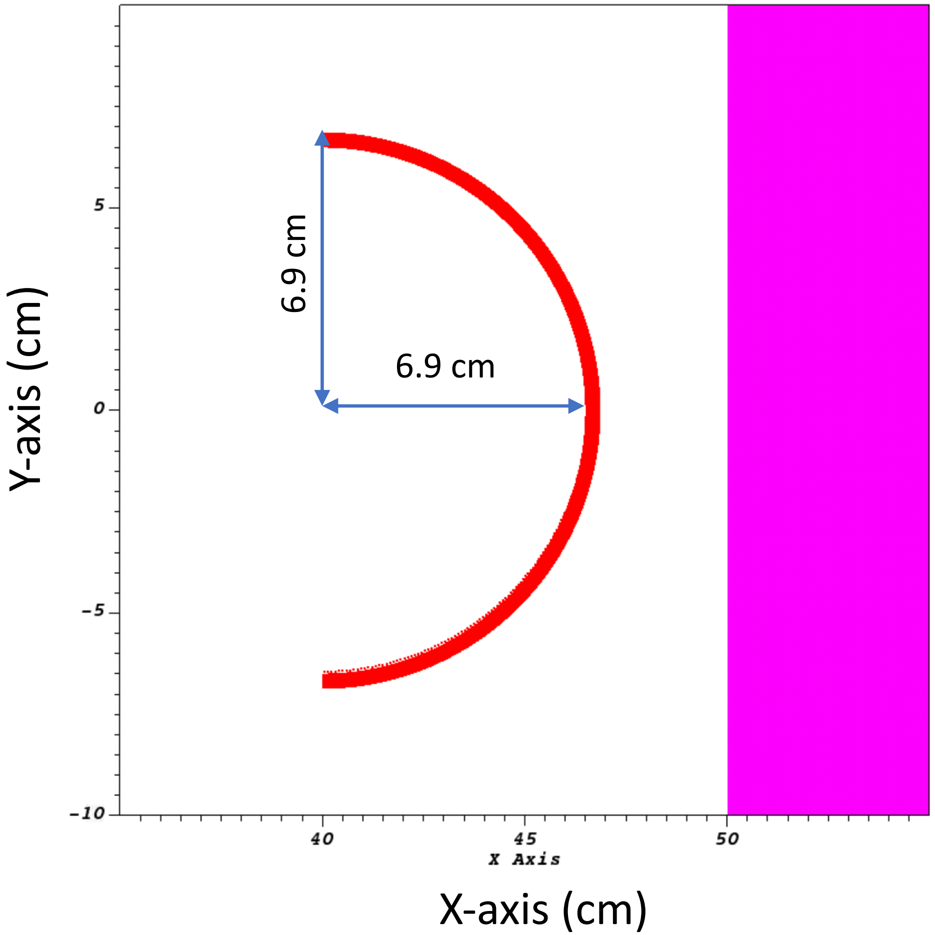


Image: T. Chang using Spheral in ALE3D

Shaped Approximations

- Our goal is to develop a hemispherical shell approximation for the EFP to improve computational efficiency in 3-D simulations
- @t=250 us (too early to compare*)

EFP Volume Excavated	Hemisphere Vol. Exc.
~5700 cm^3	~5400 cm^3 (6% difference)

- Didn't account for boulders, non-normal impact, etc.

Comparison of simulated EFP vs hemispherical shell approximation in 2D

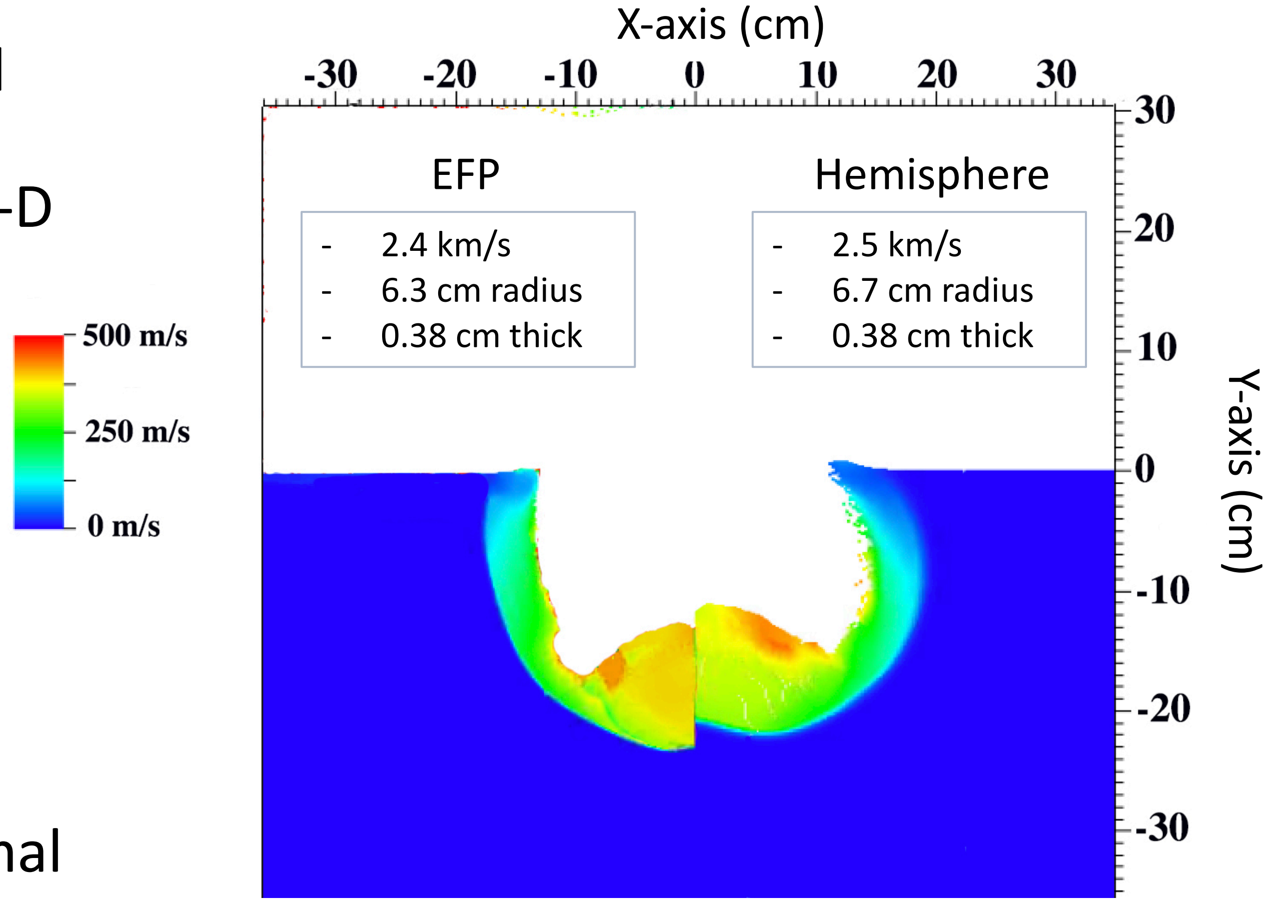
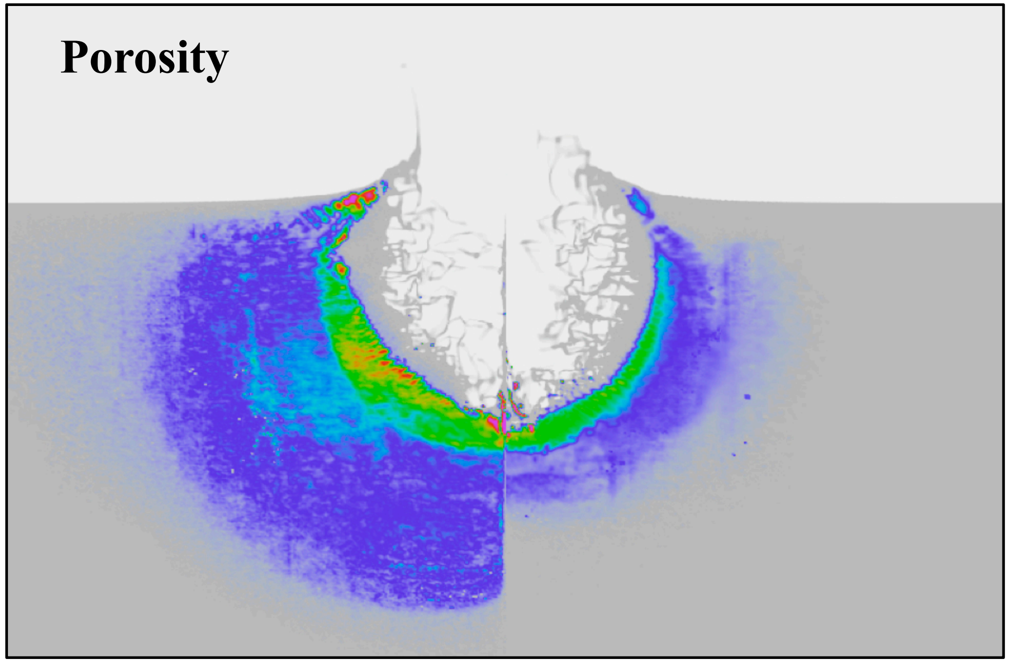


Image: T. Chang using ALE3D

* Crater formation takes ~500 s

Future Work modeling impact using Spheral, 3D will allow us to investigate Ryugu’s properties

- Will use hemispherical-shell impactor
- Will explore various porosity, strength, composition, non-normal impact, surface boulders, etc.



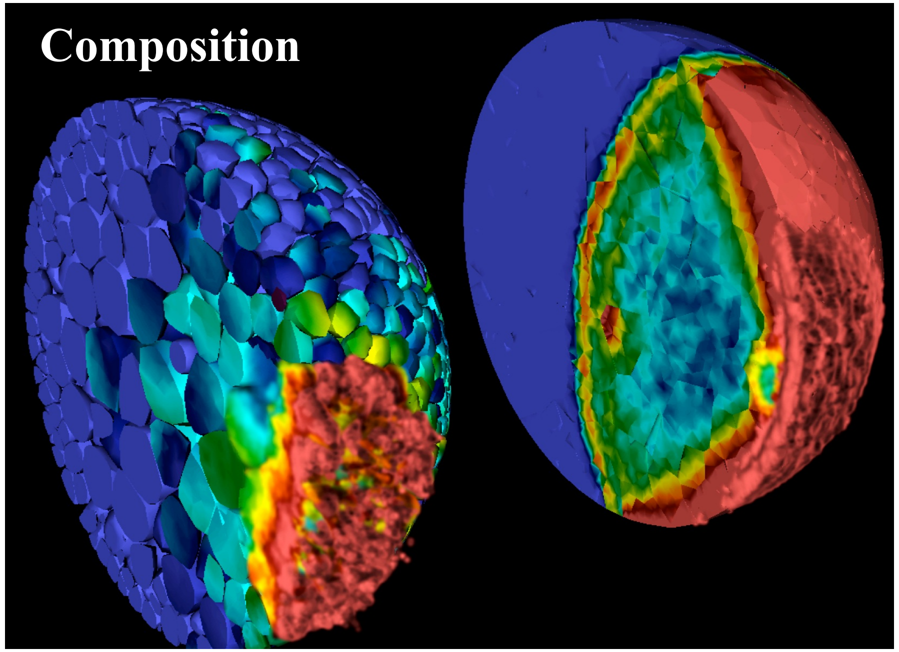


Image Credits: Herbold, LLNL using Geodyn-L

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