Impact Cratering on Icy Satellites

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Impact Cratering

- One of most important geological processes in planetary science
- Useful scientific tool

Erulus on Dione; ~120 km across
Crater Morphology

- Simple Crater
  - Bowl shaped depression with raised rim
    - Nearly parabolic
  - Depth, $d$, some small fraction of diameter, $D$
  - Ejecta blanket extends $\sim 1 \ D$
Complex Craters

• At larger diameters
  – Rim is terraced
  – Central peaks/pits
  – $d/D$ much lower than in simple craters

• Give impression of collapsed feature

• Transition diameter scales with target gravity and material
Complex Crater Cross Section

- Central peak not rim-slumped material
  - Peak material uplifted from depth
- On icy satellites, largest craters have central pits
Glaringly Obvious Observation

- Most craters are circular!
- Circularity major reason why a volcanic origin for craters on the Moon favored over impact until about the 1950s
  - WWII: lot of research into hypervelocity impacts (tank busting)
  - Recognized that planetary impact behaves more like a subsurface explosion than a surface collision
Impact Mechanics

• Three (artificial) stages
  – Contact & compression
  – Excavation
  – Modification
Planar Impact Approximation

- Impactor speeds > shock speeds in materials
Excavation Stage

- Two intertwined parts
  - Expanding and attenuating shock wave in target
  - Excavation flow
- Explosion of buried energy explains circularity of all but most oblique impacts
Excavation

- Flow field ejects and displaces material
  - Appears to emanate from some subsurface point
    - Shallow stuff ejected
    - Mid depth stuff displaced somewhat up/outwards
    - Deep stuff displaced downwards
Excavation

• Velocities ~30-50% peak particle velocities behind shock
  – Excavation takes s to m, depending on crater size

• End product: transient crater
  – Depth of transient crater
    ~1/3 to ¼ the diameter
  – All planetary craters get modified in next stage
Simple vs. Complex Craters

• Simple craters in “strength-dominated regime”
  – Transient crater topography insufficient to cause failure of bedrock

• Complex craters in “gravity-dominated regime”
  – Gravity overcomes material strength
Simple vs. Complex Craters

- Transition diameter abrupt
- Scales inversely with gravity of target
- Ice vs. rock
Depth to Diameter

- Depths are exponential
- Final depth scales with gravity and target material (in gravity-dominated regime)

![Graph showing depth vs diameter for Moon and Ganymede](image)
Impacts and Craters of All Scales

- Ceres: not an icy satellite per se
  - Largest asteroid in A/B ($R \sim 476$ km)
  - Low mean density ($\sim 2077$ kg m$^{-3}$)
  - Expectation: rocky core with 50-100 of ice crust
Ceres: A Prediction

- Icy near surface like icy satellites but...
- High average surface temperature (up to 180 K)
- McCord et al. [2011]: warm ice flowing glacial-like so efficient, only freshest craters should survive ➔ crater relaxation
Crater Relaxation

- Finite element analysis of elastic-viscous-plastic deformation
- Mechanical response to gravity loaded topography
- Rate depends on size and thermal structure
Ganymede Results

- For $q = 1 \text{ mW m}^{-2}$
  - Curves for different diameters ranging from 25 to 125 km are shown.
  - The apparent depth relaxation fraction increases with time.

- For $q = 10 \text{ mW m}^{-2}$
  - Similar curves are shown with an increased relaxation fraction compared to the lower heat flux case.
  - The relaxation fraction is higher for the same diameter at the same time.

The graphs illustrate the effect of different heat fluxes on the apparent depth relaxation fraction over time for various diameters.
Back to Ceres

• Small craters strongly relaxed in short time unless high latitude
  – Not much area
• Modern “cooler” regime actually warmer
Back to Ceres

• Large craters pasted, even at high latitudes (with sufficient time)

• Prediction: a giant cue ball in space
  – Dawn arrives in 2015
  – A probe for layering?
A Probe for Layering

- Large icy satellites → internal oceans
  - Many phases of ice
A Probe for Layering

• Formation of “large craters” should sample oceans
  – Expressed in morphology and $d/D$ ratios for fresh craters

Europa (10 km scale bars)

Adapted from Schenk [2002]
A Probe for Layering

• Depths to oceans
  – Europa: ~20 km
  – Ganymede & Callisto: ~100 km
• Expected to be ~150-200 km!

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A Probe for Layering

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• Crater relaxation to the rescue!!
  – No such things as “fresh” large crater on Ganymede and Callisto

Adapted from Schenk [2002]
Crater Relaxation: A Powerful Tool

- Study of relaxed craters can reveal clues to evolution of icy satellites → Rhea & Iapetus

From White et al. [2013]