EART160 Planetary Sciences

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Last Week - Volcanism

• How and why are melts generated?
  – Increase in mantle potential temperature; or
  – Reduction in solidus temperature (e.g. water); or
  – Thinning of the lithosphere

• How do melts ascend towards the surface?
  – Initially via porous flow through partially-molten rock
  – Later by flow in macroscopic fractures (dikes)

• What controls the style of eruption?
  – Magma viscosity, volatile content, environmental effects

• What controls the morphology of surface volcanic features?
  – Volcano morphology controlled mainly by viscosity
  – Flow characteristics can be used to determine material properties

• How does volcanism affect planetary evolution?
  – Advection of heat; sequestration of heat-producing elements
This Week - Impact Cratering

• Important topic, for several reasons
  – Ubiquitous – impacts occur (almost!) everywhere
  – Dating – degree of cratering provides information on how old a surface is
  – Style of impact crater provides clues to the nature of the subsurface and atmosphere
  – Impacts modify surface and produce planetary regolith
  – Impacts can have catastrophic effects on planets (not to mention their inhabitants)
  – Samples from other planets!
Impact Cratering - Topics

- Why and how do impacts happen?
- Crater morphology
- Cratering and ejecta mechanics
- Scaling of crater dimensions
- Cratered landscapes
- Planetary Effects
Why do impacts happen?

- Debris is left over from solar system formation (asteroids, comets, Kuiper Belt objects etc.)
- Object perturbed by something (e.g. Jupiter) into an orbit which crosses a planetary body
- As it gets closer, the object is accelerated towards the planet because of the planet's gravitational attraction
- The minimum impact speed is the planet's escape velocity, typically many km/s

“The next big event for astronomers will be Friday April 13th 2029. Scientists predict that the asteroid Apophis (~400m diameter) will be coming only 32,000 kilometres from the Earth, which is close enough to hit a weather satellite and even be visible without a telescope.”
Where do impactors come from?

• In inner solar system, mostly asteroids, roughly 10% comets (higher velocity, ~50 km/s vs. ~15 km/s)
• Comets may have been important for delivering volatiles & atmosphere to inner solar system
• In outer solar system, impactors exclusively comets
• Different reservoirs have different freq. distributions
• Comet reservoirs are Oort Cloud and Kuiper Belt
• Orbits are perturbed by interaction with planets (usually Jupiter)
• There may have been an “impact spike” in the inner solar system when the giant planets rearranged themselves (not quite as unlikely as it sounds)
Gravity

• Newton’s inverse square law for gravitation:

\[ F = \frac{Gm_1m_2}{r^2} \]

Here \( F \) is the force acting in a straight line joining masses \( m_1 \) and \( m_2 \) separated by a distance \( r \); \( G \) is a constant \((6.67\times10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2})\)

• Hence we can obtain the acceleration \( g \) at the surface of a planet:

\[ g = \frac{GM}{R^2} \]

• We can also obtain the gravitational potential \( U \) at the surface (i.e. the work done to get a unit mass from infinity to that point):

\[ U = -\frac{GM}{R} \]

What does the negative sign mean?
Escape velocity and impact energy

• Gravitational potential \[ U = -\frac{GM}{r} \]

• How much kinetic energy do we have to add to an object to move it from the surface of the planet to infinity?

• The velocity required is the escape velocity:
  \[ v_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{2gR} \]

• Equally, an object starting from rest at infinity will impact the planet at this escape velocity

• Earth \( v_{esc} \approx 11 \text{ km/s} \). How big an asteroid would cause an explosion equal to that at Hiroshima?
Impact velocities

- Impact velocity depends on escape velocity plus the velocity of the object “at infinity”:
  \[ v_i^2 = v_{esc}^2 + v_\infty^2 \]

- For small targets, what matters is \( v_\infty \)
- For large targets, what matters is \( v_{esc} \)
More Impact Velocities

• For synchronous satellites, we expect there to be more impacts on the *leading* than the *trailing* side. Why?
How often do they happen? (Earth)
Impact Velocities

- Crater formation process is controlled by the impact velocity compared with the *sound speed* of the material.
- Sound speed $c$ is given by $c \approx \sqrt{E / \rho}$
  
  Here $E$ is Young’s modulus and $\rho$ is density.

- Typical sound speeds are 4 km/s (rock) and 1 km/s (ice).
- Impacts are typically *hypersonic*.
- Slow impacts (e.g. at Pluto) may produce different-looking craters.
Crater Morphology

- Typical depth:diameter ratio is $\sim 1:5$ for simple (bowl-shaped) craters

Mars, MOC image
Craters of different shapes

- Crater shapes change as size increases:
  - Small – simple craters (bowl-shaped)
  - Medium – complex craters (central peak)
  - Large – peak ring / multi-ring basins

- Transition size varies with surface gravity and material properties

SIMPLE: Moltke, Moon, 7km
COMPLEX: Euler, 28km, 2.5km deep
BASIN: Hellas, Mars
Simple Crater

- Breccia
- Impact melt
- Impact ejecta
- Fractured bedrock
- Central peak uplift

Complex Crater
Shape Transitions

For silicate bodies:

- Simple
- Complex
- Peak ring
- Multi-ring
Icy satellite shape transitions

Europa, scale bar=10km

Note change in morphology as size increase

- Depth/diameter ratio decreases as craters get larger
- $g$ similar to that on the Moon
- Simple-complex transition occurs at smaller diameters than for Moon – due to weaker target material? (ice vs. rock)
- Largest basins different to silicate bodies (effect of ocean?)
Ceres looks like an icy satellite – why?
Simple-complex transition depends on $g$
Why does the transition happen at larger diameter on Mercury than Mars?
Pluto – Highest Res

80 m px\(^{-1}\)

- Ejecta Blankets
- No obvious secondary craters
- Nested craters (subsurface layering)
- Youngest craters are darkest
- Doublets?

Image courtesy Kelsi Singer
Charon crater morphology

- Bright rays, dark ejecta, lobate/potentially layered ejecta, central peaks sometimes hard to identify

All scale bars = 30 km

All names are informal.

Image courtesy Kelsi Singer
Viscous relaxation

\[
d = d_0 \exp(-t / \tau)
\]

\[
\tau \sim \frac{\eta}{\rho g D}
\]

White et al. (2013)
Simple Craters

Excavation depth is $\sim D/10$

Useful expression: volume of a bowl-shaped (parabolic) crater is $\pi D^2 d/8$
Excavation depth is typically only \(~1/3\) of crater depth.
Unusual craters

1) Crater chains (*catenae*)
2) Splotches
3) Rampart Craters (Mars)
4) Oblique impacts

Crater chains occur when a weak impactor (comet?) gets pulled apart by tides.

Comet Shoemaker-Levy, ripped apart by Jupiter’s tidal forces.
“Airbursts”

- Tunguska, Siberia 1908
- Result of (weak) impactor disintegrating in atmosphere
- Thick atmosphere of Venus means a lack of craters smaller than about 3 km (they break up in atmosphere)

- Venus “dark splotches”
Our data are based on observations made by US DoD and DoE space-based systems in geostationary orbits. These systems are designed to detect the signature of nuclear explosions and other objects of military interest . . . “
Rampart Craters (Mars)

- Probably caused by melting of subsurface ice leading to slurry ejecta
- Useful for mapping subsurface ice

Tooting crater, 28 km diameter

Stewart et al., Shock Compression Condens. Matt. 2004
Oblique Impacts

- Impacts are most like explosions – spherical shock wave leads to circular craters
- Not understood prior to the space age – argument against impact craters on the Moon
- Only very oblique (>75°?) impacts cause non-circular craters
- Non-circular craters are rare
- But non-circular ejecta patterns are more common

Mars, D=12km
Herrick, Mars crater consortium
Large oblique impacts

- Large basins are often elliptical
- Geometry is different for large vs. small impactors (only large impactors sense the curvature of the target)
Crater Formation

- Impactor is (mostly) destroyed on impact
- Initial impact velocity is (usually) much greater than sound speed, creating shock waves
- Shock waves propagate outwards and downwards
- Heating and melting occur
- Shock waves lead to excavation of material
- Transient crater appx. spherical
- Crater may then collapse to final form

Note overturned strata at surface

1. Contact/compression
   - Compression Stage
     *adapted from: Gahn et al., 1968*

2. Excavation
   - Excavation
     *adapted from: Gahn et al., 1968*

3. Modification
   - Post-Cratering Modifications
     *adapted from: Gahn et al., 1968*
Timescales

• Contact and compression
• Time for shock-wave to pass across impactor
• Typically less than 1s

\[ t = \frac{2r}{v} \]

• Excavation
• Free-fall time for ejected material
• Up to a few minutes

\[ t = \sqrt{\frac{2d}{g}} \]

• Modification
• Initial faulting and slumping probably happens over a few hours
• Long-term shallowing and relaxation can take place over millions of years
Contact phase

- Peak shock pressure $P_{\text{max}} \sim \rho v_i^2$
- Strength is not usually important – why?
- Pressure constant within isobaric core (radius comparable to impactor)
- Pressure decays as $\sim r^{-3}$ outside
- Heating also decays with distance

- Larger craters experience more heating
- Material closest to ground zero experiences greatest shock and heat
Meteorites from Mars

• How does this happen?
• Spallation – effect of free surface

Spallation region – high ejection velocities, material relatively unshocked

• How do we know they are from Mars?

Strength vs. Gravity

- Making a crater requires both material strength of the target and gravity to be overcome.
- Which of these dominates depends on crater size.

We can balance these two effects:

\[ \rho gd \approx \frac{1}{5} \rho gD \approx Y \]

where \( Y \) is the yield strength (~1 MPa).

- On Earth, transition occurs at ~0.15 km; 1 km on Moon.
- Laboratory experiments on Earth are always in the strength regime; bomb tests can be in gravity regime.
- For most craters, gravity dominates and we can ignore strength (significant simplification!)
Crater Sizes

- A good rule of thumb is that an impactor will create a crater roughly 10 times the size (depends on velocity)
- We can come up with a rough argument based on energy for how big the transient crater should be:

$$D \approx \left( \frac{v_i^2}{g} \right)^{1/4} \left( \frac{\rho_p}{\rho_t} \right)^{1/4} L^{3/4}$$

- E.g. on Earth an impactor of 0.1 (1) km radius and velocity of 10 km/s will make a crater of radius 2 (12) km
- For really small craters, the strength of the material which is being impacted becomes important

Does this make sense?
Transient vs. Final Diameter

- Impact characteristics set transient crater size
- Transient craters are initially bowl-shaped
- If they are too large, they undergo slumping and collapse
- Final crater diameter is larger than transient diameter
- So to determine impact characteristics, we need to convert from final to transient diameter:

\[ D_{\text{fin}} = 1.17 D_{\text{tr}}^{1.13} / D_{\text{sc}}^{0.13} \]

Here \( D_{\text{sc}} \) is the simple-complex transition diameter. Why?
How big a (transient) crater?

A semi-empirical formula based on impact experiments gives:

\[
D_{tr} = 1.61 \left( \frac{\rho_p}{\rho_t} \right)^{1/3} L^{0.78} v_i^{0.44} g^{-0.22} \sin^{1/3} \theta
\]

Where \( \theta \) is the impact angle (90°=vertical).

How does this compare with our simple theoretical estimate?

\[
D \approx \left( \frac{\rho_p}{\rho_t} \right)^{1/4} L^{3/4} \left( \frac{v_i^2}{g} \right)^{1/4}
\]

The Chixculub (dinosaur-killing) impact basin is 180 km in diameter. How big was the projectile? Take \( v_i = 20 \) km/s. How much energy was released? (cf. Krakatoa \( 10^{18} \) J)

[ \( D_{tr} \) appx. 100 km, \( L \) appx. 10 km ]
Melt Production

- Basin volume grows as $\sim (mv^2)^{3/4}$
- But melt volume is expected to scale linearly with kinetic energy ($\sim mv^2$) (why?)
- So bigger basins generate proportionately more melt
- Largest basins (e.g. South-Pole Aitken) generated km-thick melt ponds which then crystallized

Lack of olivine in big lunar basins
Ejecta

- Particles ejected beyond the crater rim on *ballistic* trajectories
- Mean ejecta thickness falls off as $\sim(\text{distance})^{-3}$
- Most material deposited within 3 crater radii
- Material launched with higher velocities travels further and impacts at higher speed

$$S_{\text{max}} = \frac{v_{\text{ej}}^2}{g}$$  (Why?)

Most ejecta is travelling *slowly* compared to the original impact velocity
Atmospheric Effects

• Small impactors burn up in the atmosphere
• Venus, Earth, Titan lack small impact craters
• Venus’ thick atmosphere may produce other effects (e.g. outflows)

After McKinnon et al. 1997

![Radar image of impact-related outflow feature](image.png)
Atmospheric Effects

- A good rule of thumb is that an incoming projectile breaks up when it has encountered a mass of atmosphere equal to its own mass

\[ z = \frac{2 \rho_s d}{3 \rho_a} \]

(Assumes \( \rho_a \) is constant)

Does this make sense?

So the minimum size of projectile which will make it through the Earth’s atmosphere is \( d \sim 4 \text{m} \) (why?)

How big a crater would this make?

What would the minimum projectile size on Venus be?
Atmospheric Effects

Study of ancient (exhumed) craters on Mars
Constraint on paleo-atmospheric pressures

Kite et al. 2014

Study of volcanic bomb sag on ancient Mars
Another (non-impact) constraint on paleo-pressures.

Manga et al. 2012
Airburst triggered 65,000 landslides

Spatial pattern suggests shaking via atmospheric pressure waves, not seismic shaking

Burleigh et al. 2012
Surface Modification

- Micrometeorite bombardment causes preferential down-slope motion (diffusive process - see Week 7)
- Over time, causes topographic smoothing on airless bodies
- Also destroys boulders & creates regolith
Impact destruction of boulders

Boulders > 2m in diameter

Basilevsky et al. 2013

• Boulders on the Moon only survive ~50 Myr
• We can tell this because of
  – Extremely high-resolution images of the lunar surface
  – The Apollo astronauts returned samples allowing craters to be dated
How do we date surfaces (1)?

- Crater densities – a more heavily cratered surface is older.
- The size-distribution of craters can tell us about the processes removing them.
- Densities reach a maximum when each new crater destroys one old crater (*saturation*). Phobos’ surface is close to saturated.
- Lunar crater densities can be compared with *measured* surface ages from samples returned by Apollo missions.

![Image of young and old cratered surfaces](image-url)
Saturation

Equilibrium situation in which addition of one new crater destroys one old crater (on average)
Calibrating the lunar cratering curve

Stoffler & Ryder (2001)
How do we date surfaces (2)?

- It is easy to determine the relative ages of different surfaces (young vs. old)
- Determining the absolute ages means we need to know the cratering rate (impacts per year)
  - We know the cratering rates on the Earth and the Moon, but we have to put in a correction (fudge factor) to convert it to other places – large uncertainties
  - The rate of cratering has declined with time (see diagram)
Some lavas are *very* young (<20 Myr). So it is probable that Mars is volcanically active *now*. How might we test this?
New craters on Mars

• Important because we can use these observations to calibrate our age-crater density curves
• Existing curves look about right

Malin et al. *Science* 2006

Probably mis-identified
Evolving impactor populations?

- One complication is that the population of impactors has changed over time
- Early solar system had lots of debris => high rate of impacts
- More recent impact flux has been lower, and size distribution of impactors may also have been different
- Did the impact flux decrease steadily, or was there an “impact spike” at ~4 Gyr (Late Heavy Bombardment)?
Crater Counts

- Crater size-frequency plots can be used to infer geological history of surfaces
- Example on left shows that intermediate-size craters show lower density than large craters (why?)
- Smallest craters are virtually absent (why?)
- Most geological processes (e.g. erosion, sedimentation) will remove smaller craters more rapidly than larger craters
- So surfaces tend to look younger at small scales rather than at large scales
Complications

- Rate of impacts was certainly not constant, maybe not even monotonic (Late Heavy Bombardment?)
- **Secondary craters** can seriously complicate the cratering record
- Some surfaces may be buried and then exhumed, giving misleading dates (Mars)
- Very large uncertainties in absolute ages, especially in outer solar system

Pwyll crater, Europa (25 km diameter)
Cratering record on different bodies

- Earth – few craters (why?)
- Titan – few craters (why?)
- Mercury, Phobos, Callisto – heavily cratered everywhere (close to saturation)
- Moon – saturated highlands, heavily cratered maria
- Mars – heavily cratered highlands, lightly cratered lowlands (plus buried basins) and volcanoes
- Venus – uniform crater distribution, \(~0.5\) Gyr surface age, no small craters (why?)
- Ganymede – saturated dark terrain, cratered light terrain
- Europa – lightly cratered (\(~0.05\) Gyr)
- Io – no craters at all (why?)
- Pluto & Charon – heavily cratered, few small craters
Which one is Venus?

Strom et al. 1994
Planet-scale effects

• In order of decreasing energy:
  – Mantle stripping (Moon formation; Mercury?)
  – Changing axial tilt (Uranus?)
  – Global melting (magma oceans)
  – Crustal blowoff
  – Atmospheric blowoff (Mars?)
  – Volatile delivery (comets?)
  – Mass extinctions
Impact Cratering - Summary

- Why and how do impacts happen?
  - Impact velocity, comets vs. asteroids

- Crater morphology
  - Simple, complex, peak-ring, multi-ring

- Cratering and ejecta mechanics
  - Contact, compression, excavation, relaxation

- Scaling of crater dimensions
  - Strength vs. gravity, melting

- Cratered landscapes
  - Saturation, modification, secondaries, chronology

- Planetary Effects
Useful Equations

\[ v_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{2gR} \]

\[ P_{max} \approx \rho v_i^2 \]

\[ D_{tr} = 1.61 \left( \frac{\rho_p}{\rho_t} \right)^{1/3} L^{0.78} \nu_i^{0.44} g^{-0.22} \sin^{1/3} \theta \]

\[ S_{max} = \frac{v_{ej}^2}{2g} \]
Deleted/backup material follows
Evolving impactor population

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- Early solar system had lots of debris => high rate of impacts
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Hartmann; W are numerical simulation results, boxes are data from Moon/Earth

Needs updating – Nice model and ages of ancient basins
Something about R plots?
65000 landslides airburst

- “Lebanon” 2m wide iron meteorite on Mars
Venusian Impact Craters

- Mars Old Plains
- Mars Northern Plains
- Mars Young Volcanoes
- Mars Tharsis Plains
- Venus (89% of Surface)
Fig. 2. Schematic representation of the compression stage of the formation of an impact crater.
Slope = \frac{P_2 - P_1}{V_2 - V_1} = -(\rho_1U)^2

Rayleigh Line

Hugoniot

Driven by shock

Waste heat
The Lunar Cataclysm Hypothesis

Formation of Earth and Moon from Accreting Planetesimals

After Kring (2003)

Flux of Impacting Asteroids and/or Comets

Cataclysmic Bombardment of Earth and Moon

Earliest Isotopic Evidence of Life on Earth (~3.8 Ga)

Earliest Fossil Evidence of Life on Earth (~3.5 Ga)

Time (billions of years)

4.5 3.9 Today
Pike, USGS Prof. Pap. 1980
Central Peaks

- Visual onset of central peaks at:
  - ~ 8-10 km - Pluto
  - ~ 8 km - Charon
Ceres