Comets are important for Astrobiology because they can tell us about the early solar system. Why might they preserve a record of the early solar system?

A – Most are stored cold at large distances from the sun
B – They are too small to have endogenic processes
C – They are unaffected by the heat of the sun
D – All of the above
E – A & B
Which does not represent an exogenic processes that could be important for Astrobiology?

A – Exogenic processes affect the heat budget of the planet
B – They are important for delivery of materials
C – They are potentially related to mass extinctions
D – They can help us remotely date and explore other surfaces for resources
E – They are all important for astrobiology

Exogenic Processes

Processes arising from space
• Interaction with meteoroids
  – Meteorite impacts
  – Regolith formation
• Interaction with plasmas
  – Radiation Damage
  – Volatile implantation
• Everything in SS is affected
  – It happens now
  – It happened more in the past

• Interaction with meteoroids
  – Relative Surface ages
  – Excavation of materials
  – Resources
Lecture Overview

- **Impact Formation Processes**
  - Kinetic energy
  - Typical velocities in the SS
  - Goal of understanding how to recognize craters
  - Understand what we can learn about a planet from craters

- **Impacts and Mass Extinction**
  - The K-T Impact

- **Examples of Craters in SS**
  - Affect of atmospheres
  - The Deep Impact mission

- Craters on Jupiter’s Moon, Ganymede
- Tycho crater, The Moon

Craters that are familiar
Zooming in on very small craters
Scale of laboratory experiments

Barringer Crater, AZ
50,000 years ago
Evidence of Earth Impacts

- Tectonics, aeolian, life processes erase . . . .
  - Old structures hard to see

Vredefort, S. Africa
300 km diam, 2.0 Gy
Magnetic anomaly
Traces impact

- Recent Peruvian impact
  - Only casualty was a cow
  - 9/15/2008
  - 4.5 m deep, 13 m wide
  - Entry velocity 12.8 km/s
Lunar Impacts

• Recent lunar impacts
  – 2005-2010
  – 200 impacts of 1 lb or greater
  – Only on dark side

• Meteorite impact flash
  – 25 cm diameter rock
  – Velocity 38 km/s
  – Flash 0.4 sec long

Not Quite as Portrayed in the Movies
Impact Energies

- **Kinetic Energy**
  \[ KE = 0.5 \, m \, v^2 \]

- **Momentum**
  \[ P = m \, v \]

- **Velocities**
  - Orbital velocity (any orbit)
    \[ v^2 = GM \left(\frac{1}{r} - \frac{1}{a}\right) \]
  - Circular velocity
    \[ v^2 = \frac{GM}{r} \]
  - Escape velocity
    \[ v^2 = GM \left(\frac{1}{2r}\right) \]

- **Example**
  - Take a Ni-Fe meteoroid
  - 30 m diameter, \( v = 15 \) km/s
  - KE \approx \text{few} \times 10^6 \text{ tons TNT}

Cratering Mechanics

- **Characterized by high velocities**
  - Hypersonic – faster than the speed of sound
    - 0.33 km/s in air
    - 1-4 km/s in rock

- **Orbital velocities**
  - Earth orbital velocity \( 30 \) km/s
  - Parabolic velocity \( 42 \) km/s
  - Earth impactors can have
    - \( v = 30 + 42 = 72 \) km/s
    - \( v = 42 - 30 = 12 \) km/s
**Average Impact Velocities in SS**

<table>
<thead>
<tr>
<th>Body</th>
<th>Local Bolides</th>
<th>Asteroids, Short Period Comets</th>
<th>Long Period Comets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>4.7</td>
<td>20</td>
<td>62</td>
</tr>
<tr>
<td>Venus</td>
<td>11.5</td>
<td>18</td>
<td>47</td>
</tr>
<tr>
<td>Earth</td>
<td>12.5</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td>Moon</td>
<td>6.1</td>
<td>14</td>
<td>38</td>
</tr>
<tr>
<td>Mars</td>
<td>5.6</td>
<td>10</td>
<td>31</td>
</tr>
</tbody>
</table>

Mike Carr, Surface of Mars

**Experiments – Crater formation**

- **NASA Ames Vertical Gun Range**
  - Used to simulate cratering
  - Typical velocities 17,895 mph (~8 km/s)

Schulz et al (2007) Icarus 190
Ejecta Blankets – A look at Sub-surface

- **Inverted stratigraphy**
  - Brings material from deeper layers to surface
  - Sometimes this is different composition
- **Secondary craters**
  - Large blocks ejected from primary impact → field of nearby small craters
- **Firdousi Crater (Mercury)**
  - 96 km in diameter
  - 3 color image – note “fresher” exposed material
Crater Formation

- **Contact & Compression**
  - Contact – shock wave
  - Compression in front
  - Strength of shock wave >> strength of rock
- **Excavation**
  - Projectile and target melting
  - Material behaves like a fluid
- **Modification**
  - Target material sent into motion
  - Formation of ejecta blanket
  - Secondary craters form
- **Final Structure**
  - Mass ~ 100 x projectile is ejected
  - Duration 10’s of seconds
  - Final structure: inverted stratigraphy

From French, 1998
Impact Features

- **Ejecta blankets**
  - Deposition of fine debris
- **Secondary craters**
  - Impacts from ejected clumps of material
  - Comet break up → crater chains

Depth Diameter Relations

- **Crater Diameter scales with**
  - Projectile size
  - Projectile velocity
- **Crater morphology depends on**
  - Planet gravity $F = GM/r^2$
  - Structure, density, composition of target
  - Presence of atmosphere
- **Complex crater formation**
  - Gravity sufficient for rebound
- **Craters are a function of**
  - Original shape (set by impactor)
  - Later modification
<table>
<thead>
<tr>
<th>Simple (bowl)</th>
<th>Complex (central peak, slumping walls)</th>
<th>More Complex (Multiple rings, etc.)</th>
<th>Basin (Enormous!)</th>
</tr>
</thead>
</table>

- Few km
- Tens of km
- Hundreds of km
- > Hundreds

**Depth Diameter Relations**

- Ilmenite ($\text{FeTiO}_3$) abundant on moon (source of O)
- How to use craters to find minerals?
  - Multi-color imaging $\rightarrow$ Ti-rich areas
  - Some minerals are only visible in certain craters
  - Use depth / Diameter relations to get depth

Lunar mare Tranquilitatis as seen from the Clementine mission. Red indicates low titanium abundance
**Caloris Basin – Mercury**

- **Basins – largest impact structures**
  - Caloris 1300 km diameter
  - Seismic waves pass through planet
  - Formation of “weird terrain” at antipode
    - Hills 2 km high – vertical ground movement
- **Crater types / sizes for the Moon**
  - Simple bowl < 10 km
  - Central peak 10-150 km
  - Peak clusters/rings 100-220 km
  - Multi-ring basins > 220 km

**Using Impacts for Dating**

- **Saturation Cratering – Crater counting**
  - When adding more craters covers old ones
  - Calibrated by Lunar rocks, this occurs only for the oldest surfaces
  - Crater counts can give relative ages
- **The Late Heavy Bombardment**
  - Possible spike in impacts 3.8 Gy
Given the ubiquitous nature of impacts in the Solar System, why does the Earth have so few craters?

A – There is not much old crust available because of plate tectonics
B – Aeolian processes
C – Life processes
D – A and B
E – A, B, C
Lunar Craters

- **Orientale multi-ring basin**
  - Age > 3 Gy
  - Lava flowed into maria from fractured crust
  - Inner ring 320 km diameter
  - Outer Cordillera 930 km diameter

Craters on Mercury

- Similar to Lunar craters
A long lobate scarp on Mercury formed when it shrank as the core cooled. Did this form before or after the marked crater?

A – Before  B – After

Craters on Venus

- Thick Atmosphere
  - Ejecta – cloud of debris
  - Wind streaks
- Higher gravity than Moon, Mercury
  - Smaller complex craters
    - Simple bowl: 2-4 km
    - Central Peak: 8-30 km
    - Peak clusters: 20-80 km
    - Peaks/rings: 40-90 km
    - Multi-ring basins: 60-300 km
Mars Craters

- **Different morphology**
  - Effect of sub-surface volatiles
  - Effect of atmosphere

Victoria Crater 0.73 km

Gale Crater – 154 km, MSL landing site

Craters on Ice

- **Ganymede & Callisto (top), Europa (bottom)**
  - Change in morphology with size
  - Top scale bar = 30 km
  - Bottom scale bar = 10 km
- **Crater heights subdued**
  - Ice relaxation
The K-T Impact

- **65 Myr Cretaceous-Tertiary**
  - Marked by a thin layer of sediment
  - 75% of all species died globally
  - Rapid < 1000 yrs
- **Causes**
  - Massive volcanic eruption?
  - Asteroid impact?

The K-T Layer

- **Cm-thick layer rich in Iridium**
  - Found globally
  - Common in asteroids
  - Rare on Earth surface (atomic weight = 192) – why?
  - When Earth differentiated – sank to core
- **Suggested extra-terrestrial source**
  - But where was the crater?
  - Were there alternate explanations?
Volcanos – Deccan Traps

- **Flood basalt eruption**
  - Source deep in mantle
  - Duration can be very long

- **Massive Eruptions**
  - Dust, ash and aerosols into atmosphere
  - Long term climate change
  - KT extinction was too brief

<table>
<thead>
<tr>
<th>Where</th>
<th>Myr Ago</th>
<th>Last Myr</th>
<th>How Big Mkm³</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siberia</td>
<td>250</td>
<td>1</td>
<td>1-4</td>
<td>90-95% extinction of life (PT extinction)</td>
</tr>
<tr>
<td>Ontong Java, Indonesia</td>
<td>122</td>
<td>3</td>
<td>36</td>
<td>Largest event in last 300 Myr</td>
</tr>
<tr>
<td>Kerguelen, Antarctica</td>
<td>118</td>
<td>4.5</td>
<td>4-5</td>
<td>Global environmental crisis</td>
</tr>
<tr>
<td>Deccan Traps, India</td>
<td>60-68</td>
<td>30 kyr</td>
<td>0.5</td>
<td>Global 2 deg temperature drop</td>
</tr>
<tr>
<td>Columbia River, US</td>
<td>17-14</td>
<td>3</td>
<td>0.2</td>
<td>Later flooded by Yellowstone flows</td>
</tr>
</tbody>
</table>

The K-T Impact Crater

- **Crater found in Yucatan Peninsula**
  - 180 km in diameter (10 km diam impactor)
  - Found during a petroleum survey

- **Impact evidence**
  - Gravity anomaly → anomalous density distn.
  - Shatter cones (2-30 GPa pressure wave through rocks)
  - Shocked quartz (high pressure)
  - Ring of cenotes (sinkholes)
Chixulub Impact Animation

Chixulub Impact Effects

- **Mega-tsunami**
  - Yucatan would have been covered by a shallow sesa
  - Tsunamis could have had wave heights of 100 m
- **Shock waves → global earthquakes**
- **Excavated material**
  - Re-Entry into atmosphere – widespread fires
For the same size impactor and the same speed, which planet would have the largest crater?

A – Mercury
B – Mars
C – Earth
D – Moon
E – They will all be the same

Cooling and Warming

- Dust and particulates in atmosphere – block sunlight
  - Global cooling for as much as a decade
- CO₂ liberated during impact
  - Global warming
  - Ocean acidification
- Alternate ideas . . . .
Small Scale Interactions

- **Micrometeorites**
  - Regolith formation ~ 1 mm/10^6 yr
  - Pitting of surfaces
  - Gardening (surface turn over)
- **Sputtering**
  - Erosion ~ 1 Angstrom / yr
- **Plasma / Cosmic rays**
  - Interaction with charged particles
  - Radiation damage
  - Volatile implantation

Summary of Small Impacts

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux</th>
<th>Energy</th>
<th>Velocity</th>
<th>Depth</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Wind</td>
<td>3 x 10^6</td>
<td>1 keV</td>
<td>400 km/s</td>
<td>300 A</td>
<td>Implant volatiles Radiation damage</td>
</tr>
<tr>
<td>Solar Flares</td>
<td>1 x 10^2</td>
<td>10 keV - 100 MeV</td>
<td>mm → cm</td>
<td></td>
<td>Radionucleide production Nuclear tracks</td>
</tr>
<tr>
<td>Galactic CR</td>
<td>1</td>
<td>100 MeV - Few GeV</td>
<td>cm → m</td>
<td></td>
<td>Tracks Radionucleides New isotopes</td>
</tr>
</tbody>
</table>

- **Sources**
  - Solar Wind – flow of particles from the sun, CR – cosmic rays (high energy particles from deep space)
- **Fluxes**
  - Number of particles per second
- **Energies**
  - Expressed in electron volts – k = 1000, M = 1 million, G = 1 billion
The Shoemaker Levy 9 Impact

- **Comet SL9**
  - Discovered in 1993 – 21 fragments
  - Broke with close Jupiter approach in 1992
- **Impact science**
  - Molecules dredged up from lower atmosphere
  - Waves traveled through atmosphere
  - NH₃ and CS₂ persisted in atm for 14 mo

- 1st impact, 24,000K fireball

- HST UV image
- Collision of fragment W seen by Galileo spacecraft 7/22/1994
Re-Useable Missions

- **DI → EPOXI**
  - Explore comet Hartley 2
  - Stardust → Stardust-NExT
  - Return to 9P/Tempel 1
The DI Crater Challenge – Arrival Time

- > 500 whole/partial nights worldwide
- 25 telescopes, 11 countries

- Last chance to affect arrival time was ~1 yr pre-encounter
- The Rotation period was changing
- We had very little fuel left
- We used it all . . . . So did we see the crater?

Target effects

Schultz, et al 2009
Crater rays emerging from DI site superimposed on Stardust-NExT

Deep Impact

Stardust-NExT

(from Schultz et al., 2007)
Impact Physics – Surface Material Strength

- Crater imaged ~ 50m across
- Consistent with impact into surface with texture/strength of “lightly packed snow”
- Open Questions
  - Modification by ejecta fallback
  - Change in 5.5 years?

From P. Schulz

Richardson & Melosh (2012); Wellnitz et al. (2012)
**LCROSS Experiment**

- **Lunar Crater Observation and Sensing Satellite Goals**
  - Confirm presence of water in permanently shadowed areas
  - ID the cause of H signatures seen at lunar poles
  - Determine amount of H₂O in regolith
  - Determine regolith composition

Launch on June 18, 2009 at 5:32 p.m. ET
Summary

- **Impact Energy**
  - Comes from orbital velocity, impactor mass
- **Occur all over solar system – morphology depends on**
  - Impactor composition
  - Target composition, gravity
  - Presence of an atmosphere
- **Impact Effects**
  - Deliver and remove materials
  - Mass extinctions / climate change
Impact Melt

- Impact Melt
  - Xx
- Tektites
  - Xx

Vredefort Impact melt deposit – S. Africa