CRATERING RATE COMPARISONS BETWEEN TERRESTRIAL PLANETS.

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Problems and approaches

• Early projectile flux (>3.3 Ga) may differ from the modern flux, and early craters share ~90% of craters, counted on the Moon

• Modern projectile flux may be modeled with the celestial mechanics and estimated from dated lunar and terrestrial impacts

• First approximation – assume early projectile flux similar to the modern one, but more intensive.
Observed projectiles

- Mostly – asteroids: less than 5% of observed NEAs may be dormant comets see Morbidelli et al., *Icarus* 2002 “From magnitudes to diameters: The albedo distribution of near Earth objects and the Earth collision hazard”

- Assumption #1: Observed population is in quasi-stationary state – if a body change the orbit, the other body occupies its orbit ($a,e,i$ phase point).

- Assumption #2: under-counting of objects with $H<18$ ($D_p > 1$ km) may be estimated for NEA
NEA: q<1.3 a.u.
Asteroid like orbits:
N_{18} \sim 700, \text{ av. albedo } 0.083

Comet-like orbits:
N_{18} \sim 300, \text{ av. albedo } 0.163

Total N_{18} \sim 1000\pm 200
Chaotic motion of planet-crossers

Example - Itokawa

Modern classification – how much time an asteroid spends in a phase space area of interest (residence time)
Gross picture of modern projectiles
Bottke et al., 2002
NEA v.s. bolides

- Impact rate:
- 1. observed NEAs -> collision probability (Opik-type approach) -> impact rate
- 2. Bolides burned in the atmosphere: impact rate -> restored trajectories -> collision probability -> orbital population
Orbits with high collision probability have small residence time. Can we miss high-probability projectiles?


Procedure: sort orbits by collision probability, compute sliding average.

Pleasant result: average probability is approx. the same.
Bolide database v.s. NEO: inclinations
Asteroid-like v.s. comet-like bolides
Inter-planetary comparisons

- Test case – Earth/Moon cratering rate comparison (same projectile flux)
- Other terrestrial planets – estimates only
- Estimates of projectile population
- Estimates of projectile orbital distribution
- Estimates of crater sizes (scaling law)
Earth-moon comparison: same projectile population

Small crater on the moon:
1 - South Ray crater;
2 - Cone crater,
3 - North Ray crater (Moore et al., 1980);
4 - Tycho crater (Koenig&Neukum)

Approximately constant crater accumulation rate in <100 Ma areas
Global count of terrestrial bolides

letters to nature

The flux of small near-Earth objects colliding with the Earth

P. Brown*, R. E. Spalding†, D. O. ReVelle†, E. Tagliaferri§
& S. P. Worden||

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Using cratering scaling law the impact rate is transferred into lunar cratering rate
Scaling law – two main cases

For non-porous rocks
\[ D_{tc} = 1.16 \left( \frac{\delta}{\rho} \right)^{1/3} D_p^{0.78} (U f_{ang})^{0.44} g^{-0.22} \]

For dry sand
\[ D_{tc} = 1.25 \left( \frac{\delta}{\rho} \right)^{1/3} D_p^{0.83} (U f_{ang})^{0.34} g^{-0.17} \]
Strength to gravity transition

Scaled crater size

Absolute crater size

~50 m on Earth

~300 m on the moon
Lunar craters: strength -> gravity

Multiringed basins — illustrated by Orientale and associated features

H. J. Moore, C. A. Hodges, and D. H. Scott

\[ D_{sg} \sim 0.65 \text{ km} \]
Scaling of terrestrial data:
\[ D_{sg} \sim 0.05 \times (g/g_{moon})^{0.3} \text{ km} \]

Fig. 12. Crater radius and average radius of continuous blanket of ejecta, as mapped by many individuals (see, for example, Wilhelms and McCauley, 1971). Craters smaller than 0.65 km are separate population.
“Bolide” craters on the moon

Non-porous scaling: Too many craters (or craters are too large)

Porous scaling: good fit.

Dry sand – good proxy for regolith?

Projectile flux is constant? (if “yes”- not enough room for “overwhelming majority” of secondaries)
NEO’s size-frequency distribution

The best available to date estimates of global annual impact rate of NEO:
1. It is not a simple power law function
2. For $H<18$ there is no visible difference with Main belt
3. 100 Ma large Earth craters are in accord

Ivezic et al 2001
Jedicke et al 2002
SFD: Lunar craters v.s. NEO

Porous rock scaling well reconciles observed NEO and counted lunar cratering records.

Could be lunar crust porous?
Seismic profile: $C_p \sim 1 \text{ km s}^{-1}$ for upper 1 km

Bad news for “other” planets – lunar curve may be not directly scalable as regolith thickness and megaregolith porosity may be different in the upper crust, changing the population of small craters (< 1 to 3 km)
Lunar scaling modification to reconcile NEA-lunar craters
Figure 1. Cumulative (a) and incremental (b) perihelion distribution of planetary crossing asteroids (PCAs) of different size (characterized by magnitude $H$). The $N(q)$ dependence of PCAs with $H < 15$ compromises the completeness of observation and the numerosity at near-Earth orbits.
Observed projectiles-2006

- Black-2000
- Red - 2006

Earth: $e=0.0167$
Venus: $e=0.0067$
Mercury: $e=0.2056$
Mars: $e=0.0934$

$N(H<15)\times 12$
$N(H<15)/40$
Separate asteroid-like ($T_J > 3$) and comet-like ($2 < T_J < 3$) orbits
Planetary orbit variations
Cohen et al., 73

Mars orbit variation

Fig. 1. Secular variations of the eccentricities of the terrestrial planets: Mercury, Venus, Earth, Mars, respectively. Taken from Cohen et al. (1973).


e varies from ~0 to ~0.1
With the timescale ~2 Ma.
i varies from ~2° to ~7°
With the timescale ~1 Ma

Assumption #3: orbits (phase space population) of Mars-crossers is the same (variation timescale > 2 Ma)

Fig. 3. Model results over 10 Myr.
### Mars impact probability-2006

<table>
<thead>
<tr>
<th>Asteroid-like orbits</th>
<th>N_proj</th>
<th>v_imp</th>
<th>&lt;P/1year/body</th>
<th>&lt;P/km2/year/body</th>
<th>P_tot/km2/year</th>
<th>R_bolide</th>
<th>2002</th>
<th>Ivanov</th>
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<tbody>
<tr>
<td>H&lt;17</td>
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<td></td>
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<td>Earth</td>
<td>204</td>
<td>19.3</td>
<td>3.48E-09</td>
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<td>2.34E-15</td>
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<td>1.73</td>
<td>10.9</td>
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<td>Comet-like orbits</td>
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<td>Earth</td>
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<tr>
<td>moon</td>
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<td>25.8</td>
<td>4.10E-11</td>
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<td>Mars, e=0.03,i=2</td>
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</tbody>
</table>

Step (b) in our formulation is to update the Mars/Moon impact ratio, $R_{bolide}$. A review of asteroid dynamics by Bottke (private communication) suggested a value of $R_{bolide} \sim 3.15$ (revised upward from his 2001 value of $R_{bolide} \sim 2.76$), and an independent review of observed Amor and Apollo asteroid statistics by Ivanov (2001) suggests $R_{bolide} \sim 2.0$. Bottke’s value includes a variety of populations, emphasizing asteroid dynamics but also taking into account estimates of comet populations and observations of Mars crossers.
All terrestrial planets

<table>
<thead>
<tr>
<th>Planetary body</th>
<th>$N_{H&lt;17}$</th>
<th>Average impact rate * 10^{-15} km^{-2} yr^{-1}</th>
<th>Average collision probability per one body (planetary crosser), Ga^{-1}</th>
<th>Average impact velocity, km s^{-1}</th>
<th>$R_b$ **</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>34</td>
<td>0.715</td>
<td>1.574</td>
<td>35.4</td>
<td>0.92</td>
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<tr>
<td>Venus</td>
<td>89</td>
<td>0.876</td>
<td>4.53</td>
<td>24.2</td>
<td>1.12</td>
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<tr>
<td>Earth</td>
<td>194</td>
<td>1.31</td>
<td>3.443</td>
<td>19.3</td>
<td>1.68</td>
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<td>The moon</td>
<td>194</td>
<td>0.781</td>
<td>0.157</td>
<td>17.5</td>
<td>1</td>
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<tr>
<td>Mars, current orbit, $e=0.0934$</td>
<td>2680</td>
<td>3.85</td>
<td>0.208</td>
<td>9.4</td>
<td>4.93****</td>
</tr>
<tr>
<td>Mars, $e=0.05$***</td>
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<td>2.42</td>
<td>0.244</td>
<td>10.2</td>
<td>3.10****</td>
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<td>Mars, $e=0.01$</td>
<td>869</td>
<td>2.0</td>
<td>0.336</td>
<td>10.5</td>
<td>2.58****</td>
</tr>
</tbody>
</table>

* Average impact rate is the global number of impacts per a time unit, divided by the surface area of a planet.

** "Bolide ratio" is the ratio of the impact rate of projectile of the same size per unit area to the same value for the moon (for the moon $R_b = 1$ by definition).

*** This value of eccentricity is close to the average value for a time span of 10 Ma and longer still limited to the available Mars orbit modeling duration (Ward 1992).

**** not corrected for the incomplete observation of Mars crossers (see Ivanov, 2001) for an example of a correction.

$R_b \sim 1.8$ for Mercury

From impact to craters

• Scaling law: Crater size for the given projectile impacting different planets
• Population of projectiles: size-frequency distribution (SFD) for projectiles (derived from lunar craters)
• Population of craters (SFD of projectiles, projected to the new planet (eg. Mars).
Close to real scaling law IS NOT a simple power law!

Depending on upper crust porosity $D/D_p$ ratio may vary by a factor of 2!
The same projectile forms impact craters of different size on different planets. (e.g. Neukum and Ivanov’94).

The single value of $R_b$ results in variable ratio of crater diameters. Consequently, crater rate ratio ($R_c$) vary with a crater diameter!

Figure 21. Comparison of crater diameters on various planets for projectiles of the same diameter. Changes due to surface gravity and different impact velocity are taken into account in the presented model. For Earth and Venus the practically useful range of diameters lies above $D = 1$ km. (a) Earth; $D_{18/\text{Moon}} = .3$ km; values of $\omega$: 1 = 0.81; 2 = 0.85; and 3 = 0.89. (b) Venus; $D_{18/\text{Moon}} = .3$ km; values of $\omega$: 1 = 0.81; 2 = 0.85; 3 = 0.89. (c) Mercury; $\omega = .85$; values of $D_{18/\text{Moon}}$ are: 1 = 0.3 km; 2 = 1.2 km; 3 = 2.4 km. (d) Mars; $\omega = .85$; values of $D_{18/\text{Moon}}$ are: 1 = 0.3 km; 2 = 1.2 km; 3 = 2.4 km.
Assuming a kind of scaling laws and projectile SFD one can speculate about $R_c$

Mercury (Neukum et al., 2001)  
$R_c$ from 0.9 to 1.3  
$R_b = 0.9$

Mars (Ivanov, 2001)  
$R_c$ from 0.6 to 1.6  
$R_b = 2$ (version 2001)

Figure 5. The Mars-to-moon ratio of a number of impact craters with same diameter. Hartmann Production Function (HPF) and Neukum Production Function (NPF) are recalculated from the moon to Mars using the Model 1 (one average impact velocity and one average impact angle of 45°) and the Model 2 (the full ensemble of impact velocities and impact angles). All recalculation except NPF - Model 2 use the gravity crater scaling law with the Croft’s collapse model. The NPF - Model 2 is recalculated assuming the strength-to-gravity cratering regime transition with $D_{eg}$ at 300 m on the moon and 100 m on Mars. See details in the text.
What’s new in 25 years?

<table>
<thead>
<tr>
<th>Planet/Moon cratering rate ratio, $R_c$</th>
<th>Basaltic Volcanism, 1981</th>
<th>This talk, Constant $R_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>2 (0.5-&gt;5)</td>
<td>0.9 – 1.3</td>
</tr>
<tr>
<td>Mars</td>
<td>2 (1 -&gt; 4)</td>
<td>0.6 –1.6 (2002)</td>
</tr>
</tbody>
</table>

Actually, very modest progress. New dated rocks are valuable.
What is ahead?

1. Late heavy bombardment possibly differs in SFD and average impact velocity.
2. Due to non-gravity effects near-Earth NEO SFD may be steeper than near Mars (Yarkovsky effect, YORP).
3. Small craters may be secondary, not primary craters.

These items may be improved before new sample return missions using modeling and existed databases.
Conclusions

• To recalculate cratering rate from one planetary body to another one we should know celestial mechanics of “projectiles” (current accuracy of factor of 2)
• Scaling laws (target strength and porosity for small craters) add another factor of 2 uncertainty
• Any current planet crater chronology should be treated with the accuracy of a factor of 2 (at best!)

However, many interesting things may be learned just in this meeting!