Asymmetric impacting on the Moon and its dependence on debiased NEA models

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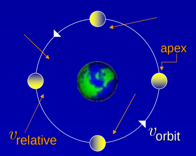
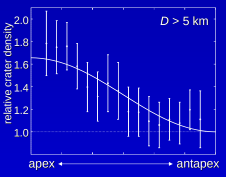
Motivation: Rayed crater distribution on the Moon





- Synchronized rotational & orbital motion of satellites (1:1 commensurability)

⇩

- More craters around apex
  - ➢Typically observed on Galilean satellites of Jupiter
    Shoemaker & Wolf (1982)
    Zahnle et al. (1998, 2001)
- Confirmed on the Moon
  - ➢Morota & Furumoto (2003)
    Clementine 750nm basemap images
  - ➢Young, rayed craters
    < ~1 Gyr

■ Small $v_{relative}$ (vs. v_{orbit})

⇩

Strong symmetry

■ Large $v_{relative}$

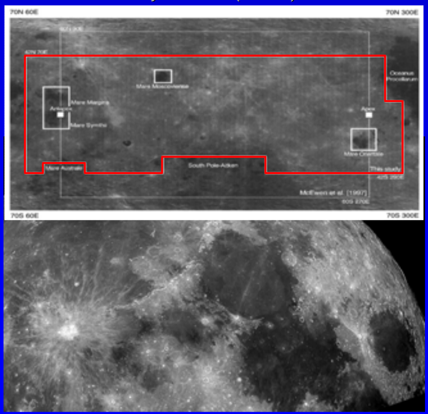
⇩

Weak asymmetry

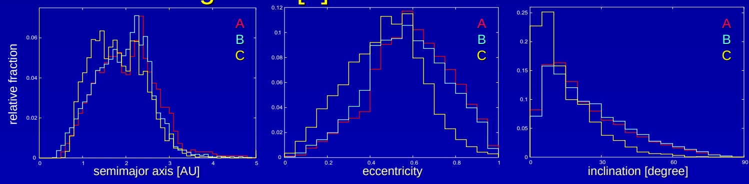
- Potential constraints on the origin of the projectiles
- This poster - Confirmation of the lunar crater asymmetry by numerical integrations
  - ➢ w/ debiased NEA populations
  - ➢ w/ steady-state NEA model

See Ito & Malhotra (2006, *Adv. Space Res.*, **38**, 817-825; 2010, *Astron. Astrophys.*, **519**, A63) for more detail

Search area by Morota & Furumoto (2003, *EPSL* **206**, 315-323)
Total 222 rayed craters (*D*>5km) detected



Numerical integration [1]: Initial conditions and method



■ Debiased NEA population (A)
➢ Bottke *et al.* (2002, *Icarus*, **156**, 399-433)
18,000 particles

- 5 source regions
  - ➢ ν_6 resonance
  - ➢ 3:1J MMR
  - ➢ Mars-crossers
  - ➢ outer MB
  - ➢ TNO disk

■ Debiased NEA population (B)
➢ Morbidelli (2006, unpublished)
18,000 particles

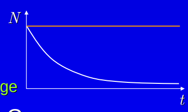
- 5+2 source regions
  - ➢ ν_6 resonance
  - ➢ 3:1J MMR
  - ➢ Mars-crossers
  - ➢ outer MB
  - ➢ TNO disk

■"Raw" NEA-like particle population (C)
➢ Apollos, Amors, Atens-like 18,000 particles as of 2010 July (~7,000 original + clones)
➢ No debiasing procedure, mostly *H* >18

(+2: high-i components)
➢ Hungaria
➢ Phocaeas

Steady-state NEA model

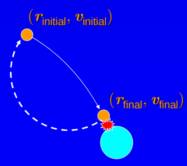
- In many previous studies
  - ➢ $N_{particle}$ just decreases
  - ➢ v_{impact} distribution changes
    - ➢ along with orbit distribution change



- NEA flux ~ constant over 3 Gyr
  - ➢ From lunar crater record
  - ➢ Constant supply of particles

■ Steady-state NEA flux in numerical model

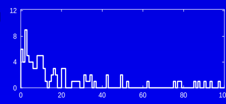
$(r_{final}, v_{final}\ ;\ t_{final})$
$\rightarrow\ (r_{initial}, v_{initial}\ ;\ t_{final})$

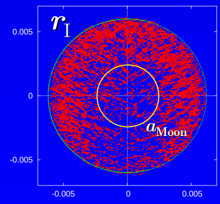


- Reproduction of steady-state NEA flux

Need more particles for the Moon

~3,000 test particles at ~2AU
→ ~100 collisions on the Earth
→ a few collisions on the Moon
→ Statistically no meaning?



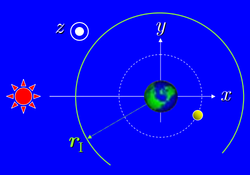


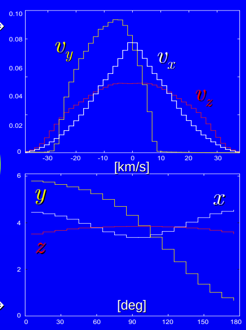
But: many more encounters at the Earth's activity sphere (r_I ~ 144 R_{Earth})
→ ~10^6 close encounters

→ Good to make an orbital distribution function $f\ (a, e, i,\ \ldots\ ;\ t)$

Encounter statistics at Earth's r_I

Encounter velocity →





Encounter position →

More particles for the Moon

Generate many particles ("clones") from the orbital distribution function $f\ (a, e, i,\ \ldots\ ;\ t)$

3,000 particles
↔ 10^6 encounters

⇩ x 1,000

10^9 clones
↔ 3,000,000 particles

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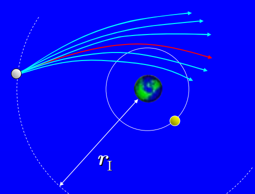
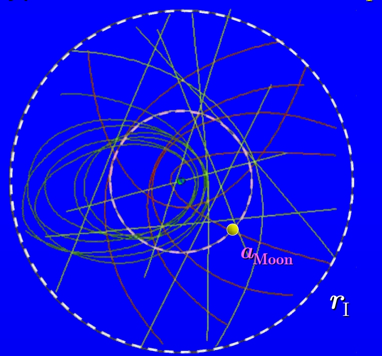
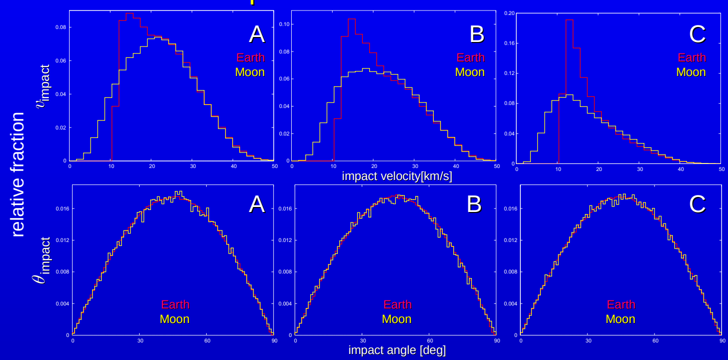
Orbital integration of Earth + Moon + Sun + 10^9 "cloned" particles
→ Numerical integrations [2] (Total N_{clone} ~ 10^{10})



Typical orbits within Earth's r_I



Impact statistics on the Moon

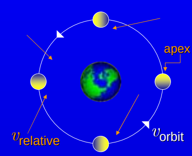


	N_{clones} (10^{10})	$N_{imp,E}$ / $N_{imp,M}$	$\overline{v_{impact,M}}$ (km/s)
A	2.11	20.4	22.4
B	1.87	17.9	22.3
C	2.74	25.5	17.7

Impact velocity on the Moon
- Debiased population (A,B) → larger
- Daw NEA population (C) → smaller

Impact angle
- Quite isotropic for both of the Earth and the Moon

Asymmetric v_{impact} distribution



- Leading → larger v_{impact}
- Trailing → smaller v_{impact}

v_{impact} → $v + \delta v$
⇩
D_{crater} → $D + \delta D$
➢Horizontal shift of N-D relation
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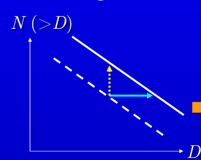
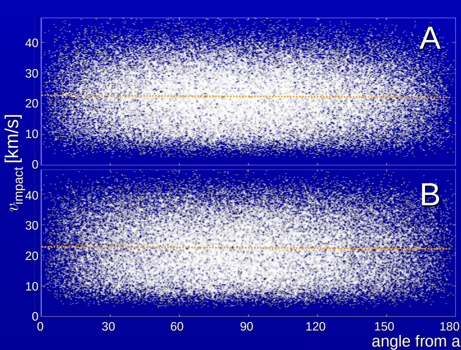
N_{crater} → $N + \delta N$
➢Vertical shift of N-D relation

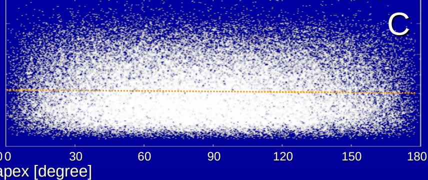


■Apparent change of crater density on leading/trailing (very small for the Moon)

Asymmetric v_{impact} distribution

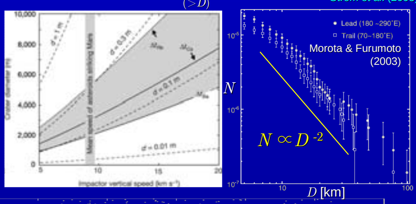
$v_{orbit,M}$ (~1 km/s) ≪ $v_{impact,M}$ (~22 km/s)

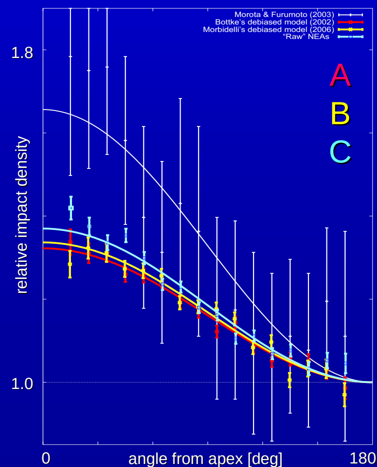




✓ Crater scaling : $D \propto v_{impact}^{0.44}$ — Pi-group scaling (Melosh 1989)

✓ Size distribution : $N \propto D^{-2}$ $(>D)$ — Morota, Furumoto (2003), Strom et al. (2005)





Conclusion

- Both debiased models (A,B) yield similar results in terms of the cratering asymmetry
  - ➢ Weaker asymmetry than the actual rayed crater record, implying the existence of more "slower" objects
- Raw NEAs have lower v_{impact}
  - but still not consistent with the rayed crater record
- Rayed crater data should be updated (Kaguya, ...), as well as the NEA orbital distribution (Pan-STARRS, ...)

Also check: Gallant *et al.* (2010, *Icarus*, **202**, 371-382), Le Feuvre & Wieczorek (2008, *Icarus*, **197**, 291-306), Werner & Medvedev (2010, *Earth Planet. Sci. Lett.*, **295**, 147-158, 2010)