Impacts in the Earth-Moon System
What, When and Why?

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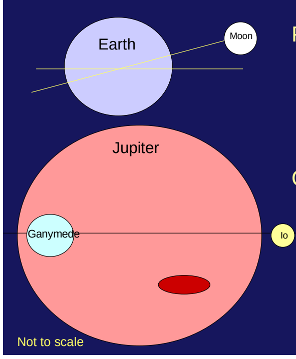
The Moon

- 1/4 the size of Earth
- 1/6 the gravity of Earth
- Covered in impact craters
- No atmosphere
- A little bit “wet”

The Moon



Physical uniqueness
- Size is > 1% M_{Earth}
- (usually moon ~ 0.15% M_{Planet})

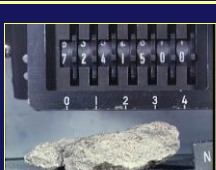
Orbit
- Not in equatorial plane or plane of ecliptic
- Inclined 5.1° to Earth

To the Moon!

- 12 men between 1969 and 1972
- ~2.5 day trip to landing sites on lunar nearside
- >800 lbs of samples returned to Earth
- Moon is lifeless but holds secrets about Solar System’s early years

What We Learned: Lunar Samples

Astronauts brought back over 800 lbs of volcanic and impact rocks and lunar dirt


Apollo 17 lunar rock sample no. 72415,0; 32g


Volcanic rock, as seen under a microscope


Apollo 15 sample 15221,21

What We Learned: Moon’s Origin

Impact by a Mars-sized object (1970s)

Object and outer layer of Earth were flung into geosynchronous orbit, forming a hot disk

Dense material fell to Earth

Less dense material formed the Moon

Bulk composition
- Similar to Earth’s mantle: Fe, Co, Ni, P, S


Supported by models of Canup and Asphaug (2000)

What We Learned: Surface Geology

Highlands: Ca, Al
(heavily cratered – when?)
Maria: Fe, Ti
(lava-filled impact basins: ~3.8 Ga)

Cratered just as heavily as the nearside

Impacts!


Schrodinger Crater

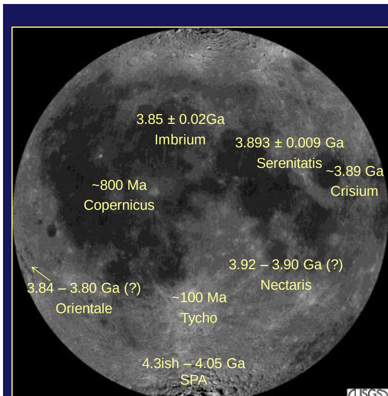

Copernicus, Tycho


Wolf Creek, AUS


Clearwater Lakes, CAN


Meteor Crater, AZ


Rotter Kamm, Nambia



Wilhelms (1987), Hartmann (2000), Ryder *et al.* (2000), Koeberl (2006)

Stratigraphy

Crater counting

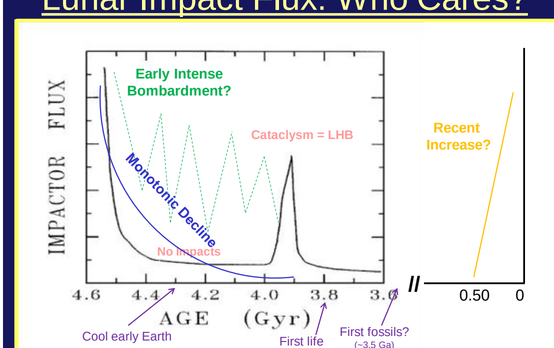
A15, A17 breccia sample ages
(Dalyrymple & Ryder, 1993, 1996)

The Impact Flux

Interpreting the time-varying impact flux is one of the top science priorities as determined by the NRC in 2007

- crystalline melt rocks in Apollo samples
- crystalline melt clasts in meteorites
- zircons
- crater counting
- lunar impact glasses

Lunar Impact Flux: Who Cares?

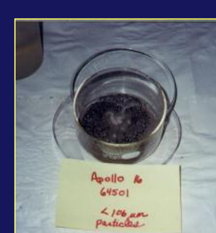


Modified from Zellner (PhD thesis); Hartmann (1965, 1966, 2000), Tera *et al.* (1974), Culler *et al.* (2000)

Lunar Regolith Samples

Apollo 11 footprint in lunar regolith

Billions of years impacts have pulverized the surface into a fine powder called *regolith*



Regolith looks and feels like sticky brown talcum powder

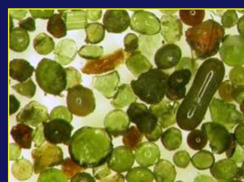
Lunar Glass Samples

Glasses are formed when regolith is melted during a high-temperature event

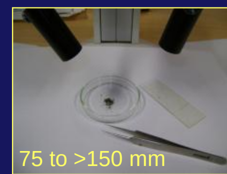
Where, when, how often impacts, volcanism occurred

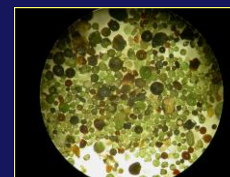


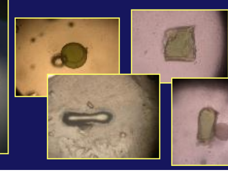
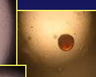

Glasses are small, numerous, and homogeneous.



Selecting/Prepping Samples

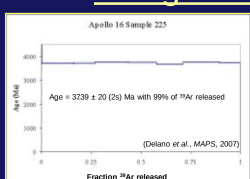


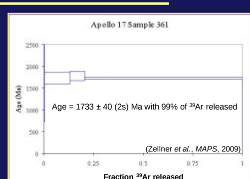


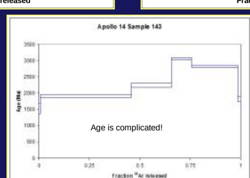



Apollo 15
15221,21

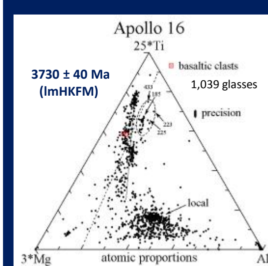
Ar Ages: Plateau Plots



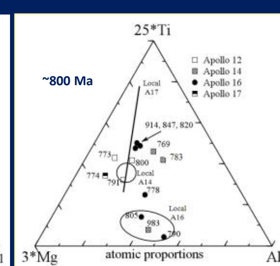




Composition, Age, and Shape



Delano *et al.* (2007): 1 large distant impact produces 4 glass shards w/ same age



Zellner *et al.* (2009): 9 glass shards and spheres from 3 landing sites indicate 7 impacts w/ same age

Composition and Size

Gombosi *et al.* (2015): proposed that melt structure (composition) and diffusivity of radiogenic ^{40}Ar could be described by

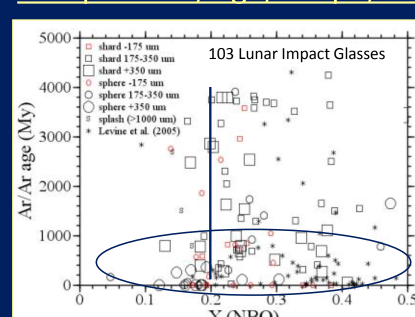
$$X_{NBO} = \frac{2(X_{NC} - X_{FC})}{2 - (X_{NC} - X_{FC})}$$

Ar diffusivity is inversely proportional to X_{NBO} value

after Lee (2011) and Mysen and Richet (2005)

X_{NC}: network-modifying, charge balancing (eg. FeO, MnO, MgO)
X_{FC}: network-modifying (e.g., TiO_2, Al_2O_3)

Composition, Age, Shape, and Size



Zellner and Delano (LPSC, 2014)

Lower limit to X_{NBO}.

Spheres are more likely to have young ages.

Data from:
Delano *et al.* (2007)
Zellner *et al.* (2002)
Gombosi *et al.* (in rev.)
Zellner *et al.* (2009a, b)
Levine *et al.* (2005)
Hui (2011)
Ryder *et al.* (1996)
Morris *et al.* (1986)
Borchardt *et al.* (1986)

X_{NBO} and Size

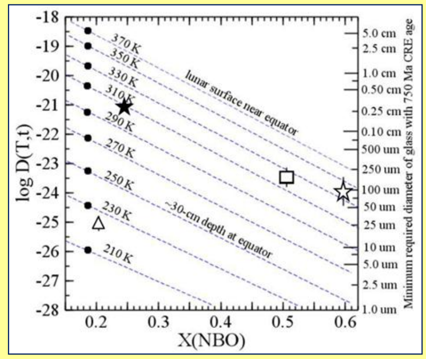
Working Hypothesis to determine a_{min}:

By knowing X_{NBO}, the minimum size of glass needed to potentially yield the true $^{40}Ar/^{39}Ar$ age of melting can be estimated.

We propose that lunar impact glasses need

$$D = \frac{a^2}{\pi^2 t}\left(2\pi - \frac{\pi^2}{3}f - 2\pi\sqrt{1 - \frac{\pi}{3}f}\right)$$

McDougall and Harrison, 1999



● A 16 impact glass 61502,13,3 (Gombosi *et al.* 2015)

☆ A 15 volcanic glass (15426)

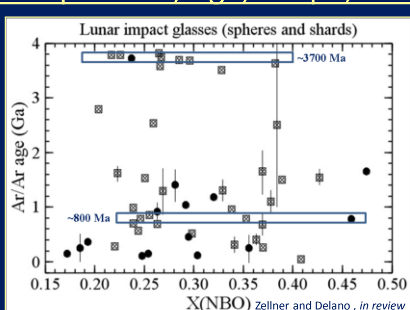
□ Apollo 17 volcanic glass (74220)

★ A 17 impact glass (C6/301, 71501)

△ A 16 impact glass (G3/225, 64501).

Zellner and Delano, *in review*

Composition, Age, Shape, and Size



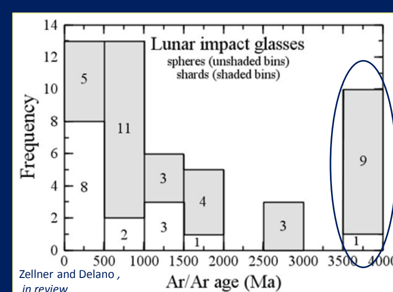
Zellner and Delano , *in review*

Data from:
Delano *et al.* (2007)
Zellner *et al.* (2002)
Zellner *et al.* (2009a, b)
Hui (2011)
Ryder *et al.* (1996)

Abundant: age ~3700 Ma

Rare: 1800 Ma ≤ age ≤ 3200 Ma

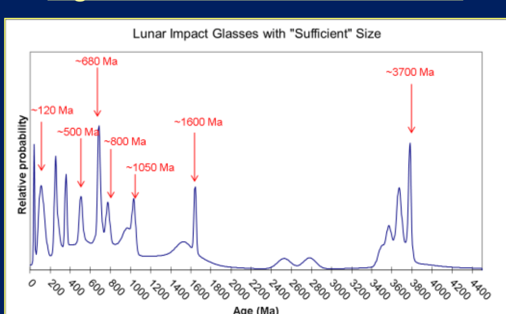
Spheres vs. Shards



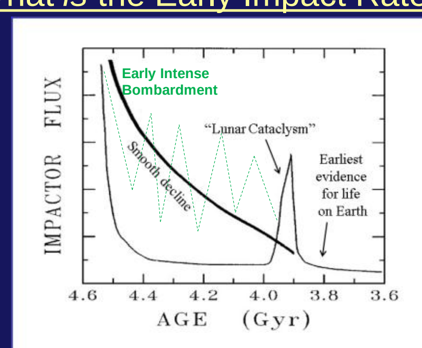
Zellner and Delano , *in review*

Spheres are dominated by ages <1000 Ma and are rare at ages ≥1500 Ma, consistent with being fractured into shards.

Age Distribution of Glasses



What *is* the Early Impact Rate?



New Orbital Data

Lunar Reconnaissance Orbiter Data

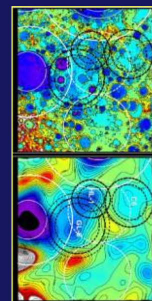
LOLA

LROC

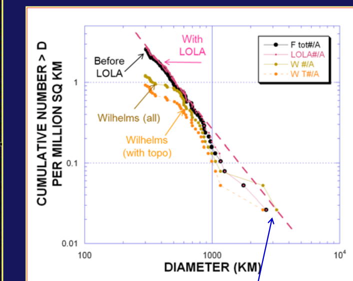
New Interpretations

More Data and More Sophisticated Analytical Techniques

What's New?: LOLA Data



Frey (2011, 2012): >100 >300-km QCD (LOLA data, crustal thickness maps)



More basins w/ larger diameters than determined by previous crater studies

What's New?: LOLA Data

Crater Size Frequency Distribution, ≥20 km

Higher-res data allow more large craters to be found, which affects crater counts (density)

Show transition from Pop I to Pop II impactors *prior* to 3.9 Ga (not *at* 3.9 Ga, Strom *et al.* 2005)

Result: Serenitatis is much older than Nectaris

Fassett *et al.* (2012)
Spudis *et al.* (2012)

Nectaris ejecta superposed on Serenitatis

What's New?: New Interpretations

Recalibrated $^{39}Ar/^{40}Ar$ standards show similar ages in several different samples

Result: They all derived from Imbrium and represent one event

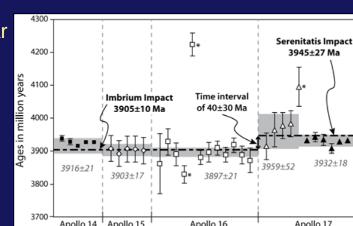
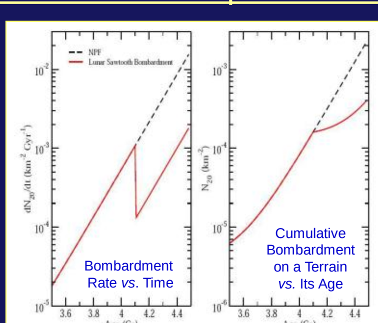


Figure 1: Filled symbols=U-Pb ages. Open symbols=Ar-Ar ages. The grey bands represent the mean ages and their errors for each landing sites and correspond to the italicized numeric values given in the figure. The symbols marked with an asterisk are excluded from the average calculation.

Grange *et al.* (2010)
Merle *et al.* (2014)

What's New?: New Interpretations

Sawtooth pattern can explain the non-existence of the E-Belt asteroids , with LHB at ~4.1 Ga (age of Nectaris), but not very high



Morbidelli *et al.* (2012)

What's New?: New (but still uncertain) Ages

Crater	Age	Age (as of 2006)
SPA	4.2 Ga (?)	4.3ish – 4.05 Ga
Serenitatis	>4.1 – 3.87 Ga	3.893 ± 0.009 Ga
Nectaris	4.1 Ga (?)	3.92 – 3.90 Ga (?)
Crisium	~3.9 Ga (?)	~3.89 Ga
Imbrium	3.77-3.90 Ga+	3.85 ± 0.02Ga

+ Imbrium's age is based on Apollo 14 and Apollo 15 samples, whose geologic provenance is not well-established

Norman (2008); Grange *et al.* (2010); Spudis *et al.* (2011)

Summary: Lunar Impact Rate

Lunar Samples are being re-analyzed
- Lunar ages re-calibrated, rocks re-analyzed
- Few lunar impact glasses with ages ≥ 3.9 Ga
  - Limited by available K?
  - Limited by number of impact events?

Glass spheres turn into shards over time

Duration and nature early lunar impact flux still uncertain

Other Impacts: Kaguya (2007)

Scientific objective:
Obtain information about the lunar surface environment with HDTV images and video

Crash landing on June 11, 2009

Earth-rise Video

Leibnitz Video

A sequence of images shows the bright flash as Kaguya strikes the Moon. (Photo: Jeremy Bailey, Steve Lee, Anglo-Australian Observatory). No water was detected in the impact ejecta.

Other Impacts: LCROSS (2009)

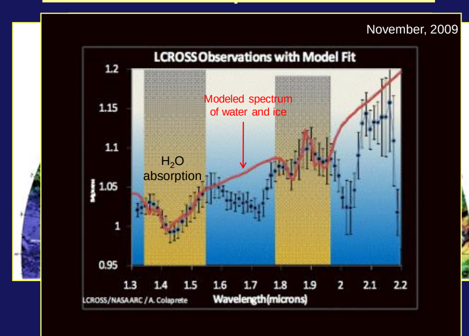
Lunar Crater Observation and Sensing Satellite (LRO)

Purpose: look for water on the Moon

Centaur impact into shadowed region of crater
- LCROSS, other analysis of debris in 6 km dust plumes

LCROSS impact a few km farther away

LCROSS Impact: Cabeus



Other Detections of H_2O

Clementine (H_2O): polar regions

Lunar Prospector (neutrons): 2.6 - 26 billion gal

M^3, Chadrayaan-1(OH or H_2O): 32 oz/ton at/near surface

Volcanic samples (Saal *et al.* 2008) showed some trace amounts

Cassini (1999 flyby), Deep Impact (2009 flyby) detected bond between O and H

Apollo samples – not so contaminated after all!

Origin of H_2O

Exogenic: brought by comets

Endogenic:
O in rocks/soil + H in wind → H_2O or hydroxyl

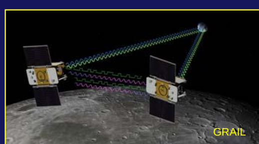
Water migrates to poles, accumulates in cold traps of permanently-shadowed area

Adsorbed in soil and not as pools of liquid or ice

Other Missions

Current Missions: GRAIL, 2011 (gravity field, thermal history)
LADEE, 2012 (atmosphere, dust environment)
Future Mission: ILN, 2013? (geophysical network of 2-4 landed stations)

International Collaboration will be key ($$$$)



Back to the Moon!

Lots of interest in the Moon:
ESA, China, India, Japan, US (LRO/LCROSS)

Volatiles? Water?
Active interior?
Other resources?

Locales for settlement?

Future Settlement?

Maybe.... farside is good for deep-sky observing (cosmology)

Resources could be extracted (once we have the technology to do so)

Humans can make quick decisions that robots can't

Prefer permanently-*sunlit* areas, which do exist at poles

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