The Violent Early Solar System, as Told by Sample Geochronology

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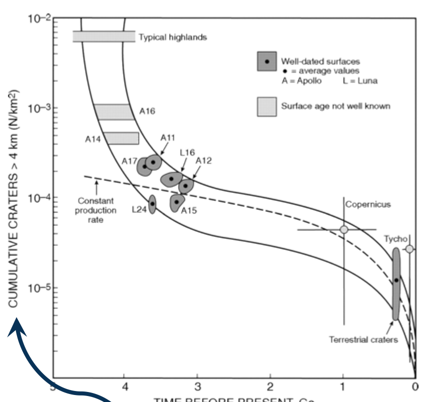
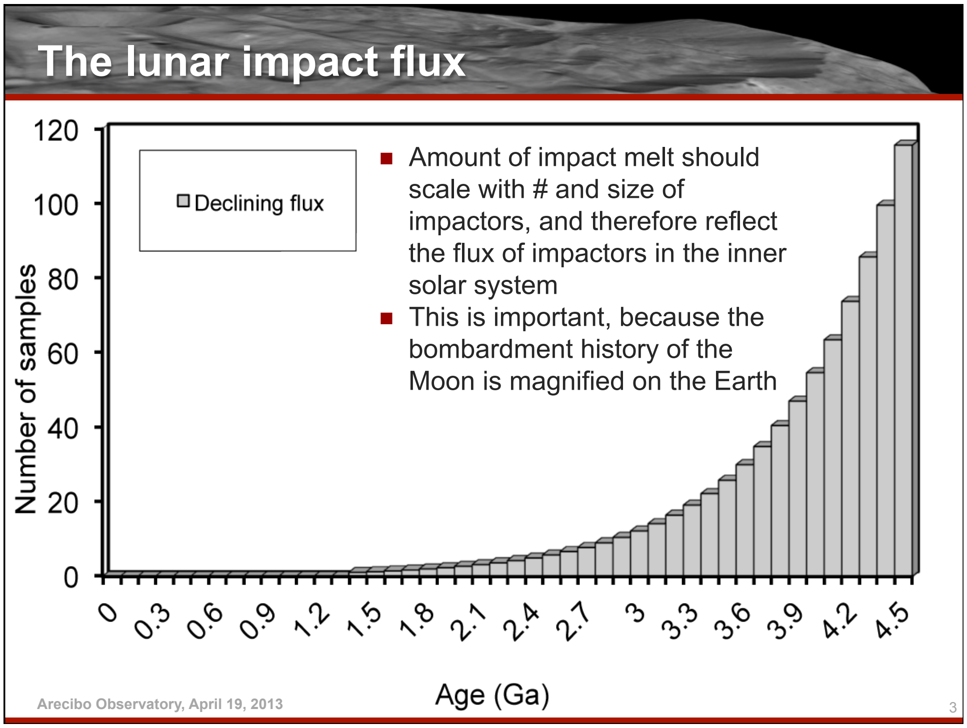
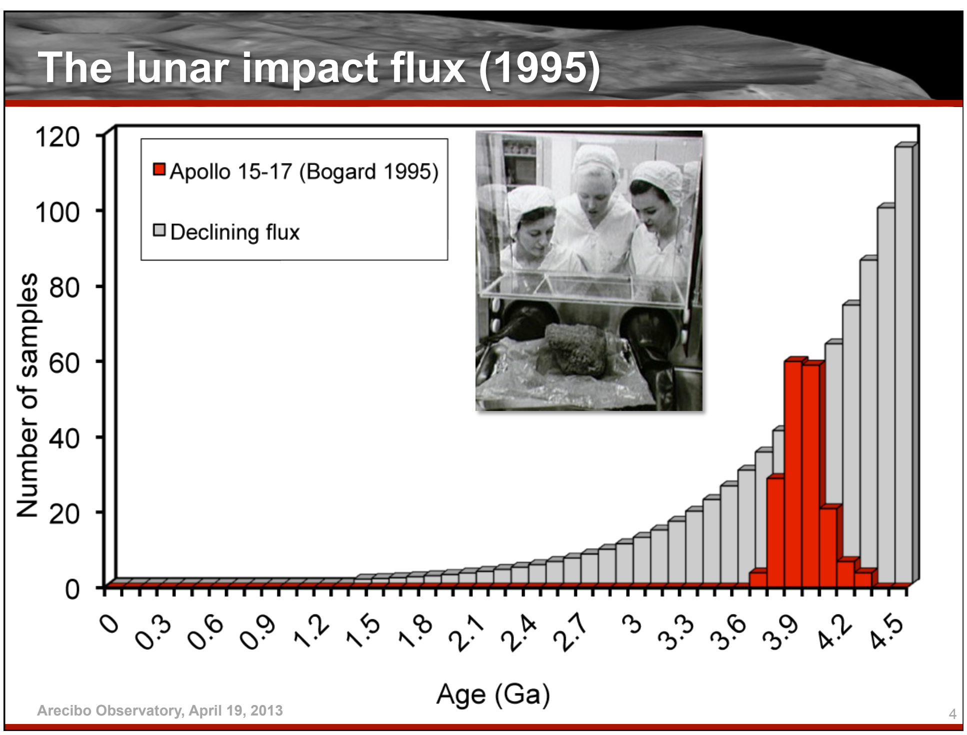
The absolute planetary timescale

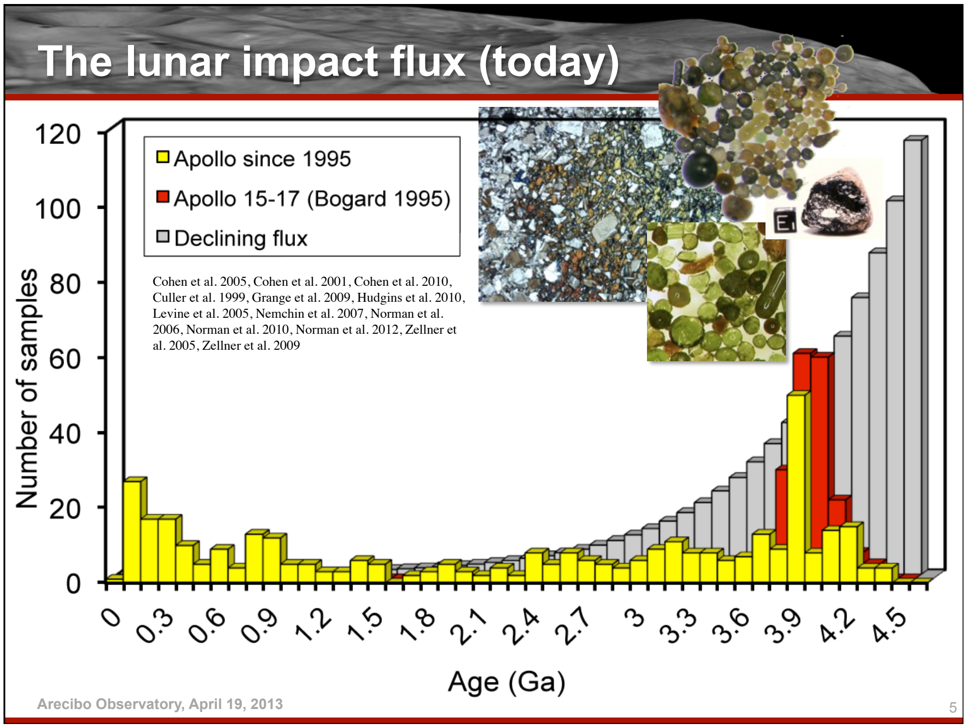
- One of the legacies of the Apollo samples is the link forged between radiometric ages of rocks and relative ages according to stratigraphic relationships and impact crater size-frequency distributions
  - Ejecta from Copernicus at Apollo 12
  - Imbrium Basin impact-melt breccias from Apollo 14 and 15
  - KREEP-poor IMBs from Apollo 16 record the age of Nectaris and/or Imbrium
  - Highland massifs at Apollo 17 give age of Serenitatis, and younger samples from Tycho
  - Materials from Luna 24 record the age of Crisium basin



This axis depends on both elapsed time and rate of impacts/time = flux


The lunar impact flux
120
100
80
60
40
20
0
Number of samples
Declining flux
Amount of impact melt should scale with # and size of impactors, and therefore reflect the flux of impactors in the inner solar system
This is important, because the bombardment history of the Moon is magnified on the Earth
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
3.3
3.6
3.9
4.2
4.5
Age (Ga)
Arecibo Observatory, April 19, 2013
3


The lunar impact flux (1995)
120
100
80
60
40
20
0
Number of samples
Apollo 15-17 (Bogard 1995)
Declining flux
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
3.3
3.6
3.9
4.2
4.5
Age (Ga)
Arecibo Observatory, April 19, 2013
4


The lunar impact flux (today)
Apollo since 1995
Apollo 15-17 (Bogard 1995)
Declining flux
Cohen et al. 2005, Cohen et al. 2001, Cohen et al. 2010, Culler et al. 1999, Grange et al. 2009, Hudgins et al. 2010, Levine et al. 2005, Nemchin et al. 2007, Norman et al. 2006, Norman et al. 2010, Norman et al. 2012, Zellner et al. 2005, Zellner et al. 2009
Number of samples
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100
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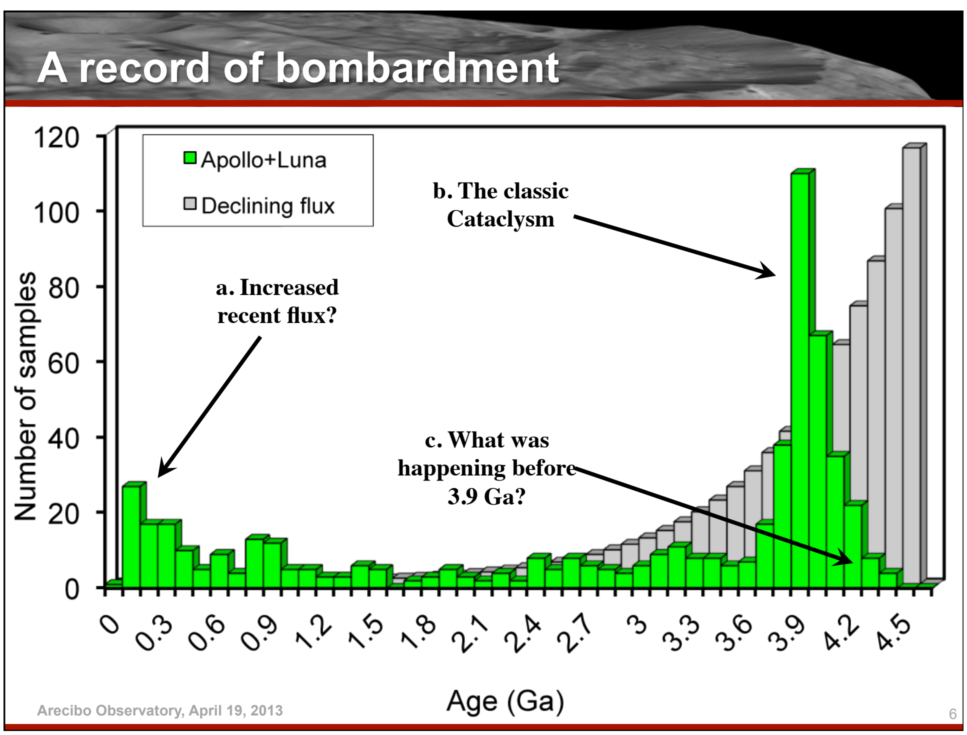
Age (Ga)
Arecibo Observatory, April 19, 2013
5


A record of bombardment
Apollo+Luna
Declining flux
b. The classic Cataclysm
a. Increased recent flux?
c. What was happening before 3.9 Ga?
Number of samples
120
100
80
60
40
20
0
0
0.3
0.6
0.9
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2.7
3
3.3
3.6
3.9
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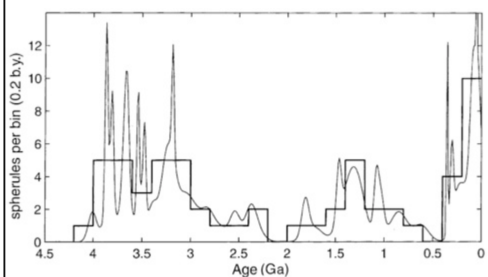
4.5
Age (Ga)
Arecibo Observatory, April 19, 2013
6

Increased recent flux?

- Spherule dating shows increase at 400 Myr ago (Culler et al. 2000)
- Modeling predicts that the lunar impact flux over the last 3 Gy has been relatively constant – asteroids driven out of the main belt through a combination of collisions, non-gravitational (Yarkovsky) thermal drift forces, and resonances, with an equilibrium size distribution

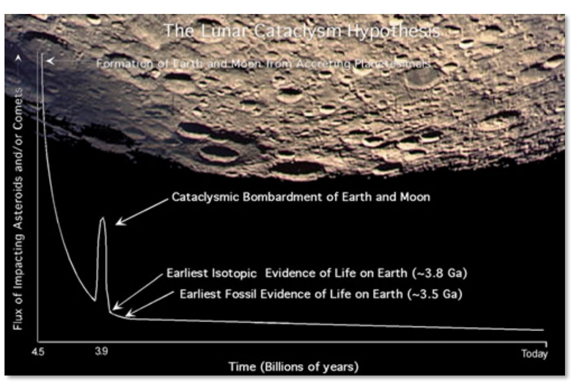


- Increase and diversity of young spherules may be related to increasing porosity of upper regolith, or gardening under of older spherules (Hörz 2000, Muller et al. 2000)
- But asteroid breakup events happen! (e.g. L-chondrite parent body at 460 Myr, Baptistina at 160 Ma, Bottke et al. 2007)

The classic Cataclysm

Excathedra

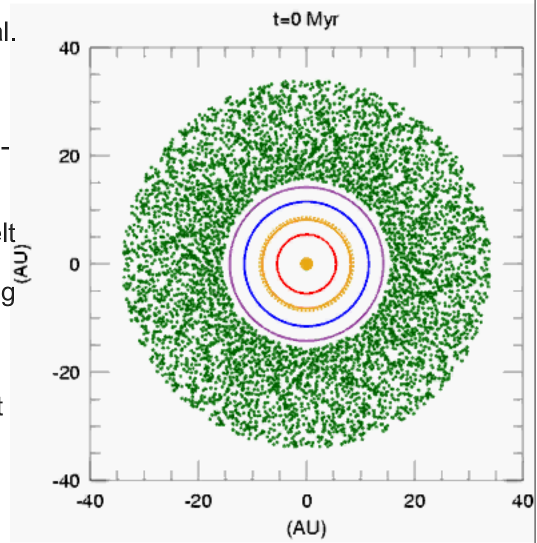
- Many Apollo 14, 16, 17 rocks crystallized at 4.5 Ga but experienced Pb loss at 3.9 Ga Tera et al (1974)
- Subsequent Rb-Sr and Ar-Ar ages on impact-melt rocks corroborate the large number of ~3.9 reset or disturbance ages



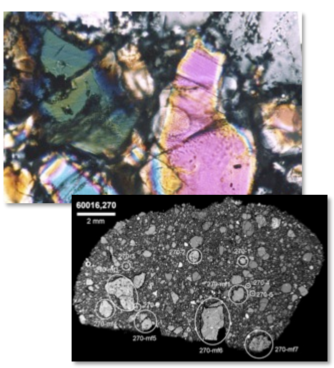
- Elements of the classic cataclysm:
- Widespread lunar metamorphism by impact
- Created at least three large basins in <0.2 Gyr (Serenitatis, Imbrium, Orientale)
- Resurfaced much of the lunar nearside
- An important time in Earth-Moon system

The classic Cataclysm

- Nice Model (Tsiganis et al., Morbidelli et al. and Gomes et al. 2005): Planet/planetesimal interaction causes Uranus and Neptune to migrate outward (destabilizing icy planetesimals - Trojan asteroids) and Jupiter to move inward, sweeping resonances through asteroid belt (late heavy bombardment)
- Consistent with secular sampling of asteroid belt (Strom et al. 2005); modeling of main belt asteroids predicts production of large lunar basins, long tailoff at Earth, and siderophile veneer (Minton and Malhotra 2010; Bottke et al. 2011)



What was happening before 3.9 Ga?



- Apollo breccias and clasts with reset ages of 4.1-4.3 Ga (Norman et al. 2010, Shuster et al. 2010, Hudgins et al. 2008)
- Zircon grains in Apollo breccias with overgrowth or recrystallization ages 3.9-4.3 Ga (Pidgeon et al. 2007, Grange et al. 2011)
- Impact events at 4.2 Ga proposed for lunar melt breccias based on Sm-Nd and Re-Os dating (Norman et al. 2007, Fischer-Gödde & Becker 2012)
- Clasts in Apollo 16 "ancient" breccias all date to ~3.9 Ga (Cohen et al. 2010); new solar wind trapping model confirms this measure of antiquity is not reliable (Joy et al. 2012)
- Are these recording ancient basin-forming impact events?
- Sawtooth model (Morbidelli et al. 2012) puts time constraints onto the Nice model framework, with Imbrium at 3.9, Nectaris at 4.1 and 2/3 of all basins prior to that.

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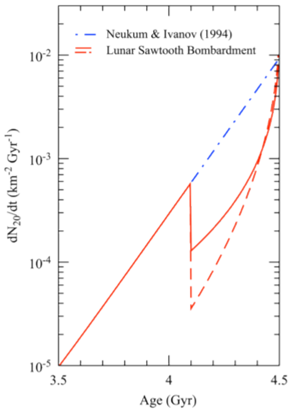

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Where else can we look?

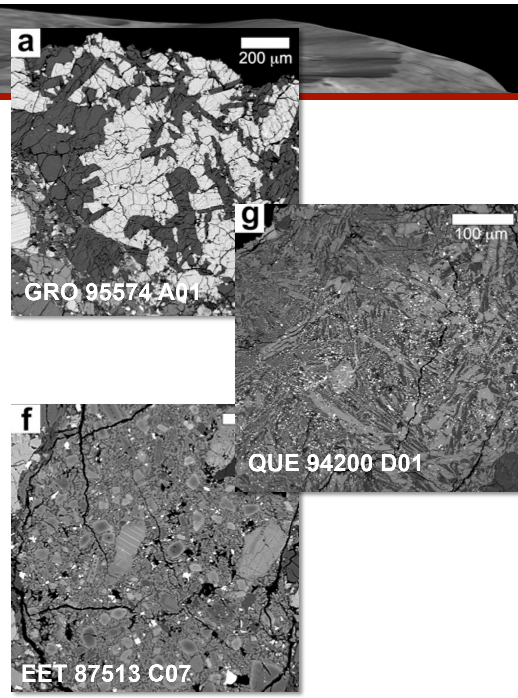
- HEDs = Howardites, Eucrites, Diogenites, largest achondrite group, spectrally linked to Vesta
- The HED parent body globally differentiated and fully crystallized around 4.56 Ga (Lugmair and Shukolyukov, 1998)
  - Eucrites – basaltic crust
  - Diogenites – cumulate mantle
- Dawn shows that Vesta is extensively cratered and covered with a well-developed regolith spectrally similar to howardites
  - Howardites - polymict regolith breccias
- Regolith brecciation and heating by impacts should be reflected in HED disturbance ages

Impact-melt clasts in howardites

- Most dated rocks and clasts are eucrites - heated and degassed without fundamentally changing their character
- Impact-melt clasts are less common, smaller, but possibly more likely to have been fully degassed, and largely unstudied
- Characterized texture, bulk composition, mineralogy, and ^{40}Ar-^{39}Ar ages of 37 individual clasts within howardites EET 87513, QUE 94200, GRO 95574 and QUE 97001 in 100-µm thick, polished sections

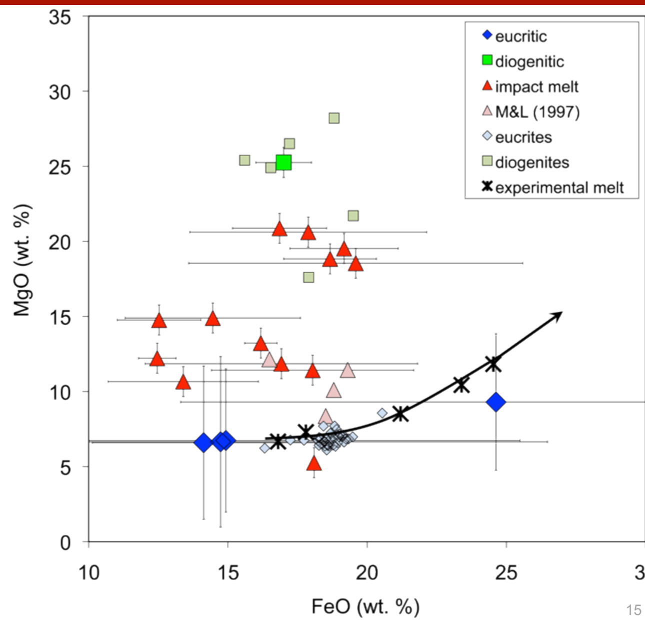
Clast textures

- A01, eucritic clast with a classic basaltic texture consisting of blocky feldspar (gray) and pyroxene (white)
- D01, acicular pyroxene and plagioclase in an impact-melt clast
- C07, also a microporphyritic impact-melt clast, but with a higher proportion of relic clasts



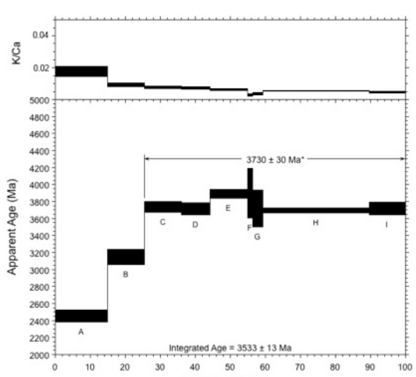
Clast compositions

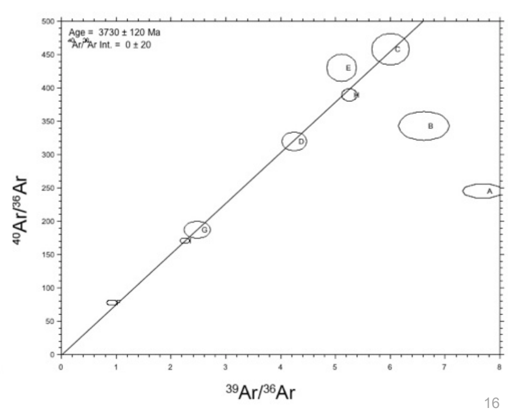
- Impact-melt clasts have a composition intermediate between eucrites and diogenites
- Clasts are not a previously-unknown evolved basaltic product (sorry Duck)



^{40}Ar-^{39}Ar data

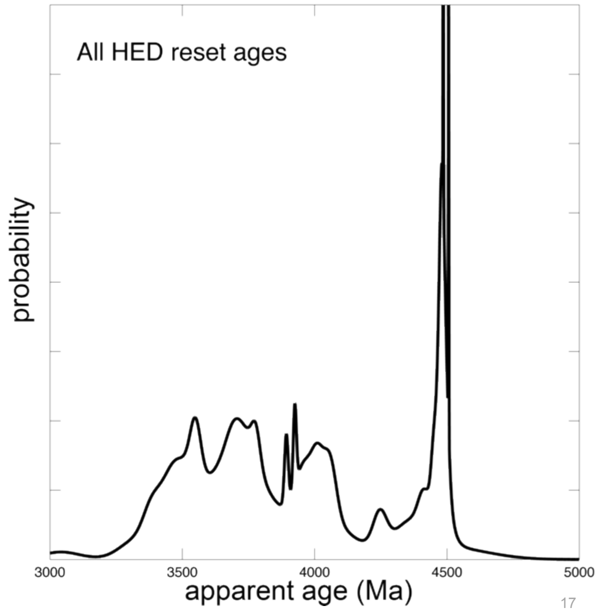
- Not all clasts produced good Ar-Ar data (not enough heating steps, discordant “plateaus”, etc.)
- Data examined using plateau plots, isochrons, and inverse isochrons, most conservative interpretations chosen





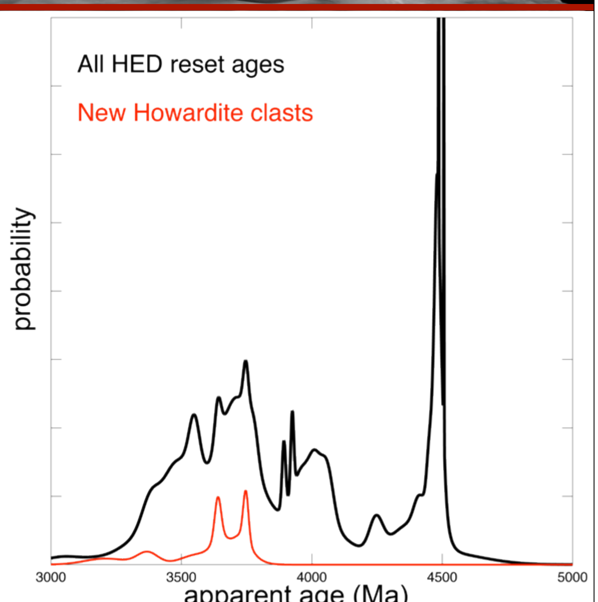
Disturbance ages in HEDs

- Age distribution of all HED impact-reset rocks (Bogard and Garrison (1993, 2003)
  - a short, intense spike at 4.48 Ga,
  - followed by a period of relative quiescence, then
  - ramping up between about 4.0 and 3.5 Ga



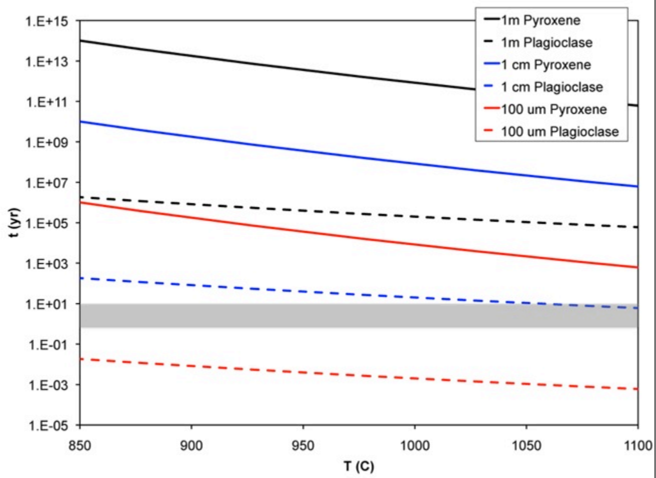
Impact-melt ages

- New impact-melt ages (11) predominantly 3.6-3.8 Ga
- Fall well within the age distribution of all HED impact-reset rocks



Resetting material on Vesta

- Significant diffusion in 100-10,000 y (cooling of an impact blanket) takes >800°C
- Typical impact *v* between objects in the main belt (5 km/s) imparts too little energy to raise T more than a few hundred °C



Diffusion coefficients in plagioclase and pyroxene (Cassata et al. 2008, 2010; Weirich et al. 2012)

Melting material on Vesta

- Melting material requires even more energy = higher relative *v*
- Main belt velocity distribution unlikely to explain so much melt from so many different impact events spaced so closely in time

herefore probably most of the Vesta
esult of highly velocitous impacts
et al. 2010)?

- Cometary flux of the Nice model (Gomes et al. 2005)?

Conclusions

- Impact-melt clasts in howardites are rare but present – formed by that impact-mixing of other 4 Vesta regolith
  - Textures demonstrate they were melted and recrystallized
  - Compositions demonstrate they are a mixture of eucrites and diogenites
- Impact-melt clast ages range between 3.5 and 4.0 Ga
  - Coincident with most Ar-reset ages of eucrites and eucritic clasts
- Forming impact melt on the surface of Vesta well after solar system accretion demands IOUVs (impacts of unusual velocity)
- **Vestal Cataclysm = A period of bombardment beginning around 4.0 (and extending to 3.5 Ga) caused by a distinct, high velocity population of impactors**
- Demonstrates the power of synergy between samples, sample ages, and dynamical models (thanks NLSI!)

New samples from the oldest lunar basin

- SPA Sample Return mission concept highly ranked by the 2003 Decadal Survey
- Science objectives address:
  - the timing and nature of bombardment in the inner Solar System and subsequent effects on planetary evolution and processes
  - planetary differentiation and magmatic evolution
  - crustal evolution and the impact process
- Sample return is required to achieve laboratory-precision data (isotopic data, ages, trace-element geochemistry) on multiple samples

Requirements for dating the SPA event

- An impact-melt rock from the SPA basin-forming event.

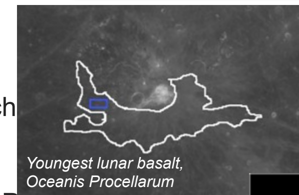
Requirements for dating the SPA event

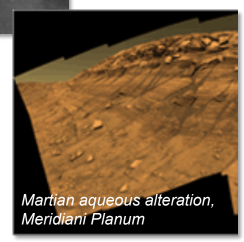
- An impact-melt rock from the SPA basin-forming event.
- Will there be one in a random scoop sample?
  - SPA is a different starting point from Apollo sites - the basin melt sheet is the basement rock
  - Modeling shows that SPA material is mostly indigeneous
- How will we recognize it compared to other rocks?
  - Petrographically / texturally
  - Geochemically / mineralogically
  - Trace / siderophile elements
  - Isotopic ratios
  - Geologic context
- How will we know its age is the SPA basin-forming age?
  - Dominated by age of the SPA basin
  - Bounded by younger ages of subsequent craters and basalts
  - Possibly bounded by older ages of igneous rocks

OK, but what if we can't get samples?

- Sample return from everywhere we'd like ages isn't feasible
- Instruments to measure rock ages (geochronology) have been proposed, but none have yet reached TRL 6, because isotopic measurements with sufficient resolution are very challenging
- We have proposed a new approach using flight-heritage components combined in a novel way to make the required measurements (PIDDP 2010)


Ancient Martian Crust, Syrtis Major
Image: NASA/JPL/University of Arizona


Youngest lunar basalt, Oceanis Procellarum


Martian aqueous alteration, Meridiani Planum

Laboratory vs flight instruments

- In the laboratory, very precise ages (±0.02 Ma) can be obtained on very small samples
  - Mass spectrometers are large (room-sized)
  - Replicate analyses can be run, subsamples can be separated and dated
  - Same sample can be analyzed by multiple techniques
  - Samples can be well-characterized and studied (microscopy, electron microprobe, etc.)
- Some challenges for a flight instrument include
  - Miniaturization
  - Accuracy and reproducibility of measurements
  - Confidence in interpretation of results
  - Sample preparation

How do we go from this……

to this?

KArLE principles

- Several in situ instruments to measure rock ages have been proposed and developed (e.g. AGE, MAX, etc.)….but none have yet flown, because
  - Isotopic measurements with sufficient resolution are challenging
  - Correct interpretation of results as an age (rather than a numeric ratio) is challenging
- The ^{40}K-^{40}Ar system (and its variant, Ar-Ar) is a proven technique sensitive to crystallization, aqueous alteration, and impact in returned samples

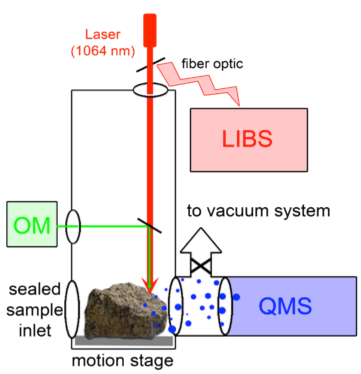
$D = D_0 + P\,(e^{\lambda t} - 1)$ *event separates parent from daughter*

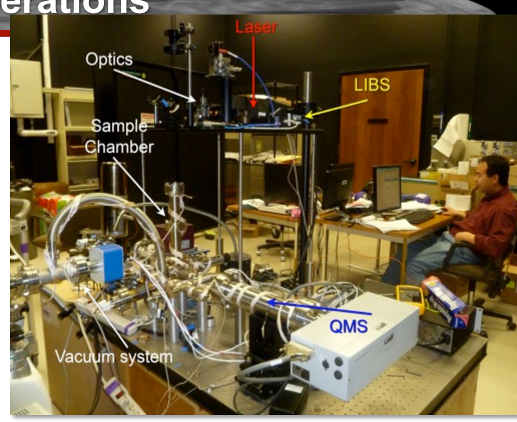
$t = 1/\lambda \ln [\,1 + \Delta D/\Delta P\,]$ *age isochron from multiple points*

$\sigma_t = 1/\lambda\ \sigma_D / (\Delta PD)$ *uncertainty from technique and sample heterogeneity*

- KArLE is a new development effort under the NASA Planetary Instrument Definition and Development Program (PIDDP) begun in 2011
  - Based on flight components (limited new technology development)
  - Uses instruments that you would want on a lander/rover anyway
  - No consumables – can take thousands of measurements
  - No special sample preparation
  - Target accuracy ±100 Myr for a 4 Ga sample

KArLE concept of operations

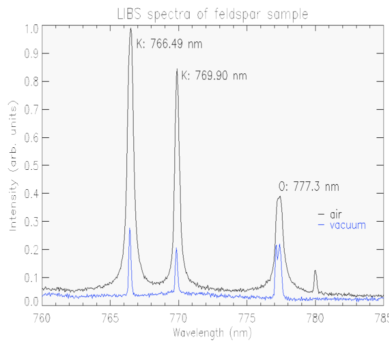


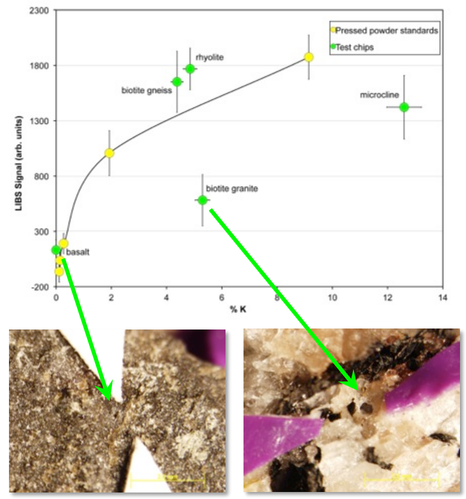


- Sample introduced by the spacecraft – no special sample preparation required
- Infrared laser ablates a pit in the rock
- K measured using laser-induced breakdown spectroscopy (LIBS)
- Liberated Ar measured using quadrupole mass spectrometry (QMS)
- K and Ar related by volume of the ablated pit using optical measurement (OM)
- Similar to laser (U–Th)/He dating technique in use in terrestrial laboratories

Laser-Induced Breakdown Spectroscopy (LIBS)

KArLE Breadboard	Flight Equivalent
Ocean Optics LIBS 2500+ Quantel laser, 1064 nm, 40 mJ, 1-20 Hz	MSL ChemCam (without telescope) Quantel laser, 1067nm, 30 mJ per pulse, 15 Hz





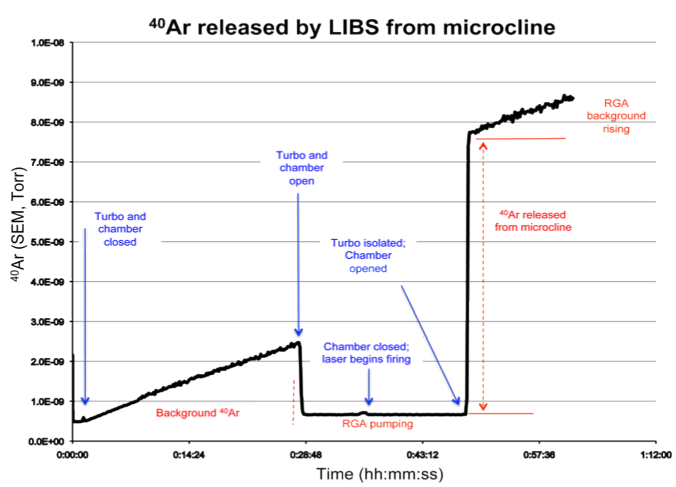
Pressure dependence: *LIBS spectra of microcline chip in air (100 shots) and in vacuum (1.7E-07 torr; 200 shots).*

Heterogeneity*: LIBS calibration curve using pressed powder samples. Test chips analyzed with XRF for bulk K_2O content, but vary in mineral K content.*

Quadrupole Mass Spectrometry (QMS)

KArLE Breadboard	Flight Equivalent
Hiden HAL/3F 51 Residual Gas Analyzer 1-50 Da ± 1 Da; 6E17 cps/mol	MSL Sample Analysis at Mars (SAM) mass spectrometer 2-535 Da ± <1 Da; 1E18 cps/mol

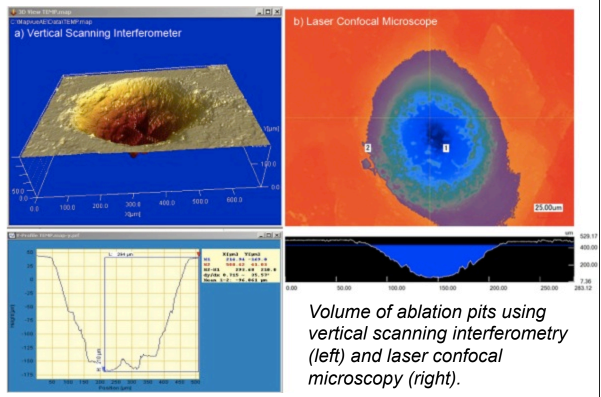
Background, volume of release, laser pulse rate: *^{40}Ar abundance in rhyolite during LIBS ablation. Ar buildup from background is small compared to the release from the sample. The measurement is the total release from 370 laser shots.*



Relating K and Ar measurements

KArLE Breadboard	Flight Equivalent
Keyence VK-X200 Laser Confocal Microscope KLA/Tencor MicroXAM Vertical Scanning Interferometer	Phoenix Atomic Force Microscope

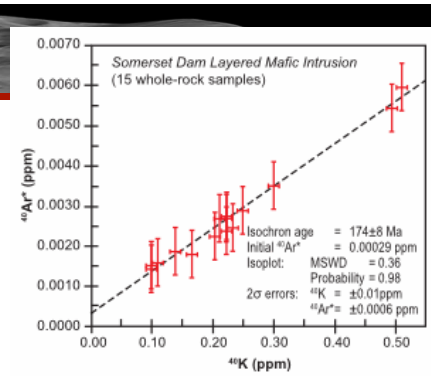
- Volume × rock density yields the ablated sample mass - necessary to relate absolute Ar and relative K measurements
- Optical metrology with a measurement goal 2% in ablation volume, constrained by ***distance to sample, vibration environment, pit dimensions, pit geometry***, etc.



Volume of ablation pits using vertical scanning interferometry (left) and laser confocal microscopy (right).

Deriving an age

- An age is the interpretation of a geologic event
  - remote sensing for geologic setting
  - imaging and microscopic imaging for petrology
  - microanalytical techniques for chemical and mineralogic composition and variation
- Multiple measurements to ensure validity of fundamental assumptions
  - Isochron helps age precision
  - Variation shows whether the sample components are cogenetic
  - Intercept shows whether the system has been closed to addition/loss



El Capitan *(Opportunity sol 29)*
False color

KArLE PIDDP Goals / Success Metrics

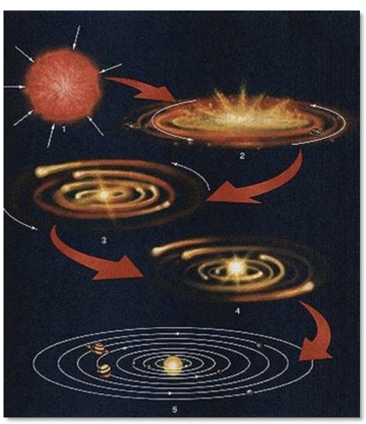
- Each individual component is accurate to the standards and has 10% or less uncertainty
- Measured ages of real samples come within 10% of the published age
- Trade between uncertainty in each age and the number of measurement points is fully characterized
- Operational workflow and component requirements of the breadboard are fully understood
- A candidate flight design produced whose mass, volume, and power are well-characterized is produced

PIDDP
2011-2014
Breadboard
(component tests and trades)
TRL 1-4

MatISSE
2014-2017
Brassboard
(integration and environment tests)
TRL 4-6

Mission
2017-?
Flight Unit
(flight unit build and qualification)
TRL 6-9

A violent early solar system…and beyond



- A post-Apollo view of a dynamic solar system
  - Precise ages of returned lunar samples & meteorites
  - Large numerical simulations of planet formation & migration
  - In situ investigation of impact-affected terrains
- Spitzer observations show a band of icy dust around Eta Corvi (1 Gyr old) – a possible extrasolar system cataclysm where outer icy bodies are pummeling inner rocky worlds

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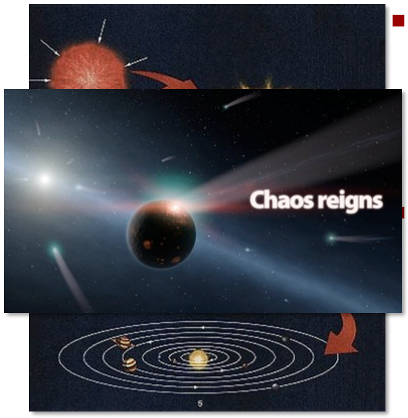

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- ***Catastrophe*** – 1,700 lunar craters / 22,000 terrestrial impact craters
- ***Catalyst*** – delivery of 10^{23} g of asteroidal/cometary material to the Earth
- ***Cauldron*** – impact-generated hydrothermal systems may be niches
- ***Crucible*** – extreme environments affect evolutionary paths