noun: Moon Age and Regolith Explorer
Revealing the Impact History of the Inner Solar System

Principal Investigator
Dr. F. Scott Anderson
and the MARE team
Outcome of MARE?

• Demonstration of what can now be done using new technology and recent developments in cratering chronology

• Opportunities for the future direction of LEAG (see Conclusion)
MARE Team

- **PI:** F. Scott Anderson
  - DPI: Phil Christensen
  - PS: David Draper
  - DPS: Samuel Lawrence
  - PM: Kim Ess
  - DPM: Jon Olansen
  - PSE: Ken Bollweg
  - Payload: John Andrews

- **Science:**
  - Marc Norman: Geochronology, geochemistry
  - Jeff Plescia: Cratering, Geochronology
  - Stuart Robbins: Crater counting
  - Jim Head: Crater counting, geology
  - Josh Bandfield: Mineralogy, thermophysics
  - Vicky Hamilton: Mineralogy
  - Rachel Klima: Mineralogy
  - Jonathan Levine: Geochronology
  - Ryan Ziegler: Geochemistry
  - Alan Treiman: Geochemistry
  - Harry Hiesinger: Crater Counting
  - Jacob Bleacher: Geology, Volcanology
  - Michelle Minitti: Geology, operations

- **Instruments**
  - Tom Whitaker: Lunar CDEX (µscopic chemical imaging & Rb-Sr dating)
    - Peter Wurz: Lunar geochemistry & mass spectrometer subsystem
      - Steve Beck: Laser subsystem
  - Phil Christensen: IRES (NIR/IR point spectrometer; mineralogy and thermophysics)
  - Aileen Yingst: EEC (Context and microscopic imager; MAHLI variant)
  - Sean Dougherty: MDA: Arm, gripper, rake
  - Kris Zacny: HoneyBee Grinder (RAT variant)

- **Morpheus/NAVIS & ALHAT team**
MARE Goals

• Goal 1: Determine the impact history of the inner solar system
  – Determine age of lunar mare basalts SE of Schiaparelli crater
  – Fill major gap in lunar crater chronology to bridge young and old terrain
  – Assess implications for lunar and inner solar system history

• Goal 2: Assess evolution and differentiation of the interiors of one-plate planets
  – Determine geochemistry and mineralogy of young basalts
  – Determine petrological and thermal evolution of the lunar mantle
  – Apply insights to understanding of one-plate planet evolution

• Addresses Goals and Objectives of DS, LEAG, SCEM
What is the problem?

- Multiple crater flux models with major differences
- Many crater counts consistently higher than previous efforts
- More craters observed in LROC data; implies higher impactor flux

![Graph showing relationship between crater density and measured age](graph.png)

- Constrained by samples
- No Well Provenanced Samples
- Debated
- Robbins, 2014
- Neukum et al, 2001

SPA Missions

- Longer Bombardment Era
- Shorter Bombardment
- Debated
Robbins, Marchi Models Imply 1 Ga Correction

~1.1 Ga correction!

Modified from S.J. Robbins, 2013
Goal 1: Reveal the history of the inner solar system

- Important solar system events occurring during 3-3.5 Ga
- Flux curve defines solar system events

Life is Hardy
Later planetary impacts mean...

Fragile Life Can Survive
Dry & Un-inhabitable Early
Cold Early

Early planetary impacts mean...

Wet & Habitable Late
Late Volcanism

Unexplored

1 km Craters/km²

Important events
1 Ga changes everything

Longer Bombardment Era
Shorter Bombardment

Measured Age (Ga)

3 1
MARE Overview

- Land and measure the chronology (CDEX-LARIMS) and composition (CDEX-LAMS, IRES, EEC) of a 1.8-2.8 billion year old planetary surface
  - MARE’s robotic arm & rake will acquire and assess 20 lunar rock samples
    - Threshold: 5
    - Baseline 10
    - 10 more as operational contingency
    - Plus acquisition contingency: ~50 samples, 30% usable
    - Binomial jujitsu: 98%+ odds of 9 measurable samples
- Stereoscopic, panoramic and microscopic images provide geospatial context
- NIR & TIR mineralogy and thermophysics of sample and site

~1.8-2.8 Ga
DRR 1 Site ~23.7°N 47.4°W: SE of Schiaparelli

- Crater count well understood
- Lunar Prospector:
  - Chemically homogenous
  - 4-6 ppm Th => 7-8 ppm Rb
- Extremely smooth
- 2-m DTM for ALHAT
- 50-1000+ rocks + rake results
- DRR2: N of Flamsteed Crater
NAVIS Lander based on JSC Morpheus

- Only full-scale test-bed lunar lander currently in active testing, including 15 of flights and demonstrated autonomous high precision landing
NAVIS Lander

- Solar Panels
- Radiators
- Liquid Oxygen & Methane Tanks
- CDEX
- Grinder based on RAT by HBR
- IRES
- 4-Degree of Freedom Arm Based on Mars Phoenix by MDA
- EEC
- Soil Rake
- Rock Gripper

Rock Selection Zone: 12 m², 226° Arm Rotation
Chemistry and Dating EXperiment

- CDEX-LARIMS for Rb-Sr
- CDEX-LAMS for elemental abundance
- Miniaturization under MatISSE
Lunar Analog Duluth Gabbro

- TIMS: 1094±14 Ma
  \[ \frac{^{87}\text{Sr}}{^{86}\text{Sr}} = 0.7055 \pm 3 \]
  - Dates for Duluth and Zagami are published

- Accurate abundances, e.g. Rb ~4.4 ppm
  - 2X harder than DRR1

- Intercept good to <1%
  - Precision meets requirement, but
    - Accuracy 3X worse
  - Further calibration expected to improve this
What does this mean for flux-curves

- Can differentiate models at 2-\(\sigma\) (2 x 200 Ma) for expected age range
- 3 samples to be confident of provenance
- Improvement in age to \(\sim\)140 Ma (current limit due to systematic error)

![Graph showing age constraints and expected age range](modified_from_SJ_Robbins_2013)

<table>
<thead>
<tr>
<th>Time (Gyr)</th>
<th>Δ Age in models (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td></td>
</tr>
<tr>
<td>2(\sigma) (400 Ma)</td>
<td></td>
</tr>
<tr>
<td>2(\sigma) (280 Ma)</td>
<td></td>
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</tbody>
</table>

Expected age range

Modified from S.J. Robbins, 2013
Science Instrument Complement

Chemistry and Dating Experiment (CDEX)
- Laser-Ablation Mass Spectrometry (LAMS)
  - Elemental, and isotopic analysis
  - ±2% accuracy for > 1 wt%
  - ±5% for > 1000 ppm abundance
  - 240 point analyses per sample

Infrared Reflectance and Emission Spectroscopy (IRES)
- Point NIR and TIR spectra
- Wavelengths 1 to 2.5 um and 5.5 to 50 um
- Based on MER Mini-TES
- 10 cm⁻¹ resolution

Laser-Ablation Resonance Ionization Mass-Spectrometry (LARIMS)
- Rb-Sr age ± 200 Ma
- Minimal sample preparation
- Robust Aerospace laser system
- High TRL mass spectrometer

Eagle Eye Camera (EEC)
- Hi-res, stereoscopic images
- Pre/post analysis images
- Focus 2.1 cm to ∞
- Based on MSL MAHLI
Conclusions: Clives Questions

• **What are the implications** of new observations for the geologic evolution of the Moon and solar system geology?
  
  • Recent crater flux models have major implications for the history of the Moon and inner solar system requiring new chronology measurements from multiple terrains
  
  • **How do current mission results** affect the current Decadal Survey and influence our planning for the next?
  
  • Add unifying theme for a campaign of dating missions for the Moon and inner solar system
  
  • **How do these new discoveries affect** planning for future human missions?
  
  • Humans provide the perfect sample acquisition for in-situ triage and sample return
  
  • **What future measurements are needed** to address unknowns, including strategic knowledge gaps, regarding the Dynamic Moon?
  
  • More chronology!
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