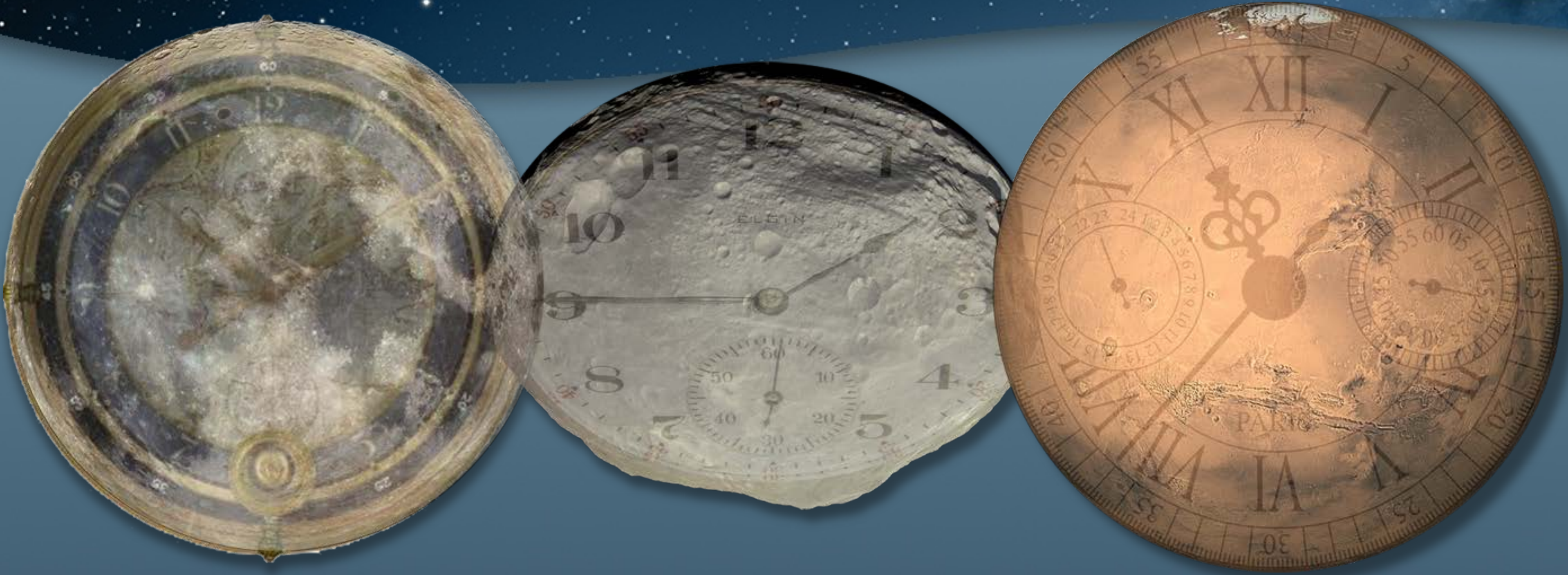


Geochronology for the Next Decade

A Planetary Mission Concept Study for the 2023 Decadal Survey

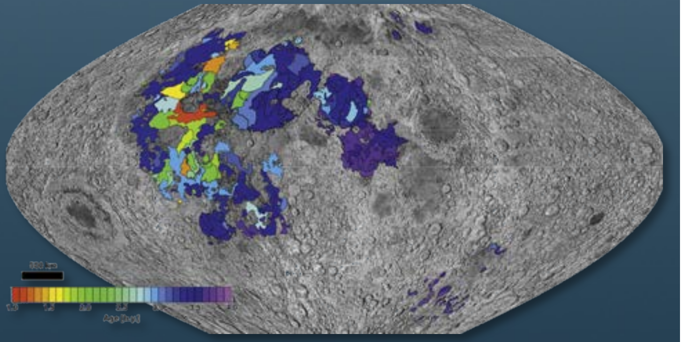
PI: Barbara Cohen, NASA GSFC (barbara.a.cohen@nasa.gov)

Study motivation and goals

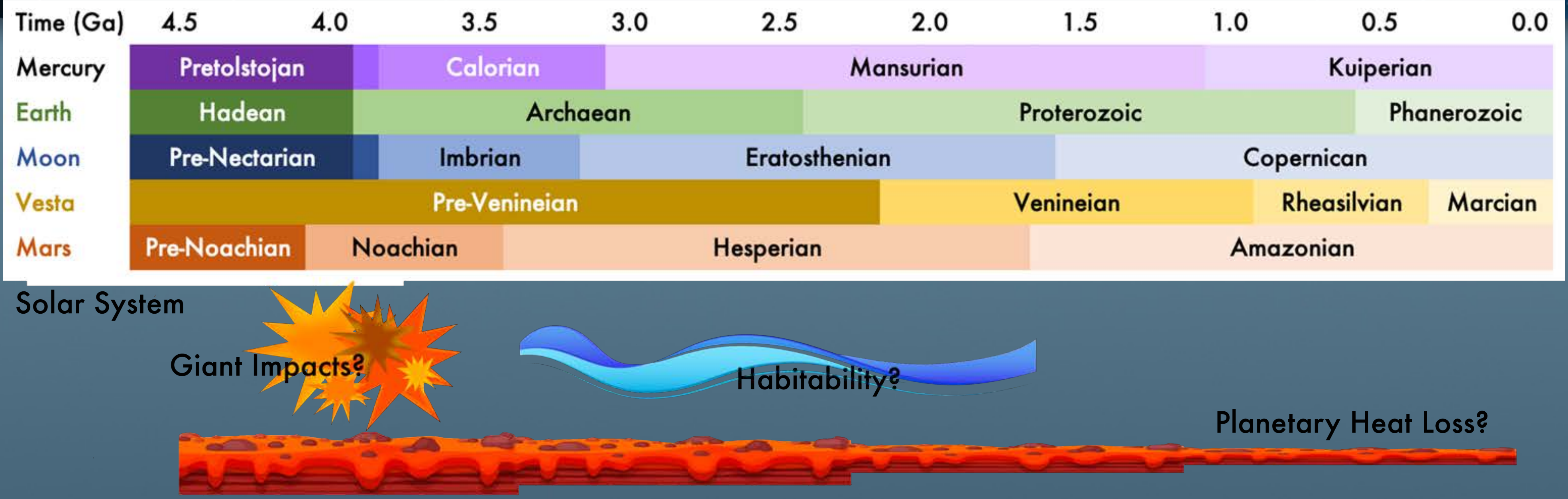
- **Geochronology:** determination of absolute ages for geologic events
- **Motivation**: Major advances in planetary science can be driven by absolute geochronology in the next decade, calibrating body-specific chronologies and creating a framework for understanding Solar System formation
  - Traceable to 2014 NASA Science Goals, p.61; Planetary Science Decadal Survey: p.151, p.143; LEAG, MEPAG, and SBAG goals documents
- **Why Now?** In the last two decades, NASA has invested in the development of in situ dating techniques; K-Ar and Rb-Sr instruments will be TRL 6 by the time of the next Decadal Survey period
- **Study Goals:**
  - Assess how in situ geochronology could be accomplished in the inner solar system (Moon, Mars, and asteroids) – multiple CML 3-4 studies
  - Give the next Decadal Survey panel a viable alternative -- or addition to -- sample return missions to accomplish longstanding geochronology goals within a New Frontiers envelope


Rheasilvia basin, Vesta


Ancient Martian Crust, Syrtis Major


Lunar volcanic units

Geochronology in the next decade



- **Science Goal**: Create a common framework for the history of the inner solar system bodies by dating major events on the Moon, Mars, and Vesta
- **Science Objectives**:
  - Determine the chronology of basin-forming impacts and constrain the time period of heavy bombardment in the inner solar system
  - Constrain the 1 Ga uncertainty in solar system chronology from 1-3 Ga, informing models of planetary evolution including volcanism, volatiles, and habitability
  - Constrain the timing and longevity of hydration and habitability across the inner worlds

Science Goals, Objectives, and Measurements

- Radiometric dating, or the process of determining the age of rocks from the decay of their radioactive elements, has been in widespread use for over half a century
- Measure the parent and daughter isotopes in a pair to determine when a rock closed to addition or loss of its radioactive elements. Here we consider two pairs, Rb-Sr and K-Ar.
- Lots of rocks are amenable to Rb-Sr and K-Ar dating in terrestrial labs, including igneous rocks, phyllosilicates/clays, and sulfates. Each mineral can record a different event in the rock's history.
- An age is an interpretation, requiring accurate and precise measurement of the isotopes *and* adequate knowledge to interpret that measurement.

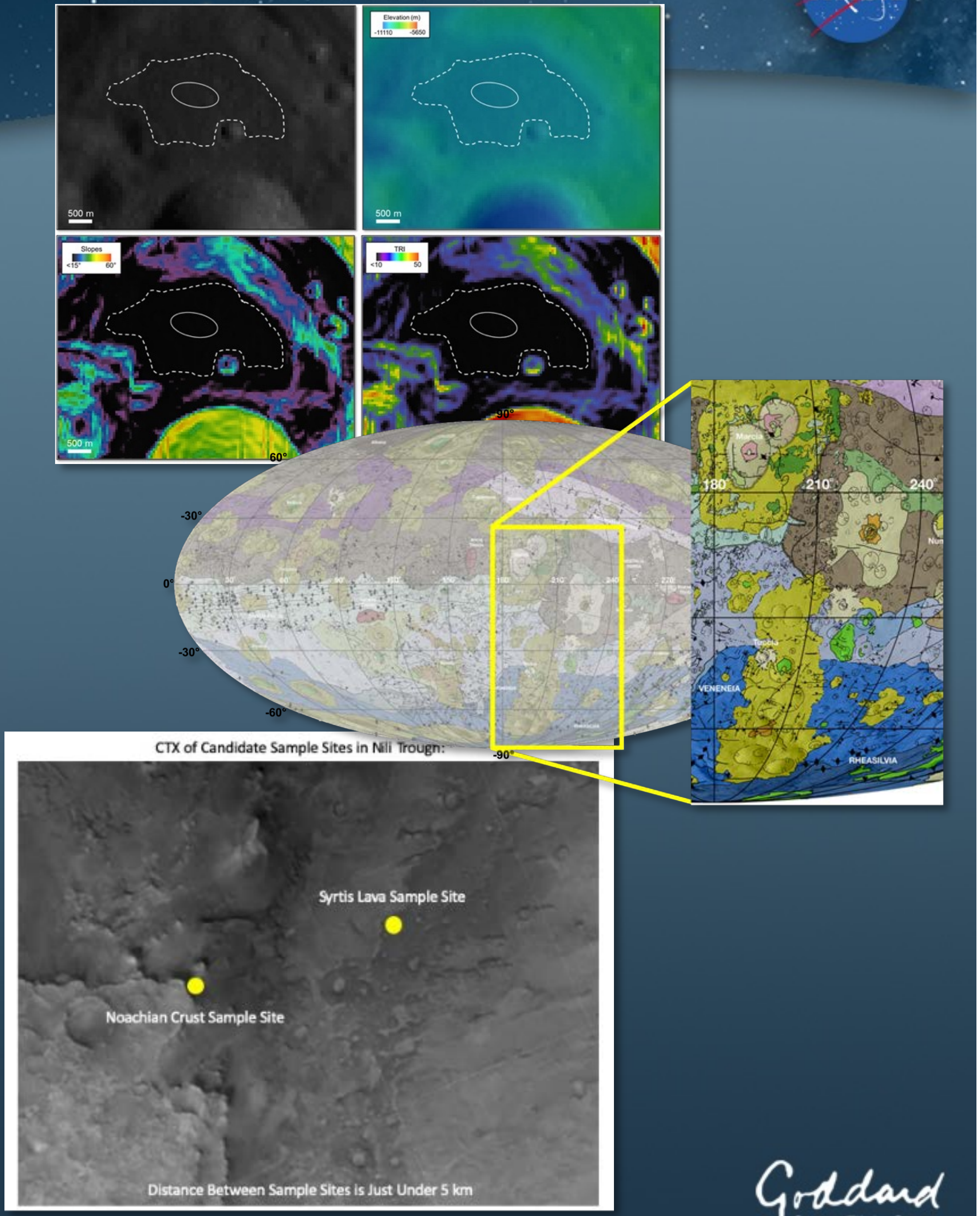
- Required Measurements:
  - Measure the age of the desired lithology with precision ±200 Myr
  - Contextualize the desired lithology using petrology, mineralogy, and/or elemental chemistry
  - Relate the measured lithology age to crater counting of the lithology's terrain
- Driving Mission Requirements:
  - Payload: Collect, characterize, and date at least ten 0.5-2 cm sized samples of lithologies that address the science objectives
  - Mobility: Conduct sample analysis at 2 different sites on each body to address different objectives

Science Traceability Matrix

Science Objectives	Measurement Goals	Measurement Requirements	Mission Support
Determine the chronology of basin-forming impacts and constrain the time period of heavy bombardment in the inner solar system Constrain the 1 Ga uncertainty in solar system chronology from 1-3 Ga, informing models of planetary evolution Establish the history of habitability across the Solar System	Measure the age of the desired lithology with precision ±200 Myr	Use Rb-Sr radiometric chronology to directly measure the age of samples derived from the target lithology	Collect, triage, and analyze 10 0.5-2 cm sized samples at each site * see additional information on sampling statistics Conduct sample analysis at 2 different sites on each body ** see additional information on sites Remotely sense the workspace around the landing legs to provide sample context and of landing site at low and high sun angles to create spatially contiguous maps
		Use K-Ar radiometric chronology to directly measure the age of samples derived from the target lithology	
	Contextualize the desired lithology using petrology, mineralogy, and/or elemental chemistry	Measure the major- and trace-element geochemistry of the samples to establish parentage and evolution of lithologies	
		Identify the mineralogy by mapping abundances of olivines, pyroxenes, oxides, plagioclases; Identify aqueous alteration minerals including phyllosilicates, sulfates, carbonates, and other hydrated salts	
		Image the samples at the microscale to determine grain size, petrology, etc.	
		Determine the composition of the surface unit to place the lithologies into a regional and global context	
	Relate the measured lithology age to crater counting of the lithology's terrain	Determine the geology of the landed site and map discrete lithologic units to relate them to maps and crater counts determined from remote sensing	

Candidate Landing Sites

- Moon
  - Craters that excavate the impact-melt sheets of Crisium or Nectaris Basin to establish the chronology of basin-forming impacts
  - Young lunar basalts to correlate crater count with crystallization age
- Vesta
  - Rheasilvia basin to establish the chronology of basin-forming impacts
  - Marcia Crater to access and date a diversity of vestan stratigraphy
- Mars
  - Many sites vetted for Curiosity / Perseverance provide access to a range of Noachian and Hesperian materials: clays, carbonates, sulfates, lavas such as Nili Fossae Trough, Mawrth Vallis, NE Syrtis



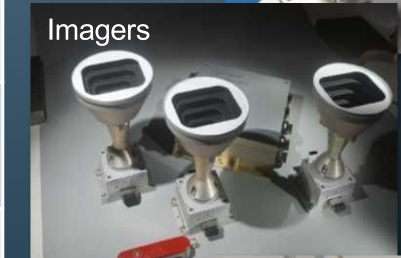
Payload concept

- Measurement requirements could be met by carrying a single notional payload
- Study payload comprises *representative* instruments - ***generalizable and scaleable*** to any suite of instruments that can accomplish the Measurement Requirements
- Most elements would be TRL 6 in 2023 (start of next Decadal) – so we did not account for additionalpayload development costs in this study architecture

Measurement Requirement	Measurement	Payload Element	Element Lead	TRL in 2023
Geochronology	Rb-Sr geochronology	CDEX	Scott Anderson / SWRI	6 (MatISSE / DALI)
	K-Ar geochronology	KArLE	Barbara Cohen / GSFC	6 (DALI)
Sample & site context	Trace-element geochemistry	ICPMS	Rick Arevalo / UMD	4 (PICASSO) – *6 (DALI or MatISSE*)
	Mineralogy	UCIS-Moon	Bethany Ehlmann / JPL	6 (DALI)
	Visible/color imaging and micro-imaging	Panoramic and microimagers	Aileen Yingst / MSSS	9 (MSL / CLPS)
Sample Handling	Acquire, prepare, and introduce samples to analysis instruments	PlanetVac	Stephen Indyk / Honeybee Robotics	9 (CLPS / MMX)


CDEX


UCIS

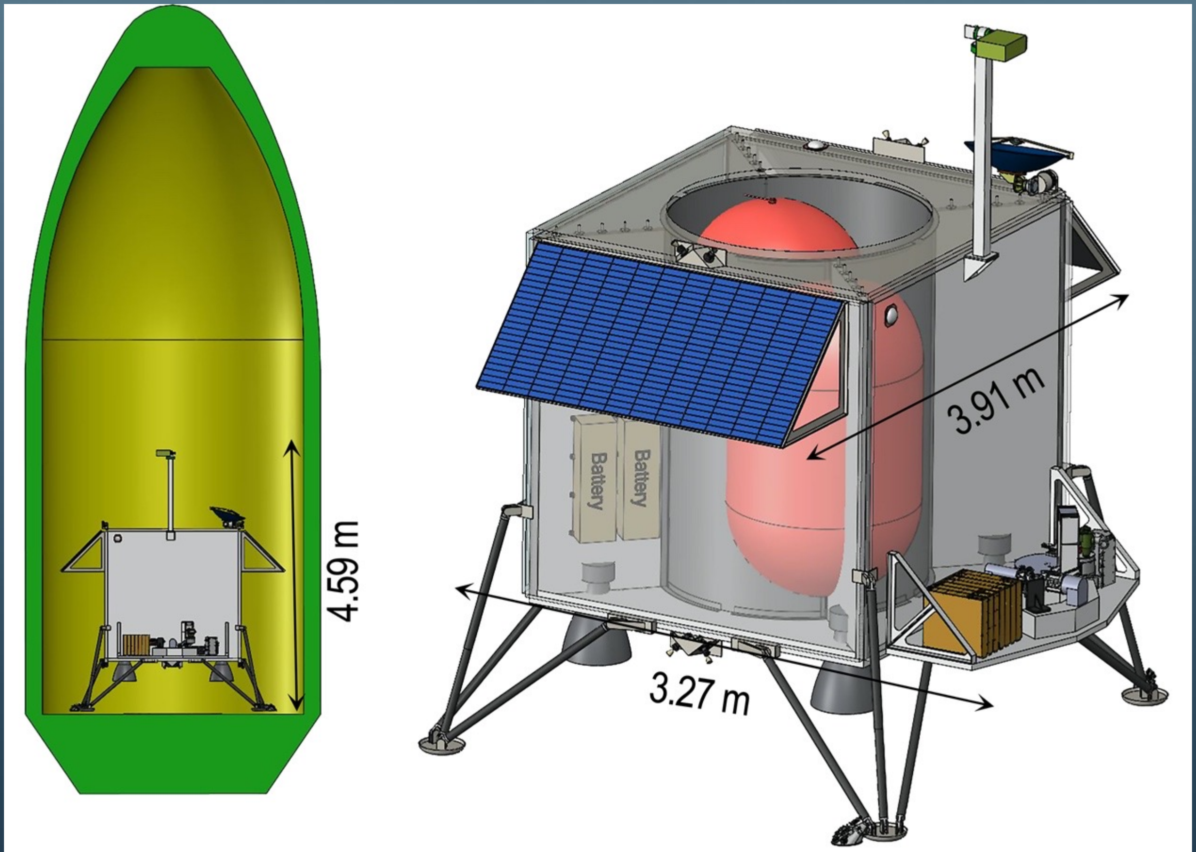

Imagers


PlanetVac

Payload totals: 178 kg / 60 Gb / 180 W peak power

Lunar lander concept

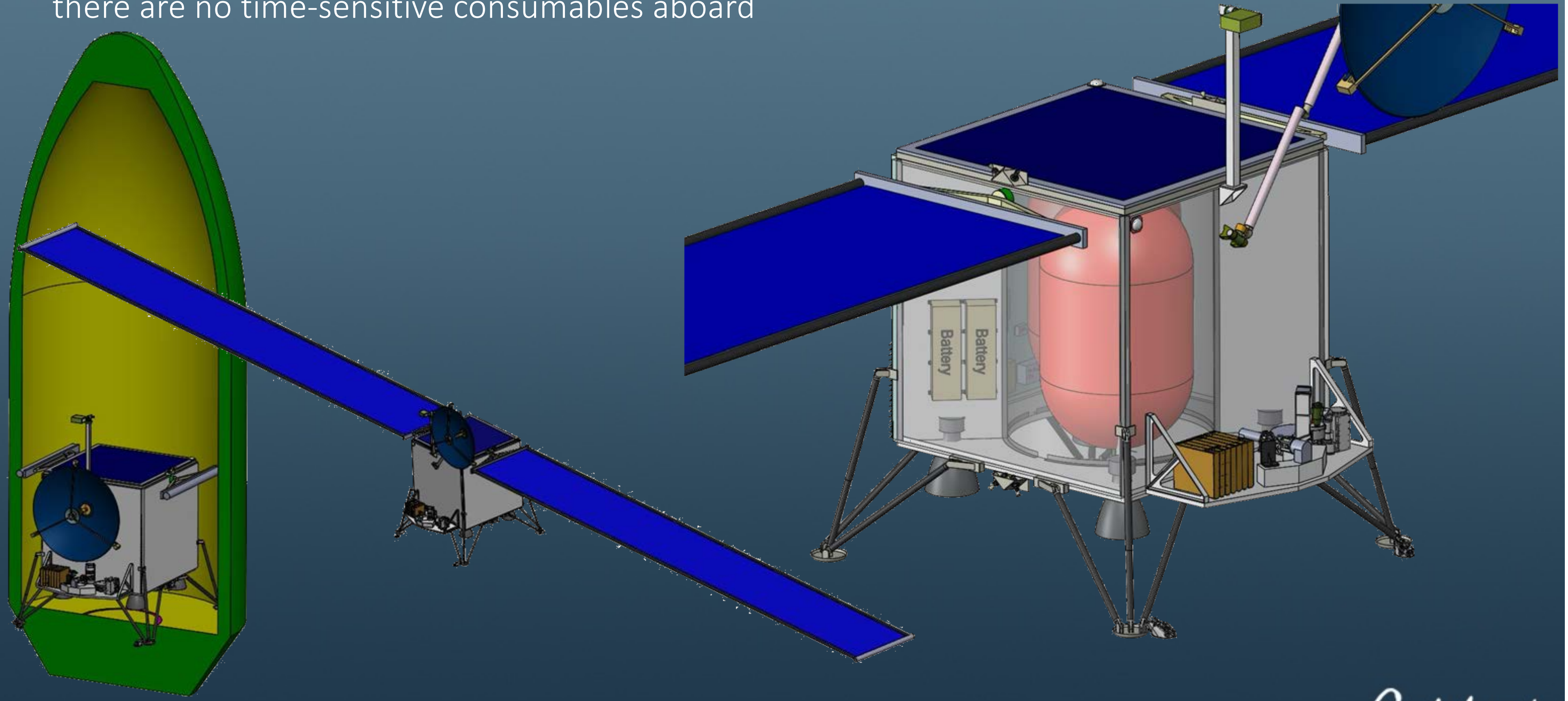
- We conducted a full Mission Design Lab (MDL) focused on a lunar hopper to widely-separated sites (100’s of km) – design did not close in a New Frontiers envelope
- Downsized the lunar hopper concept without the extra propellant, structure, and power needed to hop
- Single lunar lander design closes with full payload and concept of operations



- Class B mission - Selective Redundancy/fault tolerance
- Falcon 9 Heavy launch vehicle
- Direct insertion to land using 4 Aerojet R-40B engines with Terrain-Relative Navigation (TRN)
- Redundant Processor for Landing and all other CPU control functions
- 2 body-mounted TjGaAs solar panels and 1100Ahr battery
- X-band comm
- Lifetime 1 year / 12 nights

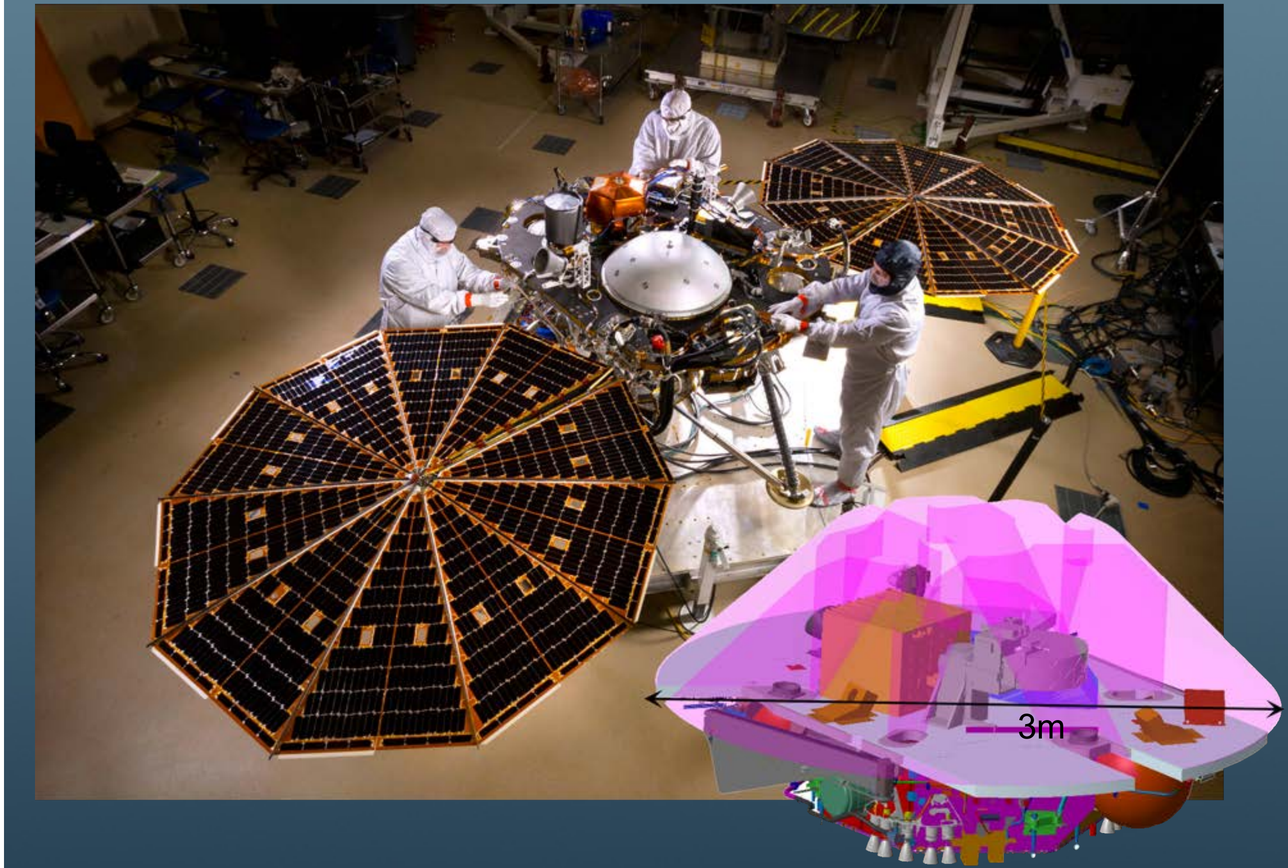
Vesta hopper concept

- Translate lunar concept to Vesta
  - Trajectory designed to arrive when landing sites have solar illumination, Rheasilvia (south pole) has yearlong cycle of illumination/eclipse
  - Large rollout solar arrays that can retract for hopping
  - Added compression and data latency
  - Increased surface mission lifetime to 2 years –this isn’t a huge issue since it takes years in cruise and there are no time-sensitive consumables aboard



Mars lander concept

- Worked with Lockheed to upsize a Phoenix/Insight lander concept, closes with full payload and concept of operations



- Class B mission - Selective Redundancy/fault tolerance
- Falcon 9 Heavy launch vehicle
- Mars EDL similar to Phoenix / InSight
- TRN not required in this study
- Daily ~ 700 W-hr/sol for payload operations, which would pace payload use during Mars surface operations
- Context imaging divided over ~16 sols to ensure consistent lighting conditions
- 20-sample science operations would be complete at Sol 340, 450 sols were budgeted for margin

Summary of architecture options

- Vesta has an architecture option that meets full sample science at multiple sites in a New Frontiers cost
- For the Moon and Mars, both cost and payload mass preclude significant mobility, whether by hopper or by rover
- NF-class single-site landers at the Moon and Mars can carry full payloads for ~1 year of operations. Sites may exist where multiple objectives could be met by analyzing more rocks.

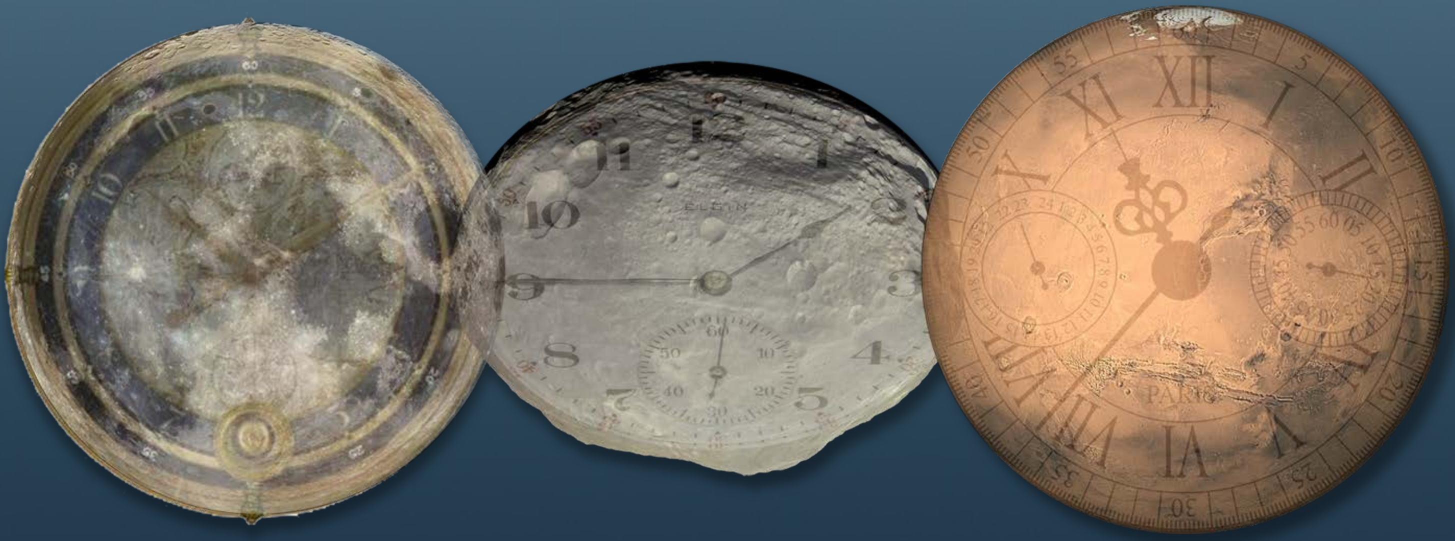
Target	Science Goal	Sample Science	Multiple Sites	Cost Class
Moon	Determine the chronology of basin-forming impacts	Full	Single lander	New Frontiers
	Constrain uncertainty in lunar chronology from 1-3 Ga	Full	Single lander	New Frontiers
	Do both	Reduced	Hopper 100's of km	Flagship
Mars	Validate crater-counting ages on Mars	Full	Single lander	New Frontiers
	Bound the epoch of habitability	Full	Single lander	New Frontiers
	Do both	Reduced	Rover 10's of km	Flagship
Vesta	Establish the Vestan chronology	Full	Hopper 100's of km	New Frontiers

Evaluation

- Feasible New Frontiers-class missions exist that would carry a capable instrument payload to conduct *in situ* dating with the precision to answer community-identified science goals
  - NASA investments in *in situ* dating instruments make a feasible payload, including dating by multiple corroborating methods and extensive characterization to give confidence in results
  - New remote-sensing work, geologic mapping, and site evaluation efforts have expanded the locations where safe landing sites can access lithologies of interest
  - Compelling cases can be made for specific science questions to be answered using targeted single-site landers at the Moon and Mars.
- Ours is not the only payload option! Cases could be made for well-bounded questions using smaller payloads (e.g., single method of radiometric dating, downsized characterization suite), perhaps in Discovery or CLPS, or aboard mobile rovers
- Such missions would also be able to conduct a broad suite of geologic investigations
  - Geologic site investigations, geomorphology, ground truth
  - Major, minor, and trace-element analyses
  - Volatile element analyses, atmospheric monitoring
  - Organic molecule analysis
  - Soil properties, geotechnical properties
  - Long-lived monitoring (weather, space weather, etc)
  - Radio science and laser retroreflectors

Conclusions and Recommendations

- Geochronology underpins cross-cutting, big-picture, community-identified science goals across the inner solar system, creating a framework in which to interpret planetary histories
- Geochronology measurements may be flexibly accomplished on dedicated missions or as part of “normal” geology missions, by sample return or *in situ* measurements, depending on the science question and need
- We ask the Decadal Survey to consider such a geochronology framework as a fundamental advance that could be made in the next decade and consider possible ways the community could accomplish such a goal – including a chronology-focused mission in the New Frontiers list – with flexibility in implementation by sample return or by *in situ* dating



Backup

- Team membership
- Sampling Statistics
- Payload conops, power, and data
- Mission engineering trades and drivers
- Schedule and costing

Geochronology PMCS team

SCIENCE DEFINITION TEAM

Barbara Cohen (PI), GSFC
Kelsey Young* (DPI), GSFC
Kris Zacny, Honeybee Robotics
Ryan Watkins*, PSI
Sarah Valencia*, GSFC
Tim Swindle, U of Arizona
Stuart Robbins*, SwRI
Noah Petro, GSFC
Dan Moriarty*, GSFC
Stephen Indyk, Honeybee Robotics
Juliane Gross*, Rutgers University
Jennifer Grier, PSI
Nicolle Zellner, Albion College
John Grant, Smithsonian
Caleb Fassett, MSFC
R. Aileen Yingst, PSI
Ken Farley, Caltech
Ben Farcy*, U of Maryland
Bethany Ehlmann*, Caltech
Darby Dyar, PSI
Natalie Curran*, GSFC
Carolyn van der Bogert, University Westfalische
Ricardo Arevalo*, U of Maryland
Scott Anderson, SwRI
**early career*

GSFC ENGINEERING TEAM

Mike Adams
Ginger Bronke
Eric Cardiff
John Crow
Gerard Daelemans
Amani Ginyard
Kyle Hughes
Stephen Indyk
Cameron Jerry
Andrew Jones
Richard Lynch
Stephen Meyer
Ryo Nakamura
Anthony Nicoletti
Dave Palace
Miguel Benayas Penas
Glenn Rakow
Bruno Sarli
Marcia Segura
Thomas Spitzer
David Steinfeld
John Zuby

LOCKHEED MARTIN (MARS LANDER CONCEPT)

Richard Warwick
Noble Hatten
Mark Johnson
Scott Francis
Madeline O'Neil
Tim Lin

GSFC MISSION DESIGN LAB TEAM

Maryam Bakhtiari-Nejad
Grant Barrett
Bob Beaman
Emily Beckman
Kaitlyn Blair
Jennifer Bracken
Thomas Carstens
Angel Davis
Paul Earle
Luis Gallo
Camille Holly
Frank Kirchman
Steve Levitski
Blake Lorenz
Mike Machado
Dick McBirney
Khashy Parsay
Sara Riall
Russ Snyder
David Steinfeld
James Sturm
Huaizu You
John Young

Sampling statistics

How many rocks do we need?

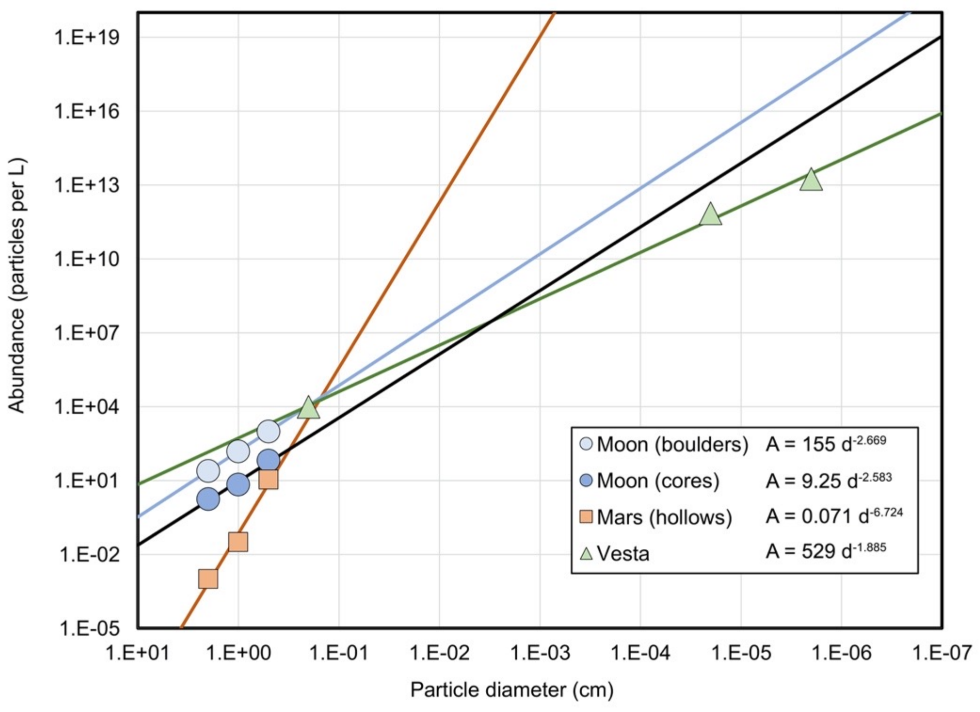
- Confidence requires 3 samples of the lithology to agree in age
- Allow for some rocks and experiments being uncooperative = 10 samples analyzed per lithology of interest
- Allow for some rocks at each site being not what we want = **30 samples acquired per lithology**

Instruments require rocks measuring 0.5-2 cm in diameter to obtain sufficient analyses.

How many rocks of correct size (0.5 – 2 cm in diameter) are in the regolith?

This volume must be excavated and sieved and samples delivered to the instruments. Few L is readily accommodated by dual PlanetVac inlets or a scoop & sieve.

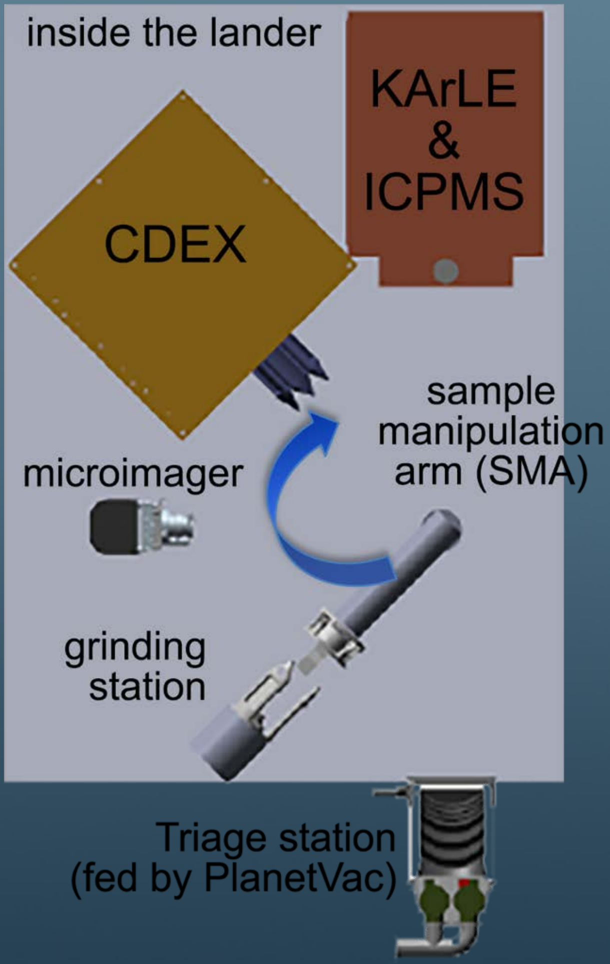
Body	Volume for 30 samples (L)
Moon (boulders)	0.03
Moon (cores)	0.62
Mars (bedrock)	small
Mars (hollows)	2.68
Vesta (Kapoeta)	similar to Moon



Instrument layout / functional requirements

- Instrument positioning is flexible and can adapt to lander configuration

- PlanetVac dislodges, transports, and sieves samples of correct size, regolith falls out a screen
- Samples fall into triage station for characterization by mast instruments
- SMA grabs a sample and delivers it to internal stations for analysis
- KArLE and ICPMS share an internal sample handling carousel



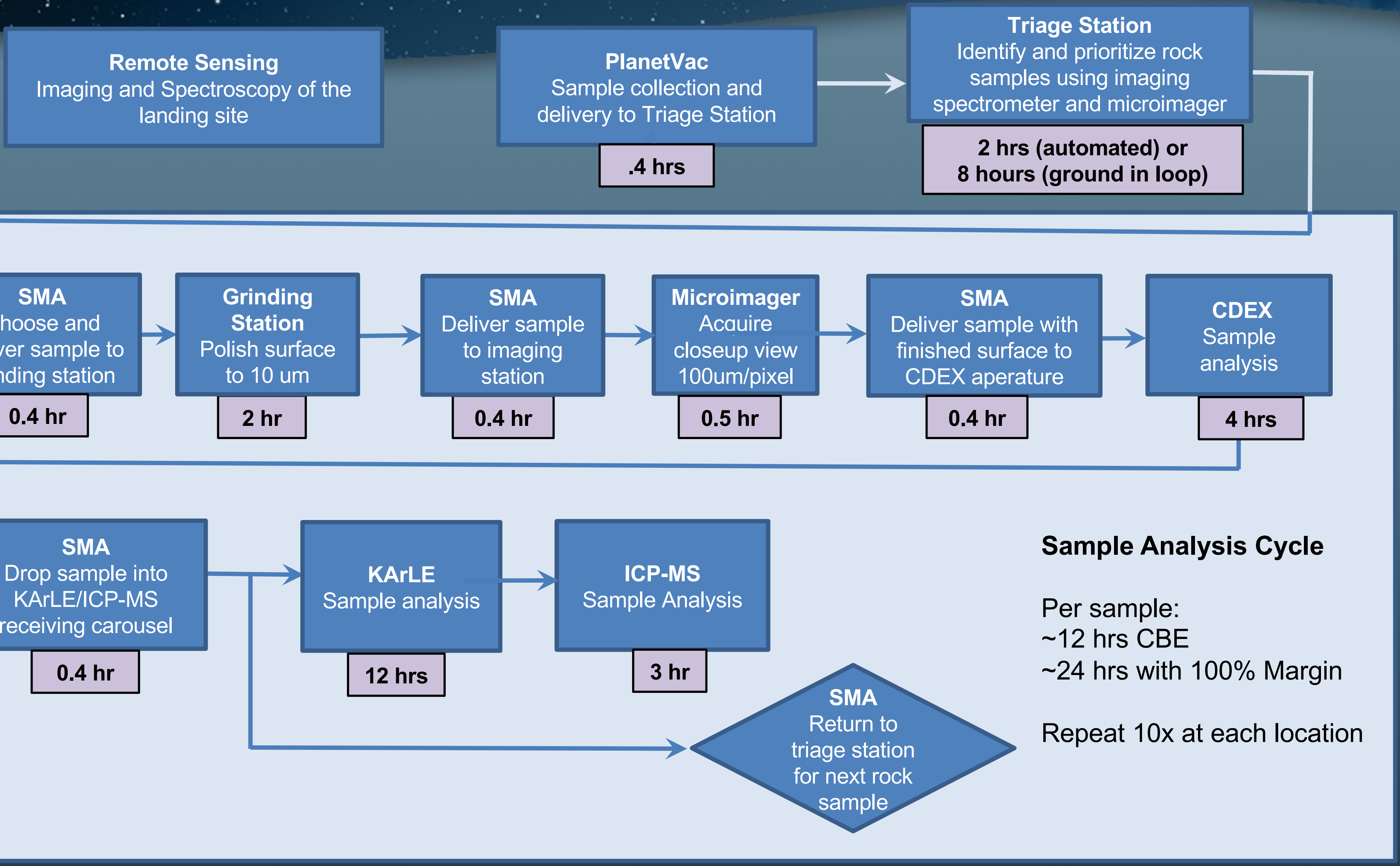
on a mast

UCIS
- Panoramic spectroscopy
- Spectroscopy of samples in the triage station
- Spectroscopy of area around lander footpads

Stereo Imagers
- Panoramic imaging
- Image soil around lander footpads

Microimager
- Image samples in the triage station

Surface operations concept



Remote Sensing
Imaging and Spectroscopy of the landing site

PlanetVac
Sample collection and delivery to Triage Station
.4 hrs

Triage Station
Identify and prioritize rock samples using imaging spectrometer and microimager
2 hrs (automated) or
8 hours (ground in loop)

SMA
Choose and deliver sample to grinding station
0.4 hr

Grinding Station
Polish surface to 10 um
2 hr

SMA
Deliver sample to imaging station
0.4 hr

Microimager
Acquire closeup view 100um/pixel
0.5 hr

SMA
Deliver sample with finished surface to CDEX aperature
0.4 hr

CDEX
Sample analysis
4 hrs

SMA
Drop sample into KArLE/ICP-MS receiving carousel
0.4 hr

KArLE
Sample analysis
12 hrs

ICP-MS
Sample Analysis
3 hr

SMA
Return to triage station for next rock sample

Sample Analysis Cycle

Per sample:
~12 hrs CBE
~24 hrs with 100% Margin

Repeat 10x at each location

Payload mass and power

Payload Element	Mass (kg) (incl 30%)	Peak Power (W) (incl 30%)	Data Generation (Mbit) (postcompression)
CDEX			
CDEX instrument	71.5	182	22400
Grinding station	7.4	26	N/A
Postgrind Imager	0.8	9	1500
Sample Manipulation Arm	13	26	1600
KArLE			
KArLE Instrument	29.8	130	21220
ICPMS	12.4	133	38
UCIS (Including DPU)	6.5	39	11268
Panoramic Imagers (total for 2)	1.5	19	1454
Microimager	1.4	10	180
Imaging DEA	1.4	0	N/A
Sample acquisition and triage			
PlanetVac	20.8	42	30
Triage station	3.8	8	N/A
Electronics box	3.0	30	
Totals	173		59690

Mission Drivers & Requirements

Mission Requirement (Top Level)	Mission Design Requirements	Lander Requirements	Ground System Requirements	Operations Requirements
Mission Lifetime of at least 6 months Conduct sample analysis at 2 different sites on each planetary body Reliability Category 2, Class B	Launch Vehicle Falcon 9 with 5m fairing Less than 1 m/s velocity at 1 m above surface during Landings	Deliver [170] kg of science instruments to lunar surface Land Safely with clearance for 0.5m boulder Provide interfaces for instruments Collect, triage, and analyze 10 0.5-2 cm sized samples at each site Image the landing site from the lander to the horizon to create spatially contiguous maps at two different sun angles Image the workspace around the landing legs to provide sample context Data Storage [350 Gbits] Return at least [200 Gbits] per lunar day 28 V power System Provide [250] W power to the science instruments 0.1 ms timing accuracy with 10-6 stability relative to ground station Execute stored command sequence Monitor instruments execution of stored commands Place instruments in safe state and notify Ground of any faults Continue operating instruments that do not have faults	34m DSN Antenna at Ka at 100 Mbs Receive house keeping & science data telemetry Provide commanding Plan and transmit command sequences Record/Archive science data Provide critical event telecom coverage: Launch thru Sep, TLI, [LOI], Landing, S/A Deployment, Instrument Deployments, Hop (takeoff and landing) Perform Lander Health and Safety checkout, then monitor SOH	Manage time correlations Monitor Lander state of health Implement contingency procedures Implement science sequences Inventory data & re- transmit if needed Perform ops sim testing

Schedules and costing

- Schedule development against a New Frontiers average mission life cycle schedule. Spacecraft and instrument development estimates fit within this family.

- Payload Costing:
  - CDEX, KArLE, UCIS, and ICPMS completed:
    - NASA Instrument Cost Modeling (NICM) cost estimates via GSFC Cost Estimating & Analysis (CEMA) Office
    - Analogous mission/parametric cost modeling via GSFC Resource Analysis Office (RAO)
  - All payload elements also have a grassroots cost estimate from each payload element lead
- Lander Costing:
  - Lunar hopping mission, Lunar single site mission, and Vesta asteroid hopping mission have Master Equipment Lists (MELs)
  - SEER-H parametric cost modeled cost estimate for lunar and Vesta missions
  - Lockheed developed Mars single site lander cost estimates