Science Questions & How They Might Be Addressed By the Presence of Humans/ Human Support Structure

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Roadmap for Human Exploration

- Outlines a plan that extends human exploration beyond low-Earth orbit (LEO)
- Includes multiple destinations (the Moon, asteroids, and eventually Mars)
- Highlights the need for a robotic program that
  - Serves as precursor explorers, then as
  - A parallel mission element partner,
  - Before we have a fully developed human exploration program
Elements of a Lunar Robotic Program

- It is essential that we restore the capability of lunar surface operations and
- Sample return
NASA's Resource Prospector Robotic Lunar Surface Element

**RESOLVE (Regolith & Environment Science and Oxygen and Lunar Volatile Extraction)**

**Sample Acquisition**
- Auger/Core Drill [CSA provided]
  - Complete core down to 1 m; Auger to 0.5 m
  - Minimal/no volatile loss
  - Low mass/power (<25 kg)
  - Wide variation in regolith/rock/ice characteristics for penetration and sample collection
  - Wide temperature variation from surface to depth (300K to <100K)

**Sample Evaluation**
- Near Infrared Spectrometer (NIR)
  - Low mass/low power for flight
  - Mineral characterization and ice/water detection before volatile processing
  - Controlled illumination source

**Resource Localization**
- Neutron Spectrometer (NS)
  - Low mass/low power for flight
  - Water-equivalent hydrogen ≥ 0.5 wt% down to 1 meter depth at 0.1 m/s roving speed

**Volatile Content/Oxygen Extraction**
- Oxygen & Volatile Extraction Node (OVEN)
  - Temperature range of <100K to 900K
  - 50 operations nominal
  - Fast operations for short duration missions
  - Process 30 to 60 gm of sample per operation (Order of magnitude greater than TEGA & SAM)

**Volatile Content Evaluation**
- Lunar Advanced Volatile Analysis (LAVA)
  - Fast analysis, complete GC-MS analysis in under 2 minutes
  - Measure water content of regolith at 0.5% (weight) or greater
  - Characterize volatiles of interest below 70 AMU

**Operation Control**
- Flight Avionics [CSA/NASA]
  - Space-rated microprocessor

**Surface Mobility/Operation**
- CSA mobility platform
  - Rover nicknamed “Artemis Jr.”
  - Low mass/large payload capability
  - Driving and situation awareness, stereo-cameras
  - Autonomous navigation using stereo-cameras and sensors
  - NASA contributions likely for communications and thermal management

**RESOLVE Instrument Suite Specifications**
- Nom. Mission Life = 10+ Cores, 12+ days
- Mass = 60-70 kg
- Dimensions = w/o rover: 68.5 x 112 x 1200 cm
- Ave. Power: 200 W
A Roscosmos-led Series of Robotic Lunar Surface Elements

- **2015**: Luna-25 (Luna-Glob-Lander) Technology of polar soft landing, study of lunar South Pole (1450/530 kg)
- **2016**: Luna-26 (Luna-Glob-Orbiter) Global orbital studies of the Moon
- **2017**: Luna-27 (Luna-Resource-1) Studies of South Pole regolith and exosphere in cooperation with India (2200/810 kg)
- **2017**: Luna-28 (Luna-Resource-2) Cryogenic samples return from South Pole (3000 kg)
- **2020**: Luna-29 (Luna-Resource-3) Lunokhod mission (3000 kg)

ESA participation is currently being explored
EXPLORATION – DEVELOPMENT OF ORION AND SLS VEHICLES

EFT-1 (December 2014)
EXPLORATION – DEVELOPMENT OF ORION AND SLS VEHICLES

EFT-1 (December 2014)

EM-1 and EM-2 (2017 and 2021)

ESD Mission Overview

Exploration Mission One (EM-1)
First Uncrewed BEO Flight
2017

- Mission objectives
  - Demonstrate integrated spacecraft systems performance prior to crewed flight
  - Demonstrate high speed entry (~11 km/s) and TPS prior to crewed flight
- Mission description
  - Un-crewed circumlunar flight – free return trajectory
  - Mission duration ~7 days
- Spacecraft configuration
  - Orion Uncrewed
- Launch vehicle configuration
  - SLS Block 1, 5-segment RSRMV, 4 RS-25, 70mt
  - Interim CPS
- Launch site
  - KSC LC-39B

Exploration Mission Two (EM-2)
First Crewed BEO Flight
2021

- Mission objectives
  - Demonstrate crewed flight beyond LEO
- Mission description
  - Crewed lunar orbit-capable, or other destinations
  - Mission duration 10-14 days
- Spacecraft configuration
  - Orion Crewed
- Launch vehicle configuration
  - SLS Block, 5-segment RSRMV, 4 RS-25, 70mt
  - Interim CPS
- Launch site
  - KSC LC-39B
EXPLORATION – DEVELOPMENT OF ORION AND SLS VEHICLES

EFT-1 (December 2014)

EM-1 and EM-2 (2017 and 2021)

And, within the framework of the Global Exploration Roadmap:
- Human-assisted sample return
- Humans to the lunar surface
NASA Human Spaceflight Architecture Team (M. Lupisella and M. R. Bobskill, 2012)

**Preliminary Earth-Moon L1 / L2 Notional Mission “Streetview.”**

**Mission Summary**
- Crew visits Deep Space Facility (DSF) located @ E-M Lagrange point. Crew tests & demonstrates future exploration systems & operations, controlling assets on the lunar surface, performing lunar surface observations, and other deep space science tasks. DSF could be derivative of ETM and moved between E-M L1 & L2 points and be visited multiple times.
- Uses ETM and MPCV (first MPCV/SLS mission beyond test flights) for crew pressurized volume
- First crew arrives for first DSF mission, later crews bring further infrastructure, stay for longer durations
- Station-keeping (with ACS, RCS?)
- NEA stack assembly in situ?

**Mission Benefits**
- Develop habitation capabilities & reduce risk for future exploration missions
- Enhance lunar & space science: e.g., survey farside, control robots on surface, perform surface assembly (e.g., farside radio telescope)
- Perform exploration research & technology ops: crew+robot autonomous ops, long delay comm, advanced EVA systems, measurements (e.g., radiation shielding)
- Demonstrate deep space assembly
- ETM serves as foothold in deep space
Lunar Sortie DRM

MOON

100 km Low Lunar Orbit

LOI by CPS 1
ΔV = 0.952 km/s

Orbital Maint. by Lander
ΔV = 0.053 km/s

CPS 1

Disposal Orbit TBD

Disposal Orbit TBD

Ascent by Lander
ΔV = 1.968 km/s

7 d at Moon

7 d at Moon

Descent by Lander
ΔV = 2.150 km/s

Plane Change Contingency by MPCV
ΔV = 0.129 km/s

Dock All Elements
(crew transfer)

Dock All Elements
(crew transfer)

Orbital Maint. by MPCV
ΔV = 0.003 km/s per day

RPOD by MPCV
ΔV = 0.032 km/s

EDL

Ascent Stage

Ascent Stage

4 d Transit

TCM burns by MPCV
ΔV = 0.011 km/s

MPCV SRM

MPCV SRM

Lunar Lander
Block 1 CPS 1

Lunar Lander
Block 1 CPS 2

MPCV with Crew
Block 1 CPS 2

Lunar Surface
Mission Duration – up to 7 days
Block 1 CPSs (no LBO)
Lunar Lander requires Low Boil-off

Notes:
• spacecraft icons are not to scale
• ΔV's include 5% FPR
• RCS burns not displayed in chart
• Not all discrete burns displayed

NASA Human Spaceflight Architecture Team (Connolly et al., 2012)
Lunar Destination Activities
The Missing Element

- Human-rated lunar lander (European concept pictured)

- Until this capability is developed, we will be limited to missions with crew in cis-lunar space and robotic lunar surface components
Developing the Human Exploration Elements

- NASA’s SLS and Orion vehicles
- ESA service module
In 2007, The National Research Council published a report called *The Scientific Context for Exploration of the Moon*, which provided NASA with scientific guidance for an enhanced exploration program that would provide global access to the lunar surface through an integrated robotic and human architecture.

The report outlined 3 major hypotheses, identified 8 science concepts, and, within those concepts, it identified 35 specific investigations.

Importantly, the report also prioritized those investigations.
The “BIG” ideas to be explored:

- Giant impact hypothesis for the origin of the Moon
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- Lunar magma ocean hypothesis and fundamental principles of planetary differentiation
- Lunar cataclysm and inner solar system cataclysm hypotheses
Where on the Moon can these objectives be addressed?

Guided, in part, by the 2007 National Research Council report called *The Scientific Context for Exploration of the Moon*,

We conducted a six-year series of summer studies to identify suitable landing sites on the Moon.

Stacking maps of the locations where each investigation could be addressed, we identified sites where a particularly large range of objectives could be addressed at the same time.
• Schrödinger basin on the lunar far side, within the South Pole-Aitken basin, is the location where the largest range of objectives can be addressed.

• For studies of polar volatiles, Amundsen crater may be a better target than Shackleton crater.

• Most of the NRC (2007) objectives can be addressed within the South Pole-Aitken basin on the lunar far side,

• But to truly resolve all of the NRC (2007) objectives, global access to the Moon is required
Schrödinger Basin
w/i the South Pole-Aitken Basin

SPA Image: LRO-LOLA/NASA GSFC SVS
A mission to Schrödinger basin can:

Address the 1\textsuperscript{st} and 2\textsuperscript{nd} highest priorities of the NRC (2007) report plus many more of the other NRC (2007) goals:

1a, 1b, 2a, 2c, 2d,
3a, 3b, 3c, 3d, 3e,
5a, 5b, 5c, 5d,
6b, 6c, 6d, 7a, 7b, 7c

And potentially:
1c, 1d, 4a, 4b, 4c

Background SPA image: LRO-LOLA/NASA GSFC SVS
Schrödinger Basin w/i the South Pole-Aitken Basin

For those reasons, we have focused a lot of attention on Schrödinger basin. It is a very good target for future robotic and human exploration.
Schrödinger Basin
within South Pole-Aitken Basin

Sta 1 = impact melt breccia
Sta 2 = peak ring material
Sta 3 = Antoniadi secondary crater
Sta 4 = pyroclastic deposit
Sta 5 = central melt sheet
Sta 6 = deep fracture

O’Sullivan et al. (2011)
Schrödinger Basin w/i the South Pole-Aitken Basin

Detailed studies by:
- Kramer, Kring, Nahm, & Pieters (Icarus 2013)
- Kumar et al. (JGR 2013)
- Chandnani et al. (LPSC 2013)

Using M³ data, LOLA data, and LROC data.

Peak ring exposures of anorthositic, noritic, and troctolitic rocks

Pyroclastic vent suitable for ISRU

Hurwitz & Kring
Experience suggests

- The best results would be obtained by a trained crew on the lunar surface.

- If crew cannot be delivered to the lunar surface, then significant progress can be made robotically or with an integrated robotic and human architecture (e.g., deploying crew to Earth-Moon L2 above the lunar far side in Orion).
Re-examining the details:

• Our previous landing site study of Schrödinger Basin assumed crew were landing.

• In an integrated robotic and human exploration program that is consistent with the multi-agency Global Exploration Roadmap, we re-evaluated the landing site and stations for a robotic surface asset.

Burns, Kring, Norris, Hopkins, Lazio, & Kasper (2013)
EXAMPLE ROBOTIC TRAVERSE (SITE C)

SITE C
28.8 km, 1 km/hr
13.5 days (total traverse time)

Addresses NRC (2007) priority:
Station 1: 2, 3, 7
Station 2: 2, 3, 7
Station 3: 2, 3, 7
Station 4: 2, 3, 7
Station 5: 2, 3, 5, 7
Station 6: 1, 3, 6, 7
Station 7: 3, 5, 6, 7

Plus ISRU studies in the vicinity of the pyroclastic vent

Gullickson et al. (2014)
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Station 7: 3, 5, 6, 7

Plus ISRU studies in the vicinity of the pyroclastic vent

Gullickson et al. (2014)
These studies have even identified the specific rocks that should be sampled.
EXAMPLE ROBOTIC TRAVERSE (SITE C)

SITE C
28.8 km, 1 km/hr
13.5 days

Average slope: 6.1°
Maximum slope: 15.8°

Where samples can be loaded into the ascent vehicle for return to Earth

Gullickson et al. (2014)
ILLUMINATION - SITE C

- Mission planned 2021
- Optimum period of sunlight = 6\textsuperscript{th} August 2021 - 19\textsuperscript{th} August 2021

Potts et al. (2014)
ILLUMINATION - SITE C

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Potts et al. (2014)
ILLUMINATION - SITE C

- Mission planned 2021
- Optimum period of sunlight = 6th August 2021 - 19th August 2021

Potts et al. (2014)
SOLAR IRRADIANCE - SITE C

- Mission planned 2021
- Optimum period of sunlight = 6\textsuperscript{th} August 2021 - 19\textsuperscript{th} August 2021

Incidence sunlight (i.e., sunlight power on surface)

Potts et al. (2014)
SOLAR IRRADIANCE - SITE C

- Mission planned 2021
- Optimum period of sunlight = 6th August 2021 - 19th August 2021

Incidence sunlight
(i.e., sunlight power on surface)

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SOLAR IRRADIANCE - SITE C

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Incidence sunlight
(i.e., sunlight power on surface)

Potts et al. (2014)
Iron anomaly that has been used to define regions with SPA melt extends into the Schrodinger basin.

Within that region, look for low-Ca pyroxene exposures, which can reflect crystallized SPA melt.

Hurwitz & Kring (2014)
POTENTIAL SCHRÖDINGER & SPA IMPACT MELT DEPOSITS

• Basin walls more likely to host SPA melt
  – Possible exposures of SPA melt
  – Slumped terraces, fallen rocks

• Possible Mission
  – Sample candidate SPA impact melt
  – Compare with Schrödinger melt

Low-Ca pyroxenesis: red and pink
Anorthosite (blue)
Olivine (green)
(Kramer et al. 2013)

Candidate SPA Impact Melt
Schrödinger Impact Melt
Hurwitz & Kring (2014)
POTENTIAL SCHRÖDINGER & SPA IMPACT MELT DEPOSITS

- Basin walls more likely to host SPA melt
  - Possible exposures of SPA melt
  - Slumped terraces, fallen rocks
- Possible Mission
  - Sample candidate SPA impact melt
  - Compare with Schrödinger melt
    - 15–18 km away on plains floor
    - Slope from plains to lower rocks: 5.5°

LOLA topography: 2x vertical exaggeration
An option we have been exploring

Earth-Moon L2 Mission:

- L2 located 60,000 km above the lunar surface
- Orion launched and maneuvered into a halo orbit around L2
- The mission can also be conducted using the DRO architecture

Burns, Kring, Norris, Hopkins, Lazio, & Kasper (2013)
PREPARING FOR HUMAN ASSISTED SAMPLE RETURN (PER THE GER)

Exploration risk reduction:

• Demonstrate Orion in deep space and high speed Earth-entry

• 30 to 35 day mission into trans-lunar space

• Crew will travel 15% farther than Apollo and spend 3 times longer in deep space

• Practice tele-operation of rovers

Burns, Kring, Norris, Hopkins, Lazio, & Kasper (2013)
PREPARING FOR HUMAN ASSISTED SAMPLE RETURN (PER THE GER)

Science objectives:

- Land and explore a region within SPA (for example, Schrödinger Basin)
- Geologic measurements will be made.
- A sample will be collected and returned to Earth.
- An astrophysical system will be deployed.

Status: Integrated science and engineering studies continue.

Burns, Kring, Norris, Hopkins, Lazio, & Kasper (2013)
Science objectives:

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Burns, Kring, Norris, Hopkins, Lazio, & Kasper (2013)
An Orion mission to Earth-Moon L2 is a feasible alternative to DRO for tele-robotics missions.

A large area of the lunar farside is continuously visible from a compact L2 halo orbit.

Even in limb sites like Schrödinger Basin there are areas where communication to the halo orbit can last from dawn to dusk.

LRO and Clementine imagery courtesy NASA and NRL

Lockheed Martin (courtesy of Josh Hopkins)
TRAJEKTORY FOR SAMPLE CAPTURE IN EARTH-MOON L2

Lockheed Martin (courtesy of Josh Hopkins)

Depart from Free Return

Orion Trajectory

Ascent Trajectory

Periods when Orion has line-of-sight to landing site in the center of SPA Basin are shown in green.

Combined Trajectory by JPL
Periods when Orion has line-of-sight to landing site at Schrödinger Basin pyroclastic vent are shown in green.

Trajectory is compatible with Orion delta-V and duration capabilities.
Telerobotic rover has 11 day operating duration with one telecom gap of ~1.5 days when Orion is not visible.
TRAJECTORY FOR SAMPLE CAPTURE IN DRO FROM SPA BASIN

Periods when Orion has line-of-sight to landing site in the center of SPA Basin are shown in green.

Orion Trajectory

Target DRO

Orion DRO

Depart from Free Return

Rendezvous and Capture

SRV DRO Insertion

EM-L1

EM-L2

Orion DRO Insertion

Sample Ascent

Lockheed Martin (courtesy of Josh Hopkins)
SAMPLE CAPTURE MISSION TIMELINE COMPARISON

Lockheed Martin (courtesy of Josh Hopkins)
PREPARING FOR HUMAN ASSISTED SAMPLE RETURN (PER THE GER)

Additional options:

• Deploy a communication satellite from Orion to support additional surface activity after crew returns to Earth

• If long-term station-keeping by crew is implemented in an L2 or distant retrograde orbit (DRO), then additional tele-ops can be conducted with the first rover and potentially other landed assets.
Conclusions

Schrödinger basin is one of the highest priority landing sites based on a global assessment of the NRC (2007) objectives

It can be used to test the

- Lunar Cataclysm Hypothesis
- Lunar Magma Ocean Hypothesis

It can provide ISRU resources

- Pyroclastic deposits
- & potentially volatile-rich deposits

The Moon is the best and most accessible place in the Solar System to answer fundamental planetary science questions.