A LUNAR L2-FARSIDE EXPLORATION AND SCIENCE MISSION CONCEPT WITH THE ORION MULTI-PURPOSE CREW VEHICLE AND A TELEOPERATED LANDER/ROVER

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A novel concept is presented in this paper for a human mission to the lunar L2 (Lagrange) point that would be a proving ground for future exploration missions to deep space while also overseeing scientifically important investigations. In an L2 halo orbit above the lunar farside, the astronauts would travel 15% farther from Earth than did the Apollo astronauts and spend almost three times longer in deep space. Such missions would validate the Orion MPCV's life support systems, would demonstrate the high-speed re-entry capability needed for return from deep space, and would measure astronauts' radiation dose from cosmic rays and solar flares to verify that Orion would provide sufficient protection, as it is designed to do. On this proposed mission, the astronauts would teleoperate landers and rovers on the unexplored lunar farside, which would obtain samples from the geologically interesting farside and deploy a low radio frequency telescope. Sampling the South Pole-Aitkin basin (one of the oldest impact basins in the solar system) is a key science objective of the 2011 Planetary Science Decadal Survey. Observations of the Universe's first stars/galaxies at low radio frequencies are a priority of the 2010 Astronomy & Astrophysics Decadal Survey. Such telerobotic oversight would also demonstrate capability for human and robotic cooperation on future, more complex deep space missions.

I. INTRODUCTION

The Moon's farside is a possible early goal for missions beyond Low Earth Orbit (LEO) using the Orion Multi-Purpose Crew Vehicle (MPCV) to explore incrementally more distant destinations. The lunar L2 Lagrange Point is a location where the combined gravity of the Earth and Moon allows a spacecraft to be synchronized with the Moon in its orbit around the Earth, so that the spacecraft is relatively stationary over the farside of the Moon (Fig. 1).

The farside has been mapped from orbit but no humans or robots have ever landed there. There are two important science objectives on the farside. The first would be to return to Earth multiple rock samples from the Moon's South Pole–Aitken (SPA) basin, one of the largest, deepest, and oldest impact basins in the solar system. A sample return from SPA was designated as a priority science objective in the NRC Decadal Survey *Vision and Voyages for Planetary Science in the Decade 2013-2022* [1]. The second objective would be to deploy a low radio frequency telescope on the farside where it would be shielded from human-generated radio frequency interference (RFI) from the Earth, allowing astronomers to explore the currently unobserved *Dark Ages* and *Cosmic Dawn* of the early Universe. These observations were identified as one of the top science objectives in the NRC Decadal Survey *New Worlds, New Horizons in Astronomy and Astrophysics* [2]: "Cosmic Dawn: Searching for the First Stars, Galaxies,

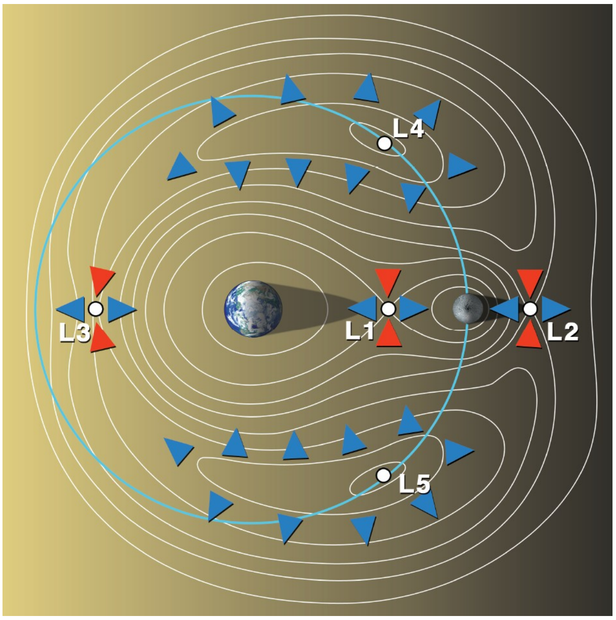

Fig. 1: The Lagrange Points for the Earth-Moon system. We propose an early mission with Orion placed in a halo orbit at Earth-Moon L2. Astronauts would teleoperate robots on the lunar farside to gather samples from ancient impact craters and deploy a low frequency array of radio antennas to observe the first stars and galaxies in the early Universe.

and Black Holes." Thus, this proposed mission would fulfill some of the top science goals of *both* the Planetary Sciences and Astrophysics Decadal Surveys.

The robotic lander and rover would be launched first on a slow but efficient trajectory to the Moon, to ensure that the rover is on its way before the crew is launched. Next, three astronauts would be launched in an Orion spacecraft using NASA's heavy-lift Space Launch System (SLS). Orion would fly past the Moon for a gravity slingshot maneuver towards the L2 point. Orion would use its propulsion system to enter a halo orbit around the L2 point. From this vantage point 64,000 km above the farside of the Moon, Orion would have continuous line-of-sight visibility to both the entire farside of the Moon, and the Earth (Fig. 2).

This paper begins with a more detailed overview of the Orion MPCV L2-Farside mission concept in Section II. In Section III, a landing site is proposed for the robotic lander/rover on the farside – the Schrödinger crater that lies within the South Pole-Aitken basin. The scientific advantages of this young impact basin are described. In Section IV, a discussion of the geological telerobotic exploration of the Schrödinger crater is presented. In Section V, the deployment of a roll-out polyimide, low frequency antenna array is described along with the science goals that include measurements of the lunar ionosphere, interplanetary nanoscale dust, and detection of the first stars and galaxies via redshifted 21-cm radiation from neutral hydrogen. A summary of this mission concept is given in Section VI.

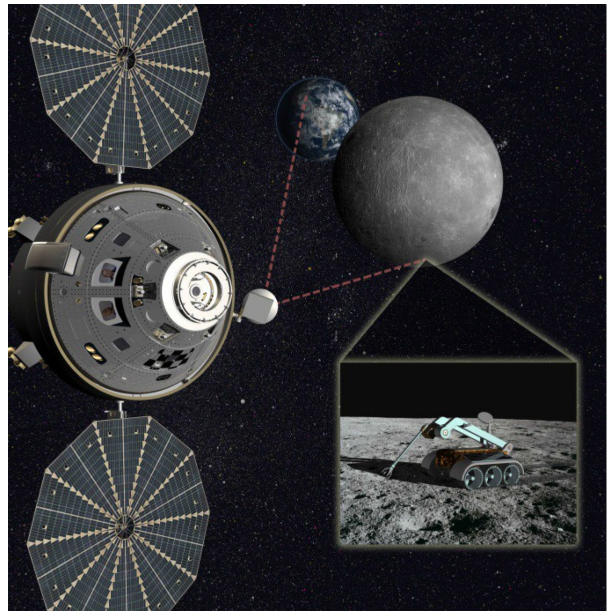

Fig. 2: Schematic picture of the Orion MPCV L2 mission where astronauts teleoperate a rover on the lunar farside.

II. THE ORION MPCV L2-FARSIDE MISSION CONCEPT

II.I Overview

The Orion Multi-Purpose Crew Vehicle (MPCV) spacecraft has core capabilities that will enable the L2-Farside mission since the MPCV was designed from its inception to support lunar missions.

Orion consists of four major elements, shown in Fig. 3. The Launch Abort System (LAS) at the top is designed to pull the spacecraft away from launch vehicle in the event of an emergency during ascent. The conical Crew Module (CM) contains the pressurized living space for the astronauts, as well as most of the vehicle avionics. The CM returns the crew to Earth, using a heat shield and parachutes. The CM also has a docking adapter at the top to connect to other spacecraft. Below the CM is the Service Module (SM), which provides most of the utility functions on the spacecraft. It contains the propellant tanks and main engine for propulsion, the tanks of water and oxygen for life support, solar arrays for power, a thermal control fluid loop with radiators to cool the capsule, and a phased array antenna for long distance communication. A Spacecraft Adapter connects Orion to its launch vehicle. External jettisoned panels cover the solar arrays, radiators, and thrusters during ascent.

Orion has all the necessary capabilities to operate in deep space and for a long duration, such as solar arrays for power generation, regenerative amine beds rather

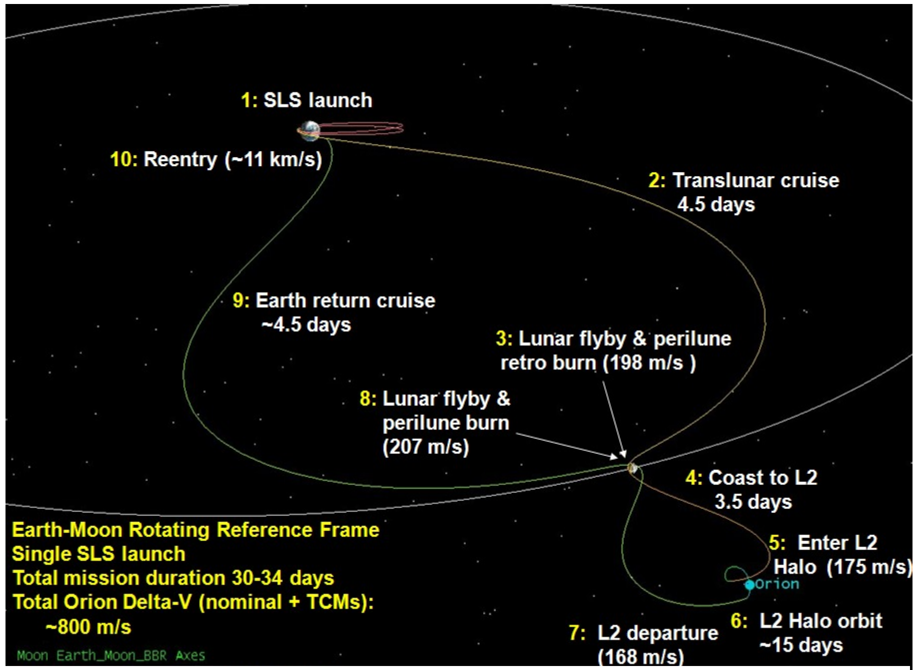

Fig. 4: The L2-Farside mission can be performed using a single SLS, along with the Orion MPCV.

Fig. 3: The Orion MPCV spacecraft. From top: LAS, CM, SM, Spacecraft Adapter.

than single-use lithium hydroxide canisters to remove CO_2, and the design robustness necessary to ensure the vehicle withstands Micro-Meteoroids and Orbital Debris (MMOD) impacts. These capabilities allow Orion to meet the needs of lunar missions and provide sufficient performance for the mission. Table 1 highlights several of the Environmental Control and Life Support Systems (ECLSS) along with the technology that supports the function.

II.II Mission Concept

The L2-Farside mission concept would send astronauts in the Orion to the second Earth-Moon Lagrange point, a location where the combined gravity of the Earth and Moon allows a spacecraft to be synchronized with the Moon in its orbit around the Earth, so that appears to hover over the farside of the Moon (Fig. 1). Prior to this proposed mission, the Orion will undergo several development tests to ensure crew safety and mission viability. The first Exploration Flight Test (EFT-1) is scheduled for 2014 to verify the crew module can survive high speed re-entry into the earth's atmosphere from a Lunar return trajectory. Three additional test flights are planned for the Orion and include a high altitude abort, an un-crewed flight around the moon in 2017, and a crewed flight soon after that.

The proposed mission to explore the Moon's farside would be performed using a heavy lift launch vehicle, the Space Launch System (SLS), under development by NASA and the Orion configuration designed for lunar missions.

A robotic lander and rover would be launched first. Next, three astronauts would be launched in the Orion MPCV (Fig. 4). Orion is designed to carry up to four astronauts, but reducing the crew to three for this mission provides each person with more living space in the Crew Module. The Orion MPCV would fly past the Moon for a propulsive gravity slingshot maneuver towards the L2 point, where it would use its propulsion system to enter into a halo orbit around the Lagrange point. The total transfer time to L2 does increase by a few days with a lunar swing-by compared to a direct trajectory but the ΔV savings are substantial enough to justify the additional trip time. A trajectory that has a total transfer time from Earth to L2 of approximately 8 days has been developed.

Function	Technology
CO_2 and H_2O control	Solid amine bed
O_2 provision & pressure control	O_2 and N_2 tanks with total pressure and oxygen sensors
Fire detection & suppression	Smoke detectors and nitrogen suppression
Food provision	Prepackaged food
Waste management	Toilet with fecal collection containers and urine venting
Water management	Water tanks

Table 1: Orion ECLSS architecture.

At L2, approximately 64,000 km above the farside of the Moon, the Orion would have continuous line-of-sight visibility to both the entire lunar farside and the Earth. Astronauts could operate a rover on the lunar surface and stay in contact with mission control at the same time, orbiting the L2 point for about two weeks—long enough to operate a rover through the full length of a lunar day.

The Moon is close enough to Earth that rovers could be controlled from Earth using a simple relay satellite. However, controlling the rovers from an orbiting spacecraft like Orion would be useful practice for future Mars missions. As envisioned by the Augustine Committee, the first human missions to Mars may not attempt the difficult step of landing on the surface, but may instead orbit Mars and control robot rovers on the surface [3]. This may be more effective than controlling the rovers from Earth, because Mars is so far away that the speed-of-light delay slows down operations. The lunar L2-Farside mission would develop and implement operational methods for this type of joint human/robot exploration. In particular, it would address how much control and decision-making should be executed by the handful of 'on-site' astronauts in a spacecraft and what would be done by the larger staff, with more resources, at a distant mission control center.

II.II.I Mission Duration

The Orion was designed to original Constellation architecture requirements, which specified that the vehicle had to support four astronauts for 21 days going to and from the Moon, with a 180-day unoccupied period in lunar orbit, plus 30 days of contingency loiter capability for a mission extension. Although the standard crewed duration of 21 days is shorter than the 30-35 days required for this mission, it could be easily increased by adding one extra water tank and using larger diameter oxygen storage tanks. This would provide enough supplies to get to L2, stay for a 14 day lunar daylight cycle, and return. If multi-month stays at L2 are desired, more living space and supplies would be required. Lockheed Martin has collaborated with international industry partners to investigate how derivatives of vehicles currently used to supply the International Space Station could be delivered to L2. Orion could dock to one of these vehicles to take advantage of additional supplies and living space.

II.II.II Propulsion

The Orion is equipped with a main engine burning MMH and N_2O_4 propellants. The propellants are space-storable and the propulsion system is capable of multiple restarts, providing significant mission flexibility. The propellant tanks on Orion were based on original Constellation work for worst-case lunar landing site locations, lunar orbital geometries, and abort requirements, based on analysing more than 2 million different trajectory cases. All together, the Orion propulsion system provides a critical required capability.

The Orion main engine thrust level of 33 kN (7500 lbf) is driven by ascent abort requirements. During a launch abort late in ascent during ISS missions, Orion is required to have sufficient thrust to push its landing point away from the middle of the North Atlantic Ocean and either back towards Newfoundland or downrange to Ireland in order to ensure that the crew lands within range of land-based rescue forces. This thrust level required is greater than the thrust level required to adjust the trajectory prior to reorienting for re-entry as well as in-space maneuvers.

II.II.III Re-entry

Orion is capable of re-entry at just over 11 km/s inertial velocity. Orion is also designed to reach a coastal landing zone near San Diego at any time in the lunar cycle, in order to reduce the cost of recovery operations. Depending on the position of the Moon, this sometimes means that Orion must perform a skipping re-entry to reach the landing site, which increases the total heat load during re-entry.

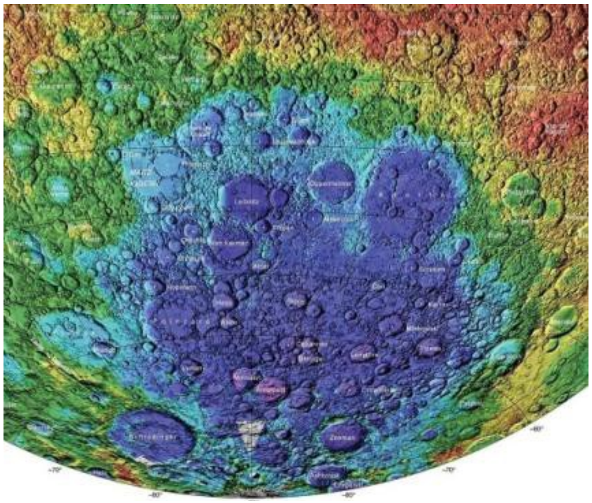

Fig. 5: False-colored topography of the southern lunar farside highlighting the 13 km deep South Pole-Aitken basin (blue colors) and the surrounding highlands (yellows and reds). Schrödinger basin (also blue) is in the lower left portion of the South Pole-Aitken basin and lies within 500 km of Shackleton crater at the lunar south pole.

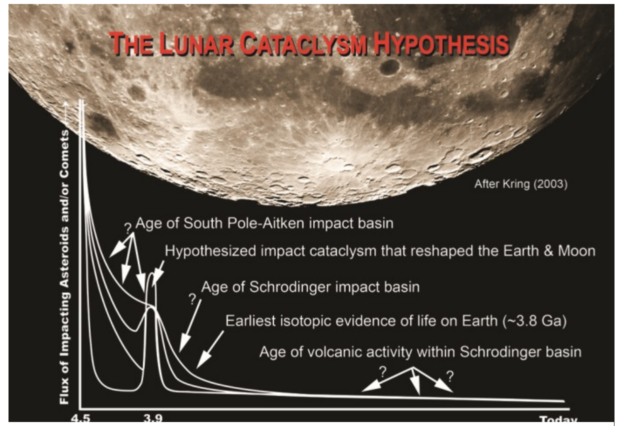

Fig. 6 : Schematic diagram illustrating the evolution of the impact flux to the Earth and Moon as a function of time from 4.5 billion years ago to the present day. Following the accretion of the Earth and Moon, the impact flux declined at a still unknown rate (illustrated with multiple curves). Apollo samples suggest there was a surge in the impact rate circa 4 billion years ago. The South Pole-Aitken basin represents the oldest basin-forming event and the Schrödinger basin represents the second youngest basin-forming event. Soon after that period of bombardment, we find the earliest isotopic evidence of life on Earth. Diagram modified from Kring [5].

III. THE SCHRÖDINGER IMPACT BASIN

Impact craters larger than 300 km on the Moon are called basins to highlight their vast size and dramatic topography. Basins have broad flat floors, an uplifted peak ring, and a series of collapsed blocks of the Moon's crust that slumped inward from the basin rims during the final phase of their formation. Schrödinger basin is the best preserved impact basin of its size on the Moon and provides tremendous science and exploration opportunities, safe landing zones, and a landscape that could be navigated by robotic assets. The basin lies on the lunar farside, is centered at 75° south, 132.4° east, and was produced within the immense South Pole-Aitken basin (Fig. 5), which is a primary target for investigations outlined by the National Research Council [1,7]. The 320 km diameter structure is ~4 km deep and hosts a 150 km diameter inner peak ring that rises up to 2.5 km above the basin floor. The east, west, and south sides of the basin are ~200, ~245, and nearly 310 km from the limb of the Moon. A landing site on the relatively flat floor of the basin interior would be comfortably 350 to 450 km from the limb(s).

Schrödinger has been mapped as Imbrian in age (≈3.8 billion years old) based on the number of craters superposed on the basin and its corresponding ejecta blanket [9,10]. It is the second youngest basin and, thus, one of the last basins to have formed during the intense basin-forming impact period that re-shaped planetary surfaces throughout the inner solar system before 3.8 billion years ago (Fig. 6). Not only does Schrödinger reflect evolutionary processes occurring at that time, its basin walls and uplifted peak ring contain rock from older episodes in lunar history. In addition, long after the basin was produced, magmas rose beneath the crater floor and produced small eruptions of volcanic material that may be less than 1 billion years ago. Thus, collectively, missions to Schrödinger basin would be able to access rock produced over a very broad fraction of the Moon's history.

IV. TELEROBOTIC GEOLOGICAL INVESTIGATION OF THE LUNAR FARSIDE

IV.I Lunar Surface Science Priorities

A particularly attractive lunar farside location is Schrödinger basin, where the first and second highest priorities in the NRC report *The Scientific Context for Exploration of the Moon* [7] and over half of the remaining goals in that report could be fulfilled. Because it lies within the South Pole-Aitken basin, it is also a featured target of the NRC Decadal report *Vision and Voyages for Planetary Science in the Decade 2013-2022* [1].

The highest science priority is to test the lunar cataclysm hypothesis, which suggests the Earth and Moon were severely modified by a swarm of asteroids circa 3.9-4.0 billion years ago. The concept of an impact cataclysm emerged from analyses of samples

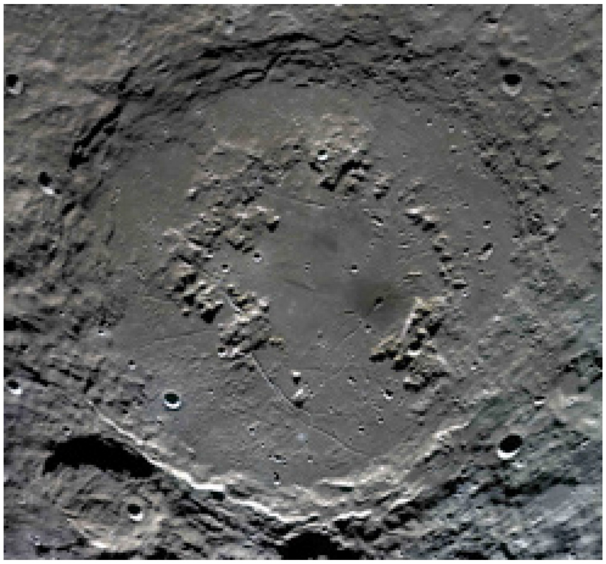

Fig. 7. An image of the ~320 km diameter Schrödinger basin. The relatively flat floor is covered with solidified impact melt that could be sampled to determine the age of the basin. An uplifted peak provides outcrops of rock from the lunar magma ocean. Two dark-colored regions within the crater are volcanic deposits that erupted more recently and provide evidence of magmatic processes deep within the lunar interior.

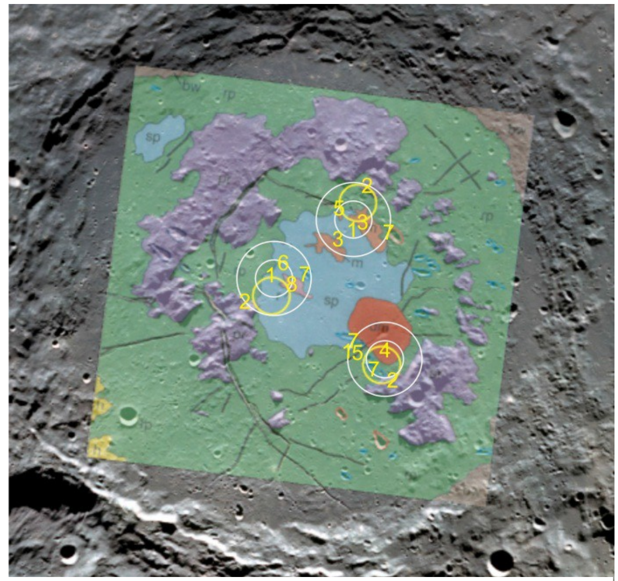

Fig. 8 : Three potential landing sites and stations developed by O'Sullivan et al. [8]. The landing sites would provide access to impact melt lithologies (in all cases), uplifted samples of the lunar magma ocean (in all cases), mare volcanism (in one and possibly two cases), and pyroclastic volcanism (in one case). Yellow circles represent 10 km diameter region in which all lithologies exist. White circles, centered around prefered landing sites, represent 10 and 20 km radial distances. Geologic units were mapped by Shoemaker et al. [9].

collected by Apollo astronauts. All of those samples, however, were collected in a relatively small region of the Moon (representing less than 5% of the surface) and none of them provide any information about events on the lunar farside, which remains a completely unexplored region.

To evaluate that hypothesis, it is critical that the ages of basins be measured to determine the magnitude and duration of the basin-forming epoch. Among the most important targets is Schrödinger basin, which represents the type of impact activity that occurred immediately prior to the earliest evidence of life on Earth (Fig. 7).

The second highest priority is to determine the age of the oldest basin-forming event to anchor the beginning of the basin-forming epoch. The oldest (and largest) basin is the South Pole-Aitken basin. Because Schrödinger formed within the South Pole-Aitken basin, samples of the latter will exist within Schrödinger. Thus, in one geologic terrain, samples for both the oldest and the second youngest basins could be collected, essentially bracketing the entire basin-forming epoch.

In addition to solving the two highest priority chronological problems, those same impact melt samples could be used to determine the source of projectiles and their chemical compositions. Some models suggest comets are responsible, while others suggest asteroids are responsible. That data would, in turn, provide the information needed to test proposed mechanisms for the impact flux, some of which include dramatic shifts in the orbits of the giant planets. These data could also be used to calculate the delivery of biogenic elements and any environmental consequences produced by the bombardment, which have been tentatively linked to the origin and early evolution of life on Earth. If the sample collection system were mobile with sufficient range, then sampling of melts from other craters and basin-forming events may also be possible.

Schrödinger basin would an excellent probe of the lunar interior. Normal faults in the modification zone of the basin expose subsurface lithologies and their stratigraphic relationships. The uplifted central peak ring exposes even deeper levels in the Moon's crust and directly taps rocks produced within the lunar magma ocean [4,11]. Furthermore, clasts of subsurface lithologies were excavated and entrained in impact melt breccias deposited within the crater. Thus, by combining observations of the modification zone, central uplift, and impact breccias, one can generate a cross-section of the lunar crust several 10's of kilometers deep. The volume of material beneath the impact site that was melted extends to nearly to the base of the Moon's crust. Because that melt was well-mixed, samples of it would provide an average chemical composition of entire crust of the south polar region of the Moon. Consequently, while collecting samples to determine the impact flux to the lunar surface, one would also be collecting samples of the lunar interior.

The combination of impact and volcanic samples of different ages would provide the data needed to calibrate the crater counting chronology used to determine the ages of surfaces around the entire Moon.

IV.II Landing Sites

Specific landing sites are being studied to facilitate the objectives defined above [8]. To illustrate the feasibility of landed surface operations, we step through those landing sites here (Fig. 8). However, additional studies [4,6,11] are providing higher fidelity views of the interior of the basin and will need to be incorporated into a new landing site study that features the capabilities of robotic assets.

The first proposed landing site explored occurs on the northern portion of the central melt sheet, which provides a relatively smooth surface for landing. A sample of the Schrödinger impact melt could be collected at the landing site and secured for return to Earth. From that location, a rover could access two mare-type volcanic deposits to determine the source of the lavas in the lunar interior and to provide an age of the eruptions. Faults and fractures could also be accessed. Those tectonic features and much younger small craters that puncture the melt sheet could be used to evaluate the amount of chemical and mineralogical differentiation that occurred. If one could expand the mobility from 10 to 20 km, then one could also access samples of the lunar magma ocean in the central peak ring. Small craters along the way were produced by blocks of rock ejected from the Orientale basin; if remnants of those blocks could be found, then samples of the far western portion of the moon could also be collected.

The proposed second landing site is located on the central melt sheet in the western part of the inner basin. A rover deployed from this location could collect samples of that melt before exploring an intriguing ridge whose origins are unclear, all within 10 km. If mobility was extended to 20 km, then the rover could access the peak ring and its samples of the lunar magma ocean. Some of the small craters in this region appear to have been produced debris from Antoniadi crater; if any remnant debris is found, it would provide samples of yet another part of the Moon.

The third proposed landing site is located on an impact melt-bearing breccia, rather than the central melt sheet. Thus, landing and surface operations may be more challenging here than at the other two sites. However, this landing site would provide access to a dramatic pyroclastic vent that distributed the types of materials targeted for future ISRU purposes. That vent is located ~8 km from the proposed landing site. That vent is also very deep and produces a permanently shadowed region, thus providing an opportunity to study lunar volatile issues. Dramatic graben occur in the vicinity of the vent that could be used to study both the magmatic and tectonic history of the region.

IV.III Lunar Surface Operations

This mission concept is designed to produce high-quality science while testing operational ideas that would feed forward into future exploration activities elsewhere on the Moon, asteroids, the moons of Mars, and the surface of Mars. When the crew arrive on station in a halo orbit about the Earth-Moon L2 position, a lander with a rover would already have been deployed within Schrödinger basin. A pre-planned traverse with geologic stations would have also been developed by the mission's science team. From the L2 location, crew would then implement that traverse sequence using telerobotic commands from the Orion platform. Based on their observations during the traverse, crew may need to modify the pre-mission plan to successfully accomplish mission objectives. All activities would be monitored in nearly real time by the Mission Operations Center and Science Operations Center in Houston, because Orion could relay the video and command sequences from the lunar farside in an E-M L2 spacecraft configuration. Consultation between crew and the Science Operations Center could also be implemented during the traverse as needed.

The primary objective of the surface activities would be to collect samples for return to Earth and document the geologic context of those samples. Because high precision analyses would be conducted on Earth, the amount of instrumentation on the rover could be minimized. An imaging system would be needed for navigation, station context, and sample documentation. That system should have a dynamic range for operations under a variety of lighting conditions. Supplemental illumination for shadowed and/or nighttime operations may also be needed. Mechanical devices like an arm with grappling capability would be required for sample collection and potentially trenching. If the mission is designed to reduce the risk for future long-duration human exploration missions, then a radiation monitor may be deployed and, at some point, potentially buried beneath regolith for in-situ testing of radiation shielding by the regolith. Long term monitoring of surface conditions may be possible, if a communication relay asset is left in the L2 location when the crew returns to Earth. Schrödinger basin is also sufficiently large and geologically interesting to provide multiple mission opportunities that would test a variety of operational scenarios while generating high-priority science results.

At the end of the traverse activities, the rover would return to the lander, transfer samples to the ascent vehicle, and then retreat to a safe stand-by distance from where its imaging systems could capture the ascent and monitor any dust pluming created by that ascent. If the rover is configured with an Advanced Stirling Radioisotope Generator or otherwise has a nighttime survivability mode, post-sample return operations may also be possible.

Earth-based telerobotics have previously been demonstrated with the Lunakhod on the Moon and Pathfinder, Spirit, and Opportunity on Mars. This would, however, be the first demonstration of telerobotic operations on a planetary surface from a space-based platform. The crew would need to have significant geologic training to conduct the operations [e.g., 12]

In summary, in-situ geologic reconnaissance with a return of samples to Earth from the Schrödinger basin could tackle the first and second highest priorities of the NRC [7] report. Of the eight concepts identified in that report, seven of them could be addressed within the basin and over twenty of the reports objectives could be considered. For these reasons, the Schrödinger basin is arguably the highest priority landing site on the lunar surface.

V. A LOW RADIO FREQUENCY TELESCOPE ON THE LUNAR FARSIDE

V.I The Radio-Quiet Farside

At radio frequencies <100 MHz, the lunar farside is the only location in the inner solar system that is free of human-generated radio frequency interference (RFI). Both the Radio Astronomy Explorer-2 (RAE-2) [13] and the Apollo Command Modules, which had RF systems at low radio frequencies, observed complete cessation of emissions from Earth when they passed into the radio-quiet zone above the lunar farside. This contrasts with observations from the ground or Earth orbit where both RFI and the Earth's ionosphere seriously interfere with astronomical observations (Fig. 9). Thus, the lunar farside is ideal for observations and experiments at radio low frequencies.

We have investigated the electromagnetic (EM) environment of the Schrödinger basin on the lunar farside by running an EM wave propagation simulation tool (developed by Y. Takahashi) based on a finite-difference time-domain (FDTD) method [14]. We examined low frequency diffraction effects from Earth-based RFI around the Moon's limb and in the crater as well as the impact of the electrical properties of the lunar surface. The initial results from our simulations

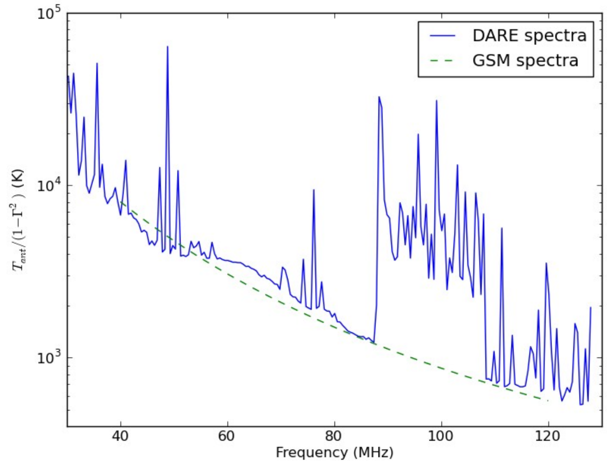

Fig. 9: Recently measured radio spectrum over most of the frequency range relevant for Cosmic Dawn observations. The ordinate axis is antenna temperature ($P=kT_{ant}\Delta\nu$, where P is the power measured by the radio receiver, k is Boltzmann's constant, and $\Delta\nu$ is the frequency bandwidth). This spectrum was acquired in the National Radio Quiet Zone surrounding the Green Bank site of the National Radio Astronomy Observatory. Note the saturation by RFI in the FM radio band (88–108 MHz). The undulating baseline at frequencies below about 80 MHz is due partially to the effects of the Earth's ionosphere. The green dashed line is the expected radio emission from the Milky Way.

indicate that incoming RFI EM waves experience $\gtrsim$ 80 dB attenuation before it reaches the crater interior. In order to detect faint cosmological signals described in Section V.II.III, this attenuation is sufficient to establish the Schrödinger basin as a potential location for the proposed radio array. Currently, we are further developing this existing toolbox to carry out detailed, high resolution simulations of the lunar farside for incident EM waves $\gtrsim$10 MHz.

V.II Polyimide Film Antennas Deployed on the Lunar Surface

We have developed a novel approach for the deployment of large numbers of radio antennas on the lunar surface using polyimide film as a backbone. Polyimide film is a flexible substance with a substantial heritage in space flight applications. In this concept, a conducting substance is deposited on the polyimide film to form the antenna. The film would be rolled for storage in a small volume during transport. Once on the Moon, the polyimide film would be unrolled to deploy the antennas. The antennas would then be electronically phased to produce a radio interferometer where the angular resolution (θ) depends upon the wavelength (λ) and maximum distance between dipoles (D) such that $\theta \sim \lambda/D$.

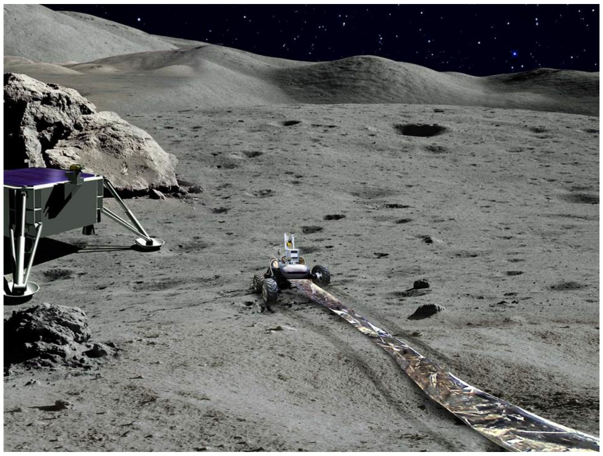

Fig. 10: Artist's impression of a telerobotically-operated rover deploying a polyimide film-based antenna. The lander that would carry the rover and antenna array to the surface is visible to the left.

The film would also contain the transmission line system for conducting electrical signals back to the central node at the intersection of the arms. A central processor would provide digitization and filtering, and then would downlink the data to the MPCV for transmission to Earth.

We have undertaken two tests of metal-coated polyimide films in the field and in the lab [15]. First, a test was conducted to assess the electrical performance of such an antenna. The feed point impedance of a single polyimide film antenna lying directly on the ground has been measured as a function of a wide radio frequency range. Good agreement has been found with computer simulations, and, in one set of tests, absorption of the received power levels was consistent with that expected from the Earth's ionosphere. Second, using a vacuum chamber at U. Colorado, we simulated the lunar environment in which the polyimide film is to be placed. The chamber contained a UV lamp to simulate solar radiation on the Moon and the table upon which polyimide film was placed was thermally cycled between equivalent lunar day (100 C) and night (-150 C) temperatures. No significant stiction was detected in the cycled polyimide film. No changes in the tensile strength, electrical conductivity, or flexibility were measured beyond the 5% level after repeated thermal cycling and UV exposure indicating that the polyimide film is an excellent choice for low frequency antenna backbone material.

We propose to deploy the polyimide film antenna array using a single rover that would emerge from a robotic lander. The rover would be teleoperated by astronauts aboard the Orion MPCV at L2. Fig. 10 illustrates this rover deployment strategy. A teleoperated rover deployment of polyimide film antennas would offer the opportunity for real-time visual inspection of flaws via high definition video and rapid decisions on replacement or redeployment of damaged components to ensure the viable operation of the radio array. Most importantly, this would demonstrate the feasibility of telerobotic deployment of large structures at remote locations in the solar system including, in the future, Mars and asteroids.

V.II The Science Program for a Farside Low Frequency Radio Array

V.II.I Measurement of the Lunar Ionized Atmosphere

The lunar atmosphere is the exemplar and nearest case of a surface boundary exosphere for an airless body in the solar system, and the recent Planetary Sciences Decadal Survey [1] noted the importance of tracking the evolution of exospheres, particularly in response to the space environment. Determining and tracking the properties of the lunar atmosphere both robustly and over time requires a lunar-based methodology by which the atmosphere could be monitored over multiple day-night cycles from a fixed location(s), such as a lunar relative ionosphere opacity meter (*riometer*).

Reviews of the state of knowledge of the lunar atmosphere at the close of the Apollo era indicate significant advances in knowledge of the composition, sources and sinks, and influences on the lunar atmosphere but also significant questions about all of these topics [e.g., 17,18]. Exposed to both the solar and interstellar radiation fields, the daytime lunar atmosphere is mostly ionized. Enduring questions include the density and vertical extent of the ionosphere and its behaviour over time, including modification by robotic or crewed landers.

ALSEP measurements during the Apollo missions found a photoelectron layer near the surface with electron densities up to 10^4 cm^{-3} [19]. Further, dual-frequency radio occultation measurements from the Soviet Luna spacecraft suggest that the ionosphere's density is both highly variable and can extend to significant altitudes, exceeding 10^3 cm^{-3} well above 10 km (Fig. 11). However, the interpretation of the Luna data is model dependent, as Bauer [20] concluded that the Luna data were consistent with no significant lunar ionosphere.

In addition to an ion or molecular component to the plasma layer above the Moon's surface, there are reports of a "horizon glow" from both crewed and robotic missions [e.g., 21,22]. There is widespread agreement that this "horizon glow" is likely due to electrostatically charged dust that is levitated above the surface. Such a component would also contribute free electrons to the atmosphere.

More recently, there have been a series of spacecraft-based remote sensing efforts to measure the lunar ionosphere. Pluchino et al. [23] performed dual-

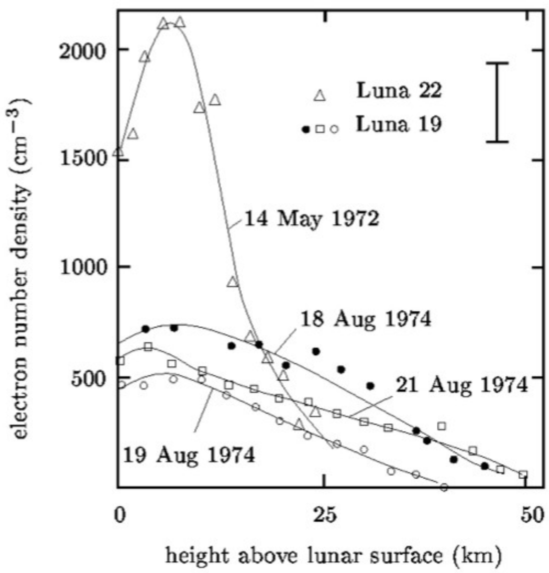

Fig. 11: Lunar ionosphere electron densities derived from dual-frequency radio occultation measurements during the Luna 19 and Luna 22 missions [16].

frequency (2200 and 8400 MHz) lunar occultation observations of the SMART-1, *Cassini*, and Venus Express spacecraft. One of the experiments on the Japanese SELENE (KAGUYA) mission used a series of dual-frequency measurements (at 2200 and 8500 MHz) in an effort to detect the lunar ionosphere [24]. In general, an increase in the electron density on the solar illuminated side of the Moon has been observed, consistent with the expectations for the presence of a lunar ionosphere.

The principle underlying *relative ionospheric opacity measurements* (riometry) is that the refractive index of a fully or partially ionized medium (plasma) is a function of frequency and becomes negative below a characteristic frequency known as the *plasma frequency*. At frequencies below the plasma frequency, an electromagnetic wave cannot propagate through the medium and is reflected upon incidence. The plasma frequency is given by $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ where n_e is the electron density, e is the charge on the electron, and m_e is the mass of the electron. With $\omega_p = 2\pi\upsilon_p$, and substituting for physical constants, $\nu_p = 9\ \mathrm{kHz}\,(n_e/1\ \mathrm{cm}^{-3})^{1/2}$.

A riometer exploits this characteristic of a plasma to measure the ionospheric density. If a broadband reference emitter with a known spectrum is observed through the ionosphere, the ionosphere's plasma frequency, and in turn the (peak) ionospheric density, can be determined from the frequency at which absorption occurs. By monitoring the plasma frequency, a riometer can track changes in the ionospheric density over time. In practice, the most commonly used reference emitter is the non-thermal radio emission from the Milky Way Galaxy. This Galactic emission has the favorable properties of being both extremely well characterized and constant in time.

Riometers have been used for decades, in remote and hostile environments, for tracking the properties of the Earth's ionosphere. Only a few antennas are needed for a riometer, and deploying such would serve as an initial demonstration of the technologies en route to the deployment of a larger array. In addition to basic lunar science, riometer measurements would support lunar exploration by tracking the modification of the lunar atmosphere by exhaust from the sample return rockets and future landers.

V.II.II Measurement of Interplanetary Nanodust

Interplanetary space is pervaded by dust with sizes ranging from nanometers to tens of microns and larger. Recent work on interplanetary dust has revealed a substantial population of nanometer-size dust, or nanodust, with fluxes hundreds of thousands of times higher than better understood micron-sized dust grains. This nanodust tends to move with the speed of the solar wind, or at hundreds of km/sec, as opposed to more typical Keplerian speeds of tens of km/sec. Since impact damage grows faster than the square of the impact speed for high speed dust, this nanodust can generate significant damage when it impacts an object such as a spacecraft, or a planet, or the Moon, or an asteroid. In this section, we describe how a low frequency radio array is ideal for measuring the distribution of dust particles as a function of size in interplanetary space, and ultimately for understanding how dust modifies the surfaces of planets and other objects in the solar system.

Dust has many sources, including collisions between asteroids, escaping gas from comets, and condensation within the solar atmosphere. Additional dust streams into the solar system from interstellar space. The size, speed, and mass distribution of dust in interplanetary space and its variation with time tell us about the history of these sources. Measurements of dust properties have been performed with dedicated dust instruments specifically designed to characterize dust particles [25]. More recently, it has been shown that space-based radio receivers can also be used to measure dust. These radio instruments function by measuring the electrical signals produced when dust grains impact objects at high speed and create expanding clouds of plasma [e.g., 26,27 and references therein]. Work on the use of radio receivers for studying dust have shown that radio observations have two particular strengths when it comes to conducting a survey of the interplanetary dust population. First, radio arrays are very sensitive to nanodust, a major fraction of the dust population in the

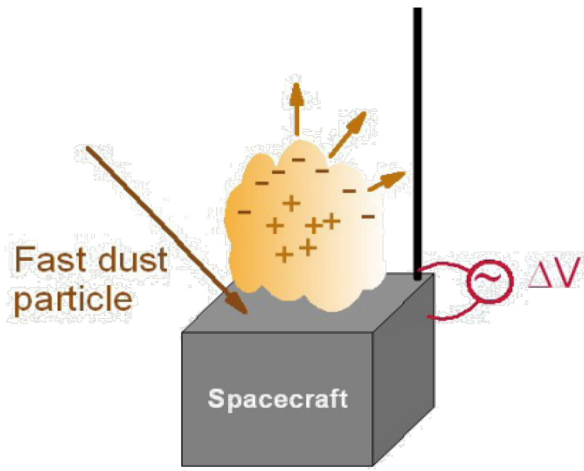

Fig. 12: Creation of an expanding cloud of plasma surrounding a spacecraft after the impact of a dust grain. Since ions and electrons in the cloud have the same thermal energy, the electrons expand much more quickly.

solar system that produces weak signals in standard instruments. Second, a radio array is also ideal for searching for the highest mass, but rarest dust particles. This is because the entire surface area of the array, which for lunar concepts would exceed thousands of square meters, becomes a single sensitive dust detector.

Recently, Meyer-Vernet et al. [26] proposed that small signals seen by the electric field antennas on one of the STEREO spacecraft may be due to nanometer scale dust particles. In order to determine the range of masses, and the uniqueness of radio measurements of dust properties, Zaslavsky et al. [27] analyzed dust impacts recorded by the STEREO/WAVES radio instrument onboard the two STEREO spacecraft near 1 astronomical unit (AU) during the period 2007-2010.

The impact of a dust particle on a spacecraft produces a plasma cloud whose associated electric field can be detected by on-board electric antennas (Fig. 12). When a grain impacts an object at extremely high speeds (a hyperkinetic impact), it generates a cloud of high temperature plasma of total charge approximately proportional to $mv^{3.5}$, where m is the mass of the grain and v is the speed. Since ions and electrons in the cloud have the same thermal energy, the electrons expand much more quickly, and create a large potential drop along the antenna. Analysis suggests that this technique works very well for measurements that cover the mass intervals $10^{-22} - 10^{-20}$ kg and $10^{-17} - 5\times10^{-16}$ kg [27]. The flux of the larger dust agrees with measurements of other instruments on different spacecraft, and the flux of the smaller dust grains agrees with theoretical predictions.

For a lunar radio array with 3 arms of 500 m length each and average antenna width on the arms of 1 m, the surface area would be 1500 m^2. Given the expected flux distribution, this would correspond to approximately 1000 impacts/sec for nanodust, and detections of the heavy 10 micron dust several times a minute.

V.II.III Cosmic Dawn – The First Stars and Galaxies in the Early Universe

The Astrophysics Decadal Survey [2] identified "Cosmic Dawn" as one of the three science objectives guiding the science program for this decade. The Survey asked "What were the first objects to light up the Universe and when did they do it?" In other words, how and when did the first stars, galaxies, and quasars form in the early Universe leading to the rich structure that we observe today with observatories such as the Hubble Space Telescope? In the science program articulated in the NRC Astronomy and Astrophysics Decadal Survey [2], the *Epoch of Reionization* (EoR) and *Cosmic Dawn* were identified as science frontier discovery areas that could provide the opportunity for "transformational comprehension, i.e., discovery."

Using the Moon as a platform for probing Cosmic Dawn via low radio frequency astronomy observations has been recognized in other reports and community documents. As recent examples, both of the NRC report *The Scientific Context for the Exploration of the Moon* [7] and *The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities"* produced by the Lunar Exploration Analysis Group (LEAG) [28] discuss the scientific value of a lunar radio telescope.

Burns et al. [29] have developed a concept for a new cosmology mission that would be the first to explore the Cosmic Dawn epoch of the Universe. The science described by [29] could be accomplished via low radio frequency antennas in lunar orbit or by the farside polyimide array discussed in V.II.

The specific science objectives for the Cosmic Dawn observations include (1) When did the first stars form? (2) When did the first accreting black holes form? (3) When did Reionization begin? (4) What surprises does the end of the Dark Ages and the beginning of Cosmic Dawn hold (e.g., dark matter decay)? We propose to use the highly-redshifted hyperfine 21-cm transition* from neutral hydrogen to track the formation of the first luminous objects by their impact on the intergalactic medium (IGM) at redshifts 11 – 35 (80-420 million years after the Big Bang).

The measurement approach proposed here is to track the influence of the first stars, galaxies, and black holes

* The 21-cm spectral line arises from a "spin-flip" transition when angular momentum vectors for the proton and electron flip from parallel to anti-parallel.

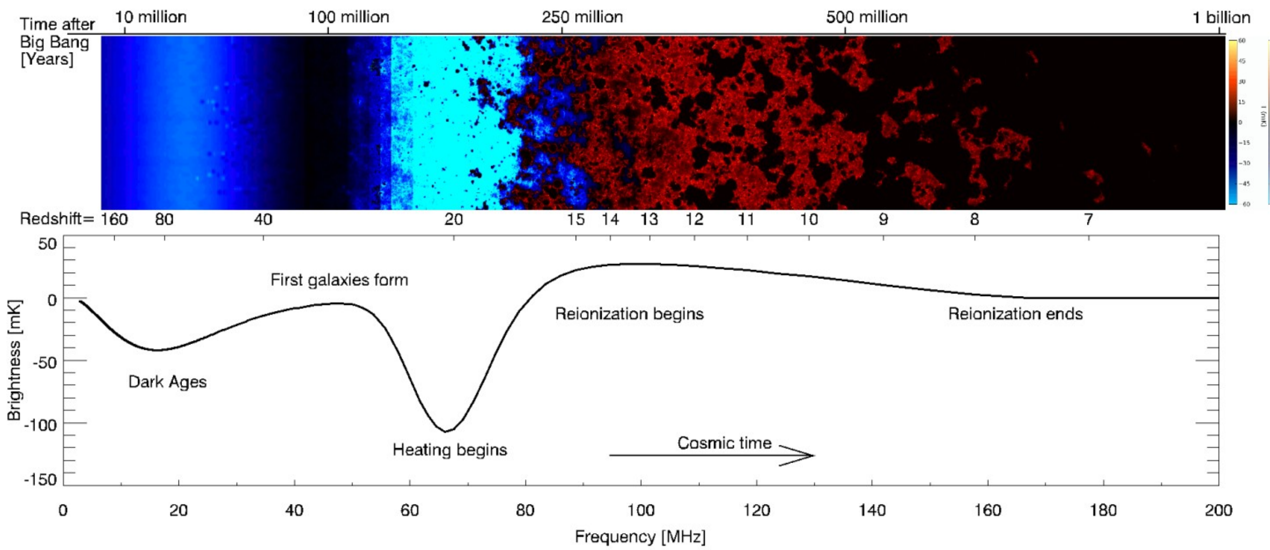

Fig. 13: (*Top*) Time evolution of the 21-cm brightness from just before the first stars form (Dark Ages) through to the end of the EoR. Color indicates the strength of the 21-cm brightness as it transitions from absorption (blue) to emission (red) and finally disappears (black) due to ionization. (*Bottom*) Expected evolution of the sky-averaged 21 cm brightness from the "Dark Ages" at $z = 150$ to the end of the EoR sometime before $z = 6$. The frequency structure is driven by the interplay of gas heating, the coupling of gas and 21 cm temperatures, and the ionization of the gas. Figure is courtesy of Jonathan Pritchard [30].

on the neutral IGM by means of the intensity of the hydrogen hyperfine transition with a rest frequency of 1.42 GHz (21-cm). Because of the expanding Universe, the observed frequencies at the Cosmic Dawn epoch will be lowered to 40-120 MHz. Fig. 13 shows a model of the sky-averaged, redshifted 21-cm spectrum from the Dark Ages (before the first stars) into Cosmic Dawn and Reionization. The brightness of this signal evolves with redshift, with several key inflection or "Turning Points" indicated in Fig. 13. By measuring the frequencies of these Turning Points, we would determine (a) the redshifts of when the first stars ignited and galaxies formed, (b) when the first black holes turned on and began heating the IGM via X-rays from their accretion disks, and (c) when the Universe began its final phase transition in evolving from an all neutral hydrogen IGM during the Dark Ages to an all ionized IGM at the end of the EoR. Observations on the radio-quiet lunar farside, which is also free of ionospheric effects at these frequencies, would observe an unexplored, crucial epoch in the early Universe that would bridge a gap in our knowledge as advocated by the Astronomy and Astrophysics Decadal Survey [2].

VI. Summary and Conclusions

The lunar farside is a huge, unexplored "new world" in Earth's backyard. It is dramatically different from regions of the Moon investigated by Apollo, containing only ~1% maria versus 31% for the nearside. The farside includes the South Pole-Aitken basin (SPA), the largest and deepest basin on the Moon, and possibly the oldest impact site in the inner solar system. Because of the Moon's tidal locking with respect to the Earth, the farside may be the only known radio-quiet site that could be used to probe the faint, low radio frequency signals coming from the Dark Ages and Cosmic Dawn of the early Universe.

We have proposed a novel human/robotic mission concept that would be the first to explore the farside and perform high priority science from its surface. The Orion MPCV, launched by NASA's SLS, would be placed into a halo orbit about the Earth-Moon Lagrange point L2. Such an orbit would place Orion astronauts in a unique position to see both the lunar farside and to have direct communications with Earth.

A separate unmanned robotic craft is proposed to land within the Schrödinger basin, which itself lies inside the SPA. Schrödinger has the unique attribute of being one of the youngest impact basins on the Moon but within the oldest basin. We propose the first telerobotic exploration of this basin, controlled by astronauts aboard Orion. A sample return from the SPA was identified as a high priority for the 2011 Planetary Sciences Decadal Survey [1]. It would be a powerful test of the lunar cataclysm and lunar magma ocean hypotheses, two of the most fundamental ideas that emerged from the Apollo program.

We also propose to take advantage of the unique radio-quiet zone of the farside to deploy a polyimide film low radio frequency array using telepresence. This array would be the first to definitively measure the density, and its diurnal variations, of the ionized lunar atmosphere. It could also serve as a powerful detector of high velocity nanodust which may be the major force in weathering airless bodies such as the Moon and asteroids. Finally, this array is designed to detect highly redshifted 21-cm signals from the early Universe's Cosmic Dawn which would be the first measure of how and when did the first objects (stars and quasars) "light up" the Universe – a top science objective of the 2010 Astronomy & Astrophysics Decadal Survey [2].

Robotic operation of a rover on the lunar farside controlled by astronauts in the Orion MPCV at L2 would offer several potential advantages for exploration and science operations. First, this mission would demonstrate realistic proof-of-concept exploration strategies that would be needed for both early missions to asteroids and to the Mars environs (including Deimos and Phobos). Second, telerobotic exploration and deployment of science instruments on the surface facilitated from L2 is potentially more efficient than either teleoperation from Earth or autonomous rover operation. According to Lester & Thronson [31], the "cognitive horizon" for telepresence is ≈0.5 s. The two-way latency between L2 and the farside is ~ 0.4 s, but the two-way latency between the Earth and the farside of the Moon is about 3.0 s assuming relay through L2. Although it is certainly possible to teleoperate rovers from Earth, Lester & Thronson argue that even this added latency decreases efficiency and increases risk, especially for complex geological investigations. Third, deployment of polyimide film antennas by a teleoperated rover would allow Orion astronauts to inspect potential flaws in the film and transmission lines, and to replace or redeploy more film as needed.

In summary, the proposed L2-Farside mission would offer a number of science and exploration "firsts". It would be the first mission to the surface of the Moon's farside. It would be the first to investigate and potentially return samples from the oldest impact basin in the inner solar system, holding a key to understanding the formation and evolution of the Earth-Moon system. The L2-Farside mission would deploy a novel polyimide film low radio frequency array in a proven radio-quiet zone which could be the first to observe the currently unexplored epoch of the Universe when the first stars and galaxies formed. Finally, this mission would be the first to demonstrate teleoperation of rovers by astronauts in orbit to undertake geological explorations and to collect samples as well as to deploy sophisticated instrumentation on an extraterrestrial body.

VII. Acknowledgements

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