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Small Penetrator Instrument Concept for the Advancement of Lunar Surface Science

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Abstract

Fundamental scientific objectives concerning the surface and subsurface material and dynamics of the Moon are the drivers for the use and advancement of penetrators, which emplace a suite of scientific instruments by impact into a planetary surface, typically at velocities of dozens to hundreds of meters per second. Small lunar penetrators are poised to become a valuable new tool for lunar science and exploration during the next decade. These low-cost ballistic probes can be deployed in large numbers from orbit, or from descending robotic or crewed vehicles, in order to explore and characterize the diversity of extreme lunar shallow subsurface environments. In this paper, we describe the general overview of penetrator objectives, potential instrumentation, and how these would benefit the advancement of lunar science at various extreme environments.

Unified Astronomy Thesaurus concepts: Lunar probes (969); Lunar science (972); The Moon (1692); Lunar composition (948); Lunar surface (974)

1. Introduction

Lunar exploration during the next decade will see many opportunities for human and robotic missions. Some key next-decade mission goals currently under consideration include sample return, lunar network science, and exploring extreme environments. The extreme lunar environments that have thus far been identified via analysis of orbital data include (but are certainly not limited to): permanently shadowed regions at the lunar poles (Watson et al. 1961; Feldman et al. 1998; Campbell et al. 2006; Paige et al. 2010; Hayne et al. 2015; Li et al. 2018; Rubanenko et al. 2019); steep topographic slopes (Kreslavsky & Head 2016); extreme rocky regions (Bandfield et al. 2017); lunar caves and pits (Hong et al. 2014); and lunar swirls (Blewett et al. 2011; Glotch et al. 2015). These extreme environments present significant challenges in terms of accessibility, as well as potentially significant rewards for science. Small penetrators hold great potential for precursor and survey missions, and for the exploration of extreme lunar environments, producing early science data and geotechnical information crucial to scientific goals and future mission planning.

Penetrators have been proposed as miniature planetary exploration vehicles for several decades, but have yet to fly successfully (see Lorenz 2011). Penetrators are intended to be self-contained vehicles with a suite of instruments designed to function after traversing some distance into a solid target, utilizing the kinetic energy of their arrival. This design excludes "mole"-type drills, such as those on Beagle 2, or InSIGHT (Richter et al. 2002; Wippermann et al. 2020), and penetrometer instruments designed specifically to measure mechanical properties as part of a much larger vehicle, such as those on the Huygens probe or Venera landers (Lorenz et al. 1994; Atkinson et al. 2010). For the purpose of this report, we define the small penetrator concept as a small probe encasing several instruments, to be used at some depth below the planetary surface. A better objective for the use of penetrators would be to deploy several penetrators across geologically diverse surfaces for a wider range of measurements, particularly given the wide range of geological and environmental conditions on the Moon. In this paper, we describe the scientific opportunities afforded by these penetrators, and their general characteristics, as well as the scientific objectives dependent on their regional emplacement on the lunar surface.

1.1. Previous Planetary Concepts

The basic design and technology for penetrators has existed for several decades, originating largely from military designs (e.g., Simmons 1977; Bogdanov et al. 1988; Lorenz 2011); however, only in the mid-1990s were such proposed concepts and testing adopted for use in solar system exploration. Lorenz (2011) has given a programmatic overview of previous planetary penetrator concepts, from Mars (Surkov & Kremnev 1998; Smrekar et al. 1999; Lorenz et al. 2000) to Titan (Atkinson et al. 2010) to comets (such as the proposed Comet Rendezvous/Asteroid Flyby CRAF mission; Lorenz et al. 2006). Unfortunately, these concepts from the 1960s–1980s faced technological or budgetary constraints, or a lack of robustness in terms of deployment and landing approach.

A notable proposed mission with penetrator components was the Japanese Lunar-A mission, a geophysics-focused mission to the Moon. This mission was to use penetrators as seismometers, and perform a heat flow measurement on the Moon, with at least one penetrator deployed at the far side of the Moon to record a differential crustal measurement. This

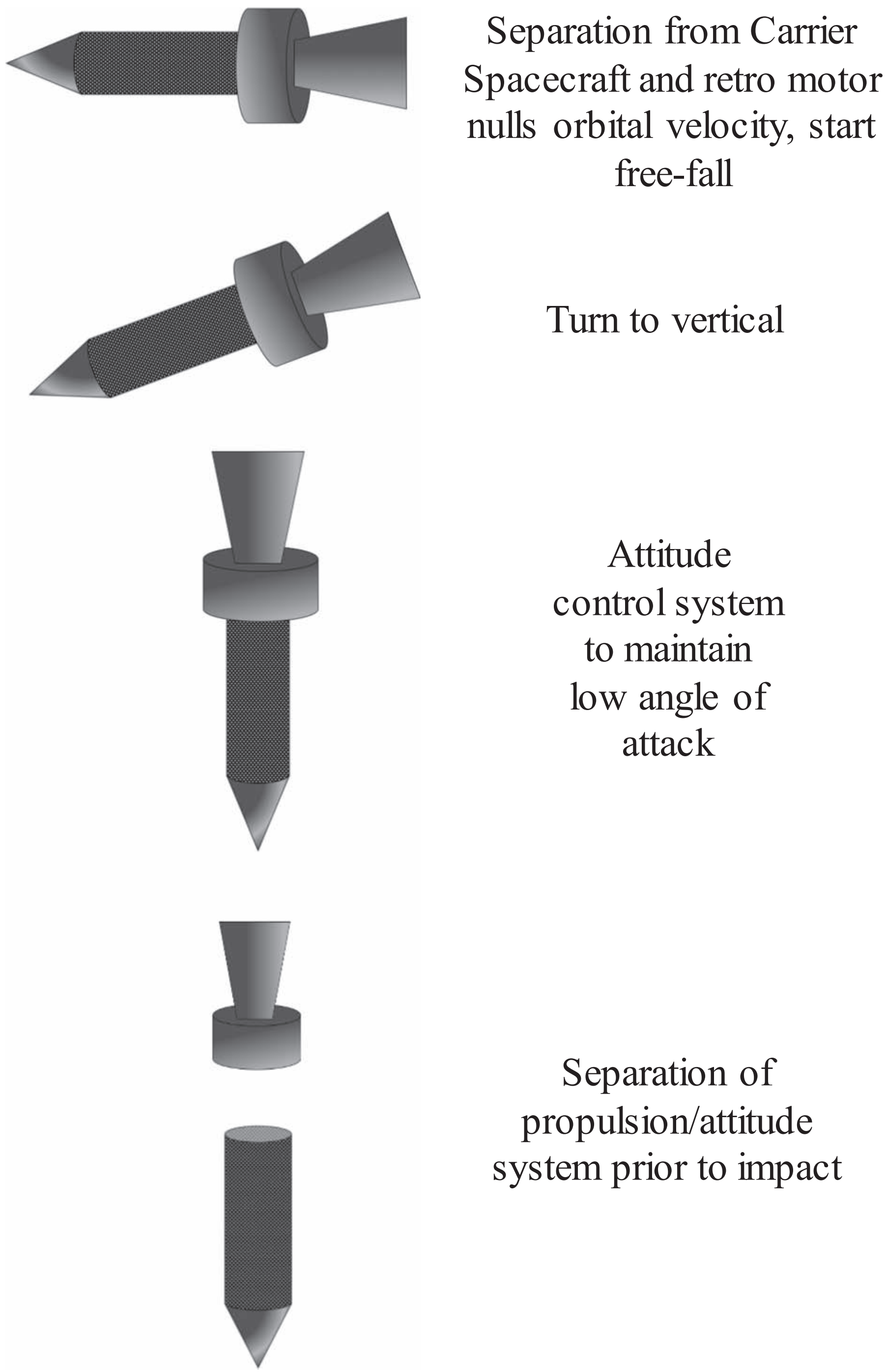

Figure 1. Illustration of the "delivery concept" of the Lunar-A penetrator, adapted from Lorenz (2011).

mission was initially developed by the Institute of Space and Astronautical Science of Japan, which was assimilated into the current Japanese Aerospace Exploration Agency, formed in 2003. The shock tolerance of components, and attitude dynamics for successful penetration were key elements in the initial studies (Mizutani et al. 1990, 1995; Hayashi et al. 1993). An example of the proposed attitude dynamics of Lunar-A is shown in Figure 1. Unfortunately, several electronic failures (among others) occurred during early penetrator development and testing, primarily due to inadequate materials to ensure the safety of impact-driven components, leading to the cancellation of the project in 2007 (Normile 2007; Lorenz 2011).

Another notable proposed penetrator mission was the MoonLITE concept, comprising a small orbiter and four penetrators (Gao et al. 2008). The primary goal was to investigate the seismic environment and deep structure of the Moon by emplacing a network of seismometers via penetrators. These penetrators would be spread over the lunar surface, with the objective being to land one pair on the near side, and another pair on the far side. Heat flow measurements were also proposed. While this mission concept has been deemed discontinued, the MoonLITE study did lead to the European Space Agency (ESA) LunarNet concept (Smith et al. 2012), as well as concepts for penetrator science on icy outer solar system bodies (Gowen et al. 2011).

2. Scientific Objectives

The key potential advantages of penetrators over conventional landers include: low mass and low cost, flexible options for multiple deployments, and the ability to achieve subsurface emplacement. Potential disadvantages include limited mass, high-g loading, and uncertain reliability of emplacement. Nevertheless, penetrators are best utilized as exploration tools in extreme environments where varied and uncertain subsurface conditions are likely to be encountered. For example, a key advantage of penetrators for the study of the Moon's polar regions is that they can be deployed into extreme thermal and low-light environments that are difficult to access (and sometimes operate in) by other means. Penetrators can also be deployed to multiple sites within a region of interest in order to sample the compositional and geological diversity within that region (e.g., the heterogeneity of polar ice deposits on scales of meters, Hurley et al. 2012).

By measuring their acceleration during ballistic emplacement, penetrators naturally provide information regarding the vertical density structure of their targets. Subsequent measurements after emplacement can provide a diverse range of thermal, geophysical, and compositional information, depending on the payloads, communications capabilities, and lifetimes of the penetrators. Today, more than 30 yr later, improved electronics miniaturization technologies, as well as shock tolerance and mitigation, have once again made penetrators an attractive technical option for planetary exploration. In the case of the Moon specifically, a wide variety of next-generation penetrator missions have been advocated (Mosher & Lucey 2006; Shiraishi et al. 2008; Smith et al. 2012; Eubanks et al. 2020; Riu et al. 2020).

Penetrator scientific objectives may address key issues related to the origin and evolution of the lunar surface, as well as possible areas of astrobiological significance (particularly in regions associated with polar ice) (Gao et al. 2008). In general, the scientific objectives for the penetrator counterpart of any lunar mission are: (i) to further our understanding of the origin, internal structure, and early geological evolution of the Moon; (ii) to better understand the origin and flux dynamics of volatiles; (iii) to collect in situ surface data for the purpose of enhancing mechanical data relating to the surface and subsurface regolith; (iv) to obtain "ground truth" geochemical data to ultimately complement orbital remote-sensing observations; (v) to collect surface and subsurface data that will help in the planning of future human exploration.

With regard to geological points of interest on the lunar surface, some extreme environments, such as pits and swirls, are geographically localized, while permanently shadowed regions are extensive at the lunar poles, comprising $\sim$40,000 km^2 in area (Hayne et al. 2021). Previous studies of these regions of interest suggest that their temperatures, and the abundance of surface/subsurface volatiles, are quite diverse (Colaprete et al. 2010).

2.1. Mission Concept Examples

During the next decade, NASA plans to deploy a number of large and small soft-landers to the lunar surface. There are two examples of lunar penetrator mission concepts that demonstrate the potential utility of this technology to enable and enhance sustained lunar exploration during the next decade by means of the first in situ exploration of extreme lunar environments. From an investment standpoint, penetrators can act as a precursor mission, piggybacked onto a lander during a descent phase, to facilitate the improved targeting of a landing site, and/or a larger-scale New Frontier-class mission, all at a relatively lower risk (i.e., 2 or 3 can fail out of a cluster of 6, and still complete the primary survey mission) and lower cost.

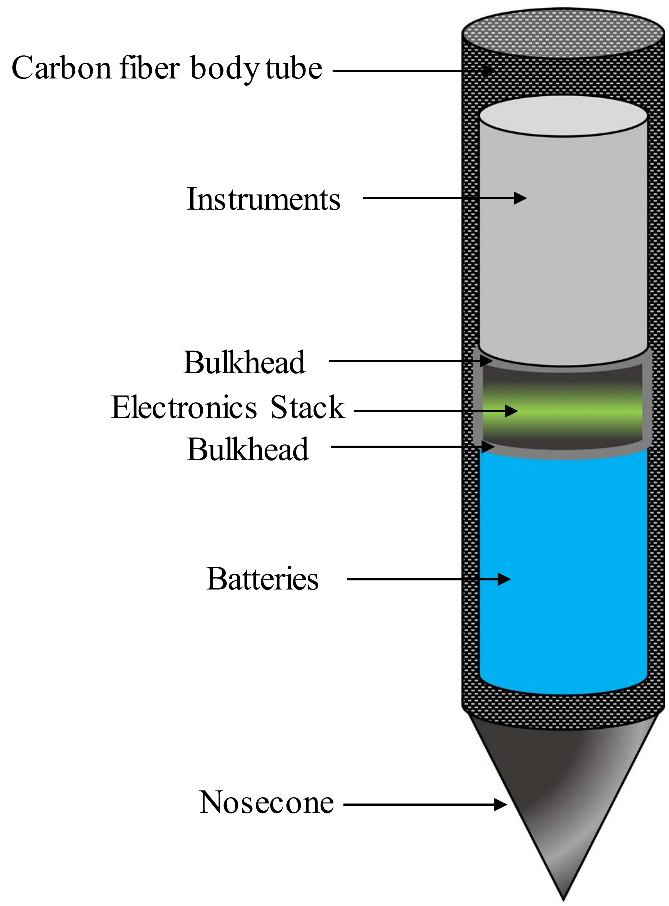

Figure 2. Small ~1.5 kg piggyback penetrator design schematic.

2.1.1. Small Lander Piggyback Penetrators

These landers could include multiple small penetrators as "piggyback" payloads (Figure 2) that could be deployed during terminal descent. These penetrators would be ballistically emplaced downrange of the lander, and be targeted to extend the scientific reach of the landers into extreme environments (e.g., a deep, hazardous crater, or permanently shadowed region).

Depending on their deployment locations and payloads, piggyback penetrators could address a wide range of scientific and exploratory objectives. Possible mission scenarios for short-lived penetrators could include scouting out regions of permanent shadow for rovers or astronauts, or exploring the particle and field environments above and below the surface of lunar swirls. There are also opportunities for synergistic observations between landers and piggyback penetrators emplaced in the surrounding area in order to perform studies of lunar regolith composition and structure.

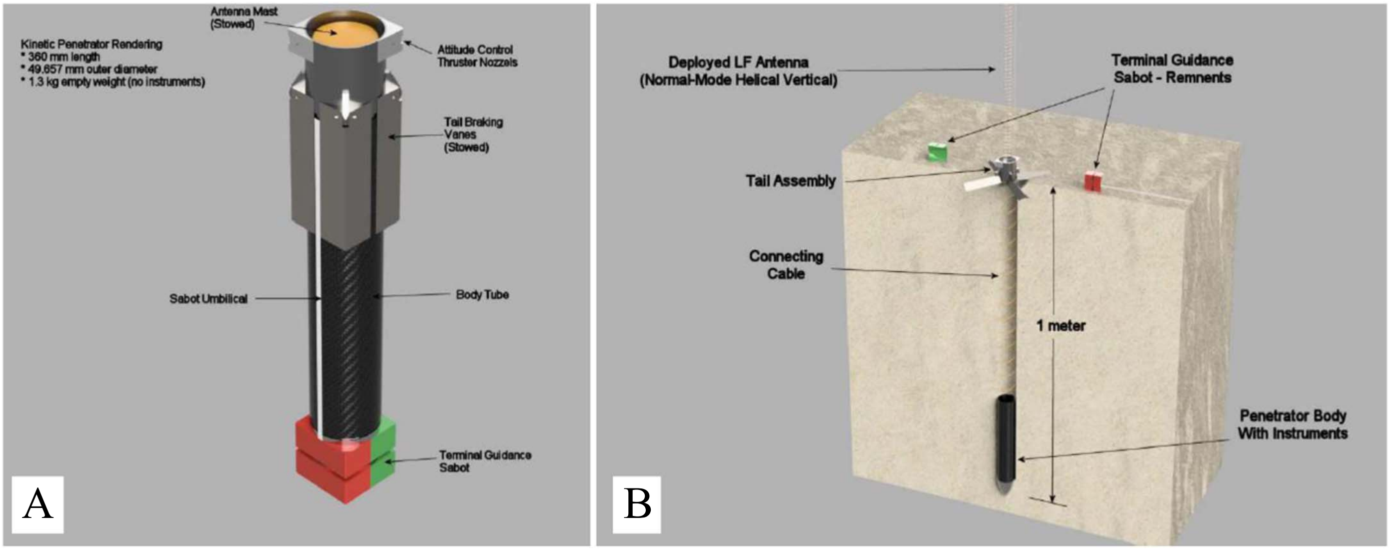

Figure 3. (A) A standard Mote penetrator before deployment; the default Mote design is scaled so that four will fit within the volume allotted to a 3-U cubesat. The terminal guidance uses optical flow detection in the sabot, along with cold-gas thrusters in the tail, to provide active three-axis orientation control during descent. (B) A Mote penetrator after deployment with a nominal 1 m penetration into the lunar regolith. The electronics and most of the scientific payload would be carried in the penetrator itself, and would be automatically deployed 1 to 2 m into the lunar regolith. Other instruments and communications antennas would be carried in the tail section, which in this design uses drag fins to remain on the surface. The terminal guidance sabot is no longer required on reaching the surface, and would be dispersed during the landing.

2.1.2. Mote Ballistic Penetrators

Ballistic penetrators allow for rapid initial scientific investigation and communications in problematic terrain, such as permanently shadowed regions (PSRs), volcanic vents, lava tube pits, and skylights (Smrekar et al. 1999; Eubanks et al. 2020). In addition, they allow for the distribution of instrument arrays over regions of interest, such as scarp faults and lunar swirls. The ~1.5 kg Mote penetrators developed by Space Initiatives Inc. for lunar operations (Figure 3) will have onboard processing, communications, and sensors, which could be delivered either by a dedicated mission, or carried by a NASA Commercial Lunar Payload Services (CLPS) Lander.

After deployment, the Motes fall ballistically, impacting the surface at up to 300 m s^{-1}, and penetrating 1 m (or more) into the typical lunar regolith, resulting in a sensor array spread —in a nominal mission—over ~1 km^2 of the lunar surface. The Mote offers a modular approach to instrument delivery. Each penetrator provides power, communications, and control, carrying up to a half kilogram of sensors. For any given deployment, the sensors can be varied among the penetrators used for the mission.

2.1.3. Dedicated Penetrator Missions

NASA's Discovery and New Frontiers programs provide opportunities for larger-scale science-driven missions that could incorporate sophisticated penetrators aimed at better defining the global distribution and detailed properties of polar ice deposits. One concept for such a mission is as follows:

This self-contained mission concept would include an orbiter, two descent vehicles, and approximately four penetrator probes, which would be deployed to high-latitude targets in both polar regions. The descent vehicles would use solid rocket motors to precision-target the penetrators at optimum vertical and horizontal velocity, while orbiters would relay data between the penetrators and Earth. The penetrators would be targeted to a range of cold-trap locations to sample the diversity of lunar polar environments, including deep, permanent shadow. The number of penetrators and their capabilities are scalable, depending on mission cost and mission risk posture. For this mission example, the penetrator landers are the primary payload, and can therefore select the landing site, whereas the piggyback penetrators are secondary, and limited to the landing site of the primary lander.

2.1.4. Lifetimes and Communications

Onboard communication systems for penetrators have been trialled as part of the New Millennium Deep Space 2 mission (DS-2), which consisted of two 1.2 kg impact penetrometers, deployed from the Mars Polar Lander. These penetrometers consisted of accelerometers, a soil–water detection experiment, and a communication system (Keese & Lundgren 1994; Smrekar et al. 2001; Riu et al. 2020). While it landed successfully, repeated attempts at Earth-contact communications were unsuccessful (Lorenz 2011). Delivery of data after touchdown is mission-critical. There are two possible options: (i) direct communication with Earth (most likely via windows of opportunity to downlink with the Deep Space Network); (ii) retrieval of data via an orbital or landed relay, which would put high constraints on the dependence of another lunar mission component (orbital/lander) to act as relay. Each of the options are ideal, depending on the type of penetrator (see Table 1). These options also incur changes in transfer duration times, depending not only on the type of communication employed, but also on the windows of opportunity for direct contact, or on lander distance (Lorenz 2011; Riu et al. 2020). With reference to piggyback and Mote ballistic penetrators, these have a much shorter lifetime, so communications and data collection would certainly need to be retrieved by the respective lander in a sufficient timeframe. For dedicated penetrator missions, the lifetime is much longer (Table 1), such that data retrieval could be stored and retrieved over a longer timeframe.

Table 1
Penetrator Class Types and Respective Mission Frame Regarding Deployment, Communications, Lifetime, and Target Location

Penetrator Mission Class	Piggyback/Mote Ballistic	Dedicated
Deployment	Lander terminal descent	Descent vehicle
Communications	Lander relay	Orbital relay, Direct to Earth
Lifetime	∼1 week	∼1 yr
Target Locations	∼10 km downrange of lander	Any location on surface

Table 2
Penetrator Payload Element Options and Respective Objectives

Example Payload Elements	Measurement Goals and Parameters	Key Contributions to Science and Exploration
3-Axis Accelerometers	Regolith vertical density structure, volatiles detection to <1 m depth	First-order measurement of general regolith characteristics in polar cold traps
Thermal Probes	Regolith temperature and thermophysical properties	Volatile stability, regolith ice content, heat flow
Seismometers (Active and Passive)	Seismic wave velocity (long period and short period)	Regolith structure, regolith depth, ice content, lunar interior
Dielectric Probes	Dielectric permittivity	Ice content
Neutron Spectrometers	Hydrogen abundance versus depth	Abundance and distribution of water and other H-bearing species
Gamma Ray Spectrometer	Elemental composition	Major elements, radioactive elements, hydrogen detection
APX Spectrometer	Elemental composition	Formation and evolution of the lunar crust
Oven/Evolved Gas Analyzer	Trace volatile abundances and isotopic ratios (e.g., D/H)	Origins and history of lunar volatiles
Radio Science	Low frequency radio; shallow lunar surface science and particles and fields	Lunar librations and existence of liquid or solid core, long-range lunar communications network
Charged Particle Detectors	Cosmic rays and solar wind particles	Solar wind environment in PSRs, Lunar swirls properties and origins
Heat Flow Sensors	Subsurface temperature gradient and thermal conductivity	Heat flow; Constraints on the composition and thermal evolution of the lunar interior; Proximity of heat-generating elements (e.g., thorium in KREEP)
Magnetometer	Field strength, direction, and variations with time	Formation processes of Lunar swirls; Deflection of solar wind at the lunar poles
Cavity Ringdown Spectrometer	Detailed volatile composition and variations with depth	Origins and history of lunar volatiles
Microscope	Crystal and grain structure	Nature of volatiles, regolith properties
LIBS/XRS Spectrometers	Elemental and molecular composition of subsurface minerals	Lunar mineralogy
Other Spectrometers	Raman and Heterodyne Fringe Spectrometers	Water composition and chemistry, organic chemistry

3. Instrument Science Payloads

3.1. General Overview

Small penetrators have the potential to accommodate a wide range of scientific payloads, which can be tailored to meet specific mission objectives. Section 3.2 gives a brief overview of examples of potential penetrator instruments, and their potential contributions to lunar science and exploration. Technological advancements in instrument miniaturization have enabled the deployment of multiple instruments in each penetrator.

3.2. Suite of Instruments

3.2.1. Cameras/Microscopes

Camera instrumentation is a basic, but essential instrument to include on a penetrator, with particular reference to the descent stage prior to impact. It can provide near-nadir observations of the surface and geological context of the penetrator. This would be particularly useful within a crater, where solar angles can be imaged at different altitudes prior to impact. An understanding of crater morphology and shadowed areas could prove useful in the context of micro cold traps (Hayne et al. 2021). Microscopes would also be useful for regolith studies, in conjunction with spectrometer instruments. Microscopic imaging of the regolith would provide information on the crystal and grain sizes, and optical maturity of the soil, and with the addition of spectroscopy, Hapke models of the localized composition could be improved (Lucey et al. 2000; Noble et al. 2007).

3.2.2. Fringe/Fiber Optic Spectrometers

The types of spectrometers having potential for inclusion in a penetrator suite are elemental and molecular composition-specific instruments, including Raman and heterodyne fringe spectrometers (Table 2). These can be useful for the analysis of water composition and chemistry, and organic detection (Livengood et al. 2019). Spectrometers would also prove useful for the examination of certain mineralogical occurrences on the Moon, such as the presence of nanophase metallic Fe, as discovered in the Apollo samples (Taylor et al. 2001; Noble et al. 2007; Pieters & Noble 2016). This mineral has been demonstrated to be the main cause of darkening and reddening in the VIS/NIR wavelength range, characteristic of lunar space weathering (Keller et al. 1998; Sasaki et al. 2001). Evaluating these minerals would further elucidate the effects of space weathering (possibly due to ion irradiation and micrometeorite bombardment), including the presence of oxidized material. Aside from oxidized minerals, spectrometers could also provide a detailed assessment of water composition and hydroxyl (OH) compounds at the poles and in equatorial regions (Honniball et al. 2020).

3.2.3. Magnetometers

Lunar magnetic anomalies are localized magnetic fields caused by permanently magnetized material within the first few meters of the lunar crust (Hood 2014). These anomalies were first detected by magnetometers on the Apollo 15 and 16 subsatellites (Coleman et al. 1972), and have scales of up to hundreds of kilometers. Understanding these lunar magnetic anomalies could provide clues as to (i) geodynamic history and existence of a lunar core dynamo; (ii) the magnetic effects of large-scale impacts; and (iii) the role of solar wind ion bombardment in producing space weathering on minerals. Recent magnetometer data has been acquired by the Lunar Prospector (1998–1999) and Kaguya (SELENE) (2008–2009) (Mitchell et al. 2008; Purucker & Nicholas 2010; Tsunakawa et al. 2010). However, penetrators with magnetometer instruments could be useful with respect to localized magnetic anomalies, and to better understand magnetic-oriented mineralogy. Penetrators could also help further our understanding of field strength, deflection of the solar wind at the poles (Starukhina & Shkuratov 2000; Crider & Vondrak 2002), and lunar swirl formations such as the Reiner Gamma swirl, where the planned 2023–2024 CLPS landings show potential for the use of ballistic penetrators.

3.2.4. Dieletric Probes

Dielectric permittivity, which is one of the most fundamental electromagnetic parameters, is a measure of the capability of a material to keep electrical charges physically separated by electrical polarization. It is a constant, relating the electric field to the electric displacement in a material; as such, dielectric permittivity is the ratio of permittivity of the material to vacuum (Heiken et al. 1991). Knowing the dielectric permittivity of a material greatly affects the interpretation of lunar penetration radar (LPR) data science, particularly given that the range resolution for the depth and thickness of surface materials depends on the dielectric constant, as well as the LPR transmitting bandwidth (Wright et al. 1984; Chenet et al. 2006). Knowledge of the dielectric constant, primarily gleaned from regolith samples at the Apollo landing sites, from depths of no more than 3 m (Heiken et al. 1991; Jiang et al. 2008; Neal 2009), is limited, and could be improved by multiple penetrator studies using dielectric probes.

3.2.5. Thermal Sensors

Thermal probes are beneficial for measuring the thermal flux from the penetrator's impact, and its possible interaction with subsurface materials. Regolith temperature and thermophysical properties are the main objectives behind the inclusion of thermal sensors. Thermal sensors would be useful at the lunar poles, particularly in the context of thermal flux at PSRs, and micro cold trap dynamics. Evaluating the thermal flux at volatile-rich areas could also provide clues as to solar interactions with the lunar environment, particularly in relation to irradiative processes.

Thermal probes could also measure geothermal heat flow. This measurement would be accomplished by deploying two separate sensors at different depths along the probe, and measuring the difference in temperature, either below the diurnal and seasonal thermal waves (∼10 cm–2 m), or with a long enough temporal baseline to remove these oscillations.

3.2.6. Seismometers

Seismometers, active or passive, can provide clues as to regolith structure, depth, ice content, and, the lunar interior in general (see Table 2). The Early Apollo Scientific Experiment Package and the Apollo Lunar Surface Experiments Packages from the Apollo astronauts were equipped with three-axis long period and vertical-axis short-period seismometers (Latham et al. 1970; Bates et al. 1979). Much has been learned from the instrumentation in these early seismometers, and the objectives for the proposed Lunar Geophysical Network (Neal et al. 2019; Weber et al. 2020) could be further enhanced by means of the multiple deployment of penetrators, particularly as an array. Some outstanding questions regarding the seismicity of the lunar surface include the seismicity of the South Pole. Nakamura et al. (1979) report that one of the largest shallow moonquakes occurred ∼6° from the lunar south pole, with a moment magnitude of 4. The event depth remains unknown, and uncertainties as to the magnitude and origin of the moonquake is as yet unknown. The impact rate at the lunar south pole is also another outstanding question, where the use of seismometers for flux analysis would be useful in terms of future crewed missions.

However, seismometer instruments need to be designed not only to be easily mounted in a penetrator, and therefore to be impact-resistant, but also to be capable of carrying out an array of scientific objectives. Penetration survival experimentation was undertaken during the MoonLITE studies, using small, high-frequency, solid-state seismometers (Gao et al. 2008; Smith et al. 2012). The LunarNet concept utilizes a MEMS-based (Micro-Electro-Mechanical Systems) microseismometer as a spring/proof mass system, which converts any external vibration to a displacement of the proof mass (see Smith et al. 2012 for optimization and design). This concept explored two operational modes in regard to seismic detection. The first was the *global network mode*, which proposed the use of a horizontal axis trigger with an initialization time of 30 s, due to the fact that lunar seismic events (typically more than 100 s; Nakamura 1983; Logonné et al. 2003), were observed during the Apollo experiments to exhibit stronger signals in the horizontal axes as compared to the vertical axes (Smith et al. 2012). The second, or *full operation mode* is a three-axis operation for local seismic events, operating for up to one month at the beginning of the mission to characterize the local seismic environment. After one month, the microseismometer would then operate in the power-saving *global network mode* (Smith et al. 2012). The concept of a microseismometer is also underway for other missions, including Netlander and ExoMars. The ESA gave the microseismometer a Technology Readiness Level of 5 for ExoMars, but additional impact survival requirements have reduced this to an estimated value of 4 (Smith et al. 2012).

3.2.7. Neutron/Gamma-Ray/APX Spectrometers

Nuclear spectroscopy instruments would assess subsurface hydrogen deposits and elemental composition to provide geological context within ∼1 m of the penetrator body (Table 2). Gamma-ray instruments have been included on numerous lunar missions, from Apollo 15 and 16 to several orbital missions (e.g., Lunar Prospector, Kaguya, Chang'e), providing global to regional elemental composition maps. Concentrations of volatile hydrogen, radioactive elements (K, Th, U), and major elements (e.g., Al, Ti, Fe, Mg, Si) at a local scale around the penetrator body would be quantified by measuring gamma-rays produced by galactic cosmic ray interactions in the subsurface, which peaks ∼0.5 m below the surface (e.g., McKinney et al. 2006; Mesick et al. 2018). A neutron spectrometer could be used in addition to infer the presence of hydrogen at even higher sensitivity than gamma-ray measurements, as demonstrated from orbit by the Lunar Prospector and Lunar Reconnaissance Orbiter missions. Moreover, it is sensitive to the presence of trace elements Gd and Sm (Elphic et al. 2000). These unique elemental and volatile abundance measurements would detail the near-surface stratigraphy of cold traps, and provide local regolith geochemistry.

4. Landing Site Science

4.1. General Overview

Small penetrators, while benefiting from being deployed globally across the lunar surface, should also have specific objectives with respect to certain lunar regions. The lunar surface offers a variety of geological environments, some too extreme for rovers or human exploration. Each major geological region offers a unique opportunity for penetrators. Here, we list potential objectives for penetrators at different generalized geological regions on the Moon.

4.1.1. Permanently Shadowed Regions

Polar volatile deposits are still one of the Moon's biggest mysteries. Several previous studies have observed evidence of a range of volatiles present in the Moon's PSRs (Watson et al. 1961, 1962; Stacy et al. 1997; Feldman et al. 1998, 2000; Campbell et al. 2006; Colaprete et al. 2010; Mitrofanov et al. 2010; Paige et al. 2010; Hayne et al. 2015; Fisher et al. 2017; Li et al. 2018; Rubanenko et al. 2019). The nature and distribution of these volatiles are highly uncertain. During the next decade, exploring and sampling these volatiles could yield several exciting sciences, including (but not limited to): (i) the discovery and of resources and their potential utilization for future solar system exploration; (ii) fundamental new insights regarding the origin and evolution of volatiles on the Moon; and (iii) the origin of volatiles in Earth's water, and water in the inner solar system (Hayne et al. 2021). Some PSRs, being adjacent to illuminated terrain, provide potential options for access by conventional rovers and landers. However, accessing deep PSRs, which have no direct solar illumination for tens of kilometers, temperatures <100 K, rugged terrain, and unknown surface and subsurface geotechnical/electrical properties, appears outside the capabilities of current-technology landers and rovers. These PSRs are cold enough to sequester H_2O ice for billions of years (Vasavada et al. 1999). However, current orbital remote sensing (mainly mapping efforts from the NASA Lunar Reconnaissance Orbiter—LRO) are typically limited to >100 m resolution. Micro-scale cold traps could exist at spatial scales down to centimeters (Hayne et al. 2021), which could potentially be detected (and thus studied) using small penetrators. To explore these difficult-terrain areas would require in situ reconnaissance of these regions in order to obtain a first-order understanding of their general characteristics and geological/chemical diversity, followed by more detailed in situ studies, and possibly returned samples.

Shackleton crater is a region of high scientific potential for a variety of penetrator deployments, in particular a detector emplaced on the rim of the PSR for observation. For example, boulders and boulder tracks could be investigated (Bickel et al. 2019; Bickel & Kring 2020; Sargeant et al. 2020) to evaluate their regolith-bearing capacity before robotic (or crewed) assets attempt to traverse. Aside from the PSR volatile investigations, Shackleton crater also has a layered terrain that may be indicative of sequential ejecta blankets (Campbell & Campbell 2006; Spudis et al. 2008). As such, this crater represents an interesting geological and mineralogical priority site.

One major constraint associated with the delivery of low mass/cost penetrators is the limited volume/power available for scientific payloads. While there has been a concerted effort toward instrument miniaturization, the Research & Development community still has a way to go to meet these constraints. The instrument examples discussed here meet these constraints. The subset of sensors or instruments that provide information on temperature, hardness, pressure, conductivity, and layering include load/accelerometer sensors, temperature sensor arrays on both the aft body (surface) and forebody (subsurface) (Blaes & D'Agostino 2005). Soil conductivity measurement devices, similar to those constructed for the regolith scoops on both the Mars Volatiles and Climate Surveyor and Phoenix robotic arms, allow a thermal pulse to be generated, followed by measuring decay time and temperature profile (Boynton et al. 2001; Hoffman et al. 2008). Pressure sensors provide data on ice/soil compression. Similarly to the water detection experiment used by Mars Deep Space 2 (DS-2), a small auger released from the side of the forebody retrieves an ice/regolith sample, is retracted back into a sealed oven enclosure, heated to release the volatiles (water/gases), and is interrogated by an infrared tunable diode laser (IR TDL) to detect water (Blaes & D'Agostino 2005). Other laser wavelengths can be used to detect gases such as CH^4, H^2, He, and O^2. Instruments such as dielectric spectroscopy electrodes and solid phase microextraction electrodes are able to perform bulk chemistry measurements on samples to identify minerals, metals as well as organics (Reyes-Garcés et al. 2017). Solid phase microextraction utilizes doped microelectrodes in contact with a sample to isolate select organic species. Utilizing the retrieved sample in the auger, a miniature microscope can examine granular/crystalline structures (Lord & Pawliszyn 2000). Spectrometers that can separate out derivative chemistries for water and hydrated minerals include the Raman water/ice spectrometer, and the Heterodyne Fringe Miniature Spectrometer, which again examine water, trace gases, and trace organics (Sonnabend et al. 2002). Both of these spectrometers use laser interrogation techniques, and do not need to be in contact with samples. Lastly, there is great interest in the scientific community in mapping subsurface stratigraphy. The Mars InSight seismometer has been repackaged to fit into a penetrator forebody (within the Heat Flow and Physical Properties Package HP^3 Penetrator) with a diameter of less than 7 cm (Kedar et al. 2017). However, it should be noted that the heritage of this instrument includes work undertaken for the proposed MoonLITE penetrators (Smith et al. 2012; Kedar et al. 2017; Zhang et al. 2019), with reference to potential challenges in terms of adaptability and survivability. Once the primary science payload probes have been released, one

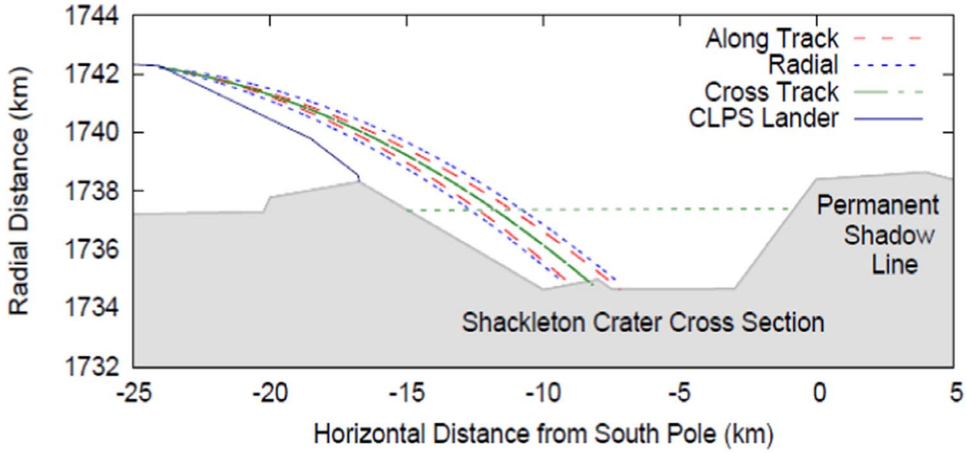

Figure 4. Deployment of Mote penetrators into the Shackleton Crater PSR. The Motes are assumed to be deployed from a CLPS Lander with sufficient velocity to proceed into the center of the PSR, while the CLPS lander proceeds to soft land at the crater rim. The CLPS landing profile shown here was developed from discussions with CLPS providers. While the actual landing profile will depend on the choice of lander and its terminal guidance, in any realistic profile the lander will touch down at least one minute, possibly several minutes, after the Motes reach the surface.

additional probe or impactor mass-generates the pulse signal, which is then recorded/mapped by the remaining active seismometers. The embedded microseismometers can then act as a geophone array.

Figure 4 shows the deployment of a Motes ballistic penetrator into the Shackleton crater from a CLPS-type landing delivery onto the rim of the crater. The Motes are deployed 24 km downrange, and 5 km above the mean lunar surface, taking 78 s to reach the crater floor and to penetrate 2.8 km below the mean lunar surface. At the time of landing, the CLPS lander will still be well above the surface of the crater rim, which is a prime spatial and temporal opportunity to observe IR emissions from the gas plumes emitted by surface volatiles vaporized by each Mote penetrator's kinetic energy. Deployment of penetrators into a PSR would immediately provide geochemical information within the upper 2 m of the regolith. Regolith information would be provided on the basis of the deceleration profile of the landing sequence by the penetrator, and its depth of penetration. This process would heat the regolith, and information about the thermal characteristics of the upper regolith would then be provided by the instrument suite on board the penetrator. A major landing site for the Mote penetrators would be the "mound" unit, the largest feature on the Shackleton crater floor (Haruyama et al. 2008; Zuber et al. 2012), using a horizontal spread of Motes (due to a horizontal separation velocity of $10\,\mathrm{m\,s^{-1}}$ imparted at deployment) sufficient to blanket the 210 m high mound unit with penetrators.

4.1.2. Mare Basins and Lunar Swirls

The samples acquired by the Apollo 11 astronauts were basalts from the mare basins (Papike et al. 1976; Ringwood & Kesson 1976). Analyses of these rocks led to the hypothesis that the mare plains were re-melts of a lunar interior that had previously experienced profound chemical differentiation events, produced by the crystallization of a large lunar magma ocean (Sedaghatpour & Jacobsen 2019). Among the samples were glassy spheres of ultramafic mineralogy, formed during volcanic eruptions into the cold lunar vacuum (Grove and Krawczynski 2009). Such high-temperature and high-pressure processes on the lunar mare basalts and volcanic glasses necessitate further investigation of the geochemical and physical aspects of the regolith. Understanding the regolith processes from post-volcanic processes using small penetrators can give us clues as to the extent and depth of the lunar magma ocean, solidification processes, and the possible thermophysical parameters of the regolith that formed the glasses. We recommend a swath of multiple penetrators across large mare basins (6 or more) to obtain heterogeneous measurements, particularly to estimate thermal and lithospheric differences across these magma basins.

The Orientale mare basin is a potential candidate for penetrator science, specifically in terms of investigating the multi-ring impact basin. Moon Mineralogy Mapper (M^3) spectral reflectance and imaging data have been used to examine the mare basalt emplacement (Whitten et al. 2011; Varatharajan et al. 2014) and help with modeling the formation ages of the Orientale Basin, with specific investigations being undertaken into the density and thermal barriers to basaltic magma ascension and eruptions (Whitten et al. 2011). Penetrators strewn across this multi-ring basin would lead to interesting future evaluations of the mineralogy, geochemistry, and mare basalt thermodynamics in this region, to further improve multi-ring and mare basin formation and sequence models.

Another interesting feature with respect to the potential of penetrator reconnaissance and in situ science are the Irregular Mare Patches (IMPs), unusual mounds surrounded by hummocky and blocky terrain (Qiao et al. 2020). As reported by Qiao et al. (2020), their complex formation mechanism is still under debate. Penetrators could provide a more effective geochemical study of these locations. However, because IMPs are relatively small, targeting accuracy would need to be established for penetrator landings. Some technologies have been proposed and used in experiments for the purpose of aiming landers and penetrators toward a target on a planetary surface, utilizing orbital optical navigation (Wang et al. 1991) and sophisticated autonomous attitude determination and control subsystems (Badrakalimuthu et al. 2010).

4.1.3. Highlands and KREEP Basalts

The lunar highlands and their alkalic rocks yield important information in terms of the development of the lunar crust, specifically regarding the crystallization ages of a variety of rocks. Mineral and chemical modeling of all known pristine highland alkali suite (HAS) rocks, and radiogenic isotopic analyses from the Apollo 14 landing site of HAS rocks, further explored the potential link between pristine KREEP (*Potassium—Rare Earth Elements—Phosphorous*) basalts and lunar quartz and granites (Taylor et al. 1980; Snyder et al. 1995). Regions with substantial KREEP materials or of interest to penetrator science, particularly with reference to the geochemical-specific suite of instruments (e.g., spectrometers). Snyder et al. (1995) report that these KREEP basalt melts contain trapped residual liquid of the large-ion lithophile element, which could be better understood using penetrators.

Overall, the instrumentation most suited to KREEP-type terrains, most notably the Procellarum KREEP Terrane (PKT; Elphic et al. 2000; Grimm 2013), for onboard penetrators would be spectrometers, specifically gamma-ray, APX, and XRS (Metzger et al. 1973; Lawrence et al. 1998; Elphic et al. 2000). The penetrator's impact may indeed thermalize the residual subsurface liquid, but spectrometers would have the potential opportunity to observe the resulting vapors, similarly to the approach of the Lunar Crater Observation and Sensing Satellite ejecta plume study (Hess & Parmentier 2001; Colaprete et al. 2010). KREEP basalts also have high concentrations of radioactive elements (Th, U, and K) (Metzger et al. 1973; Korotev 1998; Borg et al. 2004). Gamma-ray spectrometers would not only detect hydrogen and radioactive elements, but these observations could be compared to Apollo 15 and 16 mapping and sample collections (and modern compositional mapping efforts) of radioactive materials in localized areas on the lunar surface (Metzger et al. 1973). Researching these radioactive elements within lunar rocks offers two main objectives: (i) the study of lunar magmatism and the geochronology of lunar basalts; and (ii) lunar prospecting.

Primordial solidification of the Moon's upper layers resulted in the formation of a variety of igneous rock types that subsequently melted and mixed, creating a diversity of compositions. However, it was the final stage of crystallization that produced the strongly enriched incompatible elements in KREEP (Borg et al. 2004). The decay of the radioactive elements in KREEP is thought to provide the thermal energy necessary for recent lunar magmatism (Warren & Wasson 1979; Hess & Parmentier 2001; Borg et al. 2004).

Among the objectives of the LRO mission are finding potential safe landing sites and locating potential resources (Taylor & Martel 2003; Shevchenko 2014). Imaging from LRO has shown the Moon to have areas with concentrations of titanium, whose great abundance still puzzles researchers. Lunar rocks range from one to ten percent titanium, whereas Earth rocks contain around one percent (Shevchenko 2014). Titanium and the abundance of radioactive rocks in the KRT present various opportunities for future lunar prospecting and for penetrator science to elucidate the chemical structures and abundances of these elements in the lunar igneous rocks. Pre-targeting such resource-rich locations with penetrators prior to human exploration would also help constrain the safety of future prospecting, observing safe (or unsafe) levels of radioactivity, or other harmful chemicals, such as sulfur dioxide and hydrogen sulfide, although such sulfur-containing minerals and volatiles could also represent useful lunar resources (Watson et al. 1961; Gibson & Johnson 1971; Taylor & Martel 2003; Toutanji et al. 2005; Sanders & Larson 2012).

4.2. Penetrators for Artemis

Future crewed Artemis missions plan to explore the lunar south polar region. The proximity of smaller cold traps to adjacent illuminated terrain may provide access to precursor rovers and landers. However, deeper PSRs may prove to be inaccessible to such landers and rovers. The deployment of penetrators, equipped with a suite of instruments, prior to human exploration would be useful in areas of such high uncertainty.

In the lunar polar regions, astronauts will be entering a new and relatively poorly-understood plasma and radio frequency environment (as opposed to the direct sunlight and solar wind encountered during the Apollo EVAs). Many regions in the polar latitudes will have no direct line of sight with the Earth, and in shaded areas (where there are higher thermal velocities of solar wind electrons; Lyon et al. 1967; Johnson 1971) can create large regions with charge separation. The Moon is within the complicated dynamic plasma environment of the Earth's magnetotail ∼25% of the time, and the remainder of the time is subject to supersonic solar wind (Bhardwaj et al. 2015). Non-neutral plasmas are therefore likely to form in shadowed lunar craters, and also possibly in the lunar wake, which are likely to prevent grounding of astronauts and their equipment by virtue of the local plasma (Rhodes & Farrell 2019a, 2019b). This leads to potentially hazardous surface charging, which must be better characterized if this safety hazard is to be preventable (or at the very least manageable). Penetrators carrying instruments to study the plasma environment, such as magnetometers and charged particle detectors, would prove invaluable for hazard assessment of locations prior to crewed missions, such as the Shackleton crater PSR (Figure 5). The electrons will diffuse into the crater interior in as little as 5 ms, while the ions cannot diffuse all the way into the depth of the crater in the crater crossing time, and so will presumably form back-currents from the far wall of the crater. This could cause a non-neutral electron cloud inside the crater, leading to the development of large negative surface potentials exceeding −100 V in the PSR (Farrell et al. 2020). Note that the electron cloud would rotate on the crater floor as the direction of the solar wind rotates during the month; the penetrator deployment shown in Figure 4 would facilitate the observation of this process.

A Mote penetrator deployed network (6+ penetrators) with solar power (or nuclear batteries) could be set up in advance of the Artemis crewed landings, to provide mobility and communications support on the lunar surface. This may also include terminal landing navigation, in addition to acting as an "astronaut cell phone" for communications, as well as positioning, navigation, and timing when out of line of sight of either the Earth or any lander.

5. Conclusions

Small penetrators represent exciting new platforms for lunar science and exploration during the next decade, providing opportunities for vastly expanded in situ reconnaissance of extreme lunar environments. Penetrators have the unique potential to overcome obstacles to exploring scientifically strategic and unexplored regions, and to provide a solid basis for the next wave of missions capable of detailed characterization. Owing to the diversity and extensive geographic scale of these regions, a multiplicity of probe locations would be

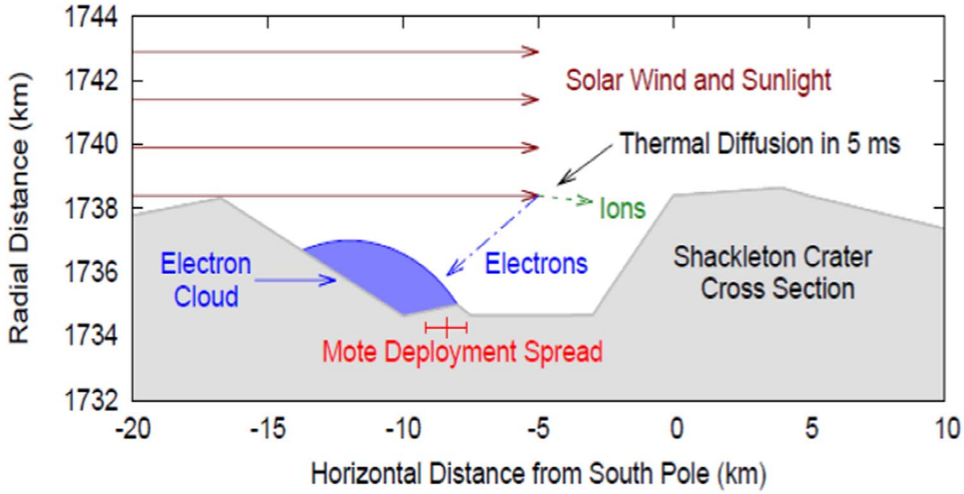

Figure 5. Illustration of how a large PSR crater (in this case, the Shackleton Crater) could be partially filled with a non-neutral electron cloud from the supersonic solar wind. Shackleton Crater (diameter of ∼20 km) with the supersonic solar wind (at a velocity of ∼400 km s^{-1}) would pass in about 50 ms.

required (typically a recommended four–six probes for a high-priority scientific site)—a task ideally suited to penetrators.

With the infusion of technological development funding for the penetrators themselves, as well as for their instrument payloads, it will be possible to build upon the work of past NASA and military penetrator projects to create full-scale engineering models, capable of realistic end-to-end testing. During the next decade, we envision that penetrator systems will take their place alongside orbiters, landers, and rovers in NASA's stable of planetary exploration tools, providing access to extreme environments throughout the solar system, and ultimately representing the future of reconnaissance for human exploration.

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