Return to the Moon: Exploration and Resources

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Introduction

For the first time since the Apollo 17 mission in December, 1972, humans are returning to the Moon—to explore, to test resource-extraction and production technologies, and most importantly, to learn how to live on another world in preparation for the long-range goal of landing humans on Mars and beyond.

NASA's Artemis mission is named after Apollo's twin sister and the Greek Goddess of the Moon. Its goal is to land humans on the Moon by 2024 (NASA, 2020). To reach the Moon and safely return astronauts to Earth, Artemis will use a variety of new spacecraft systems. These include the Space Launch System (SRS), Orion Crew Vehicle, and the Lunar Terrain Vehicle (LTV) for reconnaissance missions (Fig. 1). Artemis is planned to be a measured, step-by-step program over a three-year period (Fig. 2). Early Artemis missions, beginning in 2021-2022, will first characterize the Lunar surface with an assortment of 16 instruments. Polar soil samples will be collected and analyzed for contents such as water and other volatiles. Later in 2022, Artemis will test navigation techniques in Low Lunar Orbit (LLO). An uncrewed mission (Artemis I) will be launched in Low Earth Orbit (LEO) to test the heat-shield system designed to withstand the high temperatures (ca. 5,000° F) of Earth re-entry. The crewed phase of the Artemis program begins in 2023 with launch of the PPE (Power and Propulsion Element) and HALO (Habitation and Logistics Outpost) systems, followed by Artemis II, a 10-day crewed flight around the Moon to test navigation, communication, and life-support systems in a lunar flyby. Finally, in 2024, astronauts with land near the Moon's South Pole, where abundant water-ice resources are known to occur in permanently shadowed regions in crater floors.
China is also seriously engaged in lunar exploration. The objectives of China's Chang'e program are to (1) explore and characterize both the lunar Nearside and Farside, (2) evaluate the lunar-resource potential, and (3) establish a permanent human presence on the Moon. The Chang'e-5 mission recently returned samples of the lunar regolith (unconsolidated upper soil layer) to Earth. This is the first sample-return mission since 1976 when the former Soviet Union's 1976 Luna 24 mission successfully returned samples from Mare Crisium (The Planetary Society, 2021). The Chang'e lander, which touched down in Oceanus Procellarum, located in the northwestern quadrant of the lunar Nearside, collected 1.7 kilograms (3.7 pounds) of regolith with a mechanical scoop and a drill capable of penetrating 2 meters (6.6 ft) underground. An ascent vehicle transported these samples to a service module in lunar orbit. The service module left lunar orbit for Earth, and then released the Earth-return capsule shortly before arrival to Earth. Future Chang'e missions will target the Lunar Farside and Polar areas.

Lunar Resources

The Moon has a variety of resources that can be used for manufacture of rocket fuel, power systems, and construction for long-term, human habitation (Ambrose, 2013). Water-ice is an important lunar commodity. It is the source of hydrogen and oxygen for rocket propellant, with hydrogen being the fuel and oxygen being the oxidizer. For example, the Saturn V rocket that took astronauts to the Moon in the Apollo program in the 1960s and 1970s used hydrogen for its second and third stages, with liquid oxygen for combustion.

A long-term presence on other worlds such as the Moon, to be economically viable and sustainable, will require *in situ resource utilization* (ISRU) of a variety of resources, including regolith materials for construction of a Moon base and solar power installations. Optimal sites for human habitation are located near the poles. These are areas where deposits of water ice and other volatiles occur in topographically low areas such as crater floors in areas of no solar illumination (Bussey et al., 2005; Spudis, 2008, 2018). In addition, topographically high crater rims exposed to near-constant sunlight in polar regions can serve as areas for solar-power installations.

Other important lunar resources include (1) hydrogen and oxygen occurring other than water ice (implanted in the lunar regolith from the solar wind [Wurz, 2005; Crider and Vondrak, 2000; Sinitsyn, 2014]), (2) helium-3 also implanted in the regolith (Schmitt, 2006; 2013), (3) uranium and thorium (Glotch et al., 2010; Yamashita et al.,

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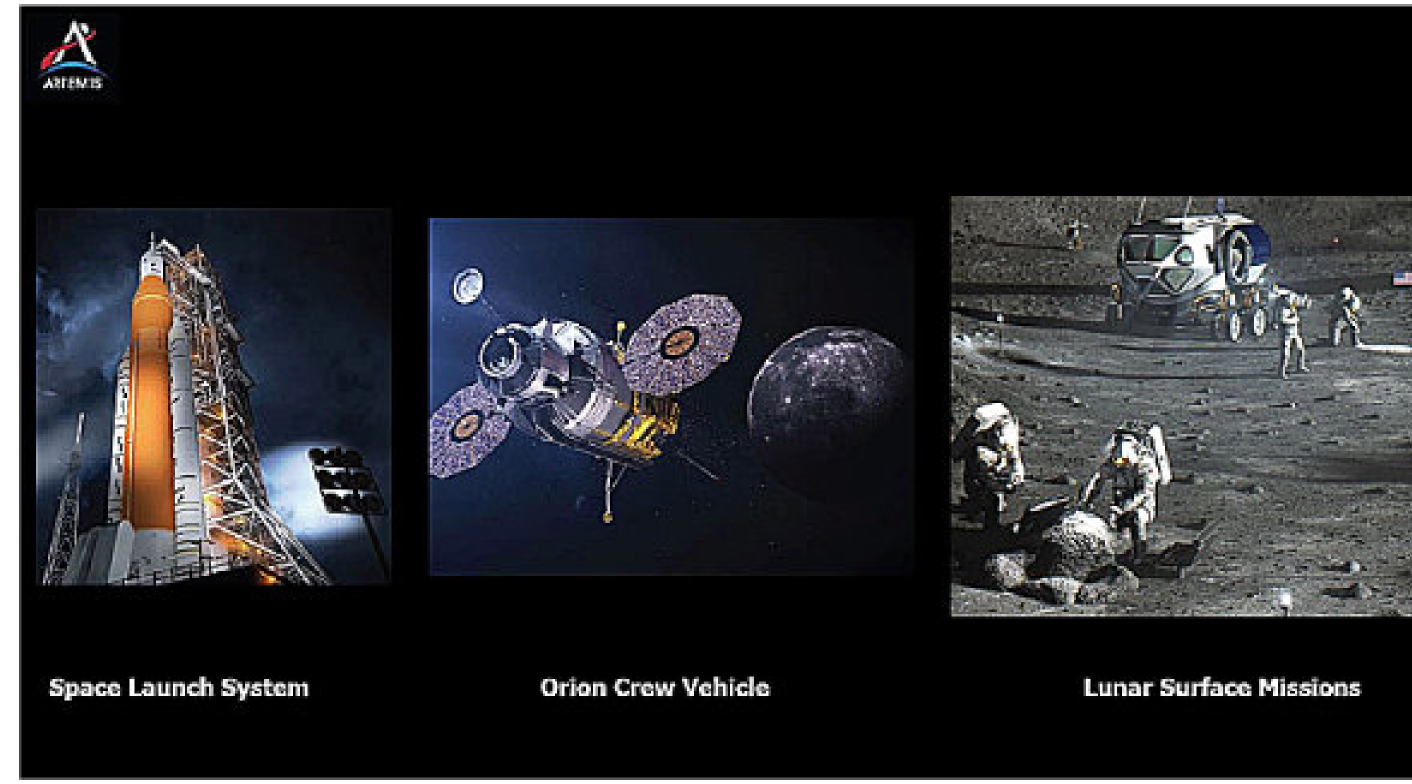

Figure 1. Major components of the Artemis mission, including from left to right, the Space Launch System (SRS), Orion Crew Vehicle, and the Lunar Terrain Vehicle (LTV) for reconnaissance missions. Modified from NASA (2020).

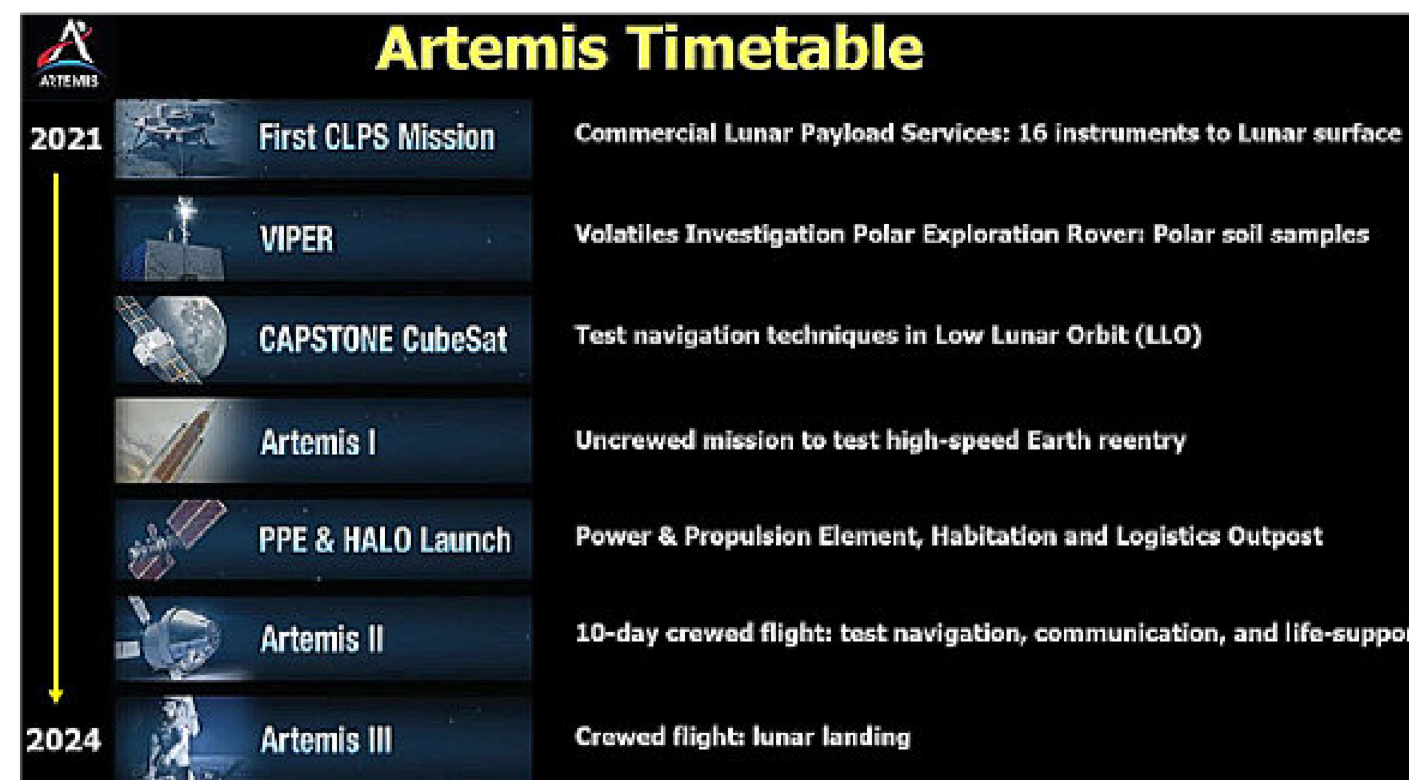

Figure 2. Artemis timetable. The first crewed flight to the Moon is scheduled for 2024. Modified from NASA (2020).

2010), (4) regolith-related metals such as titanium, iron, and aluminum (Papike et al., 1998; Elphic et al., 1998; Meyer et al., 2010; Wieczorek et al., 2012), (5) volatiles and elements of pyroclastic origin that include iron, zinc, cadmium, mercury, lead, copper, and fluorine, (Saal et al., 2008), (6) rare metals and platinum-group elements such as nickel, platinum, palladium, iridium, and gold that may occur within segregated impact melt sheets and layered mafic extrusives (Taylor and Martel, 2003; Schmitt, 2008), and (7) other volatiles such as nitrogen, carbon, and lithium that occur either with breccias or in exhalative deposits (Mathew and Marti, 2000). Many of these resources are summarized in Heiken et al. (1991) and more recently in Crawford (2015).

Water-Ice

The average lifting cost today to exit materials from Earth's gravity well into LEO is approximately $35,000 per kilogram, although this number is being reduced with more-efficient rockets and reusable lift vehicles. Rather than manufacture rocket fuel on Earth and incur the tremendous cost of escaping Earth's gravity well, it will be cheaper to manufacture rocket fuel in space. Because the Moon's axis has a low, 1.5-degree tilt, numerous permanently shadowed regions (PSRs) exist near the poles. Commonly occurring in deep crater floors, PSRs are cold, only a few degrees above absolute zero. For most of the Moon's long, 4.5-billion year history, volatiles such as water-ice and ammonia, and a host of elements and other compounds such as methanol, sodium and sulfur dioxide, accumulated in PSRs as ejecta from impacts of volatile-rich asteroids and comets (Fig. 3). These polar volatiles have for many years hypothesized to exist near the lunar poles (Watson et al., 1961). Although most of these volatiles were lost to space where they settled in sunlit areas, some accumulated in shadowed, *cold* traps in polar areas that have been relatively stable over long periods of time (Fig. 4).

Studies regarding the abundance of cometary and asteroidal material in the Solar System suggest that 20 to 50% of these volatiles should be in the form of water ice near the poles (Hodges, 1980; Ingersoll et al., 1992; Butler, 1997). Other volatiles of cometary origin that may be present at the Moon's poles include methane and ammonia ices, as well as lesser amounts of carbon monoxide, carbon dioxide, methyl cyanide (CH_3CN), and sulfur (Whipple, 1985). However, several long-term processes operating over billions of years are suspected to have reduced this percentage of water ice and other volatiles, including losses from meteorite impacts (Arnold, 1979), photodissociation from ultraviolet light associated with hydrogen Lyman-α emissions (Morgan and Shemansky, 1991), and erosion as a result of collisions from other cosmic-ray and solar-wind particles (Lanzerotti et al., 1981; Crider and Vondrak, 2003; Crider and Vondrak, 2007).

The late Paul Spudis with the Lunar Planetary Institute estimated that between 100 million and 1 billion metric tons of lunar water-ice exist at each pole (Spudis, 2018). This range reflects uncertainties in actual thickness and depth of burial of the water ice, and from the variety of imaging techniques that have been used.

Helium-3

The Moon's regolith is the unconsolidated, upper layer that composes the lunar soil. It contains Helium-3, an isotope of helium that originates from Helium-4 atoms from the solar wind interacting with high-energy cosmic rays. Planetary bodies in the Solar System with atmospheres and magnetospheres such as the Earth and Jupiter are shielded from accumulation of Helium-3, but airless bodies and those with weak to non-existent magnetic fields such as the Moon, Mercury, and asteroids have been passively accumulating Helium-3 from the solar wind for billions of years.

Helium-3 is a potential source of nuclear energy from fusion. It's value as a new source of energy stems from being a low-neutron-emitting source of nuclear energy with a low potential for damage to reactor vessels. In addition to its potential for power generation, Helium-3 can also serve as rocket fuel for nuclear engines, reducing reliance on conventional, chemical propellants.

The distribution of Helium-3 on the Moon is in part controlled its affinity for titanium-iron oxides (for example ilmenite: $FeTiO_3$) in basalts in the regolith (Fig. 5). Lunar Helium-3 occurs in the first few meters of the regolith, which means that it could potentially be mined by strip-mining. It can then be liberated by heating the regolith to 600° C. Even though greatest concentrations of Helium-3 range from only 30 to 50 parts per billion (ppb), the global resource, which includes all concentrations ≥10 ppb, is estimated to be approximately 650 million metric tons (Fa and Jin, 2007). Apollo 17 astronaut Harrison Schmitt estimates that potential Helium-3 resource at 40 ppb in

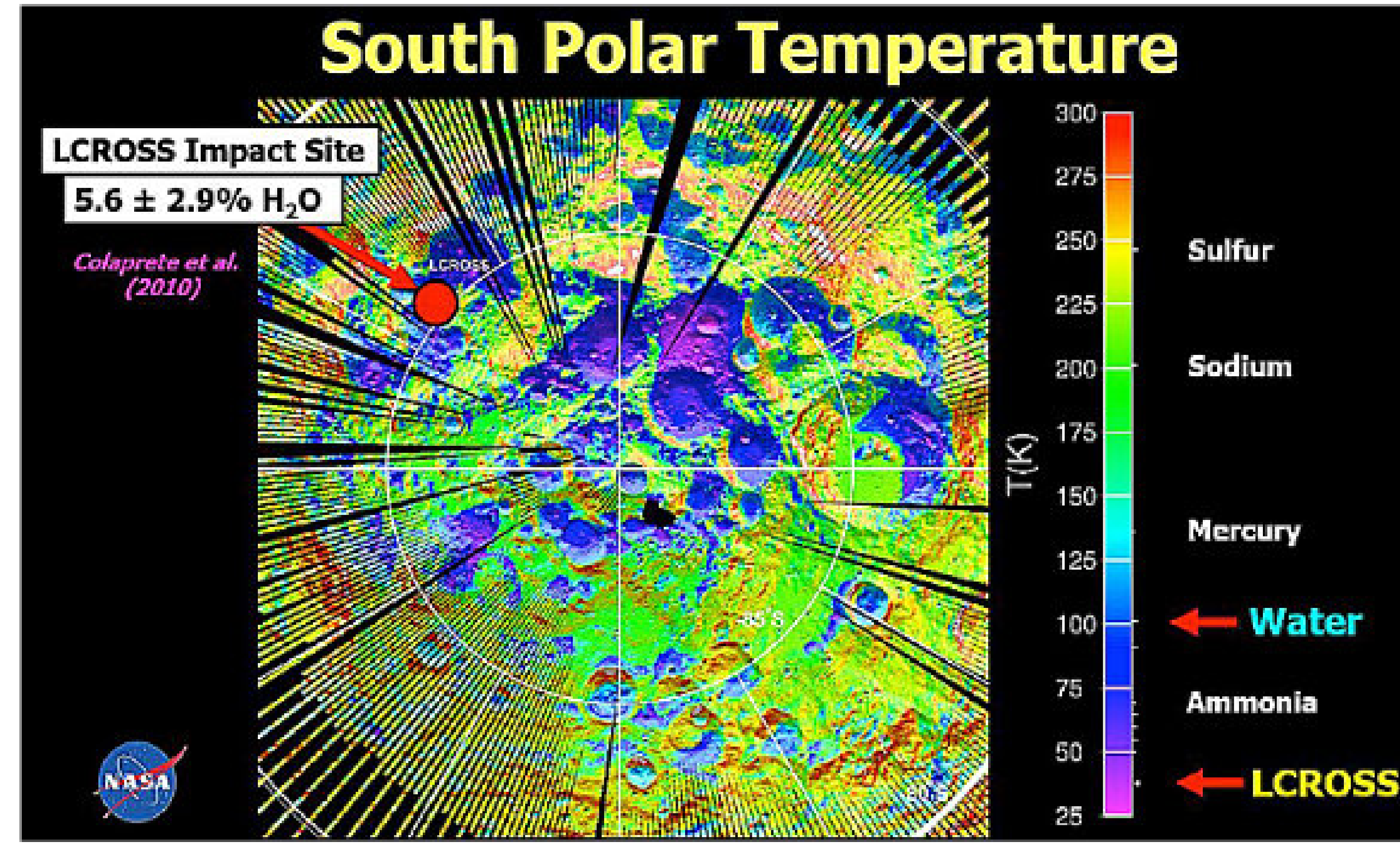

Figure 3. South polar temperatures, LCROSS (Lunar Crater Observation and Sensing Satellite) impact site, and stability temperature of volatiles potentially occurring in polar regions of the Moon. Temperature scale is Kelvin. Modified from Colaprete et al. (2010).

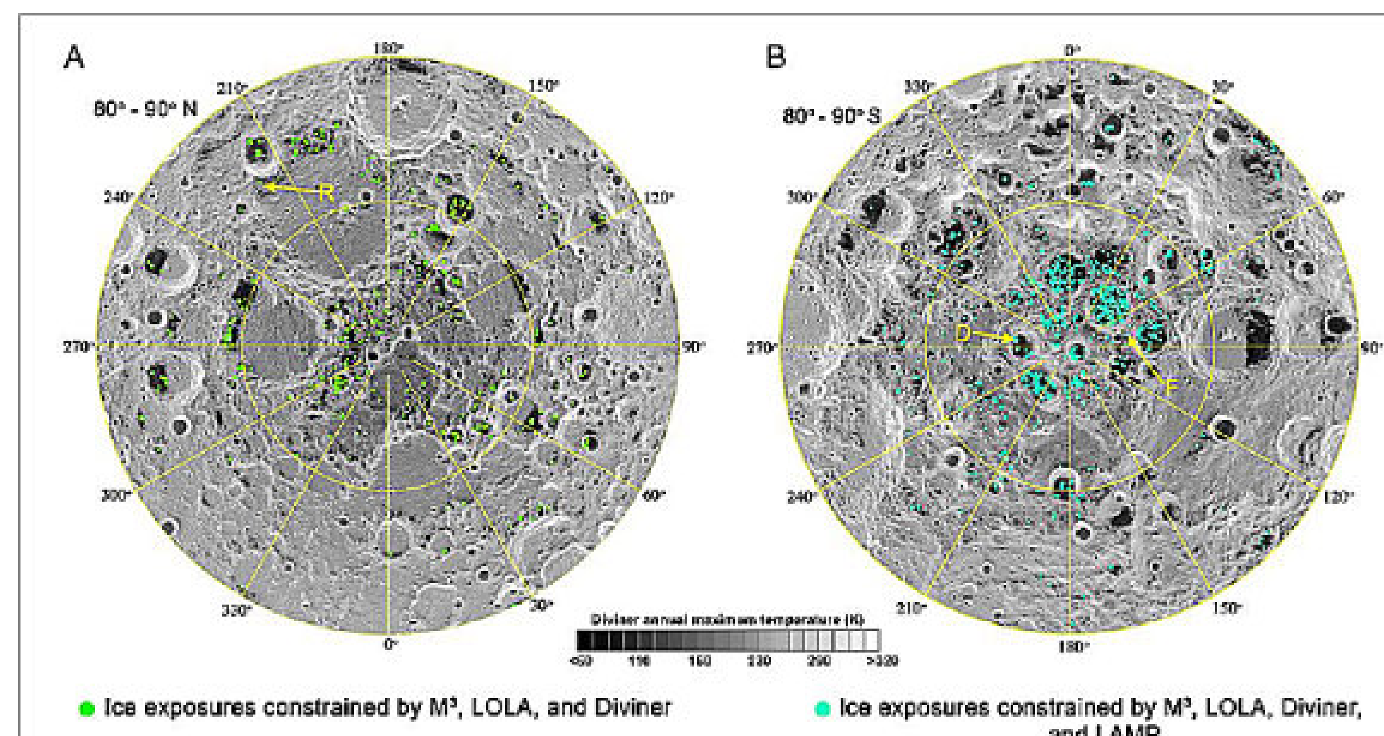

Figure 4. Presence of surface water ice (green and aqua-green dots) in permanently shadowed regions (PSRs) at the North (A) and South Polar (B) Regions of the Moon. Abbreviations: M³ (Moon Mineralogy Mapper), LOLA (Lunar Orbiter Laser Altimeter), Diviner (Full name Diviner Lunar Radiometer Experiment [DLRE]), and LAMP (Lymon Alpha Mapping Project). From Li et al., 2018.

the north and south polar regions alone are more than 33,000 metric tons. Schmitt states that 100 kilograms if Helium-3 has the steam coal equivalent value of $140 million with coal valued at $2.50/million Btu, so the economic potential is considerable (Schmitt, 2006, 2013).

Titanium and Other Metals

Recent analysis of crater-penetration data in Mare Imbrium in the northwestern quadrant of the lunar nearside, as well as other mare-fill units (and therefore potential related metal resources) are thicker than previously inferred (Thomson et al., 2009). The bulk regolith also has a variety of metals, principally titanium, and aluminum, and lesser concentrations of iron. High values of titanium concentration (TiO_2 content 1 to 11 wt.%) occur in young (2.7-3.6 Ga [billion-year]) mare-fill units in Oceanus Procellarum on the northwestern part of the lunar nearside (Elphic et al., 1998). In addition, high concentrations of titanium (>6 wt.% TiO_2) occur in 3.4- to 3.8-Ga basalts in Mare Tranquillitatis (Hiesinger et al., 1998).

Aluminum is ubiquitous on the Moon, being a common component of silicates in breccias and basalts. In addition, many lunar basalts are rich in iron, with some having FeO abundances between 17 and 22 wt.% (Papike et al., 1998). Potassium, associated with rare-earth elements and phosphorus, occurs in late-stage intrusive melts in Oceanus Procellarum and isolated areas in Mare Imbrium. Although K_2O concentrations in KREEP (Potassium/Rare-Earth-Elements/Phosphorus) materials is commonly only 1 to 2 wt.%, the K_2O content in granitic materials, which may be concentrated in silicic domes, may be as great as 5 to 8 wt.% (Glotch et al., 2010; Jolliff et al., 2011).

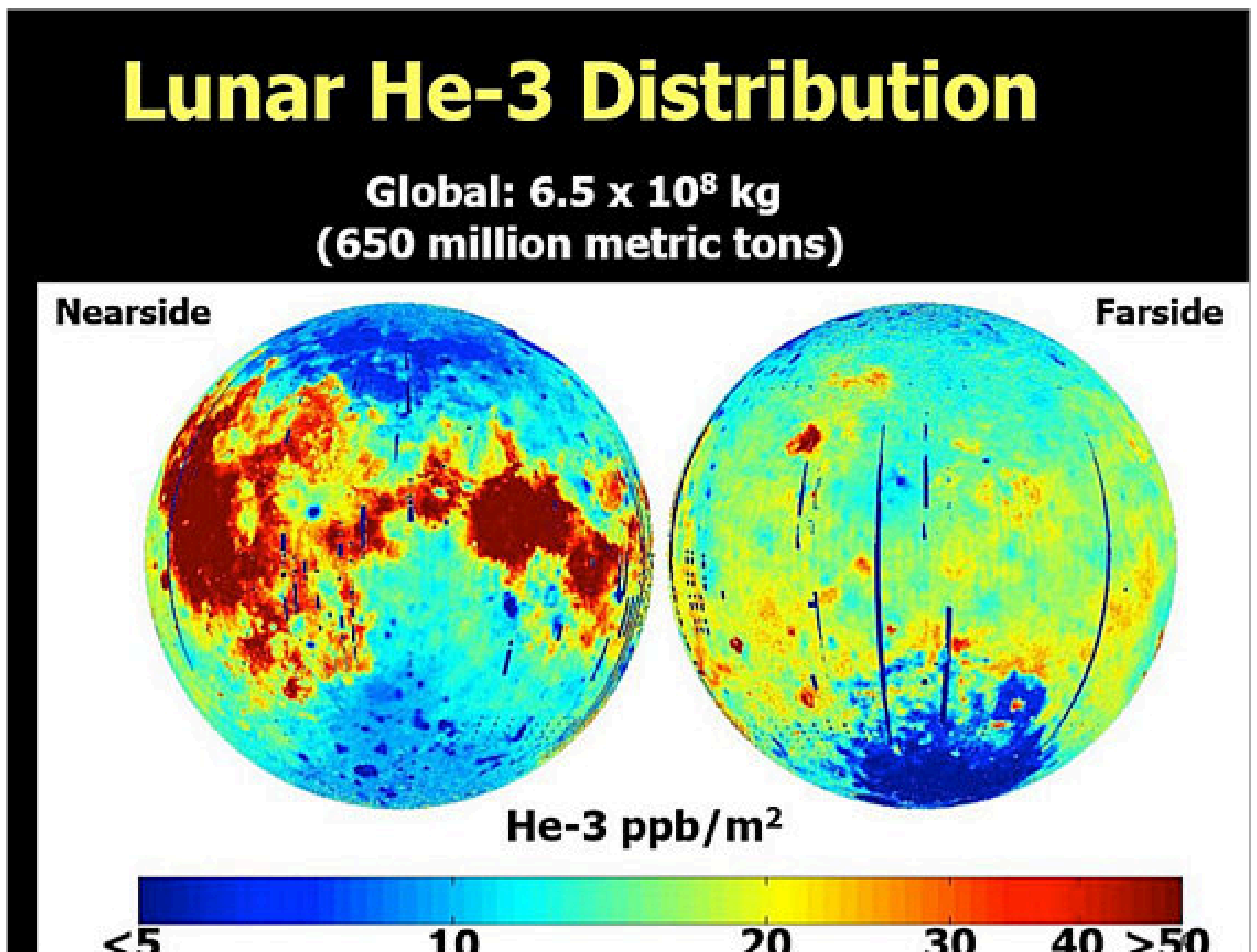

Figure 5. Distribution of Lunar Helium-3 in the lunar regolith. Relatively greater concentrations (more than 30 parts per billion) are much more abundant in nearside lunar maria. In contrast, the lunar farside is relatively sparse in Helium-3 because it is dominated by felsic crust (Jolliff et al., 2000). Modified from Fa and Jin (2007).

Thorium and Uranium, Rare Earth Elements, and Volatiles

Thorium and uranium are also sources for power generation and rocket propulsion in Space (Campbell et al., 2013). Thorium is relatively abundant in the southern part of Oceanus Procellarum, where it is associated with late-stage melts rich in KREEP constituents (Jolliff et al., 2000). Although thorium and uranium are present only as trace elements in most lunar rocks, even in those with abundant KREEP constituents, they may be most concentrated in regolith developed on the slopes and at the base of rhyolitic domes such as Mons Gruithuisen in northwest Mare Imbrium, Compton-Belkovich on the lunar farside (Jolliff et al., 2011), and in pyroclastic deposits in Rima Bode superimposed on highlands between Sinus Aestuum and Mare Vaporum, all of which are located on the lunar nearside (Hagerty et al., 2009). Compounds containing rare earth elements (REEs) are also associated with KREEP deposits and silicic domes.

The Moon also contains volatiles such as nitrogen and carbon, the building blocks of plastics and foodstuffs that will be vital to sustain life on the Moon, in very low levels of concentration (commonly <2 and <10 ppm, respectively) that are bound in breccias, the regolith, and possibly in recent volatile deposits (Mathew and Marti, 2000). Volatiles, including water, also occur in lunar pyroclastic glasses, many at levels greater than 300 parts per million (ppm) (Milliken and Li, 2017) and some greater than 600 ppm (Saal et al., 2008). Hauri et al. (2011, 2015) have also demonstrated that the source of Apollo 15 and 17 pyroclastic glasses sampled by the Apollo 15 and Apollo 17 missions are as volatile-rich as the Earth's upper mantle.

Conclusions

The Moon contains a variety of resources that can be used for manufacture of rocket fuel, power systems, and construction for long-term, human habitation. A primary rationale for in-situ resource development on the Moon and on other bodies in the Solar System is cost-effectiveness—i.e., cheaper than lifting materials from Earth's gravity well. This especially pertains to rocket propellants and construction materials for lunar facilities, where dwellings can be constructed directly from the lunar regolith, helium-3 can be mined in titanium-rich regolith, and water-ice can be harvested and processed in non-illuminated areas in polar regions. Moreover, the Moon also hosts other valuable commodities that include metals (titanium, aluminum, and iron), as well as radiogenic materials such as thorium and uranium.

The Moon is a nearby, natural laboratory where we will learn how to live off-world. Lessons learned on the Moon—construction, mining, fuel processing, energy development, and human survival—will enable us to more efficiently and safely live on other worlds—notably Mars, a more Earthlike planet that is currently the focus of exploration by the Curiosity and Perseverance missions.

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