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Water Ice Resources on the Moon

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Abstract

To be economically viable and sustainable, a long-term presence on the Moon, will require in situ resource utilization (ISRU) of a variety of resources, including regolith materials for manufacture of rocket fuel, power generation, and Moon base construction. Missions from NASA's Artemis and China's Chang'e programs are currently underway to explore, characterize, and evaluate the lunar water ice resource in polar areas. Rather than manufacture rocket fuel on Earth and incurring the tremendous cost of escaping Earth's gravity well, it will be more cost-effective to manufacture rocket fuel on the Moon. Hydrogen resources for rocket fuel on the Moon are concentrated near the poles, where water ice and other volatiles exist in cold traps in permanently shadowed regions (PSRs) in crater floors. For most of the Moon's long, 4.5 billion year (gigaannum [Ga]) history, volatiles such as water ice and ammonia, and a host of elements and other compounds such as methanol, sodium, carbon dioxide, carbon monoxide, ammonia, and sulfur dioxide accumulated in PSRs as ejecta from impacts of volatile-rich asteroids and comets. Local concentrations of water ice near the lunar South Pole locally exceed 5 wt%, although values of 0.5 to 4 wt% are more common. Estimates of the water ice resource at each pole vary from 100 million to 1 billion metric tons. This range reflects uncertainties in the actual thickness and depth of burial of the water ice and from the variety of imaging techniques that have been used.

General Resource Base

To be economically viable and sustainable, a long-term presence on the Moon, will require in situ resource utilization (ISRU). Lunar resources include materials for construction of a Moon base, power systems, rocket fuel, and other materials for sustaining human habitation (Ambrose, 2013). Eight (8) major types of lunar resources are:

1) water ice in polar areas (Crider and Vondrak, 2000; Spudis, 2008),
2) non-polar hydrogen and oxygen implanted in the lunar regolith from the solar wind (Wurz, 2005; Sinitsyn, 2014),
3) regolith-implanted helium–3 from the solar wind (Schmitt, 2006, 2013),

4) uranium and thorium in silica-rich domes and KREEP (potassium–rare earth–phosphorus) basalts on the lunar nearside (Glotch et al., 2010; Yamashita et al., 2010),
5) basalt-hosted metals such as titanium, iron, and aluminum (Papike et al., 1998; Elphic et al., 1998; Meyer et al., 2010; Wieczorek et al., 2012),
6) volatiles and elements of pyroclastic origin that include iron, zinc, cadmium, mercury, lead, copper, and fluorine (Saal et al., 2008),
7) 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
8) other volatiles such as nitrogen, carbon, and lithium in breccias or 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 Significance, Origin, and Resources

Water ice is an important source of hydrogen and oxygen for rocket propellant, using hydrogen for fuel and oxygen for the oxidizer (Ambrose, 2013). The Saturn V rocket that conveyed astronauts to the Moon in the Apollo program in the 1960s and 1970s used hydrogen for its second and third stages, and liquid oxygen for combustion. Current average lifting costs to launch materials from Earth's gravity well into LEO (low Earth orbit) is approximately $35,000 per kilogram, although this cost 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 more cost-effective to manufacture rocket fuel on the Moon (Ambrose, 2013).

Hydrogen, rather than oxygen, is the primary indicator of lunar water ice (Spudis (1996). Oxygen is abundant on the Moon, occurring in silicate and oxide minerals and glasses in all lunar materials. In contrast, hydrogen is less abundant than oxygen on the Moon. Hydrogen occurrence on the lunar surface is in part the result of exposure of the regolith to the solar wind that consists of streams of charged particles (Haskin and Warren, 1991; Schmitt; 2006; Gillis-Davis, 2008; Pieters et al., 2009; Sunshine et al., 2009; Clark, 2009). Although levels of hydrogen in the regolith are small in nonpolar areas, local levels of concentration are sufficient for mining rocket propellants (Spudis (1996). An ~0.4 mi^2 (1 km^2) area of typical mare regolith which has a concentration of 40 parts per million (ppm) could be mined to a depth of ~3.3 ft (1 m) to extract an equivalent amount of hydrogen to launch the Space Shuttle (Spudis, 1996). In contrast, elevated levels of hydrogen and water ice occur in polar areas; e.g., a value of 5.6 wt% water ice is inferred near Cabeus crater near the lunar South Pole (Stopar and Meyer, 2019) (Figure 1). Values as great as 30 wt% of water ice have been inferred from spectral reflectance data (Li et al., 2018), although values of 0.5 to 4.0 wt. % are more common near the lunar poles (Mitrofanov et al., 2010).

Optimal sites for accessing water ice resources and for human habitation are located where there are areas of water ice and other volatiles, which occur in topographically low areas, such as crater floors, in areas of no solar illumination (Bussey et al., 2005; Spudis, 2008) (Figure 1). In addition, topographically high crater rims exposed to near-constant sunlight near these unilluminated crater floors can serve as areas for solar-power installations (Bussey et al., 2005). Commonly occurring in deep crater floors, PSRs are cold (Vasavada et al., 1999). Recent results from the Lunar Radiometer Experiment (Diviner) indicate temperatures as low as 35K (-397^{o}F) in PSRs (Figure 2). The Diviner instrument, onboard the Lunar Reconnaissance Orbiter (LRO), is designed to measure surface temperatures on the Moon. For most of the Moon's multi-Ga history, volatiles such as water ice, ammonia, and a host of elements and other compounds such as methanol, sodium, carbon dioxide, and sulfur dioxide accumulated in PSRs as ejecta from impacts of volatile-rich asteroids and comets. Bussey et al. (2003) estimated that ~2900 mi^2 (~7500 km^2) of PSRs occur within $12^{\circ}$of the North Pole and ~2500 mi^2 (~6500 km^2) of permanent shadow exist within 12° of the South Pole. These values were obtained by simulating conditions of illumination of bowl-shaped, simple craters <12 mi (<20 km) in diameter. Their study demonstrated that craters as far as 20° from the pole contain significant amounts of permanent shadow, with seasonal effects being independent of crater size and latitude for latitudes >70°N or S.

Initial indications of anomalously high hydrogen levels at the poles came from the Clementine mission in 1994, based on radar signatures of polarized anomalies from deeply shadowed craters such as Shackleton near the Moon's South Pole (Spudis, 1996; Nozette et al., 2001;). The presence of enhanced hydrogen levels in polar regions is further demonstrated by 1999 Lunar Prospector mission (Feldman et al., 1998). Epithermal-neutron data suggest that hydrogen enrichment is correlated with PSRs (Elphic et al., 2007) and that water ice may occur as disseminated grains at greater than 1% abundance (Feldman et al., 2001; Eke et al., 2009).

The leading explanation for anomalously high hydrogen levels in lunar polar regions is that water ice deposits and other volatiles accumulated as ejecta from lunar impacts from water- and volatile-rich comets and asteroids that settled in PSRs in the last 3 Ga. Based on physical chemistry computations and models, Watson et al. (1961) suggested that evaporation rates for water and mercury should be low in lunar polar areas because of low temperatures in PSRs. Other compounds such as sulfur dioxide, hydrogen chloride, ammonia, and krypton were also inferred be present. Studies regarding how much cometary and asteroidal, impact-related material may have been transported over the surface of the Moon 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). Arnold (1979) estimated that the amount of water delivered to the Moon from cometary impacts over the past 2 Ga could be as much as ~1010 metric tons (~1013 kg). Although volatiles deposited on the lunar surface rapidly sublimate in sunlit areas where the temperature reaches 100°C during the day, these materials would be stable in areas of permanent shadow where the temperature is slightly above absolute zero.

Several long-term processes operating over billions of years are suspected to have reduced the percentage of water ice and other volatiles in lunar polar areas, including losses from impacts from meteorites (Arnold, 1979), photodissociation from ultraviolet light associated with hydrogen Lyman–α emissions (Morgan and Shemansky, 1991), and erosion because of collisions from other cosmic-ray and solar-wind particles (Lanzerotti et al., 1981; Crider and Vondrak, 2003; Crider and Vondrak, 2007). Moreover, the absence of bright radar anomalies in lunar polar areas that coincide with deeply shadowed craters as observed from terrestrial-based radar data, as well as data from neutron spectroscopy from the Lunar Prospector mission, suggests that the water ice does not occur in surficial layers, but rather in disseminated form at shallow levels at 10 to 25 in (35 to 65 cm) below a layer of dry regolith (Gläser et al., 2021).

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, depth of burial of the water ice, and from the variety of imaging techniques that have been used. These imaging techniques are from LRO and Chandrayaan–1 missions. They include the Lyman Alpha

Mapping Project (LAMP), thermal imaging from Diviner (Diviner lunar radiometer experiment), Lunar Explorer Neutron Detector (LEND), and LOLA (Lunar Orbiter Laser Altimetry), as well as radar, ultraviolet reflectance, and near-infrared spectral analysis.

An indirect measurement of the amount of water ice that may exist near the lunar South Pole was conducted on October 9, 2009, by impacting the empty Centaur upper stage of the LRO launch vehicle into the floor of Cabeus crater near the south pole of the Moon (Figures 1 and 2). An ejecta plume was created by the impact. The orbiting LRO spacecraft measured the absorption of sunlight from the ejecta plume in the near infrared, detecting both water vapor and ice. A value of 5.6 ± 2.9 percent by wt% of water was inferred from spectra of the ejecta plume (Spudis, 2018). Other materials detected in the plume include methane (CH_4), carbon monoxide (CO), and ammonia (NH_3).

Current and Future Investigations

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. Artemis is planned to be a measured, step-by-step program over a three year period. An orbiting Lunar Gateway system is also underdevelopment. It will have a habitation module, airlock, and a Power and Propulsion Element (PPE) (Cook, 2022). The Lunar Gateway will be a small, lunar orbiting space station, a staging base for lunar crews to land on the Moon.

Early Artemis missions, beginning in 2021–2022, first characterized the lunar surface with an assortment of 16 instruments. An uncrewed mission (Artemis I) was launched on November 16, 2022, with the objectives of flying around the Moon and successfully returning to Earth (NASA, 2022). After its 1.4 million mi (2.2 million km) mission, the Orion spacecraft returned to NASA’s Kennedy Space Center on December 30, 2022. The crewed phase of the Artemis program begins in 2023 with launch of the PPE 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 will land near the Moon’s South Pole, where abundant water ice resources are known to occur in PSRs in crater floors.

Robotic missions on the Moon are also planned to characterize and evaluate the lunar water ice resource. NASA’s Polar Resources Ice Mining Experiment–1 (PRIME–1) will be the first NASA robotic mission of the Commercial Lunar Payload Services (CLPS) in support of Artemis (Cook, 2022). Planned to land near Shackleton crater near the lunar South Pole (Figure 1), PRIME–1 will drill up to 3 ft (1.8 m) deep into the regolith. A mass spectrometer will analyze drill cuttings for water ice and other volatiles.

VIPER (Volatiles Investigating Polar Exploration Rover) will also investigate natural lunar resources in a PSR on the western edge of Nobile crater near the lunar South Pole. Launch of the VIPER mission is scheduled for November 2023 or possibly later (Cook, 2022). The VIPER rover's mission is planned for 100 days, during which it will go on traverses for several kilometers, collecting data on different types of regolith in varying degrees of solar illumination, including areas in complete darkness. VIPER's Neutron Spectrometer System (NSS) will detect subsurface water, after which the rover will visit prospective locations. It will then use a 3.3 ft (1 m) long TRIDENT drill to acquire samples for water ice analysis by two onboard spectrometers.

China is also seriously engaged in lunar exploration and resource characterization. The three main 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 to Earth. This was 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 3.7 lb (1.7 kg) of regolith with a mechanical scoop and a drill capable of penetrating 6.6 ft (2 m) 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.

Summary and Conclusions

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. A primary rationale for in-situ resource development on the Moon 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 in relatively greater concentrations can by mined in titanium-rich regolith, and water ice can be mined and processed in PSRs. 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 Ga 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. 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. Estimates of the water ice resource at each pole vary from 100 million to 1 billion metric tons. This range reflects uncertainties in the actual thickness and depth of burial of the water ice and from the variety of imaging techniques that have been used.

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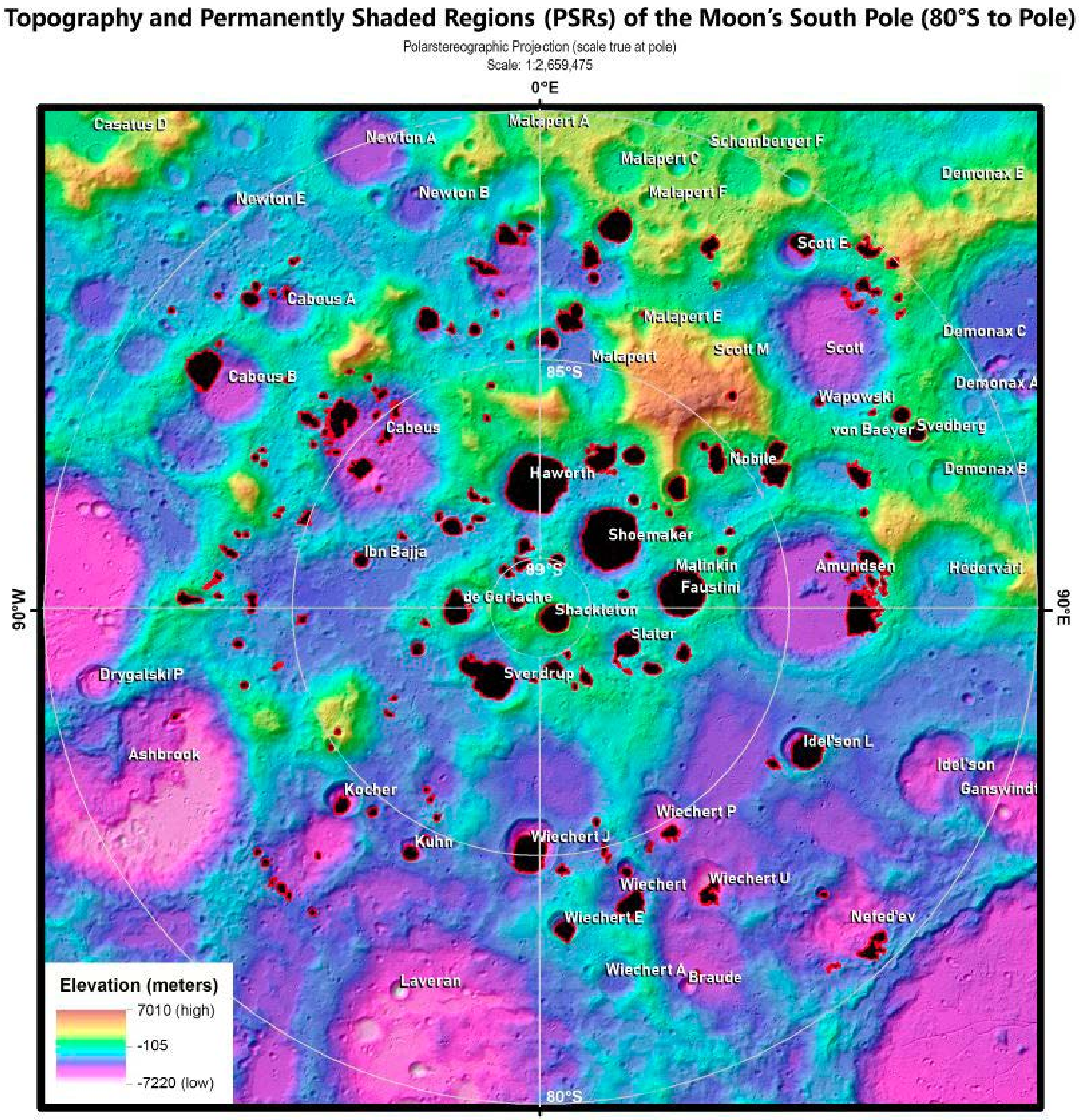

Figure 1. Topography and permanently shaded regions (PSRs) of the Moon's South Pole (80°S to pole). PSRs cover approximately 3% of the Moon's south pole (from Stopaer and Meyer [2019]. Cabeus, site of the LCROSS impact (Figure 2), is 59 mi (98 km) across.

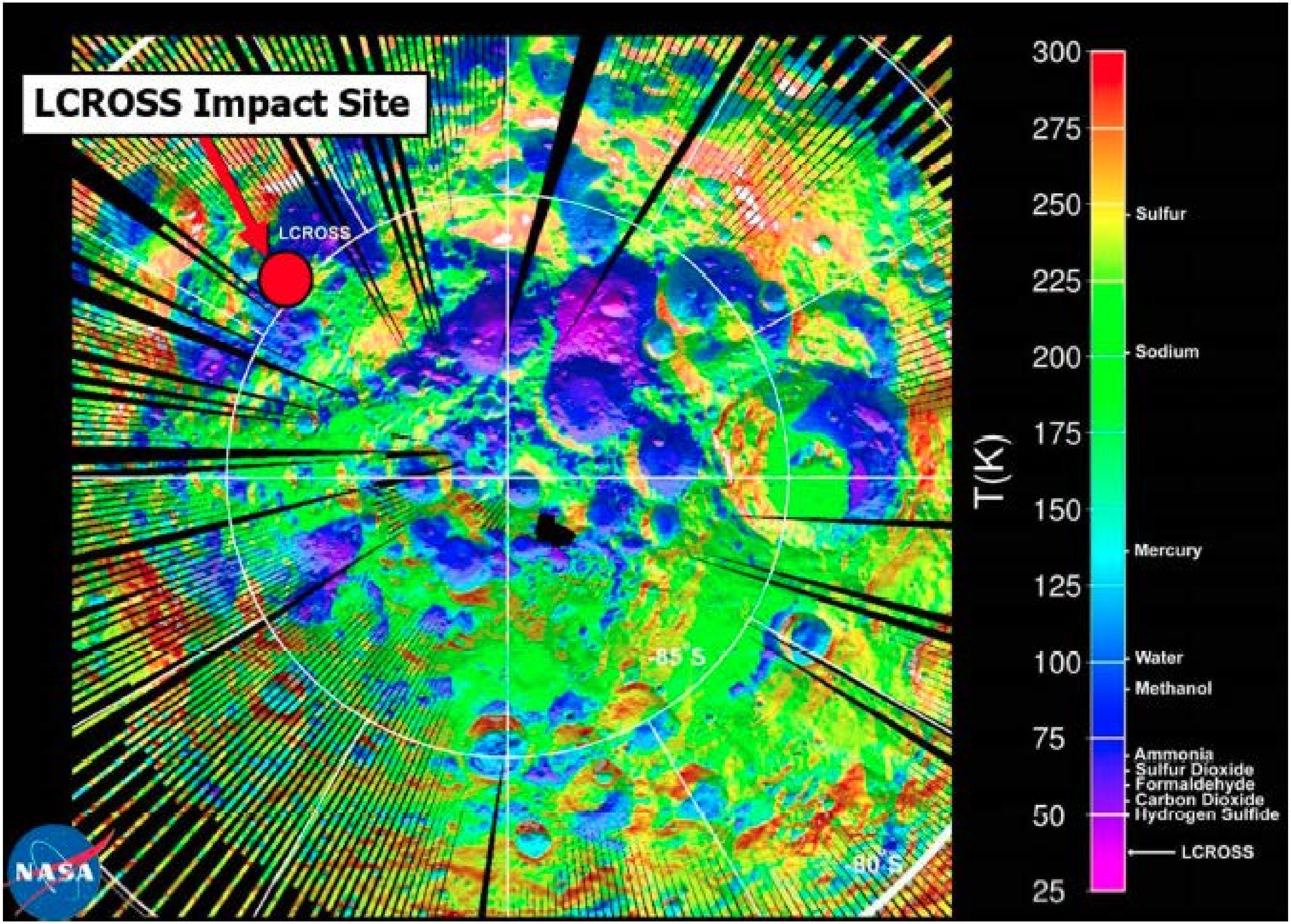

Figure 2. South polar temperatures, LCROSS (Lunar Crater Observation and Sensing Satellite) impact site (Cabeus crater, upper-left part of figure; also shown in Figure 1) (modified after Colaprete et al. [2010]). Temperature scale is Kelvin, with purple areas ranging from 25 to 50K, dark blue from 50 to 100K and warmest temperatures in white (>300K). Also shown are sublimation temperatures for various chemical species at lunar surface conditions.