Permanently Shaded Regions: Future Exploration Of A Unique Solar System Environment.
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Introduction: Permanently shaded regions (PSRs) are locations on planetary bodies that do not see the Sun for geologically long periods of time, and therefore have unique properties compared to other locations on planetary bodies. If PSRs exist on airless planetary bodies, they will have very cold temperatures (<~120 K) because they radiate directly to space with no source of heat input other than residual interior heat from the body itself and small amounts of multi-bounce thermal photons from nearby sunlit locations. The low temperatures that exist for long durations within PSRs can result in a variety of interesting effects. One of the most intriguing is that volatile materials, especially water ice, can become trapped within PSRs as a direct consequence of the cold temperatures. Thus, while the residence time of volatiles for non-PSRs is short with timescales of days to weeks, the residence time of volatiles within PSRs can be geologically long (millions to billions of years).

The type examples of PSRs within the solar system are those that exist on the Moon and Mercury. The axes of rotation for both these bodies are nearly perpendicular to their orbital plane around the Sun (1.5º for the Moon, 0.034º for Mercury, where 0º would be exactly perpendicular)[1, 2]. Because the Moon's and Mercury's rotational orientation has been stable for billions of years [1, 3], there are craters near the poles of both bodies that are sufficiently deep such that their interiors do not see the Sun, and they are therefore PSRs.

Volatiles Within PSRs: The existence of PSRs does not guarantee they will accumulate volatiles over time, but only makes such accumulation possible. There is a range of possible volatile sources that can include sources interior (endogenous) or exterior (exogenous) to the planet. Endogenous sources could be residual volatiles from ancient volcanism as well as more recent volatile releases or outgassing events [4]. There is a large variety of exogenous sources that can include comets, asteroids, interplanetary dust particles, solar wind, and even occasional giant molecular clouds that may pass through the solar system [5]. In terms of their time of delivery, all sources can in principle be continuous and/or episodic. In a broader sense, it is now being recognized that "dry", airless planetary bodies have a volatile transport system [5, 6], and when there are PSRs, such as on the Moon or Mercury, the PSRs are a key sink in such a transport system.

A fundamental result that has emerged from these studies is that in spite of similar PSR environments, the quality and quantity of volatile enhancements at the Moon and Mercury are very different. At Mercury, there is strong evidence from many types of measurements that its PSRs contain large amounts of volatiles. In contrast, while the Moon shows evidence of volatile enhancements within its PSRs, the volatile abundances are much less than at Mercury and appear non-uniform across different PSRs. Trying to understand these Mercury/Moon differences directly leads to trying to understand how the volatiles reached the PSRs and their time history within the PSRs. Much understanding has been gained, but many fundamental facts and properties of PSRs are not yet known. As a consequence, there is still significant information and data that need to be gathered about PSRs to enable further understanding. While some of these data can be obtained remotely from orbital spacecraft, measurements will ultimately need to be acquired inside PSRs from the surface of Mercury and the Moon.

It is for these reasons (and others explained below) that PSRs have become a topic of intense study and interest within planetary science. Specifically, studies of PSRs apply to all of NASA's Planetary Science Goals (**Table 1**). Because PSRs are so different than other planetary environments, they contain a wide range of fascinating effects, processes, and targets of scientific study. In addition to volatile enhancements, other interesting attributes about PSRs include unique surface charging and space plasma physics effects [7, 8, 9], potentially distinctive geotechnical properties of the persistently cold and volatile-rich regolith [10, Schultz et al., 2010], and the possible organic synthesis that may take place within PSR volatiles due to long-term cosmic ray bombardment [11]. Because of their unique nature, PSRs can be difficult to study, and even now in the early 21st century there are many fundamental aspects of PSRs that are not understood. Nevertheless, current and future studies of PSRs hold great promise. PSRs are a significant scientific resource, not only for what they can reveal about their host planetary bodies, but because they have been trapping volatiles for up to billions of years, they are a storehouse of solar system volatile materials, and are therefore a resource for future studies of solar system history. Finally, for at least the Moon, the existence of volatile enhancements, and especially water ice, can enable future human exploration to the Moon and elsewhere beyond in the solar system [12].

Planetary Science Goal	**PSR Application**
ORIGINS	Study time history of solar system volatiles [5]
WORKINGS	Study unique processes that operate within PSRs [7, 8, 9]
LIFE	Study pre-biotic but possible organic material in a cold, stable environment [11]
RESOURCES	Prospect for and possibly utilize PSR volatiles for future solar system exploration [12]

Table 1. Studies of solar system PSRs address all of NASA Planetary Science goals.

PSR Exploration in 2050: Much has been learned in the first half-century of PSR exploration. While the field started with a few speculative studies about possible volatile enhancements within PSRs [13], it has reached a well-bounded understanding of the nature of PSRs and volatile enhancements within PSRs [14]. However, while a broad understanding is now known, there are still many basic and fundamental aspects of PSRs and PSR volatiles that are still not understood. The nature of the soil and layering (mechanical, detailed composition) are still largely unknown. Models have been generated and predictions have been made about processes that operate within PSRs, but actual knowledge of such processes is limited. The major question of why the PSR volatiles are so different at the Moon and Mercury is still not resolved.

A new leap in knowledge will require landed measurements from within a PSR. Such measurements are essential but challenging. One of the biggest challenges is the need to operate a landed spacecraft in the very cold PSR environment, which is difficult for engineering (power, thermal, mechanical) and operational reasons. At Mercury, there is the additional challenge of safely landing a spacecraft in the deep gravitational well at Mercury's location near the Sun. Nevertheless, such missions would reveal fundamentally new information about PSRs (composition, stratigraphy, processes) that would likely challenge and expand our current understanding of PSRs.

There are no currently planned PSR-only-landed missions, but NASA is currently studying a lunar polar rover called Resource Prospector (RP) that would carry out investigations in sunlit regions near south pole PSRs [15]. While the RP rover will not be designed to survive in large, deep PSRs, it may still investigate small shaded regions in which enhanced volatiles might be present and PSR-like process might be operating. There are also reports that the Russian and Chinese space agencies are planning lunar polar missions, although details of PSR-specific missions are unclear. In any case, an in-situ PSR mission (or series of missions) will likely be accomplished by some or multiple space agencies and will provide significant changes in our understanding of PSR volatiles.

A sequence of such missions could be accomplished during the time leading up to 2050. After the reconnaissance work carried out by RP, a dedicated PSR-only lander could be delivered to a large lunar PSR and obtain the first in-situ data from within a large PSR. While mobility might be desired for such a mission, the information gained from even a static lander would likely transform our current understanding of PSR environments. After this initial mission, increasingly complex missions could be staged to carry out more detailed investigations of lunar PSRs. Finally, using information gained and technology developed from this round of missions at the Moon, one or more missions could be sent to other PSRs in the solar system, such as the PSRs at Mercury, and maybe even newly discovered PSRs, like what is thought to exist at the asteroid Ceres [16].

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