THE LUNAR VOLATILE SYSTEM IN SPACE AND TIME: SUPPLIES TO THE LUNAR POLES. P.G. Lucey; D. Hurley; W. Farrell; N. E. Petro; M. Cable; D. Dyrar; T. Orlando; M. McCanta; E. Fisher; K. Hibbitts; P. Prem; M. Benner; P. Hayne; R. Green; C. M. Pieters; K. Mandt; M. Horanyi; J. Halekas; S. Li.

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Introduction: The revolution was not televised, but it was published in Science. A series of papers in the years 2008, 2009, and 2010 [1,2,3,4] forced upon the lunar science community a new paradigm, where the Moon changed from an anhydrous, desiccated world, to one where water is an essential part of the conversation.

The revolution invites a rethinking of lunar volatile evolution in time and space, assembling pieces that have been developing over the past decade, of which the poles are a vital part. The lunar volatile system can broadly be divided into three epochs: (1) in the last billion years volatile inputs are dominated by the solar wind and by the steady impact of small meteorites; (2) from one billion years ago to the stabilization of the lunar crust just over four billion years ago volatile inputs from large volcanic eruptions [6] and impacts by large comets and wet asteroids [7] dominate; and (3) comprises the formation of the Moon and events shortly thereafter, when the Moon acquired its initial volatile inventory that is seen today in the lunar samples, and driving lunar volcanism throughout its history. Each of these epochs contributed to the lunar polar deposits and showed critical inputs to their present conditions.

The Dynamic Now: The solar wind and small meteorites introduce volatiles into the system, and may induce chemical reactions in surface materials that may contribute molecular water and perhaps other mobile species into the lunar atmosphere, potentially available for cold trapping at the lunar poles. The solar wind has been suggested as a source of surface hydrogen ’deposits’ for decades, since [8] proposed formation of hydroxyl from reaction of solar wind protons with lunar surface oxygen. Similarly, molecular water was proposed to form in space weathering reactions involving reduction and production of nanophase iron [9]. However, how much hydrogen is converted to mobile species available to the poles is not known. Hydrogen is the largest component of the solar wind in the form of protons with energies around ~1 keV, including intense coronal mass ejections with energies ranging up to 10s of keV. One of the surprising discoveries of Chandrayaan-1 was the presence of promptly reflected high energy neutral hydrogen atoms that constitute a large fraction of the incoming solar wind [10]. The balance of the solar wind may lie in lower energy and thermal energies [11], but this range of reflected solar wind hydrogen remains unmeasured at the Moon. The measurement gap allows that little solar wind is available for surface reactions to supply the poles.

The diurnal, latitude and temperature variation in the strength of the lunar 3 μm band observed by M3 and Deep Impact is suggestive of the presence of mobile water that migrates along temperature gradients, requiring continuous production of molecular water from solar wind [4]. Alternatively, the varying signal may be produced from in-place variations in hydroxyl abundance with no mobile compounds. Hydroxyl may be formed from solar wind, then lost to H₂ with increasing temperature [12,13] with no participation by molecular water. Even the variations in abundance suggested by the spectral studies have been called into question as being plausibly attributed to contamination by lunar thermal emission [14]. Therefore the ability of the solar wind to produce molecular water as a source for the poles remains conjecture, and the subject of active research.

The abundance of water in the atmosphere is now tightly constrained by LADEE observations from 50 km. The background level of atmospheric water in thermal equilibrium with the surface is very low, less than 1 molecule per cubic centimeter, and this in turn constrains a continuous source like solar wind production of water, perhaps casting additional doubt on the equating of spectral variation with abundance variation. There is a potential alternative however: production of water may feature interactions of neighboring hydroxyls at the surface, and water formation from this process may produce water that is rotationally hot, but kinetically cold, and so would not rise to altitudes to be sampled by LADEE.

LADEE’s neutral mass spectrometer did observe large spikes in water abundance often coincident with meteor showers [15]. This water can be attributed to that borne by the meteorites themselves, or possibly to the impacts providing enough energy to favor water production on the surface from chemical energetic pathways not available to diurnal lunar surface temperatures.

LADEE also may have revealed a lunar carbon cycle with its detection of methane in the atmosphere.
Lunar Polar Volatiles 2018 (LPI Contrib. No. 2087)

Approximately the volume of water ice possibly stored by the Moon could sequester about 500 km$^3$ of molecular water, bringing the current abundance of about 100 ppm, the regional content of volatile species to more than 1%. This opens the door to production of other mobile carbon species such as alcohols on the illuminated surface. Significantly, carbon species were detected in the LCROSS plume [18,19].

The contemporary processes that may contribute volatiles to the poles from locations moonwide are only glimpsed by current measurements. The hydrogen budget is incompletely measured so the magnitude of the potential solar wind contribution is poorly constrained. Directly detected mobile species that may supply polar cold traps are limited only to LADEE’s methane and water measurements; other data, such as the varying 3 µm band are suggestive, but not definitive of the presence of mobile water.

The Violent Middle Ages: Looking farther into the past, the impact rate was dramatically higher and impacts of large comets and wet asteroids were common. In the beginning, the constituent ices of an asteroid or comet nucleus vaporize; a significant part of this vapor remains gravitationally bound to the Moon, transforming the tenuous, collisionless lunar exosphere into a collisionally thick, transient atmosphere [7,19] that may provide very large inputs to the lunar system. The importance of volatile contributions from lunar volcanic eruptions has only recently been recognized [6], with temporary atmospheric pressures estimated to exceed 1% terrestrial and collisional lifetimes in the 10’s of millions of years. Reconciling these two potential sources of thick, ferociously reactive water vapor atmospheres with the properties of lunar soil has yet to be done, but the likelihood of large inputs of volatiles into the lunar system seems inescapable.

The implications of such temporary atmospheres has barely been touched. The atmospheric heat transport may drastically increase the temperature of the polar cold traps, and drastically reduce the diurnal surface temperature contrast. Alternatively, the collisional atmosphere may be difficult to develop as from its outset it is subject to collapse upon the entire 100 K night side cold trap, with sunrise subjecting the mass of volatiles piecewise to photochemical loss. Regardless, from a thermophysical standpoint, during these high flux volatile inputs, the Moon would be an utterly different place.

During this era, the vigor of the impact rate also caused the regolith itself to be a significant volatile sink that may interrupt flows to the poles. Even assuming the current abundance of about 100 ppm, the regolith could sequester about 500 km$^3$ of molecular water, approximately the volume of water ice possibly stored in permanent shadow in the upper meter at 1 wt. % abundance. The impact and volcanic volatile contributions dwindled over time and the formation of the cold traps themselves may have post-dated most of the activity [20]. If there were once thick ice sheets in the PSRs, those have eroded, presumably by impacts [21].

The Beginning of History: Via the volcanic eruption route, the polar cold traps may have been partly supplied by the Moon’s internal water. There is some access to the inferences about initial inventory through measurement of the volatile abundance of volcanic glasses, and remote measurements of water contents of deeply derived geologic units.

Conclusion: Throughout lunar history, volatile sources and cycles have provided potential supplies to the lunar poles, but many first order aspects remain unmeasured or only incompletely measured and much remains to be understood.