On Lunar Volatiles and Their Importance to Resource Utilization and Lunar Science

White Paper for the Inner Planets Sub-Panel of the Planetary Decadal Survey for 2011-2020

Author: Arlin Crotts, Professor of Astronomy,
Columbia Astrophysics Laboratory, Columbia University,
550 West 120th St., New York, NY 10027
Telephone: (212) 854 –7899, arlin@astro.columbia.edu

September 14, 2009

Finding volatiles at the Moon's surface is a prime goal of lunar science e.g., the reason for the *LCROSS* mission. There are major and recent findings regarding endogenous volatiles in the Moon, however, which must receive more attention and analysis given their likely bearing on these issues. The implications promise significant potential in terms of *in situ* resource utilization as well as our understanding of the lunar interior and its origin.

Prime, recent findings are careful analyses (Saal et al. 2008, Hauri et al. 2009) showing picritic glasses from the deep interior that form fire fountain spherules are rich in volatiles, especially sulfur and water. Since spherules form as droplets in ballistic arcs through the vacuum, outgassing implies even higher volatile abundance in the magmatic state. Contrary to our usual view of the lunar volatile content, magma from this part of the deep interior appears nearly as volatile-rich as some basalts on Earth e.g., along mid-ocean ridges (Saal et al. 2008). High volatile levels are also implied for lunar apatite (McCubbin et al. 2008, 2009).

Why do these volatiles exist at all? How are they consistent with views of the Moon's origin? Where do they arise? How do they propagate to the surface? Do they still leak out? Might they have accumulated nearer the surface on their way to the vacuum?

The Moon's atmosphere consists primarily of ^{40}Ar, by mass, due to ^{40}K beta decay. The locus of this argon is unclear, but appears to outgas episodically on timescale of roughly a month or less (Hodges & Hoffman 1975). This amount of argon derives deeper into the interior than the regolith, 100 km or more, and might as easily arise in the asthenosphere (Hodges 1977).

Large amounts of episodic outgassing from the interior seem to still occur. On at least four occasions, the heavy radioactive gas ^{222}Rn has been detected pooling on the lunar surface (Gorenstein et al. 1974, Lawson et al. 2005). Statistically, these sites correspond well to optical transient phenomena locations reported by observers on Earth (Crotts 2008, 2009). Also, other sites on the surface have been eroded recently but not by impacts, as determined by optical maturity measures, crater counts and other techniques. The most viable hypothesis for these features is recent, massive outgassing (Schultz, Staid & Pieters 2006).

Radiogenic gas (^{40}Ar, ^{222}Rn, presumably ^{4}He) leak from the deep interior, as did molecular gas long ago (at least H_2O and SO_2 presumably). This connection should be studied. More urgent, however, is the possibility that water vapor outgassing long ago near the poles would tend to freeze out before reaching the surface (Crotts & Hummels 2009). Over large areas this might occur at depths sufficiently far below the surface and cold enough for ice to persist over geologically prolonged timescales. This promises a valuable exploration resource and a unique portal into the interior.

There have been several recent instruments planned to study related questions, but by design or bad luck none will address the core issues. The *Chandrayaan-1* mission has failed, taking with it the NASA-sponsored Moon Minerology Mapper (M^3), which was the only instrument capable of isolating hydrated minerals via hyperspectral imaging. The otherwise successful *Kaguya* (*SELENE*) suffered an electrical failure that seems to have limited results from its alpha particle spectrometer, the only instrument sufficiently sensitive to find lunar ^{222}Rn outgassing. In principle, the *LADEE* satellite could study the spatial distribution of neutral species in the lunar atmosphere, but in its planned equatorial orbit it will at best provide a global composition measurement.

Since the rocket exhaust from a single Orion/Altair mission might double the mass of the lunar atmosphere, the National Research Council's *Scientific Context for the Exploration of the Moon* (SCEM) calls upon NASA to establish now the lunar atmosphere's composition, sources of origin, spatial distribution and propagation to the poles. The SCEM is very detailed about its goals regarding volatiles, laying out several tasks that must be done. The SCEM (Finding 7) urges that we must "understand and characterize the lunar atmosphere. The lunar atmosphere is tenuous and therefore fragile. Its pristine state is vulnerable to alteration from robotic and human activities." The NRC urges NASA (SCEM Recommendation 7): "To document the lunar atmosphere in its pristine state, early observational studies of the lunar atmosphere should be made, along with studies of the sources of the atmosphere and the processes responsible for its loss. These include a full compositional survey of all major and trace components of the lunar atmosphere down to a 1 percent mixing ratio, determination of the volatile transport to the poles, documentation of sunrise/sunset dynamics, determination of the variability of endogenous and exogenous sources, and determination of atmospheric loss rates by various processes."

The SCEM demands much more about volatiles. Unfortunately, few if any of these goals are being met. Science Goals 4b, 4c, 8b, 8c and 8d call on us to (4b) "Determine the source(s) for lunar polar volatiles." – (4c) "Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions." – (8b) "Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity." – (8c) "Use the time-variable release rate of atmospheric species such as ^{40}Ar and radon to learn more about the inner workings of the lunar interior." – (8d) "Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps." While *LADEE* addresses part of SCEM Recommendation 7 (and Goal 8b), its current design does not address Goals 4b, 4c, 8c or 8d. What can be done?

LADEE with its current scientific payload retasked into a nearly polar orbit (perhaps 70^{O} inclination to still allow a sharp terminator crossing) could address most of these goals, perhaps in the second phase of an extended mission. We have much more work required, however, in as little as 10 years depending on the outcome of the Augustine process. In general that we need another round of reconnaissance, with these and other instruments on polar orbits, before we have finished our homework prior to crewed lunar missions. There has been no successful ^{222}Rn re-survey with a sensitive alpha-particle spectrometer, barring some suddenly favorable outcome from *Kaguya*. A survey for hydrated minerals near the poles will not occur until M^3 or similar instrument flies again. Mass spectrometry of the lunar atmosphere for a polar orbit mission should be rethought to accomplish 4b, 4c and 8d. We need a polar-orbit mapping mission in the next decade to not forsake many of the SCEM goals. Additionally, if there is subsurface ice near the poles (likely 10 – 30 meters deep), we need new penetrating radar maps at wavelengths of 0.5-2 meters and at lunar-orbital spatial resolution to find it. In addition to upcoming lunar landers, we still need work from polar orbit.

For now we can likely accomplish some of this from Earth, with the connection between lunar outgassing and optical transient events visible through the telescope (Crotts 2008, 2009). TLPs are a long-standing mystery, but this connection has been long suspected. “Transient Lunar Events” are identified as unsolved problem #13, requiring “a permanent monitoring system on the lunar surface” in the *Lunar Sourcebook*’s 15 outstanding questions (from the 1986 *Lunar Geoscience Working Group*). Little has changed in our understanding of TLPs since 1986, even though prior to that time TLPs were seen as a priority by geophysical workshops and the international astrophysical community (Geake et al. 1976, Various authors 1977). Despite the TLP controversy in the U.S. (Cameron 1991, Shehan & Dobbins 1999), our group (Crotts et al. 2008) has developed the tools to perform objective, robotic imaging surveys for these with the potential of mapping TLPs and clarifying their outgassing connection.

References:

Cameron, W.S. 1991. *Sky & Tel.*, 81, 265.

Crotts A.P.S. 2008, *ApJ*, 687, 692.

Crotts, A.P.S. 2009, *ApJ*, 697, 1.

Crotts A.P.S. & Hummels C. 2009, *ApJ,* submitted (also http://arxiv.org/abs/0706.3952).

Crotts, A.P.S., et al. 2009, LPSC, 39, 2430.

Geake J.E. 1976, *Report of Ad Hoc Working Group, Comm. 17, IAU*, Proc. IAU Gen. Ass'y, 16, p. 150.

Gorenstein, P., Golub, L. & Bjorkholm, P.J. 1974, Science, 183, 411.

Hauri, E.H., Saal, A.E., van Orman, L.A., Rutherford, M.C. & Friedman, B. 2009, LPSC, 40, 2334.

Hodges, R.R., Jr. 1977, Phys. Earth & Planet Inter., 14, 282.

Hodges J.H. & Hoffman, R.R., Jr. 1975, LPSC, 6, 3039.

Lawson, S.L., Feldman, W.C., Lawrence, D.J., Moore, K.R., Elphic, R.C., Belian, R.D. & Maurice, S. 2005, JGR, 110, E09009.

Lunar Geoscience Working Group 1986, *Status & Future of Lunar Geoscience*, NASA SP-484.; also Grant H.H., Vaniman D.T. & French B.M. 1986, *Lunar Sourcebook* (Cambridge U. Press), p. 654.

McCubbin, F.M., Neksavil, H., Jolliff, B.L., Carpenter, P.K. & Zeigler, R.A. 2008, LPSC, 39, 1788.

McCubbin, F.M., Neksavil, H., Jolliff, B.L., Carpenter, P.K. & Zeigler, R.A. 2009, LPSC, 40, 2246.

Saal, A.E., Hauri, E.H., Cascio, M.L., van Orman, L.A., Rutherford, M.C. & Cooper, R.F. 2008, Nature, 454, 192.

Schultz, P.H. Staid, M.I. & Pieters, C.M. 2006, Nature, 444, 184.

Sheehan, W. & Dobbins, T. 1999, *Sky & Tel.*, 98, 118.

Various authors in TLP special issue, 1977, *Phys. Earth & Planet. Interiors*, vol. 14.