MONITORING LUNAR SURFACE CHANGES DURING AND AFTER THE *KAGUYA* MISSION.

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Introduction: Outgassing from the lunar surface appears evident in several ways: every lunar orbital mission capable of sampling a large fraction of the Moon's surface in terms of ^{222}Rn sources has detected episodic emission of this short-lived, radioactive gas [1,2], plus a decades-old residual of decay products from previous radon outgassing [2,3]. Also, several fresh, large features indicate massive lunar outgassing events over the past several million years [4,5]. Additionally, there are the enigmatic "transient lunar phenomena" (TLPs), which are frequently described by observers as producing a gaseous or nebular appearance over small areas of the lunar surface. Recent work shows with high statistical significance that the persistent sites of these reports are correlated with loci of ^{222}Rn outgassing [6], both episodic and long-term.

The only detector for many years hence that will detect gas particles emanating from the lunar surface is the Alpha-ray Detector (ARD) currently in lunar orbit onboard *Kaguya (SELENE)* [7], which is many times more sensitive and/or will be in use much longer than previous ^{222}Rn alpha-particle detectors. Given a high correlation between TLPs and radon sources, *Kaguya*/ ARD offers a unique opportunity, combined with ground-based observations, to understand the nature of lunar outgassing events and their putative connection with TLPs. A key point is that while any ^{222}Rn alpha-particle detector is sensitive to the outgassing itself, not its indirect optical effects, it will only map the outgassing to a resolution of ~100 km due to the random walk of atoms between the event and its detection (as well as the degradation of resolution due to the altitude of the satellite above the surface). In contrast, the prompt optical counterpart or longer-term effects of the outgassing upon the regolith surface might describe the location and substructure of the event on kilometer or sub-kilometer scales. This abstract summarizes a variety of observations underway to exploit this opportunity. Since at this date these observations and the *Kaguya* mission have just started, this is necessarily a work in progress. Some of this program is also described elsewhere [8,9].

Monitoring for Transients: Currently our group is operating a robotic imaging monitor at Cerro Tololo Inter-American Observatory which images the entire nearside lunar surface several times per minute, during most of the time when the Moon is more than about 40^{o} above the local horizon and when the weather permits. We are also preparing a second monitor for use in Australia. Funding permitting (currently pending), we plan to install identical monitors in Utah, Hawaii and western Russia, as well [10]. Each monitor will consist of a 0.3-meter telescope imaging the entire lunar disk onto a 16-million pixel CCD at a resolution of 0.7 arcsec per pixel, at a rate of several times per minute. (While several groups are conducting high-speed video searches for impact events, we are concentrating on comprehensive, longterm monitoring of longer timescale events.) If all of these monitors are operational before the end of the *Kaguya* mission (nominally, not before October 2008), they will allow nearly continuous imaging monitoring of the lunar nearside surface while ^{222}Rn outgassing is being monitored from orbit. These images are fed into a reduction and transient detection pipeline, which allows surface brightness enhancements at the level of ~1% or better to be detected [9]. In contrast, a visually-detected TLP must produce a contrast enhancement at least several times larger than this to be marginally detectable.

Before/After Imaging: If a ^{222}Rn outgassing or TLP event produces a permanent change in the lunar surface, this might be evident in a time-series of images taken at the same viewing and phase angles. While several missions overlap with *Kaguya* and carry high-resolution imagers (*Chang'e-1, Chandrayaan-1* and, of course, *Kaguya* itself), and there are several bands in the optical/IR that are useful. In the optical, long-term reddening of the lunar regolith can be detected easily by many instruments, but the age-dependent pyroxene surface Fe^{2+} feature at 950 nm is more difficult, and varies in wavelength structure according to composition [11].

A more novel approach of ours is motivated by recent detection of significant endogenous hydration in lunar picritic glasses [12]. These were likely once at higher pre-eruption levels [13] likely sufficient to produce hydration absorption signatures in the infrared [14], particularly at 2.9 μm. Initially unhydrated regolith can develop these signatures (including associated narrow features at 3.4 μm) after several years in the presence of water, but they are lost in vacuum and/or high temperature conditions on timescales of weeks [15,16]. If outgassing is partially volcanic in nature rather than purely due to radioactive decay, regolith that has been subject to these outgassing flows for millions or billions of years might bear these infrared signatures, at least for a few weeks after being exposed. A reasonable model of such an outgassing event [17] indicate one would displace many tons of subsurface regolith as a fine coating over a large surface area (a few or tens of km^2).

We are engaged in two types of ground-based observations in order to detect possible surface changes in these various bands, as might be caused by outgassing events. First, at the Infrared Telescope Facility (IRTF) and MDM 2.4-meter telescope, we are completing "before" epoch imaging in the optical and infrared corresponding to these bands. In the optical, in particular, the lunar surface is being imaged at high spatial resolution using "Lucky Imaging" of the kind which has successfully delivered resolution of planets at the ~0.2 arcsec level [18]. After the completion of *Kaguya,* we will complete "after" epoch imaging, plus have pending proposals for *Hubble Space Telescope* imaging of selected sites in special circumstances. There are also several interesting combinations of imaging from frequent ground-based imaging and imaging from lunar orbit e.g., *Kaguya* or *Chang'e-1* that might yield interesting comparisons, which we detail elsewhere [9].

Also detailed elsewhere [9], we have also completed hyperspectral scans in the optical and infrared of extensive areas of the Moon, using the IRFT, MDM 2.4-meter and Kitt Peak National Observatory 2.1-meter telescopes. While these cannot achieve the spatial resolution of the *HST* or Lucky Imaging data, they have high spectral resolution (typically $R = \lambda/\Delta\lambda = 300$) which allow detection of minute changes in reflectivity over small areas and wavelength ranges. These are uniquely valuable in detecting changes in near-infrared changes in Fe^{2+} absorption structure tracing mineral compositional changes, and in maximally sensitive changes in the transient hydration bands near 3 μm.

Finally, we plan to implement an accelerated version of our robotic imaging monitor pipeline, allowing real-time detection of optical transients (pending the success of current support requests). The current archive of TLP reports indicates a typically-reported event timescale of about 1000s [6], which is sufficient to allow more powerful observing strategies to be brought to bear if the robotic lunar imaging monitors deliver a prompt alert. There are many prompt follow-up observing options possible: real-time spectroscopy, polarimetry, high-resolution imaging. Many of these options are detailed elsewhere [9].

References: [1] Gorenstein P. and Bjorkholm P. J. (1973) *Science, 179,* 792-794. [2] Lawson S. L., Feldman W. C., Lawrence D. J., Moore K. R., Elphic, R. C., and Maurice S. (2005) *JGR, 110*, E09009. [3] Gorenstein P., Golub L. and Bjorkholm P.J. (1974) *Science*, *183,* 411-413. [4] Schultz P. H., Staid M. and Pieters, C. M. (2001) *LPS XXXI,* Abstract #1919. [5] Schultz P. H., Staid M. and Pieters, C. M. (2006) *Nature, 444,* 184-186. [6] Crotts A.P.S. (2007) *ApJ, submitted,* (preprint: http://lanl.arxiv.org/abs/0706.3949). [7] Nishimura J. et al. (2006) *Adv. Space Res., 37*, 34. [8] Crotts A. P. S. et al. (2007) *LPS XXXVIII,* Abstract #2294. [9] Crotts A.P.S. (2007) *ApJ, submitted* (preprint: http://lanl.arxiv.org/abs/0706.3954). [10] http://www.astro.columbia.edu/~arlin/TLP/ [11] Hazen R.M., Bell P.M and Mao M.K. (1978) *LPS IX*, 483. [12] Saal A.E., Hauri E. H. & Cooper R.F. (2007), *LPS XXXVII*, 2148. [13] Saal A.E., Hauri E. H., LoCarcio M., Van Orman J., Rutherford M.J. & Cooper R.F. (2007), in *Water in Planetary Basalts*, 2009. [14] Akhmanova M. V., Dementev B. V., Markov, M. N. and Sushchinskii N. M. (1972) *Cosmic Res., 10*, 381. [15] Markov M. N., Petrov V. S., Akmanova M. V. and Dementev B. V. (1979) in *Space Res., Proc. Open Mtgs. Working Groups* (Pergamon: Oxford), p. 189. [16] Pieters C. M. et al. (2005) http://moonmineralogymapper.jpl.nasa.gov/SCIENCE/Volatiles/ [17] Crotts A.P.S. and Hummels C. (2007) *ApJ, submitted,* (preprint: http://lanl.arxiv.org/abs/0706.3952). [18] Cecil R. and Rashkeev D. (2007) *ApJ, 134*, 1468-1474.