PROBING LUNAR VOLATILES: INITIAL GROUND-BASED RESULTS.

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Introduction: We present initial results from several probes (outlined below) to characterize volatiles originating from or residing below the lunar surface.

The first paper [1] in this series presents a merging of existing samples of episodic lunar events (moonquakes, outgassing events, radon release episodes and optical transient lunar phenomena - TLPs) by correlating them geographically (and temporally). By requiring statistical consistency in the sample of ~1500 TLPs after they are subdivided according to likely randomizing parameters and by discarding discrepant portions of the sample, we isolate robust rates of reports consistently to certain classes of features: sites along the interface between maria and highlands, and fresh, large impact craters e.g., Kepler, Tycho, Copernicus. An extreme case is Aristarchus, which is unique in representing both categories, given that it coincides with a 50,000 km^2 plateau of highland-like elevation. We find that these reported events are likely due to real lunar outgassing (~85% of the time by our estimates), since they correspond closely to the loci of ^{222}Rn release episodes, according to two separate statistical tests, which each indicate that this result cannot be random, each at the $\sim 10^{-4}$ probability level. We confirm proximity of moonquakes to mare edges, in detail.

Further in [2] we consider methods by which lunar outgassing might generate TLPs, other ways in which events might interact with the regolith, and the manner in which gas might propagate above the surface. Key among these points is the extent to which the fraction of vented gas depends crucially on the ionization state of the gas, how the gas/regolith interaction depends on the gas flow rate, and the likely extent to which water might be retained in an ice layer about 10-15 m below the surface, near the triple point temperature.

Briefly we discuss each of the proposed follow-up observations and probes, and preliminary results from some of these that have reached implementation.

Optical/IR Remote Sensing From Earth: The strong correlation (not necessarily one-to-one) between optical transients and radon outgassing implies that much can be learned about the spatial and temporal distribution by observing the Moon from Earth. We have implemented a simple technique to provide consistent, digital and objective monitoring of optical transient with greater sensitivity than the human eye looking through a telescope (the manner of many TLP reports). We have constructed a robotic lunar monitor [3] at Cerro Tololo (Chile) feeding an automated reduction pipeline, which we plan to have fully operational by March 2007. An example of data that this monitor might deliver is shown in Fig. 1a. To this image we have added a synthetic TLP and used another image taken in the same time series to indicate the differential signal which might be obtained from a TLP several times too faint to be seen by a human eye, but easily detected by our software, as shown in Fig. 1b. This demonstrates in a realistic situation that faint TLPs can be detected automatically; furthermore our software can do so on a real-time basis compared to inferred TLP durations (~30 to 3000 s). This can allow the TLP distribution to be studied in an objective manner, and for alerts to be transmitted during a TLP.

Once our alert system is functioning sufficiently rapidly (< 1000s), this opens the possibility of taking rapid followup observations, notably spectroscopy. Our hyperspectral imaging shows that this is possible at high sensitivity. On the MDM Observatory 2.4-meter/CCDS, we scanned the spectrograph slit in 1-arcsec (1.9 km) intervals across Oceanus Procellarum, at resolution 0.8 nm over 580-1020 nm. A reconstructed image, slicing the hyperspectral cube at ~558 nm is shown in Fig. 2a, versus a standard optical image in Fig. 2b. This shows that the nature of the regolith spectral reflectance function is sufficiently uniform (and flat-fielding of the data is well-behaved) so that a sensitivity of 1% in 0.8 nm band is attained, meaning that even small enhancements due to spectral line or band emission are detectable, at a level ~1000 times more sensitive than the human eye.

These two capabilities suggest a program in which subsurface volatiles could be detected directly, even if they are not in gaseous form. Hydration of the regolith produces absorption bands at 2.9 and 3.4 μm. If a TLP event is sufficiently violent to liberate subsurface regolith affected by water, presumably from ~10 m below the surface, material showing this absorption might persist on the surface for sufficient time (depending on the solar illumination conditions) for a spectrum, this time in the infrared L-band, to reveal changes in these spectral features from previous scans.

Ground Penetrating Radar (GPR): Studies have been made at wavelengths penetrating ~10 – 20 m into the regolith [5,6] (with Arecibo/Greenbank). We would predict a likely signature in such data for the presence of subsurface water ice would be a relatively featureless, low-return signal at these depths, since the radio dielectric constant of ice is near that of regolith grain material. Ice would reduce regolith scattering versus regolith/vacuum, and increase absorption.

Curiously, the 70 cm radar return from the region around the crater Aristarchus [5], the major site of outgassing traced by ^{222}Rn/TLP activity, is also the locus of an anomalously large dark radar halo, compared to small halos around some other craters. In fact, this dark region seems to extend over much of the Aristarchus plateau. Near the impact zone of Aristarchus, however, the radar-dark area is also unusually smooth. In contrast, the rest of the plateau, while dark, includes high-return zones associated primarily with small impacts.

Explaining this dark feature has been difficult [5]. However, if there was subsurface water ice there, the Aristarchus impact several hundred million years ago would have melted it over a large area, which would eventually re-freeze, causing an extensive, smooth, dark radar zone. Furthermore, subsurface liquid water would tend to seep downhill, extending this zone to the south and east, as observed. There is significant, independent, non-radar evidence supporting the hypothesis of extensive volatiles in the Aristarchus plateau [7], which we will present at this meeting, time permitting.

Concepts for Orbital Remote-Sensing and In-Situ Probes: In a recent paper [8] we describe how observations and programs described above, particularly optical monitoring, can feed into future programs using new techniques for further characterizing lunar volatiles. Most of these require platforms in orbit or on the lunar surface, but ground-based alternatives are possible in some cases. Some examples:

High Resolution Imaging: While with current systems resolution better than 1 km is difficult over large areas, the TLP monitor will indicate areas in which activity is or has occurred. This can be coordinated with follow-up imaging by the *Hubble Space Telescope* or future instruments. An alternative is the "Lucky Exposures" technique of selected, short-duration, ground-based image stacking. To monitor the entire surface will take imagers in lunar proximity. One less-expensive alternative might be imagers attached to communications platforms that would be required to maintain full-globe lunar communications, either via radio or lasers from L2 halo orbits and/or L1.

Other Lunar Orbital Remote-Sensing: Detectors in lower lunar orbit might map in detail alpha-particle release e.g., ^{222}Rn, and GPR return from 10-20 m depths. This might be coordinated with a network for global positioning or gravitational potential mapping.

In-Situ Probes: AEOLUS is studying a staged approach, informed by the previous techniques, designed to locate and characterize subsurface volatiles with maximal efficiency. This depends on many techniques. A concept under development is a mass spectrometer to provide continuous monitoring across a large mass range, with detailed ballistic directional reconstruction.

References: [1] Crotts A. (2006) submitted (see http://xxx.lanl.gov/astro-ph). [2] Crotts A. et al. (2007) *ApJ*, submitted (see http://xxx.lanl.gov/astro-ph). [3] Hickson P., Crotts A., Pfrommer T., Cseresnjes P. & Bergier A. (2007) in prep. [4] Tomaney A. & Crotts A. (1996) *AJ*, 112, 2872. [5] Ghent R. R., Leverington D. W., Campbell B. A., Hawke B.R. & Campbell D.B. (2004) *LPS XXXV*, Abstract #1679.[6] Thompson T.W. & Campbell B. A. (2005) *LPS XXXVI*, Abstract #1535. [7] Crotts A. & Hummels C. (2006) *Science*, submitted (see http://xxx.lanl.gov/astro-ph). [8] Crotts A. (2007) *ApJ*, submitted (see http://xxx.lanl.gov/astro-ph). -

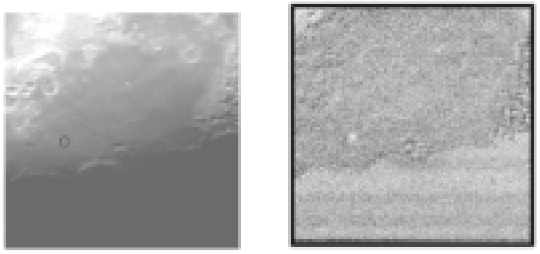

Figure 1: (a) a portion of the Moon imaged with the same pixel scale, angular resolution and signal-to-noise typical of our monitor, within a time series of images (taken on the CTIO 0.9-meter in 2001). To this a fake point-source TLP signal is added (small black circle) at a level invisible to the naked eye. (b) After processing this image series with our software reduction pipeline, a signal-to-noise map is produced, showing the easily recognized "TLP" at the 20-sigma level.

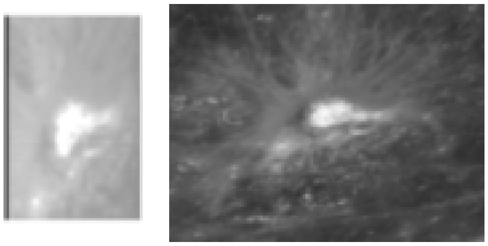

Figure 2: (a) an image of Aristarchus produced from our hyperspectral scan, in a 0.8 nm band adjacent to the 558-nm neutral atomic oxygen line, (b) a white-light (blue sensitive) image of the same region (courtesy James Ferreira).