VOLATILE ANALYSIS BY PYROLYSIS OF REGOLITH (VAPOR) ON THE MOON USING MASS SPECTROMETRY.
D. P. Glavin[1], I. L. ten Kate[1], W. Brinckerhoff[1], E. Cardiff[1], J. P. Dworkin[1], S. Feng[1], K. Fristad[2], S. Gorevan[3], D. Harpold[1], A. L. Jones[1], P. R. Mahaffy[1], D. Martin[1], M. Moore[1], E. Patrick[1], D. Roberts[3], P. Roman[1], and T. Stephenson[1], [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, daniel.p.glavin@nasa.gov, [2]University of Oslo, Norway, NO-0316, [3]Honeybee Robotics, New York, NY 10001.

Introduction: The identification of lunar resources such as water is a fundamental component of the NASA Vision for Space Exploration. The Lunar Prospector mission detected high concentrations of hydrogen at the lunar poles that may indicate the presence of water or other volatiles in the lunar regolith [1]. One explanation for the presence of enhanced hydrogen in permanently shadowed crater regions is long term trapping of water-ice delivered by comets, asteroids, and other meteoritic material that have bombarded the Moon over the last 4 billion years [2]. It is also possible that the hydrogen signal at the lunar poles is due to hydrogen implanted by the solar wind which is delayed from diffusing out of the regolith by the cold temperatures [3].

Previous measurements of the lunar atmosphere by the LACE experiment on Apollo 17, suggested the presence of cold trapped volatiles that were expelled by solar heating [4]. *In situ* composition and isotopic analyses of the lunar regolith will be required to establish the abundance, origin, and distribution of water-ice and other volatiles at the lunar poles. Volatile Analysis by Pyrolysis of Regolith (VAPoR) on the Moon using mass spectrometry is one technique that should be considered. The VAPoR pyrolysis-mass spectrometer (pyr-MS) instrument concept study was selected for funding by the NASA Lunar Sortie Science Opportunities (LSSO) Program. VAPoR is a miniature version of the Sample Analysis at Mars (SAM) instrument suite currently being developed at NASA Goddard for the 2009 Mars Science Laboratory mission (Fig. 1).

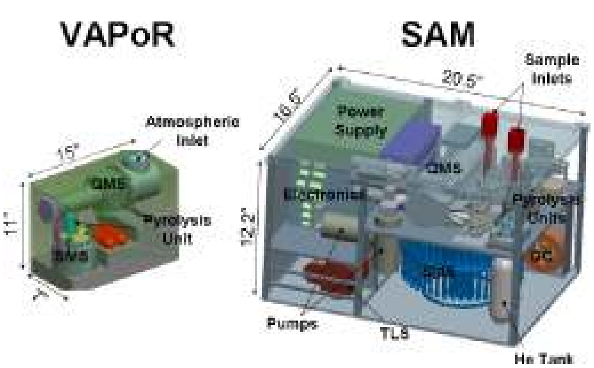

Figure 1. The VAPoR pyr-MS instrument will enable a detailed *in situ* characterization of lunar resources with reduced power, mass, volume, cost, and complexity compared to the SAM instrument suite.

Measurement Objectives: There are at least three key lunar science measurement objectives that can be achieved by the VAPoR instrument: (1) Measure the isotope ratios of carbon, hydrogen, oxygen, and nitrogen (CHON)-containing volatiles including water, and noble gases in polar regolith to establish their origin (see Fig. 2), (2) Understand the processes by which terrestrial organic compounds are dispersed and/or destroyed on the surface of the Moon to prepare for future human exploration and life detection on Mars, and (3) Measure the abundance of volatiles that can be released from lunar regolith for *in situ* resource utilization (ISRU) technology development.

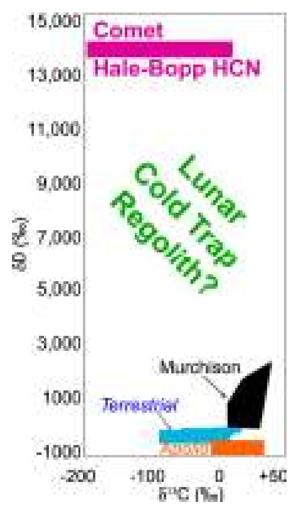

Figure 2. Isotopic analysis of water and other volatiles evolved from the lunar regolith by VAPoR can be used to constrain their origin(s). Solar wind implanted volatiles from the Apollo regolith, terrestrial organics, carbonaceous meteorite organics, and cometary volatiles show distinct H and C isotopic signatures. The nature and source of H in the polar cold trap regolith is unknown.

Future *in situ* investigations of a variety of locations on the Moon by VAPoR would also help assess the organic contamination of the Moon by lunar spacecraft and humans [5]. Laboratory hydrogen isotopic measurements of water extracted from lunar soils have revealed that the water was primarily of terrestrial orgin, probably from the Apollo spacecraft and astronauts [6]. There have been no direct *in situ* measurements of the lunar regolith to determine the extent of organic contamination of lunar soil samples prior to their return to Earth. Isotopic measurements of water, organics, and other volatiles would help distinguish terrestrial contamination from volatiles of lunar or exogenous origin. These studies would provide valuable "ground truth" data for Mars sample return missions and help define contamination and planetary protection requirements for future Mars bound spacecraft carrying life detection experiments.

Evaluation of ISRU related technologies will be of primary importance for future long term exploration of both the Moon and Mars. Laboratory studies on Earth of the Apollo lunar soils indicate that these materials evolve a variety of volatile gases including H_2, N_2, CO_2, CO, SO_2, and O_2 and the noble gases He, Kr, Xe, and Ar by heating the regolith under vacuum to elevated temperatures [7]. It is not known how the abundances of these volatiles vary over the surface of the Moon, or how much their concentration is enhanced in the polar cold trap regions. *In situ* measurements by VAPoR will enable an evaluation of the volatile content of the lunar regolith including water, oxygen and ^{3}He as well as their extraction efficiencies as a function of temperature. These studies would provide valuable data for ISRU technology development.

Instrument Concept: The VAPoR instrument suite will include a solid sample manipulation system (SMS) containing 6 pyrolysis heater cups, atmospheric inlet, noble gas enrichment getter, and mass spectrometer, all developed components of SAM. These components can be integrated into an autonomous robotic or human deployed package that would require minimal resources. The resource requirements for VAPoR (mass: 7-15 kg; power: 25-50 W; volume: 15”x11”x7”; telemetry rate: 1 kbps) are estimates based on the SAM instrument suite. Future testing of a prototype instrument will be required to validate these estimates.

Lunar regolith surface or subsurface samples could be delivered to the VAPoR instrument solid sample inlet robotically by a lander/rover scoop or drill, or collected and delivered to the inlet by an astronaut. The VAPoR SMS consists of a 6-cup exchangeable carousel mechanism designed to receive lunar regolith samples and heat the samples to elevated temperatures. Vacuum pyrolysis at temperatures up to 1400ºC has been shown to be an efficient way to release volatiles from lunar regolith [7]. Development and testing of a vacuum pyrolysis system here at Goddard has shown that O_2 can be released from lunar analog materials under vacuum at temperatures above 1200ºC [8].

The VAPoR gas handling system does not require pumps or carrier gases for the analysis of lunar volatiles. Atmospheric gas samples can be introduced directly into the mass spectrometer by opening an atmospheric inlet cap connected to the ion source region. For solid samples, evolved gases are introduced into the mass spectrometer by molecular diffusion. A separate chemical getter attached to the mass spectrometer will be used to efficiently remove active gases such as N_2 from the gas volume, which will enable enrichment of noble gases and methane required for higher precision isotope measurements. After saturation the getter can be regenerated *in situ* by heating to 900ºC.

A quadrupole mass spectrometer for the SAM instrument suite is currently in fabrication and test at GSFC. An identical design could be used for VAPoR within the resources of the current concept. Mass spectrometers can detect a variety of volatile species including water, noble gases, and organic compounds over a large dynamic range as demonstrated by the Galileo Probe Mass Spectrometer measurements of the atmosphere of Jupiter (Fig. 3). Highly miniaturized Micro Electro Mechanical Systems (MEMS)-based reflectron time-of-flight mass spectrometers are also currently being developed at GSFC. These mass spectrometers could enable a significant reduction in mass and power (mass 0.4 kg, power: < 1 W) compared to traditional quadrupole mass spectrometers (mass: 1.3 kg, power: 14.5 W) while maintaining the scientific return.

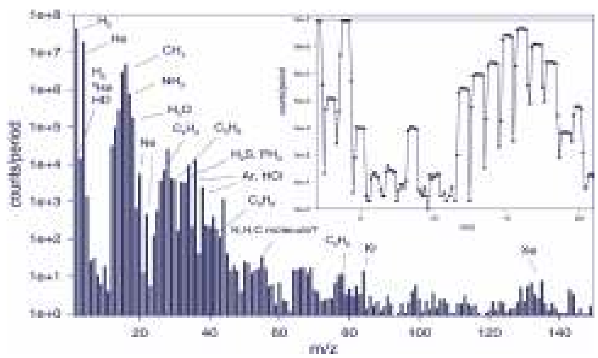

Figure 3. The VAPoR mass spectrometer will detect a wide range of volatiles in the lunar atmosphere and regolith. Above: Galileo probe mass spectrum showing the range of volatile species detected in the atmosphere of Jupiter.

References: [1] Feldman, W. C. et al. (1998) *Science,* 281, 1496-1500. [2] Chyba, C. and Sagan, C. (1992) *Nature,* 355, 125-132. [3] Crider, D. H. and Vondrak, R. R. (2002) *Adv. Space Res.,* 30, 18869-18874. [4] Hoffman, J. H. and Hodges, R. R. (1975) *The Moon,* 14, 159-167. [5] Glavin, D. P. et al. (2004) *Int. J. Astrobio.,* 3, 265-271. [6] Epstein, S. and Taylor, H. P. Jr. (1972) *Proc. 3rd Lunar Sci. Conf.* 3, 1429. [7] Gibson, E. K. Jr. and Johnson, S. M. (1971) *Proc. 2nd Lunar Sci. Conf.* 2, 1351. [8] Matchett, J. et al. (2005) *Space Res. Roundtable VII,* Oct. 25-28, Houston, TX.

Acknowledgements: The authors appreciate grant support from the NASA Lunar Sortie Science Opportunities (06-LSSO06-0002) and the Goddard Internal Research and Development Programs.