**LunaR: A VERSATILE RAMAN SPECTROMETER FOR LUNAR EXPLORATION.** E. Cloutis[1], M. Daly[2], C. Caudill[1], E. Lalla[2], S. Potin[1], D. Applin[1], S. Connell[1], J. Freemantle[2], J. Kuik[1], E. Lymer[2], S. Manigand[1], A. Parkinson[1], S. Sidhu[1], N. Turenne[1], and A. Allen[3]. [1] Centre for Terrestrial and Planetary Exploration (C-TAPE), University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba, Canada, R3B 2E9; e.cloutis@uwinnipeg.ca. [2] Department of Earth & Space Science & Engineering, Lassonde School of Engineering, York University, Toronto, Ontario, Canada. [3]Nova Analytic Labs, Portland, ME, USA.

**Introduction:** The Government of Canada has committed to participation in lunar exploration. As part of this effort, the Canadian Space Agency has created the Lunar Exploration Accelerator Program (LEAP) "to provide a wide range of opportunities for Canadian science and technology activities in lunar orbit, on the Moon's surface, and beyond" [1].

Under the LEAP program, a research team involving the University of Winnipeg and York University is exploring the utility of Raman spectroscopy for inclusion on future lunar landed missions. This study involves three parallel tracks: science value, engineering design and fabrication, and mission opportunities.

**Raman spectroscopy for lunar exploration:** The potential applications of Raman spectroscopy to lunar science and exploration have been determined in the context of Canadian priorities for space and planetary exploration [2]. Areas of application include Planetary Science (Astrobiology (AB), Planetary Geology, Geophysics and Prospecting (PGGP), Planetary Space Environment (PSE), and Space Health (SE).

The potential for Raman spectroscopy to explore and characterize the lunar surface has been demonstrated in multiple studies. These have shown that Raman spectra of Apollo lunar samples and lunar meteorites exhibit emission peaks that can be related to the presence of specific minerals in these samples [3-9]. In addition, compositional changes in major lunar minerals, such as $Fe^{2+}$-Mg substitutions in pyroxene and olivine, and Na-Ca in plagioclase feldspar, can lead to shifts in Raman peak positions, changes in peak shapes, and appearance or disappearance of peaks [10-13]. It can also be used to characterize poorly crystalline/amorphous lunar phases [14].

**The LunaR project:** The LunaR study is being undertaken via three parallel and interrelated tasks: Science, Engineering, and Missions.

*LunarR – Science:* Raman spectroscopy can be applied to a wide variety of landed lunar mission types. In the science aspects of LunaR, we are quantifying Raman performance for detecting specific minerals, and constraining the composition of minerals which have solid solution cation substitutions (e.g., plagioclase feldspar, olivine, pyroxene). We have already demonstrated proof of concept on Apollo lunar regolith samples, lunar meteorites, and compositionally diverse silicates (Figures 1 and 2). During this study we will extend our investigation to additional lunar samples and terrestrial minerals. They will be characterized by both a commercial Raman instrument and the Raman breadboard we are fabricating. We will use these data, and spectra from previous investigations to develop a searchable spectral library with peak-matching capabilities, and derivation of mineral compositions.

*LunaR – Engineering:* Our engineering and design approach begins with a "baseline" close-up instrument. It will employ a continuous wave 532 nm laser for Raman excitation (with output power of between 30 and 150 mW), a wavelength range of ~200-4000 $cm^{-1}$, <~6 $cm^{-1}$ resolution, and a stand-off distance of ~10 cm. We are also exploring some augmented instruments. We are targeting an instrument mass of <<3 kg for the baseline and all the augmented options.

The augmented options we are studying include:

(1) Spatial heterodyne Raman spectrometer (SHRS). A spatial heterodyne instrument that we are investigating should be more rugged, have less moving parts, provide lower mass, greater optical efficiency, and a wider field of view [15, 16]. Reduction in mass, volume, and power requirements would enhance its opportunities for flight on future missions.

(2) Raman + passive reflectance. The ability to combine passive reflectance spectroscopy with laser-based interrogation of targets on Mars has been demonstrated by the ChemCam instrument on the NASA Mars Science Laboratory rover [17]. ChemCam combines passive reflectance spectroscopy with laser-induced breakdown spectroscopy (LIBS)), for more robust target identification. For our passive reflectance spectrometer, we are targeting a wavelength range of ~200-1100 nm with spectral resolution of a few nm. This wavelength range could be used to identify spectral features associated with various elements, such as iron, and their oxidation states [18], as well as improved determination of ilmenite abundances [19].

(3) Stand-off Raman. The ability to conduct Raman spectroscopy at greater stand-off distances (up to at least a few meters), is expected for the SuperCam instrument on the Mars Perseverance rover [20], and even greater stand-off distances have been demonstrated in the laboratory [21]. A greater stand-off capability

would provide greater flexibility in terms of accommodation on landed systems.

(4) X-Y scanning and contextual imaging. In combination with (3), a scanning capability would increase the area that could be examined by a Raman spectrometer, and allow for remote characterization of shadowed regions. Scanning capability would be particularly advantageous for fixed landers. Contextual imagery has been shown to be particularly useful for ChemCam, where the actual analytical points targeted by the instrument's LIBS instrument can be determined [22].

*LunaR – Missions:* With multiple nations, organizations, and commercial entities actively engaged in future lunar landed missions, flight opportunities for a low mass-power-volume instrument such as LunaR are diverse. Appropriate missions include fixed landers and rovers. The goals of these missions will vary and can include technology demonstrators, exploration of sunlit regions, and exploration of permanently-shadowed regions (PSRs) for identification of water ice deposits.

Because Raman spectrometers are an active remote sensing technique, they can operate in any lighting conditions, making them extremely versatile and appropriate to wide range of landed lunar missions types and terrains.

**Lunar Raman spectroscopy:** While no Raman spectrometers have yet been deployed on the lunar surface, one is expected to fly on the CNSA Chang'e-7 mission [23]. This will be an important validation and demonstration of Raman spectroscopy for lunar exploration.

**Summary and future activities:** Our Phase 0 study will be completed in August 2021. It will be used as a roadmap for future instrument development and hopefully flight on a near-term lunar mission. At this conference, we will report on the latest results of this Phase 0 study.

**Acknowledgments:** We wish to acknowledge the support provided by the Canadian Space Agency through their Lunar Exploration Accelerator Program (LEAP). This study is also being supported with funding from NSERC, UWinnipeg, CFI, and MRIF.

**References:** [1] https://asc-csa.gc.ca/eng/funding-programs/programs/leap/about.asp. [2] Hipkin V.J. et al. (2017) *LEAG 2017*; abstract #5054. [3] Perry C.H. et al. (1972) *Moon, 4*, 315-336. [4] Ling Z.C. et al. (2011) *Icarus, 211*, 101-113. [5] Righter K. et al. (2005) *MaPS, 40*, 1703-1722. [6] Huidobro J. et al. (2018) *EPSC*, Abstract #EPSC2018-883. [7] Cao H. et al. (2019) *J. Raman Spectr., 51*, 1652-1666. [8] Haskin L.A. et al. (1997) *JGR, 102*, 19293-19306. [9] Dennewaldt T. et al. (2015) *J. Material Sci., 50*, 122-137. [10] Mouri T. and Enami M. (2008) *J. Mineral. Petrol. Sci., 103*, 100-104. [11] Huang E. et al. (2000) *Amer. Mineral., 85*, 473-479. [12] Bersani D. et al. (2018) J. Raman Spectrosc., 49, 684-698. [13] White W.B. (1975) In: *Infrared and Raman Spectroscopy of Lunar and Terrestrial Minerals*, 325-358. [14] Zeng X. et al. (2020) *JGR, 125*, e20220JE006674. [15] Allen A. and Angel S.M. (2018) *Spectrochim. Acta B,* 91-98. [16] Kaufman M. et al. (2018) *Atmos. Meas. Techn., 11*, 3861-3870. [17] Johnson J.R. et al. (2015) *Icarus, 249*, 74-92. [18] Burns R.G. et al. (1972) *Moon, 4*, 93-102. [19] Robinson M.S. et al. (2007) *GRL, 34*, L13203. [20] Wiens R.C. et al. (2021) *Space Sci Rev., 217*, 4. [21] Misra A. et al. (2018) *Appl. Spectrosc., 73*, 320-328. [22] Maurice S. et al. (2012) *Space Sci. Rev. 170*, 95-166. [23] Zou Y. et al. (2020) *LPSC, 51*, Abstract #1755.

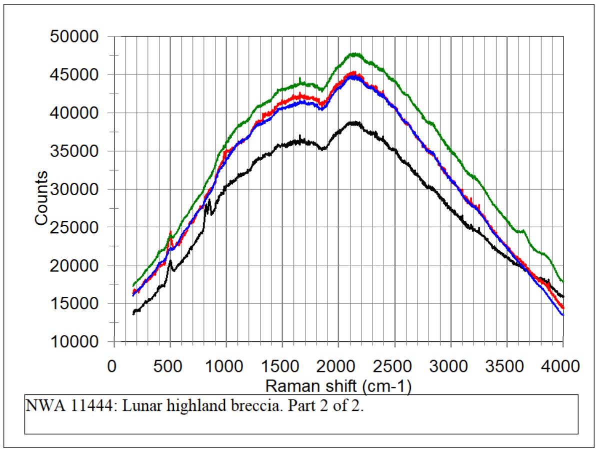

Figure 1. 532 nm Raman spectra of lunar meteorite NWA 11444 (collected at C-TAPE with a B&W Tek iRaman 532 nm instrument).

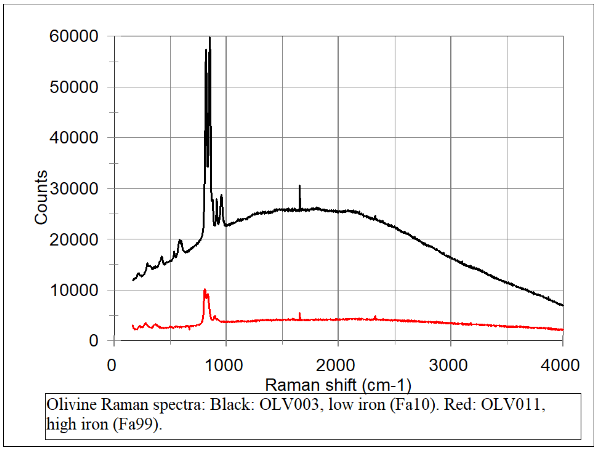

Figure 2. 532 nm Raman spectra of a low- ($Fa_{10}$) and high- ($Fa_{99}$) iron content olivine (collected at C-TAPE with a B&W Tek iRaman 532 nm instrument).