LUNAPIX & MAPX: PARTICLE INDUCED X-RAY EMISSION – X-RAY FLUORESCENCE (PIXE-XRF) INSTRUMENTS FOR LUNAR AND PLANETARY SCIENCE. D. F. Blake[1], R. Henderson[2], T. Bristow[1], P. Sarrazin[3], P. Lucey[4], A. S. Yen[5], E. Rampe[6], K. Zacny[7], K. A. Thompson[8], M. Gailhanou[9] and S. Webb[10] [1]NASA Ames Research Center (david.blake@nasa.gov), [2]Lawrence Livermore National Laboratory, [3]eXaminArt LLC, [4]Univ. Hawaii, [5]JPL, [6]NASA Johnson Space Center, [7]Honeybee Robotics, [8]SETI Institute, [9]CNRS – Universite Paul Cezanne, [10]SSRL/SLAC.

Introduction: Alpha Particle X-ray Spectrometry (also called PIXE-XRF) instruments have returned nearly all *in-situ* elemental information from Mars and the Earth's moon [1-3]. The ^{244}Curium radioisotope sources used in these instruments are uniquely suited to fluorescing the elements of geological and biological interest since they emit γ-rays of 14 and 18 KeV that efficiently fluoresce the mid-Z elements Ca-Zr and α-particles of 5.8 MeV that efficiently fluoresce the low-Z elements Na-K. When compared to X-ray Fluorescence instruments such as PiXL [4], PIXE-XRF instruments do not require X-ray tubes, High Voltage Power Supplies or complex mechanical movements. Measurements are made of ~2 cm areas of regolith simply by pressing the contact plate of the instrument onto the surface to be analyzed with a robotic arm.

PIXE-XRF instruments are listed in the payloads of four missions identified by the recent Planetary Science Decadal Survey [5]: The lunar Intrepid mission, the Endurance-SPA missions (New Frontiers-Class Endurance-A and Flagship-Class Endurance-R), and the Mars Life Explorer mission.

Here we describe two PIXE-XRF instruments in development by our group: 1). *LunaPIX* utilizes a Silicon Drift Detector (SDD) to collect an overall analysis of a 2 cm diameter area; 2). *MapX*, a first-of its-kind *imaging* PIXE-XRF instrument, simultaneously collects X-rays from a 2-D area of the regolith and directly images them onto a 512 X 512 pixel detector.

LunaPIX: LunaPIX is a robotic arm-deployed instrument that is held on the surface or hovered just above the surface of the regolith to be analyzed (Fig. 1).

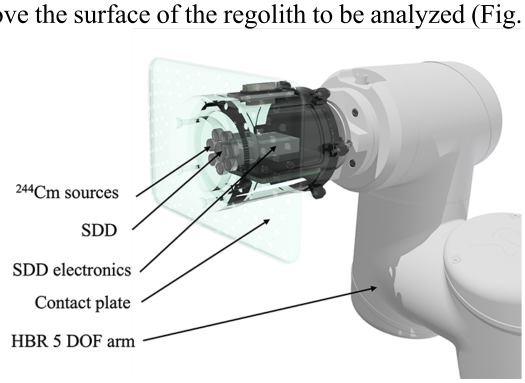

Fig. 1: LunaPIX Arm Unit attached to the HoneyBee Robotics robotic arm. During an analyses, a contact plate (translucent in this image) is pressed onto the regolith. An SDD and six ^{244}Cm sources can be seen recessed from the contact plate.

During an analysis, X-rays fluoresced from the surface are summed into a histogram of X-ray counts vs. X-ray energy that constitutes an X-ray Fluorescence Spectrum of the sample (e.g., Fig. 2).

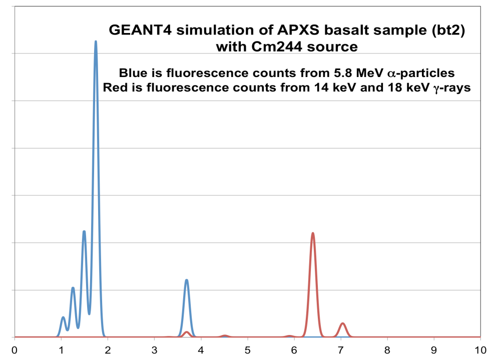

Fig. 2: Simulated spectrum of APXS basalt sample bt2, calculated using GEANT4 and a Fundamental Parameters model of LunaPIX. Red spectrum = γ-ray fluorescence, blue spectrum = α-particle fluorescence (30 mCi ^{244}Cm).

Calculated LunaPIX detection and quantification limits for a 10^4 sec. acquisition using 30 mCi ^{244}Cm are shown in Table 1. These values are in-family with those of APXS instruments flown on previous missions.

Table 1: LunaPIX detection and quantification limits for an element in a basalt matrix, 30 mCi ^{244}Cm sources, 10^4 sec.

Element	(Z)	Det. (ppm)	Quant. (ppm)
C	6	1470	3700
N	7	477	954
O*	8		
F	9	363	755
Na	11	420	1100
Mg	12	390	1100
Al*	13		
Si*	14		
P	15	310	940
S	16	210	650
Cl	17	220	690
K	19	310	980
Ca	20	540	1700
Ti	22	380	1200
V	23	290	920
Cr	24	240	760
Mn	25	280	870
Fe*	26		
Ni	28	200	610
Zr	40	50	200

*Major elements contained in the matrix are not shown.

“Touch and go” analyses are possible in 10-30 minutes with reduced accuracy. If necessary, additional ^{244}Cm sources can be added to meet the science requirements of particular missions. All components of LunaPIX (with the exception of the ^{244}Cm sources) are being developed to TRL-6 in MatISSE and DALI programs.

MapX: MapX is a native full-frame elemental imager that utilizes an X-ray Micro-Pore Optic (MPO) lens to directly focus X-rays fluoresced from the sample onto an energy-discriminating Charge-Coupled Device (CCD) detector. (Fig. 3).

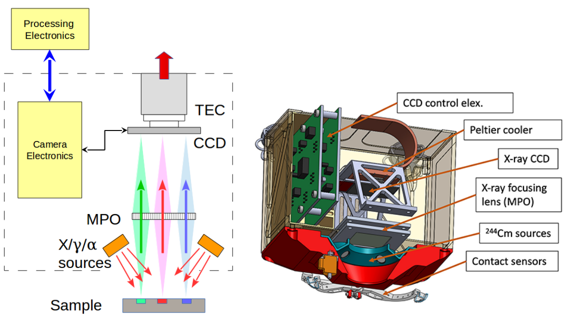

Fig. 3: (left) Fluoresced photons from the sample that are emitted in the direction of a CCD imager are focused by an X-ray lens called a MicroPore Optic (MPO) onto the CCD, resulting in a 1:1 image of the sample in its elements. (right) SolidWorks^{TM} cross-section of the MapX flight instrument.

During an analysis, the CCD is exposed and read several times per second and the detected X-ray photons are summed into an HDF-5 data cube that contains a complete XRF spectrum for each x,y position on the sample. Reduced data products include element maps and Regions of Interest (ROI) having common compositions that are identified using a machine learning algorithm. ROI images are returned along with quantifiable XRF spectra for each. Figure 4 shows a partial dataset from a 10-minute “touch-and-go” analysis collected in a MapX prototype. Because MapX analyses are stored as HDF-5 data cubes, new data products (e.g., element line scans, element correlation plots, etc.) can be generated from previous analyses as long as the data are stored on the instrument.

The X-ray optical characteristics of MapX were determined by ray-tracing simulation [6] and by direct measurement on SSRL Beam Line 2-3 [7]. MapX elemental images have a FWHM lateral spatial resolution of 100 µm at focus with a gradual degradation to 200 µm over a ±5 mm depth of field. This result suggests that rough, unprepared regolith surfaces can be imaged with minimal loss of spatial resolution.

Preliminary testing of instruments with ^{55}Fe: LunaPIX and MapX TRL-6 prototype instruments will be tested under flight-like conditions at NASA/ARC using ^{55}Fe sources (NASA/ARC does not have an NRC license for Cm).

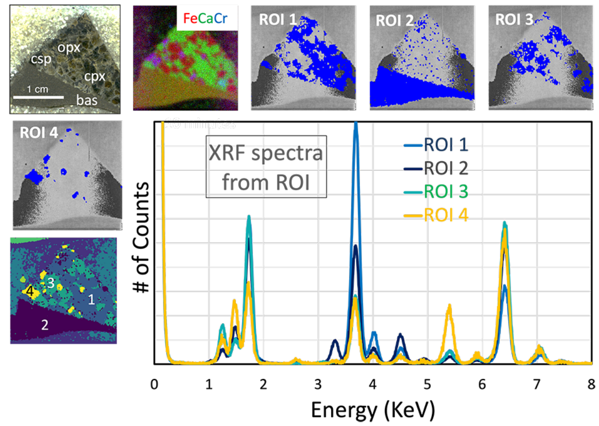

Fig. 4: MapX-III prototype partial dataset from a sample containing basalt (bas), orthopyroxene (opx), clinopyroxene (cpx) and chrome spinel (csp). Optical image (1 cm scale bar), 3-color FeCaCr map, and ROI 1-4 chosen from the HDF-5 data cube by a machine learning algorithm. Returned spectra are from the 3 identified minerals plus basalt. 10-minute “touch-and-go” analysis.

Fabrication of ^{244}Cm sources: Future work includes the fabrication and characterization of ^{244}Cm sources at LLNL. Sources will be prepared and γ-assayed for intensity and heterogeneity. Thin metal coatings will be electroplated onto the sources to reduce or eliminate “self-transfer,” a process that can contaminate samples with Cm fragments during analysis. The flight prototype instruments will be transferred to LLNL for testing with these sources and a final flow-down of source requirements will be made based on the science goals and objectives of a particular mission.

Acknowledgements: This research and development effort was funded under NASA’s PICASSO (#13-PICASSO13_0111), MatISSE #16-MATISE16_2-0005) and DALI (#18-DALI18_2-0006) programs to DFB.

References: [1] Rieder, R. et al., (1997) *Science*, **278**, 1771–1774. [2] Rieder, R. et al. (2003) doi:10.1029/2003JE002150. [3] Campbell, J.L. et al. (2012). *Space Science Reviews*, **170**, Issue 1-4, p. 319-340. [4] Allwood, A.C., et al. (2020). https://doi.org/10.1007/s11214-020-00767-7 . [5] National Academies of Sciences, Engineering, and Medicine (2022) https://doi.org/10.17226/26522. [6] Gailhanou, M. et al. (2018). *J. Appl. Optics,* https://doi.org/10.1364/AO.57.006795. [7]. Sarrazin, P. et al. (2018). *JINST* **13**, https://doi.org/10.1088/1748-0221/13/04/C04023