PORTABLE ELECTRON MICROSCOPY FOR SPACE: TO ISS AND BEYOND.

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Introduction: Electron microscopes (EM) are highly attractive tools for a variety of applications due to a unique blend of strong optical scattering, high native resolution, large depth of focus, and variety of signals including characteristic X-ray emission, enabling high-magnification structural imaging and chemical analysis. Ground-based EM's have been essential in NASA research for many years. For example, in mineralogy and petrology, EM is used to understand the origin and evolution of the solar system, particularly rocky bodies [1]. In microbiology, EM has been used to visualize the architecture of tissues and cells. In engineering/materials science EM has been used to characterize particulate debris in air and water samples, determine pore sizes in ceramics/catalysts, understand the nature of fibers, determine the composition and morphology of new and existing materials and characterize the micro-textures of vapor deposited films. EM is highly effective at investigating the nature of a wide variety of nanoscale materials/biomaterials at the core of many of NASA's inquiries.

Despite exquisite optical performance and versatility supporting a wide range of industries from basic science research to industrial process monitoring, EM has through its ~100-year history been widely regarded as a high-end tool, with limited reach outside the laboratory, due in particular to inherent complexity and need for vacuum. EM's are traditionally large, heavy, and have high power consumption. They are also expensive, and so tend to be housed in centers at universities and large research institutions, or at major industrial sites possessing ample laboratory space, support staff, supplies, and skilled operators. Since most organizations cannot support having their own EM, samples are often sent to these large institutions and service centers to be imaged, at great expense and often with delay of weeks to months for complex analyses. Complexity, high cost, and significant maintenance associated with collecting EM image data has until now severely limited the fields in which EM is used [2]. Making EM accessible outside constrained laboratory environments will bring EM's performance and versatility to a much broader range of scientific and engineering endeavors.

Portable SEM demonstrator on ISS: Mochii™ is a portable commercial scanning EM developed by the coauthors at Voxa in Seattle, WA to address the need for EM outside the laboratory (Fig. 1) [3]. This tiny low voltage microscope, which fits in the overhead bin of an airplane, has features that bring accessible and on-demand EM imaging to new applications previously hindered by size, complexity, and cost. Among these features are hand-carryable form-factor and low power consumption (0.25m tall, <12 kg, <80 W), user-friendly native wireless tablet interface, multi-user and remote capabilities, an integrated metal evaporator for easy sample preparation, and optional energy-dispersive X-ray analyzer (EDS) for chemical identification (Fig. 2).

We are in process to prepare a spectroscopy-enabled Mochii "*S*" for manned spaceflight, under NASA's SBIR program. Many of NASA's core inquiries will be significantly enhanced by on-site analyses including on manned vehicles and also robotic missions, and enable NASA to address a current blind spot (e.g., micronic particles and structure-chemical relationships) in its detection and analysis toolset. Mochii will demonstrate real-time, on-site imaging and compositional measurements aboard the International Space Station (ISS), accelerating answers to many scientific inquiries and mission decisions. The Mochii ISS demonstrator will serve as a platform for validating and learning best practices on this unique portable platform and serve as a springboard for future planetary and lunar missions science on manned and robotic missions beyond Low Earth Orbit (LEO).

Example space applications: Mochii is an excellent analytical tool for the morphological, textural and chemical characterization of extraterrestrial samples and impact craters produced by exposure to the space environment. Of particular interest are lunar, cometary, asteroidal and Martian samples. Fig. 2 shows the presence of a discrete assemblage, outlined by a dashed red line, composed of organic matter on the surface of the Martian meteorite Nakhla. The image on the right is a carbon map of the outlined region obtained by an EDS detector. The SEM/EDS system used to collect these data is part of the suite of electron beam instruments located at NASA JSC. The BSE image and carbon map of Nakhla are representative of the types of data that can be obtained by Mochii.

A second example highlighting some advantages of EM in space is in the study of microgravity crystallization dynamics [4-5], shown in Fig. 3. NaCl is optically transparent and its fine faceted surfaces are difficult to clearly image using light microscopy. EM elucidates these tiny structures and amplifies sensitivity to differences in experimental conditions during crystal growth. While these samples were imaged post-mission using Mochii EM on Earth, on-site EM coupled with elemental microanalysis will enable these and other experiments to be conducted on-vehicle, including those in which irreversible phase or chemical transitions occur in the presence of gravity or atmospheric conditions. Such studies would be impossible if re-entry back to Earth is required before analysis.

One particularly clear need for a Mochii on the ISS is to quickly identify mysterious particles that are causes or byproducts of malfunctions in vehicle and payload systems. Such particulates are often found on ISS and can take several months to return to earth for analyses to guide mission decisions, despite imparting significant risk to crew safety.

On-vehicle crew time is extremely precious, and innovations in this area facilitate effective use on ISS. Collaborative easy-to-use and responsive multi-user interfaces enable scientists on the ground to remotely operate the system while minimizing the impact to crew time. Another innovation is a quick-release optical column cartridge system that enables instant removal and insertion of factory pre-aligned full column cartridges with pre-packaged optical configurations [6]. These innovations minimize impact to end users' cognitive and service load and support more efficient analyses and reduce overhead, a key in field use where time can be essential.

Portable EM represents a significant paradigm shift in microscopy, taking high-resolution analytical microscopy and microanalysis out of the lab and into novel environments, increasing access to important scientific phenomena at the micro- and nanoscale [7].

References:

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[7] This work was supported by Voxa, NASA, Jacobs, and ARES.

Figure 1. Voxa's Mochii™ Electron Microscope (left) with iPad controller (right) with high resolution image of the head of a wheat plant [1].

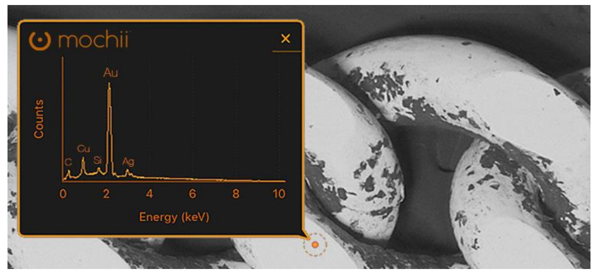

Figure 2. Energy-dispersive X-ray (EDS) spectrum acquired with Mochii S on gold alloy.

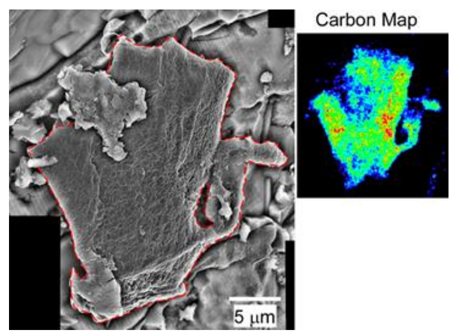

Figure 3. Left: SEM image of carbonaceous matter on freshly fractured surface of the Mars meteorite Nakhla. Right: EDS carbon map of the region outlined by the red dashed line in left image.

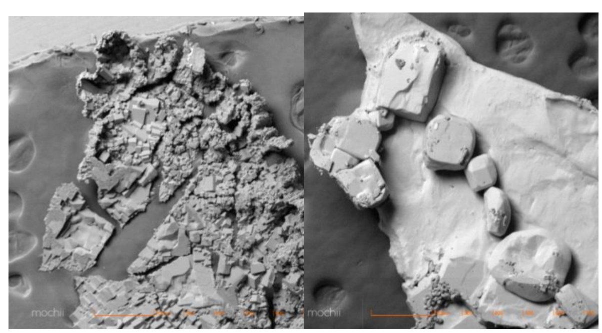

Figure. 4. (left) NaCl polycrystals formed in earth gravity by evaporation, and (right) large single crystals of NaCl formed in microgravity by evaporation, both imaged in Mochii at same magnification. A small number of nucleation sites form large stable monolithic crystals in microgravity.