Developing Miniature Wolter-I X-ray Optics for Planetary Science. J. Hong[1], S. Romaine[2], B. Ramsey[3], L. Nittler[4] and J. Grindlay[1], [1]Havard University, Cambridge, MA, USA (jhong@cfa.harvard.edu), [2]Smithsonian Astrophysics Observatory, Cambridge, MA, USA, [3]Marshall Space Flight Center, Huntsville, AL, USA, [4]Carnegie Institution Of Washington, Washington, DC, USA

Introduction: Comparative study of surface variation of the elemental abundance of diverse planetary bodies can provide clues to their formation and evolutionary history. X-ray fluorescence (XRF), intrinsic to atomic energy levels, carries a unique signature of the elemental composition of the emitting bodies (e.g., Figure 1 (*a*) [1]). Unlike optical and infrared spectra that can be altered by space weathering, XRF can probe more than 10–20 μm deep below the surface (e.g., see [2, 3]), and thus it is a powerful diagnostic tool to understand the true chemical and mineralogical composition of the planetary bodies.

The optical images of Comet 67P/Churyumov–Gerasimenko taken by the Rosetta mission such as the image shown (e.g, Figure 1 (*b*), see also [4]) have revealed rich surface features and outgassing activities. If the Rosetta mission was equipped with a high resolution X-ray *Imaging* spectrometer, it could have directly identified elemental composition of diverse structures of the comet nuclei surface and coma in the image. For instance, an X-ray telescope with sub-arcminute angular resolution and a square degree field of view (FoV) can measure the surface elemental abundance of ~1000 different segments in the region marked by the orange square in Figure 1 (*b*). Such an X-ray observation can greatly improve our understanding of the geological history of the comet nuclei and the physics behind the volatile activity.

Applications of X-ray imaging spectroscopy reach far beyond the study of elemental composition. Whether it is exospheric escape from Mars, pion reactions on Venus or sprite lighting on Saturn, sensitive X-ray imaging spectroscopy of planetary objects will greatly improve our understanding of the target bodies and the Solar System as a whole. Until now virtually all the X-ray spectrometers employed in planetary missions have been limited to simple collimator-type instruments without imaging capability. To make powerful, yet compact lightweight X-ray optics affordable for many future planetary missions where mass, volume and power for each instrument are limited, we have started a new program to develop miniature X-ray optics (MiXO) using metal-ceramic hybrid shells.

Technical Approach and Status: Nearly all modern X-ray astronomy missions utilize grazing-incidence optics with Wolter-I geometries which combines reflection from a parabolic and a hyperbolic surface in a barrel shape mirror. To increase the collecting area of these telescopes, several mirror shells of varying diameter can be nested one inside the other along the same optical axis. The majority of X-ray missions employ either Al foil, glass or nickel as the telescope substrate material.

Our new approach illustrated in Figure 2 (*a*) combines the plasma thermal spray technology with the electroformed Nickel replication process to largely replace thick high density NiCo shell (8.9 g/cm^3) with thin, light ceramic compound (2.3–2.9 g/cm^3) [5, 6]. In our metal-ceramic hybrid technology, the ceramic (~200 μm thick) provides the necessary stiffness to hold the figure of the mandrel and supply the rigidity needed for handling, while the thin metal (~ 30 μm thick) provides micro-roughness required for X-ray reflection. In parallel, we are also investigating minimum thickness of NiCo layer required for self-supporting NiCo-only shells. Thin (<~120 μm) NiCo-only shells can be potentially used for inner small shells without need for the supporting ceramic layers.

Figure 3 (*a*) shows recently fabricated hybrid shells (62 mm diameter × 18 cm long, designed for small FoV: <~ 0.1 deg^2) composed of 100 μm NiCo + 50 μm Bond layer + 200 μm Al_2O_3. A hybrid shell shows 2.1 arcmin resolutions with X-rays, whereas a 100 μm NiCo-only shell from the same mandrel shows about 1.1 arcmin resolution, which is limited by the polishied figures of the mandrel used for shell fabrication. Currently measures to reduce stress in the bond coat of conical shells are explored to improve the resolution using relatively thick (100 μm) NiCo substrate. Our new program for planetary science will start with flats (e.g., Figure 3 (*b*)) to identify minimal thickness (~ 30–50 μm) of NiCo layers where the newly found spray parameters remain valid without leaving imprints on NiCo layers during thermal spray, and thus eliminating need for an additional barrier layer between the metal and ceramic layers. We also started a new mandrel design to produce wide field (~1 deg^2) miniature X-ray shells suitable for planetary applications.

Telescope Design: Nearly all planetary targets for in-situ observations are diffuse sources, and thus a large FoV coverage with high resolution is essential in achieving sensitive X-ray observations. Modified Wolter-Schwarzschild or polynomial mirror geometries enable high angular resolution (<30 arcsec to 1 arcmin) over a wider FoV (~1 deg) than the standard Wolter geometry consisting of parabolic and hyperbolic surfaces [7, 8]. The off-axis resolution improvement with non-Wolter surfaces, however, requires the best focal surface, i.e., non-planar detector, which is not likely feasible for small instruments of planetary application. We, therefore, employ mirror shells of the standard Wolter geometry but with varying lengths, and we defocus each shell slightly to improve off-axis resolution. Defocusing trades off the on-axis resolution against off-axis resolution, leveling out the resolution over the FoV.

A baseline telescope configuration using MiXO (Figure 2 (*b*)) consists of ~50 shells with diameters of 6 cm to 14 cm and matching shell lengths of 7 cm to 10 cm, providing a grasp of ~30 cm^2 deg^2 at 1 keV. The focal length is set at 70 cm, but it offsets about 400 µm – 1.2 mm from the outer most to the inner most shell. This enables ~30 arcsec geometric resolution over 1 deg^2 FoV. Thus, even with additional degradation (<~20 arcsec) from surface roughness and shell alignments, sub arcmin resolution (~40 arcsec) is expected to be maintained over 1 deg^2 FoV.

Plan and Application: We plan to build three working modules of two shells each suitable for use in the baseline telescope configuration to demonstrate the feasibility of the technology for planetary science. Their performance will be fed back to modeling full X-ray telescope designs with high-fidelity.

MiXO enables diverse telescope configurations suited for various mission profiles. For instance, a modular version utilizing seven small optics with one common focal plane can cover about 7 deg^2 with relatively higher sensitivity in the hard (> 2 keV) X-ray band (Figure 2(*c*)). Given the relatively rapid development and deployment, CubeSAT is becoming a popular platform for space application. A free-flying CubeSAT configuration using MiXO can be envisioned in a 1 × 6 U package with 3–9 cm diameter optics with ~50 cm focal length. Another 1 × 6 U would be needed for the spacecraft functions including star cameras, so such a free-flyer MiXO telescope can be complete in a 2 × 6 U form factor.

References: [1] Weider S. Z. et al., (2015) *Earth & Planetary Science Letters*, 416, 109. [2] Tormbka J. L. et al., Science 289, 2101, [3] Binzel R. P. et al., 2010) Nature 463, 331 [4] Capaccioni, F. et al., 2015 Science, 347, a0628. [5] Hong J. et al. (2015) *Earth Planets & Space* 68, 35. [6] Romaine S. et al., (2015) SPIE, 91441H [7] Conconi et al. (2010) *MNRAS*, 405, 877 [8] Saha et al., (2014) *SPIE*, 914418

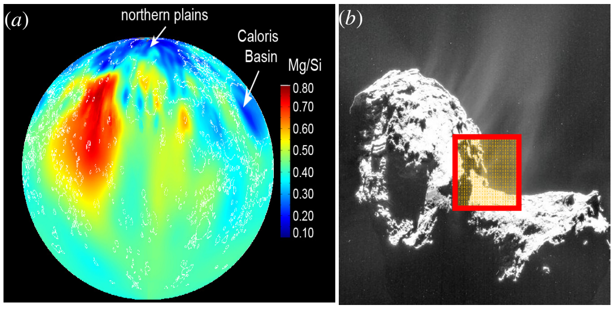

Figure 1 (*a*) Mg/Si abundance distribution of Mercury measured by the X-ray Spectrometer on MESSEGER. [1] (*b*) Comet 67P/Churyumov–Gerasimenko taken by NAVCAM on the Rosetta mission reveals the outgassing jets (Courtesy of European Space Agency-ESA, see also [4]).

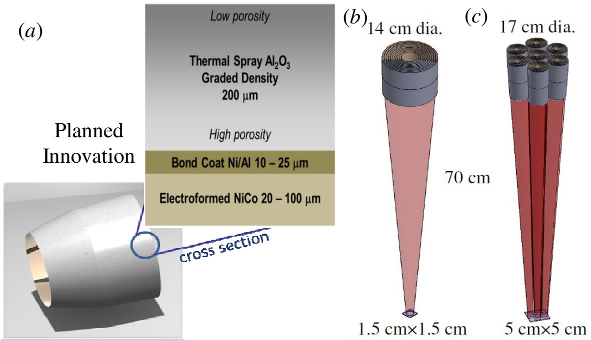

Figure 2 (*a*) Planned layer composition of lightweight metal/ceramic hybrid X-ray mirror shell: 30 µm NiCo + 10 µm Bond coat + 200 µm Al_2O_3. (*b*) A baseline MiXO telescope (optics mass ~1.1 kg, ~1 deg^2 FoV) (*c*) A wide-field version (optics mass ~1.8 kg, ~7 deg^2 FoV) optimized for hard (> 2 keV) X-ray bands. The design is easily scalable for smaller or bigger telescopes.

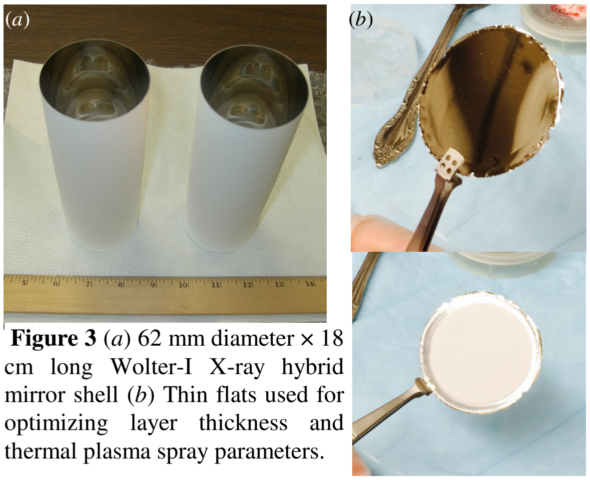

Figure 3 (*a*) 62 mm diameter × 18 cm long Wolter-I X-ray hybrid mirror shell (*b*) Thin flats used for optimizing layer thickness and thermal plasma spray parameters.