Miniature Lightweight X-ray Optics (MiXO) and CubeSat X-ray Telescope (*CubeX*) for Solar System Exploration.

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Introduction: We report the recent progress in development of miniature X-ray optics (MiXO), which can enable powerful, yet compact lightweight X-ray optics affordable for many future planetary missions. We also introduce a new concept of a CubeSat X-ray telescope (*CubeX*) capable of both X-ray fluorescence (XRF) imaging and X-ray pulsar timing based navigation (XNAV) by employing the MiXO and a novel focal plane configuration with no moving parts.

Comparative studies of surface variations in the elemental composition of diverse planetary bodies can provide clues to their formation and evolutionary history. 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. X-ray *Imaging* spectroscopy can greatly improve our understanding of the origin and geological history of target bodies by identifying the elemental composition of individual surface features (e.g., boulders versus craters) and activities (e.g., outgassing).

Deep space navigation is a critical issue for small planetary missions. Millisecond pulsars (MSPs), whose spin rates range from a few to a few 10s of milliseconds, provide stable natural clocks in the sky comparable to precise atomic clocks. With recent technological advances of X-ray telescopes and discoveries of many new X-ray MSPs in the last decade, XNAV has become a plausible approach to greatly assist, or even outperform, NASA's Deep Space Network (DSN) or ESA's European Space Tracking (ESTRACK) and to realize low-cost autonomous deep space navigation (e.g., [4]). For instance, the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) program plans to test the feasibility of XNAV on the International Space Station (ISS) [5] using the Neutron-star Interior Composition Explorer (NICER) mission [6].

Recent Development Progress of MiXO: X-ray telescopes utilize grazing-incidence optics with Wolter-I geometries, where X-rays can be focused through reflections from a parabolic and a hyperbolic surface in a barrel shape mirror. Our new approach for MiXO combines plasma thermal spray technology with the electroformed Nickel replication (ENR) process to largely replace thick high density NiCo shells (8.9 g/cm^3) with thin, light ceramic compounds (2.3–2.9 g/cm^3) [7, 8]. In our metal-ceramic hybrid technology, the lightweight 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.

Flat mirror samples are being used to efficiently optimize thermal plasma spray parameters and thus to minimize the thickness of the NiCo layer below 100 μm. We have manufactured 2" NiCo flat samples of various thicknesses (30, 50 and 80 μm). Two different methods are being investigated to apply the coating: (1) apply a bond coat followed by spraying ceramic, (2) co-spray a mixture of bond coat + ceramic, followed by the ceramic-only spray. Spray parameters are varied to study changes in stress. The initial results show that the co-spray technique produces a better surface roughness in both 50 and 80 μm NiCo layers. Figure 2 shows a picture of the front side of the co-sprayed 50 μm NiCo flat sample (a) and an amplified surface profile measured by a Zygo profilometer (b). In the case of the 30 μm NiCo flats, some deformation was visible, requiring further optimization. We plan to continue with the test to optimize spray parameters for thin (<50 μm) NiCo layers that can achieve sub arcmin angular resolution.

In parallel, we are also investigating the minimum thickness of NiCo-only shells required to be self-supporting. The state of the art ENR X-ray mirrors utilize ~200–250 μm thick NiCo shells. Thinner (<~120–150μm) NiCo-only shells can be potentially used for inner small shells without need for the supporting ceramic layers, so they can be suitable for lightweight optics. The first mandrel for MiXO is being manufactured, which can be used to build both NiCo-only and NiCo-ceramic hybrid X-ray mirrors of Wolter-I geometries. Figure 3 shows the main Al body of the first mandrel which is scheduled for polishing. The mandrel is 10 cm in diameter and 9 cm long (4.5 cm long for each bounce), and it is designed for 70 cm focal length. We plan to build and test a set of NiCo-only shells (100, 150, 200, 250 μm thick) followed by hybrid shells of various thicknesses this year.

CubeSat X-ray Telescope (*CubeX*): MiXO will enable compact and affordable, yet powerful X-ray telescopes on a variety of future planetary missions. CubeSat X-ray Telescope (*CubeX*) is a standalone free-flyer concept for a planetary X-ray imaging telescope in a multiple CubeSat form factor. *CubeX* will allow us to map the surface elemental composition of diverse airless bodies using XRF imaging and to conduct the feasibility and performance test of XNAV.

Figure 4 shows a 12U *CubeX* concept configured to perform XRF imaging of Moon. This *CubeX* is designed to rideshare to the Moon as a secondary spacecraft on a primary mission that will be inserted into a high-altitude lunar orbit (4000 × 6000 km). High resolution imaging enabled by MiXO in *CubeX* allows flexible observing conditions from relatively stable elliptical polar lunar orbits. *CubeX* can study ~8–10 key regions (~35–140 km) of geological interest on the Moon for 1 year to produce unprecedented high resolution (~0.6–2.3 km) elemental abundance maps of each region. In addition, *CubeX* can conduct delta-correction using the Crab pulsar and PSR B1937+21, and evaluate the performance of absolute navigation using XNAV by sequential observations of several MSPs during the dark side of the orbits. The focal plane consists of two high spectral resolution (< 200 eV at 6 keV) CMOS X-ray sensors and a high timing resolution (<1μs) SDD X-ray sensor. The novel configuration enables both XRF imaging and XNAV with a common MiXO module (<1' over ~1 deg^2, 50 cm focal length, ~25 cm^2 on–axis effective area at 1 keV) without moving parts (Figure 4).

Unprecedented high resolution measurements of major rock-forming elements through *CubeX* can greatly advance our knowledge of lunar geology. The Moon's proximity enables straightforward evaluation of the XNAV performance. While the Moon is a natural first step for the CubeSat/SmallSat concept development for both XRF imaging and XNAV, *CubeX* can be used to study diverse airless bodies such as Near Earth Objects (NEOs) and Martian Moons. A swarm of low cost *CubeX*s could revolutionize our understanding of NEOs and other airless bodies through rapid deployments to multiple targets.

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] Shemar, S. et al., 2016 *Experimental Astronomy* 42, 101 [5] Winternitz, L. M. B. et al. (2016) *NASA Technical Report*, p. 20160003122 [6] Gendreau, K. C. et al. (2012) *SPIE*, 844313 [7] Hong J. et al. (2016) *Earth Planets & Space* 68, 35. [8] Romaine S. et al., (2015) SPIE, 91441H

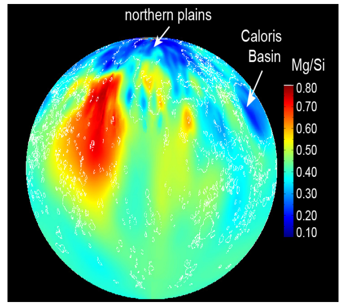

Figure 1 Mg/Si abundance distribution of Mercury measured by the X-ray Spectrometer on MESSEGER. [1]

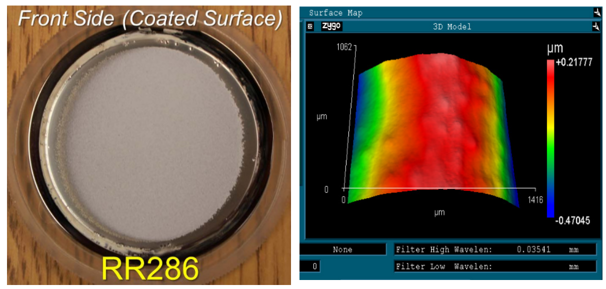

Figure 2 (*left*) 50 μm thick flat NiCo sample co-sprayed with NiAl + Al2O3 (*right*) Surface profile measured by a Zygo profilometer.

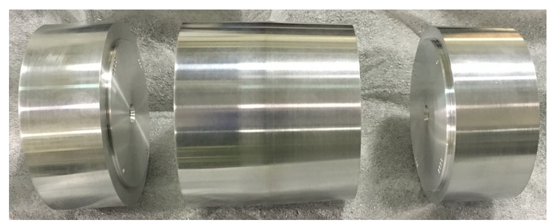

Figure 3 Three-piece mandrel for 70 cm focal length MiXO shells. The two end pieces are necessary for precision figure polishing. The main section is 10 cm in diameter and 9 cm long (4.5 cm for each bounce).

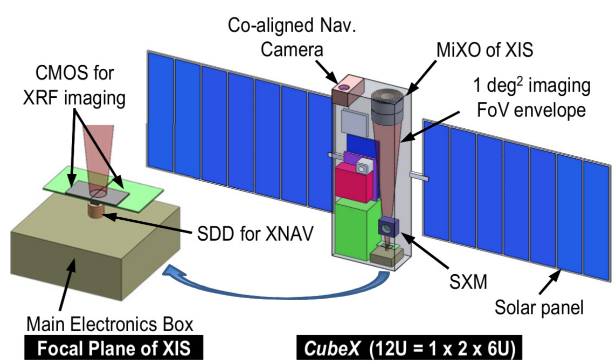

Figure 4 (*right*) Concept for *CubeX* consisting of two instruments: X-ray Imaging Spectrometer (XIS) and Solar X-ray Monitor (SXM). (*left*) Focal plane of XIS using two CMOS X-ray sensors for XRF imaging and a high timing resolution X-ray SDD for XNAV.