Miniature Lightweight X-ray Optics (MiXO) for Solar System Exploration. J. Hong\textsuperscript{1}, J. Grindlay\textsuperscript{1}, S. Rommaine\textsuperscript{2}, B. Ramsey\textsuperscript{1}, R. P. Binzel\textsuperscript{3}, W. Boynton\textsuperscript{4}, P. Georstein\textsuperscript{5}, R. Kraft\textsuperscript{6}, A. Kenter\textsuperscript{2}, M. Elvis\textsuperscript{2}, S. Wolk\textsuperscript{2}, R. Smith\textsuperscript{1}, L. Lim\textsuperscript{5}, C. Lisse\textsuperscript{7}, G. Branduardi-Raymont\textsuperscript{8}, B. Allen\textsuperscript{1}, J. Lee\textsuperscript{1}, \textsuperscript{1}Harvard University, Cambridge, MA USA (jaesub@head.cfa.harvard.edu), \textsuperscript{2}Smithsonian Astrophysical Observatory, Cambridge, MA USA, \textsuperscript{3}NASA Marshall Space Flight Center, Huntsville, AL USA, \textsuperscript{4}Massachusetts Institute of Technology, Cambridge, MA USA, \textsuperscript{5}The University of Arizona, Tucson, AR USA, \textsuperscript{6}NASA Goddard Space Flight Center, Greenbelt, MD USA, \textsuperscript{7}John Hopkins University, Baltimore, MD USA, \textsuperscript{8}University College London, London UK

Introduction: X-ray observations of planetary objects provide a unique window on fundamental processes associated with the formation and evolution of the emitting bodies and the Solar System as a whole. Future X-ray observations for planetary science require a sensitive yet compact X-ray imaging spectrometer, which is compatible with resource-limited in-situ or near-target experiments. We introduce Miniature X-ray Optics (MiXO) that can bring highly successful Wolter-I X-ray optics to planetary science within affordable mass, power, and cost constraints.

A primary science objective of planetary X-ray observation is to determine the elemental composition of diverse airless planetary bodies. The energy of X-ray fluorescence (XRF), intrinsic to atomic energy levels, carries an unambiguous signature of the surface elemental composition (>10 µm depth) of the emitting bodies. All but three atomic elements are identifiable by their K or L shell XRF lines in the 0.1 to 15 keV band. Either triggered by solar X-rays or energetic ions, XRF is a powerful diagnostic tool to understand the chemical and mineralogical composition of the planetary bodies. For example, XRF observations of asteroids can reveal their true type [1] regardless of space weathering that can redden the optical and near-infrared spectra [2]. X-ray imaging spectroscopy enables the measurement of spatial variation of both the absolute and relative elemental abundances without being constrained by the morphology and will be essential for understanding the dynamic activities of asteroids from crater-induced subsurface grain exposure to volatile depletion. For comets, near-target X-ray imaging spectroscopy will isolate the elemental composition of the comet nucleus, as the coma, optically thin in X-rays, can be spatially separated from the nucleus. The surface distribution of elemental composition will provide valuable input and the context for site selection for future sample collection. Time resolved imaging will capture dynamic nucleus features such as outgassing and break-offs of icy blocks.

In the case of large airless planetary bodies, observing environments often favor imaging to conventional collimator instruments. At Mercury, high thermal loads force spacecraft to be in highly elliptical orbits, limiting the observing duty cycle of the collimator instrument, whereas an imaging instrument is more robust against changes of orbital configurations. In Giant Satellite systems, focusing optics are essential due to intensive background from the extreme radiation environment (~10–100 krad/orbit).

Technical Approach: The proposed concept takes the technology that is being developed for lightweight optics for X-ray astronomy and adapting it for planetary missions. Fig. 1 illustrates advances of X-ray optics, starting from a ground and polished glass substrate used in Chandra X-ray Observatory and electroformed Ni shell in XMM-Newton to thin electroformed NiCo shell employed in Spektr-RG. Our new approach (Right in Fig. 1) combines the plasma thermal spray technology with the electroformed Nickel replication process to largely replace thick high density NiCo shell (1 mm, 8.9 g/cm\textsuperscript{3}) with thin, light ceramic compound (<200 µm, 2.3–2.9 g/cm\textsuperscript{3}). In our metal-ceramic hybrid technology, the ceramic provides the necessary stiffness to hold the figure of the mandrel and supply the rigidity needed for handling. Given the low energies of interest (< 15 keV) and relaxed angular resolution (30") the required micro-roughness can be achieved with a thin (~ few µm thick) layer of NiCo in principle. For the ceramic layer, with its higher stiffness relative to NiCo, a less than 200 µm thick layer would be sufficient to withstand handling and mounting forces.

The proposed X-ray optics have the following advantages for planetary missions: • High areal density (>100 cm\textsuperscript{2}/kg) enables efficient packaging • High resolution (<30", HEW) across the field of view (FoV) minimizes background. • Closed figure of revolution (compared to telescopes using segmented mirrors, e.g. micro channel optics [3]) offers maximum rigidity and strength, reducing the support structure mass. • Each shell provides a complete image (both the 1st & 2nd bounce mirrors), greatly simplifying co-alignment. • Electroforming is well suited for replicating multiple low-cost copies, ideal for modular design. • Machine-programmable mandrel surfaces enable easy optimization of profiles for wide field coverage and large effective area (e.g. polynomial surfaces). • Composition of coating layers can be optimized for each shell to improve effective area (e.g. Ir+C <8 keV, graded W/Si > 8 keV).
**Instrument Concept:** Compact lightweight hybrid X-ray mirrors enable modular design that can be easily scaled from low-cost Explorer-class to large scale Flagship missions. It offers an easy tradeoff between wide field and large effective area, depending on applications. Two examples of possible configurations using MiXO are shown in Fig. 2; the baseline option (Left) and a wide field option (MiXO-WF) (Right). Each shell in both the options consists of 20 µm NiCo + 200 µm Al₂O₃ layers. The optics with the support structure weighs ~1–2 kg under a conservative estimate. The baseline design is ~1/8th (in diameter) of the X-ray optics module of the Wide Field X-ray Telescope (WFXT, [4]), whose results are scalable to MiXO if the substrate of MiXO is <~300 µm thick. A smaller telescope similar to JUNTA [5] can be implemented without more development needs. MiXO-WF is optimized for wide field monitoring and broad band coverage with relatively higher grasp at high energies due to small grazing angles of each module (Middle in Fig. 2).

**Performance Estimates:** Observations of small targets such as asteroids with collimator instruments are susceptible to necessary changes in pointing or orbit radius which narrows their observing window. Focusing telescopes on the other hand can start observation much farther out (e.g. during the early phase of debris scouting), enable a more forgiving orbit configuration for observation, and can continue to accumulate useful data throughout the mission. We estimate that The MiXO telescope would have completed the NEAR [6] or Hayabusa’s [7] measurements even before their observations began in the mission timeline. A longer observing period also enhances a chance of success or discovery since detection of hard X-rays from heavy elements often rely on strong solar flares. In addition to the global measurement, with MiXO, the accumulated data over ~2 months (at 1 AU) during the quiet sun state alone will be sufficient for detection of ~1% spatial variation for major elements (e.g. O-K, Fe-L, Mg-K) over the entire surface. Compared to OSIRIS-Rex/REXIS [8], the baseline MiXO telescope with only 10% area of the focal plane of REXIS would detect all the major elements even before REXIS is expected to start observations, and the 20 day integration would allow minimum detectable variation of 1.6% Fe-L, 7.7% Mg-K, 100% Si-K, 600% S-K at a 50 m scale over the entire surface during the quiet sun state alone.

To locate small regions (~100 m) with the sub-1% level variation of major elements on Europa for astrobiological potential, we estimate that an array (~20) of the baseline telescopes is required. Such an array (~0.4 m²) is likely feasible only in a Flagship mission such as Jupiter Europa Orbiter. The combined active area of the focal planes in the 20 MiXO telescopes is only a factor of two larger than the focal plane of REXIS, and the total optics mass would be less than ~10 kg with ~100 µm hybrid shells (vs. ~70 kg with the current state of the art of 250 µm NiCo-only shells). Two month observations at ~100 km altitude by the 20 MiXO array will map C, N, F, Ne, Na, Mg, Al, Si, K, S, Cl, Ca, Fe at the sub-1% level relative to Oxygen over ~20 km² region at ~200 m scale.

**Summary:** MiXO can map the surface elemental composition of diverse planetary bodies from asteroids and comet nuclei to airless planets and satellites. MiXO can achieve high angular resolution (<1°) over a wide field of view (>1°) and extends X-ray imaging to higher energies (3–15 keV) for detection and mapping of heavy elements, complementing alternative approaches in planetary science such as micro-pore optics. High resolution imaging with MiXO can identify small regions with abundant organic or unusual elements. The modular design of MiXO can be easily scaled from low-cost Explorer-class to medium class New Frontiers missions. For flagship missions, MiXO will enable powerful X-ray telescopes sensitive enough to detect astrobiological evidence on Europa.


**Fig. 1** Advances of X-ray Optics. The weights (*) are for a 70 cm dia., 60 cm long mirror shell.

**Fig. 2** Example MiXO Telescopes: (Left) the baseline design, (Right) a wide-field option. The red cylinders indicate a 1.2° dia. FoV on the focal plane. The middle panel shows grasp (effective area × FoV) for Ir coating.