Miniature Wolter-I X-ray Optics (MiXO) and CubeSat X-ray Telescope (CubeX) for Solar System Exploration

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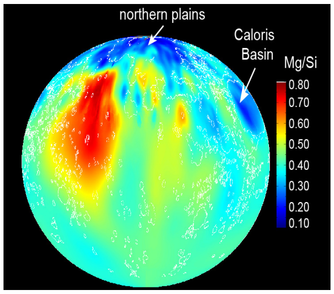
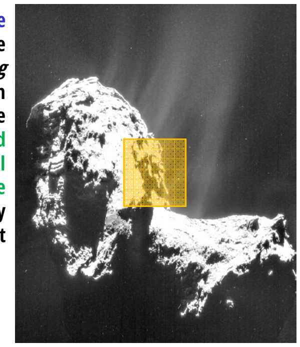
Development of Miniature X-ray Optics (MiXO) for Planetary X-ray Imaging

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. Unlike optical and infrared spectra that can be altered by space weathering, XRF can probe more than 10–20 μm deep below the surface, and thus it is a powerful diagnostic tool to understand the true chemical and mineralogical composition of the planetary bodies.

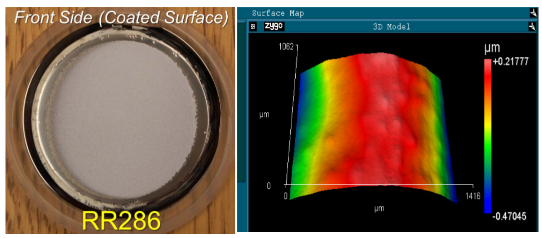


▲ Mg/Si abundance across Mercury's surface mapped with the X-ray Spectrometer (XRS) on *MESSENGER* (Weider+15). The remarkable variability of the abundance map indicates that Mercury's thin mantle is chemically heterogeneous, providing clues to the planet's early geological history.

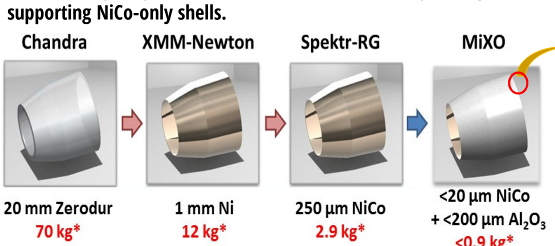
▶ Comet 67P/Churyumov–Gerasimenko taken by NAVCAM on the Rosetta mission reveals the outgassing jets (Capaccioni+15). If the Rosetta mission was equipped with a high resolution X-ray *Imaging* spectrometer, it could have directly identified elemental composition of diverse structures of the comet nuclei surface and coma in the image. 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 the figure. 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.



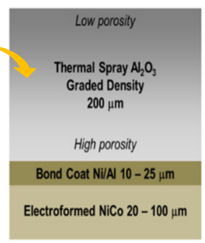
Nearly all modern X-ray astronomy missions utilize grazing-incidence optics with Wolter-I geometries which combines reflection from a parabolic and a hyperbolic surface in a barrel shape mirror. Miniature X-ray Optics (MiXO) using metal ceramic hybrid technology brings highly successful Wolter-I X-ray optics to planetary science within affordable mass, power, and cost constraints. In MiXO, 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 (Romaine+14). In parallel, we are also investigating minimum thickness of NiCo layer required for self-supporting NiCo-only shells.



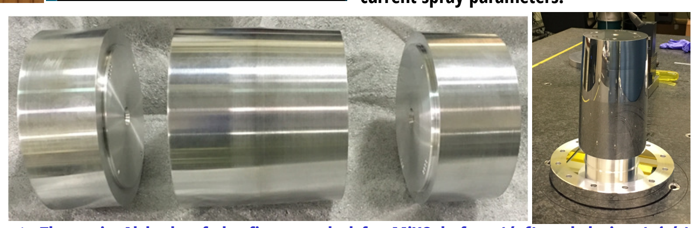
◀ Flat mirror samples are used to optimize thermal plasma spray parameters and to minimize the thickness of the NiCo layer below 100 μm. The figure shows the front side of the co-sprayed 50 μm NiCo flat sample and an amplified surface profile measured by a Zygo profilometer. The initial results show that ~50 μm NiCo can be coated without deformation using the current spray parameters.



▲ Advances of X-ray optics. The weights (*) are for a 70 cm dia. 60 cm long mirror shell.



▲ Layer composition of metal-ceramic hybrid shells



▲ The main Al body of the first mandrel for MiXO before (*left*) and during (*right*) 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. Two mandrels for nesting shells are under polishing and a first set of the MiXO shells will be fabricated in 2017 April.

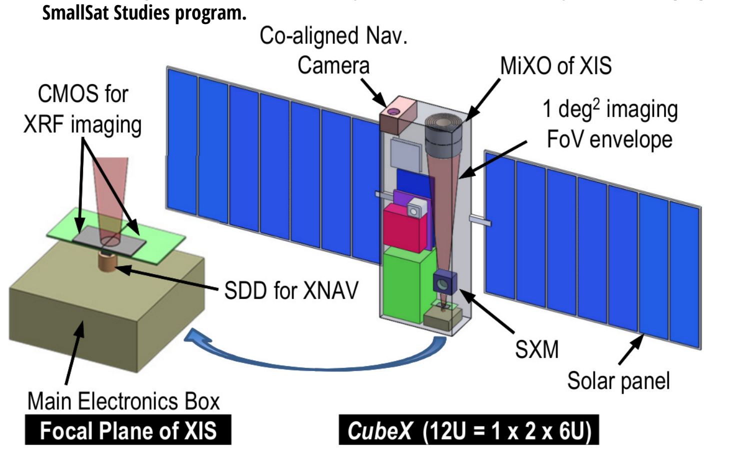
CubeSat X-ray Telescope (CubeX) for X-ray Fluorescence (XRF) Imaging and X-ray pulsar timing based Navigation (XNAV)

CubeX is an X-ray Imaging Spectrometer (XIS) with a Solar X-ray Monitor (SXM) in a 12U CubeSat form factor (1 x 2 x 6U). It will allow us to: (1) map the surface elemental composition of diverse airless bodies using X-ray Fluorescence (XRF), to understand the formation and evolutionary history of the individual bodies and the workings of the Solar system as a whole; (2) conduct the feasibility and performance test of X-ray pulsar timing based deep space navigation (XNAV, Reichley+71, Shemar+16, Winternitz+16), to lower operation costs of space navigation and enable autonomous deep space navigation. While *CubeX* can be used to study diverse airless bodies such as NEOs and Martian Moons, the Moon is a natural first step for the CubeSat/SmallSat concept development for both XRF imaging and XNAV test. Unprecented high resolution measurements of major rock-forming elements will greatly advance our knowledge of lunar geology. The Moon's proximity enables straightforward evaluation of the XNAV performance.

Key Payload & Mission Characteristics of 12U *CubeX*

Payload: X-ray Imaging Spectrometer (XIS: MiXO + 2 CMOS + SDD) & Solar X-ray Monitor (SXM: SDD + Collimator)	
Mass & Form Factor	9.5 kg in 1 x 1 x 6U for XIS + SXM
Power	14W average (17W peak)
Data Rate	8 MB/day (15 MB/day for Crab obs)
Effective Area	>25 cm^2 at 1 keV (MiXO)
Ang. Res. & FoV	<1 arcmin over 1 sq. deg (MiXO+ 2 CMOS)
Spectral res. & range	<200 eV at 6 keV, 0.2–8 keV for XRF
Time resolution	1 μs (SDD) for XNAV
Mission Characteristics	
Type, Cost	Secondary mission, \$36M
Mass & Form Factor	18 kg in 12U (=1 x 2 x 6U)
Solar Panel	Max 89 W power supply
Comm.	Iris V2 (max 300MB/day for 3 hr contact)
ADCS	~2 km position knowledge for XNAV ~30" pointing knowledge for XRF and XNAV
Lifetime, Launch	1 year from a 2023-2027 launch for solar max.
Orbit Design	Elliptical Polar Lunar Orbit, ~14 hr period, Insertion to 4000 x 6000 km orbit via primary
Propulsion	Low thrust trajectory with Hall thruster to 2000 x 8000 km orbit after 1 year
Operation (75% duty)	55% XRF +16% XNAV+ 2% Telemetry +2% EP
MOC, SOC	ARC MMOC, SAO

CubeX for the Moon will rideshare to the Moon as a secondary spacecraft on a primary mission that will be inserted into a high-altitude lunar orbit (4000 x 6000 km). High resolution imaging enabled by Miniature Wolter-I X-ray Optics (MiXO) in *CubeX* allows flexible observing conditions from relatively stable elliptical polar lunar orbits. *CubeX* will study ~8–10 key regions (~35–140 km) of geological interest on the Moon for 1 year to produce high resolution (~0.6–2.3 km) elemental abundance map of each region. *CubeX* will also conduct delta-correction using the Crab pulsar and PSR B1937+21, and evaluate the performance of absolute navigation by sequential observations of several millisecond pulsars during the dark side of the orbits. The mission and operation concept of *CubeX for the Moon* will be studied in collaboration with the NASA Ames Mission Design Center under a recently awarded NASA Planetary Science Deep Space SmallSat Studies program.



▲ *(Right)* Layout of major components of the X-ray Imaging Spectrometer (XIS) and the Solar X-ray Monitor (SXM) within a 12 U CubeSAT envelope. The XIS occupies about 6U with ~50 cm focal length and ~25 cm^2 effective area at 1 keV. *(Left)* A closed-up view of the focal plane consisting of two type of detectors: 2 X-ray CMOS sensors (< 200 eV at 6 keV) for XRF imaging and a high timing resolution SDD (1 μs) for XNAV. The SDD is placed recessed in between the two CMOS sensors. This novel configuration enables both XRF imaging and XNAV without moving parts.