CubeSat X-ray Telescope (*CubeX*) for Lunar Elemental Abundance Mapping and Millisecond X-ray Pulsar Navigation.

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CubeSat X-ray telescope (*CubeX*) is a compact, highly radiation tolerant, focusing X-ray telescope (Fig. 1) that identifies and spatially maps lunar crust and mantle materials excavated by impact craters, and also serves as a pathfinder for autonomous precision deep-space navigation using X-ray pulsars.

Elemental composition of lunar mantle and lower crust: Lunar sample and meteorite analyses and remote sensing data have led to a paradigm that very early in its history the Moon experienced a stage of large-scale melting, known as the "lunar magma ocean" or LMO, which led to differentiation of the mantle and formation of a crust with a diverse range of lithologies (e.g., [1]). However, a number of fundamental questions remain about the composition of the lunar crust and mantle and changes in composition as a function of depth in the crust (e.g., [2]).

XRF, induced either by solar X-ray flux or energetic ions, carries decisive signatures of elemental composition. X-ray observations of planetary bodies, thus, provide a powerful diagnostic tool for remotely determining elemental abundances including major rock forming elements such as Mg, Al, Si, and Fe. Through high-resolution XRF imaging spectroscopy, *CubeX* uses selected lunar sites to search for small patches of elusive lunar lower crust and upper mantle material excavated within and around impact craters.

Compositional measurements of the ejecta around 10–200 km size craters probe the vertical structure of the lunar crust to depths between 1 and 20 km since impact craters excavate material from depths approximately one-tenth of their diameter. For relatively large impact basins, impact crater central peaks and peak rings emerge from beneath excavation zones with depths roughly one-tenth of their transient crater diameter (~ half of the final crater diameter). Therefore, crater central peaks and peak rings may expose material from mid-crustal to upper mantle depths [3, 4].

The prime target sites, which include craters of various sizes from the nearside and farside of the Moon, are selected based on the data from missions like *GRAIL* and *Kaguya*, which suggest possible outcrops of deep-seated material. Informed with the surface topography from *LRO*, *CubeX*'s measurements of regional compositional variations of lunar sites such as Schrödinger and South Pole Aitken Basins will assist and provide the context for future sample return missions recommended by the Decadal Survey.

The focusing X-ray telescope in the heart of *CubeX* allows elemental measurements of geological features with unprecedented spatial resolution (~2–3km) and sensitivity over wide field (~110 km). This enables detection of small outcrops of lunar mantle and lower crust with their larger geological context in the surrounding area (e.g., Schrödinger Basin in Fig. 2).

Millisecond X-ray Pulsar Timing based Deep Space Navigation: *CubeX* also uses high resolution X-ray imaging and time series measurements to conduct X-ray pulsar timing based navigation (XNAV) and to evaluate its performance for deep space navigation. Deep space navigation is a critical component for planetary missions. Current deep space navigation mainly relies on communication from a global network of large ground-based radio antennas such as NASA's Deep Space Network (DSN) or ESA's European Space Tracking (ESTRACK). Their performance understandably degrades while the operational cost increases as the S/C travels farther away from Earth. As we approach a new era of space exploration enabled by a large number of low-cost SmallSats/CubeSats, access to the DSN or ESTRACK can be prohibitively competitive and expensive for small planetary missions, and development of autonomous deep space navigation becomes increasingly important.

One of the promising approaches for autonomous deep space navigation is to use precise time series from millisecond pulsars (MSPs). MSPs are strongly magnetized spinning neutron stars, which spin nearly 1000 times a second. Their spin rate is extremely stable, rivaling the precision of atomic clocks, and thus precise time series from MSPs can be used as a "Global Positioning System" (GPS) of our Galaxy. With recent technological advances of X-ray telescopes, XNAV has become a plausible approach for realizing low-cost autonomous deep space navigation [5, 6]. For *CubeX*, the Moon's relative proximity enables a straightforward evaluation of the XNAV performance through DSN.

***CubeX* Instruments:** *CubeX* carries two X-ray instruments: an X-ray Imaging Spectrometer (XIS) and a Solar X-ray Monitor (SXM). The XIS conducts both XRF observations and XNAV operations, while SXM monitors solar X-ray activity during lunar XRF observations. The SXM is required to properly infer elemental abundances from XRF measurements since the XRF flux and spectra depend on the incident solar X-rays on the lunar surface. The XIS is a small X-ray telescope weighing about 6 kg in a ~10 × 10 × 60 cm form factor. The XIS employs Miniature Wolter-I X-ray optics (MiXO) with high angular resolution (<1 arcmin), whose lightweight small form factor is suitable for low-cost SmallSat missions [7, 8]. The XIS focal plane combines high spectral resolution (<150 eV at 1 keV) CMOS X-ray sensors [9] and a high timing resolution (< 1 microsecond) SDD X-ray sensor [10]. This novel combination of instruments enables both XRF observations and XNAV operations without moving parts.

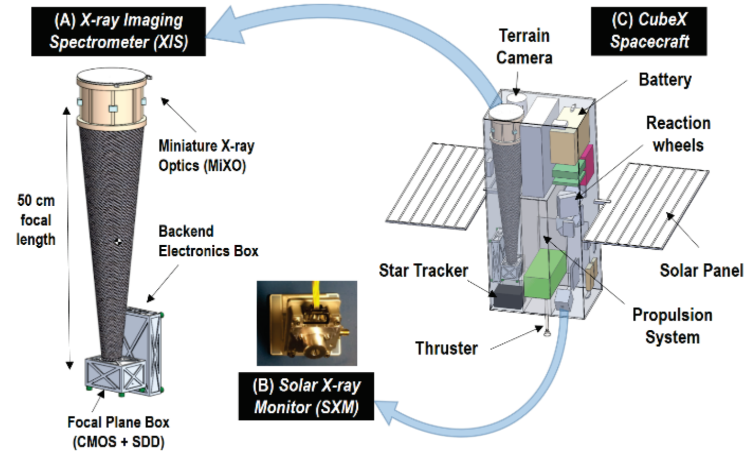

Figure 1 Two instruments onboard *CubeX*: (A) X-ray Imaging Spectrometer (XIS) and (B) Solar X-ray Monitor (SXM) w.r.t. (C) the *CubeX* S/C. The SXM picture (not to scale) shows an actual flight model of *OSIRIS-Rex*/REXIS.

Mission Design and Implementation: *CubeX* spacecraft (S/C), which is about 43 kg in total mass and 35 × 23 × 60 cm in size as shown in Fig. 1(c), is designed as a secondary S/C to rideshare to the Moon during the next solar maximum (2023-2027). *CubeX* S/C's small form factor fits well in fairing of common launchers for lunar missions. After insertion into a common elliptical lunar orbit (500 × 5000 km), *CubeX* transfers to a science-optimized quasi-frozen circular polar orbit at 6000 km for the 1-year science operation. The chosen science orbit at high altitude requires relatively low maintenance.

About 90% and 10% of the 1-year science operation are devoted to lunar XRF imaging spectroscopy and XNAV operations, respectively. For lunar XRF measurements, 2 to 4 lunar targets are observed in each orbit during the day side for 2 – 3 hr each, depending on their visibility. Such a continuous observation enhances a chance of collecting high XRF flux from the site during a bright solar flare, which can last a few hours. To meet the science requirements (<30% accuracy of major elemental abundance ratio), an exposure of > 0.5 Msec will be accumulated for each of the prime target sites and calibration sites.

For XNAV, 3 – 4 MSPs are observed in sequence for about 8 orbits of a 6-day period of each operation. A long continuous observation of a pulsar simulates a more realistic environment for deep space navigation compared to XNAV test being conducted by *NICER* on the International Space Station (ISS): *NICER* can continuously observe each pulsar only for about 20 – 30 min per orbit due to orbital constraints of the ISS.

References: [1] Wood, J. A. et al., (1970) *Science*, 167, 602 [2] Elardo, S. M. et al., (2010) *Geochimica et Cosmochimica Acta*, 75, 3024 [3] Lemelin, M. et al., (2015) *Journal of Geophysical Research: Planets*, 120, 869 [4] Kring, D. et al., (2016) *Nature communications*, *7*, 13161 [5] Shemar, S. et al., 2016 *Experimental Astronomy* 42, 101 [6] 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 [9] Janesick, J. et al., 2010) SPIE,77420B [10] LaMarr, B. et al., (2016) SPIE 99054W

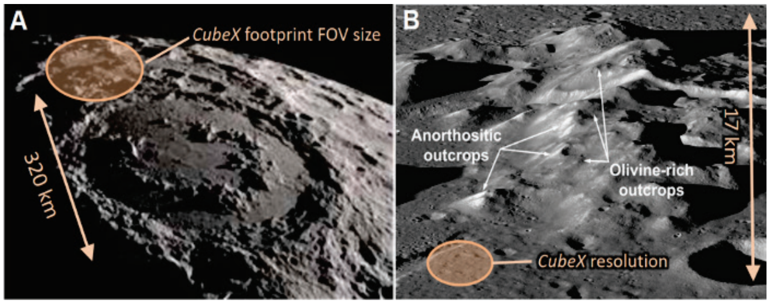

Figure 2 (A) The morphology of a peak ring is evident in this view of the ~320-km-diameter Schrödinger basin on the Moon (NASA's Scientific Visualization Studio). (B) A close-up view of a segment of the peak ring with rocks uplifted from mid- to lower-crustal levels by the impact event. The field of view is ~17 km wide through the center of the image. *LRO* Camera image M1192453566 [4]. Anorthositic outcrops are generally considered to be from highlands, whereas olivine-rich outcrops are associated with the mantle or lower crust origin.