

A High Speed, Radiation Hard X-ray Imaging Spectrometer for Planetary Investigations. R. P. Kraft¹, A. T. Kenter¹, S. S. Murray², A. Martindale³, J. Pearson³, R. Gladstone⁴, G. Branduardi-Raymont⁵, R. Elsner⁶, T. Kimura⁷, Y. Ezoe⁸, C. Grant⁹, E. Roediger¹⁰, R. Howell¹¹, M. Elvis¹, R. Smith¹, B. Campbell¹², J. Morgenthaler¹³, T. Cravens¹⁴, A. Steffl⁶, J. Hong¹, ¹Smithsonian Astrophysical Observatory (60 Garden St, MS-4, Cambridge, MA 02138, rkraft@cfa.harvard.edu), ²Johns Hopkins University, ³University of Leicester, ⁴Southwest Research Institute, ⁵Mullard Space Sciences Laboratory, ⁶Marshall Space Flight Center, ⁷JAXA, ⁸Tokyo Metropolitan University, ⁹MIT, ¹⁰Hamburger Sternwarte, ¹¹University of Wyoming, ¹²SI/NASM, ¹³PSI, ¹⁴University of Kansas

Introduction: X-ray observations provide a unique window into fundamental processes in planetary physics, and one that is complementary to observations obtained at other wavelengths. We propose to develop an X-ray imaging spectrometer (0.1-10 keV band) that, on orbital planetary missions, would measure the elemental composition, density, and temperature of the hot plasma in gas giant magnetospheres, the interaction of the Solar wind with the upper atmospheres of terrestrial planets, and map the elemental composition of the surfaces of the Galilean moons and rocky or icy airless systems on spatial scales as small as a few meters. The X-ray emission from gas giants, terrestrial planets and moons with atmospheres, displays diverse characteristics that depend on the Solar wind's interaction with their upper atmospheres and/or magnetospheres. Our imaging spectrometer, as part of a dedicated mission to a gas giant, will be a paradigm changing technology. On a mission to the Jovian system, our baseline instrument would map the elemental composition of the rocky and icy surfaces of the Galilean moons via particle-induced X-ray fluorescence. This instrument would also measure the temperature, density and elemental abundance of the thermal plasma in the magnetosphere and in the Io plasma torus (IPT), explore the interaction of the Solar wind with the magnetosphere, and characterize the spectrum, flux, and temporal variability of X-ray emission from the polar auroras. We will constrain both the mode of energy transport and the effective transport coefficients in the IPT and throughout the Jovian magnetosphere by comparing temporal and spatial variations of the X-ray emitting plasma with those seen from the cooler but energetically dominant 5 eV plasma.

For rocky, airless members of the Solar system (i.e. the Moon, asteroids, Near Earth Objects (NEOs), comets), X-ray fluorescence measurements can directly determine the elemental compositions of their surfaces. X-rays are produced by the elements C, N, O, P, and S, which are important constituents of living organisms, as well as Mg, Al, Si, Na, Cl, Fe and Ni through the absorption and fluorescence of Solar X-rays. For missions that orbit or make close approaches to rocky systems, our instrument can measure abundances on scales of a few meters, thus identifying regions en-

riched in pre-biotic organics, as well as the distribution of ices. These abundance maps can then be compared with the surface topology to better determine the system's evolutionary and geologic history. Measuring abundances inside craters provides a means to probe changing composition with depth, which further constrains the system's formation and evolution.

We are currently developing monolithic CMOS sensors for use as X-ray imaging spectrometers. Because of their low noise, high frame rates, and extreme radiation hardness, these sensors are ideal for a variety of mission concepts in planetary sciences. We propose to extend our existing laboratory detector development program and build a complete flight-prototype X-ray camera. We will integrate this camera with a lightweight imaging optic that will offer a suite of new capabilities for planetary discovery by providing X-ray imaging spectroscopy with arcminute angular and good spectral resolution ($E/\Delta E=20$ at 1.5 keV).

Instrumentation: We are currently developing a monolithic CMOS sensor in conjunction with SRI International as part of a NASA APRA grant for future X-ray astronomy missions [1]. With the APRA funding, we constructed several lots of monolithic CMOS imagers optimized for soft X-ray imaging spectroscopy, and are evaluating their performance in our laboratory system. Our monolithic CMOS technology combines several capabilities making them the ideal X-ray sensor for a variety of planetary investigations, and uniquely suited to gas giant missions.

The capabilities of our sensor include:

- 5 transistors per pixel design with separate photodiode and sense node
- 1024x1024 format with 16 μm square pixels
- Backside illumination for near unity low energy quantum efficiency

Improvements of CMOS sensors over conventional CCD technology include:

- High pixel sense node gain ($>100 \mu\text{V}/e^-$) and low read noise ($<2 e^- \text{ rms}$) for single photon counting from the X-ray into the EUV band

- 10 μ s row readout time (20 full frames per second) to handle high count rates
- Negligible fixed pattern noise (<1% rms variation in pixel response)
- Intrinsically radiation hard. The 5T pixel design shows no charge transfer efficiency change after receiving a dose of 100 krads of 2 MeV electrons. Conventional CCDs show significant degradation at 1 krad [2].
- Lower power and consequently lower heat load, thus simplifying thermal design

We will combine our sensor with a Microchannel plate X-ray optic (MCPO) to provide a substantial improvement in capability by increasing the count rate, reducing the effect of background, and providing spectrally resolved images. All previous X-ray spectrometers on planetary mission were mechanically collimated with a field of view of several to tens of degrees. Crude imaging was done by scanning the detector across the field. The improvement in signal to noise using focusing optics compared to mechanical collimators is typically several orders of magnitude, as the detector size is reduced and the optic provides the effective area needed.

Microchannel plate optics (MCPOs) have long been envisioned for use in all-sky monitors in the Lobster-eye configuration [3], but the use of MCPOs for arcminute resolution imaging is in its infancy. The most advanced focusing MCPO to date is MIXS-T [4] on BepiColombo, which has the requirement to achieve 9 arcmin HPD and uses MCPOs in a Wolter-1 conical approximation. The MIXS-T optic has a 21cm entrance aperture and 1m focal length with six sextants each consisting of six tandems (i.e. Wolter pairs). Individual sections of the 36 wedge-shaped tandems for MIXS-T are measured to be 3-5 arcmin HPD.

Integral to the camera design are two FPGAs, one for camera control functions and a second for event processing, on two distinct boards. We baseline the low power, radiation hard Microsemi (ACTEL) RTAXxxxx-SL FPGA family for the headboard detector control, and the Virtex-4 re-configurable device for the event processing applications. This two board design is particularly appropriate for a Jovian mission where the radiation environment requires rad-hard components near the sensor, and the processor board is remotely located in a common radiation "vault", such as is used on the Europa Clipper spacecraft.

The sensor must be read out sufficiently fast so that we are in single photon counting mode. Each X-ray or charged particle that interacts in the active region of the sensor deposits charge in one or more pixels. We have found empirically that pixelated Si sensors can

operate in single photon counting mode at rates in which only 1% of the pixels have signal charge in them if we use 3x3 event detection islands.

We can read our 1024x1024 pixel sensor out at 20 Hz, so we can handle rates of no more than 200,000 cts s^{-1} if all the events are single pixel events. The practical limitation to our event rate is, however, the requirement that all event processing can be done with a low power, radiation hard FPGA. We have done preliminary estimates of FPGA resources and determined that our FPGA can operate at a rate of at least 1000 cts $frame^{-1}$ (or 20,000 cts s^{-1}), and perhaps as much as a factor of a few larger than this.

One of the major technical difficulties of operating an X-ray imaging spectrometer at Jupiter is the high particle background rates. We use the Space Environment Information System (SPENVIS) modeling tool to calculate the particle fluxes at different positions in the Jupiter system and compare them to particle fluxes in the Earth's radiation belts where we have X-ray CCD data from the Chandra X-ray Observatory ACIS instrument. For the Jupiter particle environment we used the Galileo Interim Radiation Electron model [5], and the electron and proton rates from [6] and [7].

Count rates were calculated in three energy bands, 0.1 to 0.5 keV, 0.5 to 2 keV, and 2 to 10 keV, plus the total event rate on the detector, and are summarized in Table~1 for two regions in the Jovian magnetosphere assuming shielding of 10 gm cm^{-2} of Al. Our instrument has the capability to operate inside the Jovian magnetosphere at the orbit of Europa.

Band (keV)	0.1-0.5	0.5-2.0	2.0-10.0	Total
Europa	70	110	500	5400
Callisto	0.05	0.3	1.0	10.

Table 1: Background rates (cts s^{-1}) in three energy bands (keV) in good grades, and total rate (entire energy band and all event grades) at various locations around Jupiter in the detector.

References: [1] Kenter, A. *et al.* (2014), Proc. SPIE, in press. [2] Janesick J. *et al.* (2010), Proc. SPIE, 7742, 9. [3] Fraser G. *et al.* (1992) Proc. SPIE, 1546, 41. [4] Fraser G. *et al.* (2010), P&SS, 58, 79. [5] Garrett H. B. *et al.* (2003), EGS-AGU-AUG Joint Assembly Abs #6824. [6] Bourdarie S. & Sicard A. (2006), ONERA technical note 120 issue 1.2, [7] Divine N. & Garrett H. (1983), JGR, 88, 6889.