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ABSTRACT

Current lobster eye telescopes demonstrate that it's possible to produce light-weight, large field of view instruments for observing X-rays for both planetary science and astronomy. Jupiter is the most powerful particle accelerator in the solar system and the other outer planets have intricate and complicated magnetospheres which their moons often orbit within. Particle bombardment of the surfaces of their moons induces the emission of characteristic X-rays which enables their composition to be studied. An orbiting X-ray instrument would transform our understanding of the moons' composition, as well as the aurorae, atmosphere, plasma tori of outer planet systems and could also enable direct imaging of the entire radiation belt. Lobster eye telescopes are perfect for this application due to their light weight and wide field of view. This paper begins to identify a lobster eye telescope design to fulfil these science goals.

Keywords: X-ray astronomy, X-ray telescope, X-ray optics, Lobster eye optic, Micro Pore Optics

1. INTRODUCTION

1.1 Lobster eye optics

The lobster eye geometry for X-ray imaging was first introduced by Angel (1979)[1] and the use of tesselated slumped Micro Pore Optics (MPOs) in a lobster eye X-ray telescope has since been pursued by several authors.[2–5] This geometry can provide a very large field of view and in addition, due to the low density of the glass used in the optics, the completed telescope has very low mass. The geometry of the MPOs comprises a square packed array of microscopic pores of a square cross section with a 40 μm or 20 μm side. The MPOs have an iridium coating within the pores to enhance X-ray reflectivity, and a thin aluminium film is applied over the front pore apertures, which provides both an optical and UV light blocking filter, and a good thermal surface. They are spherically slumped such that all the pore axes converge on a common point, the centre of curvature. Details of the MPO production are given in Feldman et al.[6] An example of a 40 mm by 40 mm square, 1.2 mm thick, iridium coated, aluminium filmed MPO is shown in Figure 1. A lobster eye telescope can be formed by tessellating an array of single MPOs over a metal support frame with the same radius of curvature as the individual MPOs.

The point spread function (PSF) produced by a single MPO comprises of a focused spot - created by rays which undergo two grazing incidence reflections off adjacent sides of a pore, vertical and horizontal cross-arms - caused by rays which undergo one reflection, and a diffuse patch created by rays which pass straight through the MPO. Three reflection rays and higher contribute to the outer wings and the rays which go straight through the MPO create a diffuse background patch. An example of the distinctive PSF produced is shown in Figure 2.

1.2 Current Missions

As described in Hudec & Feldman,[8] several current and future missions over the next few years are using lobster eye telescopes to take advantage of the large FoV and light-weight nature of these optics. Tailored for various scientific goals, including planetary science and astronomy, below is a brief description of some of the current missions.

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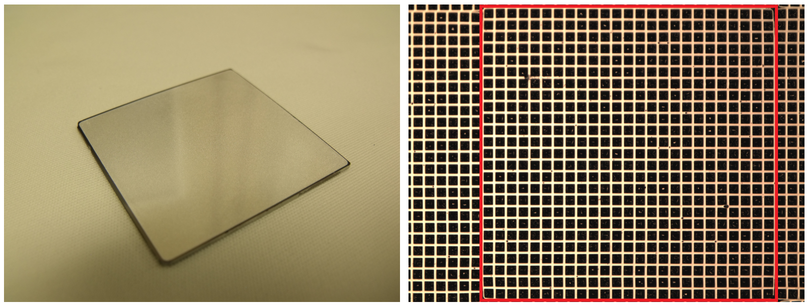

Figure 1. *Left:* a single, 40 mm by 40 mm square, iridium coated, aluminium filmed, 1.2 mm thick MPO produced by Photonis France SAS. *Right:* a microscope image of a series of individual 40 μm pores on an MPO. A single multifibre of 25 x 25 pores is highlighted in red.

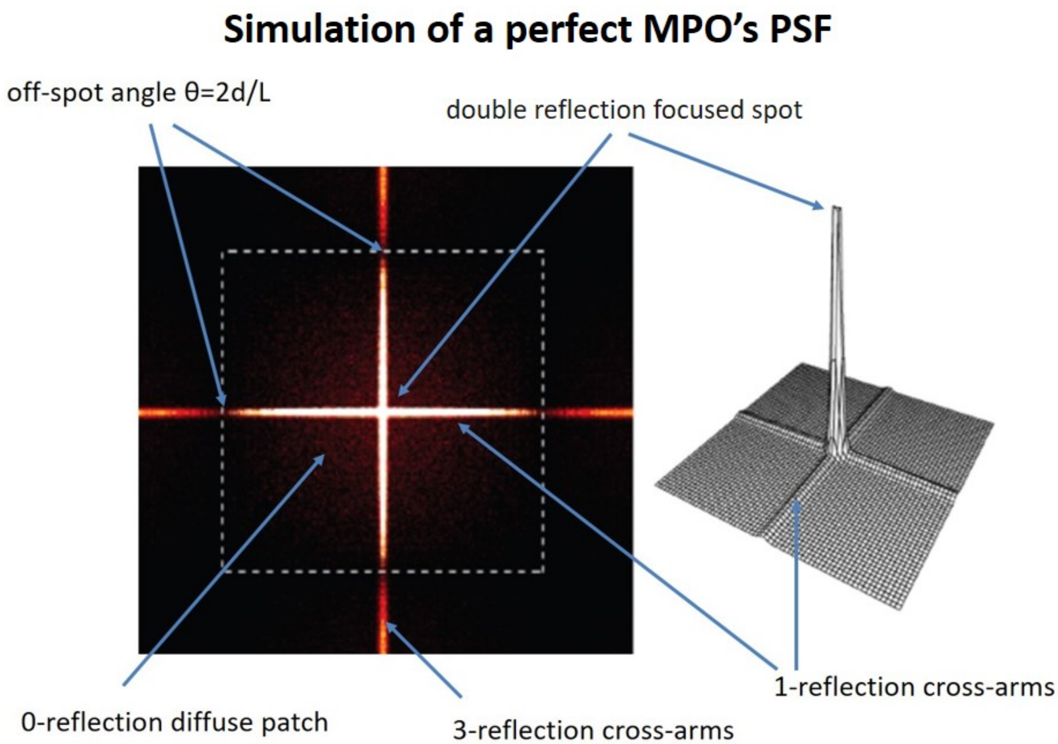

Figure 2. The simulated distinctive PSF created by a perfect, slumped MPO.[7] Rays which have undergone two reflections off the pore walls produce a high intensity central focussed spot. Rays which undergo a single reflection in the pores produce the horizontal and vertical cross-arms. Three reflection rays and higher contribute to the outer wings and the rays which go straight through the MPO create a diffuse background patch.

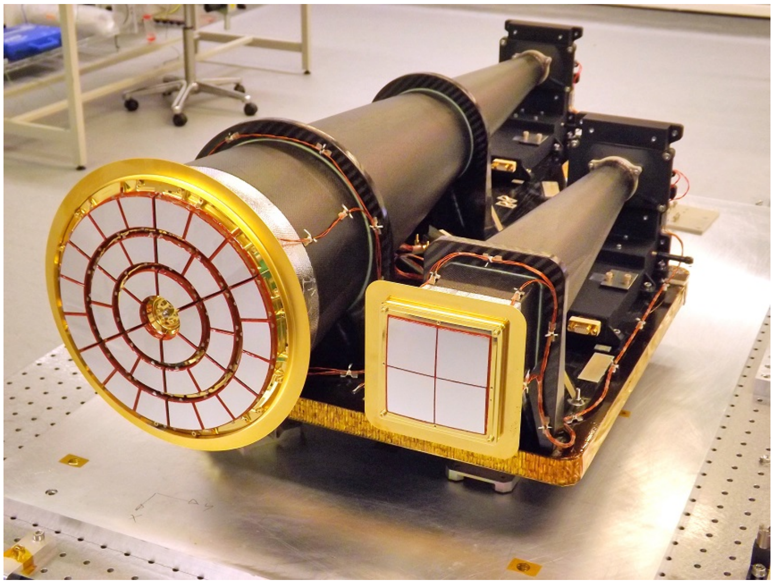

Figure 3. The flight MIXS instrument on the optical bench. The MIXS-T is on the left of the bench, and approximates the Wolter geometry. The MIXS-C is on the right of the bench and is a collimator in a 2 x 2 MPO geometry.

1.2.1 BepiColombo

The Mercury Imaging X-ray Spectrometer (MIXS)[9] on board the ESA-JAXA mission BepiColombo was the first lobster eye telescope using MPOs to be assembled. Although it was launched in October of 2018, it will not insert into its orbit around it's destination Mercury until late 2025. MIXS consists of two instruments, the telescope MIXS-T and the wide field collimator MIXS-C, shown on the left and right respectively on the MIXS optical bench in Figure 3. MIXS-T uses radially packed 20 μm square pores and two c sequential MPOs, slumped with different radii of curvature to simulate a Wolter geometry.[10] The FoV of MIXS-T is $\sim$1.1° with a 1 m focal length. The MIXS-C instrument uses 20 μm, square pore, square packed MPOs which are 40 mm by 40 mm in size and has a FoV of $\sim$10° with a 550 mm focal length. The complete MIXS instrument on its optical bench weighs $\sim$11 kgs. By using these two instruments side by side, direct X-ray imaging of the Mercurian surface using X-ray emission induced by magnetospheric particles[9] will be achieved.

1.2.2 SVOM

The Space-based multi-band astronomical Variable Objects Monitor (SVOM)[11] is a Chinese – French mission to be launched in 2023/24. It is comprised of four space borne instruments, including the Microchannel X-ray Telescope (MXT).[12] The MXT's main goal is to precisely localize, and spectrally characterize X-ray afterglows of GRBs. The MXT is a narrow-field-optimised, lobster eye X-ray focusing telescope, consisting of an array of 25 square, 40 μm square pore MPOs, with a focal length of 1.14 m. The design of the MXT optic (MOP) has a wide FoV $> 6^o$ but is optimised to give a 1^o FoV for the detector limitations. The left of Figure 4 shows the completed FM MOP. Each MPO is 40 mm by 40 mm square and there is a 2 mm gap between each MPO on the frame. The total mass of the fully assembled optic is 1.43 kg. The right of Figure 4 shows the full flight MXT during X-ray testing.

1.2.3 Einstein Probe

Einstein Probe[13] is a Chinese Academy of Science (CAS) mission due for launch in 2023, with its primary goals to discover high-energy transients and monitor variable objects. The mission consists of two instruments, the Wide field X-ray Telescope (WXT), a lobster eye X-ray telescope consisting of twelve identical modules; and the Follow-up X-ray Telescope (FXT),[14] which is a traditional Wolter X-ray telescope. Each of the WXT modules is comprised of 36 MPOs in a 6 by 6 array (left of Figure 5), with a 375 mm focal length and a total FoV of more than 3600 square degrees. Each of the twelve WXT modules, has a focal plane comprised of 4

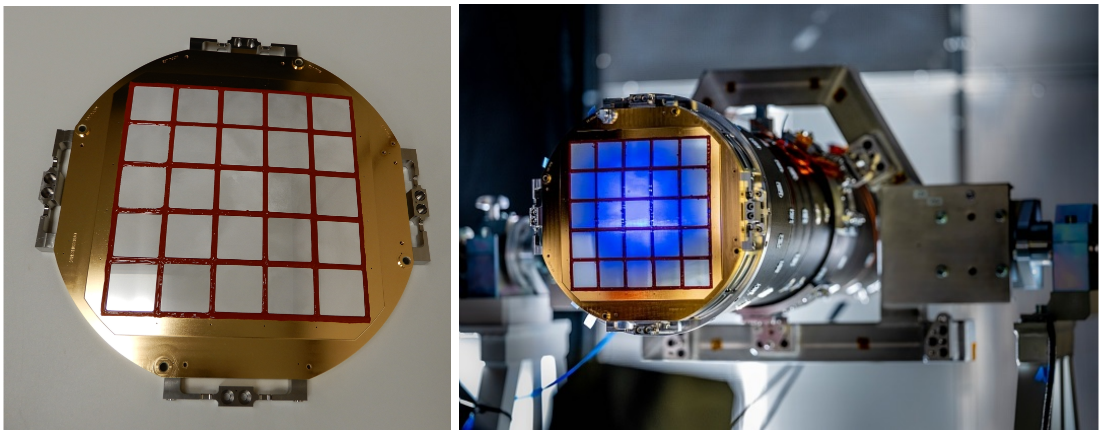

Figure 4. *Left:* the flight MXT optic, a 25 MPO array narrow field lobster eye optic. *Right:* the full flight MXT lobster eye telescope (© T De Prada CNES).

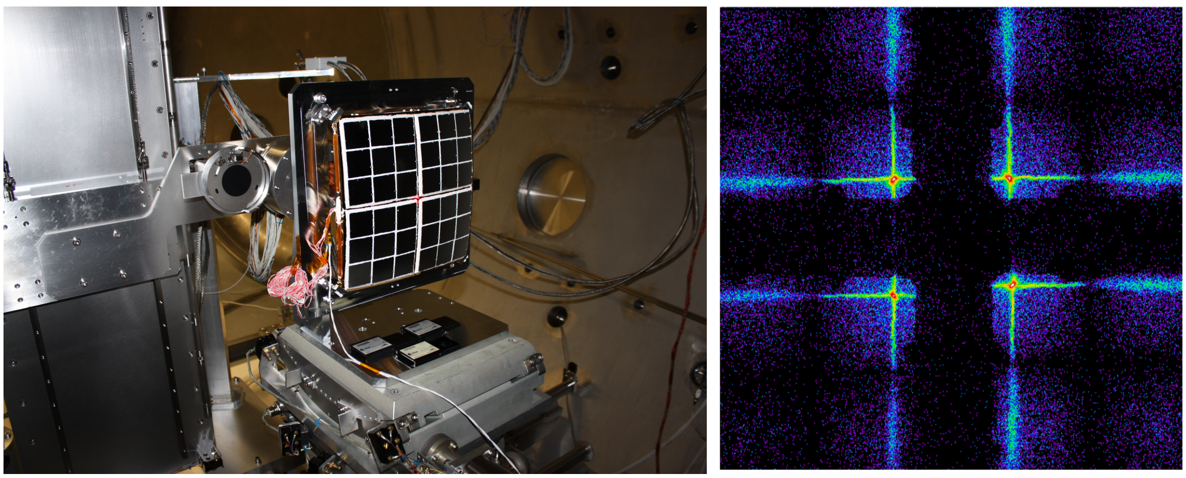

Figure 5. *Left:* A qualification WXT module installed in the PANTER beamline, MPE, Germany, prior to calibration. *Right:* X-ray image with the source centred on the module showing all 4 MPO quadrants focusing. Image taken with Cu-L (0.93 keV) X-rays at PANTER using the TRoPIC camera.[15] Images courtesy of MPE.

CMOS detectors in a 2 by 2 array. The modules are aligned so that each 3 by 3 quadrant of MPOs focuses onto a single CMOS detector, thus creating 4 discrete telescopes per module with overlapping FoVs (right of Figure 5).

1.2.4 SMILE

The Solar wind Magnetosphere Ionosphere Link Explorer (SMILE)[16] is a joint mission between ESA and CAS to investigate the dynamic response of the Earth's magnetosphere to the impact of the solar wind. From an elliptical polar orbit it will combine soft X-ray imaging of the Earth's magnetopause and magnetospheric cusps, which emit X-rays by charge exchange. This is combined with simultaneous UV imaging of the Northern aurora, and will monitor in-situ the solar wind and magnetosheath plasma conditions so as to set the imaging data into context. It is due for launch in mid 2025 with 4 separate instruments on board, including the Soft X-ray Imager (SXI). The SXI is an elongated lobster eye telescope with an array of 4 by 8 MPOs giving a FoV of 26.5^o by 15.5^o. Each MPO is 40 mm by 40 mm, 40 μm pores and a focal length of 300 mm. The wide FoV enables SXI to spectrally map the location, shape, and motion of Earth's magnetospheric boundaries. Figure 6 shows an exploded CAD diagram of the SXI instrument on the left, the structural thermal model of the full instrument during vibration testing on the top right, and a simulation of the data expected on the bottom right.

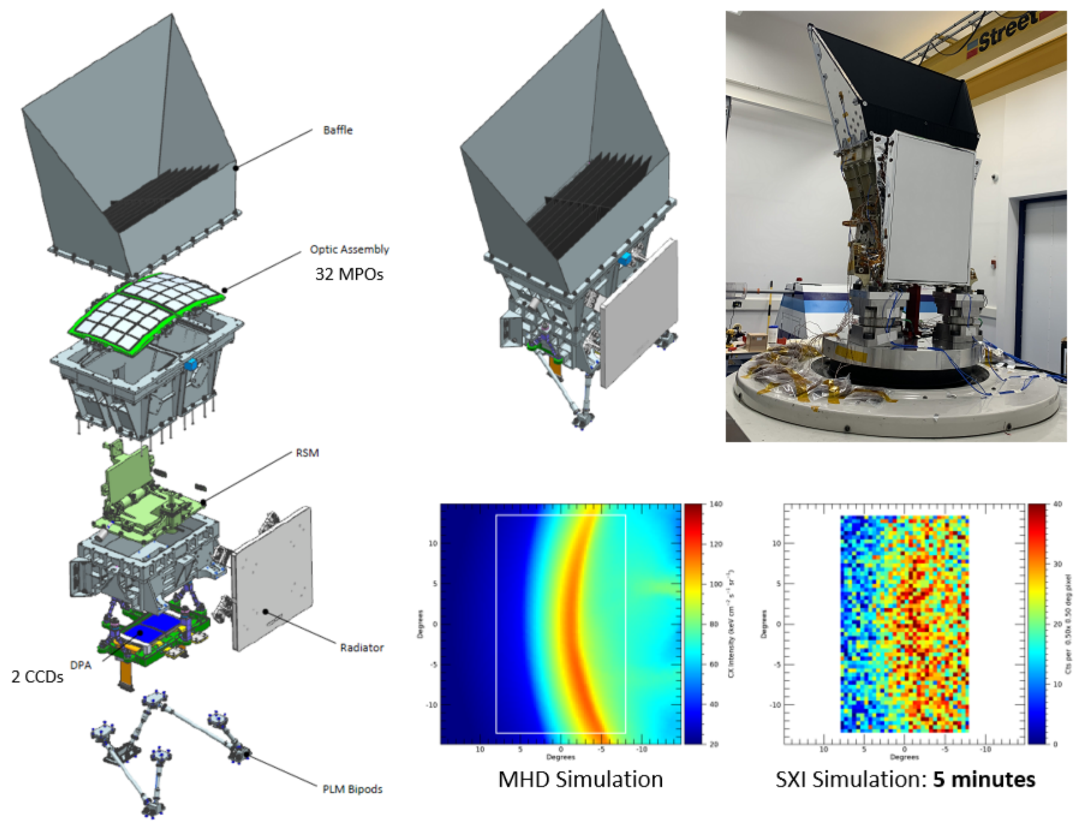

Figure 6. *Clockwise from left:* Exploded CAD diagram of the SXI instrument. CAD diagram of the complete instrument. The structural thermal model of the full instrument during vibration testing. Simulation of a typical event and as seen by SXI after 5 minutes exposure.

2. UNIQUE SCIENCE ENABLED THROUGH AN ORBITING X-RAY INSTRUMENT

The wealth of science which could be achieved at the outer planets was highlighted in both ESA's Voyage 2050[17] and in NASA's heliophysics decadal[18] and would be possible with an in-situ X-ray imager. This science spans a diverse array of disciplines including: cataloguing elemental abundances across moons, rings and atmospheres of the planets; observing a variety of aurorae indistinguishable for other wavebands; direct imaging of the radiation belts and the interfaces between neutrals and hot plasma such as neutral tori and exosphere-magnetosheath interactions, which probe the large scale structures and global dynamics of such complex systems.

Measurements have been made by Earth-orbiting X-ray telescopes that include detections of X-rays from Jupiter, the Io torus, the Galilean Satellites, Jupiter's radiation belts, Saturn, Uranus and the rings of Saturn.[19–25] For most of these objects the fluxes are too low for detailed characterisation of the signal from Earth orbit.

Figure 8 shows that the X-ray fluxes detected by a Jupiter-orbiting unmodified SXI would be 3-6 orders of magnitude (depending on the chosen orbit) higher than those detectable at Earth for the planet and 7-9 orders of magnitude higher for the moons – a paradigm shift in science capabilities. These calculations assume that moon flybys are similar to those conducted by Galileo, Juno, Juice and Europa Clipper, where Jupiter's strong gravitational pull and intense radiation belts limit such close flybys of the planet.

For the few sources (namely Jupiter's atmospheric and auroral emissions), where more detailed study has been possible, a rich array of unique science has been enabled (see Dunn, 2022[33] for review). Here, we overview the science that an orbiting X-ray instrument would make possible based on the low-signal detections obtained

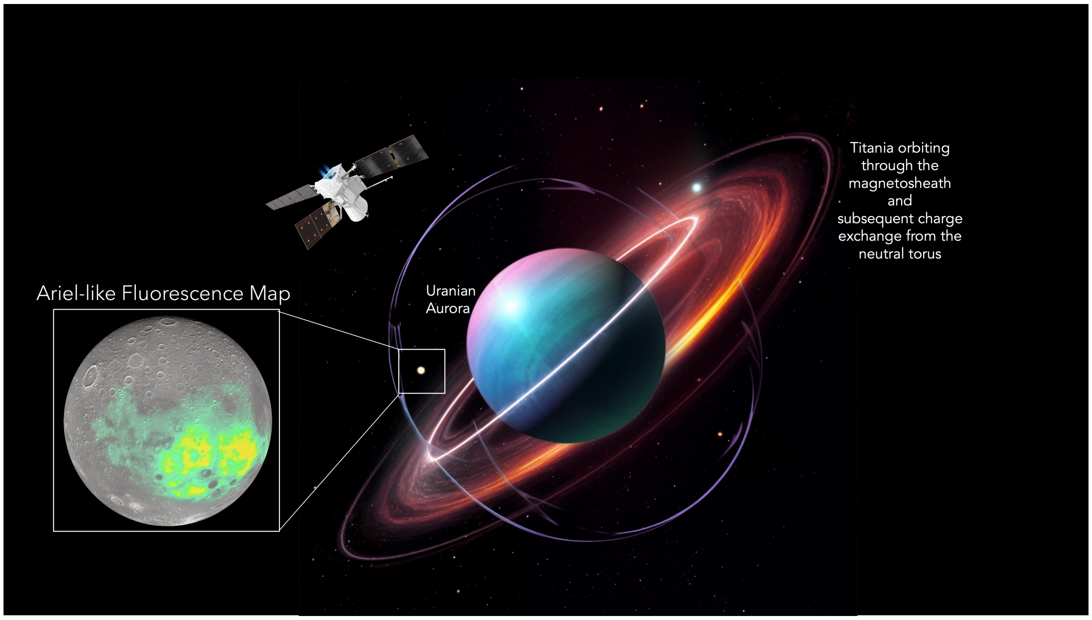

Figure 7. Example of the achievable science with an in-situ X-ray instrument at the outer planets.

so far from Earth orbit. But there are likely to be a cornucopia of new and unexpected scientific findings made possible by this step-change in X-ray signal.

Here, we overview the science enabled by a Soft X-ray Imager at the Outer planets.

2.1 X-ray Line Emission Observations of Moons, Rings and Atmospheres

An example of science that could be achieved at the Jovian moons is shown in Figure 9. At Mercury, electrons precipitate to the night-side surface in "auroral" zones where they produce characteristic X-ray emission. This emission is strongly asymmetric dawn-dusk, and is organised by the open-closed field line boundary of Mercury's magnetosphere.[34]

Within the Jovian system, the moons of Jupiter occupy the inner magnetosphere where they are insulated from direct interaction with the solar wind. Instead, Jupiter's intense radiation belts provide high fluxes of energetic electrons and ions that interact directly with the atmospheres and surfaces of Io, Europa and Callisto. Ganymede's internal magnetic field acts to control the direct precipitation of magnetospheric plasma onto the surface, perhaps similar to Mercury, with UV auroral emissions from Ganymede often observed by the Hubble Space Telescope.[35] The impact of energetic ions and electrons with moon surfaces appears to produce fluorescence emissions that characterise the elemental abundances of the surface.[21] With current SXI angular resolution of ∼10' it would be possible to map the elemental abundances across the surfaces of the Galilean satellites to few km resolution, depending on the orbit. This will break degeneracies in IR molecular composition analyses, and offer critical insights into the elemental inventories across the solar system. For astrobiological studies of Europa and Ganymede, these elemental abundances are key to the nature of the subsurface oceans and the available (a)biotic chemistry.

Convolved with the elemental abundances are characterisations of the surface impacts by energetic particles, key for e.g. understanding radiolysis of the surface and directly measuring the surface radiation environment for future landers.

It is not yet confirmed if this effect would be seen at Uranus and its moons, and it would be beyond the detection limits of the current generation of Earth-orbiting X-ray instruments. Further, Uranus' magnetosphere is highly variable with a very atypical structure due to its >90 degree orbital tilt, ∼60 degree dipole tilt and significant dipole-spin axis offset but any moon embedded in the magnetosphere (e.g. Ariel) should be expected to be subjected to significant energetic particle precipitation. The Voyager observations showed that Uranus

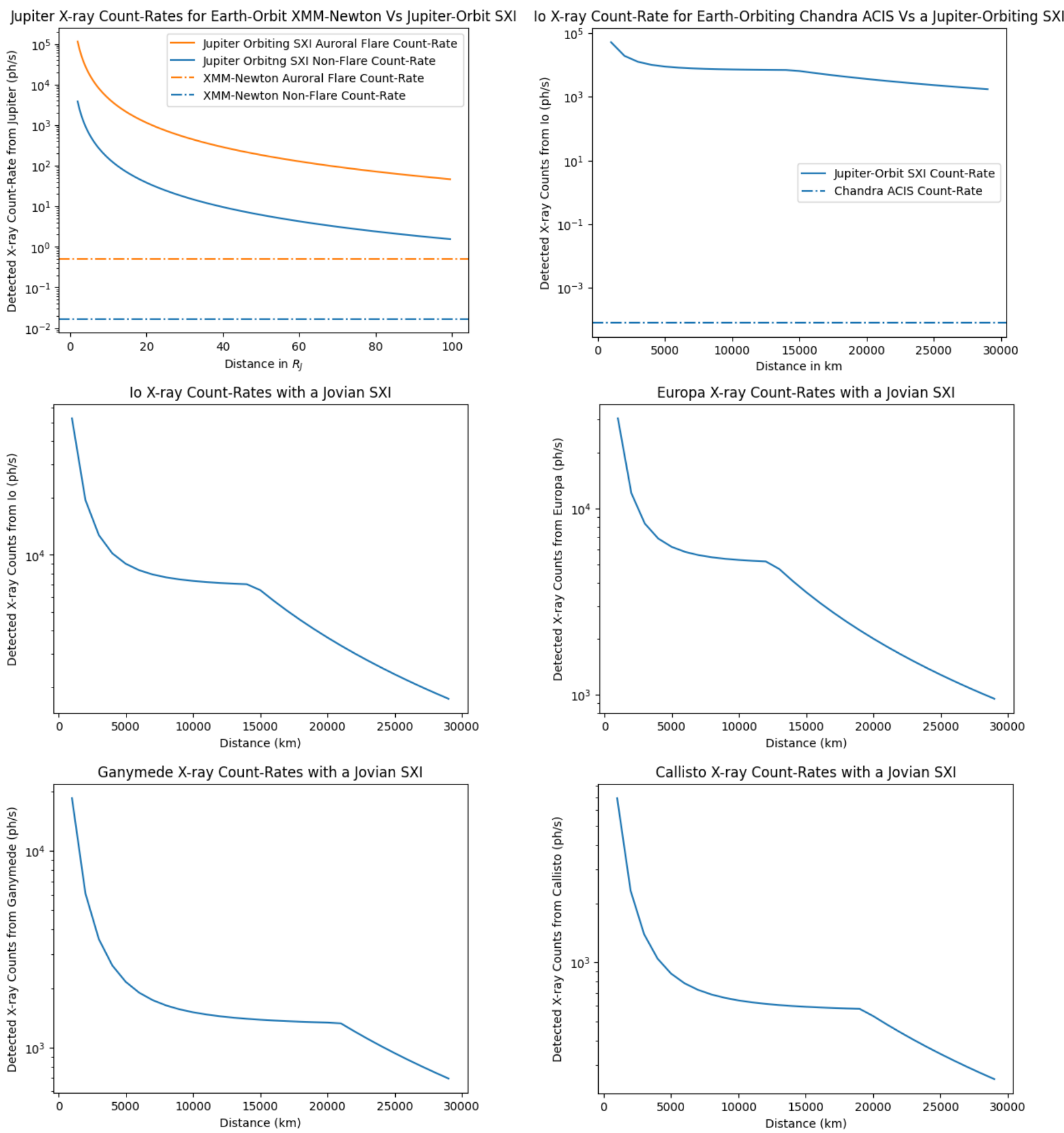

Figure 8. Count-rates of X-ray photons expected to be observed from Jupiter and the Galilean satellites for a SMILE SXI-like lobster eye instrument with a field of view of 25 x 25 degrees and an effective area of 10 cm^2. For the upper left panel these are compared with the count-rates typically detected at Earth-orbit by XMM-Newton during two types of condition and given an average Jupiter-Earth distance (e.g. Branduardi-Raymont et al.;[26,27] Dunn et al.;[28,29] Wibisono et al.[30–32]). For the upper right panel the in-orbit count-rates are compared with the count-rates from Chandra ACIS observations of Io.[19,21]

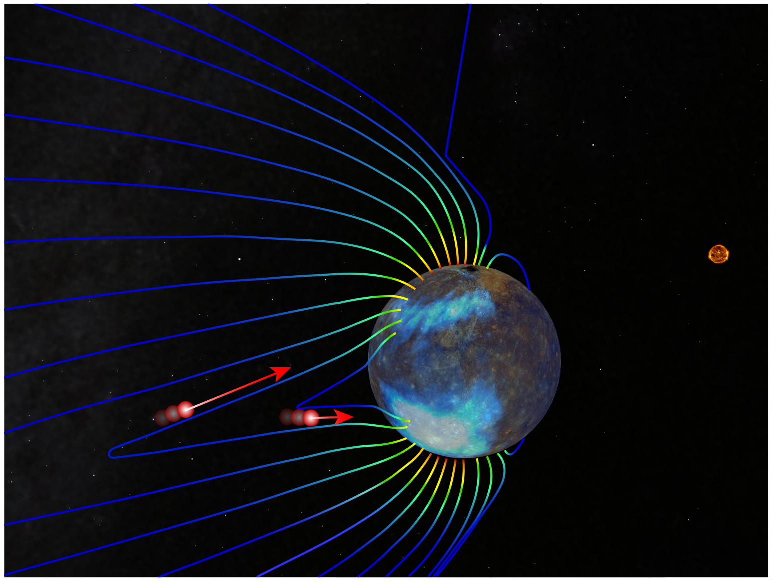

Figure 9. Electrons precipitate to the night-side surface in "auroral" zones on Mercury.

had the second most intense radiation belts in the solar system[36] after Jupiter, so that many of the moons would be expected to have sufficient fluxes of energetic particles for fluorescence emissions.

As well as the moons, which will have a similar science case to those at Jupiter and Uranus, Saturn's rings have been observed to produce X-ray fluorescence lines from Oxygen that are detectable at Earth, so that a more complete elemental catalogue will be enabled by an SXI at Saturn.

Fluorescence emissions are also thought to be a key component of the X-ray emission from Venus's atmosphere[37] and are expected to contribute $\sim 10\%$ of the Jovian atmosphere X-ray emission.[38] For the Ice Giants, where the elemental abundances are less well understood, cataloguing the elemental abundances across the moons, rings and atmosphere will provide important insights into their formation, evolution and, given the possibility of subsurface oceans in the moons, the chemistry available for life.

2.2 Magnetosheaths, Cusps and Satellite Tori

At Earth, the SMILE SXI will be used to measure the solar wind charge exchange emissions between the magnetosheath or magnetic cusp plasma and the neutral population from the exosphere. This will provide new views of the global interaction between the solar wind and the terrestrial magnetosphere.

For Jupiter, the magnetosheath may be too far from neutral populations to provide sufficient X-ray fluxes for similar studies. However, modelling of the auroral spectrum sometimes requires the inclusion of precipitation by solar wind ions to reproduce the observed signal (e.g. Dunn et al. 2020[28, 29]) and the emission has previously been suggested to connect with the Jovian cusp (e.g. Bunce et al. 2004[39]). Thus, Jupiter's ever illusive cusp – a key component in understanding the nature of the solar wind interaction with giant planets – may be detectable through an orbiting SXI. For Uranus and Neptune, where the tilted and offset magnetic field produces complex interactions with the solar wind, SMILE-SXI-like magnetosheath and/or cusp observations may be the only way to map the global interactions of the planet with the solar wind.

For hot-plasma-neutral collisions, one valuable natural laboratory in the solar system is the Io torus - a combination of a neutral and a plasma torus that orbit Jupiter close to the Io orbit, where they are produced from the Io's volcanoes. X-ray emissions from the Io Torus were observed in the first Jupiter X-ray observation by Chandra.[19] It was thought at the time that charge exchange interactions between the plasma and neutrals may contribute at least some of this emission. Recent measurements of the plasma population at the torus by the Juno spacecraft, suggest that charge exchange emissions may be the source, although further work is required to explore this.[25] Observations of the Io torus by the Jupiter-orbiting SXI would provide sufficient signal to conclusively address the source processes, but then would also allow us to use these as a natural laboratory for neutral-plasma interactions across the Universe, where it is common place for hot plasmas such as stellar winds or supernovae to collide with neutral clouds.

2.3 Radiation Belt Imaging

Jupiter is considered to be the solar system's greatest particle accelerator. Consequently, it produces radiation belts that dwarf the Earth's in size, energy and flux. Three independent observations by the Suzaku Telescope have shown the presence of a high energy, diffuse emission that is proposed to be direct images of the Jovian radiation belts.[20, 40, 41] This emission is proposed to be a product of Inverse Compton scattering by the ultrarelativistic electron population within the radiation belts. Consequently, this enables X-ray observations to image the global radiation belts at Jupiter and study how these valuable natural laboratories vary with a variety of magnetospheric and solar wind conditions, probing their temporal and spatial changes.

3. FUTURE GOALS

Work is ongoing to define the science goals and this will enable a truly optimised design for specific use cases in the coming years. Simulation and definition of the X-ray fluxes from different components (lead by Will Dunn at UCL) leads to the requirement flowdown for different science use cases, which in turn will lead to a design or designs and an assessment of whether a single design can efficiently deliver all use cases or whether there is a core element, with easy to swap subsystems to deliver the needs of different observations.

4. SUMMARY AND CONCLUSION

Lobster eye telescopes are light-weight and can provide a very large field of view, which makes them ideal candidates for in-situ X-ray imagers at the outer planets. X-ray signals from the Jovian atmosphere and moons have already been observed from Earth orbit, including line emissions that characterise the elemental abundances of the surface.[21] With the increased count rates that would be observed in orbit of the outer planets, a lobster eye X-ray instrument would be able to deliver a wealth of achievable science that addresses many of the questions set by ESA's Voyage 2050 and NASA's Heliospheric and Planetary Science Decadal Surveys. This paper begins to identify those science cases and what could be achieved with the current technology.

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