



Design and In-orbit Calibration of the MXT Optics

C. Feldman¹, J. Pearson¹, G. Butcher¹, R. Willingale², P. O’Brien², J. P. Osborne², K. Mercier³, JM. Le Duigou³, and D. Götz⁴

¹Space Park Leicester, University of Leicester, UK; chf7@le.ac.uk

²School of Physics and Astronomy, University of Leicester, UK

³Ctr National d’Études Spatiales, Toulouse, France

⁴AIM-CEA/DRF/Irfu/Département d’Astrophysique, Université Paris-Saclay, France

Received 2025 December 12; revised 2026 February 11; accepted 2026 February 13; published 2026 September 30

Abstract

The Microchannel X-ray Telescope (MXT) is one of four instruments on the Space-based multi-band Variable Objects Monitor satellite mission, launched on the 2024 June 22nd. The MXT is a narrow-field-optimized, lobster eye X-ray focusing telescope, consisting of an array of 25 square MPOs, with a focal length of 1.14 m and working in the energy band 0.2–10 keV. The design of the MXT optic (MOP) is optimized to give a 1° FoV to match the detector size, but the optic has the unique characteristics of a lobster eye design, with a wide FoV of 6° diameter, and a PSF, which is constant over the entire FoV. The MPOs on the Flight Module MOP have a pore size of 40 μm giving the optimum thicknesses across the aperture of 2.4 mm in the center and 1.2 mm at the edges. Using specific target sources, the in-orbit calibration of the optic is described here, and compared to the extensive on-ground calibration, which was carried out at the PANTER test facility, MPE, Germany. The design and limitations of the electron diverter, situated directly behind the optic, are also discussed.

Key words: gamma-rays: stars – X-rays: general – Astronomical Instrumentation, Methods and Techniques – methods: observational

1. Introduction

1.1. Lobster Eye Optics

The lobster-eye geometry for X-ray imaging, first proposed by Angel in 1979 (Angel 1979), has since been widely developed using Microchannel Plates (MCPs) or Micropore Optics (MPOs; e.g., Wilkins et al. 1989; Fraser et al. 1992; Kaaret et al. 1992; Chapman et al. 1993). Compared to traditional Wolter-type optics (Wolter 1952); this design enables a significantly wider field of view with substantially lower mass.

As detailed in Hudec & Feldman (2022), large-area lobster-eye telescopes can be constructed by tessellating spherically slumped MPO tiles onto a precision machined, spherical support frame. Each MPO consists of square, 40 μm pores etched through a glass substrate and subsequently slumped to match the spherical curvature. When mounted on a frame with the same spherical radius, the optic channels align toward the common center of curvature, enabling wide-field X-ray focusing. Typically, a thin aluminum film is applied (70–120 nm in thickness) over the front pore apertures, which provides both a filter for optical and UV light, and a good thermal surface.

The geometry of each MPO comprises a square packed array of microscopic pores, each with a square cross-section. A description of the production of the MPOs can be found in Feldman et al. (2020) and Wallace et al. (2017). An example of

an MPO and a microscope image of the pores is shown in Figure 1.

The point-spread function (PSF) of a single MPO exhibits a characteristic cross-shaped structure. The central focused spot results from photons undergoing two successive grazing-incidence reflections off adjacent pore walls. The orthogonal cross-arms arise from rays that undergo an odd number of reflections—typically single reflections—before reaching the focal plane. A diffuse background is produced by rays that either pass straight through the pores (zero reflections) or experience multiple, non-focusing reflections. Figure 2 illustrates the PSF from a single MPO.

1.2. The MXT Optic

The Space-based multi-band Variable Objects Monitor (SVOM) mission includes four onboard instruments (Cordier et al. 2026), supported by dedicated ground-based facilities. Among the onboard instruments is the French led Micro-channel X-ray Telescope (MXT) operating in the 0.2–10 keV energy range, providing high-sensitivity observations of gamma-ray burst (GRB) afterglows with rapid and precise localization.

The initial GRB positions are provided by another onboard instrument, ECLAIRs (Götz et al. 2026, Godet et al. 2026), an X-/gamma-ray wide-field (89° × 89°) coded-mask camera working in the 4–250 keV energy range, which the MXT then

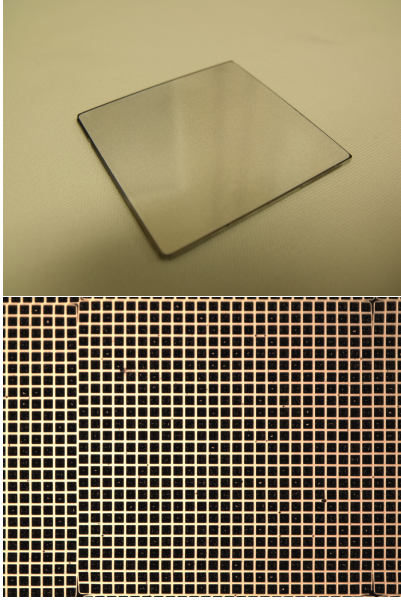


Figure 1. Top: a single, 40 mm by 40 mm square, iridium coated, aluminum filmed, 1.05 mm thick MPO Produced by Photonis France SAS. Bottom: a microscope image of a series of individual 40 μm pores on an MPO.

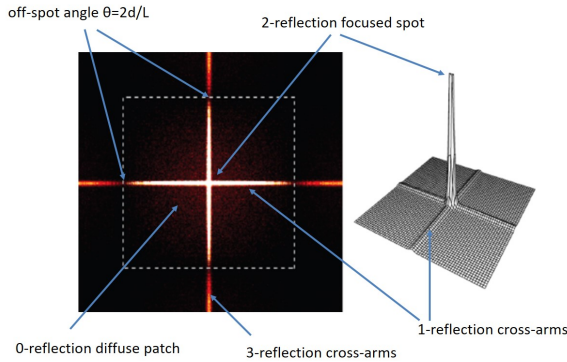


Figure 2. The distinctive PSF created by a slumped MPO (Willingale et al. 2016).

refines and enables detailed spectral and temporal analysis of the afterglow emission.

1.3. Design

The design of the MXT optic (MOP) is described in Feldman et al. (2022) and is narrow field optimized to give a $\sim 1^\circ$ detector limited field of view, but the optic has the unique characteristics of a lobster eye design, with a wide field of view $> 6^\circ$ in diameter, and a PSF which is constant over the entire field of view of the optic.

The flight model (FM) was constructed by bonding 25 individual MPOs onto a precision-machined spherical aluminum frame using a silicone-based adhesive. Each MPO

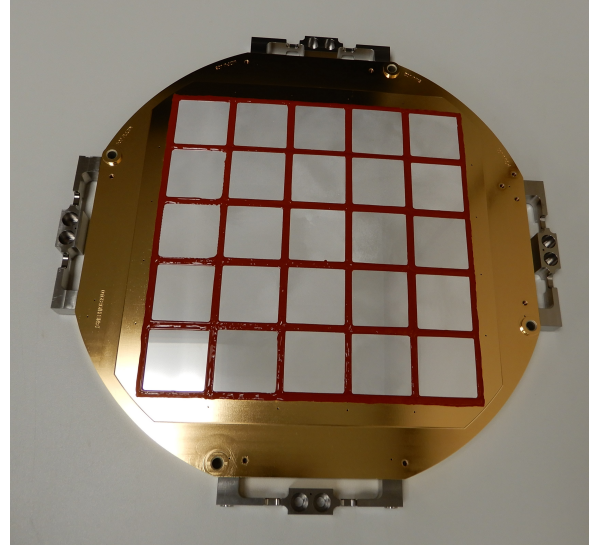


Figure 3. The FM SVOM MXT MOP.

measures 40 mm $\times$ 40 mm, with 2 mm spacing between adjacent tiles. The total mass of the fully assembled optic, including heaters, harnesses, and mounting flexures, is 1.43 kg. The completed FM MOP is shown in Figure 3.

The proto-flight model (PFM) MXT instrument was integrated at CNES in Toulouse and consists of the FM MOP, the PFM MXT pnCCD camera (Moita et al. 2026), thermal and mechanical ground support equipment (GSE), and a data processing unit.

1.4. Analysis and Modeling Software

The data analysis was conducted using the sequential ray-tracing software Q, developed by Willingale (2016). This code enables detailed modeling of individual MPO responses across a range of energies and incident angles, incorporating physical characteristics and optical distortions (Willingale et al. 2016). By inputting the measured properties of each MPO—such as radius of curvature (RoC), open fraction, and frame alignment parameters (including metrology-derived bias angles and distortions)—the software generates an accurate simulation of the full optic assembly.

The same software was employed to analyze MOP performance data obtained both at the PANTER X-ray test facility and in orbit. Due to the unique PSF structure produced by lobster-eye optics, conventional beam definitions (e.g., circular or square apertures) are inadequate. Instead, a lobster-eye beam method is used, defined by a four-pointed star geometry (Figure 4). The central core dimensions, denoted B , are optimized such that the beam encloses 50% of the total detected source flux while minimizing the enclosed sky area. This yields a robust metric of angular resolution, referred to as

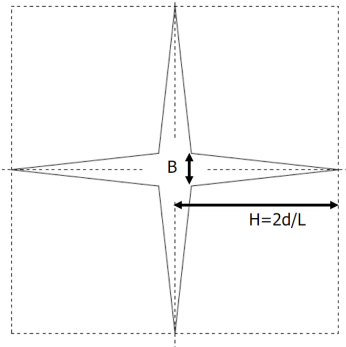


Figure 4. The lobster eye beam.

B_{HEW} .

$$\begin{aligned} f_1(x) &= 1/(1 + (2x/G)^2) \\ f_2(x) &= \eta(G/H)(1 - (x/H)^2). \end{aligned} \quad (1)$$

$$\begin{aligned} f_1(y) &= 1/(1 + (2y/G)^2) \\ f_2(y) &= \eta(G/H)(1 - (y/H)^2). \end{aligned} \quad (2)$$

$$F(x, y) = (f_1(x) + f_2(x))(f_1(y) + f_2(y))/(1 + \eta)^2. \quad (3)$$

By expanding Equations (1), (2) and (3), it is possible to calculate G , the Lorentzian width (full width at half maximum, FWHM), where $H = 2d/L$, the collimation angle of the pores and η is the brightness of the cross arms with respect to the central spot.

2. On-ground Calibration Summary

Calibration of the PFM MXT instrument was conducted at the PANTER X-ray test facility (MPE) between 13th of October and 19th of November 2021. The campaign characterized the performance of the full PFM MOP across multiple X-ray energies. Key objectives included verification of the optic's focal length, measurement of the effective area over the instrument's operational energy band, and assessment of off-axis response and vignetting effects.

2.1. PANTER Calibration Campaign

The PANTER X-ray facility carries out testing of optics, optical assemblies, and full telescopes under X-ray illumination in a 130 m long X-ray beam line, using a multi-target X-ray source, capable of generating energies from 0.28 to 10.0 keV, and also having a laser alignment system. At the detector end is a 3.5 m diameter, 12 m long vacuum chamber, multiple manipulator stages, and two mechanical-vibration isolated optical benches.

Figure 5 shows the complete PFM MXT mounted within the PANTER beam line during laser alignment. Full details on the ground calibration can be found in Feldman et al. (2022).

The MOP underwent two calibration phases at PANTER: first as a standalone optic, and subsequently as part of the

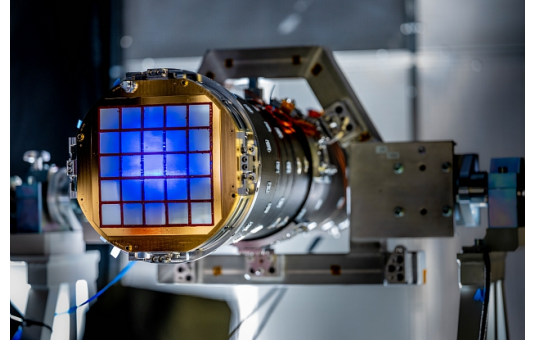


Figure 5. The PFM MXT mounted within the PANTER X-ray beam line. (Credit: CNES).

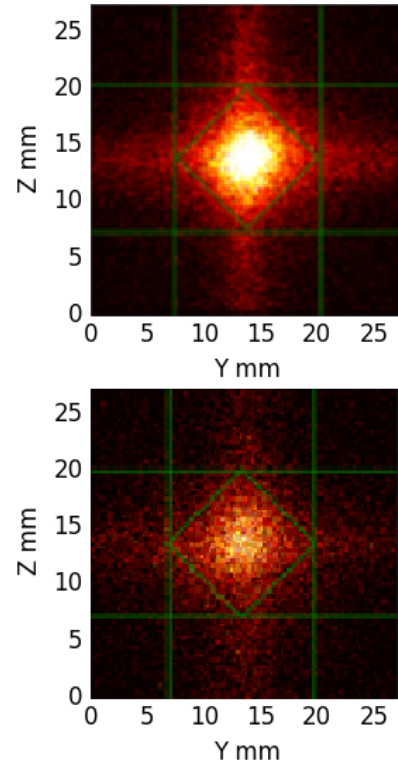


Figure 6. The X-ray image at Al-K (1.49 keV) of (top) the FM MOP at PANTER and (bottom) the full MXT at PANTER. The green lines denote areas of the image used by the analysis software.

integrated PFM MXT. On-axis images were acquired at Al-K (1.49 keV) at both the best focus and the MXT's fixed focal length; representative images are shown in Figure 6.

During standalone MOP calibration, the FWHM at Al-K was measured to be $11.23''$ with a focal length of 1137 mm. Based on this result and the focal length–FWHM curve derived from the standalone calibration, a prediction was made for the MXT's on-axis performance, accounting for the finite source distance used at PANTER.

Table 1

Comparison of the Lobster Eye Beam FWHM Measurements, at Each of the Nine Vignetting Grid Positions, Both During On-ground Calibration and In-orbit Calibration

Source Position	On-ground	In-orbit
P0	11.75 ± 0.18	11.66 ± 0.17
P1	11.12 ± 0.16	11.91 ± 0.18
P2	13.00 ± 0.20	11.21 ± 0.18
P3	11.85 ± 0.18	11.78 ± 0.18
P4	11.47 ± 0.17	12.08 ± 0.18
P5	12.31 ± 0.18	11.28 ± 0.16
P6	11.56 ± 0.17	11.81 ± 0.18
P7	12.14 ± 0.18	11.64 ± 0.18
P8	12.30 ± 0.18	10.88 ± 0.16

Following integration into the PFM MXT, the focal length was remeasured and confirmed to be 1137 mm—consistent with the standalone result and corrected for finite source geometry. At this focal length, the FWHM was measured to be 11.75 ± 0.1 .

2.2. Vignetting

The vignetting and consistency of the FWHM across the field of view were verified by rotating the full telescope bench and moving the focus to the edges of the MXT detector. The images were taken at nine grid positions and the Al-K (1.49 keV) image is shown in the top of Figure 8. The consistency in the size and shape of the PSF is demonstrated in the nine images shown in the top of Figure 8 and the values in the central column of Table 1.

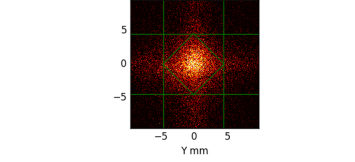
3. In-orbit Calibration

Following launch, the MXT was pointed at Cyg X-1, during the SVOM Performance Verification phase, to conduct the in-orbit calibration of the MOP. An on-axis image of Cyg X-1 was acquired, and Al-K photons ($1.49 \text{ keV} \pm 10 \text{ eV}$) were isolated for analysis. The FWHM of the resulting PSF was measured and compared to the corresponding Al-K on-axis image obtained during ground calibration. The comparison is shown in Figure 7.

A repetition of the vignetting grid measurement (Section 2.2) was performed to enable direct comparison with the corresponding on-ground calibration data. Only photons at Al-K energy (1.49 keV) were selected, and images were generated for each of the nine grid positions. The grid positions are labeled with P_0 being in the center, with the remaining eight positions numbered sequentially, from left to right starting at the top left corner.

The lobster-eye beam method was applied to determine the FWHM at each position, both in orbit and on the ground. The resulting in-orbit image is shown on the right in Figure 8, and

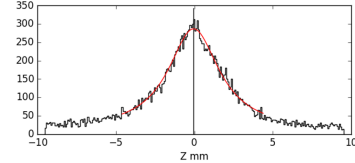
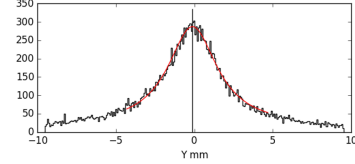
FM_MOP 000030_PANTER_MDPF_PFM_P0_20211022_124846 MXTE



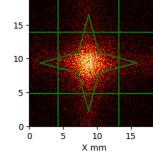
FM MXT test data
from PANTER
2021

Al-K

$G = 11.75 \text{ arc mins}$



FM_MOP MXT-EVT-CAL-P2 Al-K



MXT calibration
data 2024

CygX-1 @ Al-K

$G = 11.66 \text{ arc mins}$

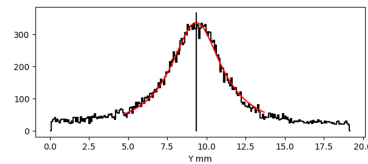
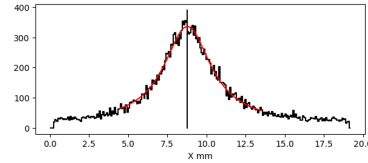


Figure 7. On-axis (P_0) image of an X-ray source at Al-K, both during (top) on-ground calibration at PANTER and (bottom) using Cyg X-1 for in-orbit calibration.

the corresponding FWHM values are listed in Table 1. The differences in the majority of cases are due to statistics, however, the in-orbit P_2 (top center) and P_8 (bottom right) images show a much cleaner and brighter double reflection spot than on the ground. This is likely due to the active MPOs in that area being in focus for an infinite source, while they were out of focus within the finite beamline thus broadening the PSF.

4. Electron Diverter Design and Performance

The MPOs onboard MXT focus X-rays via grazing incidence reflection along square microchannels. This geometry, while effective for X-ray focusing, also provides a direct line of sight from the focal plane to the surrounding

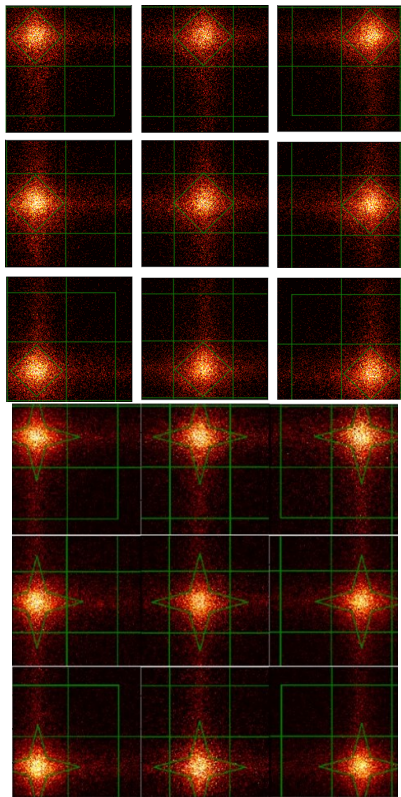


Figure 8. Vignetting grids at Al-K for top on-ground calibration and bottom in-orbit calibration. The green lines denote the lobster eye beam regions used to measure the FWHM.

environment, allowing high-energy charged particles—particularly electrons and protons—to reach the detector.

Electrons in the 0.01–10 MeV range can deposit significant energy in silicon-based detectors such as the MXT pnCCD, increasing background levels and reducing sensitivity. To mitigate this, a system of permanent magnets was installed behind the optics to deflect incident electrons away from the focal plane. The electron diverter was mounted on a separate frame and positioned as close as possible to the rear of the optic to maximize deflection efficiency while minimizing vignetting and avoiding mechanical interference during launch and testing.

The diverter design was completed using an electron ray-tracing model originally developed by one of us (Richard Willingale, University of Leicester, Willingale 2016), previously used in the design of diverters for ROSAT WFC, XMM-Newton and Swift. The magnetic field is modeled as a superposition of discrete dipoles in a user-defined configuration. Each physical magnet is approximated as a pair of dipoles separated by 3 mm along the optical axis—corresponding to the physical length of the magnets. To preserve magnetic strength, each modeled dipole carries half the moment of the full magnet.

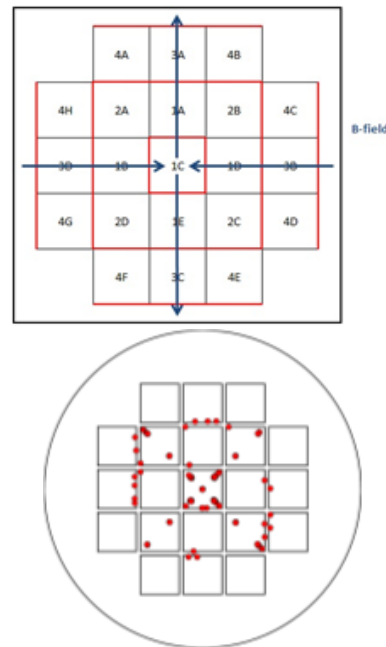


Figure 9. The MXT electron diverter (top) design showing the direction of the magnetic dipoles and (bottom) the map of impacts on the focal plane, showing the electron diverter residual transmission.

Electron trajectories were initialized at random positions on the optic's rear plane, directed toward the detector center to simulate perfect mirror focusing. Angular deviations can be added to emulate scattering if required. Electrons are propagated through the magnetic field until they either (1) reflect through the optic plane, (2) impact the inner telescope tube wall (modeled as a cylinder), (3) reach the focal plane, or (4) are trapped in the field for over 10,000 iterations, corresponding to small gyroradii electrons confined by the diverter.

The selected configuration, shown in Figure 9 (top), exhibited the lowest focal plane impact rate across the widest range of electron energies. However, due to the central MPO, a direct path remained through which high-energy electrons could reach the detector. This residual transmission is visible in the simulated impact map (Figure 9, bottom) and could not be eliminated without obstructing the MPO and reducing the effective area of the telescope. The electron diverter design is shown with the qualification model optic design, which only had 21 MPOs. For the FM optic, the magnet positions and orientations were extended to include the corner MPOs. Similar electron diverters have been designed for other lobster eye missions (Aslanyan et al. 2019).

In orbit, this residual transmission of electrons produced unexpected features in background images (Figure 10). Comparison with the simulation confirmed the pattern matched the predicted impact distribution of the transmission. As a result, the contamination is now treated as an instrumental

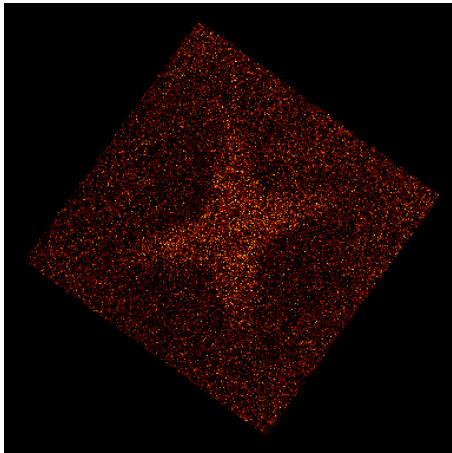


Figure 10. An example of an in-orbit background image showing typical patterns caused by high energy electron residual transmission. Image was taken on 2025 March 25th (OBSID 1996493423) with an exposure time of 2.2 ks over the 0.3–10 keV band and is displayed with a linear scale.

background component and will be removed during image processing.

5. Conclusions

The MXT telescope, employing a lobster eye optic based on 25 slumped MPOs, has been successfully calibrated both on-ground and in orbit. The design, optimized for a $\sim 1^\circ$ detector-limited field of view, maintains a uniform PSF across $\sim 6^\circ$, leveraging the inherent wide-field advantages of lobster eye geometry. On-ground calibration, conducted at the PANTER X-ray test facility, established an instrument focal length of 1137 mm and an on-axis FWHM of $11.75''$ at Al-K (1.49 keV). In-orbit calibration using Cyg X-1 demonstrated strong consistency with these ground-based measurements, validating the stability and performance of the optic post-launch.

In addition to X-ray performance, the MXT design includes a magnetic electron diverter intended to reduce charged particle background at the detector. Using a dedicated electron ray-tracing model, the optimal dipole configuration was identified to minimize focal plane electron impacts while

preserving optical throughput. However, due to the direct line-of-sight through the central MPO, a residual electron transmission remains, visible both in simulations and in-orbit data. This contamination manifests as distinct features in background images. While the residual transmission could not be physically removed without vignetting the optics, its characteristic signature enables effective removal through post-processing.

Acknowledgments

The Space-based multi-band Variable Objects Monitor (SVOM) is a joint Chinese-French mission led by the Chinese National Space Administration (CNSA), the French Space Agency (CNES), and the Chinese Academy of Sciences (CAS). We gratefully acknowledge the unwavering support of NSSC, IAMCAS, XIOPM, NAOC, IHEP, CNES, CEA, and CNRS.

This research used the ALICE High Performance Computing Facility at the University of Leicester.

References

- Angel, J. 1979, *ApJ*, **233**, 364
- Aslanyan, V., Keresztes, K., Feldman, C., et al. 2019, *RSci*, **90**, 124502
- Chapman, H., Nugent, K., & Wilkins, S. 1993, *ApOpt*, **32**, 6316
- Cordier, B., Wei, J.-Y., Zhang, S., et al. 2026, *RAA*, **26**, 104001
- Feldman, C., O’Brien, P., Willingale, R., et al. 2020, *SPIE*, 11444, 283
- Feldman, C., Willingale, R., Pearson, J., et al. 2022, *SPIE*, 12181, 121811P
- Fraser, G. W., Lees, J. E., Pearson, J. F., Sims, M. R., & Roxburgh, K. 1992, *SPIE*, 1546, 41
- Godet, O., Atteia, J.-L., Schanne, S., et al. 2026, *RAA*, **26**, 104007
- Götz, D., Crepaldi, S., Doumayrou, E., et al. 2026, *RAA*, **26**, 104013
- Hudec, R., & Feldman, C. 2022, *Lobster Eye X-ray Optics*, Handbook of X-ray and Gamma-ray Astrophysics (Springer Nature), 1
- Kaaret, P., Geissbühler, P., Chen, A., & Glavinas, E. 1992, *ApOpt*, **31**, 7339
- Moita, M., Meuris, A., Ferrando, P., et al. 2026, *RAA*, **26**, 104014
- Wallace, K., Bavdaz, M., Collon, M., et al. 2017, *SPIE*, **10567**, 105670U
- Wilkins, S., Stevenson, A., Nugent, K., Chapman, H., & Steenstrup, S. 1989, *RSci*, **60**, 1026
- Willingale, R. 2016, <https://github.com/dickwillingale/qsoft/blob/master/README>
- Willingale, R., Pearson, J., Martindale, A., et al. 2016, *SPIE*, 9905, 99051Y
- Wolter, H. 1952, *AnP*, **445**, 286