PHILOSOPHICAL TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Opinion

Article submitted to journal

Subject Areas:
X-ray astronomy, Moon

Keywords:
X-ray astronomy, Moon, Interferometry, Microcalorimeters, Occultation, Multimessenger

Author for correspondence:
P. Gandhi
e-mail: poshak.gandhi@soton.ac.uk

THE ROYAL SOCIETY PUBLISHING

X-ray astronomy from the lunar surface

P. Gandhi[1]

[1]School of Physics & Astronomy, University of Southampton, SO17 1BJ, UK

Three cases are reviewed for X-ray astronomy from the lunar surface: (1) Facilitation of ambitious engineering designs including long focal length telescopes and X-ray interferometry; (2) Occultation studies and the gain they enable in astrometric precision; (3) Multimessenger time-domain coordinated observations. Some of these use cases have relatively low mass budgets and could be conducted as early pathfinders, while others are more ambitious and will likely need to await improvements in launch technology or developed lunar bases.

1. Introduction

X-ray astronomy is just over six decades old, and has been fundamental to unlocking the hot and energetic universe on all scales [1]. Detection of high energy cosmic photons can only be done from beyond the Earth's atmosphere. Focusing of X-rays also requires specialised designs different from the normal incidence telescopes in wide use at lower energies. This has posed important constraints on the development of the field so far.

For example, grazing incidence optics is employed for X-ray imaging. At the shallow angles necessary for bringing high energy X-rays to a focus, the requisite focal lengths start to become impractically long for single satellites in orbit. Furthermore, deployment and control of large area telescopes in orbit is not currently possible due to payload launch constraints. As a result, X-ray focusing telescopes are restricted to effective collecting areas of order a few hundred sq. cm, at most, far smaller than telescope mirrors available at lower energies.

Unlike the Earth, lunar X-ray astronomy could be conducted from the surface. Telescopes and their supporting infrastructure would have to contend with surface gravity, but one that is low relative to Earth. This could substantially ease, and even circumvent, the above engineering challenges, and also open up other novel directions of scientific developments.

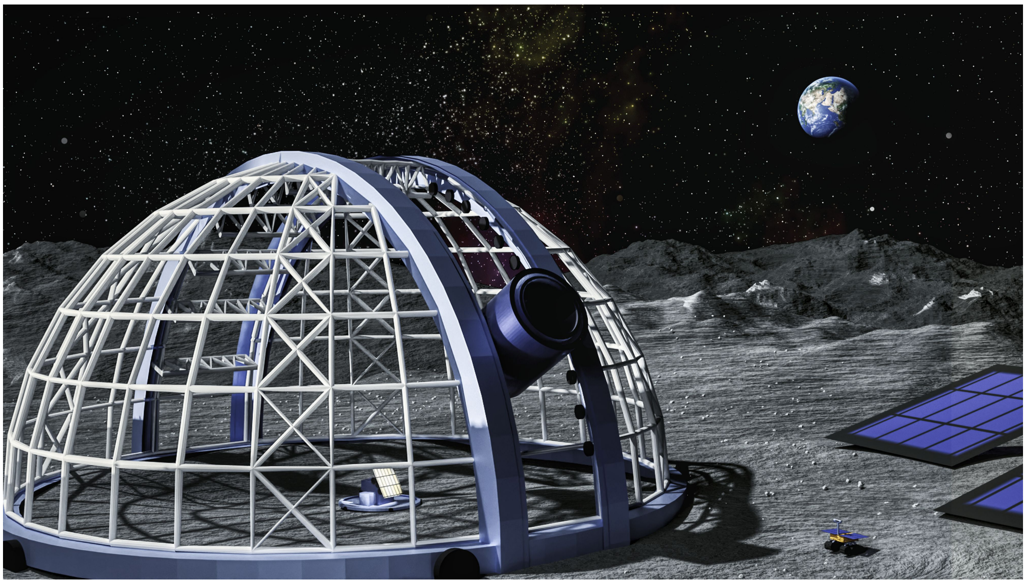

Figure 1. Artist's impression of a focusing X-ray telescope in a dome on the lunar surface. The dome comprises an open mesh supporting and directing the mirrors. The X-ray detectors are situated at the centre of the dome on the ground, separate from the mirror structure but tracking-locked. The dome can be rotated in the azimuthal direction, and railing wheels allow movement of the mirrors in altitude. Lunar topography is visible in the background, and a servicing rover is depicted in the foreground for approximate scale. Artist's Impression: S. Mandhai inc. @TheAstroPhoenix.

Humanity's return to the Moon with the Artmeis missions and proposed lunar settlement plans currently being formulated (cf. Carpenter, this volume) provide the opportunity to explore new science cases that may benefit from operation on the lunar surface. Here, we outline three such cases for X-ray astronomy. We discuss how operating from the lunar surface could facilitate the implementation of complex engineering design concepts, including long X-ray focal length telescopes and multi-telescope interferometry. Following this, two science cases are developed, centred on occultation studies of bright cosmic targets in order to enable X-ray astrometric studies, and a case for coherent multiwavelength approaches to coordinating simultaneous observations.

This article is not meant as an exhaustive review. Instead, it should be read as a pilot proposal on the need to consider and develop novel scientific exploitation opportunities offered by our nearest cosmic neighbour, even for the kinds of science that we have been carrying out from beyond the Earth for decades.

2. Facilitating Ambitious Engineering Designs

(a) Larger Area, Longer Focal Length Optics

Focusing X-ray photons requires grazing incidence optics, with the current dominant design being the Wolter type [2]. The relevant critical angles (θ) are shallow, and scale inversely with photon energy E:

$$\theta = 5.6\,\lambda\,\sqrt{\rho}\ \text{arcmin} \tag{2.1}$$

$$= 1.2\,\frac{\sqrt{\rho}}{E}\ \text{deg} \tag{2.2}$$

where ρ is the mass density of the mirror surface material in gm cm^{-3}, and λ the photon wavelength in Angstroms [3]. Imaging around 10 keV requires grazing incidence angles of small fractions of a degree. Bringing these photons to a sharp focus then necessitates long focal lengths. The *NuSTAR* mission, for instance, uses a deployable mast about 10 m in length [4].

Imagine, instead, a lunar X-ray observatory anchored to the surface. This location should allow the requisite space and infrastructure deployment needed for operation and control of long focal length telescopes. A rigid structure, such as a dome or a basic skeletal frame, capable of supporting the mirrors, orientating them, and tracking cosmic sources would be required. The X-ray detectors need not be physically attached to the same structure, if they can be tracking to the mirrors, say. An artist's impression of such a conceptual schematic design in shown in Fig. 1.

Mirror effective area scales as $\sin(\theta)$, so shallower incident angles would have smaller corresponding areas. This would pose be a challenge and detailed engineering simulations will be needed to verify the viability and practical limitations on focal length enhancements. But the relative low surface lunar gravity should ease these challenges, which should not be extreme compared to other human infrastructure likely to be proposed for the Moon.

Size will ultimately be constrained by the mirror and dome body mass that can be transported to the lunar surface. Future concept designs for large-area X-ray mirrors with state-of-the-art focusing optics include mono-crystalline Silicon as a low-density, high tensile strength substrate free of stress. The *AXIS* telescope concept, for instance, aims to achieve an order-of-magnitude improvement in effective area than *Chandra*, while maintaining similar imaging quality, and a total optics mass of ≈ 1 tonne [5]. Materials such as a Silicon would also be readily extractable from lunar mines for in-situ manufacturing in the more distant future.

Similarly, lightweight, stiff materials (e.g. Carbon fiber or other composites) would be preferred for the dome. Larger payload capacities such as with SpaceX's Starship (promising up to 100 tonnes of payload capacity[1]) would facilitate larger, more ambitious designs for lunar installation [6]. The absence of lunar winds mitigates the need for a fully covered protective dome, allowing for structure construction to be relatively light.

Another concept that could benefit is the lobster eye mirror design. These mirrors mimic the reflecting tubes that have evolved naturally as part of lobster eye vision, and provide the unique capability of ultra wide field imaging. Such a design was conceptualised several decades ago [7], but only recently demonstrated in orbit with an Einstein Probe pathfinder mission, *LEIA*, covering an instantaneous field-of-view of 340 deg^2 [8]. The typical collecting areas of current designs is modest (a few cm^2). Stacking large arrays of microchannel plates is impractical in orbit, but could be done on the Moon to boost the focal collecting area.

(b) X-ray Interferometry

Normal incidence focusing telescopes can be (and have been) designed to be diffraction-limited at all wavelengths from the ultraviolet to the radio bands. A $d = 1$ m diameter optical telescope operating at a wavelength $\lambda = 6000$ Å, say, yields an effective Airy disc size angular resolution $\theta \sim 0.15$ arcsec. X-ray observations have the potential to deliver enormous gains in angular resolution relative to longer wavelengths, given that the Rayleigh diffraction criterion scales linearly with wavelength λ. An X-ray telescope sampling 1 m of an incoming X-ray wavefront at an energy $E = 2$ keV (say, equivalent to $\lambda = 6.2$ Å) should, in principle, be capable of achieving an angular precision three orders of magnitude better ($\theta \sim 0.15$ milli-arcsec).

But X-ray telescope designs are not, currently, diffraction-limited because of the lack of technology to deliver commensurate large polished surfaces smooth to within a fraction of a wavelength needed to attain this goal.

An alternative approach would be to utilise interferometry. Bringing together signals from multiple telescopes (fringe combining) results in effective gains in angular resolution of $\sim L/d$, where L is the characteristic baseline separation of the array. Sparse interferometry with just a few telescopes primarily yields a complex 'visibility' – a measure of the spatial extent of the

[1] https://www.spacex.com/vehicles/starship/

target, but better sampling of the image plane over time can be used to reconstruct source images. Interferometry thus allows θ to improve indefinitely beyond the confines of single telescopes, in principle, being limited ultimately by the sensitivity of finite collecting areas of the array.

Uttley et al. [9] outline a concept design of an orbiting facility that could leverage X-ray interferometric gains even within a single spacecraft.[2] Phase interferometry on baselines as short as ~ 20 m would open up a vast suite of cosmic X-ray source studies, including direct imaging and resolution of the accretion discs around accreting supermassive black holes, the orbits of Galactic X-ray binaries, and the coronae around nearby active stars, to name a few. Expanding this design to a multi-spacecraft constellation would open up studies at angular resolutions on sub-micro-arcsec scales of the 'shadows' of massive black holes at the nuclei of many nearby galaxies, measurements of the elongations of gamma-ray burst afterglows at cosmological distances, and allow the capability to resolve exoplanet transits across X-ray emitting stellar discs. For reference, with a 10 km baseline, observing 10 keV (1 Å) photons yields $\theta \sim 10$ nanoarcsec. Alternate mission concepts also exist, promising the delivery of a step change in X-ray angular resolution (e.g., [11]).

But cosmic X-ray interferometry remains to be demonstrated, and there are enormous challenges associated with bringing this to fruition, specifically in enabling path-length equalization at precisions of order nanometers, across ~ 1 m+ baselines relevant for realistic telescope collecting areas. Highly rigid systems with stable pointing control will be needed in a single spacecraft. Thermal stability will also be critical (see below). These challenges are compounded for a constellation where stabilisation is needs to be maintained across the array baseline connecting free flying spacecraft, which may be separated by tens to hundreds of km or more.

Placing such an interferometer on the Moon would alleviate some of these extreme design challenges. Baselines can be fixed rigid to the ground for multi-telescope arrays across km scales. Accurate metrology calibration at X-ray wavelengths will be challenging, but still feasible over baselines with a direct line-of-sight view of each telescope (if using lasers, for instance). The horizon distance for a 3 m tall telescope structure on the Moon is about 3 km. Conversely, customisation of baselines (as is the case for the radio Very Large Array on Earth) could also be implemented on-demand for specific angular resolution needs, without the restriction of a limited fuel supply that would be relevant in-orbit.

Filling the u–v Fourier plane for imaging reconstruction can also be easily done by taking advantage of the rotation of the Moon, as is now standard for Earth-based interferometers. Tidal locking of the Moon means that this rotation will be relatively slow, though, favouring observations of order ~ 1 Ms (a duration of about two weeks).

(i) Cooling to Cryogenic Temperatures

Additional challenges will include stringent requirements on thermal stability. Specifically, precise beam positioning as well as stability of target staring will require exceptionally low thermal coefficients for the telescope structural components, or will require isothermal controls at $\sim$ mK levels. This issue might be addressed through cooling and the use of high spectral resolution devices such as Transition Edge Sensors (TES), which would also offer other advantages, discussed below.

TES are superconducting sensors with exquisite sensitivity to discriminate the energies of incident photons. As a result, they are expected to deliver orders-of-magnitude improvements in spectral resolution with upcoming microcalorimeter arrays (e.g., [12–14]). When cryogenically cooled to ~ 50 mK, thermal noise is suppressed and results in spectral resolution $E/\Delta E > 1,000$ at astrophysically important energies around 6 keV.

Lunar observatories would offer the possibility of on-demand coolant refilling, and any cryogenic cooling instruments could also benefit from the mining ^{3}He on the Moon. Alternatively, closed cycle coolers are increasingly replacing cryogenic technology. These can generate microphonic noise which not only worsens spectral resolution, but could also potentially

[2]based upon flat reflecting mirror design proposed for the MAXIM mission [10].

destabilise beam combination. Physically separating the cycling coolers from the detectors would help to lessen any microphonic noise, and will be easier to implement on the lunar surface, free from the confines of a spacecraft.

Finally, we note that the high spectral resolution attainable with cooling is also expected to enhance fringe sampling and thus the interferometric field-of-view [9]. This would, in turn, help with interferometric source localisation, overcoming the current deficiency of target coordinates accurate at the sub-milliarcsec level, a requirement for fringe acquisition and combination.

3. Astrometry with Occultation studies

Occultation of a background light source by a foreground body offers the possibility of high angular resolution studies. This relies on accurate *timing* in order to enhance spatial resolution, assuming that the occultation time can be measured accurately. With enough signal, such studies can be used to enhance spatial localisation, study their size and shape, and also search for sub-structures.

In the early days of X-ray astronomy, lunar occultations were utilised as a means to measure the spatial profile of extended sources. For instance, Bowyer et al. [15] observed a lunar occultation of the Crab Nebula using an Aerobee rocket, measuring the extent of the nebular emission. Point-source astrometric measurements have also been improved through occultation measurements (e.g., [16,17]). The need for occultation studies was largely alleviated as focusing X-ray observatories became mainstream, and as their angular resolution improved. Achieving angular resolutions much better than a few arcsec still remains challenging, though, with the few facilities such as *Chandra* capable of high quality imaging being expensive to construct and launch, and with pointed X-ray observations covering only a small field-of-view.

A return to the Moon offers the possibility of a revival of X-ray occultation studies. This is because large-area telescopes can now be made relatively cheaply. A good example here is *NICER* [18], which routinely observes transient sources gathering hundreds of counts per second, but at the expense of spatial resolution. This mitigates a key limitation of past occultation studies, which were photon-starved. Being able to place large-area telescopes on the Moon could then substantially improve on timing and occultation work, as we explore below.

Below, we consider two kinds of occultation events – due to natural, and artificial, foreground occulters. The most ambitious of these will be a challenge, but if feasible, could push X-ray studies towards accurate (fractional arcsec) astrometry, a field that has so far been the domain of only longer wavelengths.

(a) Natural foreground occultation sources

The instantaneous projected area of the Earth as seen from the Moon is 2.8 deg^2, about 13 times larger than that of the Moon seen from the Earth. Over the course of a sidereal month (27.3 days), the Earth would sweep out $\approx$ 660 deg^2 of the sky from a lunar vantage point. Due to precession of the lunar orbit, over 18.6 years the full sweep will encompass an area just shy of 20 % of the sky. For a lunar site with a view of the Earth, this should allow a wide range of occultation studies using the Earth as the foreground occulter.

Absorption and refraction through the Earth's atmosphere will blur the event, reducing astrometric precision, and would also be strongly energy dependent. A more interesting possibility could then be to instead utilise lunar topography as the foreground occulter. A near equatorial site would see the entire sky rise and then set once a month. All sources in the sky would thus be occulted by the lunar landscape twice every lunar month.

Here, we explore positional precision in an occultation event. This will depend upon the source (C_S) and background (C_B) count rates, together with the defined signal-to-noise ratio (SN_min) threshold corresponding to a significant detection. We model our estimates follow the algorithm outlined by [19]. Let us assume a small time bin ΔT during which counts are accumulated. The simplest case is to assume the high count rate limit relevant for bright sources (e.g. Galactic transients), where uncertainties are Gaussian, and with two consecutive time bins straddling the instant of occultation (i.e. the target being visible in one bin and then disappearing in the next). A source can be robustly claimed to have entered occultation within a time interval ΔT if

$$C_{\rm S}\,\Delta T \geq SN_{\rm min} \times \sqrt{C_{\rm B}\Delta T + (C_{\rm S} + C_{\rm B})\Delta T}. \tag{3.1}$$

In the small counts regime, this is modified by the need to incorporate Poisson uncertainties instead. Here, we approximate the overall noise by propagating the confidence limit formulae presented by Gehrels [20]. A detailed assessment of timing precision will require proper simulations, and will be able to utilise systemic differences in the light curve levels pre-, and then post-, occultation, in order to improve statistics beyond the information provided by the two consecutive bins straddling the occultation. It will also be instrument-specific, dependent on variability in source flux, and limited by the background. These details are beyond the scope of our evaluations here, which should thus be considered as a baseline upon which to build future simulations.

The angular speed of the occultor ($\Delta s/\Delta T$) projected into the direction of areal motion of the background source (at a relative angle α, say) then governs the angular precision Δs. In this scenario, the angular speed is $\approx$0.55 arcsec sec^{-1} for both the Earth and for lunar topographic features, as seen from the surface.

Fig. 2 shows the resultant precision Δs possible, for a wide range of count rates, assuming $\mathrm{SN}_{\rm min} = 5$, and $\alpha = 90^\circ$ between the limb of the occulter and the direction of sky areal motion. The solid curve corresponds to $C_{\rm B} = 1\,\mathrm{ct\,s^{-1}}$, whilst the dotted and dashed curves straddling it on either side correspond to background rates two dex higher and lower, respectively.

The figure demonstrates impressive gains in spatial localisation that can be made at high count rates. Specifically, at $C_{\rm S} \approx$ tens of ct s^{-1}, Δs already matches the current best X-ray angular resolution of $\approx$0.5 arcsec delivered by *Chandra*. At 500 ct s^{-1}, Δs is a few $\times$10 mas. In this regime, it becomes possible to not only accurately localise and associate source counterparts unambiguously, but also to start to measure their proper motions, directly in X-rays. For reference, 10 ct s^{-1} with a telescope of the collecting area of *NICER* corresponds to an X-ray flux $F_{0.5-10} = 2 \times 10^{-11}$ erg s^{-1} cm^{-2} for a typical X-ray power-law spectrum with photon index $\Gamma = 2$.[3] Larger collimator arrays could push this sensitivity deeper without the need for focusing optics, if the background level can be restricted to a reasonable level.

Some relevant limitations to consider here include the diffraction of photons around any occulting limb. The relevant Fresnel scale in this case will be $0.3\,\sqrt{(L/1\,\mathrm{km})(\lambda/6.2\,\text{Å})/2\pi}$ mm for 2 keV X-ray photons (say), with L being the distance to the occultor, which would need to be resolved on the detector. Furthermore, physically extended emission regions such as scattering halos surrounding compact accreting sources could lengthen the occultation event or reduce its contrast. Conversely, occultations can be used to find and study the substructures of such extended emission zones (e.g. [21]). Finally, Δs will ultimately by limited by the precision of local topographic mapping. For a hill at distance $d_{\rm km}$ km from an observing site, the height of the summit will need to be known to a precision better than $\Delta h = 0.5\,(\Delta s/0\farcs1)\,d_{\rm km}$ mm. Utlising artificial occulters, instead, could alleviate some of these limitations, as discussed below.

(b) Customised occultation sources

Having telescopes on the lunar surface within direct access enables on-demand customisation of hardware, tailored to specific observations. Artificial occulters could be deployed such that an occultation will occur for a source of interest at specific times and at any altitude and azimuth. These could be simple metallic or other custom-designed opaque plates. Deciding the number, shape, smoothness, and height above ground of the occulter then becomes a (relatively easy) engineering problem to address.

[3] Count rate $N_{\rm counts} \propto E^{-\Gamma}$.

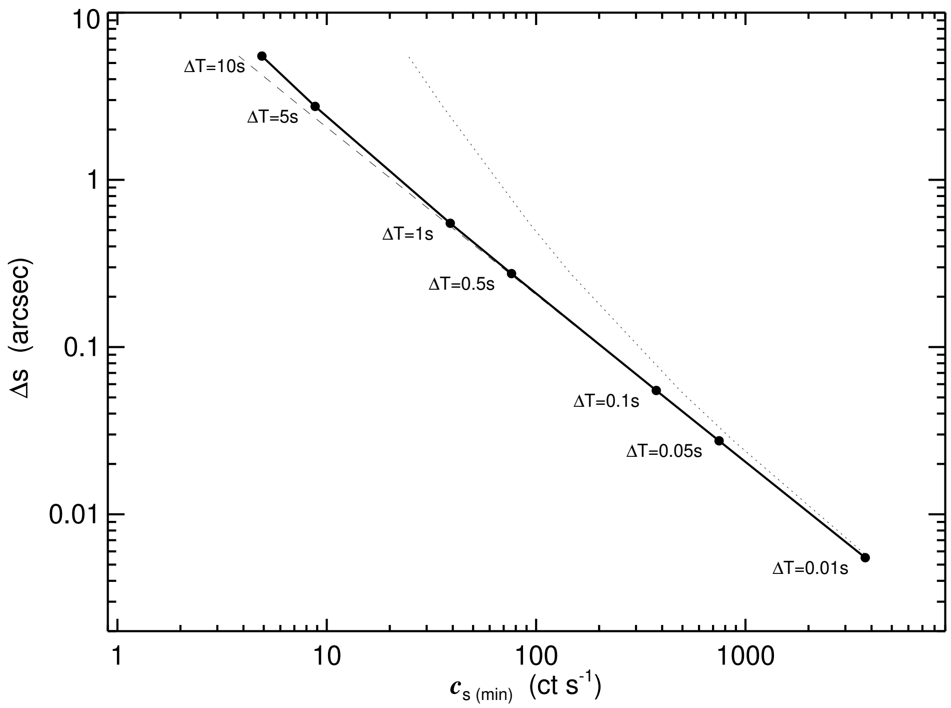

Figure 2. Astrometric constraints possible with occultation studies from the Moon. Localisation precision in arcsec is shown as a function of source count rate. The solid curve is the prediction for a background rate of $C_{\rm B} = 1\,{\rm ct\,s^{-1}}$. The dotted and dashed lines denote rates of 0.01 and 100 ct s^{-1}, respectively. Time bins ΔT corresponding to a signal-to-noise detection threshold of 5 are annotated.

Artificial occulters would be most beneficial for newly discovered transients, when a natural occultation is not imminent. The expected astrometric gain should be similar to that discussed in the previous section, and would circumvent the challenge of high accuracy topographic relief mapping.

Occultation by a plane is a one-dimensional event, so the positional accuracy is maximised in the direction normal to the occultation, and the calculations above assume $\alpha = 90^\circ$. Arranging for two occultations, with edges at orthogonal angles to each other (e.g. with a wedge) would allow gains to be made in two directions, resulting in a better reconstruction using two-dimensional astrometric information.

(c) Astrometric Reference Frames

Astrometry requires cross-calibration to a reliable coordinate reference frame. For orbiting satellites, default pointing uncertainties can be of order arcsec or larger, unless fine guiding instrumentation is deployed. Even with fine guiding, high astrometric accuracy can be difficult unless the observations utilise instrumentation with large fields of view to encompass multiple objects within a single observation. Calibration then relies upon tying some of these objects to known astrometric catalogues.

A fixed observing site on the Moon, together with occulters whose relative location is unambiguously known, mitigates much of the uncertainty associated with pointing inaccuracies. This will allow cumulative generation of an accurate absolute astrometric reference frame relevant to any given site. Regular monitoring and recalibration will undoubtedly be required to account for shifts related to tectonic activity, asteroid impacts and any other effects that impact the relative position of the telescope the occulter. We can expect this to become routine once habitation of lunar bases stabilises.

4. Multimessenger Time-domain Coordination

Opening up new parameter space inevitably leads to new discoveries [22]. Multiwavelength and multimessenger studies over the past few years have demonstrated this repeatedly through a wealth of astrophysical discoveries, because many astrophysical phenomena are inherently broadband sources of radiation.

Sources that are spatially compact are additionally expected to show *time-domain* correlations between various bands. Some of the most extreme changes in time are associated with non-thermal radiation processes such as those found in Gamma-ray bursts, kilonovae, active galactic nuclei, tidal disruption events, magnetars, and X-ray binaries, to name a few examples. Their discovery often relies on observing cadences on $\sim$weekly timescales, with some campaigns able to organise intensive daily monitoring. But physical changes can often occur on timescales faster than this. These could be state transitions in X-ray binaries, repeating fast radio bursts, jet switch-on (or off), and more.

Current monitoring strategies are often too patchy to catch these events, leading to missing out on evidence for some of the key physics connecting the various bands. The issue is compounded when the expected changes span more widely separated bands. One example is shown in Fig. 3. This shows a rapid state transition that occurred during the accretion outburst of the Galactic black hole X-ray binary V404 Cyg. Two X-ray epochs are shown, separated by a gap in the middle caused by one of the regular occultations every $\sim$90 minutes typical for orbiting satellites, when the target is hidden by the Earth. The source behaviour differs dramatically between the two epochs, with the second one being significantly brighter and spectrally 'harder' (i.e. peaked towards higher energies) in both X-rays and radio (panels b–d). Significant inter-band timing correlations also appear in Epoch 2, whilst they are absent in Epoch 1 (panels f–g). Earth occultation lasted just over 2,000 seconds, but deprived us of the exact instant of transition in X-rays. The source went on to become one of the brightest cosmic sources in the sky some hours later (for details, see [23]).

This example illustrates some of the challenges associated with current multiwavelength coordination. Observers have to contend with visibility constraints at multiple sites, typical $\sim$50%+ losses due to Earth occultation (relevant for both ground and space telescopes), while also factoring in the impact of differing weather conditions. A detailed discussion of the barriers to coordinating observational campaigns can be found in Middleton et al. [24]. Additional human factors include the current 'double jeopardy' associated with the need to have proposals accepted by multiple time allocation committees for a single coordinated campaign, and the lack of a coherent approach to multiwavelength proposing that can enable such observations as a matter of course.

As we push the boundaries of time-domain astrophysics, the demands on the need for strictly coordinated observations will rise. The campaign on V404 Cyg was far from well planned, and emerged in near real-time as the spectacular nature of the source became clear to astronomers worldwide. Opportunities for coordinated tracking of the outburst evolution were missed as a result. Despite the best will of astronomers, having widely separated facilties each with their own operational constraints can result in disjointed efforts.

The Moon offers the possibility of surmounting these barriers, by allowing a single site to host facilities capable of detecting photons across the entire electromagnetic spectrum. Telescopes from radio to X-rays (and beyond) at a single location would all be subject to (near) identical visibility constraints, and free of atmospheric disturbances. This could allow astronomers at all wavelengths to reconsider and optimise coherent approaches to observation planning and delivery. *Strict* multiwavelength and multimessenger coordination could become the default mode of operation.

The long lunar synodic day (29.5 Earth days) would allow lengthy *uninterrupted* multiwavelength monitoring of transient and variable events, at least $\sim 30\times$ longer than what is possible in Earth (ground and low orbit) observations. This will open up new observation possibilities of transient events in the Fourier frequency regime of $\sim\mu$Hz–mHz. Dual observatories on the bright and the dark sides could remove virtually all sampling gaps, delivering unprecented coordinated monitoring data.

Such a multiwavelength facility could also serve as an focus for international collaborative efforts, if multiple agencies would agree to lead the delivery of infrastructure required in individual bands (for example), with everyone benefitting from the strict simultaneity of the data that are ultimately gathered.

5. Site Considerations

Unlike low frequency radio telescopes targetting the early universe, X-ray observatories do not need to be located on the dark side of the Moon. They would also not have to be located in permanently shadowed craters, though experiments particularly susceptible to thermal variations (e.g. interferometry) may choose to avoid day–night thermal gradients by locating in either the warmer zones of the shadowed regions, or in the high illumination regions (the so-called peaks of eternal light).

Background sky count rates should not differ substantially from the rates seen by telescopes in high Earth orbit, and will benefit from the absence of the excess noise experienced in Earth's South Atlantic Anomaly. Scattered X-rays and cosmic rays from the lunar surface will, however, add to the background, especially for if pointing towards natural occulters in the environment, and a proper assessment of their impact will be necessary.

Given that there is likely to be a paucity of 'prime' observing sites on the lunar surface (cf. Krolikowski & Elvis, this volume) due to a combination of human activity and stringent requirements of other wavelengths and messengers, X-ray observatories could benefit from the fact that they will suffer from have fewer site constraints as compared to other facilities. Power requirements are not expected to be excessive either, at least in the various case studies envisaged herein.

Galactic astronomy has a long heritage in X-rays. The brightest X-ray sources in the sky beyond the Solar system will be Galactic point sources, mostly accreting compact objects. These would be the best targets for the astrometric occultation science case, as well as the coordination science case, discussed above. An optimal site would thus require good visibility of the Galactic bulge and centre region. Such a site would still undoubtedly be able to deliver cosmological studies.

Lunar dust would have to be contended with. This is true for facilities at all wavelengths. For nested shell X-ray mirrors, accumulation of dust will need to be prevented within the narrow inter-shell gaps. So locations very close to human habitation, mining and launch/landing ports would be best avoided. But lunar regolith could also serve the useful purpose of acting as a shield for any sensitive electronic equipment, with light layers of dust capable of protecting from cosmic rays.

Some of the science cases considered above may best be undertaken from craters with floors a few tens to hundred metres wide, or larger (e.g. to optimise line-of-sight visibility of other unit telescopes in an interferometric array for calibration purposes, or clear sightlines to foreground occultation sources).

Calibration sources could be easily embedded in surrounding rocks and topography, providing bright emission sources, free of Doppler variations, at a variety of focal lengths. In the longer term, construction, testing, and calibration of large-scale X-ray telescopes could be moved entirely to the lunar surface, because the absence of an atmosphere removes the need for specialised evacuated beamlines as currently required on Earth.

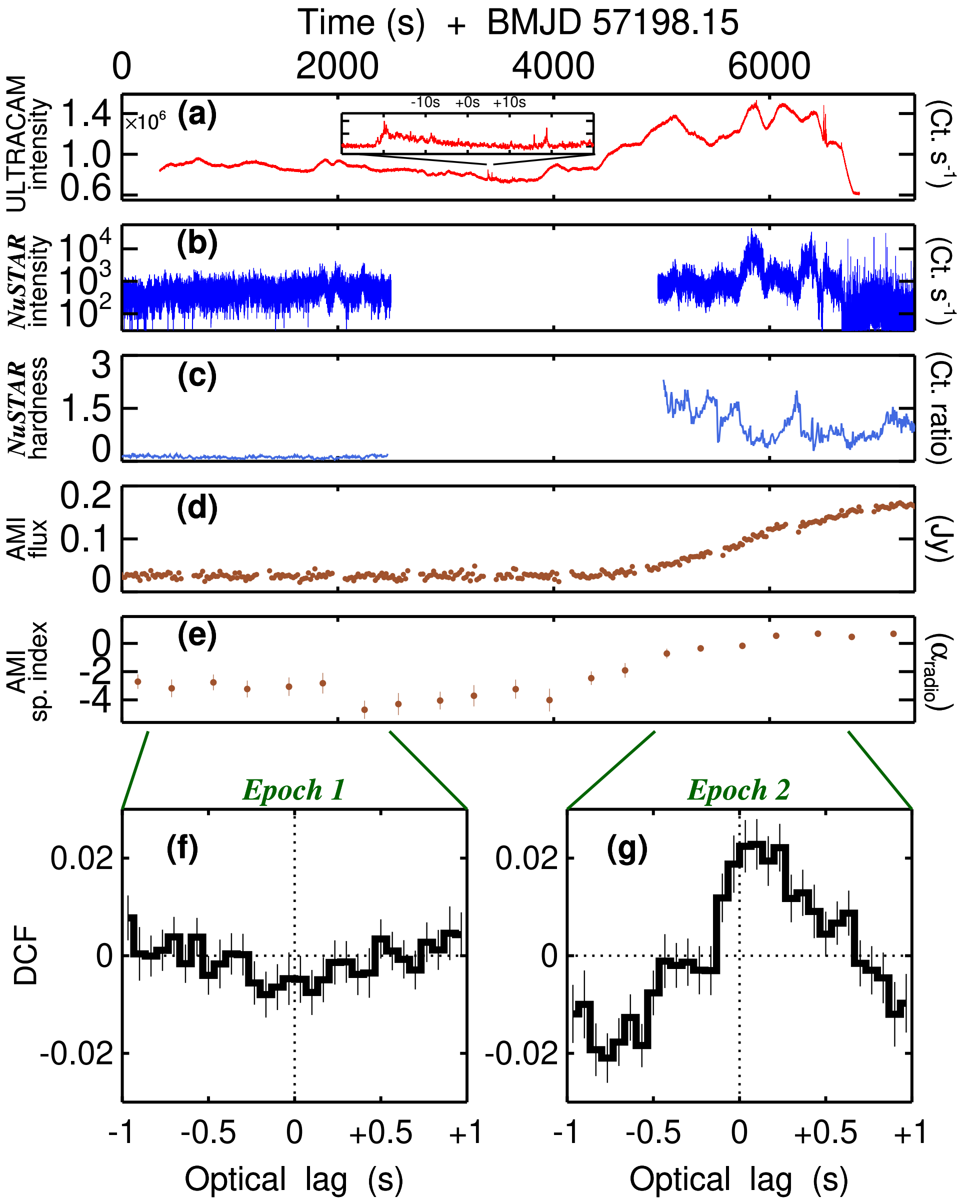

Figure 3. An example of the need for *strictly simultaneous* monitoring across the electromagetic spectrum. The black hole X-ray binary V404 Cyg underwent a spectacular but short-lived accretion outburst in 2015. The figure shows the only set of coordinated optical (Panel a), X-rays (b, c) and radio (d, e) observations that could be arranged at high time resolution with *ULTRACAM*, *NuSTAR*, and AMI. Other opportunities were missed due to day/night visibility constraints. Even here, Earth occultation of *NuSTAR* resulted in missing the instant of a physical state transition apparent from the dramatic changes visible between Epochs 1 and 2, separated by the empty gap of X-ray data in the middle. Note the significant rise in X-ray brightness (b) and spectral hardness (c) in Epoch 2, similar effects in the radio (d and e) and the appearance of significant optical/X-rays timing correlations (DCF; panels f, g), none of which is visible pre-occultation during Epoch 1. The instant of transition may have been associated with the sudden appearance of rapid (sub-second) optical fluctuations visible in the inset in panel (a) during the X-ray data gap. From [23].

6. Conclusion

X-ray astronomical observations can only be conducted from beyond the Earth's atmosphere. The benefits of X-ray astronomy from the Moon may not be immediately obvious, but we have presented several science cases and engineering considerations herein that could reap such benefits, including reengineering designs to surmount current practical restrictions to telescope focal lengths and effective areas, development of X-ray interferometery, a revival of occultation studies for improving astrometric precision, and developing a coordinated approach to multimessenger time-domain observations.

Ultimately, cost considerations will likely be the governing factor for adoption of any of these proposals. Several of the cases above can be implemented without payload capacity being a restriction. For example, *NICER* has a compact and light-weight design, with a launch mass of only 372 kg.[4] Given that Starship is expected to be able to transport up to 100 tonnes, deployment of telescopes with effective area tens of times larger than *NICER* should not pose a critical limitation.

Some of the most ambitious design infrastructure (e.g. the dome from Fig. 1) would benefit most from enhanced launch capabilities, and these likely need to await advanced settlement of Moon bases. In the mean time, it should be feasible to deploy lightweight pathfinders that can operate autonomously from the surface, once initial lunar support capability becomes operational, via the Gateway orbiting spaceport and leveraging the proposed regular landings of the European Argonaut missions (Carpenter, this volume).

Acknowledgements. PG acknowledges support from UKRI and STFC, and thanks the organisers for the opportunity to contribute this article. He also thanks R. L. Kelley and M. Elvis for very useful discussions.

References

1. Giacconi R, Gursky H, Paolini FR, Rossi BB. 1962 Evidence for x Rays From Sources Outside the Solar System. *PRL* **9**, 439–443. (10.1103/PhysRevLett.9.439)
2. Wolter H. 1952 Spiegelsysteme streifenden Einfalls als abbildende Optiken für Röntgenstrahlen. *Annalen der Physik* **445**, 94–114. (10.1002/andp.19524450108)
3. . 2000 *Soft x-rays and extreme ultraviolet radiation : principles and applications*.
4. Harrison FA, Craig WW, Christensen FE, Hailey CJ, Zhang WW, Boggs SE, Stern D, Cook WR, Forster K, Giommi P, Grefenstette BW, Kim Y, Kitaguchi T, Koglin JE, Madsen KK, Mao PH, Miyasaka H, Mori K, Perri M, Pivovaroff MJ, Puccetti S, Rana VR, Westergaard NJ, Willis J, Zoglauer A, An H, Bachetti M, Barrière NM, Bellm EC, Bhalerao V, Brejnholt NF, Fuerst F, Liebe CC, Markwardt CB, Nynka M, Vogel JK, Walton DJ, Wik DR, Alexander DM, Cominsky LR, Hornschemeier AE, Hornstrup A, Kaspi VM, Madejski GM, Matt G, Molendi S, Smith DM, Tomsick JA, Ajello M, Ballantyne DR, Baloković M, Barret D, Bauer FE, Blandford RD, Brandt WN, Brenneman LW, Chiang J, Chakrabarty D, Chenevez J, Comastri A, Dufour F, Elvis M, Fabian AC, Farrah D, Fryer CL, Gotthelf EV, Grindlay JE, Helfand DJ, Krivonos R, Meier DL, Miller JM, Natalucci L, Ogle P, Ofek EO, Ptak A, Reynolds SP, Rigby JR, Tagliaferri G, Thorsett SE, Treister E, Urry CM. 2013 The Nuclear Spectroscopic Telescope Array (NuSTAR) High-energy X-Ray Mission. *ApJ* **770**, 103. (10.1088/0004-637X/770/2/103)
5. Mushotzky R, AXIS. 2022 The Advanced X-ray Imaging Satellite (AXIS) a Probe mission concept. In *American Astronomical Society Meeting #240* vol. 54*American Astronomical Society Meeting Abstracts* p. 127.03.
6. Elvis M, Lawrence C, Seager S. 2023 Accelerating astrophysics with the SpaceX Starship. *Physics Today* **76**, 40–45. (10.1063/PT.3.5176)
7. Angel JRP. 1979 Lobster eyes as X-ray telescopes.. *ApJ* **233**, 364–373. (10.1086/157397)
8. Zhang C, Ling ZX, Sun XJ, Sun SL, Liu Y, Li ZD, Xue YL, Chen YF, Dai YF, Jia ZQ, Liu HY, Zhang XF, Zhang YH, Zhang SN, Chen FS, Cheng ZW, Fu W, Han YX, Li H, Li JF, Li Y, Liu PR, Ma XH, Tang YJ, Wang CB, Xie RJ, Yan AL, Zhang Q, Jiang BW, Jin G, Li LH, Qiu XB, Su DT, Sun JN, Xu Z, Zhang SK, Zhang Z, Zhang N, Bi XZ, Cai ZM, He JW, Liu HQ, Zhu XC, Cheng HQ, Cui CZ, Fan DW, Hu HB, Huang MH, Jin CC, Li DY, Pan HW, Wang WX,

[4] https://www.nasa.gov/sites/default/files/atoms/files/spacex_crs-11_mission_overview.pdf

Xu YF, Yang X, Zhang B, Zhang M, Zhang WD, Zhao DH, Bai M, Ji Z, Liu YR, Ma FL, Su J, Tong JZ, Wang YS, Zhao ZJ, Feldman C, O'Brien P, Osborne JP, Willingale R, Burwitz V, Hartner G, Langmeier A, Müller T, Rukdee S, Schmidt T, Kuulkers E, Yuan W. 2022 First Wide Field-of-view X-Ray Observations by a Lobster-eye Focusing Telescope in Orbit. *ApJL* **941**, L2. (10.3847/2041-8213/aca32f)

9. Uttley P, den Hartog R, Bambi C, Barret D, Bianchi S, Bursa M, Cappi M, Casella P, Cash W, Costantini E, Dauser T, Diaz Trigo M, Gendreau K, Grinberg V, den Herder JW, Ingram A, Kara E, Markoff S, Mingo B, Panessa F, Poppenhäger K, Rózanska A, Svoboda J, Wijers R, Willingale R, Wilms J, Wise M. 2020 An x-ray interferometry concept for the ESA Voyage 2050 programme. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* vol. 11444*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* p. 114441E. (10.1117/12.2562523)
10. Cash W. 2005 Imaging a black hole: MAXIM. *Advances in Space Research* **35**, 122–129. (10.1016/j.asr.2003.09.057)
11. Hayashida K, Asakura K, Ishikura A, Sakuma S, Hanasaka T, Kawabata T, Yoneyama T, Noda H, Okazaki K, Hanaoka M, Hattori K, Sawagami K, Kamogawa W, Nakajima H, Matsuhita Y, Mineta T, Yoshimoto M, Hakamata T, Ode Y, Matsumoto H, Tsunemi H, Awaki H, Terashima Y, Kawaguchi T. 2020 Sub-arcseconds to micro-arcsecond x-ray imaging with multi image x-ray interferometer method (MIXIM): concept and scalabe mission plans. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* vol. 11444*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* p. 114441C. (10.1117/12.2562193)
12. Tashiro M, Maejima H, Toda K, Kelley R, Reichenthal L, Hartz L, Petre R, Williams B, Guainazzi M, Costantini E, Fujimoto R, Hayashida K, Henegar-Leon J, Holland M, Ishisaki Y, Kilbourne C, Loewenstein M, Matsushita K, Mori K, Okajima T, Porter FS, Sneiderman G, Takei Y, Terada Y, Tomida H, Yamaguchi H, Watanabe S, Akamatsu H, Arai Y, Audard M, Awaki H, Babyk I, Bamba A, Bando N, Behar E, Bialas T, Boissay-Malaquin R, Brenneman L, Brown G, Canavan E, Chiao M, Comber B, Corrales L, Cumbee R, de Vries C, den Herder JW, Dercksen J, Diaz-Trigo M, DiPirro M, Done C, Dotani T, Ebisawa K, Eckart M, Eckert D, Eguchi S, Enoto T, Ezoe Y, Ferrigno C, Fujita Y, Fukazawa Y, Furuzawa A, Gallo L, Gorter N, Grim M, Gu L, Hagino K, Hamaguchi K, Hatsukade I, Hawthorn D, Hayashi K, Hell N, Hiraga J, Hodges-Kluck E, Horiuchi T, Hornschemeier A, Hoshino A, Ichinohe Y, Iga S, Iizuka R, Ishida M, Ishihama N, Ishikawa K, Ishimura K, Jaffe T, Kaastra J, Kallman T, Kara E, Katsuda S, Kenyon S, Kimball M, Kitaguchi T, Kitamoto S, Kobayashi S, Kobayashi A, Kohmura T, Kubota A, Leutenegger M, Li M, Lockard T, Maeda Y, Markevitch M, Martz C, Matsumoto H, Matsuzaki K, McCammon D, McLaughlin B, McNamara B, Miko J, Miller E, Miller J, Minesugi K, Mitani S, Mitsuishi I, Mizumoto M, Mizuno T, Mukai K, Murakami H, Mushotzky R, Nakajima H, Nakamura H, Nakazawa K, Natsukari C, Nigo K, Nishioka Y, Nobukawa K, Nobukawa M, Noda H, Odaka H, Ogawa M, Ohashi T, Ohno M, Ohta M, Okamoto A, Ota N, Ozaki M, Paltani S, Plucinsky P, Pottschmidt K, Sampson M, Sasaki T, Sato K, Sato R, Sato T, Sawada M, Seta H, Shibano Y, Shida M, Shidatsu M, Shigeto S, Shinozaki K, Shirron P, Simionescu A, Smith R, Someya K, Soong Y, Sugawara K, Sugawara Y, Szymkowiak A, Takahashi H, Takeshima T, Tamagawa T, Tamura K, Tanaka T, Tanimoto A, Terashima Y, Tsuboi Y, Tsujimoto M, Tsunemi H, Tsuru T, Uchida H, Uchida Y, Uchiyama H, Ueda Y, Uno S, Vink J, Watanabe T, Witthoeft M, Wolfs R, Yamada S, Yamaoka K, Yamasaki N, Yamauchi M, Yamauchi S, Yanagase K, Yaqoob T, Yasuda S, Yoshida T, Yoshioka N, Zhuravleva I. 2020 Status of x-ray imaging and spectroscopy mission (XRISM). In den Herder JWA, Nikzad S, Nakazawa K, editors, *Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray* vol. 11444*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* p. 1144422. (10.1117/12.2565812)
13. Nandra K, Barret D, Barcons X, Fabian A, den Herder JW, Piro L, Watson M, Adami C, Aird J, Afonso JM, Alexander D, Argiroffi C, Amati L, Arnaud M, Atteia JL, Audard M, Badenes C, Ballet J, Ballo L, Bamba A, Bhardwaj A, Stefano Battistelli E, Becker W, De Becker M, Behar E, Bianchi S, Biffi V, Bîrzan L, Bocchino F, Bogdanov S, Boirin L, Boller T, Borgani S, Borm K, Bouché N, Bourdin H, Bower R, Braito V, Branchini E, Branduardi-Raymont G, Bregman J, Brenneman L, Brightman M, Brüggen M, Buchner J, Bulbul E, Brusa M, Bursa M, Caccianiga A, Cackett E, Campana S, Cappelluti N, Cappi M, Carrera F, Ceballos M, Christensen F, Chu YH, Churazov E, Clerc N, Corbel S, Corral A, Comastri A, Costantini E, Croston J, Dadina M, D'Ai A, Decourchelle A, Della Ceca R, Dennerl K, Dolag K, Done

C, Dovciak M, Drake J, Eckert D, Edge A, Ettori S, Ezoe Y, Feigelson E, Fender R, Feruglio C, Finoguenov A, Fiore F, Galeazzi M, Gallagher S, Gandhi P, Gaspari M, Gastaldello F, Georgakakis A, Georgantopoulos I, Gilfanov M, Gitti M, Gladstone R, Goosmann R, Gosset E, Grosso N, Guedel M, Guerrero M, Haberl F, Hardcastle M, Heinz S, Alonso Herrero A, Hervé A, Holmstrom M, Iwasawa K, Jonker P, Kaastra J, Kara E, Karas V, Kastner J, King A, Kosenko D, Koutroumpa D, Kraft R, Kreykenbohm I, Lallement R, Lanzuisi G, Lee J, Lemoine-Goumard M, Lobban A, Lodato G, Lovisari L, Lotti S, McCharthy I, McNamara B, Maggio A, Maiolino R, De Marco B, de Martino D, Mateos S, Matt G, Maughan B, Mazzotta P, Mendez M, Merloni A, Micela G, Miceli M, Mignani R, Miller J, Miniutti G, Molendi S, Montez R, Moretti A, Motch C, Nazé Y, Nevalainen J, Nicastro F, Nulsen P, Ohashi T, O'Brien P, Osborne J, Oskinova L, Pacaud F, Paerels F, Page M, Papadakis I, Pareschi G, Petre R, Petrucci PO, Piconcelli E, Pillitteri I, Pinto C, de Plaa J, Pointecouteau E, Ponman T, Ponti G, Porquet D, Pounds K, Pratt G, Predehl P, Proga D, Psaltis D, Rafferty D, Ramos-Ceja M, Ranalli P, Rasia E, Rau A, Rauw G, Rea N, Read A, Reeves J, Reiprich T, Renaud M, Reynolds C, Risaliti G, Rodriguez J, Rodriguez Hidalgo P, Roncarelli M, Rosario D, Rossetti M, Rozanska A, Rovilos E, Salvaterra R, Salvato M, Di Salvo T, Sanders J, Sanz-Forcada J, Schawinski K, Schaye J, Schwope A, Sciortino S, Severgnini P, Shankar F, Sijacki D, Sim S, Schmid C, Smith R, Steiner A, Stelzer B, Stewart G, Strohmayer T, Strüder L, Sun M, Takei Y, Tatischeff V, Tiengo A, Tombesi F, Trinchieri G, Tsuru TG, Ud-Doula A, Ursino E, Valencic L, Vanzella E, Vaughan S, Vignali C, Vink J, Vito F, Volonteri M, Wang D, Webb N, Willingale R, Wilms J, Wise M, Worrall D, Young A, Zampieri L, In't Zand J, Zane S, Zezas A, Zhang Y, Zhuravleva I. 2013 The Hot and Energetic Universe: A White Paper presenting the science theme motivating the Athena+ mission. *arXiv e-prints* p. arXiv:1306.2307.
14. Gandhi P, Kawamuro T, Díaz Trigo M, Paice JA, Boorman PG, Cappi M, Done C, Fabian AC, Fukumura K, García JA, Greenwell CL, Guainazzi M, Makishima K, Tashiro MS, Tomaru R, Tombesi F, Ueda Y. 2022 Frontiers in accretion physics at high X-ray spectral resolution. *Nature Astronomy* **6**, 1364–1375. (10.1038/s41550-022-01857-y)
15. Bowyer S, Byram ET, Chubb TA, Friedman H. 1964 Lunar Occultation of X-ray Emission from the Crab Nebula. *Science* **146**, 912–917. (10.1126/science.146.3646.912)
16. Janes AF, Pounds KA, Ricketts MJ. 1973 Correction to the Position of GX3 + 1. *Nature* **244**, 349. (10.1038/244349a0)
17. Davison PJN, Morrison LV. 1977 A lunar occultation position for GX 9+1.. *MNRAS* **178**, 53P–56. (10.1093/mnras/178.1.53P)
18. Arzoumanian Z, Gendreau KC, Baker CL, Cazeau T, Hestnes P, Kellogg JW, Kenyon SJ, Kozon RP, Liu KC, Manthripragada SS, Markwardt CB, Mitchell AL, Mitchell JW, Monroe CA, Okajima T, Pollard SE, Powers DF, Savadkin BJ, Winternitz LB, Chen PT, Wright MR, Foster R, Prigozhin G, Remillard R, Doty J. 2014 The neutron star interior composition explorer (NICER): mission definition. In Takahashi T, den Herder JWA, Bautz M, editors, *Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray* vol. 9144*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* p. 914420. (10.1117/12.2056811)
19. Mereghetti S, Bignami GF, Zaidins C. 1990 Future Possibilities for Lunar Occultation Studies of Faint X-Ray Sources. *Experimental Astronomy* **1**, 165–171. (10.1007/BF00462038)
20. Gehrels N. 1986 Confidence Limits for Small Numbers of Events in Astrophysical Data. *ApJ* **303**, 336. (10.1086/164079)
21. Mitsuda K, Takeshima T, Kii T, Kawai N. 1990 Dust-Grain Scattering of X-Rays Observed during the Lunar Occultation of a Transient X-Ray Source near the Galactic Center. *ApJ* **353**, 480. (10.1086/168637)
22. Harwit M. 2019 *Cosmic Discovery: The Search, Scope, and Heritage of Astronomy*. Cambridge University Press. OCLC: 1099860228. e-ISBN: 9781108655088. (10.1017/9781108655088)
23. Gandhi P, Bachetti M, Dhillon VS, Fender RP, Hardy LK, Harrison FA, Littlefair SP, Malzac J, Markoff S, Marsh TR, Mooley K, Stern D, Tomsick JA, Walton DJ, Casella P, Vincentelli F, Altamirano D, Casares J, Ceccobello C, Charles PA, Ferrigno C, Hynes RI, Knigge C, Kuulkers E, Pahari M, Rahoui F, Russell DM, Shaw AW. 2017 An elevation of 0.1 light-seconds for the optical jet base in an accreting Galactic black hole system. *Nature Astronomy* **1**, 859–864. (10.1038/s41550-017-0273-3)
24. Middleton MJ, Casella P, Gandhi P, Bozzo E, Anderson G, Degenaar N, Donnarumma I, Israel G, Knigge C, Lohfink A, Markoff S, Marsh T, Rea N, Tingay S, Wiersema K, Altamirano D, Bhattacharya D, Brandt WN, Carey S, Charles P, Díaz Trigo M, Done C, Kotze M, Eikenberry

S, Fender R, Ferruit P, Fürst F, Greiner J, Ingram A, Heil L, Jonker P, Komossa S, Leibundgut B, Maccarone T, Malzac J, McBride V, Miller-Jones J, Page M, Rossi EM, Russell DM, Shahbaz T, Sivakoff GR, Tanaka M, Thompson DJ, Uemura M, Uttley P, van Moorsel G, van Doesburgh M, Warner B, Wilkes B, Wilms J, Woudt P. 2017 Paving the way to simultaneous multi-wavelength astronomy. *NAR* **79**, 26–48. (10.1016/j.newar.2017.07.002)

royalsocietypublishing.org/journal/rsta Phil. Trans. R. Soc. A 0000000