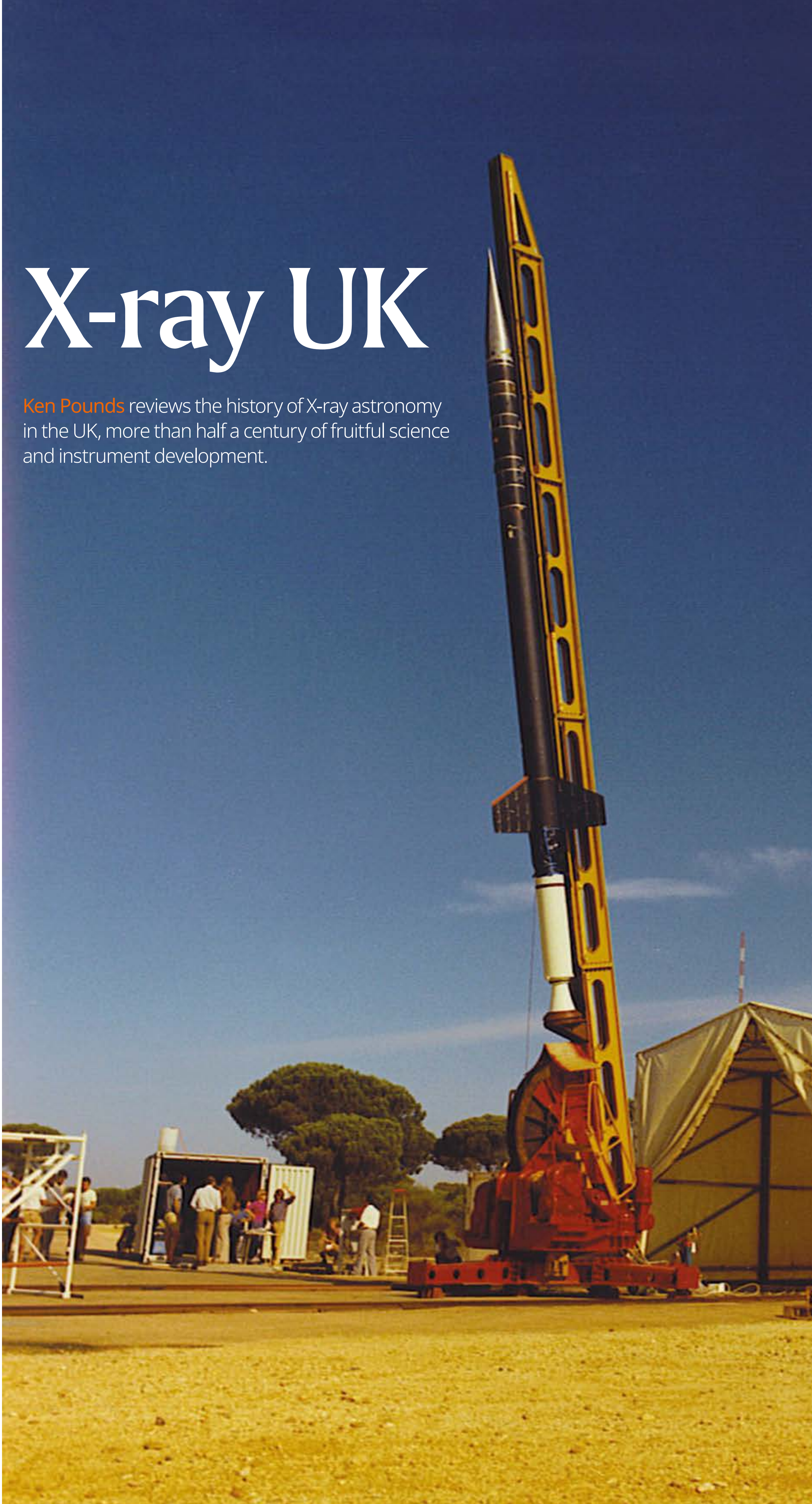
X-ray UK

Ken Pounds reviews the history of X-ray astronomy in the UK, more than half a century of fruitful science and instrument development.



1 *A Leicester Skylark rocket (SL1304) mounted on the portable launcher used at El Arenosillo in Spain. The main Raven motor sits between the fins and the payload, with the Cuckoo booster (so named as to "kick the Raven out of the nest") in white.*

(BAC/Roger Cooper)

Sixty years ago, two Skylark sounding rocket flights from Woomera in South Australia carried instruments that recorded the first solar X-ray spectra. The UK has subsequently played a significant role as X-ray astronomy has evolved into a major branch of astrophysics. Here I recall that story, with emphasis on the period leading up to the launch of the two major X-ray observatories, Chandra and XMM-Newton, which now place X-ray observations on a par with those in the optical, infrared and radio. The X-ray astronomy community, here and elsewhere, has changed markedly in that new era: where once university groups could lead the development of new missions, a large observatory is now the responsibility of space agencies such as ESA, NASA and JAXA in Japan, often working together. And the development timescales of 15–20 years no longer match the needs of early-career scientists. The few exceptions, where university groups can contribute directly, are bilateral projects, such as the Chinese/French project SVOM, for which University of Leicester is providing the X-ray optics, and HXTP, another Chinese-led project with support from University College London's (UCL) Mullard Space Science Laboratory (MSSL).

Origins

At the end of the second world war, military strategists believed future major conflicts would be carried out in or through space; the result was the development of ever more powerful missiles and rockets, particularly in the Soviet Union and the USA. An unintended consequence was the creation of a major new branch of science, where access to space brought the first opportunities to explore the solar system and to carry equipment for observing aspects of the universe previously hidden by absorption in the atmosphere.

Although on a much smaller scale, scientists in the UK were quick to realize a similar common interest with the military, with development of the highly competitive Skylark research rocket (figure 1), based on a ground-to-air missile launcher. The agreement between Harrie Massey, head of physics at UCL, and Sir Arnold Hall, director of RAE Farnborough, whereby the UK Treasury was persuaded to fund a four-year Skylark programme – and the formation of space research groups at UCL, Imperial College, Birmingham, Queen's University Belfast and Aberystwyth – provides a glimpse into the early years of UK space science (Massey & Robins 1986).

The immediate science objective was a better physical description of the Earth's upper atmosphere, hitherto directly probed only by using high-altitude balloons. That priority determined the early Skylark experiments, from 1957, and the payload of the Ariel-1 satellite launched in 1962 (figure 3). In addition to measuring the ionization profile, which was of interest in communications, the controlling fluxes of solar ultraviolet and X-radiation had to be determined. That task was the topic of my PhD research, identified a year after joining the UCL Rocket Group in 1956 – with funding from the Admiralty. We developed two X-ray instruments: a steel cassette that exposed a high-sensitivity film through thin metal foils of aluminium and beryllium, providing integrated solar fluxes from 2–8Å and 8–20Å (Pounds *et al.* 1962); and a proportional counter spectrometer (PCS; Pounds 1961). The PCS was to become the workhorse detector in X-ray astronomy for many years, as a stable and efficient photon counting device, with intrinsic – albeit modest – spectral resolution at 1–10 keV. Calibration of the first solar PCS, with argon–methane gas filling and aluminium foil window, was carried out at University of Leicester, using vacuum equipment designed for the soft X-ray spectroscopy of rare-earth metals. But the sounding rocket could provide data for only a short period; while such snapshot spectra were useful in scoping the coronal X-ray flux, the anticipated strong variability required continuous observation from orbit.

2 (Above) *The University of Leicester space research group in January 1960. From left to right: Pete Sanford, Brin Cooke, David Denne, Jim Underwood, Peter Russell, Prof. Stewardson and Ken Pounds.* (Leicester Mercury)

3 (Left) *The launch of Ariel-1 from Cape Canaveral, 26 April 1962, carrying instruments from UCL/Leicester, Birmingham and Imperial College.* (NASA)

The early UK space science programme was guided by the Royal Society's Gassiot committee chaired by Massey, who later played a leading role in the formation of the European Science Research Organisation (ESRO), forerunner of the European Space Agency (ESA). NASA offered to launch a series of small satellites and additional university groups were formed to take up the offer, with diverse targets. Leicester was to study "X-ray emission from the Sun and other stellar sources" and I accepted an assistant lectureship there in January 1960, to help that happen. Existing staff and students in the Physics Department joined the new space research group (figure 2), and we received a three-year grant of £13006 (corresponding to £0.3–1.1 million in 2019) from the Department of Scientific and Industrial Research, on advice from the (newly formed) Royal Society National Committee on Space Research, again chaired by Massey.

The initial science focus at Leicester was naturally on solar physics, given the contemporary view that ultraviolet and gamma-ray sources were more likely to be found from beyond the solar system. How wrong that prediction turned out to be!

Starfish Prime and the Sun

Our immediate priority was the forthcoming launch of Ariel-1, with instruments from UCL/Leicester, Birmingham and Imperial College. Proportional counters mounted either side of the spacecraft spin axis provided near-continuous monitoring of the solar X-ray spectrum. Launched from Cape Canaveral (now Kennedy Space Center) by a US Air Force Delta on 26 April 1962 (figure 3), all went well for several weeks, with multiple X-ray spectra showing a large flux increase and spectral hardening coincident with even quite minor solar flares (Pounds & Willmore 1963, Pounds 1965). Then, without warning, on 9 July the PCS counting rate went wild. On-board particle detectors were also being swamped (Durney *et al.* 1964). Shortly afterwards, the spacecraft solar array began to fail.

The cause was the detonation of a 1.4 megaton hydrogen bomb by the US Air Force, 640 km above Johnston Island in the Pacific Ocean (figure 4). Ariel-1 was then 7400 km away over New Zealand but on the same magnetic shell, which meant rapid exposure to a large flux of high-energy electrons. Accumulation of polymerized methane quench gas on the anode wires gradually lowered the charge gain, so that within a few weeks the PCS was essentially dead. The Ariel-1 mission survived rather longer, but not before causing a flurry of diplomatic exchanges between Washington and London. The detonation, code-named Starfish Prime, damaged or killed seven satellites including the first communications satellite Telstar, and led directly to an international ban on atmospheric tests in 1965 (Day 2008). Enhancement of the Earth's natural radiation belts remained for a decade.

> *"Operating successfully until 1980, Ariel-5 was the mission that put UK X-ray astronomy firmly on the international map"*

The full potential of the solar PCS was eventually realized on two NASA solar observatories, OSO-4 (1967) and OSO-5 (1969), showing the dramatic changes in X-ray intensity and spectral hardness linked with solar activity (Culhane *et al.* 1969, Herring *et al.* 1971). Using a collimated field of view and raster scan, the OSO-5 instrument also produced daily X-ray heliographs, which were circulated worldwide. While that programme continued as a joint effort with UCL, the Leicester group took advantage of a Sun-pointing version of Skylark to obtain early Bragg crystal spectra (Evans & Pounds 1968) and pinhole camera images (Pounds & Russell 1966) of the coronal radiation.

Scanning the sky

In July 1962, a second surprise with still greater long-term consequences followed an Aerobee 150 rocket flight from White Sands, New Mexico, by a team from American Science and Engineering (AS&E), a small military/space company in Cambridge, MA. AS&E was funded for the flight by the US Air Force, with the aim of determining the X-ray brightness of the sunlit Moon, a potential distraction in monitoring illegal weapons tests! The Aerobee had similar capabilities to the early Skylark and was unstabilized; the resulting motion allowed its three wide-field Geiger counters to cover most of the sky during a 350 s observation.

While the Moon was not seen (remaining so until ROSAT 30 years later), the data showed a remarkably bright source in the general direction of Scorpio (Giacconi *et al.* 1962). After some initial caution, and a re-flight in October, confirmation of Sco X-1, an X-ray source brighter than the non-flaring Sun at energies above a few keV, was quickly followed by detection of a second source (Tau X-1) linked to the Crab Nebula (Bowyer *et al.* 1964), transforming the scope of X-ray astronomy.

4 *The Starfish Prime hydrogen bomb explosion of 1962 seen from Honolulu. (From report to US Congress.)* (LLNL)

Skylark launches from Woomera provided early access to the southern sky for UK groups, with SL118 and 119 in April 1967 detecting both Sco X-1 and Tau X-1, together with an even brighter source in Centaurus, given the name Cen X-2 (Cooke *et al.* 1967). A month later, a rocket flight by the Lawrence Livermore Group found the same source, but six times fainter (Chodil *et al.* 1967), making Cen X-2 the first soft X-ray transient.

Further Skylark flights followed in 1968 and 1969 (SL723 and 724) with much larger PCS detectors filling the nose cone section. More than 90% of the X-ray emission in the region of Centaurus, Norma and Lupus was resolved as point sources, with broad-band spectra showing both thermal and power-law forms (Cooke & Pounds 1971).

The Sun-pointing Skylark, available from 1964, allowed more sophisticated experiments to be carried out. One such was the 1971 observation of GX3+1, a bright galactic bulge source where dust obscuration made an optical counterpart very difficult to find. Aided by predictions from Leslie Morrison at the Royal Greenwich Observatory, successive lunar eclipses of GX3+1 were observed in Skylark flights by Leicester and MSSL, obtaining a source position to within 0.2 × 5 arcsec, a precision unsurpassed for the next decade (Janes *et al.* 1972). Unfortunately, the tiny error box was empty, with no stellar counterpart identified until van den Berg *et al.* (2014) found a faint infrared source in 2010/12. Those Skylark flights did, however, show the potential of the lunar occultation technique to aid source identification – a method that later formed the basis of HELOS, Europe's first X-ray mission.

Moving into orbit

By the end of the 1960s, some 30 non-solar X-ray sources had been reliably detected, but the origin of the luminous X-ray emission in many cases remained unclear, hampered by positions uncertain to tenths of a degree. Better positions and X-ray light curves were needed for progress.

AS&E's small Uhuru satellite (1972–74) first met that challenge, with an all-sky survey finding 339 X-ray sources, including a new class of X-ray binary stars, emission from several rich galaxy clusters, and many faint unidentified sources at high galactic latitude (Unidentified High Galactic Latitude Sources, UHGLS). Giacconi had a particular interest in the UHGLS, speculating on "X-ray galaxies"

5 *All aboard the Skylark! A University of Leicester team astride SL1304, with, from the left: Jeffrey Hoffman, Roger Cooper, Roy Daldorph and Barry Giles. Hoffman later returned to the USA and trained as an astronaut; he was one of the team that repaired the Hubble Space Telescope after its launch.* (BAC/Roger Cooper)

as a new constituent of the X-ray background radiation, discovered in the 1962 Aerobee flight.

The opportunity for UK X-ray astronomers to take that next step into orbit was provided by the Ariel satellite co-operation with NASA, with the Ariel-5 spacecraft being the first designed and built in the UK, by Marconi in Portsmouth. The US Air Force provided the Scout launch on 15 August 1974, from the same former oil-rig platform in Kenya that was used for Uhuru; the low-altitude equatorial orbit ensured protection from the radiation belts and permitted a simple data and command link to ground stations at Quito and Ascension Island. Operating successfully until 1980, Ariel-5 was the mission that put UK X-ray astronomy firmly on the international map.

Three instruments viewed along the spacecraft spin axis: a PCS with grid collimators from MSSL and Birmingham; a hard X-ray scintillation counter from Imperial College; and a Bragg crystal spectrometer/polarimeter from Leicester. Looking out sideways in the spin plane were the Leicester Sky Survey Instrument (SSI) and a wide-field All Sky Monitor (ASM) from NASA Goddard. An important early result from the on-axis PCS was the detection of a highly ionized Fe xxv emission line from the Perseus Cluster (Mitchell *et al.* 1976), indicating a thermal origin for the X-ray emission from galaxy clusters.

During the first year in orbit, the Ariel-5 spin axis was fixed on the galactic pole for three extended periods of about 10 days. Among several short-lived or transient sources was A0620-00, making headlines both then and now. On Friday 3 August 1975, during the second extended plane scan, Leicester postdoc Richard Griffiths was on duty examining the SSI data plots. In addition to several dozen well-known galactic X-ray sources, he noticed a previously unseen "blip" as the scan passed through the constellation Monoceros. Griffiths had arranged a weekend away, so daily duties passed to research student Martin Elvis.

The "blip" grew rapidly, by 14 August becoming the brightest cosmic X-ray source seen (Elvis *et al.* 1975a,b), a record that stood for 30 years. The initially hard X-ray spectrum softened as the flux increased, perhaps indicating a growing accretion disc, and then ASM observations (Kaluzienski *et al.* 1977) showed a smooth exponential decay over several months, interrupted by brightening in October and February, before a rapid final decline.

Within days of discovery, A0620-00 had been linked with an optical nova, V616 Mon (Boley *et al.* 1976). An optical spectrum, delayed by several months while the nova faded, showed a solar-type star racing around a massive but unseen companion at 500 km s^{-1}. With a mass at least three times that of the Sun, excluding a neutron star (McClintock & Remillard 1986). A0620-00 is one of the most secure stellar-mass black hole candidates (Fabian 1988), and an appropriate target for the message from Stephen Hawking announced by his daughter Lucy in Westminster Abbey last year (bit.ly/2PgsUM4).

While A0620-00 remains the closest recorded black hole, at 3500 light years Hawking's words will take some time to arrive. Meanwhile, historical records of the 20th magnitude solar-type companion predict a new eruption in 2033, with an expanding atmosphere again dumping matter onto the black hole – a prime target for ESA's Athena Observatory!

Improved source positions from Ariel-5 were critical in identifying many of the faint sources at high galactic latitude from both Uhuru and Ariel-5 surveys. While some were additional rich clusters, most were shown to be normal Seyfert galaxies (Elvis *et al.* 1978), with young astronomers recruited in part from the Sussex MSc course playing a key role in solving the mystery of the UHGLS (Pounds 1976).

The Einstein Observatory

Launch of the Einstein Observatory in November 1978 took X-ray astronomy a further step towards parity with optical astronomy, the 0.9 m, 4 arcsec resolution Wolter 1 X-ray telescope providing a 100-fold increase in point-source sensitivity – finally making "normal" stars accessible at these wavelengths – and detailed X-ray mapping of supernova remnants and galaxy clusters. Again, Giacconi led the project, now based at the Harvard-Smithsonian Center for Astrophysics. An informal collaboration with Leicester provided high-efficiency coatings for the microchannel plate detector in the High Resolution Imager (Fraser *et al.* 1984), and improved image analysis software (Willingale 1981). Resulting science collaboration included leading UK roles in studies of SN1006 (Pye *et al.* 1981), Cas A (Fabian *et al.* 1980) and SS433 (Watson *et al.* 1983). After a transformative 2.5 years of operation, Einstein observations ended in April 1981.

For Giacconi's group the focus then turned to the Advanced X-ray Astrophysics Facility (AXAF; see below), a larger and higher-resolution imaging telescope, but the technological and budgetary challenge eventually led to a 20-year gap in the NASA X-ray astronomy programme.

It was particularly timely that the international science base simultaneously expanded, with the launch of the European EXOSAT in 1983, JAXA's Ginga (1987) and ROSAT (1990) led by the German Aerospace Center (DLR) leading the way. With funding restrictions in the UK having ended the national programme, collaboration in all three missions ensured a flow of new X-ray data to help maintain a growing university community in the 1980s and 90s.

EXOSAT (1983–86)

ESRO was keen to enter this new branch of space science in the late 1960s, but was constrained by a much smaller science budget than NASA, already planning two large missions for launch in the 1970s, including an imaging X-ray telescope. With the identification of many hard-spectrum X-ray sources unsuited to observation with a grazing incidence telescope, I proposed a large PCS and variable spacing, rotation modulation collimator, as an ancillary instrument on the COS-B gamma-ray mission. While that addition (COS-A) was rejected by the COS Working Group, concerned at the heavier payload and resulting lower orbit for COS-B, sufficient interest was created to invite another bid from the X-ray community, with the lunar occultation HELOS mission being selected for

Exploring Seyfert galaxies

As befits a new area of science, progress in X-ray astronomy has closely followed space missions carrying more diverse and powerful instrumentation. That link has been evident in my own interest in Seyfert galaxies, dating back to Ariel-5. The broad spectral coverage of EXOSAT showed the frequent presence of a "soft excess" above the dominant hard power law, consistent with thermal emission from the inner accretion disc (Turner & Pounds 1989), while remarkably fast, high-amplitude flux variability established during the EXOSAT "long looks" (McHardy 1988) implied the presence of a supermassive black hole, by analogy with the solar-mass holes found in X-ray binaries. The Ginga LAC high-energy response revealed a "hard excess" in several bright Seyferts (Nandra & Pounds 1994), interpreted as Compton scattering from dense matter (most likely the accretion disc) and providing a diagnostic of the dynamics and geometry of matter close to the black hole, a topic energetically pursued by the IoA group in Cambridge (Ross *et al.* 1999). Most recently, the large photon grasp of XMM-Newton has proved well suited to the study of ultrafast outflows (Pounds 2017), a signature of super-Eddington accretion in luminous AGN and – by their kinetic power – a potential feedback mechanism to explain the observed correlation of supermassive black-hole mass and stellar bulge velocity spread in the host galaxy.

the second phase ESRO programme in 1968 (described in more detail by ESA 1990). Despite a long delay linked to ESRO's financial crisis, space science emerged as part of ESA in 1975, and Europe's first X-ray mission was finally launched in 1983, renamed EXOSAT (The European X-ray Observatory Satellite).

Although few occultations were ever attempted, the deep space orbit proved a major bonus, later becoming the orbit of choice for Chandra and XMM-Newton. Data and command links benefited from the lengthy spacecraft dwell time near apogee, with a bonus of up to 75 hours of uninterrupted observation of a target source. With strong user support from ESA setting new international standards, the EXOSAT mission (Pallavicini & White 1988) laid the foundation of a strong X-ray community across Europe. UK groups did particularly well in winning almost a third of the total observing time, building on major contributions to the payload by Leicester and MSSL (White & Peacock 1988).

Ginga (1987–1991)

Ginga (1987–91), a successor to Hakucho and Tenma, was the first Japanese X-ray mission to invite international collaboration. The main instrument was the Large Area Counter (LAC), a PCS with effective area of 4000 cm^2 and sensitive over the range 1.5–30 keV.

UK involvement arose from a visit to Tokyo in 1979 by a Science Research Council delegation, exploring possibilities for science collaboration. The delegation was led by Harry Atkinson, director of the Astronomy Space and Radio Division, with John Houghton and I making the case for atmospheric physics and X-ray astronomy missions.

It emerged later that our hosts had already decided to explore UK help in building the LAC detectors, and a partnership was quickly agreed during a return visit to Leicester by the leading Japanese X-ray astronomers Minoru Oda and Yasuo Tanaka. We were able to reassign Martin Turner (figure 6) to that new task, having completed his work on EXOSAT, and he duly delivered the eight detectors on time and within budget.

During four near-flawless years in orbit, Ginga provided high-quality broad-band spectra and flux variability of some 350 X-ray sources of all types (Makino & Nagase 1992). UK groups were allocated a share of observing time, together with unlimited joint UK–Japan proposals. Exchange of young researchers between Japan and the UK added to the success of Ginga, a science collaboration later highlighted at intergovernmental level.

ROSAT (1990–98)

The power of grazing incidence optics demonstrated by the Einstein Observatory encouraged plans for an all-sky survey telescope. One such proposal was made to NASA by Massachussetts Institute of Technology and Leicester, following successful flights of a soft X-ray telescope on NASA Astrobee rockets in 1977 and 1978. While that proposal was not funded, an all-sky X-ray survey was eventually delivered by ROSAT, led by the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, with support from NASA Goddard.

An invitation for other European participation was accepted by the UK, with an ancillary extreme-ultraviolet survey telescope built by Leicester, with engineering support from Rutherford Appleton Laboratory. The prototype for the Wide Field Camera (WFC) was a further MIT–Leicester Astrobee flight carrying an 8° field of view 50–250 Å telescope (Barstow 1983). The WFC ultimately led to an all-sky catalogue containing 383 galactic and extragalactic sources in the 60–200 eV band (Pounds *et al.* 1993).

The all-sky X-ray survey yielded 135000 sources (Boller *et al.* 2017) and while the sky survey was developed within MPE, UK researchers were involved in many subsequent observations with the X-ray telescope.

Chandra and XMM-Newton

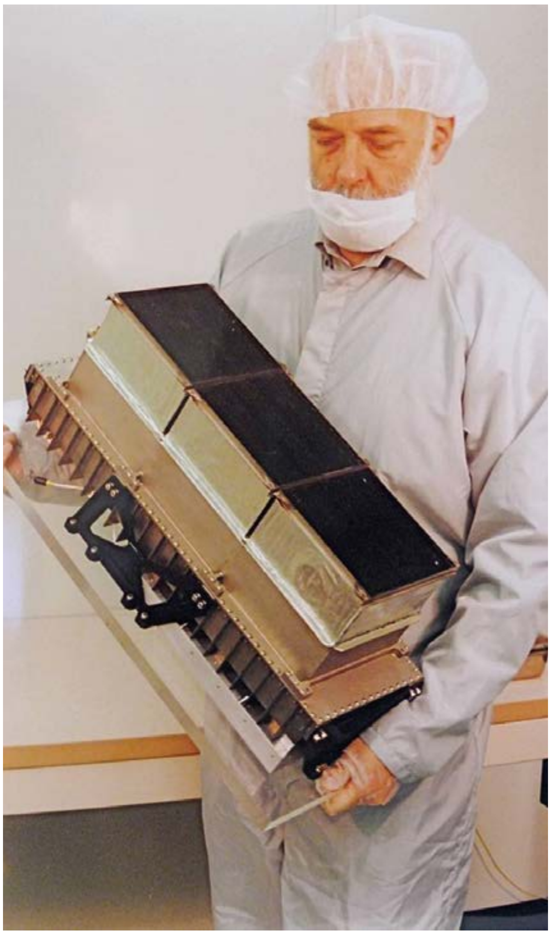
AXAF was eventually launched on 23 July 1999 and renamed Chandra after the astrophysicist and Nobel laureate Subra Chandrasekhar. Less than five months later, on 10 December, XMM-Newton – ESA's successor to EXOSAT – was launched into a similar high-apogee orbit. Still working well after 20 years, these two Great Observatories – joined from 10 July 2005 by the Japanese X-ray observatory Suzaku – have taken X-ray astronomy into a third phase, with combined observational capabilities comparable to those in the optical and infrared.

Both spacecraft and payload of XMM-Newton were the responsibility of ESA (Jansen *et al.* 2001), with MSSL being part of a consortium building the Reflection Grating Spectrometer (den Herder *et al.* 2001), and Leicester providing two of the three focal plane CCD cameras (Turner *et al.* 2001). Leicester, through the work of Turner, also played a key role in delivery of the complete imaging camera unit, which included a pn detector array from MPE for the third telescope (Strueder *et al.* 2001).

Both Chandra and XMM-Newton have followed an open access policy, supporting the growth of X-ray astronomy internationally. To date, XMM-Newton has received observing proposals from more than 40 countries worldwide. UK groups maintain a strong share of observing time, with involvement continuing from across the university sector.

A major legacy of XMM-Newton will be the serendipitous sky survey, with the latest published 3XMM-DR5 catalogue of 396910 X-ray sources, including X-ray spectra and light curves for the brightest third (Rosen *et al.* 2016). Accurate source positions and a cross-correlation with many other astronomical catalogues support source identification. As new observations are released into the public domain, the XMM-Newton Survey Science Centre

"These three observatories have combined observational capabilities comparable to those in the optical and infrared"



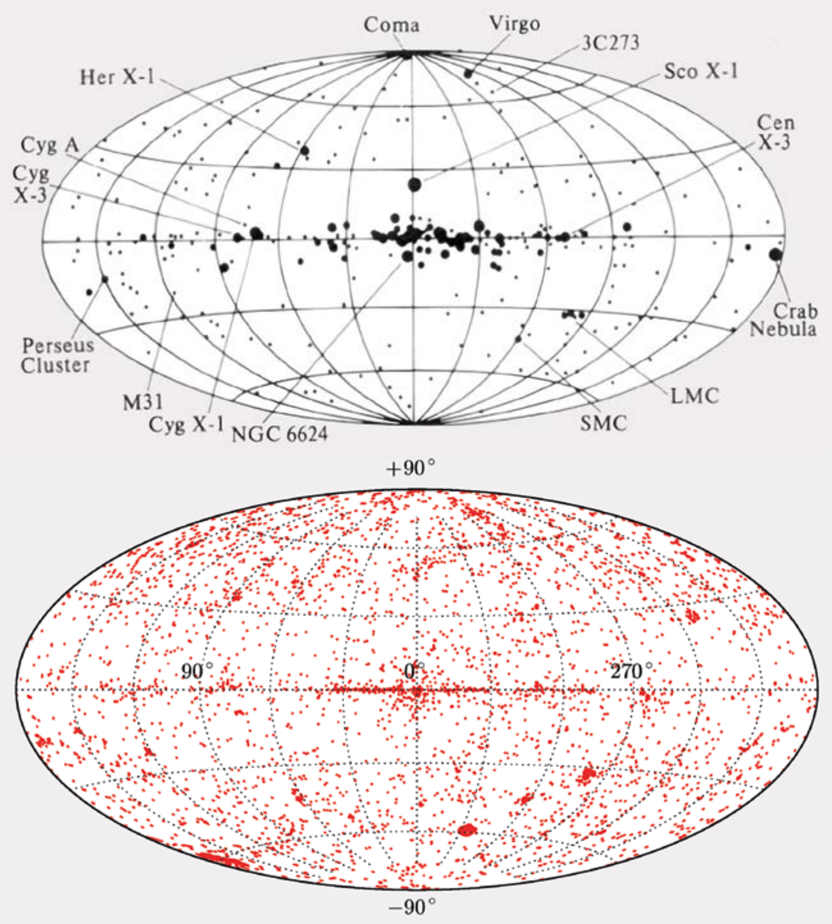
6 *Martin Turner with a detector module for the Large Area Counter instrument carried on Ginga.* (ISAS/Martin Turner)

(Watson *et al.* 2001) will process the new detections and periodically issue catalogue updates, with the number of X-ray sources increasing by about 30 000 per year.

Looking ahead

While XMM-Newton and Chandra continue to operate nominally after two highly productive decades in orbit, development has started on their successor, Athena, scheduled for launch in 2031. Before then, JAXA plans to fly a micro-calorimeter on the XRISM mission, also offering non-dispersive high-resolution spectra at 0.3–10 keV, crucially covering the K-shell energies of iron.

The Athena X-ray Observatory, led by ESA but with significant collaboration from NASA and Japan, will be the first mission having a sufficient photon grasp to fully exploit such high-resolution spectra, the topic of a recent RAS meeting (*A&G* October 2019). With the UK contributing a GDP-related share of the billion-euro project costs, university departments have a responsibility – and funding agencies a compelling reason – to maintain a strong user community over the intervening years. Fortunately, it now seems likely that ESA will continue to operate XMM-Newton for a third decade. ●



7 *Filling in the X-ray sky. (Top) Aitoff equal area, galactic coordinate plot of X-ray sources in the Ariel-5 3A catalogue.* (Warwick *et al.* 1981, McHardy *et al.* 1981) *(Bottom) Similar plot of 7781 3XMM-DR3 high-exposure XMM EPIC fields, where source density is too high to show. Full details in Rosen* et al. *(2016).*

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