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# UK contributions to the development of X-ray astronomy as a major international discipline

K. Pounds and M. Watson

Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK
e-mail: kap@le.ac.uk

**Abstract.** The historic discovery of Sco X-1 in 1962 found space science groups at UCL and Leicester well placed to respond, having a solar X-ray instrument currently in orbit and the proven and versatile Skylark sounding rocket available. Increasingly sophisticated experiments flown on Skylark from 1967 helped build scientific and technical expertise, leading to the successful Ariel 5 satellite, launched in 1974. Over the following 6 years, Ariel 5 made a number of seminal discoveries, including the first uncontested stellar black hole binary, multi-million degree gas pervading galaxy clusters, and powerful X-ray emission from Seyfert galaxies. Although by 1980 funding cuts had led to termination of the Ariel and Skylark programmes, UK university groups were able to continue a leading role in the first ESA X-ray satellite and contribute significantly to major X-ray astronomy projects led by Japan and Germany. The respective EXOSAT, Ginga and ROSAT missions ensured X-ray astronomy continued to grow strongly during an unplanned 20-year gap between NASA X-ray astronomy missions, a residual benefit being the strong international base of X-ray astronomy, currently providing powerful and complementary X-ray Observatories from the USA, Europe and Japan.

**Key words.** X-ray astronomy, Ariel 5, Skylark

## 1. Introduction

Prior to 1962, most astronomers considered that observations in the ultraviolet and gamma ray bands offered the best promise for exploiting the exciting potential of space research. X-ray observations were expected to focus on the study of active stars, with fluxes scaled from that already measured for the solar corona being beyond the reach of detection with then-current technology.

As an indication of contemporary thinking the recently formed US National Aeronautics and Space Agency (NASA) was planning a series of Orbiting Astronomical Observatories, with the first missions devoted to UV astronomy, although a proposal from the UCL and Leicester groups to make simultaneous X-ray observations of the primary UV targets was accepted in 1961, and eventually flown on OAO-3 (Copernicus) 11 years later.

The ASE/MIT Aerobee rocket flight from White Sands Missile Range in June 1962 (Giacconi et al. 1962), finding in Sco X-1 a cosmic X-ray source a hundred billion times more luminous than the Sun, began a transformation that laid the foundations for a revolution in High Energy Astrophysics.

In the UK, space science groups at UCL and Leicester were well placed to respond, with a joint solar X-ray instrument operating in orbit on Ariel 1 and the competitive Skylark sounding rocket having already made several successful launches from Woomera in South Australia (Massey & Robins 1986).

## 2. Skylark

The early (pre-IGY) development of Skylark (figure 1) was made possible by a coincidence of military and scientific interest in the properties of the Earth's upper atmosphere (Pounds 2011), with a first successful test flight taking place 8 months before the launch of Sputnik 1. Early flights concentrated on atmospheric research, together with measurements of solar Lyman-$\alpha$ and X-ray emission, the latter forming the PhD thesis research at UCL for one of us (KP). Following the successful launch of Sputnik, interest and funding for space research increased in several countries, including the UK, and a new research group was established at Leicester University in 1960, with a Royal Society grant of £13006 to study Solar and Stellar X-ray emission.

While the initial focus at Leicester and UCL was on the Sun, with joint experiments on NASA's OSO-4 and OSO-5, and on ESRO-2 during the 1960s, the discovery of Sco X-1 had a major influence on priorities, especially for the Leicester group where our solar research ambitions suffered a significant disappointment with the cancellation of the ESRO TD-2 mission in 1968.

April 1967 saw our first use of Skylark to explore the southern sky from Woomera in South Australia (Cooke et al. 1967), followed over the next 2 years by a larger and more sensitive proportional counter payload (figure 1), finding several X-ray sources in Centaurus and the Galactic centre region, exhibiting both thermal and non-thermal X-ray spectra (Cooke & Pounds 1971). With a hint of what lay ahead, repeated Skylark observations found the X-ray flux from Cen X-3 varied by an order of magnitude, while Cen X-2 briefly outshone Sco X-1, before apparently disappearing.

The availability of an attitude-controlled Skylark allowed more sophisticated experiments to be flown, including a scanning modulation collimator, Bragg spectrometers (on Puppis A and Sco X-1) and soft X-ray mapping of the Vela-Puppis supernova remnant. The luminous Galactic bulge sources remained an enigma with the crowded star fields and high dust obscuration making optical identification particularly challenging. In response, the lunar occultation of GX 3+1 was observed in successive months in 1971 (Janes et al. 1972). Skylark SL 1002 (figure 2) successfully detected the first occultation on 27 September 1971, obtaining a source location to ~0.4 arc sec. A second observation during the next lunar passage, by the MSSL/UCL group, provided a further position arc. Though the combined source location was far more precise than any contemporary value, no optical counterpart was found. [1]

With hindsight, although the science returns were rapidly overtaken, the Skylark programme was an exciting time for a group of young physicists and technicians, and the expertise gained over several years was excellent preparation for Ariel 5, the fifth in a series of small science satellites launched under a bilateral agreement with NASA and the first devoted to X-ray astronomy.

## 3. Ariel 5

Uhuru took X-ray Astronomy into orbit in December 1970, carrying a large proportional counter array to undertake a deep all-sky survey. Within a few months it was clear that many X-ray sources were variable, leading to the discovery that Cen X-3 and Her X-1 - and by implication probably many of the most luminous galactic sources - were in binary star systems, the rapid and periodic X-ray variations showing the X-ray component to be most likely a neutron star (Schreier et al. 1972; Tananbaum et al. 1972). The discovery of extended X-ray emission from several rich galaxy clusters was an even more remarkable result (Forman et al. 1972). Meanwhile

[1] The counterpart for GX3+1 is still not known with certainty, eg. Zolotukhin & Revnivtsev (2010), reflecting the large extinction and high stellar density in the region of the Galactic centre.

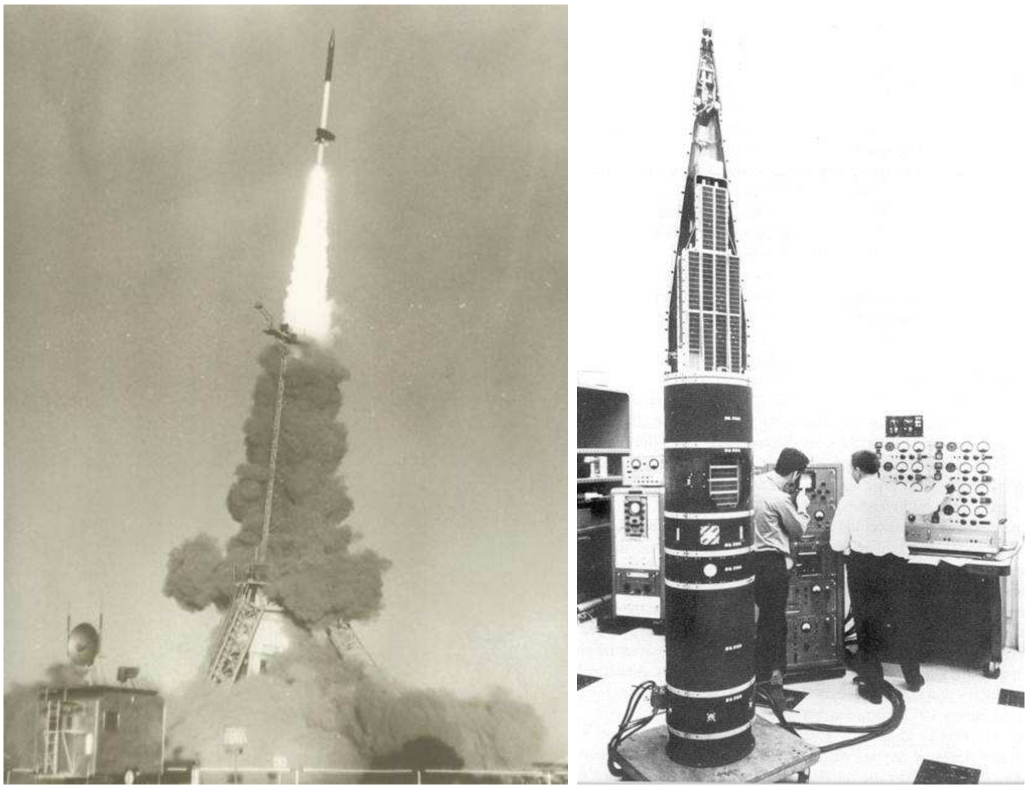

**Fig. 1.** (left panel)The Skylark sounding rocket capable of carrying a payload of 100 kg to 250 km with an above-atmosphere exposure for astronomical payloads of 5 minutes. Cosmic X-ray experiments were flown on Skylark for 10 years from 1967 (Massey & Robins 1986). (right panel) SL 723 payload in the test bay at Woomera. The 2x1380 $cm^2$ proportional counters packed under the nose cone formed the largest X-ray payload at the time

the number of known X-ray sources increased by an order of magnitude. Other Uhuru-class satellites followed, with Ariel 5 (UK), SAS-3 (USA) and Hakucho (Japan) dedicated to X-ray observations and OSO-7 (USA) and ANS (Netherlands) being solar and UV astronomy missions carrying secondary X-ray instrumentation. Like Uhuru, Ariel 5 (figure 3) was launched on a Scout rocket into a circular near-Earth orbit from a disused oil platform off the coast of Kenya. Unlike Uhuru, the scientific payload was more complex, partly through scientific choice and partly to meet the ambitions of a larger UK X-ray community, now including Imperial College (IC) and Birmingham University (BU). Four experiments viewed along the satellite spin axis, a modulation collimator and proportional counter spectrometer (MSSL/BU), Bragg Polarimeter (Leicester) and hard X-ray Scintillation Counter (IC). Viewing from the side were a Sky Survey Instrument (SSI) from Leicester, similar but smaller than that on Uhuru, and an All Sky Monitor (from Goddard Space Fight Center).

The Ariel 5 orbit was a good choice, not only in minimising background due to cosmic rays and trapped radiation, but in allowing regular data dumps from the small on-board data recorder. A direct ground and satellite link to the UK provided six orbits of *Quick Look* data reaching the experimenter groups within an hour of ground station contact. The remain-

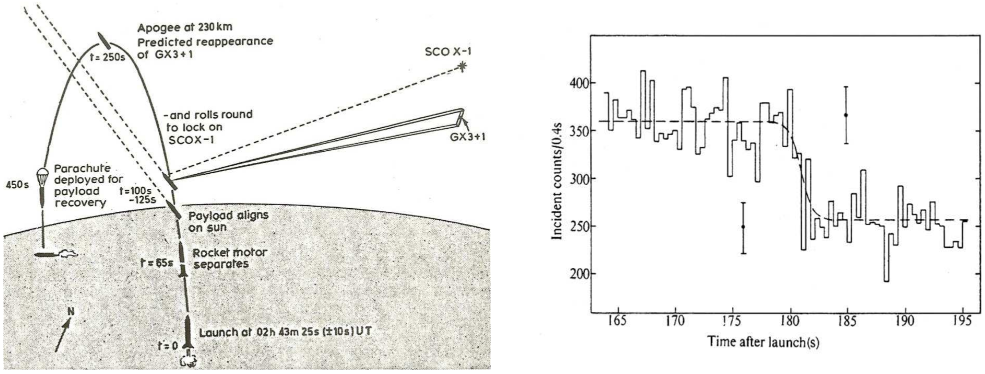


**Fig. 2.** (left panel) The launch of SL 1002 was timed to achieve apogee as the Moon's disc was predicted to occult GX 3+1. On ascent the rocket first acquired the Sun and then rolled around the rocket axis before a secondary X-ray detector locked on to Sco X-1, the payload design then ensuring the main X-ray proportional counter was pointing at GX 3+1. (right panel) X-ray counting rate falls as GX 3+1 is occulted by the Moon.

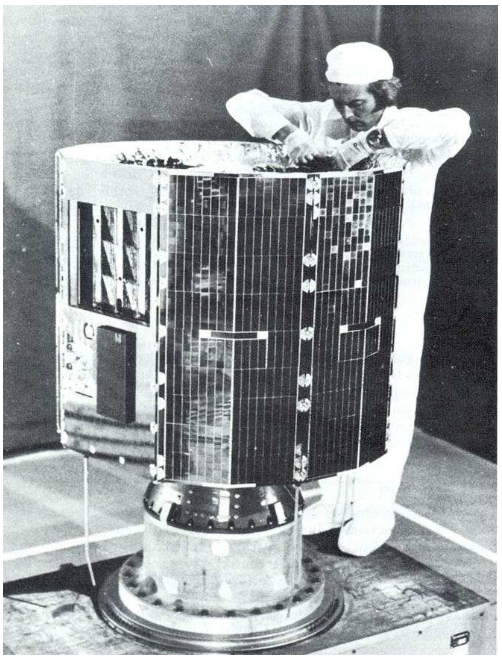

**Fig. 3.** Ariel 5 spacecraft. The Sky Survey Instrument (SSI) detector array is seen in the upper left

ing *bulk* data were generally received within 24 hours, contributing to effective mission operations and ensuring a rapid response to new discoveries.

One such discovery was particularly well-timed, with the SSI detecting a new source in the constellation Monoceros, two days before the start of the first European Astronomy Society meeting, held in Leicester, where new X-ray results from Ariel 5 and SAS-3 dominated the programme. The new X-ray source was to become one of the first secure black hole binary system.

Drift of the spacecraft spin axis was tightly controlled by a magnetorquer system, allowing extended periods viewing the same on-axis source or scan plane, with substantial scientific benefits. Figure 4 shows two examples where extended observations with the MSSL on-axis proportional counter yielded important results. The left hand panel reproduces the X-ray spectrum of the Perseus Cluster showing an emission line at ~7 keV, compelling evidence for a hot gas rather than scattered microwave background origin of the intracluster emission (Mitchell et al. 1976). The right hand panel of figure 4 shows the sinusoidal phase variations of the slow (11.6 min) X-ray pulsar, from which White, Mason & Sanford (1978) determined a 41 day binary period with the B2 supergiant identified by Bradt et al. (1977).

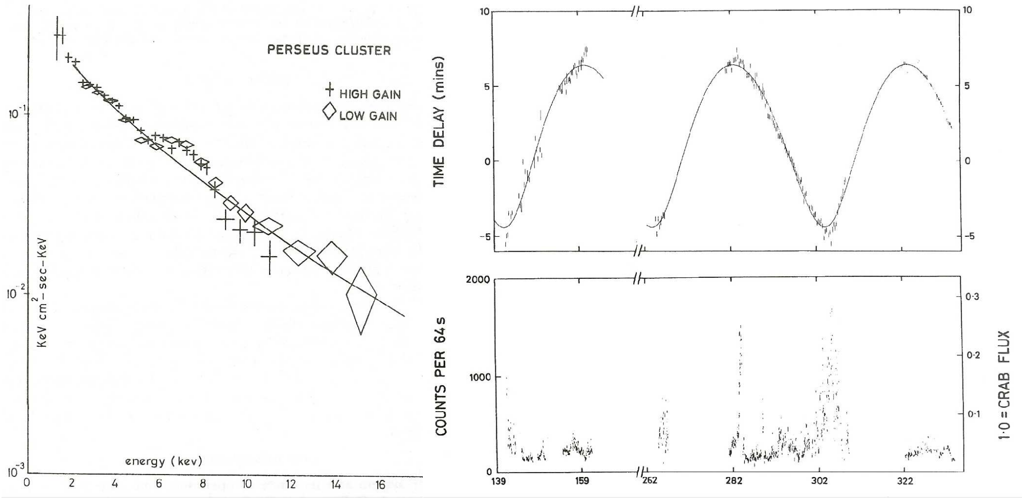


**Fig. 4.** Ariel 5 observations with the on-axis proportional counter included: (left) detection of FeXXV/XXVI line emission, evidence that the X-ray emission from the Perseus Cluster was of thermal origin (Mitchell et al. 1976); (right) continuous ~30 and ~75 day observations of the slow X-ray pulsar GX 301-2 establishing directly a 41 day binary period with the B2 supergiant star (White, Mason & Sanford 1978)

## 4. A0620-00

A0620-00 was the brightest of several X-ray transients discovered by the SSI during an extended scan of the Galactic plane in 1975. Within a week it outshone Scorpius X-1, becoming - for a while - the brightest cosmic X-ray source ever seen (Elvis et al. 1975), a record to be held for 30 years. Well before peaking at a flux level ~3 times that of Sco X-1, the new source was being monitored by Ariel 5, SAS-3 and other space- and ground-based telescopes around the world. The X-ray emission subsequently fell over several months, being continually monitored by the Ariel 5 ASM (Kaluzienski et al. 1975).

The optical counterpart of A06200-00 (V616 Mon) was rapidly identified through its nova-like behaviour (Boley & Wolfson 1975), the stellar position then allowing identification of the quiescent counterpart on the Palomar Observatory Sky Survey charts (Ward et al. 1975) with a $m_B \sim 20$ solar type star.

A more detailed optical study, when the nova light had faded, confirmed the companion as a K5V star in a 7.8 hr period binary (McClintock et al. 1983). Spectroscopic observation of the binary companion in quiescence revealed narrow absorption lines showing an extremely large amplitude radial velocity, from which McClintock & Remillard (1986) obtained a strong lower limit of 3.2 $M_\odot$ for the mass of the compact X-ray source, *independent* of distance and mass of the companion star. With reasonable assumptions regarding the K dwarf star, the lower limit increased to ~7.3 $M_\odot$, well above the maximum mass of a neutron star.

The return of A0620-00 has been forecast for circa 2033, based on the discovery from Harvard plates that V616 Mon previously flared up in 1917. Meanwhile, optical studies in quiescence have detected rapid optical flaring, with rise times of 30 seconds or less, and a power-density spectrum that may be characteristic of black hole binaries in their low state Hynes et al. (2003).

In another important step, using a SAS-3 spectrum taken in 1975 to estimate the radius of the innermost orbit, Gou et al. (2010) have shown the black hole in A0620-00 to be spin-

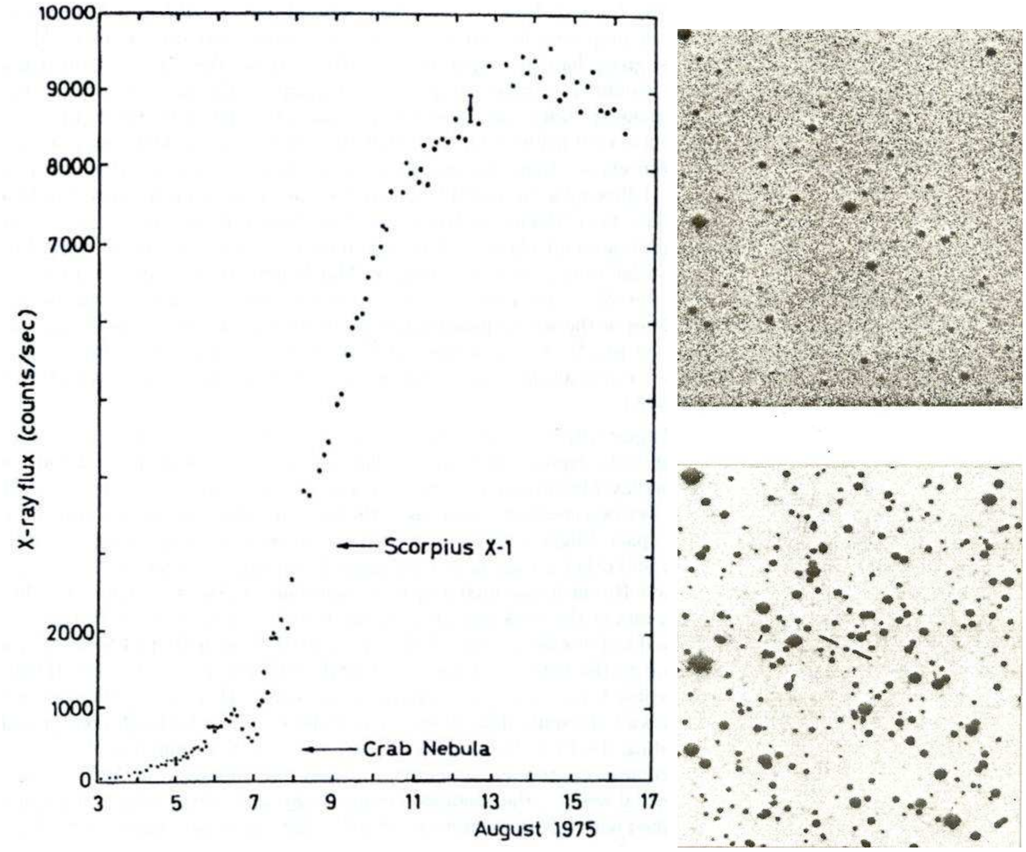


**Fig. 5.** (left) Soft X-ray transient source A0620-00 (Nova Mon) detected in an Ariel 5 Galactic plane survey. (right) Comparison of a short UK Schmidt telescope exposure taken during outburst (top) with the corresponding Palomar Sky Survey red plate (lower), from which Boley & Wolfson (1975) identified A0620-00 with the K5V star indicated

ning quite slowly, with a spin parameter $a_* = 0.12 \pm 0.19$, suggesting the radio jet seen in both flaring and quiescent states is probably disc driven.

Finally, a recent determination of the inclination of A0620-00 by Cantrell et al. (2010), has allowed the black hole mass to be refined to $6.6 \pm 0.25\ M_\odot$.

## 5. Supermassive black holes in AGN

A second important and enduring outcome from the Ariel 5 Sky Survey was in establishing powerful X-ray emission as a characteristic property of Seyfert galaxies, alongside the bright optical nucleus and broad permitted lines.

Prior to the launch of Ariel 5 the majority of extragalactic X-ray source identifications were with rich galaxy clusters. Only NGC 4151 and 3C 273 had been identified uniquely with AGN in the 3U catalogue (Kellog 1974). Indeed, it was suspected that the majority of the unidentified high galactic latitude sources might represent a new form of *X-ray Galaxy* (Giacconi 1973).

NGC 3783 was the first new identification (Cooke et al. 1976), the Seyfert galaxy

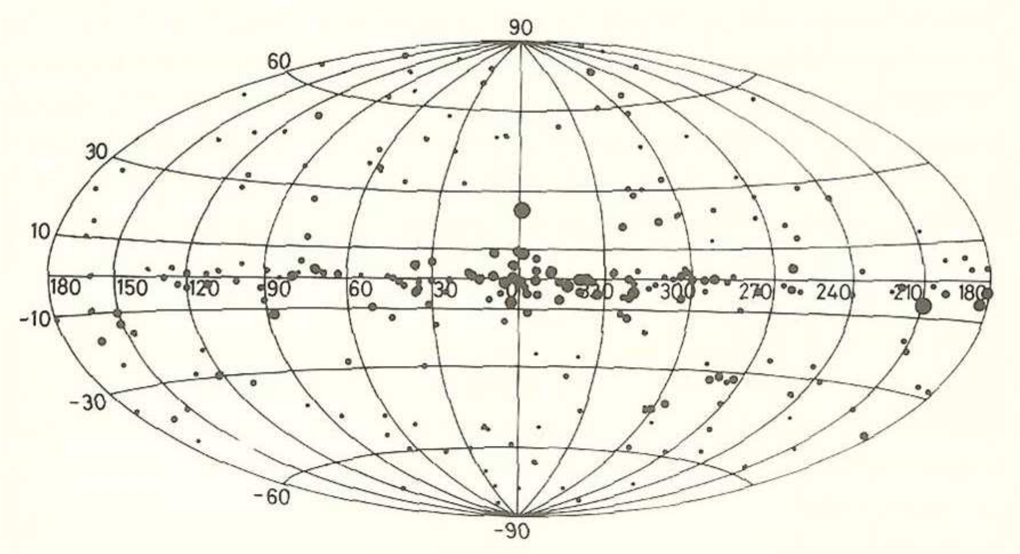


**Fig. 6.** Map of 297 X-ray sources detected with the Ariel 5 3A catalogue, plotted in Galactic coordinates with source diameter proportional to the log of the X-ray flux. Many of the faint sources at high galactic latitude were identified with Seyfert galaxies and clusters

being the brightest object in the 2A1135-373 error box (figure 7). Optical spectra obtained with the 3.8m AAT revealed the presence of FeX and other high ionisation lines, strengthening the X-ray association. 9 further coincidences of bright Seyferts with Ariel 5 sources quickly followed, enabling a report at the 1976 Relativistic Astrophysics meeting in Boston that those 10 Seyfert identifications, together with 21 new rich cluster/X-ray identifications, had essentially solved the mystery of the *UHGLSs - unidentified high Galactic latitude sources* (Pounds 1977).

Establishing powerful X-ray emission as a characteristic property of Seyfert galaxies was further strengthened when Elvis et al. (1978) showed in a sample of 15 Seyfert galaxies that the X-ray luminosity was correlated with the infrared and optical luminosity and with the width of the broad emission lines, but not with the radio flux, strongly suggesting a common origin in the innermost $\leq$0.1 pc. However, confirming Seyfert X-ray emission to be a signature of a supermassive black hole required more information, which was to come several years later.

## 6. EXOSAT

Europe's first X-ray astronomy mission had a hesitant start. An early disappointment came in 1969 when ESRO's COS Working Group chose to back a Gamma Ray mission (COS B) ahead of an X-ray contender (COS A). However, a further invitation followed in 1970, with the challenge to design an X-ray satellite competitive with NASA's Einstein Observatory, then under development. The outcome was HELOS, which one of us (KP) successfully presented to the ESRO LPAC in 1971, the concept surviving the demise of ESRO before being accepted by ESA in 1973 Harris (1999). A four-year delay in funding, coinciding with new results from Uhuru, Ariel 5, and SAS-3, and the approaching launch of the Einstein Observatory, changed priorities, and led to the payload being modified with two small soft X-ray telescopes and a Gas Scintillation Proportional Counter added

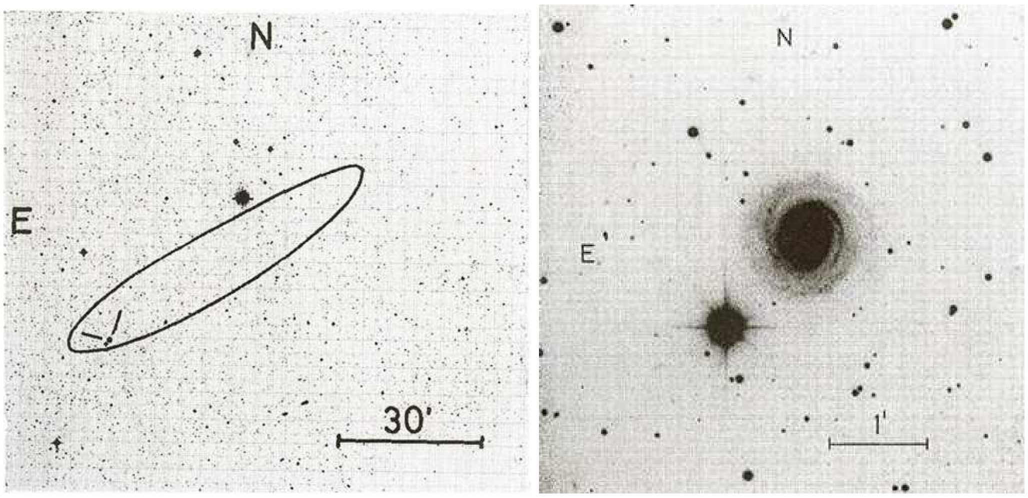


**Fig. 7.** (left) 90 % confidence error box of 2A 1135-373 superimposed on a UK Schmidt plate. The Seyfert galaxy NGC 3783 is indicated. (right) Blue 3.8m AAT image of NGC 3783, the first of a new class of X-ray emitters identified with the Ariel 5 SSI

to the primary large area proportional counter (MEDA) instrument designed for use in lunar occultations.

EXOSAT (Pallavicini & White 1988), operational from 1983-86, was a pioneering mission in several respects, establishing the value of a deep space orbit for real time operations and - as well demonstrated late in the mission - allowing long and uninterrupted observations of variable sources. One remarkable outcome of the 'long looks' was in finding the X-ray emission from several bright AGN to vary on timescales of hours (McHardy 1988), strong evidence for a super-massive black hole accretion. On-line data analysis tools and the first dedicated Guest Observer programme made EXOSAT accessible to a much wider scientific community than had previous space missions, with transfer of the data archive to GSFC in 1990 ensuring similar benefits were continued through the HEASARC.

The UK contributed substantially to the EXOSAT payload, with MSSL working with Leiden and Utrecht on the soft X-ray telescopes and Leicester with MPI Garching and Tubingen University on the MEDA. Wider interest across the UK astronomy community resulted in a strong scientific return, winning 30% of observing time over the mission.

## 7. Ginga

A joint X-ray mission with Japan was one option discussed during a UK SERC visit to Tokyo in 1979. Experience gained in development of X-ray proportional counters for Ariel 5 and EXOSAT was undoubtedly instrumental in an agreement, reached in 1982, for Leicester to collaborate in the planned ASTRO-C mission. Progress was swift and enjoyably unbureaucratic. The outcome was a highly successful collaboration in which the UK built the detectors for the Large Area Counter (LAC), an array of 8 multi-cell proportional counters with a total effective area of 4000 $cm^2$, together with low in-orbit background enabling observation of sources 5000 times fainter than the Crab Nebula. Martin Turner agreed to lead the Leicester team in development of the LAC - an inspired choice later extended to provision of the EPIC CCD cameras for XMM-Newton.

Operational from 1987-90, Ginga provided unique broad band (1.5-37 keV) X-ray spectra and high resolution (ms) timing data which had a wide scientific impact. A special issue of

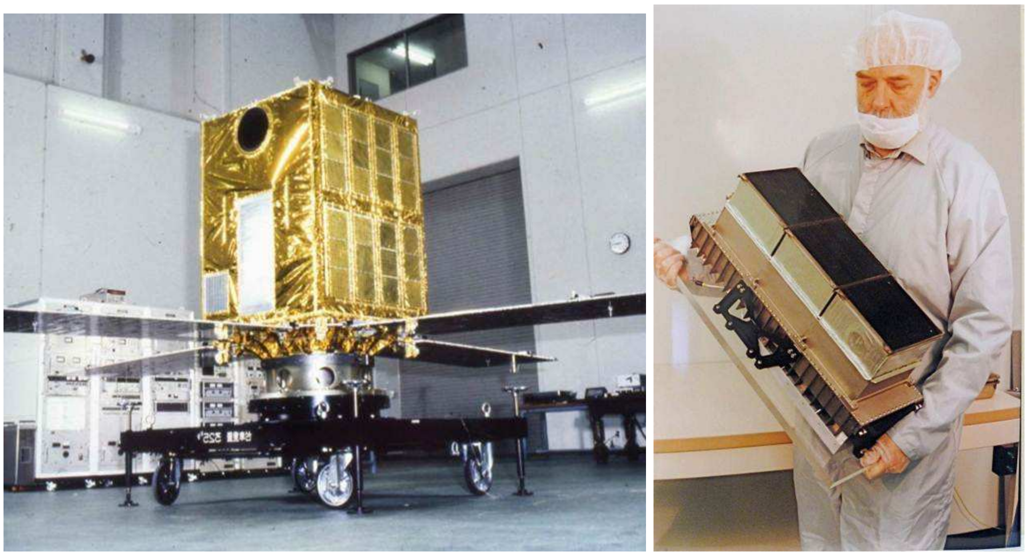

**Fig. 8.** (left) Ginga satellite with LAC array. (right) Martin Turner carefully handles a LAC proportional counter

The Publications of the Astronomical Society of Japan ( 1989) includes 29 papers covering pulsar spin-down and QPOs to soft X-ray emission from Gamma Ray Burst sources. The strong collaborative aspect of the Ginga mission is seen in over half of those early papers having Japanese and UK co-authors. Later in the mission a personal highlight was in the detection of spectral features arising from scattering of X-rays off optically thick matter, providing a valuable new tool to study dense matter, such as in the accretion disc surrounding a super-massive black hole in AGN (Pounds et al. 1990; Nandra & Pounds 1994). The succeeding Japanese satellite, ASCA, obtained higher resolution spectra finding the accompanying fluorescent Fe K line to exhibit a broad red wing (Tanaka et al. 1995; Nandra et al. 1997), widely interpreted as a gravitational red shift and inspiring a major (and continuing) research effort to explore the effects of strong gravity in black hole accretion (e.g. Fabian et al. 2000).

## 8. ROSAT

UK ambitions during the 1970s to develop an imaging X-ray telescope failed to gain support. The opportunity to take part in a comparable German initiative, offered by BMFT within the ESA community in 1979, was therefore actively pursued, with a proposal from Leicester to provide an extreme ultraviolet telescope (based on a rocket-borne prototype with MIT) being accepted and endorsed by the SERC and BMFT in 1983. Details of the development of the WFC (figure 10), with a broader involvement of UK groups, is described by Courtier (1986). The Challenger accident in 1986 delayed the planned Shuttle launch, with a Delta rocket being substituted for the eventual launch in 1990.

The first months of the mission were devoted to all sky surveys in X-rays and the EUV, with much of the remaining six years in orbit allowing detailed pointings. The major scientific legacy of ROSAT is well documented (see accompanying paper by Joachim Trumper). The WFC operated well and obtained the first all sky survey in the EUV, the 2RE catalogue containing 479 sources (Pye et al. 1995). A

**Fig. 9.** (left) The UK Wide Field Camera which flew piggy back on ROSAT. (right) First EUV detection identified as a red dwarf - white dwarf binary system (from BBC Sky at Night)

particular memory is of the first detection of a significant EUV signal, temporarily named *meaty*, and achieving public exposure in a BBC broadcast of Sky at Night (figure 10).

## 9. Resume

When X-ray Astronomy began some 50 years ago the UK was well-positioned, behind only the USA. The Skylark and Ariel 5 programmes consolidated a growing scientific and technological reputation to ~ 1980, when funding cuts left UK researchers entirely dependent on international programmes. At the same time the onset of a lengthy gap in the previously dominant NASA X-ray astronomy programme meant that international collaboration became the way forward, with UK groups able to play a strong role in world-leading missions, EXOSAT, Ginga and ROSAT.

X-ray Astronomy in 2012, with 3 major international Observatories from NASA, ESA and JAXA, all in efficient deep space orbits and offering open access to the global community, is a scientific discipline truly come of age.

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