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Forty years on from Aerobee 150: a personal perspective

BY KEN POUNDS

University of Leicester

Introduction

Before the historic discovery (Giacconi *et al.* 1962) of a bright X-ray source in the constellation of Scorpius, in June 1962, the expectation of astronomers was that observations in the ultraviolet (UV) and gamma-ray bands offered the best promise for exploiting the exciting new potential of space research. In fact the forecast for X-ray studies was limited to the study of active stars, with fluxes scaled from that of the solar corona, the only known X-ray source at that time. Optimistic flux predictions ranged up to a thousand times the Sun’s X-ray luminosity, but seemed beyond the reach of detection with then-current technology. As a reflection of the contemporary thinking, the recently formed US National Aeronautics and Space Agency (NASA) were planning a series of Orbiting Astronomical Observatories, with the first missions devoted to UV astronomy. Despite those limited expectations a proposal from University College London (UCL) and University of Leicester groups, for simultaneous X-ray observations of the primary UV targets, was made in 1961, and eventually the instrument was flown on OAO-3 (Copernicus) 11 years later. In the USA, Riccardo Giacconi and Bruno Rossi had, still earlier, published the design of a grazing-incidence X-ray telescope with nested mirrors (Giacconi & Rossi 1960). Rossi, then at MIT, made a characteristically visionary statement around that time in declaring that ‘nature so often leaves the most daring imagination of man far behind’.

The Aerobee 150 sounding-rocket flight from the White Sands Missile Range in June 1962, which found in Sco X-1 a cosmic-X-ray source a million times more luminous than the Sun (and actually brighter than the non-flaring corona at a few keV), began a transformation that has led, over the intervening 40 years, to the most vibrant area of space science, and the foundations for a revolution in high-energy

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astrophysics. Looking back, it is interesting to recall that the discovery of the first cosmic-X-ray source did not become widely known for half a year, until the paper by Giacconi and his colleagues at American Science and Engineering (AS&E) was published in *Physics Review Letters* (Giacconi *et al.* 1962), a time-scale in sharp contrast with the immediacy of communicating results on a global scale today via the Internet.

The 1960s: solar physics and X-ray astronomy with sounding rockets

Progress in the remainder of the 1960s was rapid, with the emerging discipline of X-ray astronomy developed largely by physicists with a background in cosmic-ray studies or solar physics. Further sounding-rocket observations followed, by the US Naval Laboratory (NRL) group (responsible for still earlier but unsuccessful flights (Friedman 1959), confirming Sco X-1 and finding a further source in Taurus (Bowyer *et al.* 1964a)), the AS&E group (Gursky *et al.* 1963), and a team at Lockheed (Fisher & Meyerott 1964). As momentum in this new field built up, the NRL group identified extended X-ray emission from the Crab Nebula supernova remnant in a classic use of the Moon as an occulting disc (Bowyer *et al.* 1964b), and an accurate position for Sco X-1 led to its optical identification with a 13th-magnitude blue star (Sandage *et al.* 1966).

In the UK there was a rapid development of interest and activity, building on research already underway in studies of the solar X-ray emission, led by groups at the Culham Laboratory and Leicester University, and made possible by the availability of the competitive Skylark sounding rocket. Skylark, which evolved during the 1960s to be an excellent platform for space astronomy, with the ability to point at the Sun, the Moon or a star, was meanwhile being used to obtain the first good-quality X-ray images of the solar corona (Fig. 1.1; Russell & Pounds 1966) and high-resolution spectra (Evans *et al.* 1967). The first Skylark flights to search for cosmic-X-ray sources from the Southern Hemisphere were launched in 1967 (Cooke *et al.* 1967).

Solar X-ray studies remained at a much higher profile than cosmic-X-ray astronomy throughout the 1960s, with NASA's series of Orbiting Solar Observatory spacecraft leading the way. The first international space science satellite, Ariel 1 (Fig. 1.2), including a UCL/Leicester proportional-counter spectrometer to measure the X-ray emission from the solar corona, was successfully placed in orbit on a Thor Delta from Cape Canaveral on 26 April 1962. That was just two months before the historic Aerobee 150 rocket flight and brought about a first (unplanned) link with future colleagues at AS&E.

All went well with Ariel 1 for several weeks post launch and it yielded X-ray spectra of both the quiet and the flaring corona (Bowen *et al.* 1964). Then, on 9 July

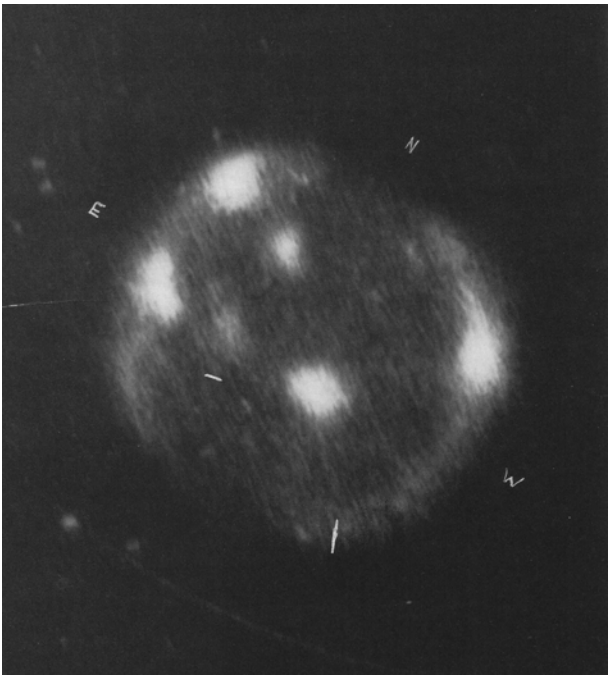


Figure 1.1. Early X-ray image of the solar corona.

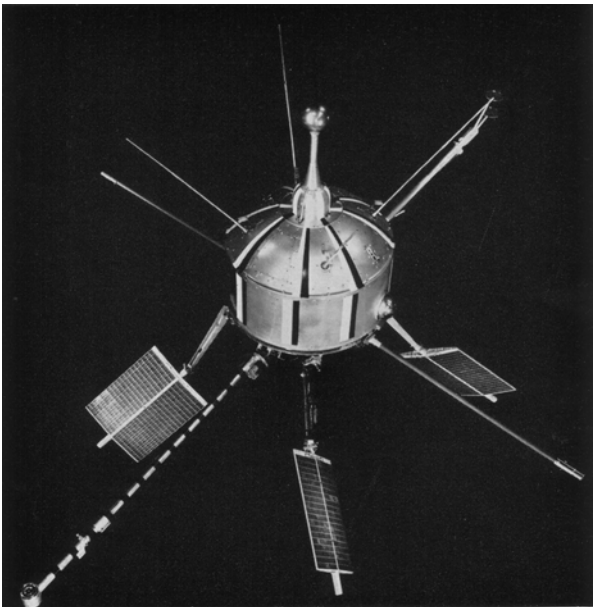


Figure 1.2. The Ariel-1 satellite.

1962, the US Air Force chose to detonate a nuclear bomb in the atmosphere 400 km above Johnston Island in the Pacific. The explosion put radioactive debris, which was to take many months to decay, into the atmosphere. The ‘artificial radiation belts’ induced spectacular count rates in several of the Ariel 5 instruments, and were a bonus for that part of the mission. Sadly, my proportional counters used methane quench gas, which was broken down by the extreme count rates to form a polymerized deposit on the anode wires, leading to a rapid loss of ‘gain’ and sensitivity. (Only 30 years later did I learn from Herb Gursky of Riccardo Giacconi’s complicity in the destruction of my first in-orbit instrument, as senior AS&E staff were present at Johnston Island to support their weapons-testing contract!)

Looking back now at those early days in space astronomy, the pace of development was remarkable. On the big stage, of course, the Apollo programme dominated attention. However, space science was also hectic, with many satellites being launched in the USA and the USSR. The UCL/Leicester solar studies developed apace, with an evolution of the Ariel 1 spectrometer flown successfully on OSO-D in 1967 (Culhane *et al.* 1969), and on Europe’s first orbiting satellite, ESRO-2 (1968). A continuous sequence of X-ray images of the corona was provided by an imaging instrument orbited on OSO-F from 1969 (Parkinson & Pounds 1971) and was published routinely in *Solar-Geophysical Data* to 1975. Within the UK national programme the frequency of Skylark launches from Woomera peaked at 20 in 1965, with a remarkable 198 flights between 1957 and 1978 (Massey & Robins 1986).

Skylark (Fig. 1.3) provided the means for the first X-ray surveys of the sky in the Southern Hemisphere from 1967 (Cooke & Pounds 1971). As the global number



Figure 1.3. Skylark cosmic-X-ray payload.

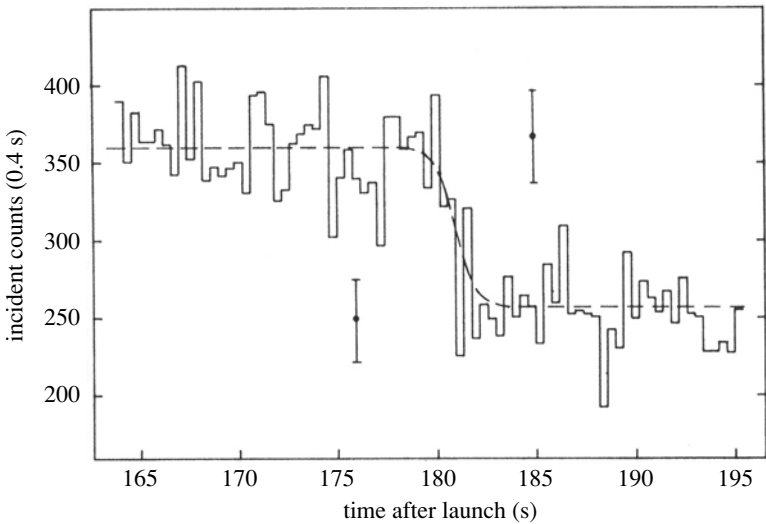


Figure 1.4. X-ray flux from GX3+1 cut off by lunar occultation.

of X-ray sources grew well into double figures, a continuing challenge was their optical identification. In some cases, the typical few-tenths-of-a-degree accuracy of X-ray source location was sufficient for a reliable association with an outstanding candidate, e.g. the bright quasar 3C 273, but ingenious techniques were developed to obtain much more precise positions for other sources (Oda *et al.* 1965).

Occasionally there were disappointments, as in the technically successful Leicester flight of a variable-length modulation collimator intended to better locate and identify the bright source Cen X-3, only for it to have disappeared! An explanation came later when Uhuru observations showed Cen X-3 to be an eclipsing binary in which the X-ray source is occulted by its companion star for a quarter of each two-day binary period.

Another heroic source-identification attempt involved two Skylark launches, in September and October 1972, to locate the source GX3+1 with arc-second precision, in order to identify an optical counterpart within the crowded sky close to the centre of our Milky Way galaxy. The idea was to observe the *c.* 2 arcmin SAS-3 error box of GX3+1 as it was being occulted by the Moon.

Given a predicted in-flight rate of *c.* 0.5 arcsec s⁻¹ for the Moon’s disc to travel across the star field, the launch window was less than one minute wide. The first firing, of SL 1002, went perfectly, the Sun-pointing rocket being held in the predetermined roll direction by locking X-ray detectors onto Sco X-1, placing the Moon in the field of view of the main X-ray detectors 96 s post launch.

The occultation of GX3+1 was successfully recorded to ± 0.5 s, or ± 0.3 arcsec (Fig. 1.4). A second Skylark flight one lunar month later was also successful, though the reduced sensitivity allowed by the use of an unstabilized (spinning)

Table 1.1. *Standard deviations of the limb positions*

experiment	timing and rocket position	lunar ephemeris	combined error
Leicester	0.2''	0.3''	0.4''
UCL/MSSL	3.4''	0.3''	3.4''

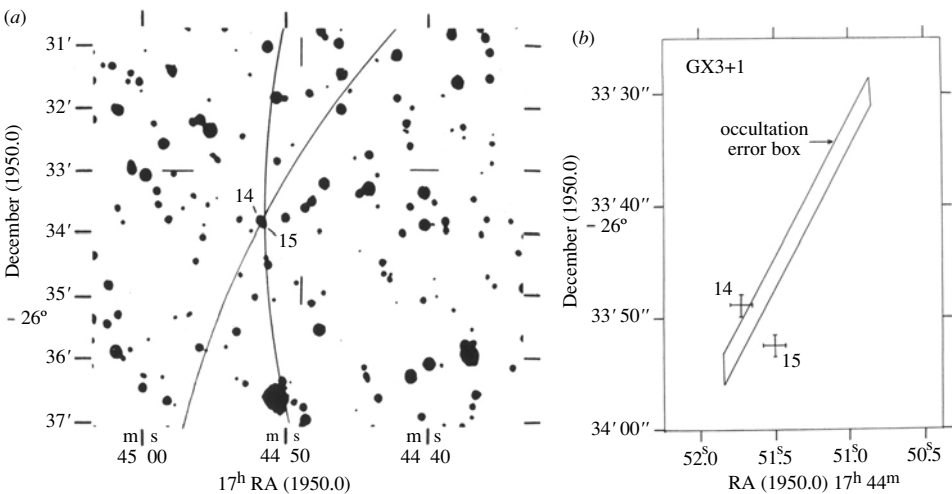


Figure 1.5. (a) Lunar arcs at occultation and (b) the GX3+1 error box.

rocket yielded a lower positional accuracy. Overall, the X-ray position of GX3+1 was determined (Janes *et al.* 1972) with a precision (Fig. 1.5 and Table 1.1) that was unchallenged until the launch of Chandra. Sadly, due to the large obscuration in the Galactic Bulge region, no optical counterpart was found in the GX3+1 error box to a limit of 21st magnitude.

Those combined Skylark launches were typical of the technical ingenuity and uncertain scientific returns which made the first decade of X-ray astronomy with sounding rockets both an exciting and an educational experience.

The second decade: the era of small dedicated satellites

X-ray astronomy enjoyed a major advance during the 1970s, with the first small orbiting satellites dedicated to observations of cosmic-X-ray sources. Uhuru led the way in December 1970, placing an array of proportional counters (effective area 840 cm²) into a circular equatorial orbit. Within a few months the extended observations made possible from orbit had shown that many X-ray sources were

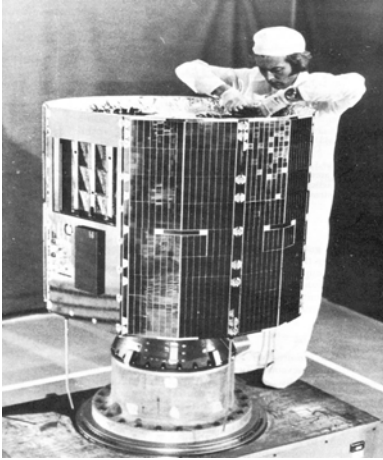


Figure 1.6. The Ariel 5 satellite.

variable. This led to the historic discovery that many of the most luminous galactic sources were in binary star systems. The equally dramatic discovery of extended X-ray emission from galaxy clusters followed, while the number of known X-ray sources multiplied. The 3U catalogue (Giacconi *et al.* 1974), listing 161 sources, was an important milestone in the development of X-ray astronomy, and the major scientific impact of Uhuru is well recorded in Giacconi & Gursky (1974).

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 with secondary X-ray instrumentation.

For astronomers in the UK, Ariel 5 (Fig. 1.6) brought an ideal opportunity to play a part in the rapid advances taking place. Like Uhuru, Ariel 5 was launched on a Scout rocket into a circular near-Earth orbit from a disused oil platform off the coast of Kenya. It carried six experiments, including a Sky Survey Instrument (SSI), similar to that on Uhuru, an All Sky Monitor from Goddard Space Flight Center (GSFC) and three X-ray spectrometers viewing along the satellite spin axis. The Ariel 5 orbit was a good choice, not only in minimizing background due to cosmic rays and trapped radiation, but in allowing regular data dumps from the small on-board data recorder. With a direct microwave, cable and satellite link to the UK (Fig. 1.7), we received six orbits of ‘quick look’ data within an hour of ground-station contact. The remaining ‘bulk’ data were received within 24 hours, an immediacy that contributed substantially to the excitement of the mission operations, while also ensuring a rapid response to new discoveries.

One such discovery was particularly well timed, with the SSI detecting a previously unseen source in the constellation Monoceros just two days before the start of



Figure 1.7. Ariel 5 data link to UK.

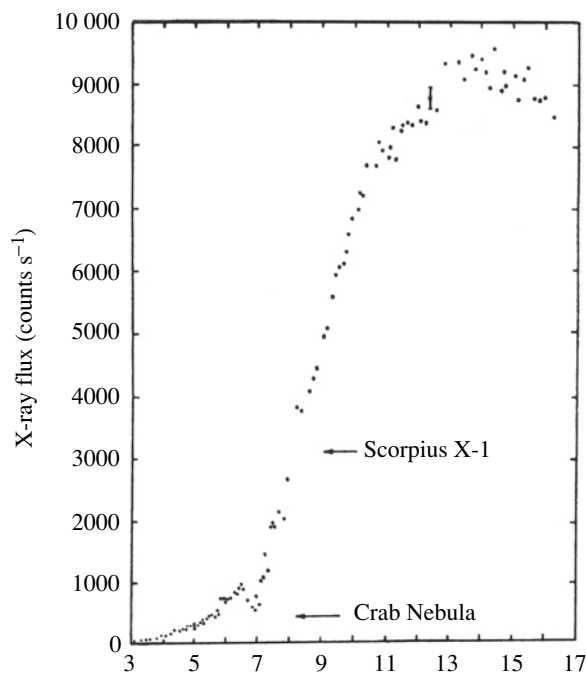


Figure 1.8. Ariel 5’s SSI discovery of A0620-00.

the first European Astronomy Society (EAS) meeting in August 1975 in Leicester, where new X-ray results from the on-going satellite missions were high on the agenda. Variable X-ray sources were by then commonplace, but what set Mon X-1 apart was its strength. By day two of the EAS meeting it was brighter than the Crab Nebula, while two days later it outshone Sco X-1 (Fig. 1.8) to become, for a few

weeks, the brightest cosmic-X-ray source seen (Elvis *et al.* 1975), a record still held today. After peaking at a flux level three times that of Sco X-1, the new source (by then renamed A0620-00) was being monitored by Ariel 5, SAS-3 and other space- and ground-based telescopes around the world (Fig. 1.9(a)) as it gradually faded from view (Kaluzienski *et al.* 1975).

Optical and radio counterparts were quickly identified and spectroscopy of the binary companion (Fig. 1.9(b)) later revealed a mass estimate for the compact X-ray-emitting component in A0620-00 to be a strong black-hole candidate (McClintock & Remillard 1986).

Soft X-ray transients became relatively common as the Ariel 5 mission continued until the satellite's attitude-control gas ran out, ending observations in 1980. A number of other discoveries had by then marked Ariel 5 as a highly successful mission. One was the detection of X-ray line emission from the Perseus Cluster galaxies (Fig. 1.10), showing that the luminous diffuse radiation was of thermal origin at $c. 10^8$ K (Mitchell *et al.* 1976).

Another important and enduring result from the Ariel 5 SSI was to establish powerful X-ray emission (alongside the bright optical nucleus and broad permitted lines) as a characteristic property of Seyfert galaxies (Fig. 1.11). The challenge of correctly identifying many previously unidentified sources, individually located to only a few tenths of a square degree, was possible only because Seyfert nuclei are also unusually bright in the optical band; even so, the initial identifications were made on a statistical basis, but held up well as new data emerged to establish Seyfert galaxies and active galactic nuclei (AGN) in general as the dominant class of extragalactic X-ray source (Elvis *et al.* 1978). In recalling the scientific contributions of Ariel 5, in an introduction to this book, based on the Royal Society Discussion Meeting, it is interesting to note that the (only) previous meeting in the same series, held 24 years ago, was largely devoted to results from Ariel 5 (Massey *et al.* 1979).

Beyond 1980: X-ray astronomy becomes a global enterprise

Notwithstanding the contributions of Ariel 5, Hakucho and ANS (the last especially for the discovery of X-ray burst sources), the US programme continued to set the pace in X-ray astronomy with two large spacecraft, HEAO-1 (a sky-survey mission from NRL and GSFC) and HEAO-2 (the Einstein Observatory), being launched in 1978. The Einstein Observatory, again led by Giacconi's team, then at the Harvard-Smithsonian Center for Astrophysics, marked another milestone in the development of X-ray astronomy, being the first imaging telescope devoted to the study of cosmic-X-ray sources, and bringing X-ray astronomy close to optical and radio astronomies as a major branch of observational astrophysics. Among many advances brought by

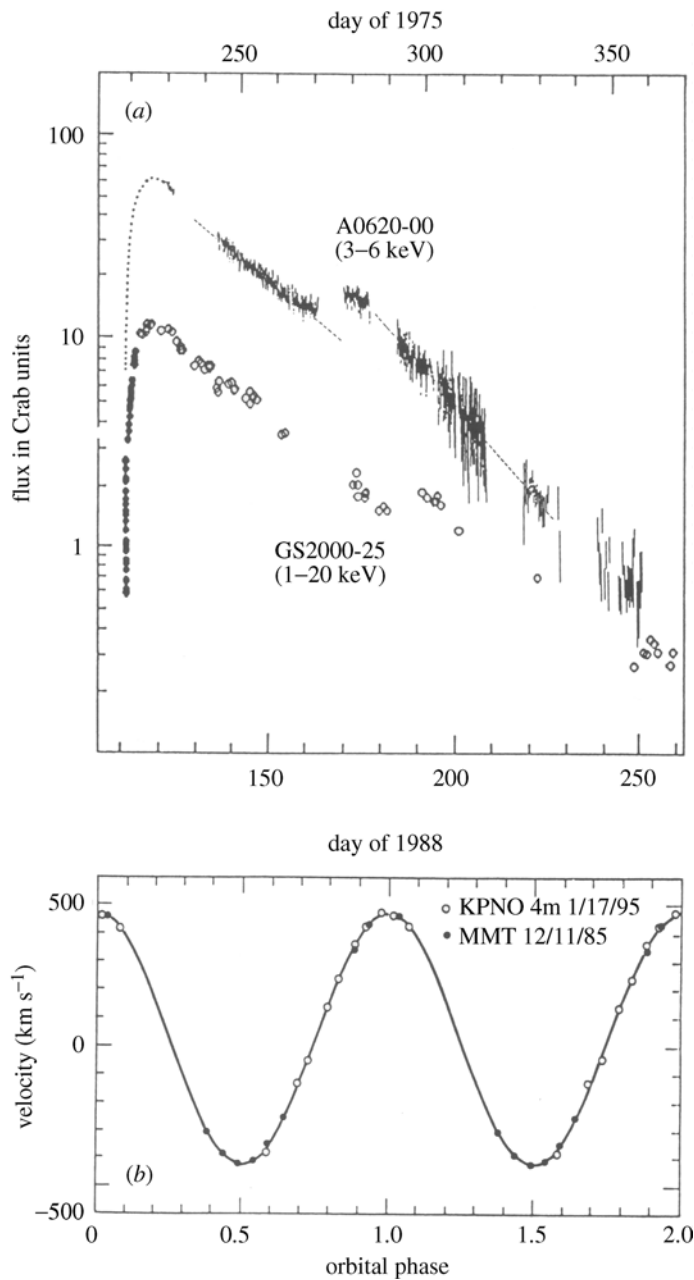


Figure 1.9. (a) Contemporary X-ray light curves of A0620-00 (in 1975) and GS2000-25 (in 1988). (b) Optical radial velocity curve of the companion to A0620-00.