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Excerpt
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Chapter 1

Birth and childhood of X-ray astronomy

1.1 The discovery of X-rays

On the second story of the building at Röntenring 8 in Würzburg, Germany, there is a plaque: 'In diesem Hause entdekte W. C. Röntgen im Jahre 1895 die nach ihm benannten Strahlen' – In this building, in the year 1895, W. C. Röntgen discovered the radiation named for him. Here was the laboratory of Wilhelm C. Röntgen, a 50-year-old professor of physics, who was studying phenomena associated with electrical discharge in gasses. On the afternoon of 8 November, working alone in his laboratory, he noticed a curious phenomenon. When high voltage was applied to the electrodes in the partially evacuated glass discharge tube, he noticed a faint glow from a fluorescent screen placed at the other end of the laboratory table. The room was dark and he had previously covered the tube with black cardboard so no light would escape. Why was the screen glowing?

That evening he verified that the discharge tube was indeed the source of the energy that caused the screen to glow, and that no visible radiation was escaping from the shrouded tube. He quickly found that the unknown radiation would pass through paper, wood, and aluminum but was stopped by heavy metals. Then, when holding a lead disc in front of the screen to observe its shadow, Röntgen also saw the shadow of bones in his hand! In a week he had measured the basic characteristics of this new form of radiation. He persuaded his wife, Bertha, to hold her hand steadily over a photographic plate for 15 minutes, making a picture showing hand and finger bones as grey shadows and the shadow of her ring sharp and black. He sent this picture and a description of his results to be published and to other scientists. He called these new rays 'X-rays' but others called them 'Röntgenstrahlung' – Röntgen radiation. The medical applications were immediately obvious and commercial X-ray machines were soon available.

The discovery of X-rays is one of the most famous serendipitous discoveries of science (Colour Plate 4). If Röntgen had been funded to investigate ways to help doctors in hospitals set broken bones, it is unlikely that he would have pursued this line of research.

In 1901, Röntgen was awarded the first Nobel Prize in physics. In 1990, a German satellite devoted to X-ray astronomy was placed in orbit and operated for 10 years. The satellite was named ROSAT (for Röntgen Satellite) and was taking data on the 100th anniversary of Röntgen's discovery. In 2002, Riccardo Giacconi was awarded the Nobel Prize in physics for pioneering work in X-ray astronomy. The authors of this book have had the pleasure of knowing Riccardo and, years ago, of observing the source he discovered, Sco X-1. Now, 115 years after Röntgen's discovery, we are finishing the initial period of exploration, and X-ray astronomy has become part of the general field of astronomy. Like traditional optical astronomers, we work with telescopes that record hundreds of sources in each field. It is still fun.

1.2 Properties of X-rays

We know now that X-rays are a form of electromagnetic radiation, like visible light, but the individual quanta of radiation, the photons, have energies a thousand times that of optical photons. Visible light, in general, does not penetrate matter. The photons are scattered from or absorbed at the surface of opaque objects. Visible light will also pass through transparent substances and will reflect from smooth surfaces. X-rays, on the other hand, go right through the surfaces of all substances. The individual photons, traveling in straight lines, either interact with individual atoms or pass through unaffected. The probability of interaction increases with Z, the atomic number of the element. Thus, in Röntgen's picture of Bertha's hand, the X-rays passed easily through the carbon ($Z = 6$) and oxygen ($Z = 8$) of flesh, but many photons were absorbed by the calcium ($Z = 20$) of bones, and all were absorbed by the gold ($Z = 79$) ring that was on her finger. The probability of interaction also depends on photon energy. More energetic photons are less likely to be absorbed.

X-rays are usually generated by accelerating an electron beam with high voltage and directing the beam to strike a tungsten target. The energy of the X-ray photons is measured in kilo-electron volts (keV), the voltage used to accelerate the electrons. A potential of 100 000 volts, for example, is capable of producing 100 keV X-rays.

1.3 The difficulties of observing X-rays from stars

Röntgen's X-rays had energies of 30–50 keV, about the same energy as X-rays used today for medical diagnostics. Astronomical X-rays are much less energetic and more easily absorbed. Most X-rays from cosmic sources cannot penetrate even the thin outer layers of the Earth's atmosphere. It is thus impossible to observe X-rays from astronomical sources with ground-based instruments. Even from mountain tops, airplanes, and simple balloons, attempted observations are hopeless. Hence, observing from above the atmosphere is essential in this field. To see any X-rays at all, it is necessary to be above 99 per cent of the atmosphere, and to detect X-rays in the band where sources are most prominent, all but one millionth of the atmosphere must be below the instrument.

Cosmic X-ray sources are most clearly detected in the range of 0.5–5 keV in photon energy (or wavelength of 25–2.5 Å). By earthly standards, these X-rays are 'soft' and easily stopped by a small amount of material. For example, three sheets of paper or 10 cm of air at one atmosphere pressure will stop 90 per cent of 3 keV X-rays. The higher the energy, however, the more penetrating, or harder, the X-rays. A rocket is needed to observe 3 keV X-rays, which cannot be seen at altitudes below 80 km, whereas 30 keV photons will penetrate to 35 km altitude, which can be reached by the highest-flying balloons. The instrument should be above 200 km to observe X-rays with energies below 1 keV in a direction parallel to the Earth's surface, as would be desirable in a survey. A few cosmic sources emit hard X-rays and have been observed with balloons but almost all work is now done with satellite-borne instruments.

It was not a trivial matter to build the first instruments that were large enough to be sensitive yet small enough to fit within a rocket or balloon payload. The instruments not only had to withstand the rigours of launch but also had to operate in a vacuum or near vacuum. Time and trial and error were needed to develop the first survey instruments. To detect, for the first time, a phenomenon that many people believed impossible, took confidence that the instruments were operating properly. Much of the early work was done by nuclear physicists, who were familiar with the type of detectors used to register the X-rays.

Because X-rays are a form of electromagnetic radiation like visible light, they can be produced by the same processes. Because the photon energies are 1000 times greater than that of optical photons, the process must be correspondingly more energetic to produce X-rays. So, if X-rays are generated in a thermal process, the temperature must be of the order of 1000 times greater than that in places where light is produced. Thus, a search for cosmic X-ray sources is a search for material at temperatures of millions of degrees, in contrast to the familiar stars with surface temperatures of thousands of degrees. Until 1962, very few astronomers believed that the Universe contained objects capable of generating detectable amounts of high energy radiation and little was expected from the first observations.

These ideas changed dramatically in the early 1960s with the discovery that there were indeed many discrete, powerful sources of astronomical X-rays. Some produce X-rays by processes unimagined until the observations forced people to consider new kinds of cosmic objects and new methods of energy production.

1.4 Electromagnetic radiation and the atmosphere

It is not an accident that our eyes operate in the narrow waveband 4000–8000 Å. Not only is a large fraction of the energy of the Sun radiated in this band but the Earth's atmosphere is almost transparent throughout this 4000 Å-wide waveband. Figure 1.1 shows the electromagnetic spectrum from radio waves to gamma-rays and depicts the depth to which each frequency can

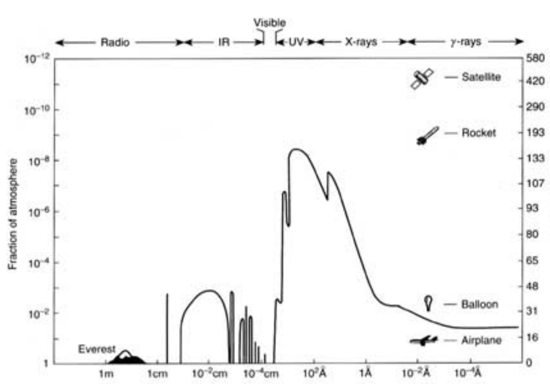

Fig 1.1 Transmission of electromagnetic radiation by the atmosphere. The solid line shows the altitude by which half the radiation from space has been attenuated. Just below this line virtually all the radiation is absorbed. Only radio, optical, and some narrow bands of infrared radiation can reach the Earth's surface. High energy γ-rays can be observed using balloons, but rockets or satellites are necessary for X-ray or UV detection.

Table 1.1 Atmospheric transmission of X-rays.

altitude (km)	energy (keV)	transmission, source overhead	transmission, source 90° from vertical
40	20	0.15	0.00
40	30	0.64	0.00
150	1	0.98	0.64
200	0.2	0.99	0.82

penetrate the atmosphere. Over twelve decades of the spectrum, from gamma-rays to the far infrared (FIR), there is only a very narrow band of radiation that reaches the Earth's surface essentially unscathed. The 'opacity' (potential to absorb) of the atmosphere is the principal difficulty facing astronomers wishing to study radiation from the stars at wavelengths outside the visible band. Until this century, the visible part of the spectrum was all that was available for study of the heavens. Only radio astronomy was able to develop at all using ground-based instrumentation, although it is now possible to undertake infrared observations from high altitude observatories through some windows less affected by water vapor.

Figure 1.1 shows the height above sea level to which radiation of each wavelength can penetrate. All radiation from the extreme ultraviolet (UV) (at 1000 Å) to X-rays to high-energy γ-rays (at 10^{-4} Å) fails to penetrate below an altitude of $\sim$30 km. It is the requirement of observing above the atmosphere that makes the study of the X-ray Universe a modern one. At 40 km altitude, typical for balloon flights, the atmospheric transmission of 30 keV X-rays from a source directly overhead will be $\approx$60 per cent. If the source is 60° from the vertical, transmission is $\approx$36 per cent. A source 90° from the vertical cannot be detected. (This direction is the 'horizon' on Earth's surface but, at high altitude, the actual horizon can be well below this direction.) Table 1.1 gives transmissions for other altitudes and energies. It shows that 20 keV is about the low energy limit of balloon-borne detectors and that a rocket has to be above $\sim$150 km to perform a useful scan. At 200 km, the transmission of even the softest X-rays is high. Because

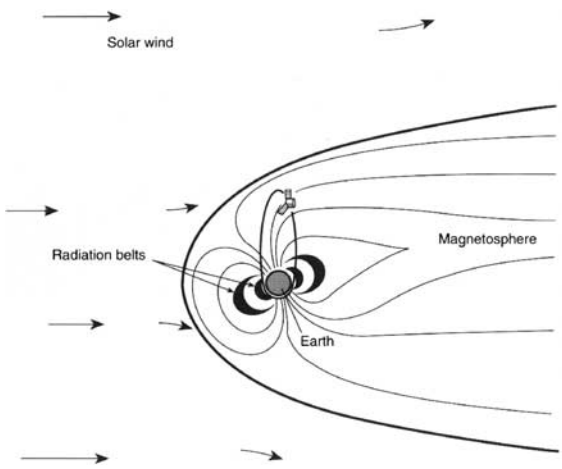

Fig 1.2 Earth and its magnetosphere. Magnetic field lines are connected to the Earth's poles and confined inside the bow shock, which is usually ~12 Earth radii distant in the solar direction. The inner and outer radiation belts are shaded. A spacecraft in the eccentric orbit shown spends most of its time above the intense zones of trapped particles but is always within the magnetosphere.

satellites operate at higher altitudes to avoid atmospheric drag, atmospheric attenuation does not limit satellite X-ray surveys.

1.5 The environment in space

Two restrictions govern orbits selected for X-ray observatories: (i) although soft cosmic X-rays can be detected at altitudes above 150 km (reached easily by rocket), a satellite in a circular orbit must have an altitude greater than 400 km or the drag of the tenuous upper atmosphere will soon lead to a fiery re-entry and (ii) because X-ray detectors are sensitive to energetic charged particles, observations are best done where particle fluxes (and detector backgrounds) are at a minimum.

Figure 1.2 shows (not to scale) the space environment in the vicinity of Earth. Inside the parabolic magnetopause, space is dominated by Earth's magnetic field. Outside, energy from the Sun, in the form of solar wind, magnetic field, and energetic particles, governs conditions. A bow shock forms just outside the magnetopause. The solar side of the magnetosphere boundary is normally 10–12 $R_\oplus$ (Earth radii) distant but can be pushed closer by solar activity. At a lower altitude, Earth is girdled by the pitted-olive shaped Van Allen radiation belts. Here, protons and electrons trapped in the Earth's magnetic field have both high energy and long lifetimes. The best orbits for observation minimise time spent in these zones, which extend from ~0.2–5 $R_\oplus$. Indeed, detectors must be powered off so as to prevent damage when in the heart of the belts.

A near-Earth equatorial orbit with altitude ≈500 km is below the belts except for a region over the South Atlantic Ocean where Earth's field is weak and trapped particles dip to lower altitudes. Earth's field keeps solar particles from this equatorial region and reduces the flux of cosmic rays. In addition, the solid Earth stops half the high-energy cosmic rays that penetrate the magnetic field. The consequent low background is an advantage, but in a near-Earth orbit, only half the sky is visible at any one time. Except for targets near the poles of the orbit, this means that the observations will be repeatedly interrupted for a large part of every ≈100-min orbital period. (This is exactly what happens with the Hubble Space Telescope.) Also, all detectors have to be turned off when passing through the South Atlantic Anomaly where charged particle flux is high. This causes another interruption on many orbits. Near-Earth polar orbits have also been used, usually because of launch site or data-receiving station locations. In these orbits, particle-induced backgrounds are low at low latitudes but high in polar regions due to precipitating solar and auroral particles.

A highly eccentric elliptical orbit will allow the spacecraft to spend almost all of the time well above the Van Allen zones. If beyond the magnetosphere, however, there is no protection from solar particles of all energies and background rates can be high after solar flares. Indeed, exceptionally large flares on the Sun can inject a huge number of energetic particles out into the Solar System. These affect the Earth by causing telecommunication problems and also spectacular auroral displays at high latitudes. Such a large flare can sometimes result in the need to turn spacecraft instruments off for several days, whereas within the magnetosphere, some shielding is provided from solar particle events. No orbit is free from transient solar particle fluxes and spacecraft operators must be vigilant to avoid damage to the sensitive detectors.

1.6 The early years (1946–1962)

The first technology useful for research above the atmosphere was that of the V2 rockets available after World War II. With these, the U.S. Naval Research Laboratory (NRL), under the direction of Herbert Friedman, was able to reveal the Sun as a powerful source of UV and X-radiation. Perversely, this discovery actually caused many scientists to lose interest in the search for other sources of X-rays, as they realised that the Sun appears as a bright source only because it is extremely close to us. A calculation of the intensity of radiation expected at the Earth from the nearest stars (assuming that they are comparable emitters of X-rays to the Sun) showed that the instrumentation available in 1960 would have had to be about a factor of 10^5 more sensitive to detect such objects. Worse still, if the stars were more distant, at a typical distance of 1 kiloparsec (kpc) or about 3000 light years, then a 1960 observation would only have been capable of discovering a process which was producing 10^{11} times the X-ray luminosity of our Sun.

Most of the rocket observations of the 1950s were devoted to more detailed studies of the Sun, although the NRL group did search (without success) for other cosmic sources. Even so, several groups kept working to develop more sensitive instruments. In the end, it was a group at American Science and Engineering (AS&E), led by Riccardo Giacconi, that was successful in the first detection of a powerful cosmic source of X-radiation.

1.7 Sco X-1

The official purpose of the AS&E experiment was to search for X-rays from the Moon, which were expected to be produced by the energetic solar wind particles striking the lunar surface, with perhaps some fluorescence from solar X-rays. A positive result would provide valuable information about the nature of the lunar surface; an area receiving much publicity and support at the time with America's commitment to a manned lunar landing within the decade. In addition, it was planned to scan a large region of sky in a search for non-solar sources of X-radiation. The first launch of this new instrument took place in October 1961. The rocket launch was perfect but the doors, designed to protect the X-ray detectors during launch and passage through the atmosphere, failed to open! In the early days, equipment was simple but often unreliable.

The second launch of the AS&E instrument, on a new Aerobee rocket, took place from White Sands, New Mexico, on 18 June 1962 and this time the doors functioned perfectly. Two of the three X-ray Geiger counters worked well and, although they failed to detect any X- rays from the Moon's surface, they made the first detection of a powerful cosmic X-ray source (Giacconi, Gursky & Paolini, 1962). This source subsequently became known as Sco X-1, the first-discovered source in the constellation Scorpius. As Richard Hirsch (1983, p. 46) comments in his history of X-ray astronomy, 'Observing Sco X-1 was the reward nature offered to scientists willing to gamble on a long shot'.

Interpretation of the data was not straightforward. With this detector, precipitating electrons could produce a signal similar to that of an X-ray source. By realising that the observed signal of 100 photons cm^{-2} s^{-1} was indeed caused by an extrasolar X-ray source, Giacconi and colleagues captured the interest of the astronomical community and started an exploration that has uncovered some truly remarkable objects.

The unusual nature of Sco X-1 was clear as soon as it had been roughly located. Figures 1.3 and 1.4 contrast the X-ray and optical appearance of Sco X-1. The source dominates an early rocket X-ray survey. An optical picture, however, containing Sco X-1 shows nothing unusual whatsoever. Until an accurate location of the X-ray source was obtained (Gursky *et al.*, 1966), astronomers had not a clue as to the nature of this source. Sco X-1 is an object which stands out like a beacon to a small X-ray detector but is visually four hundred times fainter than the faintest star that can be seen with the naked eye. In every square degree of

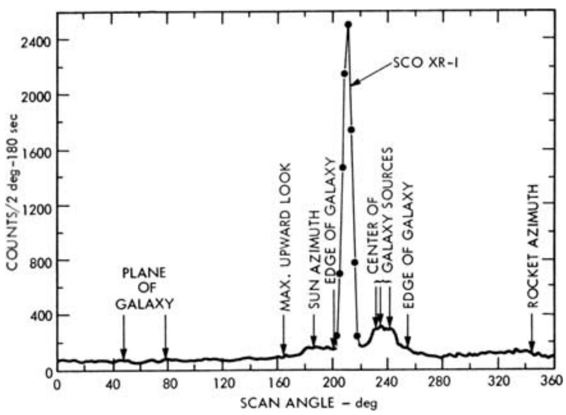

Fig 1.3 Three minutes of data from a rocket-borne X-ray detector flown in October 1967. This shows the counting rate of the detector as it scanned a great circle containing the source Sco X-1 and a cluster of sources in the direction of the galactic centre. The detector field of view was 5° by 30°. The Sun was below the horizon. The signal from Sco X-1 is very strong. (from Hill *et al.*, 1968).

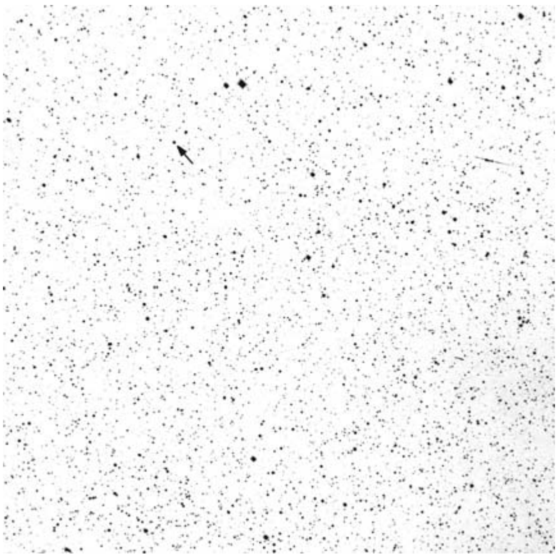

Fig 1.4 One square degree of the sky from the Palomar Sky Survey. The 13th magnitude star indicated with an arrow is the optical counterpart of Sco X-1.

the sky there are about one hundred stars visually brighter than Sco X-1.

1.8 An early history of the X-ray sky

After the discovery of Sco X-1, X-ray astronomy progressed rapidly. Evidence for two weaker sources was found on 12 October 1962 by the AS&E group (Gursky *et al.*, 1963). The NRL group confirmed and located one of these sources on 29 April 1963 using a rocket-borne detector (Bowyer *et al.*, 1964). It was identified right away as the Crab Nebula, a well-known young supernova remnant in our galaxy, and high energy X-rays from this source were detected on 21 July 1964 by George Clark (1965) of the Massachusetts Institute of Technology (MIT). (This was the first detection of high energy radiation from an extrasolar source with a balloon-borne detector.)

Astronomers were thus forced to recognise that there were many objects at stellar distances which were strong, unbelievably strong, sources of high energy photons. Small areas of the sky were then explored with great enthusiasm using rockets and balloons. The 'big picture' was not revealed until the first survey with the Uhuru satellite, launched on 12 December 1970.

The nature of the X-ray sources and the manner in which energy was generated was not obvious. It was first necessary to obtain precise locations of X-ray sources, leading to identification with optical or radio objects. The next steps were to measure the X-ray spectra and light curves to determine the emission mechanism.

Some of the brighter sources in our Galaxy radiate 10 000 times as much energy as does the Sun across all wavelengths. Almost all (99.9%) of this energy appears as X-rays. Sco X-1 is such a source. The optical counterpart is a 13th magnitude star, invisible to the naked eye and even to small telescopes. The only visual clues to its unusual nature are a blue-violet colour and an irregular variability marked by occasional rapid flickering. No optical surveys previous to the X-ray detection had indicated anything unusual. Even after the optical counterpart had been identified, the Sco X-1 system was not understood.

A convincing explanation of its nature was not found until 1971 when Uhuru discovered and measured the peculiar X-ray variation of another source that lies in the southern sky in the constellation Centaurus. This source, Cen X-3 (or 4U1118-60), is an X-ray-bright object at a declination of −60°. Although bright enough to be detected by a rocket-borne instrument, it was below the horizon for sounding rockets launched from the main U.S. facility at White Sands. It was clearly accessible, however, to those using launchers in Hawaii and Australia.

In 1967–1968, two groups surveyed the southern sky. A group from Lawrence Livermore Laboratory (LLL) detected Cen X-3 twice and derived a rough location (Chodil *et al.*, 1967). Figure 1.5 shows data from one of these flights. However, a group from Leicester observed twice and did not see it (Cooke & Pounds, 1971).

In the late 1960s it was no easy task to build detectors, calibrate them, ensure that they survived the quick but hazardous trip into space, and know where they were pointed. People took pride in their ability to distinguish real sources from the background and expected the source population to be more or less steady, like the stars. In the case of Cen X-3, both groups secretly suspected that the other had not interpreted the data properly. In truth, all these observations were carefully done and correctly interpreted. The source is highly variable. To a small detector, sometimes it appears above background and sometimes not. Furthermore, such variability is a common characteristic of most bright X-ray sources. It took a while for people to believe this.

The Uhuru observations of Cen X-3, made in 1971, were spectacular (Giacconi *et al.*, 1971; Schreier *et al.*, 1972). The X-ray observations alone determined the nature of the source.

The first surprise was the observation of a regular periodicity of 4.84 seconds in X-ray flux from Cen X-3. The modulation was high and the pulsations were easily seen during a single scan across the source. Only a rotating neutron star could produce such rapid pulsations. The period was measured accurately and it was soon discovered that the period varied slightly with time. After several days of data were collected, these variations were recognised as a Doppler shift. The neutron star was moving in a circular orbit with a period of only 2.09 days. As icing on the cake, the X-rays were observed to disappear completely for 11 hours at regular 2.09 day intervals. The source was in an eclipsing binary system.

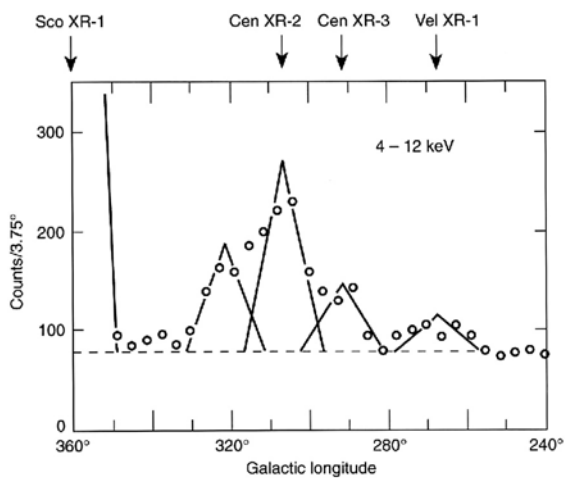

Fig 1.5 Counting rate from a rocket-borne proportional counter flown in May 1967. A slat collimator restricted the field of view to be 10° x 30°. The spinning payload caused the detector to scan a band of the sky repeatedly. By comparing the observed count rate with the expected triangular response to a point source, sources could be located. Sco X-1 was very bright and is off scale at 360°. The next strongest source at this time was Cen X-2, a transient. The source Cen X-3 was first seen in the data shown here. Note the difficulty of determining source positions in crowded regions (from Chodil *et al.*, 1967).

Here then was a rapidly spinning neutron star, probably emitting X-rays from the near-vicinity of one of its magnetic poles. It orbits a bright B0Ib star, Krzeminski's star (named after the person who identified the optical counterpart). Energy to power the X-ray source comes through accretion of material supplied by the supergiant companion. This matter is captured by the strong gravitational field of the neutron star. It acquires enough energy in the fall to the surface to both heat material to the high temperature required for X-ray emission and to supply the observed luminosity (see Chapter 11).

The other bright X-ray sources in the plane of our Galaxy were first detected in early rocket surveys (e.g. Figures 1.5 and 1.6). Most were found by groups at Lockheed (Fisher *et al.*, 1968), MIT (Bradt *et al.*, 1968) and NRL (Friedman *et al.*, 1967). The sources are mostly accretion-powered binaries, in which a normal star and a compact star are locked in a close orbit. Some, like Cen X-3,

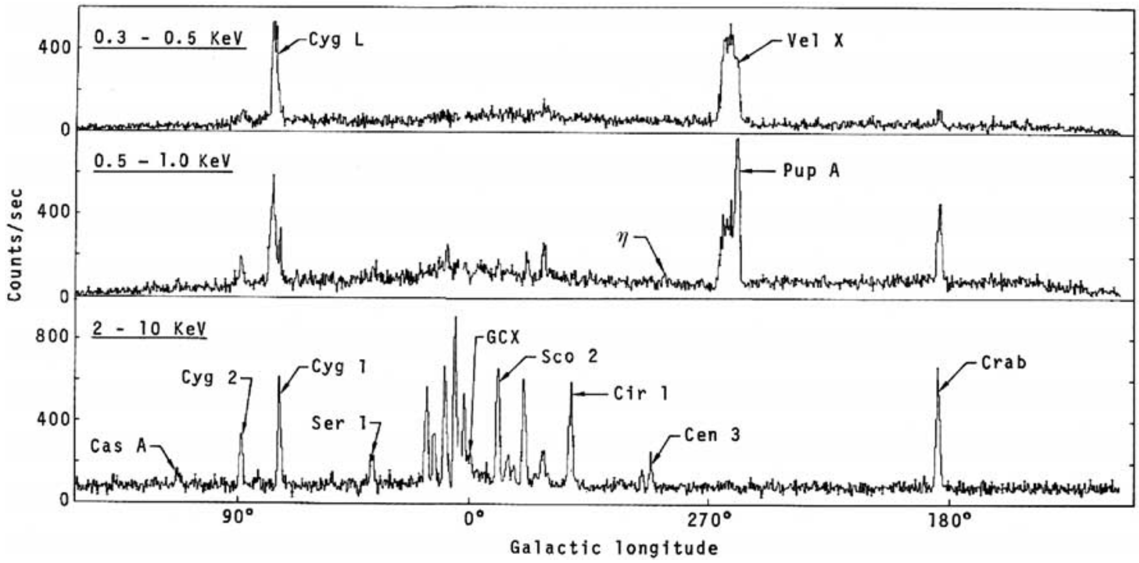

Fig 1.6 The entire Milky Way as surveyed with rocket-borne proportional counters in May 1970, May 1971, and October 1972 (Seward *et al*., 1972). Collimation was 1.3° × 20°. Data from the three flights have been combined to show counting rate as a function of galactic longitude in three energy bands. There are no soft X-rays observed from the cluster of bright sources around the galactic centre. Intervening gas absorbs the soft X-rays. The nearby supernova remnant Vela XYZ is clearly soft and extended. These data were taken using the payload shown in Colour Plate 1, which was recovered and refurbished after each flight (figure available from FDS).

consist of a neutron star and a bright O star. The optical identifications of these were quickly made. Because the O stars are physically large, eclipses of the X-ray source associated with the orbiting neutron star are not unusual. Other sources consist of dim late-type stars orbiting close to a neutron star. These optical counterparts are faint and difficult to identify. The accretion-powered sources are the most luminous in our galaxy. Some have X-ray luminosities, $L_x \approx 10^{38}$ erg s^{-1}.

Some bright sources were found by Uhuru to be within globular clusters. Clark and colleagues (1975) found more with the third Small Astronomy Satellite (SAS 3) and pointed out that this was an unusual situation. The sources occur with much higher frequency than predicted by calculations based on the ratio of stars to X-ray sources in our galaxy (Clark *et al.*, 1975). The high stellar density in globular clusters is clearly favourable for the formation of these exotic binary systems (see Chapters 11 and 12).

In 1973, soft X-rays from SS Cygni were discovered by Rappaport *et al.* (1974). SS Cyg is a cataclysmic variable (CV) and is one of the brightest and nearest of this class. It has irregular outbursts during which the star brightens from its normal 12th to 8th magnitude. SS Cyg has been monitored by the American Association of Variable Star Observers (AAVSO) since 1896. It has an outburst about every 2 months and is called a *dwarf nova*. Many CVs are now known to be X-ray sources. They are accreting binary systems consisting of a low-mass normal star and a white dwarf (see Chapter 10).

Supernova remnants are bright X-ray sources, such as the first to be detected, the Crab Nebula. The X-ray luminosity of most remnants is 10–100 times less than that of the Crab Nebula and the spectrum is soft, so absorption in interstellar gas is more severe. Nevertheless, the closer remnants were easily detected and positively identified by their spatial extent (e.g. Cygnus Loop and Vela XYZ as seen in Figure 1.6) (Grader *et al.*, 1970) or by the spatial coincidence with a non-thermal radio source such as Cas A (Gorenstein *et al.*, 1970) (see Chapter 8).

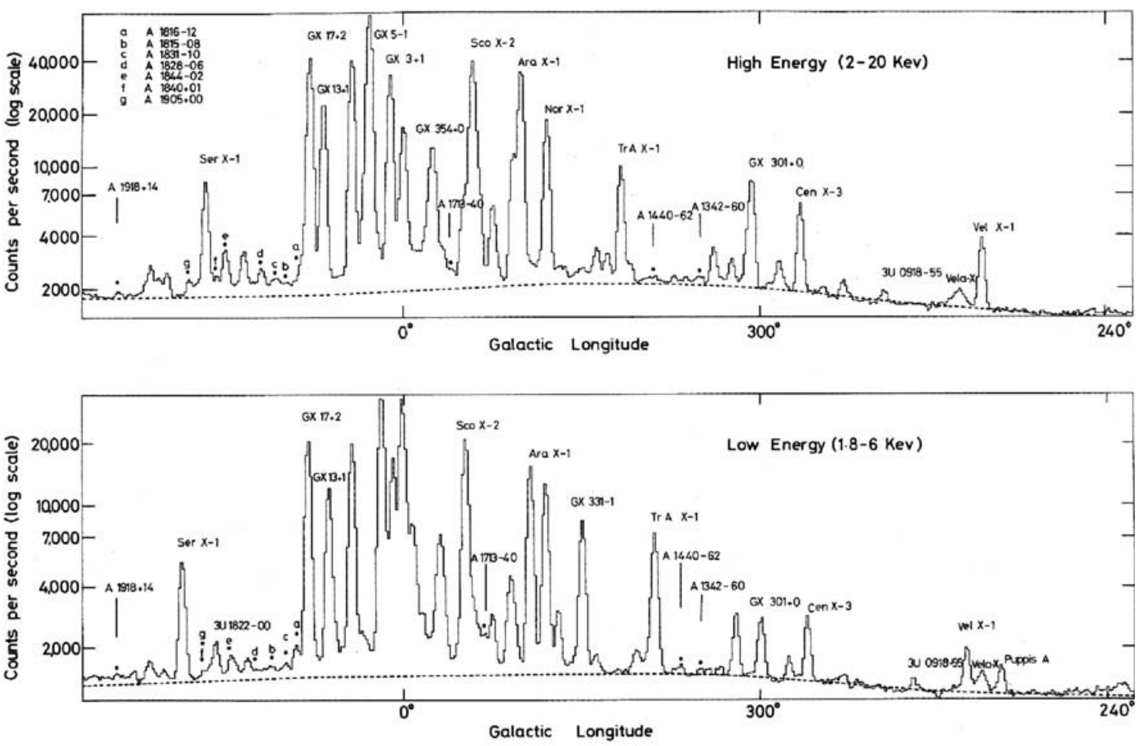

Fig 1.7 An Ariel 5 scan of the central half of the galactic plane. Two detectors scanned the sky, each with 0.7° x 10° field of view. The two collimators were inclined at different angles to aid in source location, so given sources do not appear at identical longitudes in this figure. Note the improvement in the ability to detect weak sources. (Courtesy of K. Pounds.)

Another class of sources are stars, binary perhaps, but without compact companions. The first indication of strong coronal emission from stars was obtained in April 1974 (Catura *et al.*, 1975). The X-ray luminosity was 10 000 times the X-ray luminosity of the Sun. The detection occurred by accident when the rocket-borne instruments were pointed at Capella to calibrate star sensors included in the payload for an accurate measure of pointing direction. Shortly afterwards, in October 1974, X-ray emission from a second star, the flare star YZ Canis Minoris, was observed with the ANS by Heise *et al.* (1975).

Because a bright star in an error box was a very tempting identification, false claims of X-ray detection of bright stars were not uncommon. In spite of this, it was soon evident that the coronal X-ray emission of many active stars was considerably more intense than that of our Sun (see Chapter 6).

As the sensitivity of observations increased, other sources were discovered that were not in our Galaxy. The first extragalactic source discovered was the active galaxy M87. The observation was made by Byram *et al.* (1966) with a rocket launched April 1965. In 1971, Uhuru added many quasars, active galaxies, and clusters of galaxies (Giacconi, 1974). Thus, the individual X-ray source populations were recognised as sources and identified.

Large fractions of the sky were surveyed by the first satellites devoted to X-ray astronomy. After Uhuru, SAS 3 and Ariel 5, a few hundred sources had been catalogued (e.g. Figure 1.7). The first satellite/observatory specifically designed for an all-sky survey was HEAO-1 in 1979, which used an array of large-area proportional counters. The result, shown in Colour Plate 2, was a catalogue with limiting sensitivity of 0.003 photons cm^{-2} s^{-1} containing 842 sources (Wood *et al.*, 1984). Ten years later, ROSAT mapped the sky for the first time using an imaging telescope and low-background detector. The threshold of this, the most sensitive X-ray all-sky survey to date, was 1.5×10^{-4} photons cm^{-2} s^{-1}, and the first version of the ROSAT catalogue contained more than 18 000 sources, both galactic and extragalactic (Voges *et al.*, 1999). Colour Plate 3 shows the ROSAT all-sky survey.

Flux and luminosity

Fluxes quoted are measured at the top of the Earth's atmosphere. To give an intuitive feeling for the X-ray brightness of a source, fluxes in this chapter have been quoted in units of photons cm^{-2} s^{-1}. The counting rate of an X-ray detector, $C = F_p \epsilon A$, where F_p is photon flux, ϵ is detector efficiency and A is detector area integrated over the energy range of the detector. Because detector efficiencies usually ranged from 0.1 to 1.0, and detector areas from 100 to 1000 cm^2, the counting rate of early X-ray detectors was ~100 times the photon flux quoted.

To be more precise, we should specify an energy flux (ergs cm^{-2} s^{-1}) and the exact energy range covered. The observed flux is a measure of the brightness of a source. The intrinsic luminosity, L, is related to the flux, F, through the square of the distance to the source, d. Thus, $L = 4\pi d^2 F$. As a matter of interest, in the range 0.2–10 keV, one of the most luminous X-ray sources known is the quasar PKS 2126-150, at a red shift of 3.27 and with $L_x = 5 \times 10^{47}$ erg s^{-1}. One of the least luminous extra-terrestrial X-ray sources detected is the Earth's Moon with $L_x = 7 \times 10^{11}$ erg s^{-1}, a range of physical processes that produce X-ray emission varying by 36 orders of magnitude.

In a more selective mode of operation, X-ray telescopes have accomplished deep surveys of small regions of the sky. The Einstein and ROSAT deep-survey detection thresholds were $\approx 3 \times 10^{-5}$ and $\approx 1 \times 10^{-5}$ photons cm^{-2} s^{-1}, respectively. The XMM and Chandra limits are 100 times fainter again or ≈3 photons m^{-2} hr^{-1}. This is 1 billion times fainter than Sco X-1, the brightest source in the sky. (Actually, at energies above ~1 keV, transient sources up to twice as bright as Sco X-1 have been observed. Below ~1 keV, as you know, the Sun is the brightest source in the sky.)

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