1

Observational techniques in X-ray astronomy

1.1 Instrumental sensitivity

From the viewpoint of its instrumentation, X-ray astronomy possesses a certain moral simplicity. It is a perpetual battle of good versus evil; that is, of signal versus noise.

The observation of a weak point source of X-ray flux F (photons/cm^2 (detector area) s keV (detector bandwidth)) must always be made in the presence of an unwanted background B (counts/cm^2 s keV). This may be regarded as the sum of the intrinsic detector background B_i (arising, usually, from the very complex interaction of the near-earth radiation environment with the detection medium) and the diffuse X-ray sky background B_d, discovered on the same sounding rocket flight as Sco X-1 (Giacconi *et al.*, 1962). If the quantum detection efficiency of the detector is Q counts/photon and its aperture is Ω steradians (sr), then

$$B_d = Q\Omega j_d$$

where j_d is the diffuse background flux in photons/cm^2 s keV sr.

If the observed quantities are all constant during the measurement time t, statistical fluctuations in the background B determine the sensitivity of the detector. The minimum detectable flux, F_{min}, for a given signal-to-noise ratio S is that flux which produces a count S standard deviations of B above its mean. Assuming that the bandwidth of the instrument is δE, the geometric area for the collection of source photons (and diffuse background) is A_s and the geometric area for detector background is A_b, one may show that:

$$F_{min} = (S/QA_s)\{B_i A_b + Q\Omega j_d A_s)/t\delta E\}^{\frac{1}{2}} \qquad (1.1)$$

Choosing a value of S is equivalent to selecting a confidence level for the source detection. For example, $S=3$ corresponds to 99.8% confidence.

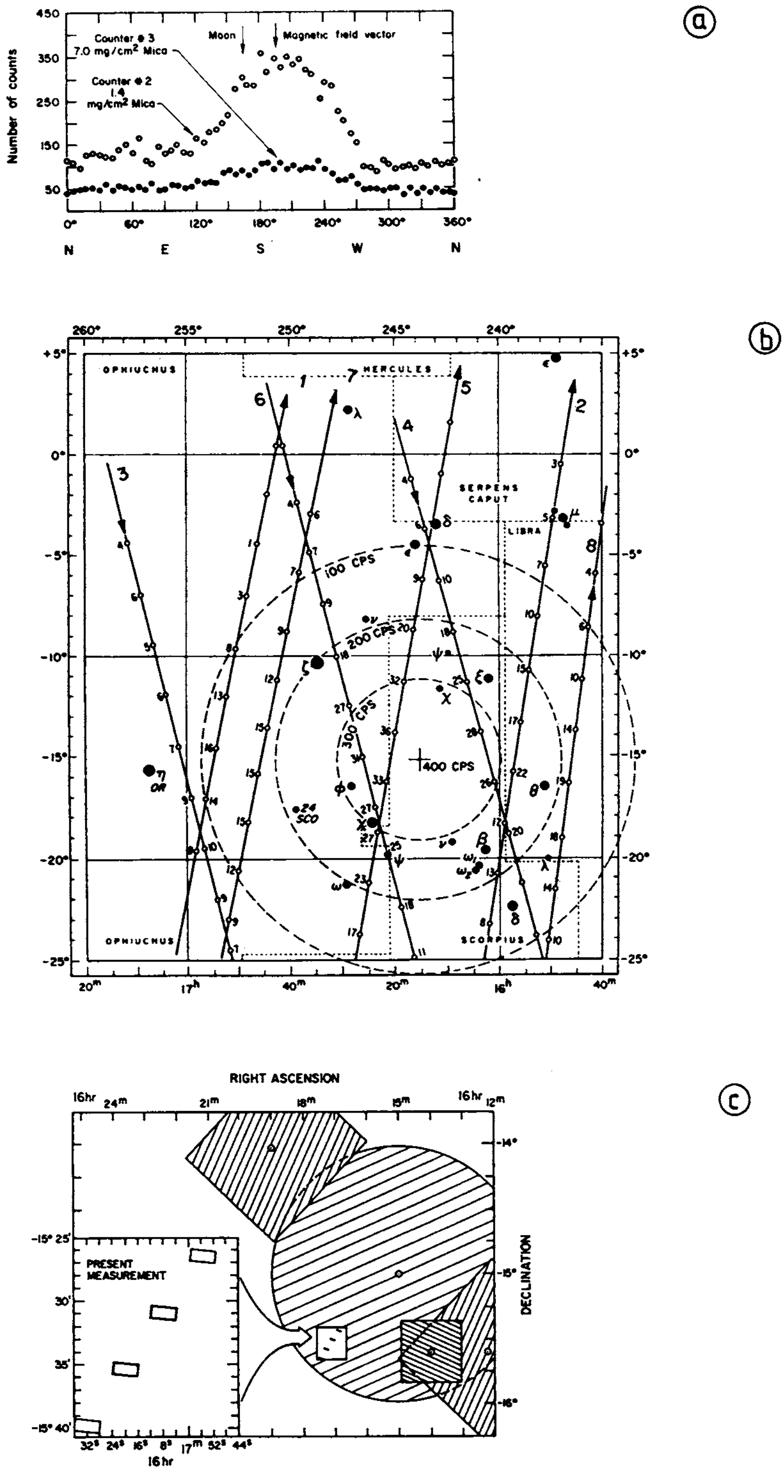
Equation (1.1) is a fundamental relationship, which remains valid down to a sensitivity limit determined by source confusion, when it becomes statistically likely that two or more sources of equal brightness are simultaneously present in each instrumental resolution element. It may be elaborated to include the real energy-dependence of terms such as F, j_d and Q. Limiting forms of the sensitivity equation can be derived to cover special observing modes, such as diffuse background dominance, measurement from a rotating or precessing platform, and so on (Peterson, 1975). Similar equations can be constructed for the detection of X-ray lines once a broad-band detection has been made. Implicit in the derivation of all such equations is the assumption that source detection is made on a photon-by-photon basis. Principally because of the weakness of the X-ray sources, integrating detectors such as X-ray film have never had a place in cosmic (as opposed to solar) X-ray astronomy. A flux of one photon per square centimetre per second (1–10 keV) observed at the earth constitutes a rather bright cosmic X-ray source. The 'standard candle' of X-ray astronomy – the Crab Nebula – contributes ~ 3 photons/cm^2 s in this energy band.

In this chapter, we shall consider the evolution of the instrumentation used in X-ray astronomy, using eq. (1.1) as our guide.

1.2 Early days

The discovery of Sco X-1 had opened a new window on the universe: astronomers worldwide rushed to look through it. The AS&E researchers were quickly rejoined in the field by Friedman's group at NRL, who, in April, 1963, not only confirmed the existence of the strong source in Scorpius but also reduced the uncertainty in its position to about one degree (fig. 1.1). During the same sounding rocket flight, the NRL group found evidence for a second source, about one-eighth as strong as Sco X-1,

Fig. 1.1. The location of Sco X-1. (a) Discovery measurements (Giacconi *et al.*, 1962). Geiger counter count rate plotted versus azimuth angle. The peak in both counters at 195° represents the detection of the first extra-solar X-ray source. (*Courtesy R. Giacconi.*) (b) Confirmation measurements (Bowyer *et al.*, 1964a). The tracks of eight scans across the Scorpius region are indicated by the straight lines, labelled at intervals with count rates per 0.09 seconds. The dashed circles indicated equal intensity contours and the cross shows the most probable source position. (*Courtesy S. Bowyer. Reprinted by permission from Nature, vol. 201, p. 1307. © 1964 Macmillan Magazines Ltd.*) (c) Modulation collimator positions (Gursky *et al.*, 1966) (inset figure) compared with those of earlier experimenters. Of the four possible collimator positions, the central pair were most probable. The optical counterpart of Sco X-1 (Sandage et al., 1966) lies at RA = 16h 17m 04s, Dec = −15° 31′ 15″. (*Courtesy H. Gursky.*)


a
Number of counts
Counter # 3 7.0 mg/cm² Mica
Counter # 2 1.4 mg/cm² Mica
Moon
Magnetic field vector
0° 60° 120° 180° 240° 300° 360°
N E S W N
b
OPHIUCHUS
HERCULES
SERPENS CAPUT
LIBRA
SCORPIUS
100 CPS
200 CPS
300 CPS
400 CPS
c
RIGHT ASCENSION
DECLINATION
PRESENT MEASUREMENT

in the general direction of the Crab Nebula, the supernova remnant (SNR) of 1054 AD (Bowyer *et al.*, 1964a).

By 1967, the US groups at AS&E, MIT, NRL, the Lawrence Livermore Laboratories and Lockheed Research Labs were competing in the search for cosmic X-ray sources with astronomers in the UK, Europe and Japan. The Space Physics Group at Leicester University, for example, had been active in solar X-ray studies since the late 1950s (Russell and Pounds, 1966). Turning their attention to the wider sky, the Leicester group undertook galactic surveys in the southern hemisphere, using the Anglo–Australian rocket range at Woomera (Cooke *et al.*, 1967). The early institutional history of X-ray astronomy in the United States has been described by Tucker and Giacconi (1985) and in the UK by Massey and Robins (1986) and by Pounds (1986).

The first observational era of X-ray astronomy may be dated from 1962 to 1970. These were the pioneering days, when the ratio of known X-ray sources to X-ray astronomers was certainly less than one-to-one. The principal discoveries during this period were made using low-background large-area proportional counters (fig. 1.2 and section 2.3) carried on sounding rockets such as the American Aerobee or the British Skylark. A typical sounding rocket trajectory, with an apogee of 200–250 km, provided some five minutes of observing time above the 100 km or so of 'soft' (i.e. low-energy) X-ray absorbing atmosphere. That is, $t = 300$ s in eq. (1.1). The experimental packages, looking out from the side of the vehicle, initially used the rocket's roll and yaw to map the sky. Later, stabilised rockets allowed slow, controlled scans to be made of selected areas of the sky. A mechanical 'egg-crate' or 'honeycomb' collimator, preceding the entrance window of the gas counter, restricted the field-of-view and gave these non-imaging ($A_s = A_b$ in eq. 1.1) instruments their directional sensitivity. Mechanical collimator design is outlined in fig. 1.3. The angular location of a point source of flux F can be determined with a collimator of

Fig. 1.2. The Leicester large-area proportional counter flown from Woomera on Skylark SL 723, 12 June, 1968. The figure shows the instrument (in the triangular nosecone) undergoing ground tests together with the Skylark upper body. X-rays transmitted by the collimator pass through a thin plastic window and are absorbed within the gas volume, releasing electrons. These electrons accelerate under the influence of an electric field, producing further electrons by collisional ionisation, until a measureable electrical pulse (proportional in magnitude to the X-ray energy) is developed at the counter anode (see Chapter 2). The detector area ($A_s = A_b$ in equation 1.1) was approximately 3000 cm^2, making this instrument the largest of its type flown up to that time. (*Courtesy K. A. Pounds.*)

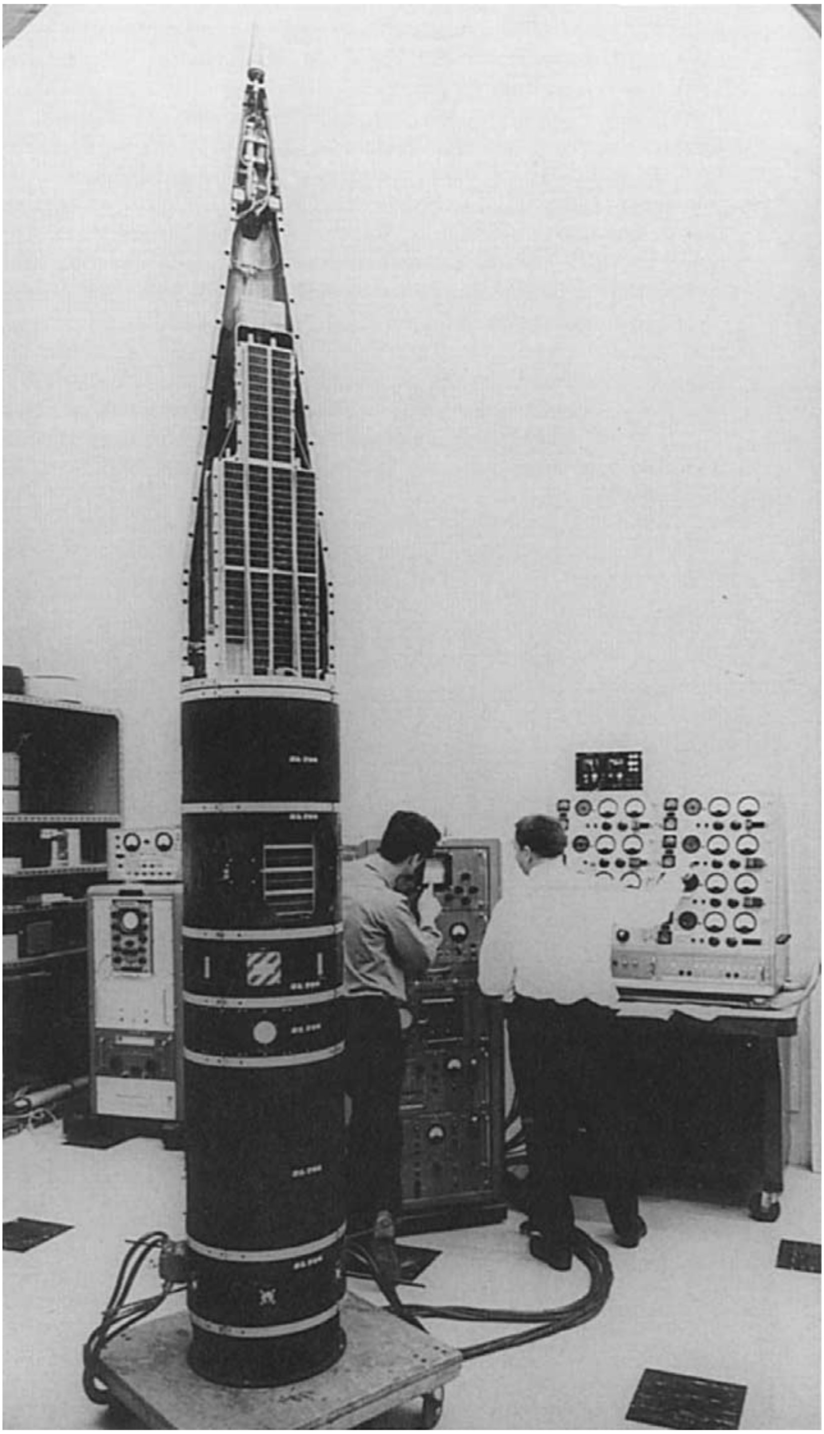
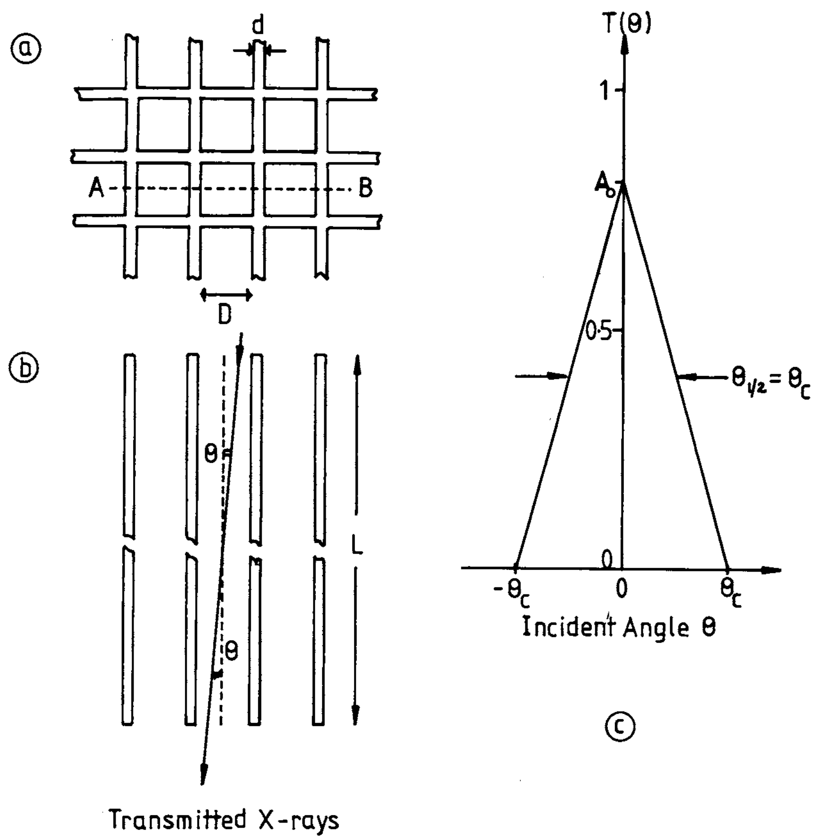


Fig. 1.3. Mechanical collimator design. (a) Plan view of regular square-section mechanical collimator. Open area fraction is given by $A_o = (D/D+d)^2$. Open areas must generally be restricted to 75–80% to preserve rigidity of the array. Collimators with circular, hexagonal and rectangular ('slit') apertures have been used in X-ray astronomy: their relative merits are discussed by Giacconi, Gursky and Van Speybroeck (1968). Collimator walls, thickness d, are usually formed from beryllium, aluminium or stainless steel. (b) Vertical section across line AB. Soft (~ 1 keV) X-rays incident at angles θ greater than θ_c (where $\theta_c = \text{arccot}\,(L/D)$) are absorbed in the collimator walls. Very low energy X-rays may be transmitted through the collimator by multiple reflection. At energies above about 20 keV, thick walls are required to completely attenuate the flux and prevent the collimator becoming transparent at all angles of incidence. (c) Point source transmission function $T(\theta)$ for the collimator of (a) and (b). For small θ: $T(\theta) = A_o\,(1-\theta/\theta_c)$. The fwhm transmission for this collimator, $\theta_{\frac{1}{2}}$, (determining the angular resolution (equation 1.2) and field of view of the collimated X-ray detector) equals θ_c. For practical large-area collimators, $L/D \lesssim 60$ and $\theta_c \gtrsim 1°$. The response of such a collimator to extended sources is discussed by Giacconi, Gursky and Van Speybroeck (1968).



full-width-at-half-maximum (fwhm) transmission in the scan direction $\theta_{\frac{1}{2}}$ to an accuracy $\delta\theta$ where (Peterson, 1975):

$$\delta\theta = \theta_{\frac{1}{2}}\,(F_{min}/F) \tag{1.2}$$

The Leicester instrument described by Cooke *et al.* (1967), for example, had a rectangular aperture, geometrically collimated to 30° × 30°. The NRL detector described by Bowyer (1965) had a circular aperture with 10° fwhm transmission. Equation (1.1) tells us that the best development strategy for such instruments is to make them as large as possible (maximise A_s). This route was vigorously followed. The total effective area (product of Q and A_s) for the pioneering AS&E Geiger counters was ~20 cm²: within a few years, gas detectors a hundred times larger had been constructed and flown (fig. 1.2).

High-altitude balloons provided an alternative to sounding rockets for observations of the 'harder' (i.e. higher-energy) component of the cosmic X-ray fluxes. Balloon X-ray astronomy is conducted at altitudes above 40 km, where the residual atmosphere has an effective column density of only 3 g cm² (Peterson *et al.*, 1972) and is thus transparent to X-ray energies $E > 20$ keV. In a typical early balloon flight, Bleeker *et al.* (1967) used a sodium iodide scintillator crystal to measure the 20–130 keV energy spectrum of sources in the constellation of Cygnus. All scintillators (Chapters 2 and 5) rely on the production by the incident X-rays of a 'flash' of visible light which may be registered using a photomultiplier of some kind. The observing time for this early experiment was forty minutes ($t = 2400$ s in eq. 1.1). Although later balloon flights provided many hours of continuous source coverage, such experiments were, and are, restricted to an energy régime where source fluxes fall steeply with increasing X-ray energy. In the case of the Crab Nebula, $dF/dE \propto E^{-2.05}$ for energies between 10 and 100 keV. The impact of balloon experiments with scintillators (section 5.2) and cooled germanium detectors (section 4.4) was, therefore, by no means in proportion to their longer observing times.

By the end of the sounding rocket era, some 30–40 discrete sources were known. A 1968 review (Giacconi *et al.*, 1968) was forced to admit that there were: '... very few precise measurements in X-ray astronomy, a situation to be expected in a field in which each major experimental group is limited to about ten minutes of observation a year'.

Of the known sources, only a few could be confidently identified with any optical or radio counterpart. The first such identification was made by the remarkable method of lunar occultation in July, 1964. The NRL group (Bowyer *et al.*, 1964b) observed the Crab Nebula during its nine-yearly eclipse by the limb of the moon. From the gradual decrease in observed count rate, the NRL researchers were able to identify the X-ray source they had observed the year before with the optically and radio-bright Crab SNR.

Given the publicised aim of the original AS&E flight of June, 1962, it is somewhat ironic that the first precise positional measurement in X-ray astronomy used the moon as a dark occulting disc, moving against the X-ray-bright sky.

Despite the very high (>0.5 arcsecond) angular resolution of the lunar occultation technique, eclipses of bright sources occurred too infrequently for it to make a major impact on the source identification problem. The limited duration of sounding rocket flights dictated that target positions already had to be known rather accurately – more accurately than could be achieved with the standard scanning proportional counter experiments (eq. 1.2 and fig. 1.3). A number of bright galactic sources *were* observed during lunar eclipses in the early 1970s: the source GX3+1 (the numbers refer to its galactic latitude and longitude in degrees), observed on two separate sounding rocket flights by the Leicester group and by the Mullard Space Science Laboratory (MSSL) of University College, London, remains the most precisely X-ray-located source of all (Janes *et al.*, 1972). Lunar occultation measurements from an orbiting satellite were made for the first (and, to date, last) time in 1972: the source was GX5-1 (Janes *et al.*, 1973). Although the European EXOSAT Observatory (which evolved from a 1960s' study called HELOS – the 'LO' standing for lunar occultation) was launched into a highly eccentric, near polar orbit specially chosen to facilitate occultations over a large fraction of the celestial sphere, no such measurements were made during the satellite's lifetime.

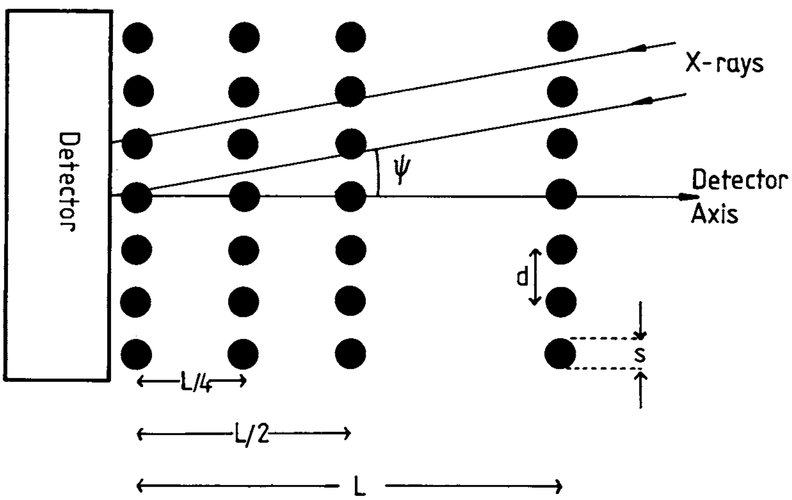
The milestone identification of Sco X-1 with a faint blue variable star (Gursky *et al.*, 1966; Sandage *et al.*, 1966; fig. 1.1) resulted, not from the use of lunar occultation, but from a novel refinement of the collimator technique.

Equation (1.2) tells us that, in order to improve the angular resolution of a mechanically collimated instrument, all we have to do is reduce $\theta_{\frac{1}{2}}$, the fwhm transmission of the collimator. Resolution of at least an arcminute is needed to confidently identify X-ray and optical or radio sources by positional coincidence alone. Unfortunately, construction of large-area collimators for the arcminute régime poses severe engineering problems, chiefly with regard to the parallel alignment of all the collimator channels. Reduction of $\theta_{\frac{1}{2}}$ in a scanning instrument also reduces the point source observing time per scan, and hence the instrumental sensitivity. This arises from the fact that the fwhm transmission essentially determines the field-of-view.

The modulation collimator (MC), first described as an instrument for X-ray astronomy by Oda (1965), achieves sub-arcminute angular resolution while retaining a large field-of-view. An arrangement of planes of wires (fig. 1.4) is aligned perpendicular to the viewing axis of a proportional counter detector. The transmission function of such a wire collimator consists of a series of narrow bands (Bradt *et al.*, 1968; Giacconi *et al.*, 1968) so that when the instrument is scanned across the region of interest a multiplicity of possible source positions results. In the AS&E/MIT experiment described by Gursky *et al.* (1966) this problem was overcome by using two four-grid collimators with slightly differing periods in a 'vernier' arrangement. In general, a unique MC source position determination depends on the availability of data from other instruments.

In the late 1960s and early 1970s, very considerable efforts were directed into the optimisation of modulation collimators. The rotation modulation collimator (RMC) (Schnopper and Thompson, 1968) is a two-grid collimator which, centred on the rotation axis of a spinning vehicle, modulates the flux from a point source in such a way that (i) the frequency of the

Fig. 1.4. Schematic representation of a four-grid modulation collimator. The three outer grids (extending into the diagram) are separated from the inner grid by distances L, $L/2$ and $L/4$. For an n-grid collimator, separations are found from $L/2^j$, where $j=0, 1, ..., n-2$. The transmission function, in the limit of small off-axis angles ψ consists of a triangular response of fwhm s/L repeating with a period 2^{n-2} (s/L) (Giacconi, Gursky and Van Speybroeck, 1968). For the AS&E/MIT Sco X-1 experiment (fig. 1.1) $d=2s=0.25$ mm and $L=61$ cm, producing a transmission band of 40″ fwhm.



modulation depends on the off-axis distance of the source (r), and (ii) the phase of the modulation depends on the remaining polar coordinate (θ). RMCs have the advantage of being unaffected by source confusion, but reduction of the data by Fourier analysis relies on the source flux remaining constant during the observation.

The variable-spacing modulation collimator, developed at Leicester (Adams *et al.*, 1972), is a device with one fixed wire grid and a second grid of the same pitch motor-driven in the direction perpendicular to the grid planes. With the instrument mounted on a stabilised star-pointing sounding rocket, this variation of the grid spacing (L in fig. 1.4) allows images to be reconstructed rather more simply than in the case of the RMC.

In all MC designs, however, accuracy in the measurement of source position is achieved at the cost of decreased sensitivity. In a scanning n-grid device, for example, the observing time per resolution element is $1/2^{n-2}$ times that of a conventional large-area proportional counter (Peterson, 1975). It is instructive to note that no second flight of the AS&E/MIT four-grid collimator was ever made. In the limited observing times available with sounding rockets, there were simply no other sources bright enough to yield a useful signal-to-noise ratio.

Only with the coming of the first X-ray satellites did the ingenious instrumentation developed during the 1960s begin to reap the full harvest of the X-ray sky.

1.3 The small satellite era

The first satellite dedicated to X-ray astronomy, NASA's Small Astronomy Satellite (SAS) A, was launched into equatorial orbit on 12 December, 1970, from the Italian San Marco platform – a converted oil rig moored off the coast of Kenya. Because 12 December was Kenyan independence day, the satellite was renamed Uhuru – the Swahili word for freedom – in orbit.

Uhuru was not the first satellite to carry X-ray detectors. Previous instruments, however, had either failed in orbit (e.g. the large detector array on OAO-1) or were small devices not intended for use in cosmic X-ray astronomy. For example, the NaI scintillator detectors (section 5.2) on the Vela 5A, B satellites (launched 1969) had as their main aim the monitoring of the atmospheric test ban treaty. These satellites, by virtue of their long lifetimes, were able to produce an unsurpassed record of the variability of the brightest X-ray sources. An animated film – *The X-ray sky 1969–76* – was produced from the Vela observations (Terell *et al.*, 1984).