

A BALLOON-BORNE DETECTOR
FOR HARD X-RAY ASTRONOMY

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ABSTRACT

The field of X-ray astronomy is introduced with a brief historical review, and an outline of the main classes of X-ray emitting objects and the source of the X-ray background. The different types of measurements and studies which can be performed in the X-ray region are described together with the sources they are best suited to observing.

This is followed by a discussion of the four types of hard X-ray detectors currently in use in astronomy: proportional counters, plastic scintillators, inorganic crystal scintillators and solid-state devices. A full description is given of the Imperial College 'Large Area Phoswich Array Detector' (LAPAD), an example of an inorganic scintillator detector, together with a résumé of its flight history.

The design of a graded passive shielding system for the LAPAD modules is outlined, including an explanation of the choice of materials, thicknesses and positioning. A prototype shield was built and tested to check these choices.

The analysis method for the LAPAD spectral data is then discussed in detail: firstly, how the measured spectrum for each source was built up, including allowances for the detector dead time and energy calibration; secondly, how the interaction matrix which models the detector's output response to a given incident photon spectrum was calculated; and thirdly, how the measured spectrum was unfolded to recover the original source spectrum, using the interaction matrix.

In the last chapter, the time-averaged spectra from some of the sources observed with LAPAD during the 1981 and 1983 flights are presented, and their implications discussed. The sources dealt with are Sco X-1, the Seyfert galaxy IC 4329A and the quasar MR 2251-178, the Nova Ophiuchi 1977 X-ray counterpart H1705-25, the galactic bulge sources GX5-1 and GX3+1, and the binary pulsar GX1+4.

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PREFACE

This thesis concerns work performed with the 'Large Area Phoswich Array Detector' (LAPAD), a balloon-borne experiment designed to observe hard X rays from astronomical sources. The LAPAD project is a collaborative effort of the Space Physics Group at Imperial College, involving several of its members in various capacities. The author's main contributions to the project have been in designing, constructing and testing parts of the detector hardware, flight support, and undertaking the data analysis.

Design, construction and testing included: fabricating some of the structural components of the detector, assembling and testing the detector modules, designing and constructing a new shielding system, co-designing and constructing the in-flight calibration system, and thermal vacuum testing the whole detector.

Flight support included: taking part in the 1981 launch campaign, writing and maintaining a set of programs to generate tables of data required for each campaign, and fabricating various new detector parts.

Data analysis included: producing the set of matrices modeling the detector response to unfold the spectra measured, creating the computer subroutines to handle the data stream and pointing aspect calculations (which will be required for all future analysis as well), creating the programs to reduce the Spectral Mode data from the raw data stream through to the unfolded spectra, producing the final spectral results for the two flights' observations, and co-writing the project's first paper (Beurle et al 1983).

CHAPTER 1 : AN INTRODUCTION TO X-RAY ASTRONOMY

X-ray astronomy comes of age this year. Twenty-one years ago, on 19 June 1962, the first cosmic X-ray source, subsequently named Scorpius X-1, was discovered with a rocket-borne detector flown by Giacconi's group from American Science & Engineering (Giacconi et al 1962). So this is an appropriate time to review what has been achieved in the field since then, and to look at some of the astrophysical problems which can be tackled with the X-ray observations of the future.

Observations tend to be divided into two energy schemes; the 'soft' and 'hard' ends of the X-ray spectrum, with rough energy ranges of 0.1 to 20 keV and 20 to 1000 keV respectively. The ~ 20 keV breakpoint arises from a combination of three factors. The two main types of detector are limited to roughly these energy divisions, with proportional counters below about 20 keV and scintillation detectors above. In addition, the atmosphere above balloon altitudes (~ 40 km) is opaque to photons below this energy, and relatively transparent to photons above it, producing a division between observations which can be made from a high-altitude balloon and observations which require a rocket or satellite platform. Cosmic X-ray spectra fall off rapidly with energy, so to detect sufficient photons, hard X-ray detectors need to be much larger than soft X-ray ones, which also causes them to be carried on balloons rather than satellites or rockets.

1.1 Past Achievements

Most X-ray astronomical observations have been made from satellites, and therefore in the soft X-ray region, although this does not necessarily reflect the relative merits or potentials of the two ends

of the spectrum. Initially, soft X-ray observations were made from rockets and hard ones from balloons, but both methods only produce a small number of measurements because of their short flight durations (a few minutes for rockets and a few hours for balloons). It was soon obvious that satellite-borne detectors were necessary if the field was to realise its full potential.

The launch of the first X-ray astronomical satellite SAS-1 (renamed Uhuru) in 1970 was followed by detectors on OAO-3 (Copernicus), Ariel 5, Ariel 6, ANS, SAS-3, OSO-7, OSO-8, HEAO-1, HEAO-2 (Einstein), Astro-A (Hakucho), Astro-B (Tenma) and EXOSAT. They brought about a vast expansion in the field; the Uhuru satellite alone increasing the number of known sources from around 30 to over 300. Of the above, the Einstein Observatory was the largest, as well as being the first to have a grazing-incidence telescope capable of producing direct X-ray images.

X rays are emitted by high-temperature plasmas or by high-energy processes occurring in violent events and in objects at extreme stages of their evolution. It is the ability to investigate these very interesting types of sources, many of whose members are relatively innocuous at other wavelengths, that is the reason for observing in the X-ray waveband. The sources can be divided into galactic and extragalactic populations, the galactic source distribution being heavily biased towards the galactic plane and the galactic center, and the extragalactic sources being uniformly distributed, when plotted in celestial coordinates (see Figure 1-1). The observed sources can be classified as follows:

a) Massive binary star systems, where matter is being transferred from a massive O- or B-type primary star onto a compact secondary object, usually a neutron star or occasionally a black hole. About a third of the galactic sources fall into this class, including Cyg X-1, Her X-1, Cen X-3 and SMC X-1 - a binary source in a nearby galaxy. Many of them

THE FOURTH UHURU CATALOG

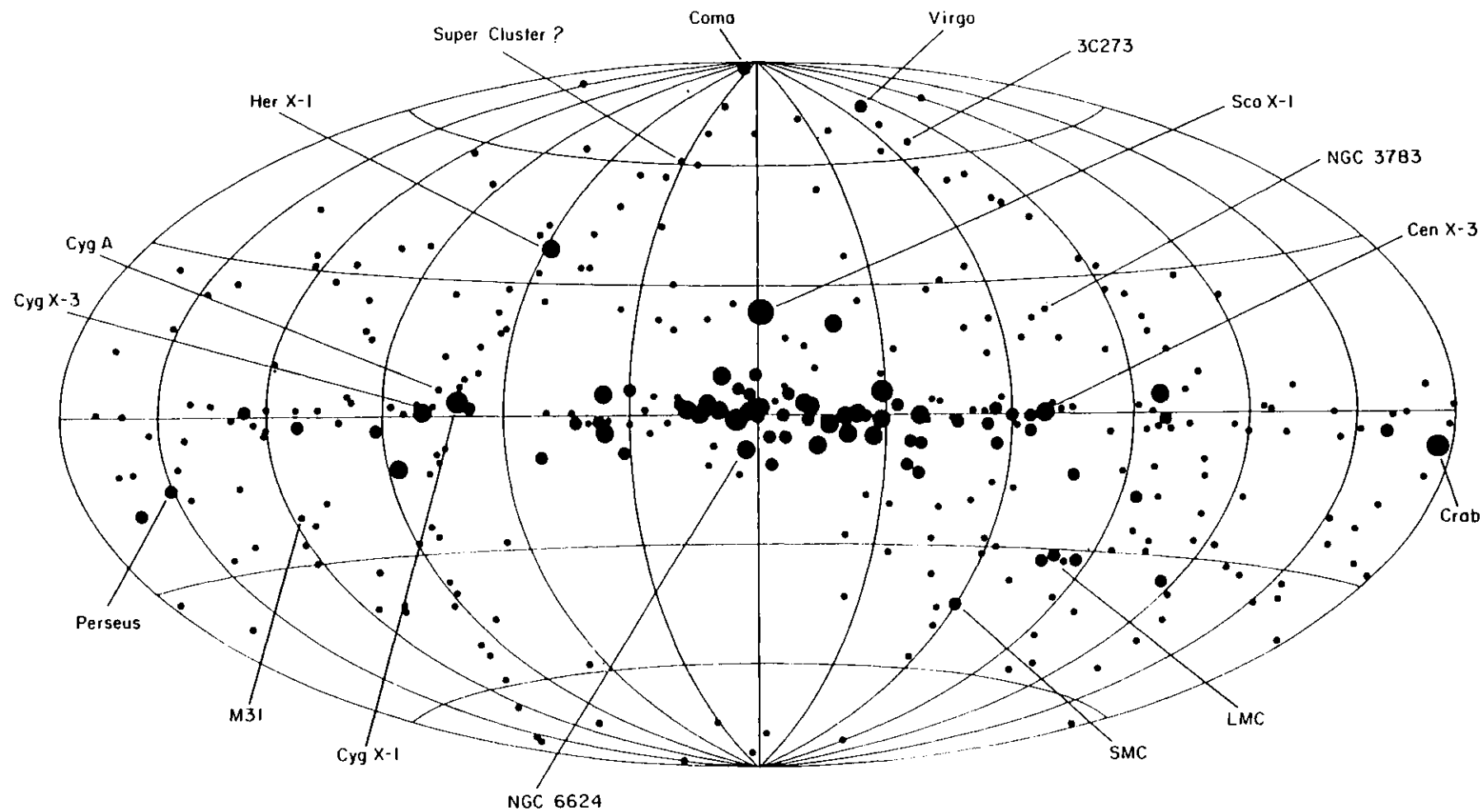


Figure 1-1. The distribution of X-ray sources in the sky, plotted in galactic coordinates. The size of each circle is proportional to the logarithm of the intensity (Forman et al 1978).

have partially pulsed X-ray emission, leading to the term 'X-ray pulsars'. In most of them, the matter overflows the primary's Roche lobe or is captured from its stellar wind, to form an accretion disk slowly spiraling down towards the secondary object, releasing gravitational potential energy which powers the X-ray emission (see Figure 1-2). Verbunt (1982) gives a fuller account of these important accretion disks.

b) Galactic bulge sources, which are probably neutron stars in low-mass close binary systems. This class comprises about a quarter of the galactic sources, including Sco X-1, Ser X-1 and 4U 1626-67. They are distinguishable from the massive binaries, because they have high X-ray to optical luminosity ratios, no stellar absorption lines, soft X-ray spectra and no pulsations or eclipses. Many emit X-ray bursts, giving them the name 'bursters'. Lewin & Joss (1981) suggest that most bursts are produced by thermonuclear flashes of helium on the neutron star's surface, except the ones from MXB 1730-335 (the 'Rapid Burster') which probably arise from accretion instabilities.

c) Supernova remnants and their pulsars, which comprise about 5% of the galactic sources. The X rays are emitted by the ejected material together with interstellar gas swept up and heated by the expanding shockwave, at a temperature of $\sim 10^7$ K (~ 1 keV), the emission being mainly thermal. The Crab Nebula is the exception to this; here the neutron star accelerates relativistic electrons in the nebula by its magnetic field, causing synchrotron radiation to be the dominant process. The pulsar itself emits $\sim 10\%$ of the X rays in pulses along with its radio and optical emission, this fraction being an increasing function of photon energy.

d) Various types of unusual stars, including: cataclysmic variables, which are late-type binary systems containing a white dwarf as the compact component with a K-, M- or N-type primary, and whose prototype is AM Her; hot white dwarf stars in nonaccreting systems,

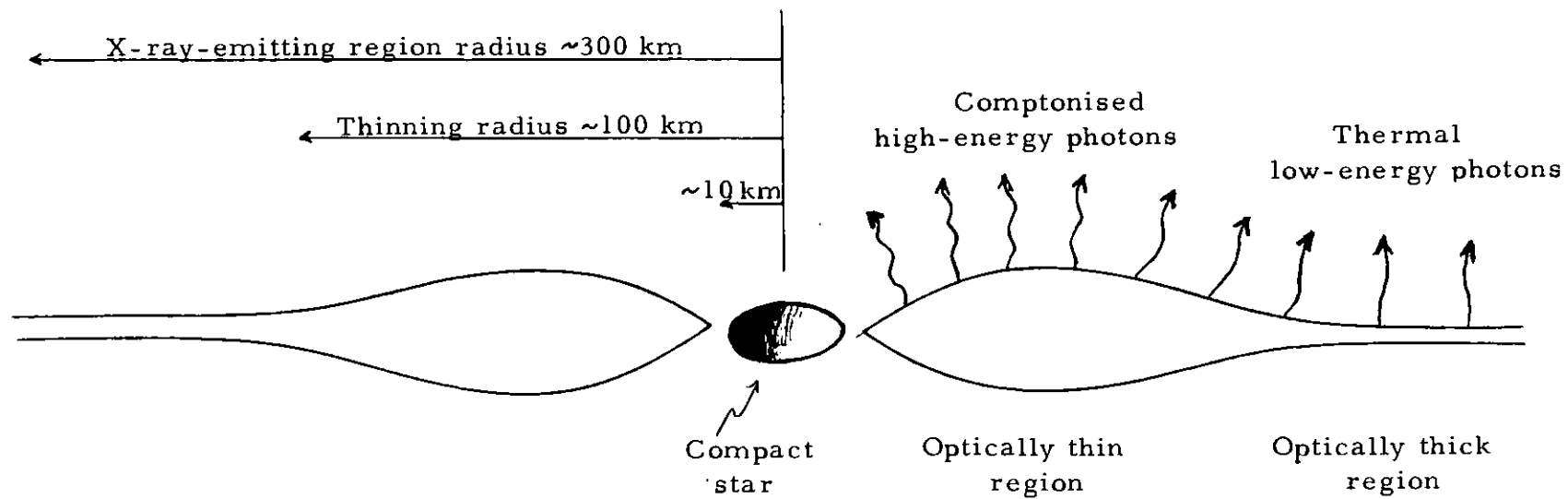


Figure 1-2. Schematic diagram of an accretion disk's central, X-ray-emitting region. The compact star may be a white dwarf, neutron star or black hole. (Adapted from Thorne & Price 1975.)

such as Sirius B; and some nondegenerate stars, such as Algol and several RS CVn variables.

e) Transients, which are X-ray sources that brighten suddenly and fade over a few tens of days. They are not well understood, though 3A 0620-003 has been traced to a recurrent nova, and others may be associated with massive binaries or flare stars.

f) The centers of active galaxies, such as Seyferts, BL Lac objects and quasars, which produce prodigious amounts of energy, most of it emitted as hard X rays and far infrared. The hard X rays are more penetrating and so should contain information about the power mechanism at the cores of these highly energetic objects. They generally have nonthermal, power-law spectra, often with a low-energy cutoff caused by absorbing material in the source. The center of our own Galaxy is also an X-ray emitter, but intrinsically much fainter than the active galactic nuclei.

h) ~~Ex~~ extended emission regions associated with clusters of galaxies, generated by intracluster gas at temperatures of $\sim 10^7$ K (~ 1 keV), emitting thermal spectra. This gas may form a significant fraction of the cluster's total mass, and is difficult to observe other than by X rays. Some clusters have been observed to have an additional, high-energy, nonthermal component to their spectra — whether this arises from the gas or from active galaxies in the cluster has yet to be determined.

As well as these specific sources, there is an isotropic X-ray background whose origin is still incompletely known, although it has been observed for over 20 years. X rays and microwaves are the only regions of the electromagnetic spectrum to have such a cosmic background. The 3K microwave background is cosmologists' best evidence for the Big Bang, so the origin of the X-ray background is likely to be of similar significance to astronomy.

There are at least two possible explanations for the X-ray

background, which has now been observed from a few keV to 100 MeV. One possibility is thermal bremsstrahlung emission from a postulated hot intergalactic medium at a temperature of ~ 40 keV ($\sim 5 \times 10^8$ K). There are however difficulties with this theory, particularly in its requirement of a very high energy density for the medium, the source of which is difficult to explain. The other most widely accepted explanation is that the background is not truly diffuse, but is produced by very many discrete sources below current detectors' resolution. Recent results using the Einstein Observatory have found $\sim 35\%$ of the background comes from cosmologically distant discrete sources, mainly quasars (Giacconi 1982). It is expected that this fraction will increase with improved detector resolution in the future, although it is likely to be a long time before the fractional contributions of discrete and truly diffuse sources can finally be determined.

1.2 Future Prospects

X-ray astronomy is continuing its rapid progress with three currently operating satellites (EXOSAT, Tenma and Hakucho), several balloon-borne detectors being flown regularly, new detection techniques under development, and a number of new satellite observatories at various stages of commissioning. These new observatories include: the West German ROSAT to be launched in 1987, which is of roughly comparable power to the Einstein Observatory; Japan's continuing series of Astro satellites with Astro-C in 1987, which will specialise in timing observations, to be followed by their large Cosmic X-ray and Gamma-ray Telescope (CXGT) in 1990; and Britain's University of Birmingham imaging X-ray detector to be flown on the Spacelab-2 flight in 1985. In the United States, NASA currently has two projects under consideration for flying at the end of the decade. LAMAR is an expandable array of modules, each a medium-sized focusing telescope in its

own right, linked together on a pointing platform to create a massive collecting area of up to a few 10^4 cm^2 ; further modules can then be added as demands require and funding permits. The more likely satellite, AXAF, is a single focusing telescope but of enormous dimensions — its six-nested mirror would have an effective collecting area of 1500 cm^2 , and with its 10m focal length would give it an angular resolution of half an arc second. It would be launched and serviced by the Space Shuttle, which could also retrieve it for refurbishing on the ground. Its sensitivity would make it the X-ray equivalent of the optical astronomers' Space Telescope and the radio astronomers' Very Large Array.

There are many different observations and studies to be performed by these soft X-ray satellites and the balloon-borne hard X-ray detectors which complement them:

a) All-Sky Survey. One of the major requirements of any field of astronomy is a comprehensive survey of the sky in that waveband: firstly to provide a base for comparison of future observations, and to find counterparts of objects seen at other wavelengths, similar to the Palomar Observatory Sky Survey plates in the optical; and secondly to generate a complete catalog of sources from which to select the most promising ones to observe in depth, and to form a complete sample for statistical studies of sources. This task will be performed by ROSAT in its first two years of operation, yielding up to a million sources with their soft X-ray strengths and precise positions, to a sensitivity 10^{-3} that of the Uhuru satellite's ability.

b) Low-Resolution Spectroscopy. The shape of the source spectrum continuum, and hence the emission process, is the most important indicator of which physical processes are occurring in the source. Determining the shape requires statistically accurate flux measurements over a wide energy range. An exponential, power-law or other characteristic spectrum is fitted to these points by adjusting its parameters. The result can

then be used to distinguish between models of the processes occurring in the object. Hard X-ray observations have a major role to play here, not only by extending the energy range of the flux measurements, but also by covering the region where the spectral shape changes in sources where there is another emission process at work. When the latter occurs, it produces a 'hard tail' (an excess over what would be expected from an extrapolation of the low-energy continuum shape), as has sometimes been observed from Sco-type sources where it is thought to arise from accretion disk instabilities, and from galaxy clusters. The harder X rays are generated from the inner regions of the accretion disks (see Figure 1-2), therefore hard X-ray spectral observations reveal the physical conditions near the surfaces of neutron stars and the event horizons of candidate black holes (e.g. Cyg X-1 and LMC X-4).

c) High-Resolution Spectroscopy. To detect fine spectral details superimposed on the continuum spectra, different detection techniques are required: diffraction gratings or Bragg crystal spectrometers at low energies, and solid-state semiconductor detectors at high energies. The first two have a low throughput and the last are very expensive, so only strong sources can be observed with them at present, though further instrument developments should improve this. The semiconductor detectors are usually cryogenically cooled germanium crystals with an energy resolution of typically 1-2 keV (see section 2.1.4). They can be used to look for spectral features such as cyclotron lines, already seen in Her X-1, which enable the magnetic field strength of the compact star, typically $\sim 10^8$ T, to be deduced. The detection of nuclear emission lines will allow the elemental composition of emitting objects to be studied; an iron line near 7 keV has already been observed from the supernova remnant Cas A, the Perseus cluster of galaxies and other clusters. Solid-state detectors can be used to study nuclear as opposed to electromagnetic phenomena, especially in compact objects and

galactic nuclei, for example the electron-positron annihilation line at 511 keV detected from the galactic center.

d) Time-Variation Studies. X-ray sources show changes in emission on a wide range of time scales, with both regular and irregular patterns. Regular periodicities vary from the 30 ms of the Crab pulsar's rotation to the 35d precessional cycle seen in Her X-1. Fine time resolution of a millisecond or better is required to study the shortest irregular fluctuations in the output of accretion-disk binary sources, in order to improve our understanding of accretion-disk mechanisms and the structure of the neutron stars within them, or to provide more positive identification of those containing black holes. Timing plays a part in the observation of all compact sources, as both total flux levels and spectral characteristics may change with time; even the output of active galactic nuclei can vary significantly in as little as 100 s (Tennant et al 1981). It is a widely used principle in astronomy that the minimum time scale of emission variations sets an upper limit on the size of the emitting region or object, using the relationship

$$R_{\max} \approx c T_{\min} \quad (1.1)$$

where R is the radius, T the characteristic time scale and c the speed of light. Temporal observations can thus provide important constraints on the size of the X-ray sources.

e) Imaging Observations. These are used to: map the structure and spectral variations of extended sources, like supernova remnants, galaxy clusters and regions around active galaxies; locate previously known gamma-ray sources, by using their hard X-ray emission, more accurately than gamma-ray detectors allow; and resolve complex source fields, like the galactic center region and clusters of galaxies. At photon energies ≤ 5 keV, grazing-incidence mirrors and position-sensitive detectors can be used to form images of extended sources and source fields. But at harder energies different techniques must be used, such as a modulation

collimator, or a pseudo-random mask on a position-sensitive proportional counter.

f) Polarimetry. Polarisation of the X-ray flux is caused when it is emitted partly or wholly by the synchrotron process, so detection of polarised emission provides a good method of discriminating between synchrotron and inverse-Compton processes, both of which produce power-law spectra. The polarised fraction if it occurs is small, generally $\leq 1\%$, and instruments capable of detecting these levels need large-aperture telescopes. Polarimetry should be useful in the study of the energy generation in active galactic nuclei, the geometry and mechanisms of accretion disks in binary systems, and possibly the extended emission regions of radio galaxies.

X-ray astronomy has grown to be of major importance to the whole field of astronomy in its comparatively short lifetime. X-ray observations provide the best method of studying accretion phenomena, neutron stars and black holes, the structure and evolution of active galaxies, and intracluster gas. They also serve as another window on several other interesting astronomical objects and processes, such as variable stars and supernova remnants. While the future may not see the discovery of major new types of X-ray sources, there is bound to be substantial progress in the knowledge of those sources already detected, and amongst other results, this should lead to the first definite identification of the existence of a black hole in the Universe.

CHAPTER 2 : HARD X-RAY DETECTORS AND THE L.A.P.A.D. EXPERIMENT

The 'Large Area Phoswich Array Detector' (LAPAD) uses inorganic scintillators to detect the X-ray photons, which is one of several possible methods of detecting cosmic X rays. As LAPAD is a hard X-ray experiment, only those four methods currently being used to detect X rays above 20 keV will be discussed. All the methods are essentially ways of turning the incident photon into an electrical pulse, which can then be processed electronically and its information stored by computer. Each detection system has different characteristic properties which can be exploited to measure different types of information about the photons, such as their energy, direction and time of arrival. The characteristics of these four systems are compared in Table 2-1.

2.1 Hard X-ray Detection Techniques

2.1.1 Proportional Counters

Although they are mainly used for soft X-ray detection, proportional counters' upper energy threshold can be raised to 100 keV or more by using a gas of high atomic number at greater than atmospheric pressure.

The basic proportional counter consists of a thin anode wire at kilovolt potential along the axis of a small earthed cylinder. The cylinder has a side window to admit the photons, and is filled with an inert gas. An entering photon interacts with the gas atoms, liberating electrons which are accelerated towards the anode by the strong electric field. They gain enough energy to create further ion pairs by collisions with other atoms, producing a cascade of electrons onto the anode giving a signal pulse large enough to be measured. One small cylinder is not a convenient geometry, so more sophisticated proportional counters have

Table 2-2. A comparison of the features of the four hard X-ray detection methods currently in use.

<u>Type</u>	<u>Approx. FWHM energy resolution at 60 keV</u>	<u>Decay constant</u>	<u>Highest at. no.</u>	<u>Energy range</u>
Proportional counter	10 %	100 μ s	51 (Xe)	0.1 - 100 keV
Plastic scintillator	50 %	3 ns	6 (C)	15 keV - 10 MeV
Inorganic crystal scintillator (NaI)	25 %	300 ns	53 (I)	15 keV - 10 MeV
Semiconductor crystal	2 %	100 ns	32 (Ge)	1 keV - 5 MeV

evolved using arrays of anode wires, each in a box-section cell formed by a set of earthed cathode wires (Figure 2-1 shows an example). The counter is shielded except for the top face, which has a thin window to contain the gas and a collimator to define a field of view. For hard X rays the gas is usually xenon with $\sim 10\%$ of a molecular quenching gas, such as methane, to stop spurious cascades caused by excited noble-gas atoms. Other developments of the concept are the multiwire proportional counter (MWPC) and the gas-scintillation proportional counter (GSPC). The MWPC has two orthogonal sets of cathode wires read out via delay lines to give positional information on the photon event, while the GSPC relies on detecting the UV light emitted by the excited atoms instead of the anode signal.

The proportional counter's main attractions are that it can be scaled up to large sizes ($\sim 1000 \text{ cm}^2$) relatively cheaply, and that it has good energy resolution, e.g. $\sim 10\%$ full width at half maximum (FWHM) at 60 keV. Its other properties are summarised in Table 2-1. It has a high quantum efficiency at the lower energies, which can be extended up to 100 keV if required, but it gives no positional information except in MWPC form.

2.1.2 Organic Scintillators

All organic scintillators, whether they are crystal, liquid or plastic, have basically similar properties. The type most often used in X-ray astronomy are the plastics, which have the scintillator incorporated in a thermoplastic polymer such as polystyrene.

The scintillation process in organic molecules works by the interacting photon or particle exciting π electrons in the benzene rings, which then deexcite by a sequence of processes including the emission of an optical photon. The scintillator is transparent at visible wavelengths, enabling the small flashes of light produced by the events to

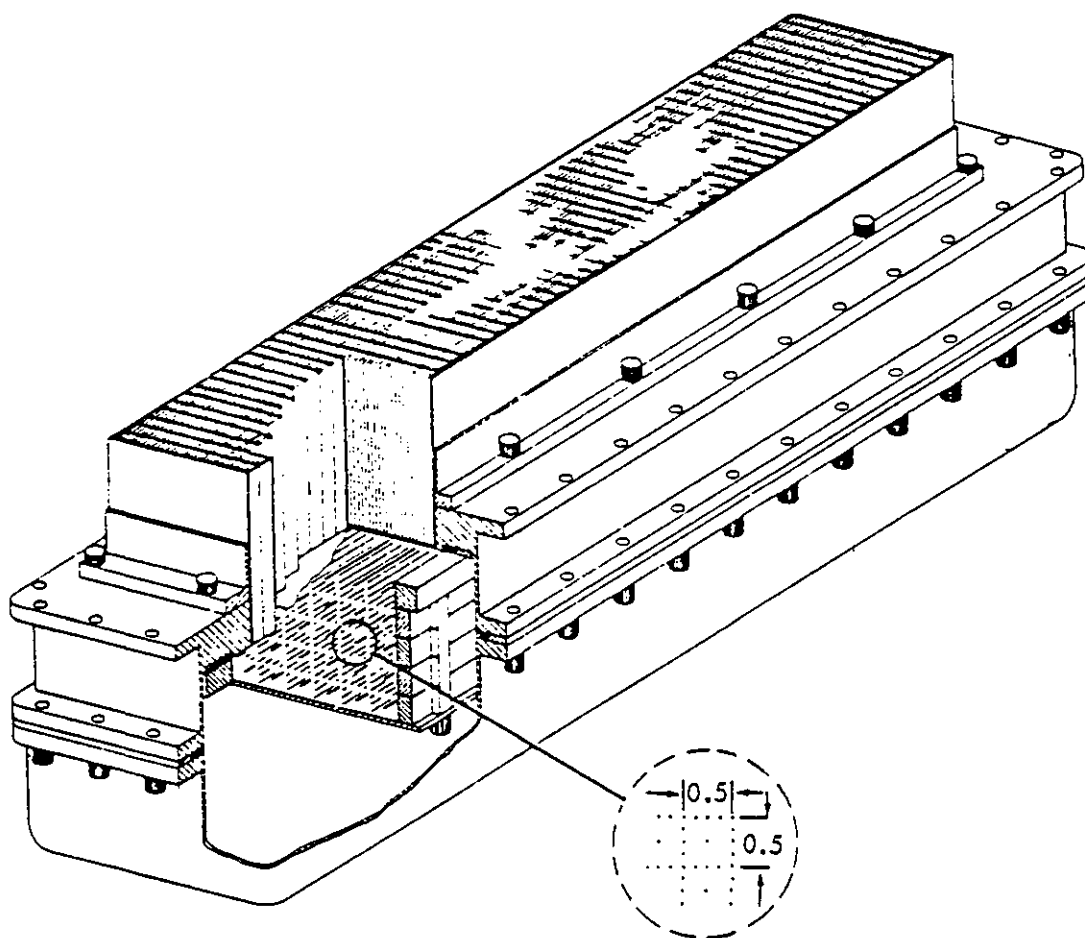


Figure 2-1. A proportional counter used in rocket-borne observations. The collimator (top) is formed of rectangular-section tubing. One detector cell is shown enlarged: the central wire is the anode and the others are cathodes (dimensions in inches). (From Holt 1970.)

be seen by a photomultiplier (PM) in contact with one of the surfaces. The PM translates each scintillation into an electronic pulse, which can then be measured or used to gate another detector's output.

Plastic scintillators suffer from three problems: they have a low light output, barely a fifth that of the best inorganic crystals; their low average atomic number results in a low quantum efficiency for hard X rays; and those which do interact, do so predominantly by Compton scattering, making the incident energy difficult to deduce. So plastic scintillator is often used in applications where just detecting the presence of a photon is required. However, its low average atomic number is of benefit for detecting particle radiation efficiently. This, together with its easy workability, enables it to be used as anticoincidence shielding to veto particle-induced events in other detectors. It has a very fast decay time (~ 5 ns), which makes it suitable for high count-rate applications. A comparison of the properties of plastic scintillator and anthracene, the best of the organics, with the major types of inorganic crystal scintillator is shown in Table 2-2.

2.1.3 Inorganic Crystal Scintillators

There is a more important class of scintillation detectors, the inorganic alkali-halide crystals, usually NaI or CsI, doped with an activating impurity such as thallium. They function in a similar way to the plastics, the difference being that the interacting photon creates electron-hole pairs which can deexcite by emitting an optical photon. The PM-output pulse height is similarly proportional to the energy lost in the crystal.

A basic detector design would be a cylindrical crystal viewed by a PM through a thick glass or perspex slab to spread the light more evenly over the photocathode. The whole detector would be surrounded by

Table 2-2. A comparison of the properties of six types of scintillator.

<u>Type</u>	<u>Max. Z</u>	<u>Light output</u> (% of NaI(Tl))	<u>Decay Constant</u> (ns)	<u>Peak λ</u> (nm)	<u>Density</u> (g/cm ²)	<u>Hygroscopic</u>
NaI(Tl)	53	100	230	413	3.67	Yes
CsI(Tl)	55	45	1000	565	4.51	No
CsI(Na)	55	85	630	420	4.51	Yes
Bi ₄ Ge ₃ O ₁₂	83	10	300	480	7.13	No
Plastic (NE 120)	6	29	3	425	~1.0	No
Anthracene	6	43	30	440	1.25	No

shielding, except for a collimated entrance window. The shield could be either a passive absorber, or an active anticoincidence system consisting of further scintillator sections monitored by their own PM's.

Collimation could be achieved by simply extending the shield forward in a long cylindrical tube, or by mounting a honeycomb of absorbing material in front of the main crystal. Figure 2-2 shows such a simple detector design. Better and more complex designs are possible, using the 'phosphor-sandwich', or 'phoswich', system first suggested by Wilkinson (1952). Two different types of scintillator, with different decay time constants, are placed in optical contact and viewed by the same PM.

An electronic decay-time discriminator circuit is used to distinguish between long and short PM output pulses, and thus deduce the medium in which the event occurred. Only events occurring wholly in the main crystal are accepted, in order to exclude photons which Compton scatter, depositing only part of their energy in the main crystal. The second crystal can be used as either an active collimator by having many holes drilled through it and being placed in front of the main crystal, or as a rear shield by being placed immediately behind it. The latter configuration also has the benefit of removing the lightpipe and PM assembly from the 'active volume' (the parts of the detector inside the shielding, where particle or gamma-ray events that occur can be detected).

These crystal scintillators have several advantages. They have high densities and high atomic numbers, producing high quantum efficiencies. Their high light output gives better energy resolution than the organics, e.g. $\sim 25\%$ FWHM at 60 keV; the best being NaI(Tl), followed by CsI(Na) and CsI(Tl). A comparison of their properties is shown in Table 2-2. An added advantage is that they can be made in various geometries, though not as easily as the organics. However, they have the disadvantage that they are hygroscopic, and must be kept sealed from the atmosphere to prevent the surface degrading. The energy range of these detectors is

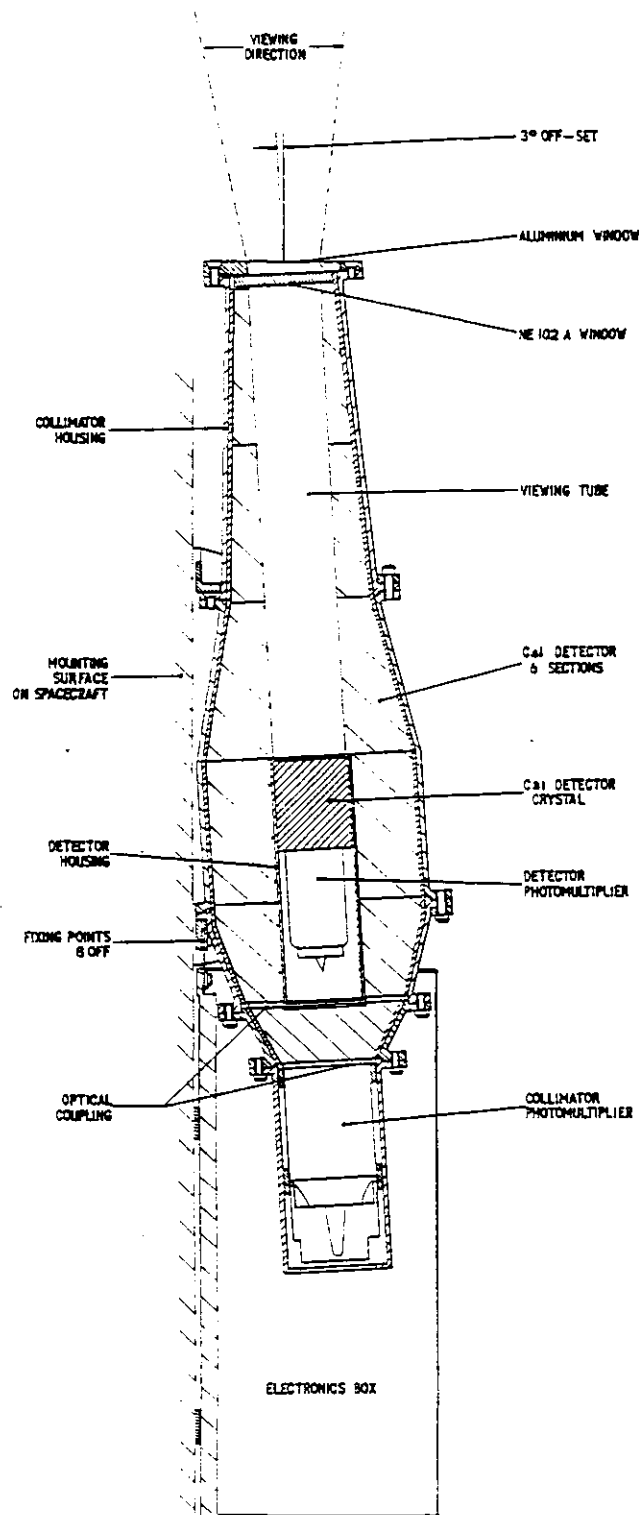


Figure 2-2. A basic scintillation detector, showing the central crystal and shield/collimator crystal arrangement. This is the detector of Expt. F on the Ariel-5 satellite. (From Coe 1976.)

limited to ~ 15 keV at the lower end by noise in the PM tube, but can extend up to several MeV depending on the thickness, density and composition of the crystal.

2.1.4 Solid-State Detectors

Large semiconductor crystals of germanium or silicon have been used as high-resolution spectrometers in the medical and nuclear physics fields for some time, but as yet have had only limited success in X-ray astronomy.

Photons interacting in the crystal produce electron-hole pairs, which migrate to the electrodes under the high electric field (~ 1 kV/cm) applied across them. The charge collected is again proportional to the energy lost in the medium, enabling the photon energy to be measured by pulse-height analysis of the detector output. Many more electron-hole pairs are created in a semiconductor than are optical photons in a scintillator. Therefore statistical fluctuations are much smaller in semiconductors and their energy resolution is much better, typically by an order of magnitude or more. To prevent thermal excitation of electron-hole pairs producing a high background noise level, the devices must be operated at cryogenic temperatures, usually being cooled with liquid nitrogen.

A typical detector for astronomical observations comprises a central germanium crystal of dimensions ~ 5 cm, enclosed by an anticoincidence shield of scintillator (see Figure 2-3). The shield has an entrance aperture with collimator and thin beryllium window, and a rear aperture for the cold finger from the cryostat. The crystal is usually kept sealed in a vacuum to prevent molecular collisions with the surface, which would increase the background level. Larger detectors use arrays of crystals rather than one monolithic crystal, as they are easier to manufacture.

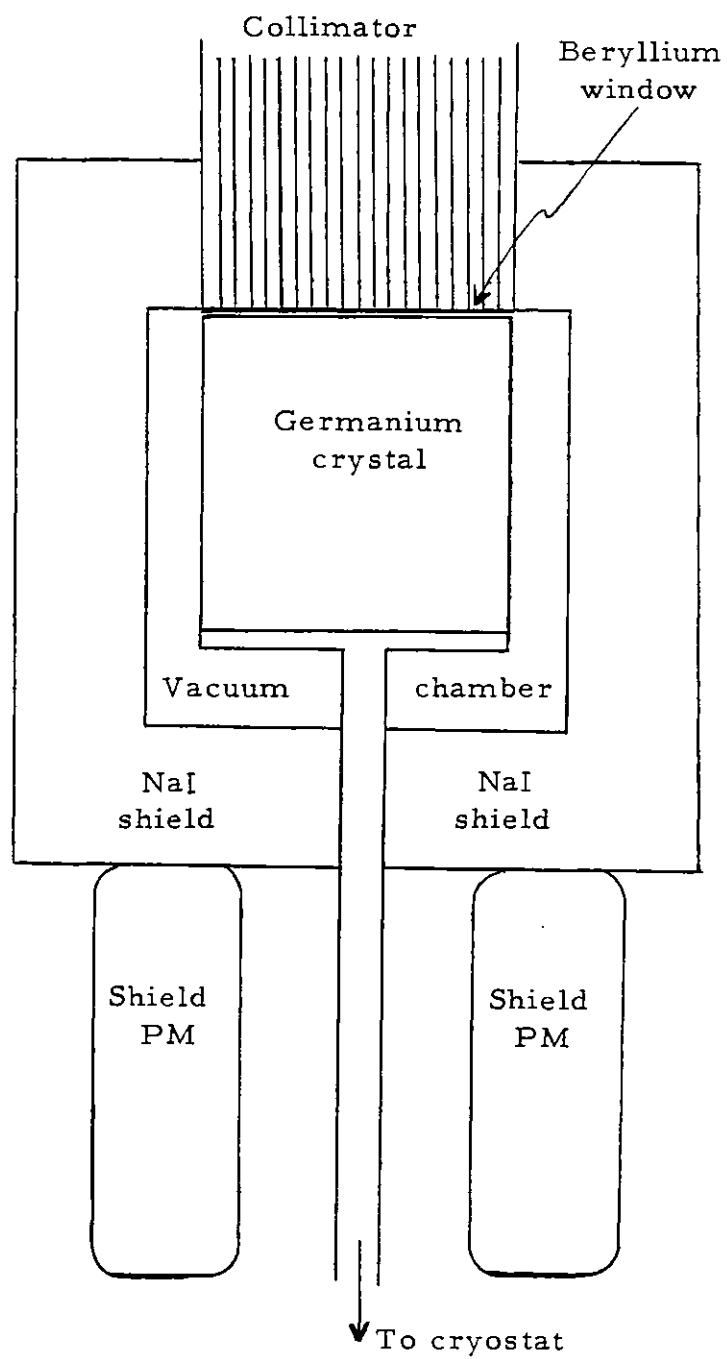


Figure 2-3. Schematic diagram of a basic semiconductor detector, showing the central germanium crystal and the anticoincidence shield surrounding it.

The main attraction of these detectors is their unparalleled energy resolution of hard X rays, their operating range extending from less than 1 keV up to several MeV. They have a typical resolution of 1-2 keV, which gives $\sim 2\%$ FWHM at 60 keV. This makes them ideal for observing spectral details, such as the cyclotron emission feature at 55 keV from Her X-1 (Voges et al 1982), the electron-positron annihilation line at 511 keV from the galactic center (Riegler et al 1981), and gamma-ray lines from nuclear processes. However, the detectors used so far have been too small and of too low an atomic number (even germanium has a Z of only 32) to have a quantum efficiency to match that of the inorganic scintillators at high energies. This is unlikely to change until semiconductor detectors of higher atomic number are available, e.g. CdTe and HgI_2 (Whited & Schieber 1979). Some of the new types being developed have the additional benefit that they can be operated at ambient temperature, so dispensing with the bulky and inconvenient cryogenic cooling systems.

2.2 The Large Area Phoswich Array Detector

The Space Physics Group at Imperial College has developed the LAPAD experiment from a prototype module in 1979 to its final status as a fully pointable array of twelve identical modules with a total collecting area of 1600 cm^2 . It is designed for balloon-borne astronomical observations in the hard X-ray region of 16-200 keV.

Each module is based on a 130mm-diameter phoswich scintillator consisting of a primary 2mm-thick NaI(Tl) crystal backed with a 14mm-thick CsI(Na) crystal (see Figure 2-4). They are viewed through a 14mm-thick Pyrex lightpipe by a 130mm-diameter EMI 9791 photomultiplier. There is a 0.1mm-thick aluminium window in front of the primary crystal to seal the phoswich unit from light and humidity. The 1.05° FWHM field of view is produced by a tantalum honeycomb collimator; and background radiation

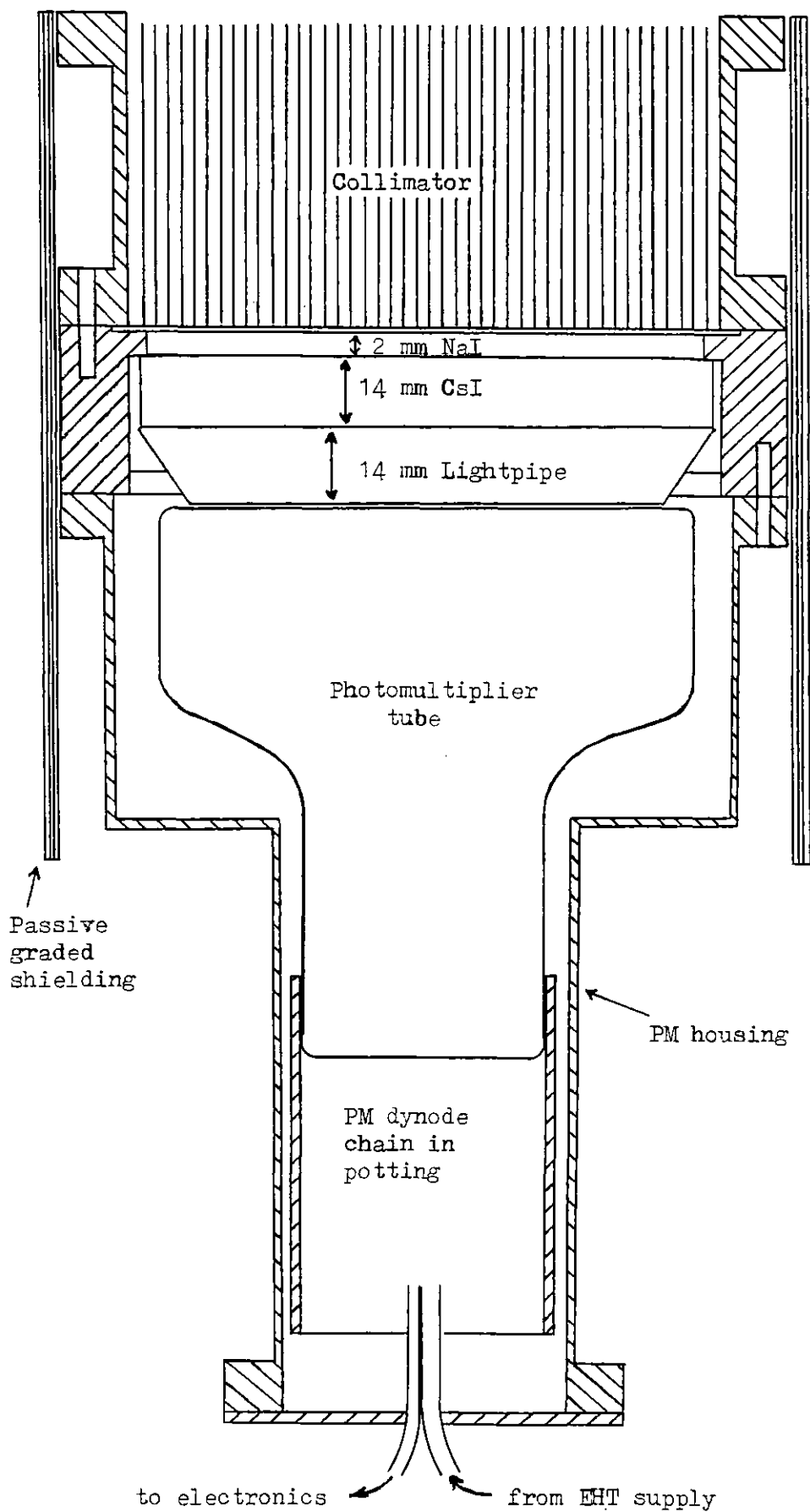


Figure 2-4. Schematic diagram of a LAPAD module. Overall dimensions are 18 cm diameter, 25 cm height, and 5 kg weight.

through the sides is screened by a passive graded shield of lead, tin and copper (2 mm: 1.6 mm: 0.3 mm). The photomultiplier, phoswich and collimator have separate aluminium housings — that of the photomultiplier being lined with magnetic-shielding foil to screen the tube from external magnetic fields. Each module is calibrated using a small (~ 10 Bq) source of Am-241 placed immediately in front of the primary crystal. This source is encapsulated in plastic scintillator, which is viewed along a perspex lightpipe by a 25mm-diameter EMI 9734 photomultiplier. Alpha-particle events in the source are used to tag its X-ray photons detected in the phoswich, which should be seen at 60 keV.

The modules are mounted in a 4 x 3 array in a supporting tray, to which are also attached the electronics boxes and EHT supply units. The tray is pointed in elevation and cross-elevation by two torque motors coupled through harmonic-drive gearboxes, and is oriented in azimuth by the University of Tasmania steerable platform on which it is flown. Overall pointing accuracy is designed to be within 0.1° . The two motors are controlled by a Z80A microprocessor, and can also be used to 'rock' the field of view in either of the two axes, across the source to an empty area of sky on either side. The rocking can be commanded in a continuous movement across the source, or in an alternating on-source/off-source sequence.

Each detector module has a set of electronics cards which discriminate between events occurring in the two crystals, and perform an approximate temperature compensation on the measured energy and rise time. A second Z80A microprocessor collects data on the energy and rise time of every event in the modules, whose rise time is in the region corresponding to events in the primary crystal. It formats this data together with the output from various housekeeping monitors (voltages, temperatures etc.) for PCM transmission to the ground station at 48 kbits/s. The event counts are formatted in three concurrent arrangements:

a) Spectral Mode — creates a matrix of the counts detected in each 12s period arranged as: 32 energy channels x 8 rise-time bins x 12 detector modules. The energy channels are 4 keV wide over the range 16-80 keV, and 8 keV wide over 80-200 keV. The highest energy channel contains counts ≥ 200 keV. This mode gives the greatest flexibility in selecting valid counts in post-flight data analysis.

b) Fast Mode — sums the counts from the twelve modules within rise-time and energy limits selected by telecommand from the ground, giving a fine time resolution of 2 ms.

c) Intermediate Mode — also sums the counts from the twelve modules within the same selectable rise-time limits set in (b), but in eight energy bands (16-32 keV, 32-48, 48-64, 64-80, 80-112, 112-144, 144-176, and ≥ 176 keV), with a time resolution of 30 ms.

At the ground station, the housekeeping data and count rates are displayed by a Research Machines 380Z microcomputer on two monitor screens to keep the control staff informed of the observations' progress. Simultaneously, the incoming raw data stream is recorded by a Racal 4DS tape deck. For the 1983 flight there were two ground stations, one located at the launch site and the other 350 km downrange. The latter was to extend the potential flight distance, which is normally limited by the radius of radio contact to ~ 700 km. The flight tapes are returned to Imperial College to be transferred onto the group's PDP-11 mini-computer for subsequent data analysis.

2.3 LAPAD Flight History

The LAPAD experiment had four flights — the first was a test flight of just one module, the others of the full array. Their details are summarised in Table 2-3. The flights were made in collaboration with the University of Tasmania, who provided the steerable balloon platform together with their own X-ray detector (see Figure 2-5). This is a

Table 2-3. LAPAD flight history

<u>Campaign</u>	<u>Launch (UT)</u>	<u>Termination (UT)</u>	<u>Float Duration</u>	<u>Sources Observed</u>	<u>Comments</u>
UTIC79 Mildura, Australia	20:00 1979 Sep 7	08:44 1979 Sep 8	8 hours at 6 mbar	—	Test flight of 1 module — no sources due to pointing failure
UTIC80 Alice Springs, Australia	19:30 1980 Nov 24	20:50	—	—	Balloon burst during ascent
UTIC81 Alice Springs, Australia	20:04 1981 Dec 1	05:19 1981 Dec 2	7 hours at $3\frac{1}{2}$ mbar	IC 4329A Sco X-1 GC region	Pointing limited by failure in Tasmanian-built elevation drive
UTIC82 Uberaba, Brazil	—	—	—	—	No flight due to bad weather at launch site
UTIC83 Cachoeira Paulista, Brazil	06:40 1983 Mar 26	17:08	7 hours at $4\frac{1}{4}$ mbar	Sco X-1 SS 433 MR 2251-178 SMC X-1	Balloon burst (?) during flight, parachute failed and payload was destroyed by impact on landing

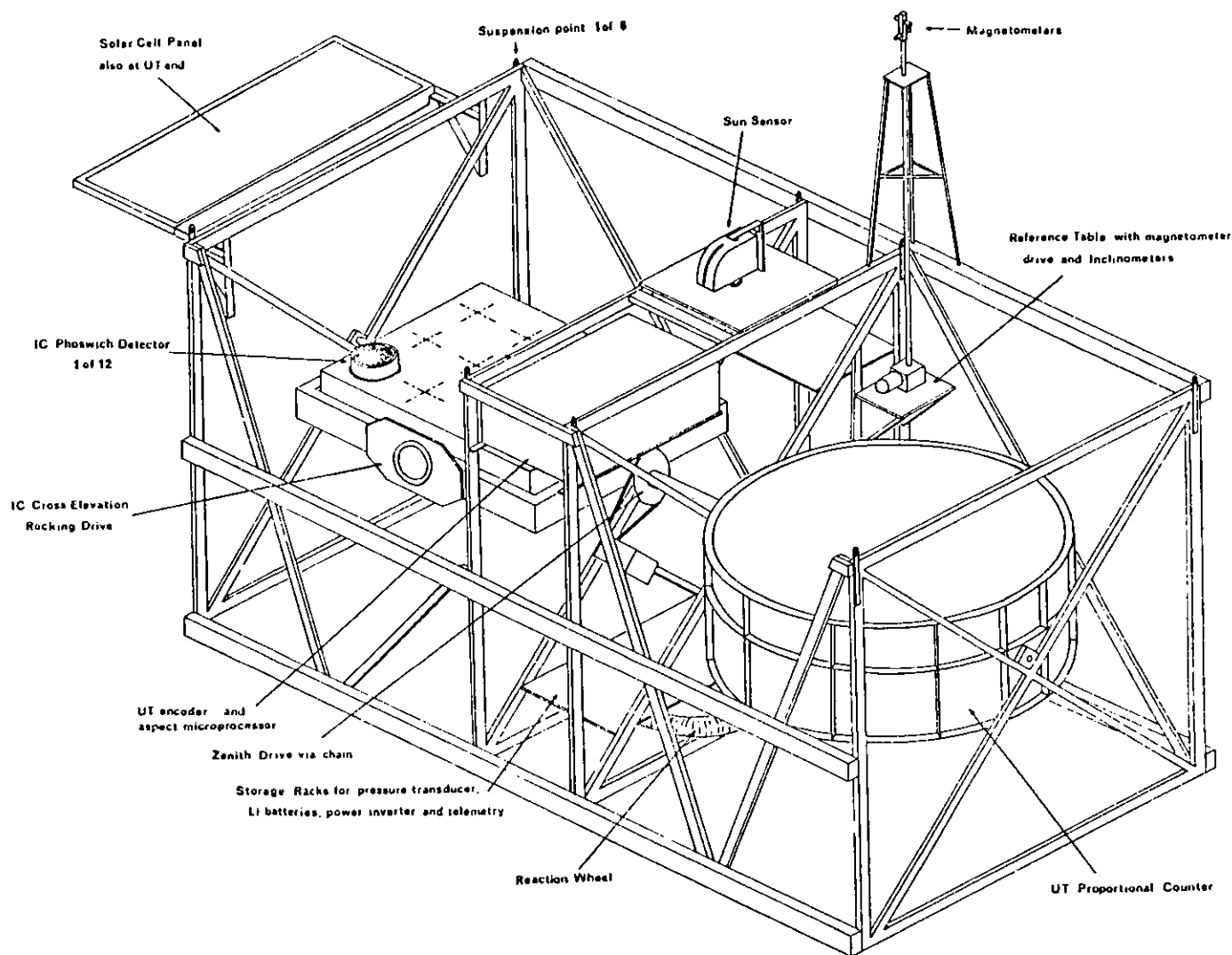


Figure 2-5. The University of Tasmania balloon platform, with the Imperial College LAPAD on the left, and the University of Tasmania proportional counter on the right.

multilayer, multianode proportional counter of active area 5200 cm^2 , filled with xenon at one atmosphere, covering the energy range 10-100 keV. It has a 2° FWHM field of view, and a laboratory-measured energy resolution at 60 keV of $\sim 25\%$ FWHM (c.f. $\sim 40\%$ for LAPAD).

A good balloon flight for such detectors should last at least 24 h at a float height of around 3 mbar pressure, enabling up to a dozen sources to be observed for 1-4 h each. Unfortunately, none of the actual flights lasted this long for various reasons. The 1979 flight was terminated early because no sources could be pointed at due to a malfunction of the orientation system. On the 1980 flight the balloon burst before reaching float altitude, though the payload was not damaged in the descent. The 1981 flight was a partial success, although it was launched well after wind turnaround due to prolonged bad weather on the ground, when the resultant high wind speed at float altitude allowed only a short flight before approaching the radio-contact horizon. In addition, a mechanical failure occurred in the Tasmanian-built elevation drive system at launch, which restricted the detectors' pointing to the range $80-85^\circ$ elevation, so only drift-scan observations of sources passing within 10° of the zenith were possible. The 1983 flight started very successfully, although a smaller balloon had to be used due to a smaller launch pad, which resulted in a lower float altitude. After $10\frac{1}{2}$ h of flight however, either the balloon burst or a cut-down command was accidentally received, the parachute failed or was fouled by the balloon, and the payload free-fell back to earth. The LAPAD equipment was largely destroyed by the impact on landing; only a few of its parts could be salvaged, such as some of the crystals and collimators.

The two partially successful flights did produce a number of useful observations, the main results of which are presented in Chapter 5. During the 7 h at float altitude on the 1981 flight, three sources passed within 10° of the zenith. The first was the Seyfert galaxy

IC 4329A, which had not been previously looked for at hard X-ray energies. The second was the very strong soft X-ray source Sco X-1, the most thoroughly studied of the low-mass binary galactic bulge sources. The third was the galactic center region, a rich source field which was observed in two drift scans as it rose and set. Figure 2-6 shows the areas of sky covered by these two scans. Good signals were detected from the sources GX1+4 and GX5-1, as well as a small signal from an old transient X-ray source H1705-25. However, no exposure was made to the galactic center itself, whose X-ray counterpart, GCX, is probably the most interesting source in the region.

The 1983 observations were hampered by large atmospheric depths to the four sources viewed, caused by a combination of the lower float altitude and the low elevation of three of the sources at the time. Viewing through a large column of air mainly affects the lower end of the detector's energy range, so the first source to be observed, the strong but soft Sco X-1, produced a much smaller signal than in the 1981 observation. The second source was the peculiar star SS 433, which had not been previously looked for above 30 keV. The third source was the quasar MR 2251-173, again not a source looked at before in hard X rays. The fourth source was the bright extragalactic massive-binary SMC X-1, a well-known source, but one whose spectrum at high energies has yet to be clearly measured. Although no signal was detected from the last three sources, the upper limits measured still provide useful constraints on the models of emission mechanisms and physical processes occurring in them.

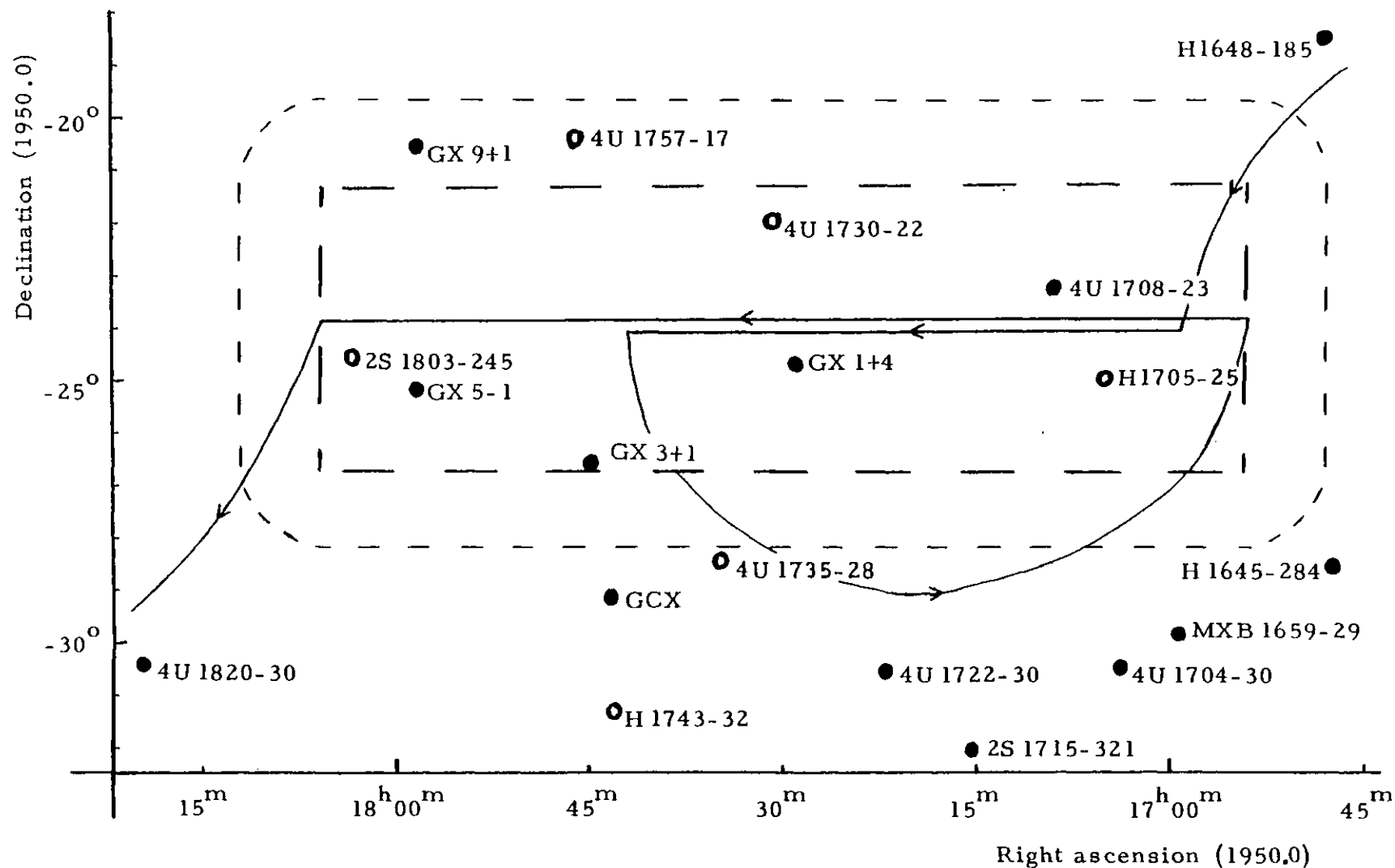


Figure 2-6. Region near the galactic center observed on the 1981 flight. Filled circles are permanent sources; open circles are transients. The inner rectangle is the area covered by the center of the field of view; the outer rectangle is the limit of the field's edge.

CHAPTER 3 : GRADED PASSIVE SHIELDING SYSTEM

The LAPAD experiment was originally designed to have an active anticoincidence shielding system, consisting of a closed cylinder of plastic scintillator surrounding each detector module. However, it was later decided to investigate the use of passive shielding, probably of the graded type, as an alternative. Shielding is required to reduce the effect of the X-ray and particle backgrounds which exist in the upper atmosphere where the detector is flown. The X-ray background is of atmospheric and cosmic origin, peaking at 30 keV and falling off with energy according to an approximate power law of $E^{-1.4}$. The particle background arises from cosmic rays and their local nuclear interactions.

The graded shielding method uses a high-Z material to absorb the background photons most effectively (Z is atomic number). However, all materials produce X-ray fluorescence if the incident photon energy is above their K-edge energy. For high-Z materials, this is above LAPAD's lower energy threshold. So lower-Z layers are inserted to absorb these fluorescent photons, progressively attenuating their energy until it falls below the detector's lower threshold, which in the case of LAPAD is 16 keV. The lower-Z layers are also more efficient absorbers of the background particle flux.

3.1 Design of the Shielding

As weight is usually of prime importance in astronomical X-ray detectors, the design must have the highest efficiency for a given weight. For the 1981 flight, this weight limit was set at about $2\frac{1}{2}$ kg per module. The final design was arrived at in three stages: using attenuation coefficients (e.g. Tait 1980), fluorescent energies and

fluorescent yields (Kaye & Laby 1973), the most effective combination of reasonable materials was found; the directions around a detector module which required shielding most were determined, to find the most effective shielding geometry; and finally the layers' thicknesses were calculated.

3.1.1 Choice of Materials

In practice there are only a few reasonable combinations of materials, as there are many constraints on the choice. They must be solid metals for handling and shaping, nonprecious for financial practicality, and nonradioactive. There should also be as few layers as possible for simplicity and ease of construction.

The main, outer, high-Z layer is responsible for most of the background radiation absorption, and the highest-Z material suitable is lead ($Z = 82$). Although depleted uranium ($Z = 92$) is available, which would be a more efficient absorber, it is naturally radioactive and would create a background component of its own. The other metals beyond lead in the periodic table are even more radioactive.

Given the main material, the lower-Z layers can now be chosen to match lead's fluorescent energy of 75 keV. Five combinations were considered as possibilities for the other layers. In order to compare the effectiveness of these combinations, the amounts needed to attenuate an arbitrary fraction (99%) of the lead's fluorescent photons were calculated (see Table 3-1). Although it was the heaviest combination, choice (e) was adopted with the tin and copper for the following reasons: Cerium is a rare-earth metal costing $\sim$ £500/kg, and almost 10 kg would be needed. Barium is chemically reactive in contact with water and is also too expensive. Antimony and molybdenum are about five times the cost of tin, itself a fairly expensive semiprecious metal. Copper was chosen over zinc as the third layer, because it was already available and has a

Table 3-1. Five possible combinations of secondary absorbers, and the amounts required to absorb 99% of lead's K-fluorescent photons ($E = 75$ keV).

	<u>Second layer</u>	<u>Third layer</u>	<u>Total weight</u> (g/cm ²)
(a)	1.0 g/cm ² of ⁵⁶ Ba (or 0.9 g/cm ² of ⁵⁷ Ce)	0.2 g/cm ² of ⁴² Mo	1.2
(b)	1.0 g/cm ² of ⁵⁶ Ba (or 0.9 g/cm ² of ⁵⁷ Ce)	0.5 g/cm ² of ³⁰ Zn (or 0.5 g/cm ² of ²⁹ Cu)	1.5
(c)	1.6 g/cm ² of ⁴² Mo	—	1.6
(d)	1.6 g/cm ² of ⁵⁰ Sn (or 1.4 g/cm ² of ⁵¹ Sb)	0.15 g/cm ² of ⁴² Mo	1.75
(e)	1.6 g/cm ² of ⁵⁰ Sn (or 1.4 g/cm ² of ⁵¹ Sb)	0.3 g/cm ² of ³⁰ Zn (or 0.3 g/cm ² of ²⁹ Cu)	1.9

virtually identical absorption coefficient at tin's fluorescent energy.

Tin is expensive to obtain in pure sheet form since it has few uses as a pure element other than for tin-plating steel. This problem was avoided by buying sheets of pewter with a high tin content (from George Johnson & Co., Birmingham). The most suitable grade they produce is 92-6-2, which is 92% tin, 6% antimony and 2% copper. The antimony presents no problem as it is an adjacent element in the periodic table, while the copper is in an acceptably small proportion and forms the following layer anyway.

3.1.2 Determination of the Positioning

Having decided on the materials for the three layers, an experiment was performed to find the positions where the shielding was most required. For this, a monoenergetic source was directed at one of the detector modules from a set of elevation angles, θ , to show from which directions most of the background photons would enter to produce counts in the detector system. Measurements were made for two X-ray energies: 122 keV (Co-57) which is an energy the shielding would substantially affect, and 1.3 MeV (Co-60) which would show what happened for photons of an energy that would be little affected (Figures 3-2 and 3-4 respectively). The first of the two was made partly as a duplication of a previous experiment by Hackett (1981), to act as a check.

The only discrepancy between Figure 3-2 and Hackett's results (reproduced in Figure 3-3) was for angles from behind the phoswich crystal. However, it was calculated that many more counts should be absorbed by the CsI rear crystal than appeared to have been in this experiment. These extra counts may have resulted from using too broad a range of pulse rise times, which would count some of the CsI pulses as valid, or from photons scattered from the neighboring detector modules. In Hackett's measurements, a different system for the pulse-height analysis

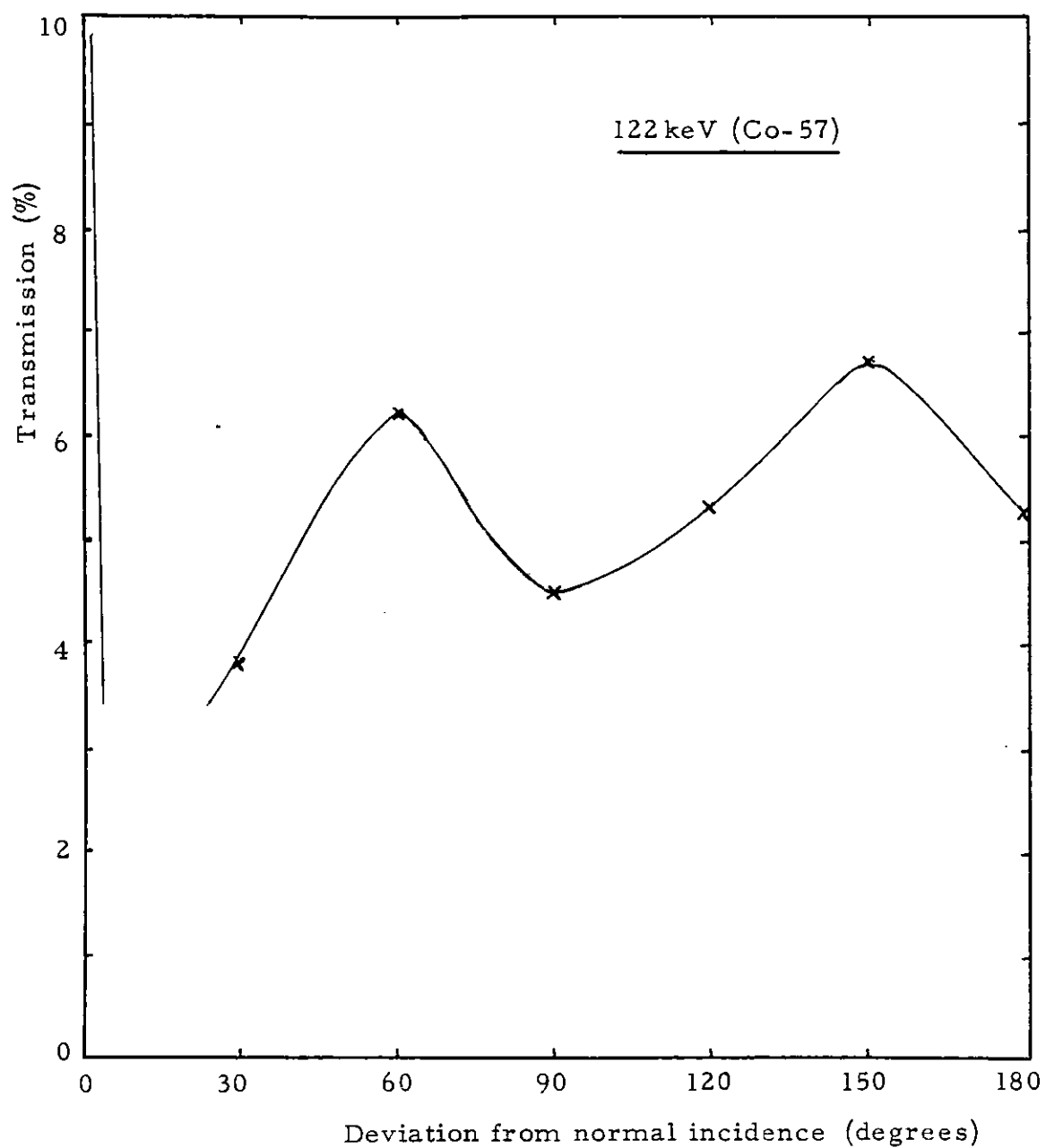


Figure 3-1. Transmission through the sides of a detector module for X rays within the LAPAD energy range (122 keV from Co-57).

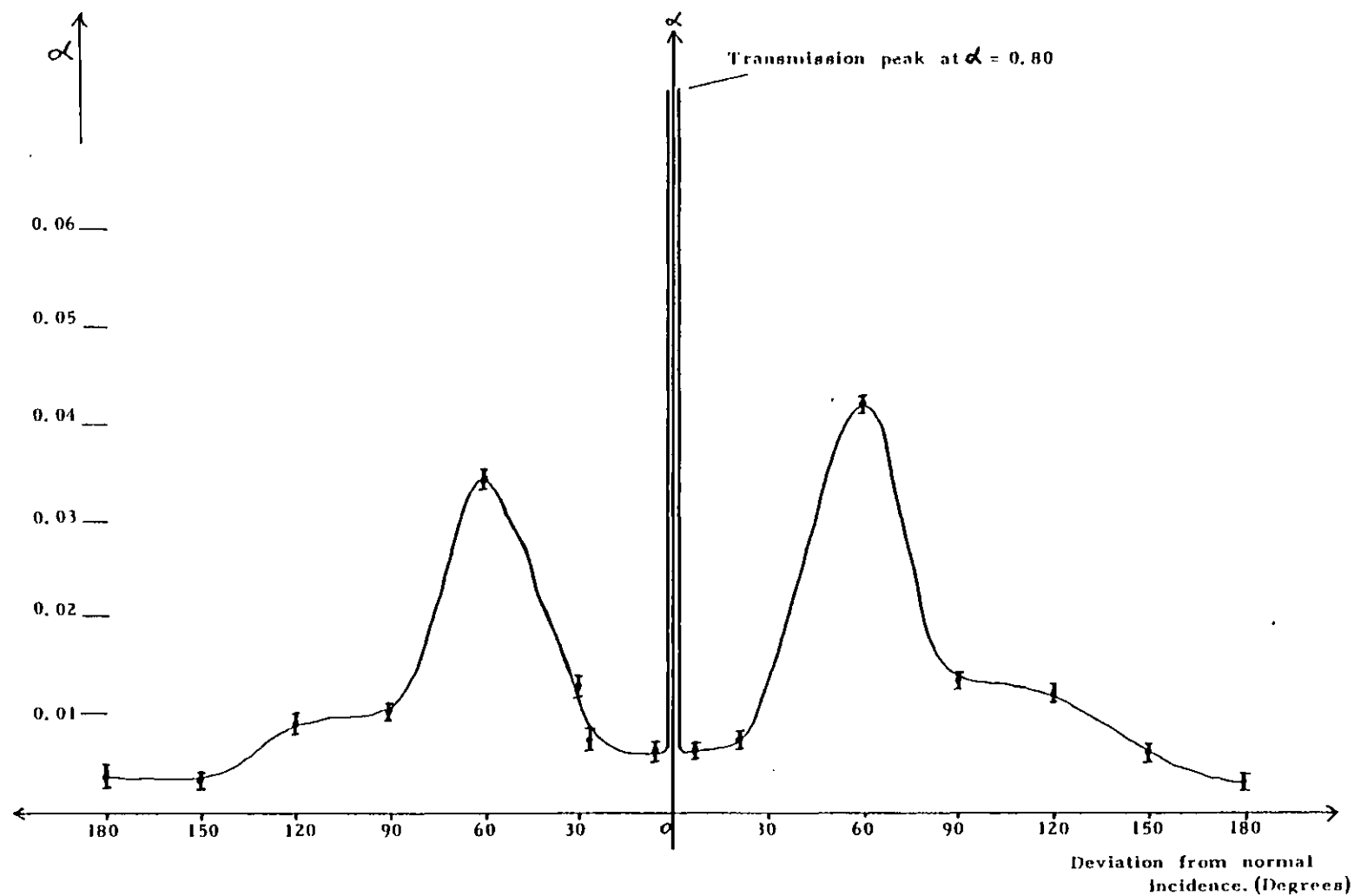


Figure 3-2. Transmission through the sides of a detector module of X rays at 122 keV (Co-57), as measured by Hackett (1981).

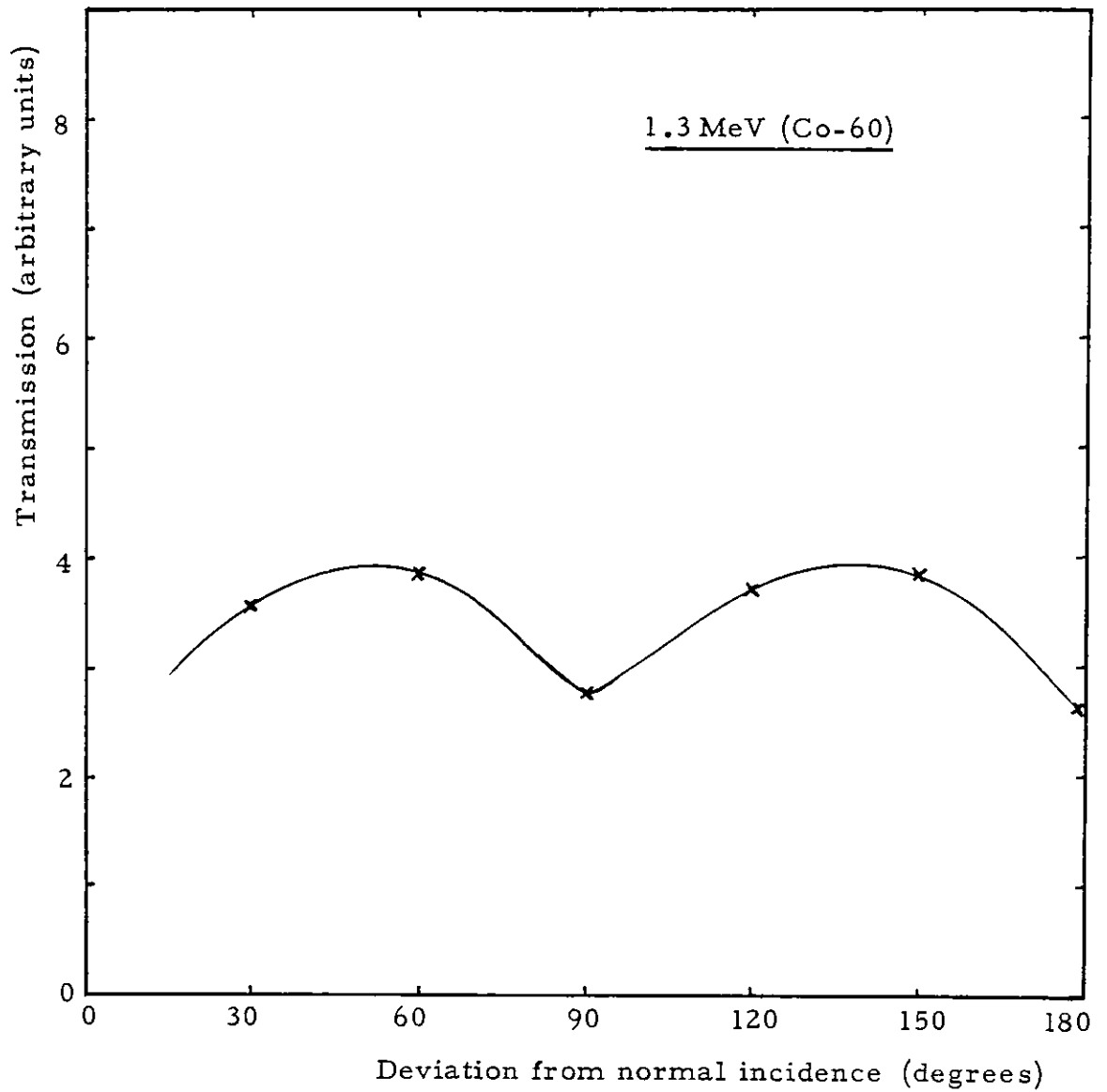


Figure 3-3. Transmission through the sides of a detector module for X rays far above the LAPAD energy range (1.3 MeV from Co-60).

was used, and the detector module was in isolation. Bearing this in mind, the Co-57 experiments showed that most photons were admitted from forward directions between 30° and 90° , and perhaps half as many from rearward directions 90° to 150° , with a minimum at 90° when the thin primary crystal is edge on ($\theta = 0^\circ$ corresponds to direction of view of collimator). This distribution is enhanced when the graph is folded with $\sin\theta$, to take into account the amount of background that would come from the solid angle corresponding to each elevation angle. (The annulus of azimuth between θ and $\theta + \delta\theta$ subtends an angle of $\delta\theta \sin\theta$ steradians; so there would be a larger total contribution from $\theta \approx 90^\circ$ than from $\theta \rightarrow 0^\circ$ or $\theta \rightarrow 180^\circ$, for a background radiation flux of uniform solid-angle distribution).

The Co-60 graph (Figure 3-4) has less variation, as might be expected from the fact that the more energetic photons are less affected by the material surrounding the phoswich crystal. It shows two approximately equal transmission peaks, from forwards and rearwards of the crystal, though again this may be affected by the pulse rise-time limits and scattering from nearby objects.

From these results, it was decided to place the shielding down the sides of the detector modules from 30° back to about 120 - 150° , with a greater thickness forwards than rearwards if possible. The module's diameter is 16 cm and the height of this amount of shielding is about 15 cm, giving a total surface area of shielding required of about 750 cm^2 per module, and hence an areal density for the shielding of 3.3 g/cm^2 .

3.1.3 Calculation of the Thicknesses

It is very difficult to calculate the optimum thicknesses of the three layers to give the greatest total absorption for a given areal density, and it cannot be done definitively. A spectrum of the expected background is required to calculate the number of photons absorbed by

2:4:1 used by a University of Leiden group (Peterson 1975), both with similar phoswich detectors. The tin to copper ratio of 5:1 compares with 3:1 used to absorb the fluorescence from a lead collimator by Lidén & Starfelt (1954).

Later, a better calculation of the ideal thicknesses for the same 3.3 g/cm^2 areal density was attempted, using a Monte-Carlo computer program, to investigate the design further. An atmospheric background spectrum falling off with an $E^{-1.39}$ power law (Ling 1975) was used as an input to a model of the processes occurring in the three layers. The fraction of incident photons transmitted was found, in a series of runs, for a set of different thickness combinations with the same 3.3 g/cm^2 total areal density. The preliminary results show that most reasonable combinations, like the one actually used, transmit 8-10% of the incident photons, but that the lowest percentages are produced by using a higher primary to secondary ratio of $\sim 3:1$. However, further work is required with the program to improve the accuracy of the results, and determine the optimum ratio of thicknesses.

3.2 Testing the Effectiveness of a Prototype Shield

The shield for only one detector module was built initially, to act as a prototype in a number of tests to investigate its design effectiveness.

3.2.1 Repeat of the Angular Survey

The first test was to repeat the previous angular-survey experiment (see section 3.1.2) with the shielding in place, to see from which directions the background photons leaked through the shield. This was only done for the Co-57 energy (122 keV), as the amount of shielding would hardly affect the 1.3 MeV X rays from the Co-60. The result is shown in Figure 3-5; the curve labeled 'without shielding' was not taken

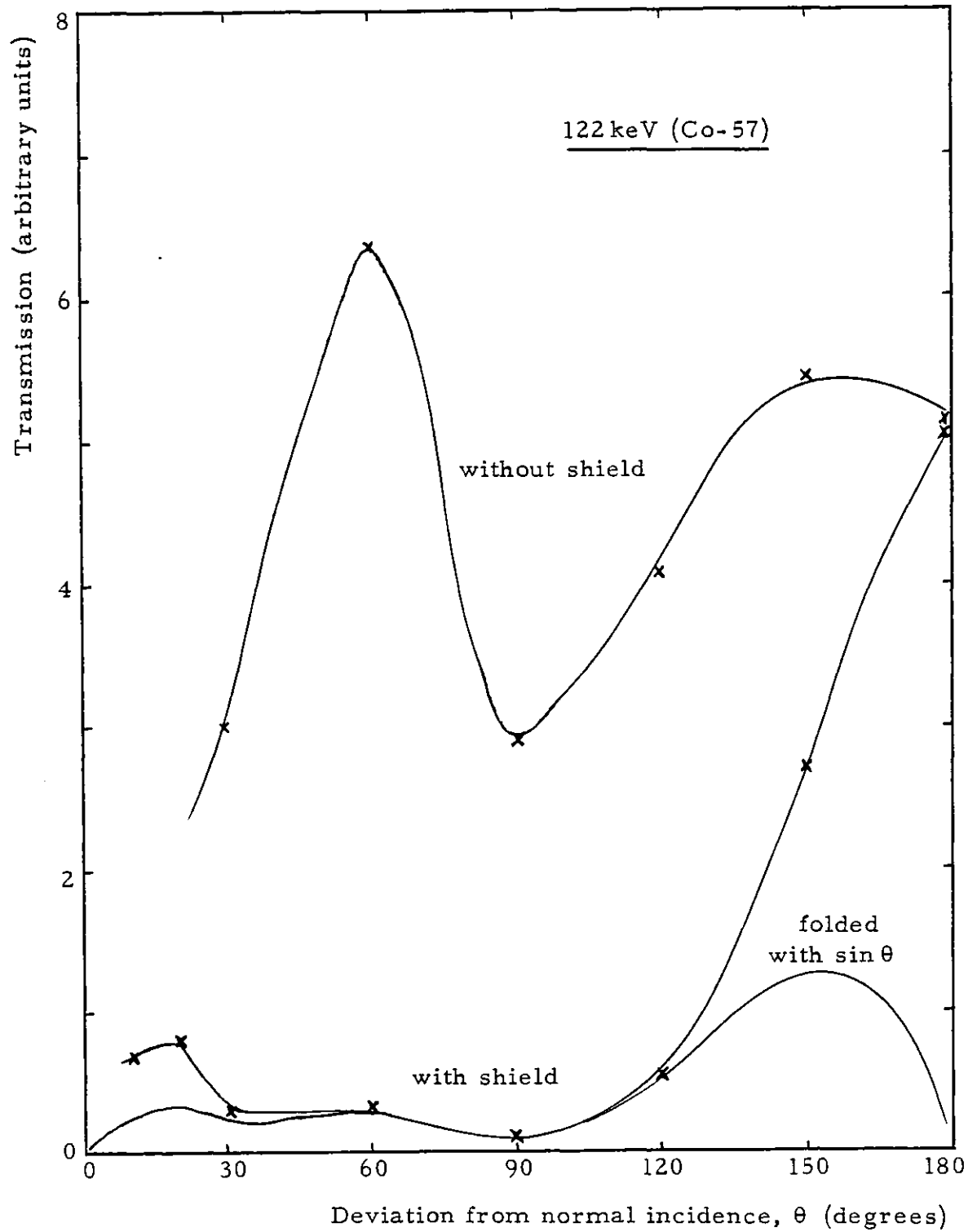


Figure 3-4. Transmission through the sides of a detector module with the prototype shield in place, for 122 keV (Co-57).

from Figure 3-2, but was remeasured at the same time as the 'with shielding' curve — this time however, a collimated source was used. It is interesting to note the lower count rate at 150° relative to 60° in this measurement. This may be a result of the fewer photons emitted in other directions to scatter from nearby objects when using the collimated source.

The 'with shielding' curve was also folded with $\sin\theta$ to take account of the solid-angle distribution. The result is a good flat distribution from 10° to 120° , showing that the shield is being effective over this range. Beyond this, it appeared that there were still many photons being detected which should have been absorbed in the rear crystal. These counts were either caused by accepting too broad a range of rise times again, or by photons being scattered on the inside of the shield. There were substantially fewer such counts in this case than without the shielding, demonstrating that it did have a large effect for these directions.

3.2.2 Transmission through the Surfaces of a Shielded Module

The second test was of a similar nature, intended to find which of the types of surface area on the shielded detector module passed most counted background photons. Four types of surface area were identified: the tantalum collimator, the annular aluminium rim of the collimator housing which separates the tantalum honeycomb from the shielding, the graded passive shielding itself, and the CsI-shielded rear of the module. Five radioisotopes covering a wide range of energies were used as X-ray sources: Am-241 (60 keV), Co-57 (122 keV), Ba-133 (356 keV), Cs-137 (662 keV) and Co-60 (1.3 MeV).

It was found that the aluminium rim acted as a significant gap in the overall shielding at the lower energies (after weighting the results for the area of the rim). At 60 keV it contributed about half the total

background, falling to about a tenth at 356 keV, and a twentieth at the higher energies. The relative importance of this unshielded rim depends on the number of photons which are transmitted by it compared to the total number transmitted by the rest of the surfaces — the latter term is approximately equal to the number transmitted by the shielding. To find this graphically, a spectrum of the X-ray background in the upper atmosphere (Ling 1975) was folded with the transmission curve of the shielding, and separately folded with the transmission curve of the 1cm-deep aluminium rim (Figure 3-5). Using the peaks (~ 350 keV and ~ 60 keV respectively) and widths of these transmitted spectra and the areas of the surfaces, the number of photons transmitted through each could be estimated. Roughly a tenth as many photons should pass through the rim as through the shielding; this represents an even smaller fraction of the photons transmitted through all the surfaces together. So the rim would not appear to be a serious deficiency in the shielding's overall effectiveness.

A similar study to the above experimental test was also made entirely by calculation. The background spectrum was roughly divided up into a small number of energy bins and the number of photons penetrating the four types of surface was calculated for each bin for comparison. The result of these very approximate calculations was that $\sim 5\%$ of the photons penetrating the boundaries of a detector module would have entered through the rim. The calculations could not take account of what fraction of those photons would trigger counts in the primary crystal, as this was too complex to model.

3.2.3 Check of the Overall Efficiency

The third experimental test was to establish what fraction of the laboratory background was already absorbed by the prototype shield, and to what extent it was possible to improve upon this. There is a point

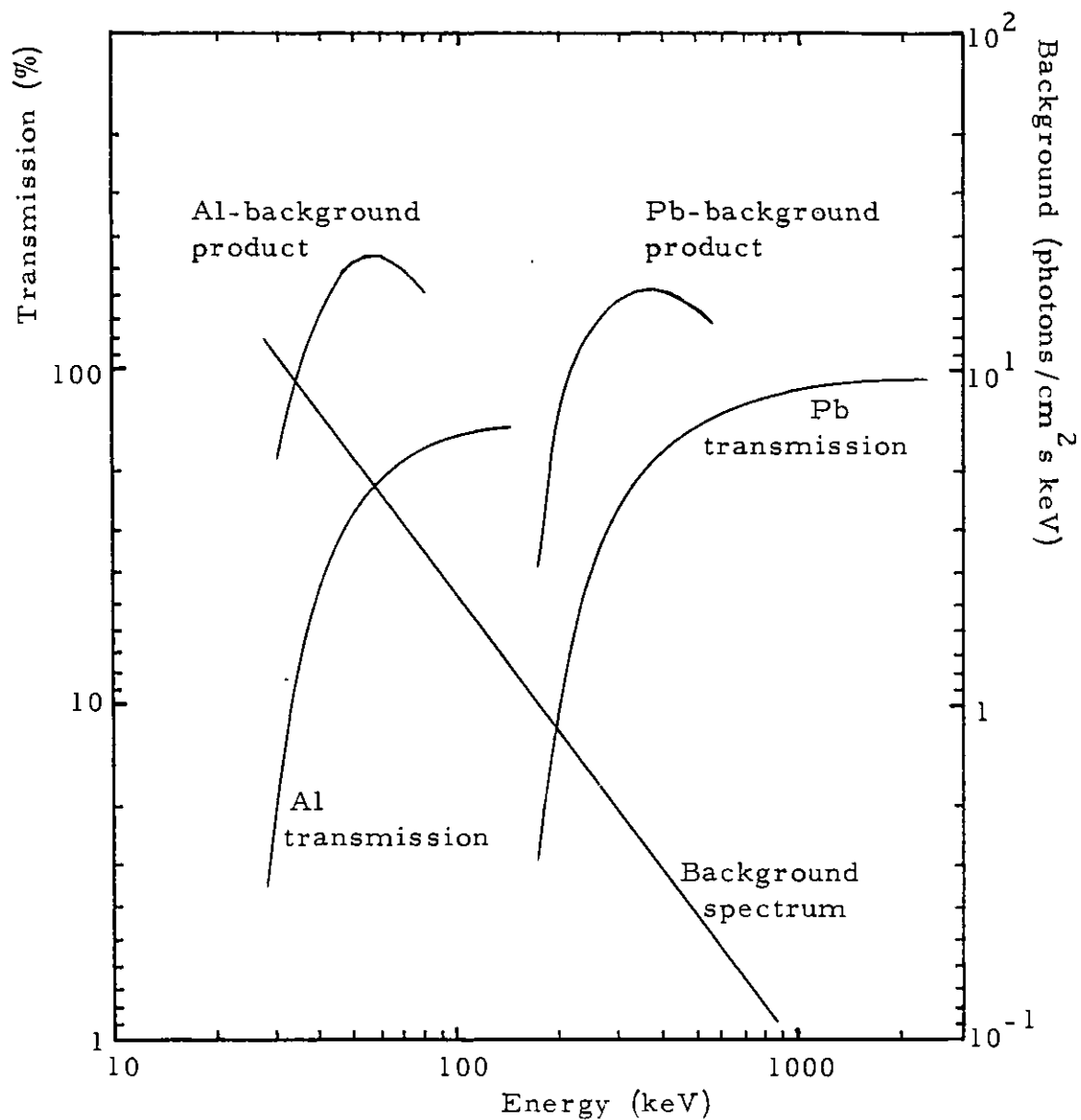


Figure 3-5. Spectrum of the upper-atmosphere background (Ling 1975) folded with the transmission curve of the lead layer of the shield, and with the transmission curve of the 1cm-thick aluminium rim, to find the relative transmission peaks.

where extra shielding material creates more background than it absorbs, though the main point of concern was the intrinsic background level of the detector module itself, caused by spontaneous events inside it. It is obviously not possible to improve on this level. The measurements obtained are shown in Table 3-2. The counts used were events of > 20 keV occurring in both crystals, to measure the total number of photons entering the detector module. In addition to measuring the count rate with the prototype shield in place, it was measured with the front part of the module blocked off using a thick lead sheet, then the same at the rear, and then both together.

Table 3-2. Background level for various shielding conditions

<u>Configuration</u>	<u>Counts/s</u>
No shielding	16.3
Prototype shield	6.1
Shield + rear blocked off	5.3
Shield + front blocked off	5.1
Shield + front & rear blocked off	5.0

It can be seen from the table that these exercises did absorb some further background photons, but few in comparison to those already absorbed. The fall in the count rate with additional shielding can be used to estimate an ultimate value, corresponding to the intrinsic count rate, of 3-5 counts/s. This shows that the prototype shielding already absorbs over 80% of the external, laboratory background, which is quite a reasonable proportion. However, care should be taken in applying this result to the performance of a module's shielding in flight, as the laboratory background is likely to be different from the upper-atmosphere background; the former is caused by radioactive decays at high energies,

instead of being a predominantly soft continuum like the latter.

3.3 Future Design Improvement

It is unfortunate that no comparison of in-flight performances can be made of the active and passive shields, since they were never flown simultaneously — after the first flight the anticoincidence facility was used for the calibration system. However, four variations on the basic design of passive shielding were flown, to investigate some of the problems found in the previous sections:

a) Shielding the collimator rim to determine how much background does enter through it.

b) Shielding the back of the module to check the assumptions that photons from the rear should be vetoed by the CsI crystal.

c) 1 mm Pb & 1.6 mm Sn } both in front of and behind the main
d) 2 mm Pb & 0.8 mm Sn }
crystal. These two were to investigate the effect of varying the ratio of primary to secondary absorbers. The 0.3 mm of copper was kept the same for both. (C.f. the standard thicknesses in section 3.1.3.)

Each variant was mounted on one of the four modules at the corners of the tray. The variations were intended to produce only small, if any, differences in the background levels of the modules concerned, in order not to risk significantly degrading the detector's performance. Since the differences are not expected to be large, and there has been no immediate requirement yet for the results, the data have still to be analysed to produce background rates for the modules separately, so comparison is not possible at this stage.

However, the background spectrum is available for the detector as a whole, i.e. averaged over the twelve modules. Spectra for the 1981 and 1983 flights are shown in Figure 5-1, and their features discussed in section 5.1.

When LAPAD is rebuilt, it would be worthwhile to incorporate the experience gained since the design of the original shielding system into devising an improved version. There may be lessons to be learned from a comparison of the four variations' background rates, and further work with the Monte-Carlo program should certainly produce a set of thicknesses closer to the optimum than the approximate calculations used earlier. It remains to be seen to what extent such improvements will lower the detector background level.

CHAPTER 4 : SPECTRAL DATA ANALYSIS METHOD

The data on the detected photons are arranged in the Spectral, Fast and Intermediate modes (see section 2.2), but only the Spectral Mode data will be dealt with in this work. The Spectral Mode stores events in an array of 32 energy channels x 8 rise-time bins for each of the twelve modules. The whole 32 x 8 x 12 array is read out and reset every 12 s for inclusion in the data format which is transmitted to the ground station. The choice as to which events are to be taken as valid can then be made during the subsequent data analysis to give maximum flexibility, instead of in real time during the flight as for the other two data modes. In principle there can be a different set of valid rise times for each energy channel of each module. Then, knowing where the detector was pointing during each 12s period, the valid events can be used to find the spectrum. The steps involved in this process are described in the first section of this chapter.

However, the resulting 'measured spectrum' is not the same as that emitted by the source, the 'source spectrum', nor is there a simple relationship between the two. The difference arises from the interactions of the photons between entering the top of the atmosphere and being detected as photomultiplier output pulses. There are a number of processes which alter the intensity and apparent energy of the photons as a function of photon energy. In order to find the true source spectrum, the effects of these processes must be removed, a technique known as 'unfolding' or 'deconvolution'. This requires an understanding of each effect and the calculation of a total interaction matrix for them, as detailed in the second section.

There are two fundamentally different methods for unfolding the

spectrum using this matrix, which are discussed in the third section. The one adopted is then described in detail.

4.1 Compiling the Measured Spectrum

There are several operations involved in compiling the measured spectrum from the raw data stream: checking for corrupt data, selection of valid counts on the basis of rise times, compensation for detector dead time, allowance for each module's error in energy calibration, and removal of the background to find the measured flux due to the source. These are all performed by computer program.

4.1.1 Removal of Corrupt Data

For each frame of 32 8-bit words, the onboard microprocessor generates four parity-checking words, which are transmitted as the first part of the following frame. If any corruption of the data occurs subsequently, it can be detected by comparison of the frame with its error-checking words. The four words are generated by the method of odd parity, in a two-dimensional arrangement, so that each bit is checked twice. This enables single bit errors to be located and corrected if required, though attempts at correction break down if there are more than a few errors per frame. With the low percentage of corrupt frames found in the observational data, it is not thought worthwhile to try to correct any.

Comparison of each frame with its error-checking words is made before it is used in the analysis, and any showing inconsistencies are omitted. In addition, an error log is made of each observation to record what fraction of the data is corrupt. During the balloon's ascent the number of bad frames can be high while the radio links are being adjusted, but after reaching float altitude it is typically $<0.1\%$ on the two flights.

4.1.2 Selection of Valid Counts

The counts to be used as valid events have then to be chosen from the eight rise-time bins for each energy channel and for each detector module. The eight bins contain a peak, corresponding to the faster NaI rise time, and the tail of the slower CsI events' distribution. Only those counts which are due to NaI events should be accepted. The bins containing the peak were found to be nos. 3,4,5 & 6, for an average distribution of the twelve modules, and for energy channels up to about 160 keV. Possible future improvements would be to find the peak bins for each module individually, and for the channels above 160 keV. The latter was not incorporated earlier, because no source signal was found above ~ 100 keV.

4.1.3 Correction for Dead Time

Each detector module has a different dead-time fraction, depending on its count rate and veto time. The onboard electronics measure this fraction for each module, using all the counts occurring in it. The dead time is typically 7-12% during the observations. The valid counts in each 12s accumulation period are corrected for this effect before being used, still keeping the modules' spectra notionally separate at this stage. If the dead-time fraction is $x\%$, the valid counts are multiplied by a factor of $\frac{1}{100 - x}$.

4.1.4 Correction for Energy Calibration

Every few hours in flight, the detector is switched into Calibration Mode to keep track of the changes in energy calibration of the modules. The channel in which the Am-241 peak falls can later be compared to where it fell before the flight when the module was correctly calibrated. The results of the nearest calibration session to each observation are then used to correct the spectrum for each module. The fraction of

counts in each energy channel which should have occurred in the adjacent channel is calculated, and the spectra adjusted accordingly. The spectra from the different modules are summed after this stage.

4.1.5 Removal of Background

The measured flux during any observation has to be split into its source and background components. This is usually done by binning the count rate by angle over the path of the detector's field of view, with the source contribution showing up as a peak at the source's position. A similar method has been adopted for this analysis, binning the count rates according to the angle of offset from the source. A triangular shape corresponding to the collimator response function is fitted to the plot for each energy channel, enabling the background and source fluxes to be resolved (see Figure 4-1).

First, a check is made that the source emission peak coincides roughly with the zero offset angle, to confirm the pointing calculations and rule out possible source confusion. Using the set of energy channels which gives the best signal-to-noise ratio, a sequence of least-squares fits is made to find the peak position of the best-fitting triangular distribution.

A precise fit is made to each energy channel independently, with this same peak position. 30 offset-angle bins of 0.2° width are used, half of them corresponding to pointing directions to the left of the source in azimuth, the other half to the right. The triangular response fitted has a FWHM of 1.6° , this being the experimentally determined shape and size of one collimator's response (Hackett 1981). A future refinement is planned to make the width a variable of the fit, like the peak position, in order to allow for any jitter in the pointing system's stability. Each of the 30 count-rate points has a different Poissonian standard deviation associated with it, so fitting the best line to them becomes a

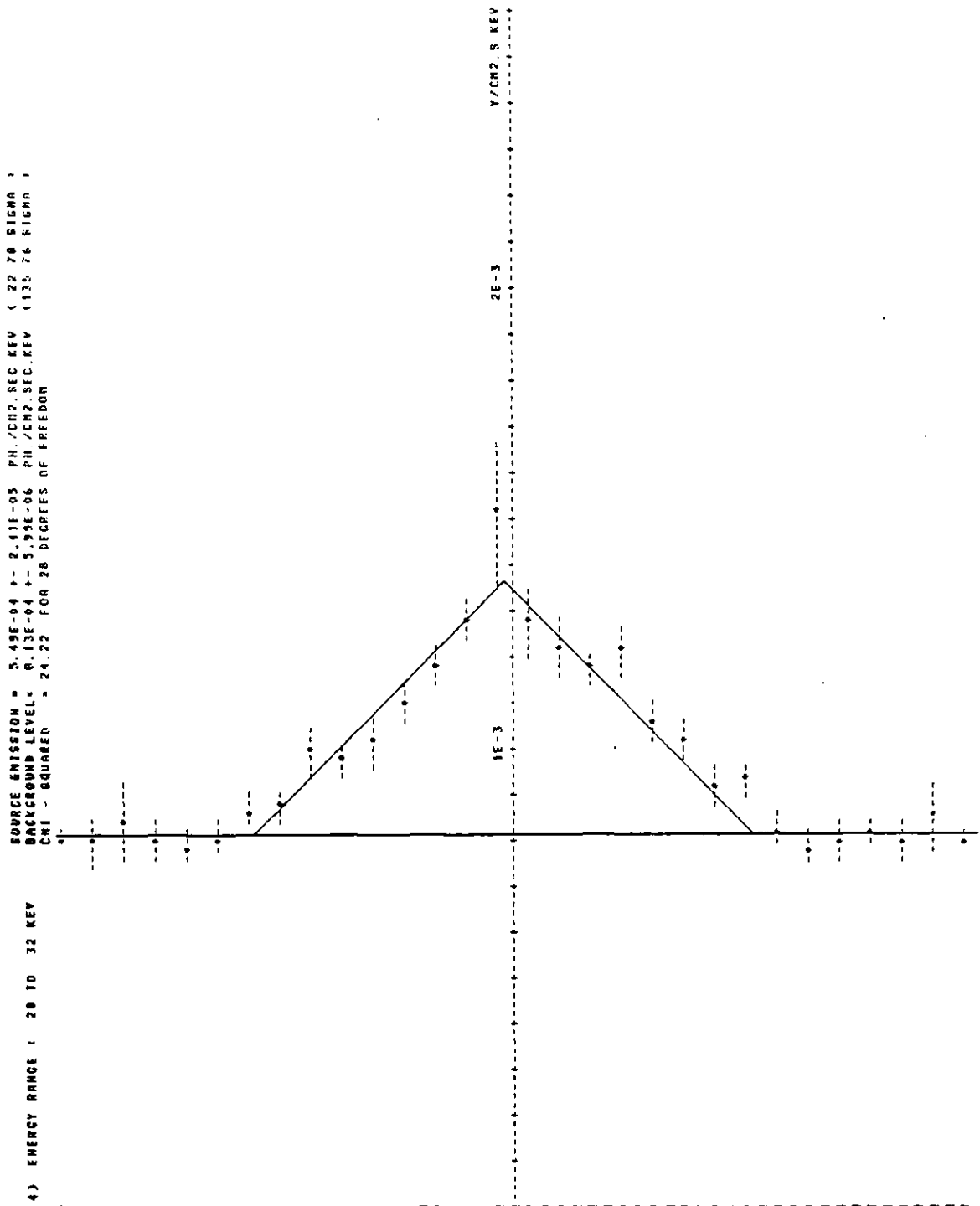


Figure 4-1. An example of the count rate against source offset angle plots produced by the analysis program, in order to calculate the source and background components. The triangular shape corresponding to the collimator response function has been drawn in by hand to illustrate the calculated fit.

weighted linear regression problem. The solutions, adapted from Riegler (1969), are

$$\text{Background Level} = \frac{\sum w_i y_i \sum w_i x_i^2 - \sum w_i x_i \sum w_i x_i y_i}{\sum w_i \sum w_i x_i^2 - (\sum w_i x_i)^2} \quad (4.1)$$

$$\text{with variance} = \frac{\sigma^2 \sum w_i x_i^2}{\sum w_i \sum w_i x_i^2 - (\sum w_i x_i)^2}, \quad (4.2)$$

$$\text{and Source Flux} = \frac{\sum w_i \sum w_i x_i y_i - \sum w_i x_i \sum w_i y_i}{\sum w_i \sum w_i x_i^2 - (\sum w_i x_i)^2} \quad (4.3)$$

$$\text{with variance} = \frac{\sigma^2 \sum w_i}{\sum w_i \sum w_i x_i^2 - (\sum w_i x_i)^2}; \quad (4.4)$$

where the weights and variances, w_i and σ^2 , are related by

$$\sigma^2 = \sigma_1^2 = w_1 \sigma_1^2 = \dots = w_{30} \sigma_{30}^2, \quad (4.5)$$

x_i are the offset angles, y_i are the count rates, and the sums are over the offset-angle bins ($i = 1$ to 30); and the formulae have been simplified by using an offset-angle scale with unit FWHM. The fitting program produces for each energy channel, the measured source flux, the background level and the χ^2 value of the fit (see Figure 4-1).

The fitting program was tested by feeding in data binned by the cross-elevation rock angle, obtained when no source was in view. All the fluxes, variances and χ^2 values calculated were consistent with random deviations.

4.2 The Interaction Matrix

There are six processes which act on the incident photon spectrum between the top of the atmosphere and being detected as photomultiplier output pulses. These processes are shown in the order in which they act in the flow diagram in Figure 4-2. The first four attenuate the flux as a function of photon energy, but the final two cause a redistribution

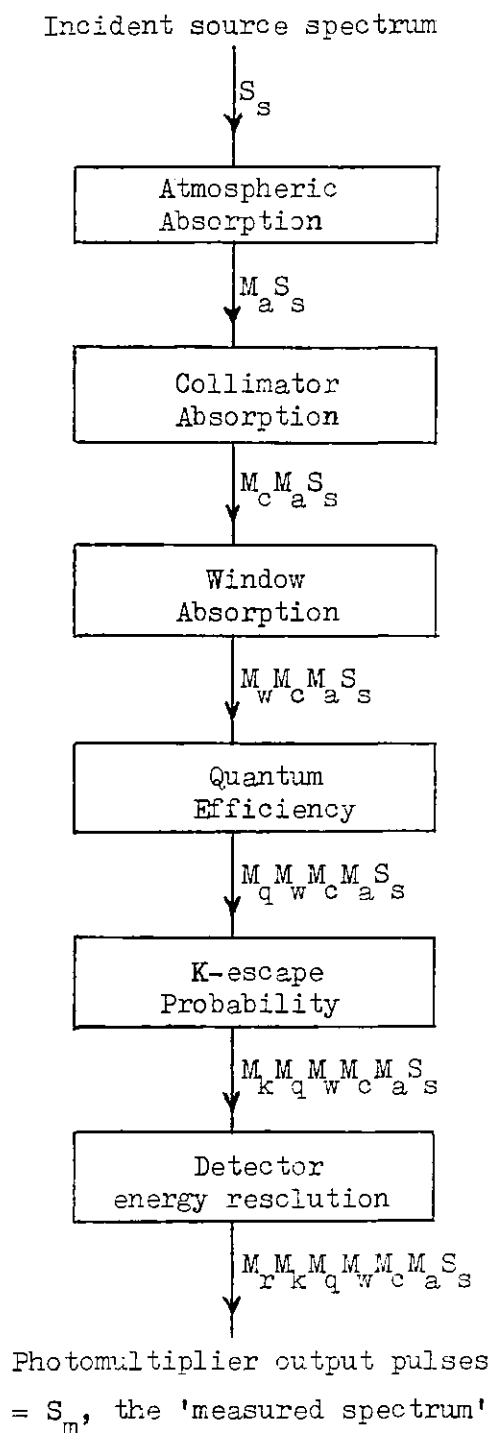


Figure 4-2. A flow diagram showing the sequence of six processes which modify the source's spectrum in the course of its detection.

of the spectrum by changing the amount of energy detected from the photon. These processes must be understood and modeled before their effects can be removed from the spectrum. For each, an interaction matrix is calculated, whose elements $M(i,j)$ give the probability that a photon beforehand in channel j will afterwards be in channel i . Because photons initially outside the 16-200 keV range can be detected within it by the redistributive effects, extra energy channels are used to model this. They are 8-12 keV, 12-16 keV and eight 8keV-wide channels covering 200 to 264 keV, chosen to include all energies which would contribute $>10^{-3}$ of the counts in any of the detector's real energy channels.

4.2.1 Atmospheric Absorption

Even though the amount of residual atmosphere at balloon altitudes is small, ~ 3 mbar, it is still a strong absorber, particularly at the low-energy end of the range where it can attenuate the flux by a factor of 100 or more, making it the largest of the six effects. Unfortunately the air pressure at float altitudes is one of the least accurately measured parameters, but this affects the intensity of the deduced source spectrum much more than its shape. The atmospheric path length to the source is the average atmospheric depth divided by the sine of the average source elevation during the observation.

The interaction matrix for atmospheric absorption, M_a , is a diagonal matrix with elements

$$M_a(i,i) = \exp(-\mu_i x) \quad (4.6)$$

where x is the atmospheric path length to the source in mass units, and μ_i is the total mass coefficient of air for the average energy of channel i . The coefficients were calculated from Davisson (1965), as are all the others in the following sections. Each observation has different values for the atmospheric depth and source elevation, so a new M_a must be calculated for each.

4.2.2 Collimator Absorption

The transmission efficiency of the collimators at normal incidence is not perfect. The thickness of the honeycomb cell walls obscures a fraction of the crystal surface area, calculated to be 6.5%. In addition, the walls are not all perfectly parallel to the main axis, casting a shadow over a further fraction of the surface area — this was calculated to be an average 14.9% for the twelve collimators, using empirically determined values for the average cell slope of each. The total average transmission efficiency is therefore 78.6%. Hackett (1981) has measured the transmission efficiency at normal incidence of one unit, finding a value of 80 ± 2 %. These results are in good agreement, and the value of 78.6% was adopted.

The interaction matrix for the collimator absorption, M_c , is a diagonal matrix with nonzero elements of 0.786.

4.2.3 Window Absorption

The 0.1mm aluminium window which seals the phoswich crystal also attenuates the photon flux, although its effect is small compared to the atmospheric attenuation. Absorption is ~10% at the bottom of the energy range, falling to <1% above 50 keV.

The interaction matrix for the window absorption, M_w , is a diagonal matrix with elements

$$M_w(i,i) = \exp(-0.01 \mu_i) \quad (4.7)$$

where μ_i is the linear attenuation coefficient (in cm^{-1}) of aluminium for the average energy of channel i . The values of these elements are listed in Table 4-1.

4.2.4 Quantum Efficiency

There is a probability that a photon will pass right through the primary, NaI crystal without interacting, giving the appearance of a

Table 4-1. The values of the window transmission fraction, quantum efficiency, K-escape peak fraction and photopeak fraction for the LAPAD energy channels.

<u>Energy Channel</u>	<u>Window Transmission</u>	<u>Quantum Efficiency</u>	<u>Escape peak Fraction</u>	<u>Photopeak Fraction</u>
16-20 keV	89 %	100 %	—	100 %
20-24	94	100	—	100
24-28	96	100	—	100
28-32	97	99	—	100
32-36	98	99	19 %	81
36-40	98	100	24	76
40-44	99	100	22	78
44-48	99	100	20	80
48-52	99	100	18	82
52-56	99	100	16	84
56-60	99	99	14	86
60-64	99	99	13	87
64-68	99	97	12	88
68-72	99	95	10	90
72-76	100	92	10	90
76-80	100	89	9	91
80-88	100	83	3	92
88-96	100	75	7	93
96-104	100	69	7	93
104-112	100	62	6	94
112-120	100	56	6	94
120-128	100	49	6	94
128-136	100	45	6	94
136-144	100	41	5	95
144-152	100	37	5	95
152-160	100	34	5	95
160-168	100	31	5	95
168-176	100	28	5	95
176-184	100	26	5	95
184-192	100	24	5	95
192-200	100	23	5	95

lower source flux than is the case. This probability is essentially zero at the bottom of the energy range, rising to $\sim 75\%$ at 200 keV, with a ^{small} sharp dip at 33 keV corresponding to the K-shell absorption edge of iodine (see Figure 4-3).

The interaction matrix for the quantum efficiency, M_q , is again a diagonal matrix, with elements

$$M_q(i,i) = 1 - \exp(-0.2 \mu_i) \quad (4.8)$$

where μ_i is the total linear attenuation coefficient (in cm^{-1}) of NaI for the average energy of channel i . The values of these elements are listed in Table 4-1.

4.2.5 K X-ray Escape

When an incoming photon is absorbed in the crystal photoelectrically, an iodine K-shell fluorescent photon may be emitted. If this photon then escapes from the crystal without being absorbed, the energy deposited will be too small by 29 keV, the average energy of the fluorescent photons. This causes a monoenergetic beam of photons to be seen at two energies, the main 'photopeak' and the lower-energy 'escape peak'. The process only occurs for incident photons above the iodine K-edge energy of 33.17 keV. The probability of K escape occurring for each channel can be calculated theoretically or by Monte-Carlo simulation.

There are formulae for calculating the fraction of events that result in K escape, see for example Lidén & Starfelt (1954). The fraction of absorbed photons which gives rise to K escape from the top surface is given by

$$P(E,t) = \frac{1}{2} \omega_k \delta_k \tau \int_0^t \int_0^{\pi/2} \exp(-\mu x - \mu_k x \sec \theta) \sin \theta \, d\theta \, dx \quad (4.9)$$

where ω_k is the K-fluorescent yield of iodine, δ_k is the fraction of photoelectric processes in the K shell for iodine, τ is the photoelectric absorption coefficient of NaI, t is the crystal thickness, μ is the total

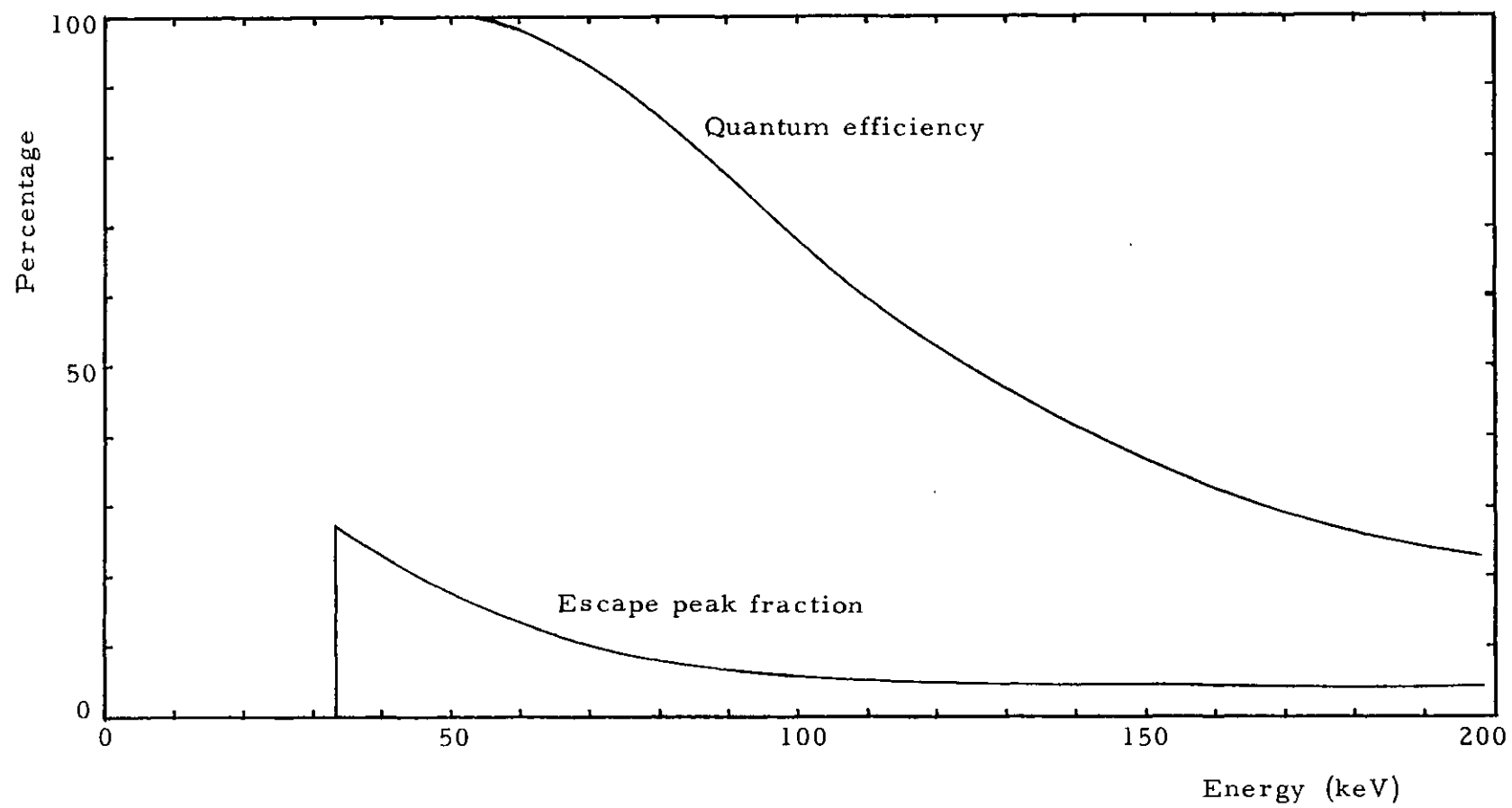


Figure 4-3. The K-escape peak fraction and quantum efficiency for LAPAD.

absorption coefficient of NaI, μ_K is the value of μ for iodine's K X-ray energy, and θ is the angle of K X-ray emission. There are similar expressions for the fractions which escape from the bottom and sides. They can be considerably simplified by the approximation $t \approx \infty$, which is only valid for thick crystals ($t > 5$ mm); for thin crystals such as LAPAD's, they require numerical evaluation.

Instead, a Monte-Carlo study was made of the K-fluorescence process in the crystal to calculate the photopeak and escape-peak fractions for each channel. The program modeled the photoelectric absorption of the incident photons, the fraction of absorptions which result in K fluorescence, and the absorption or escape of the fluorescent photons, using a path length of $20 \mu\text{m}$. The model was one-dimensional, since for the relative dimensions of the NaI disk (130×2 mm), the number of photons escaping from the sides would be negligible compared to the number escaping from the top and bottom surfaces. The calculated photopeak and escape peak fractions are listed in Table 4-1, and the escape peak fraction is plotted as a function of incident energy in Figure 4-3.

The interaction matrix for K escape, M_K , has leading diagonal elements $M_K(i,i)$ equal to the photopeak fraction for channel i , and only a few other nonzero elements, $M_K(i,j)$, given by the amount of the escape peak fraction from channel j which falls in channel i .

4.2.6 Detector Resolution

The detector modules' energy resolution is not perfect, owing to random statistical fluctuations in the numbers of optical photons generated in the crystal and electrons liberated at the photocathode, nonuniform light collection from different parts of the crystal, and nonuniformity of the photocathode. This has the effect of broadening spectral features such as lines and slopes. The numbers of photons and electrons produced will have Gaussian distributions, but the nonuniform-

ities will superimpose an asymmetric distribution. However, it can be seen from Figure 4-4, a plot of a typical module's response to three monoenergetic inputs, that the total distribution remains approximately Gaussian.

The width of the distribution is a function of energy, and differs for the twelve modules, since each has different characteristics. Coe (1976) and Morfill (1971) who have studied this problem previously, have found power-law relationships between the width and the central energy. The measured width of four spectral lines observed with module no. 1 confirms this to be true in this case as well (Figure 4-5):

$$\sigma = c E^{0.81} \quad (4.10)$$

where c is a constant of proportionality, E is the line energy, and σ is the standard deviation of the fitted Gaussian distribution. Measurements to check the similarity of the other detector modules showed substantial variations in the power-law index, ranging from 0.626 to 0.867. So a set of three line-width measurements was made for each module, using the 32 keV (Ba-133), 60 keV (Am-241) and 122 keV (Co-57) lines, to determine the power-law index and proportionality constant for each.

The interaction matrix modeling the detector resolution, M_r , has elements $M_r(i,j)$ calculated by summing over all modules the fraction of events of energy in channel j , which would be registered in channel i :

$$M_r(i,j) = \sum_{m=1}^{12} \frac{W_i}{\sigma_{jm} \sqrt{2\pi}} \exp \left[\frac{-(E_i - E_j)^2}{2 \sigma_{jm}^2} \right] . \quad (4.11)$$

σ_{jm} , the width of the distribution for channel j of module m , is found using equation 4.10 with the empirical values for its parameters. W_i and E_i are the i 'th channel's width and average energy respectively.

4.2.7 The Total Interaction Matrix

The complete model of what happens to a photon between entering the

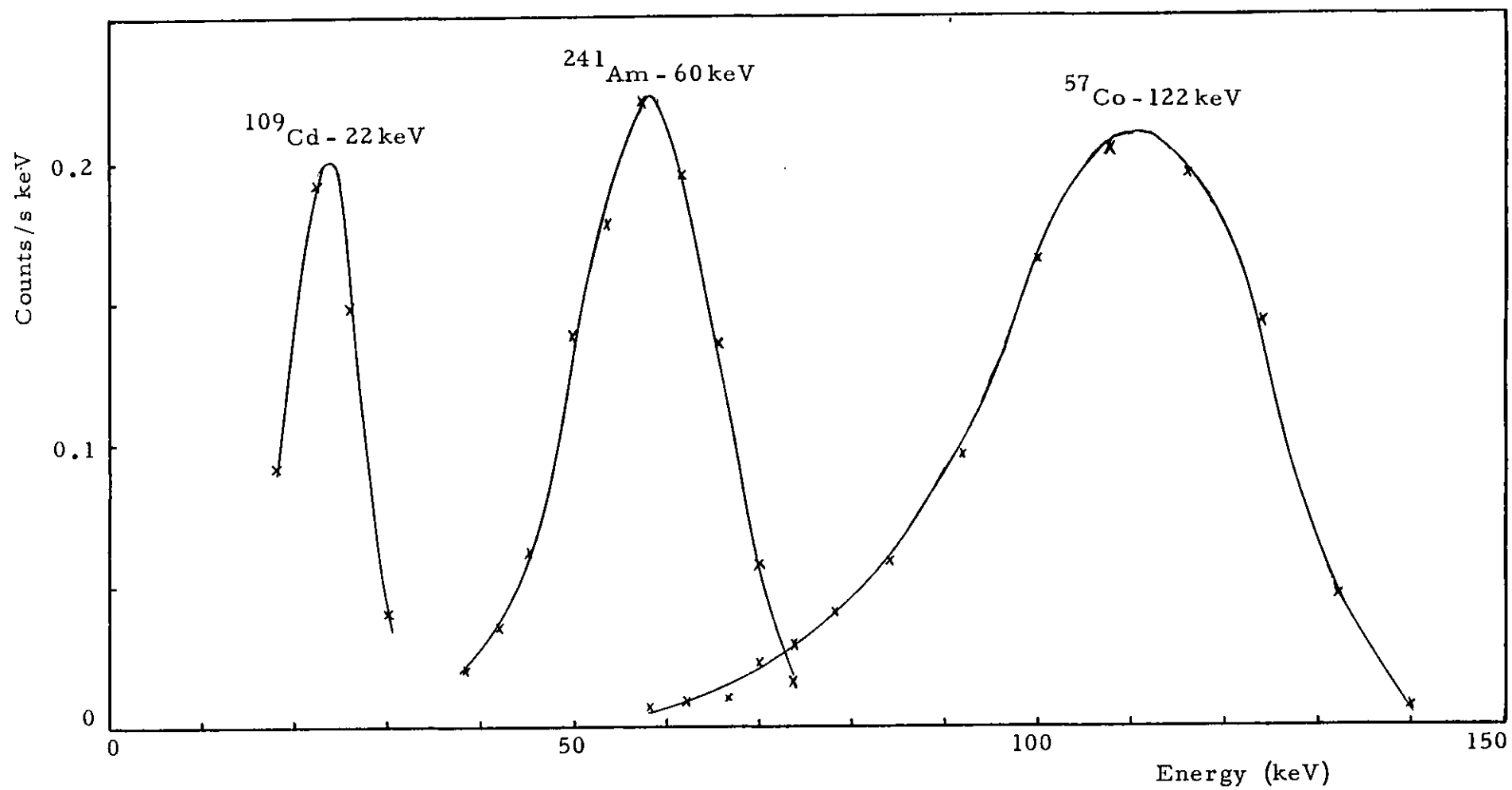


Figure 4-4. The response of module no. 1 to three X-ray lines.

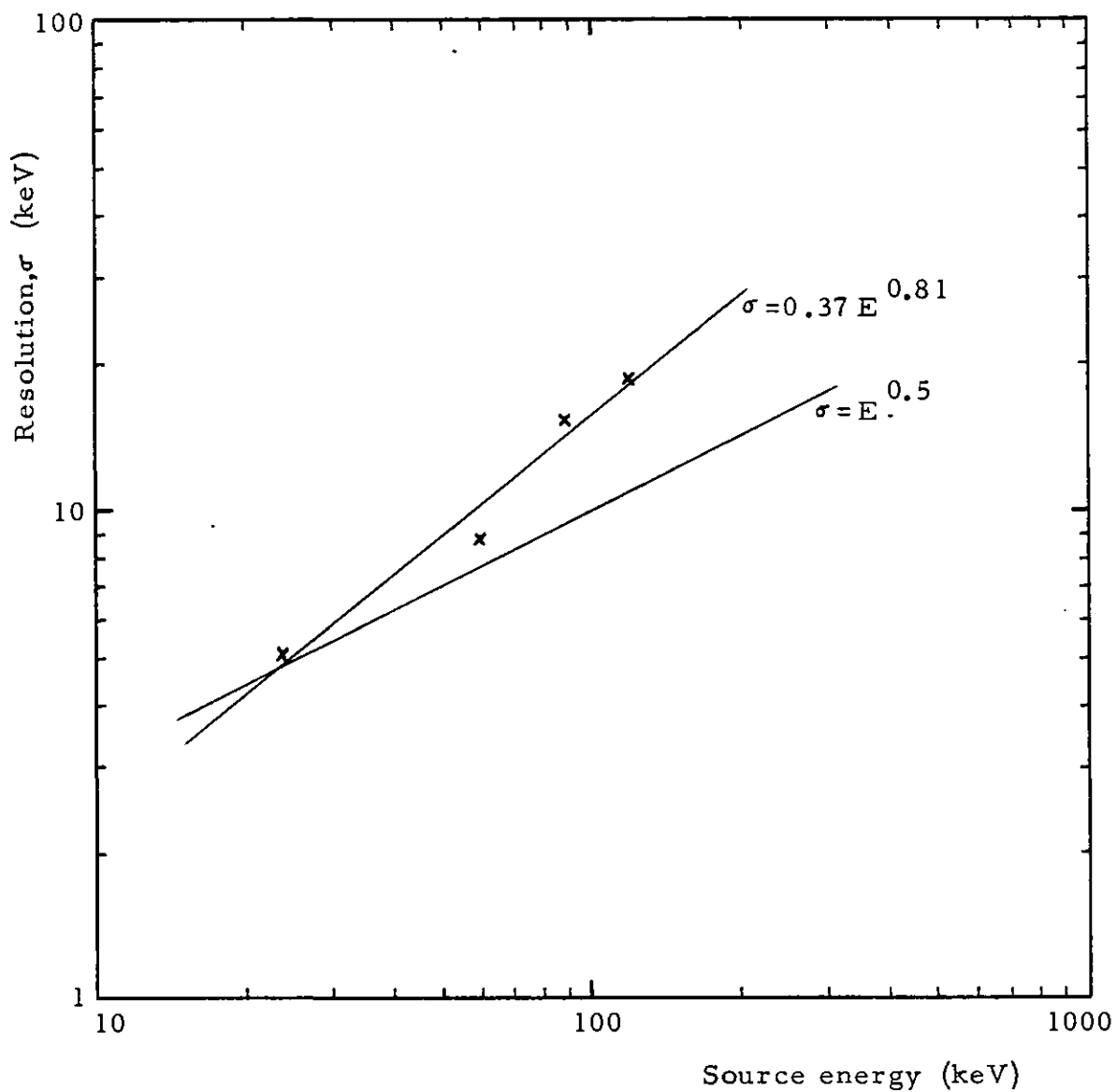


Figure 4-5. The relation between resolution and input energy for module no. 1. The best-fit straight line, having a power-law index of 0.81, is shown together with a 0.5 index line, which would be expected if the resolution came from counting statistics alone.

atmosphere and being detected as a photomultiplier output pulse is given by the total interaction matrix M :

$$M = M' M_a = M_r M_k M_q M_w M_c M_a . \quad (4.12)$$

As explained in section 4.2.1, M_a is different for each observation, so a new M must be calculated for each one, using the average atmospheric path length and M' , the invariant component of the total matrix (Figure 4-6). A typical total interaction matrix, that for the 1981 observation of Sco X-1, is shown in Figure 4-7.

4.3 Spectral Unfolding

The measured spectrum, S_m , is related to the source spectrum, S_s , using equation 4.12, by

$$S_m = M S_s = M_r M_k M_q M_w M_c M_a S_s . \quad (4.13)$$

The problem of unfolding is how to obtain S_s , given S_m and the various M 's. There are two fundamentally different approaches to its solution, which will be referred to as 'forwards' and 'backwards' unfolding. The former attempts to go directly from the observed flux points in S_m to the actual source spectrum, while the other assumes that the source spectrum has one of several characteristic shapes and finds the one which agrees most closely with the observed points. Both have their advantages and drawbacks, which are discussed in the following two sections.

4.3.1 Forwards Unfolding

This method is best described by Dolan (1972). It is the most obvious way to proceed from equation 4.13, by constructing its inverse

$$S_s = M^{-1} S_m = M_a^{-1} M_c^{-1} M_w^{-1} M_q^{-1} M_k^{-1} M_r^{-1} S_m . \quad (4.14)$$

The four diagonal matrices have diagonal inverses whose elements are

$$M_x^{-1}(i,i) = \frac{1}{M_x(i,i)} \quad (\text{for } x = a, c, w, q); \quad (4.15)$$

while the inverse of M_k can be found using a standard computer subroutine, for example one based on the method of Gaussian elimination with partial pivoting.

However, a problem arises in trying to find M_r^{-1} , and also in finding M^{-1} directly rather than by multiplying its constituent inverses. M_r is ill-conditioned — it has rows and columns some of which are nearly identical. A singular matrix, which is one with at least two identical rows or columns, has the property of a zero determinant and therefore no inverse. Ill-conditioned matrices, since they are nearly singular, have very small determinants, and require inordinately accurate calculations to find their inverses.

The way of avoiding this problem suggested by Dolan is an application of the technique of apodisation proposed by Bracewell (1953) and developed by Lloyd (1969) for applications in optics. This technique counteracts the broadening effect of the detector resolution by accentuating peaks, dips and slopes in the measured spectrum — a very similar effect to multiplying it by M_r^{-1} if it existed. If S_a is the apodised measured spectrum equivalent to $M_r^{-1} S_m$, then substitution of this into equation 4.14 gives

$$S_s = M_a^{-1} M_c^{-1} M_w^{-1} M_q^{-1} M_k^{-1} S_a \quad (4.16)$$

which can be solved straightforwardly.

The great attraction of forwards unfolding is that it should give a source spectrum untainted by any assumptions about its shape, unlike backwards unfolding. But there are other problems associated with the method of forwards unfolding. Maurer (1979) found during analysis of OSO-8 data that a systematically high flux just above the K-edge energy was being spuriously produced by the apodisation stage, caused by the sharp discontinuity in the detector response function there. Apodisation enhances statistical fluctuations in the data points as well as real

trends, although the method of error propagation should cover this. The forwards unfolding process requires measured flux values for the extra channels above and below the 16-200keV range, which must be estimated by eye, and this is considerably more uncertain than estimating source flux values in these channels using a mathematical relationship as is done in backwards unfolding. The alternative is to discard the source flux points for the affected real channels at the top and bottom of the range, but since the lowest few channels usually contain the best data statistically, this is not satisfactory. Lastly, the data points of S_a are not statistically independent, although this also is a cause of the basic method, not just the apodisation stage.

4.3.2 Backwards Unfolding

There is a less straightforward method of finding the source spectrum from equation 4.13, which is to propose a set of possible model source spectra, multiply each by M to produce model measured spectra, and find which of them is in closest agreement with the actual measured spectrum. Most astronomical X-ray spectra have a basic power-law or exponential shape, and it is this shape together with the values of its parameters which one usually wants to find from spectral observations.

The advantage of this method is that it combines finding the source-spectrum parameter values with the spectral unfolding in one operation, without needing the intermediate stage of finding the actual unfolded spectral data points. If these are required, then the ratio of the model source flux to the model measured flux can be calculated for each channel. These ratios are used to multiply the actual measured flux values to obtain the actual source flux values. By this method, any features in the spectrum are preserved, as in forwards unfolding. There is the additional benefit that the actual source flux points are then statistically independent, at least to a first-order approximation.

Its disadvantage for balloon-borne observations arises from the different M_a , and therefore M , for each observation, requiring the set of model measured spectra to be recalculated each time. Fortunately, this task can be included in the computer program which determines the best-fitting model spectrum.

4.3.3 Unfolding LAPAD Spectra

It was decided to use the backwards unfolding method for the LAPAD observations because of the problems associated with forwards unfolding, both from the apodisation technique and from the dependence of the calculated source spectrum points on the estimated measured flux in the extra channels. Backwards unfolding has also been used for many previous X-ray astronomical observations.

For each observation, an atmospheric interaction matrix, M_a , is computed and used to obtain a total interaction matrix from equation 4.12. This M is used to find the values of the relevant parameters (A , α , kT) of the best fit to the measured data for each of the three basic astronomical X-ray spectra:

$$\text{a) Power Law} \quad \frac{dN}{dE} = A E^{-\alpha} \quad (4.17)$$

from synchrotron radiation or inverse Compton scattering;

$$\text{b) Thermal Bremsstrahlung} \quad \frac{dN}{dE} = A g \frac{\exp(-E/kT)}{E} \quad (4.18)$$

from an optically thin, hot plasma;

$$\text{c) Black Body} \quad \frac{dN}{dE} = A \frac{E^2}{\exp(E/kT) - 1} \quad (4.19)$$

from an optically thick, hot plasma;

where $\frac{dN}{dE}$ is the photon number flux, kT is the electron temperature, and g is the optional Gaunt factor ($g = 1$ when excluded, and $g = E^{-0.4}$ when included).

The goodness of fit of a model measured spectrum to the data points is evaluated by the chi-squared technique:

$$\chi^2(n-2 \text{ deg. of free.}) = \sum_{i=1}^n \frac{(\text{Model}_i - \text{Actual}_i)^2}{\sigma_i^2} \quad (4.20)$$

where the sum is over the set of n data points, and the σ_i are the errors associated with each point. The acceptability of fit is judged from standard statistical tables of $P(>\chi^2)$, which in this case corresponds to the probability that the true spectrum gives a worse fit to the points than the model spectrum, which will hereafter be called the 'confidence level' of the fit.

The model and parameter values which give the minimum value of χ^2 are taken to describe the basic source spectrum. If the data points are accurate enough and the spectral range sufficiently wide to warrant it, more complex model spectra can be tried to find a better fit, and thus deduce more about the emission processes at work in the source. However, it must be borne in mind that any model whose fit gives a confidence level of $\geq 5\%$ cannot be ruled out as a possible description of the spectrum. It is sometimes not even possible to dismiss one of the three basic types for the LAPAD spectra, so such exercises must be approached with caution.

The errors in the spectral parameter values for each fit are determined by the method of Lampton, Margon & Bowyer (1976). They plot contours of constant χ^2 using the spectral parameters as axes, producing a set of ellipses centered on the parameter values of the best fit, which has $\chi^2 = \chi_{\min}^2$. They derive values of $\chi^2 - \chi_{\min}^2$ for the contours corresponding to parameter values 1σ , 2σ etc. different from the best fit. All the fits to LAPAD spectra have used two parameters, for which values with $\chi^2 - \chi_{\min}^2 = 2.3$ correspond to $\pm 1\sigma$ error levels. The analysis program prints out an array of χ^2 values in parameter space for each model, from which are taken the best-fit and $\pm 1\sigma$ -error values quoted in Chapter 5. The spectral points are then obtained by the method of section 4.3.2.

CHAPTER 5 : SPECTRAL RESULTS AND INTERPRETATION

The 1981 and 1983 flights of the LAPAD experiment yielded observations of at least 9 known X-ray sources, although several of these produced only upper-limit values to their fluxes. The main results from the spectral data of these observations are presented in this chapter. Owing to collimator damage, the University of Tasmania results from 1981 are not reliable, and their 1983 data have not yet been analysed, so no simultaneous measurements are available for comparison. Analysis of the Fast and Intermediate Mode data and temporal analysis of the Spectral Mode data will be performed by other members of the LAPAD project group, the results of which will be presented elsewhere.

5.1 Detector Background

The accuracy of source flux measurement and the minimum detectable source flux level for X-ray detectors depend primarily on the background level of non-source counts occurring in it. The background counts spectra for the two flights are slightly different, due to their different float altitudes and geomagnetic latitudes (the latter affects the local charged-particle flux). Figure 5-1 is a graph of typical background spectra, after rise-time selection, plotted in terms of the incident photon energy equivalent to the background event. It shows a number of features. The overall fall-off between 20 and ~ 100 keV arises from the distribution of the Compton scatterings in the primary crystal, which is the dominant component over this energy range (Dean & Dipper 1981). Superimposed on this is a peak at ~ 50 keV, the source of which is unclear — it may arise from missed events in the Am-241 source or from K-fluorescence X rays from the tantalum collimator, though both these possible sources produce

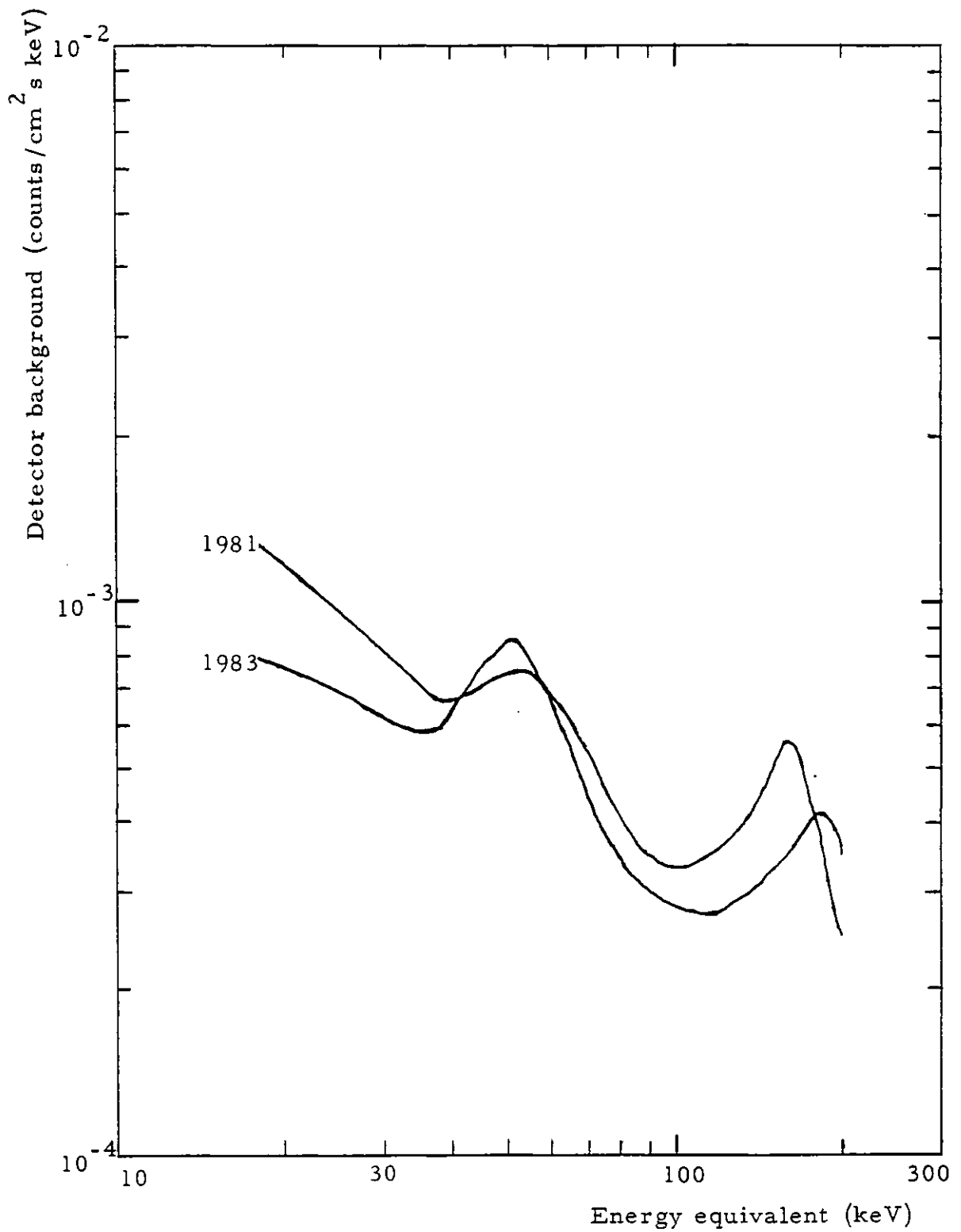


Figure 5-1. The spectrum of the background counting rates during the two flights.

X rays of slightly higher energy (59.5 and 57.5 keV respectively). The increase in the background count rate above ~ 110 keV is due to the increase in the number of atmospheric X-ray photons that penetrate the shielding, which becomes the major source at higher energies (Dean & Dipper 1981). The rapid fall-off at the top of the energy range, above ~ 160 keV, is produced by a shift in the peak event rise time out of the range of validity for the other energy channels (see section 4.1.2). It would be possible to correct for this by a different choice of valid rise times for these channels, but since no source signal was observed above ~ 100 keV, it was not investigated further.

The consequent minimum detectable count levels and the corresponding source flux levels are shown in Table 5-1 for three energies, together with their background levels. These levels are after rise-time selection, and were obtained empirically from the data analysis programs. The three energies are the centers of the three groups of energy channels used to obtain the maximum sensitivity. The values are from the 1981 flight at 3.5 mbar near Alice Springs, for 1 h of on-source/off-source counting. Values for the 1983 flight would be similar.

Table 5-1. Background levels and minimum detectable fluxes

	<u>30 keV</u>	<u>75 keV</u>	<u>150 keV</u>
Background level (cts/cm ² s keV)	1×10^{-3}	5×10^{-4}	4×10^{-4}
3 σ min. counts (cts/cm ² s keV)	3×10^{-5}	1.5×10^{-5}	1.2×10^{-5}
3 σ min. flux (photons/cm ² s keV)	1×10^{-4}	3.5×10^{-5}	6.5×10^{-5}

5.2 Scorpius X-1

Sco X-1 (= 4U 1617-15 = 3A 1617-155) is the brightest of the non-transient soft X-ray sources as well as being the first to be discovered

(Giacconi et al 1962). It is also probably the most intensely studied X-ray source; Miyamoto & Matsuoka (1977) have comprehensively reviewed all the work on it up to that date. Sco X-1 has been identified in the optical with a 13^m blue star, V818 Sco, having the appearance of an old nova, and with a 0.787d binary period. It is believed to be a close binary system containing a low-mass primary and a neutron star (although the latter is not certain). It is also a weak nonthermal radio source. In the X-ray region, it has a very soft spectrum, usually well described by simple thermal bremsstrahlung (TB) models with temperatures of about 6 keV. Hence its hard X-ray spectrum is very steep. Flare states have been seen by a number of observers, in which the flux increases by a factor of 2-3 with little accompanying temperature change.

Sco X-1 was observed on both the 1981 and 1983 flights. During the first flight, 2500 s of data were obtained in the on-source/off-source rocking mode with a triangular waveform, as were all the other observations on the two flights. The 2500 s covered the period 1981 December 2 02:20 to 03:00 UT, with an additional 2500 s of nearby background-only data immediately preceeding it, which was used to improve the determination of the background level. On the second flight, 7000 s of on/off-source data were obtained during the final ascent to float altitude, of which the period giving the most significant source signal was selected (5000 s covering 1983 March 26 09:50 to 11:15 UT). Because Sco X-1 was setting during the balloon ascent, the atmospheric path length was always high (average 6.9 g/cm^2). The consequent large attenuation at low energies coupled with the steeper source spectrum, resulted in much worse statistics for the observed flux than for the shorter 1981 observation.

The two unfolded spectra obtained are plotted in Figure 5-2. The 1981 spectrum obviously has more precise data points. As expected, power-law and black-body spectral shapes give unacceptable fits to the 1981 data (confidence levels $<1\%$), and exponential TB models fit

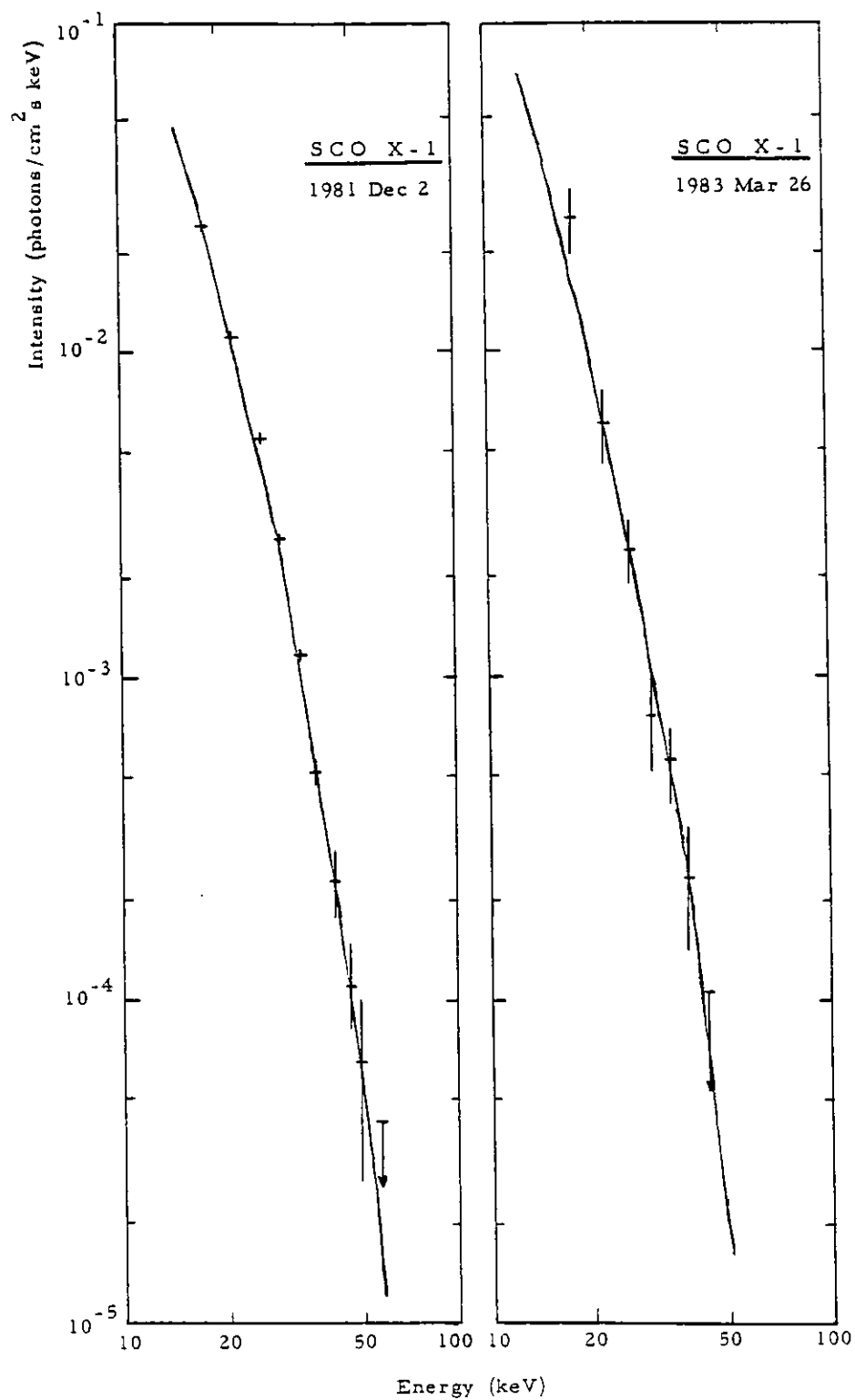


Figure 5-2. Thermal bremsstrahlung spectra obtained for Sco X-1 from the two flights, with kT temperatures of 6.6 and 5.0 keV respectively.

reasonably well. Omitting the $E^{-0.4}$ Gaunt factor approximation gives marginally better fits than including it. The intensities and temperatures of the fits are shown in Table 5-2. Values for fits with and without the Gaunt factor are given for comparability with previous results.

Table 5-2. Parameter values of the TB fits to the two Sco X-1 spectra

	<u>Spectral constant, A</u>	<u>kT (keV)</u>	<u>Confidence level</u>
<u>1981</u>			
TB (exc. Gaunt)	6.8 ± 0.6	6.6 ± 0.4	33 %
TB (inc. Gaunt)	17.5 ± 1.2	7.25 ± 0.5	25 %
<u>1983</u>			
TB (exc. Gaunt)	13 ± 4	$5.0 (+4, -0.5)$	37 %
TB (inc. Gaunt)	28 ± 9	$5.5 (+5, -2)$	36 %

Note. The model formulae are as defined in equation 4.18.

There has been some doubt as to whether Sco X-1 shows an intensity-temperature correlation which is positive (White et al 1976b) or negative (Matsuoka et al 1972), if any. The result can depend on the definition of intensity used, and the energy range studied. If changes in the spectrum follow a pivoting behavior, measurements below the pivoting energy will show the opposite correlation to measurements above it. The LAPAD data and those from other recent hard X-ray observations (see caption to Figure 5-3 for details) show a positive correlation for intensity defined as the flux at 30 keV, but a negative correlation with intensity measured by the constant of proportionality, A, of equation 4.18. Since the latter is a less arbitrary measure of the total intensity, it has been used to plot Figure 5-3, a graph of intensity against

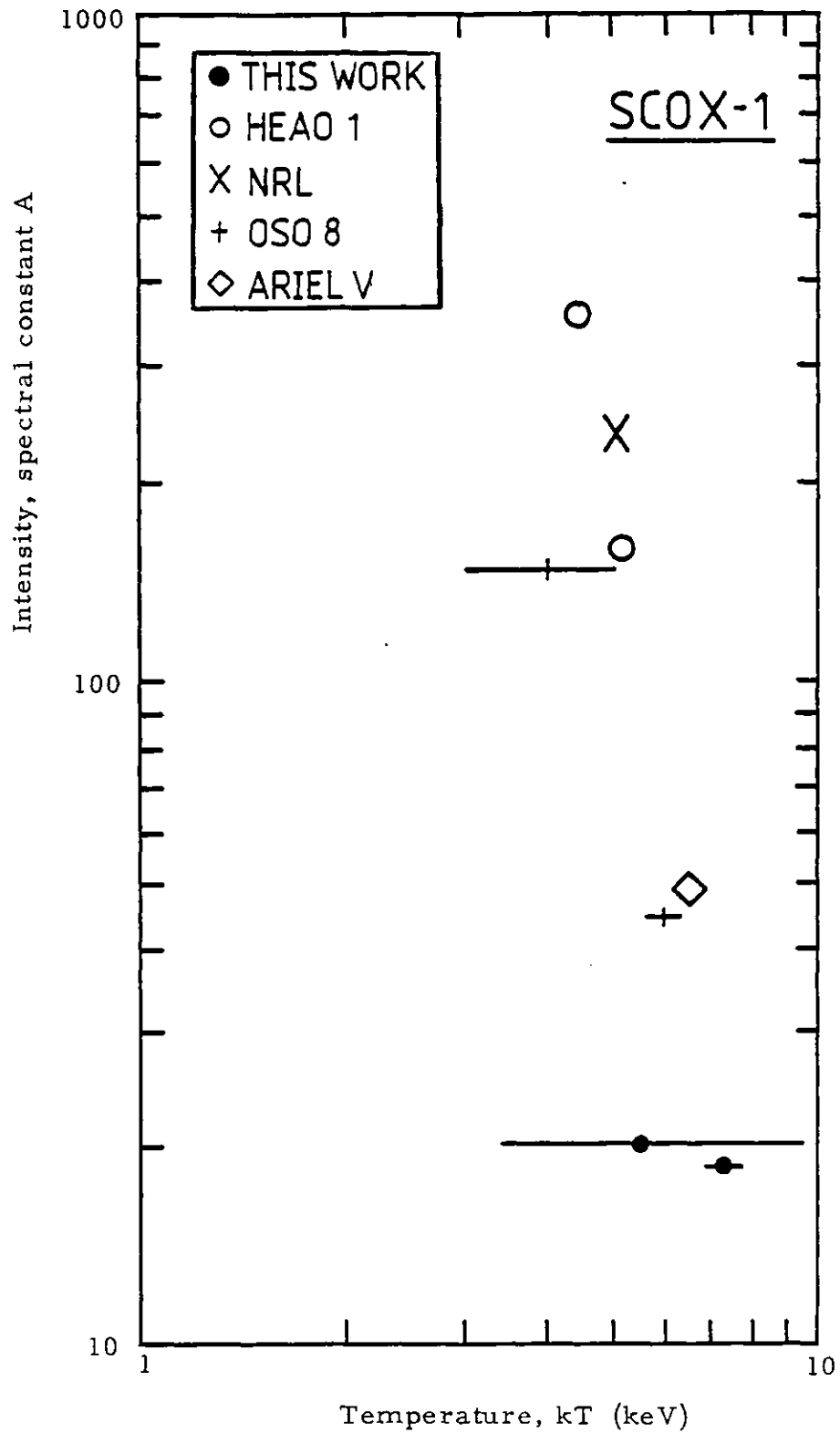


Figure 5-3. Intensity-temperature relation for Sco X-1. (HEAO-1 results from Rothschild et al 1980 and Soong & Rothschild 1983; NRL from Johnson et al 1980; OSO-8 from Coe et al 1980; Ariel-5 from Greenhill et al 1979.)

temperature for recent Sco X-1 observations, including those with LAPAD. The negative correlation is more pronounced where the same observatory has viewed the source at different times (LAPAD, HEAO-1 & OSO-8). For an unsaturated Comptonisation model of an accretion disk, it is expected that the TB spectral constant will decrease as the TB temperature rises in this way. It may be significant that the positive correlation has arisen from low-energy (2.5 - 7.5 keV) observations (White et al 1976b), while the negative correlations have occurred with high-energy (20-50 keV) observations (Figure 5-3, and Matsuoka et al 1972). It would thus seem that a set of observations of the whole X-ray spectrum is required to produce a definitive result, and check the classification by Parsignault & Grindlay (1978) of Sco X-1 as a member of that subset of galactic bulge sources which they term 'class 1'. This class is defined as sources with spectra which have direct intensity-temperature correlations and exponential continua.

Another contentious point about the hard X-ray spectrum of Sco X-1 is an excess over the extrapolated ~ 6 keV thermal shape, reported by some observers (e.g. Greenhill et al 1979), but not seen by others (e.g. Rothschild et al 1980). If it is a real feature, the reported levels of detection and upper limits of nondetection are such that this 'hard tail' must vary by at least two orders of magnitude in $\lesssim 1$ yr (from $\sim 1 \times 10^{-3}$ to $< 6 \times 10^{-6}$ photons/cm²s keV). The 1981 LAPAD results agree with those from OSO-8 and HEAO-1 (Coe et al 1980; Rothschild et al 1980; Soong & Rothschild 1983), which are the most recent available, showing no excess over a TB fit. The observations since the last detection of a hard tail are summarised in Table 5-3. The reports of a hard tail are mainly from early balloon observations (see Miyamoto & Matsuoka 1977 for a summary) and the Ariel-5 observation. The reliability of these measurements is compromised by their low statistical significance of the excess, wide fields of view, or poor energy resolution. The fact

that the more recent measurements with greater sensitivity, smaller fields of view and finer energy resolution have not found any indication of such a high-energy excess, casts some doubt on its existence in this source.

Table 5-3. Journal of recent hard X-ray observations of Sco X-1

<u>Observatory</u>	<u>Date</u>	<u>High-energy excess</u> (photons/cm ² s keV)	<u>Ref.</u>
Ariel 5	1977 Mar 1-3	$\sim 1 \times 10^{-3}$	1
HEAO-1	$\left\{ \begin{array}{l} 1977 \text{ Aug } 15\text{-}16 \\ 1978 \text{ Feb } 11\text{-}13 \\ 1978 \text{ Aug } 15\text{-}16 \end{array} \right\}$	$< 1 \times 10^{-5} (2\sigma)$	2
OSO-8	1978 Aug 20-23	$< 3 \times 10^{-4} (2\sigma)$	3
HEAO-1	1978 Sep 6-7	$< 6 \times 10^{-6} (2\sigma)$	4
LAPAD	1981 Dec 2	$< 5 \times 10^{-5} (2\sigma)$	5
LAPAD	1983 Mar 26	$< 1 \times 10^{-4} (2\sigma)$	5

References: 1 = Greenhill et al 1979, 2 = Soong & Rothschild 1983, 3 = Coe et al 1980, 4 = Rothschild et al 1980, 5 = this work.

5.3 The Active Galaxies IC 4329A and MR 2251-178

Observations were made of two X-ray-emitting active galaxies, IC 4329A and MR 2251-178, which have been variously classified as type-1 Seyfert galaxies and quasars, reflecting the blurred distinction between the two categories. Neither source has been looked at previously at energies above ~ 10 keV. Since both objects are cosmologically distant and have low apparent luminosities, it was not unexpected that only upper limits were obtained from the observations (Table 5-4).

5.3.1 The Seyfert Galaxy IC 4329A

The X-ray source 2A 1347-300 (= 3A 1346-301) was first detected by the Ariel-5 Sky Survey Instrument (SSI) in ~ 1975 . Its error box was shown

Table 5-4. Summary of IC 4329A and MR 2251-178 observations

<u>Source</u>	<u>Length, date & time (UT)</u>	<u>2σ limits (ph/cm²s keV)</u>	
		<u>16-48 keV</u>	<u>48-104 keV</u>
IC 4329A	3000 s 1981 Dec 2 00:00-00:50	6.5×10^{-5}	2.5×10^{-5}
MR 2251-178	7500 s 1983 Mar 26 13:15-15:30	5×10^{-5}	2×10^{-5}

by Elvis et al (1978) to include the previously known Seyfert-1 galaxy IC 4329A, the giant elliptical galaxy IC 4329, and just excluded another galaxy IC 4327 — all members of a cluster. In order to determine which was the emitter, Delvaille, Geller & Schnopper (1978) observed the region with the Rotating Modulation Collimator (RMC) experiment on SAS-3 and found that most, but not all, of the emission came from IC 4329A. A further observation by Dower et al (1980) with HEAO-1 found that all the flux was due to IC 4329A. Einstein Observatory spectral measurements by Holt (1981) showed that it has a power-law spectrum of photon spectral index $\alpha = 1.86$, typical of active galaxies. Its X-ray flux can vary by ~ 3 in ~ 50 d (Marshall, Warwick & Pounds 1981), but does not show variability on time scales ≤ 0.5 d in common with most other active galaxies (Tennant & Mushotzky 1983). In addition to its X-ray and optical emission, IC 4329A has been detected in the radio and infrared wavebands. It was originally classified as an extreme type-1 Seyfert galaxy by Disney (1973), but further optical studies by Wilson & Penston (1979) show that the nucleus is heavily reddened, giving a dereddened luminosity typical of quasars. If this latter classification is correct, their redshift value of $z = 0.015$ would make IC 4329A the nearest quasar, at a distance of ~ 100 Mpc.

The upper limits from the LAPAD measurement are plotted in Figure 5-4 together with the low-energy (0.5 – 4.5 keV) spectrum from Holt's (1981)

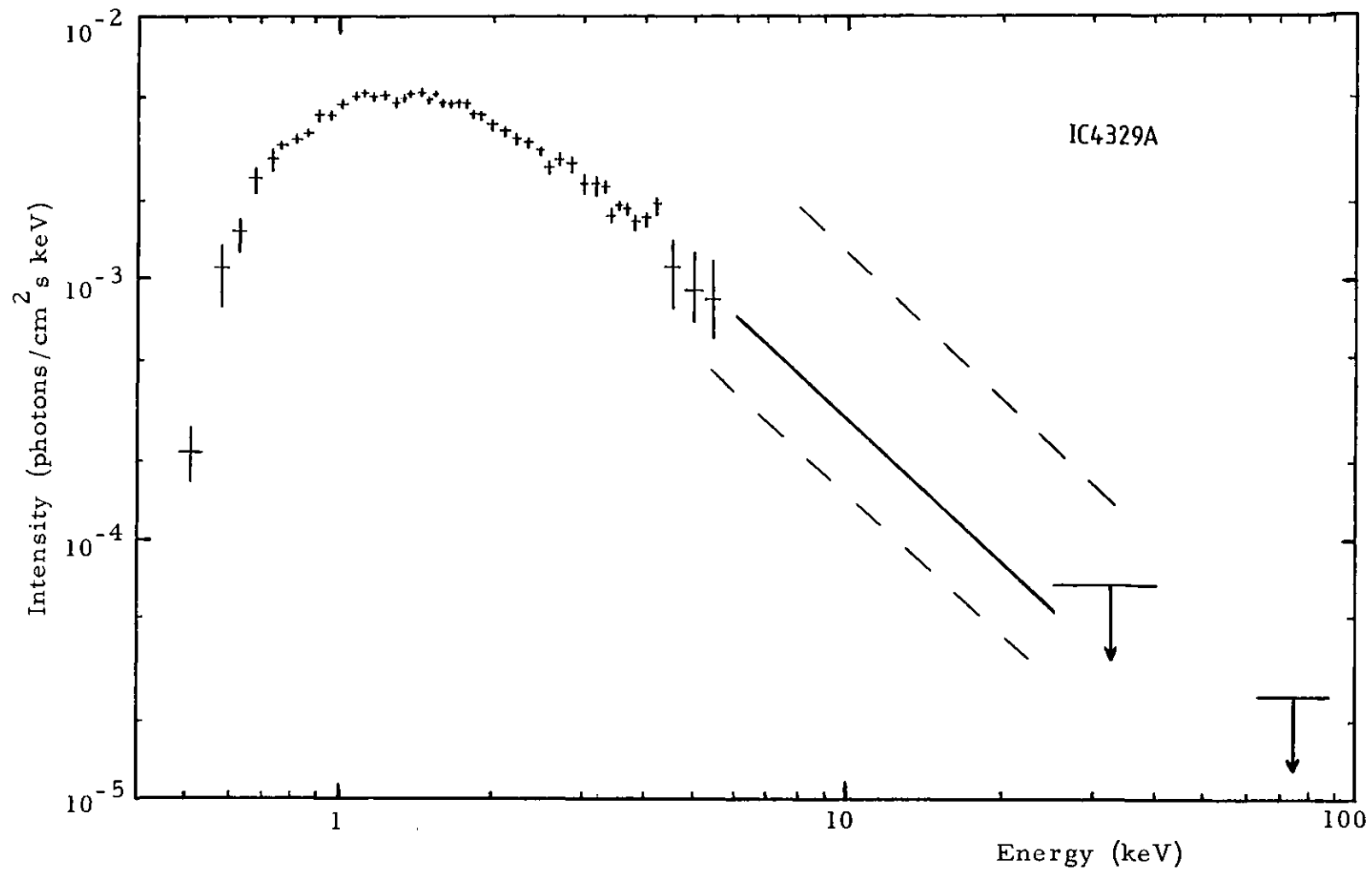


Figure 5-4. The upper limits for IC 4329A compared to the soft X-ray spectrum of Holt (1980) and an extrapolation of its power-law index of 1.86 (solid line). The dashed lines represent the relative maximum and minimum flux levels of the 3A catalog (McHardy et al 1981).

observation. Also shown, to aid comparison, is an extrapolation of the $E^{-1.36}$ power law, together with a parallel pair of lines to indicate the relative maximum and minimum flux levels (from the 3A catalog of McHardy et al 1981), since Seyferts and quasars usually keep the same spectral shape despite changes in intensity (Worrall et al 1979; Mushotzky et al 1980). The upper limits are consistent with the extrapolation in Figure 5-4 for low values of the total source flux. Alternatively, if IC 4329A had a high X-ray luminosity at the time, the limits would imply some kind of spectral steepening at an energy between about 5 and 30 keV. However, steepening was not observed for any of the dozen Seyferts studied over 2-165 keV by Rothschild et al (1983), so the latter possibility is unlikely.

5.3.2 The Quasar MR 2251-178

The X-ray source 2A 2251-178 (= 3A 2248-185) was also observed first by the Ariel-5 SSI in ~1975. Ricker et al (1978) used the SAS-3 RMC to reduce its error box to 40", and discovered that the brightest object in it was a previously unknown quasar (or possibly a type-1 Seyfert), which they designated MR 2251-178. This was the first quasar to be discovered by virtue of its X-ray emission, and only the second quasar detected at X-ray wavelengths (after 3C 273). Among quasars, its intrinsic X-ray luminosity is quite low, although it is still greater than for other types of active galaxy. Its X-ray output has been observed to be fairly constant by Marshall, Warwick & Pounds (1981) and McHardy et al (1981), unlike 3C 273. Detailed optical spectrometry by Canizares, McClintock & Ricker (1978) and infrared photometry by Soifer, Neugebauer & Matthews (1979) showed that it had a spectrum typical of other low-redshift quasars (again unlike 3C 273), which indicated that normal quasars could also be significant X-ray emitters — a hypothesis that was quickly confirmed by the Einstein Observatory's detection of many quasars in the X-ray

region. Ricker et al (1978) also reported the detection of MR 2251-178 as a weak point-like radio source at ~ 5 GHz. A deeper photographic exposure by Phillips (1980) revealed a surrounding nebulosity like that associated with several other quasars, and showed that MR 2251-178 is a member of a rich cluster of ~ 50 galaxies. Spatially resolved spectrophotometry by Bergeron et al (1983) demonstrated that this nebulosity is a galaxy with the quasar at its nucleus, and that in addition, this galaxy is surrounded by a giant H II envelope, a feature rarely found in quasars or Seyfert-1 galaxies. MR 2251-178's redshift of $z = 0.06$ implies that it is one of the nearest quasars (at ~ 400 Mpc), which makes it one of the most worthwhile active galaxies to study.

The upper limits from the LAPAD observation are plotted in Figure 5-5, together with possible extrapolations of the low-energy flux of 3.7×10^{-11} erg/cm²s over 2-10 keV given in the 3A catalog (McHardy et al 1981). Power-law extrapolations are used, since most active galaxies' spectra are better described by power laws with photon spectral indices in the range $\alpha = 1.4 - 2.0$ than any other shape. The only spectral information available on MR 2251-178 at present is the poorly determined power-law index of $\alpha = 1.5 \pm 0.5$ given by Ricker et al (1978) from their SAS-3 measurement, so extrapolations with indices $\alpha = 1.0, 1.5$ and 2.0 are shown. The LAPAD results can be interpreted in four ways:

a) There may be a spectral break from the low-energy power law at an energy ~ 50 keV, which has been suggested by Worrall et al (1980) from consideration of a black-hole model for quasar energy production. However, steepening of the spectrum in this energy region is not a common feature of active galaxies — none of the 12 observed in a HEAO-1 survey by Rothschild et al (1983) showed such behavior, nor does the similar quasar 0241+622 (Worrall et al 1980), although evidence for a steeper power law above ~ 20 keV was found by Primi et al (1979) for the extreme quasar 3C 273.

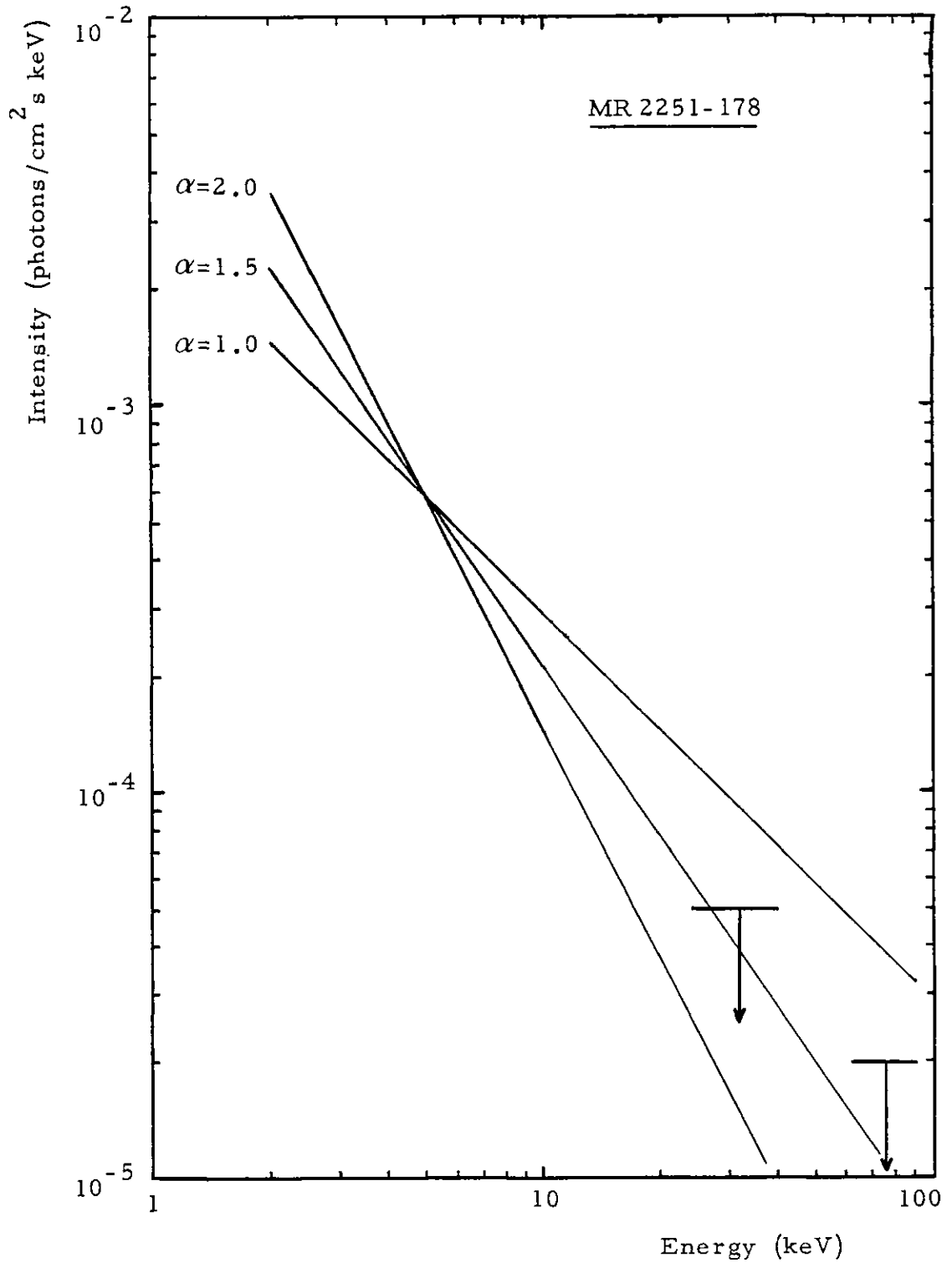


Figure 5-5. The upper limits for MR 2251-178 compared with extrapolations of the SAS-3 flux for three possible spectral indices (Ricker et al 1978).

b) Despite the classification of MR 2251-178 as an invariant source, there is a $\sim 2\sigma$ significant difference between the flux value of $(2.5 \pm 0.4) \times 10^{-11}$ erg/cm²s (2-11 keV) from SAS-3 by Ricker et al (1978) and the mean flux observed by the Ariel-5 SSI of $(3.7 \pm 0.5) \times 10^{-11}$ erg/cm²s (2-10 keV) by McHardy et al (1981). Long-term intensity variation is a common feature of active galaxies, and MR 2251-178 may be no exception. Assuming a power-law spectrum at an intensity level equivalent to the SAS-3 measurement would give a 2σ limit to the power-law index of $\alpha \gtrsim 1.4$, compared with $\alpha \gtrsim 1.6$ using the Ariel-5 average level. Of course, if the source is variable, it could equally have had an intensity level higher than the Ariel-5 average, which would create tighter constraints on the index than $\alpha \gtrsim 1.6$.

c) MR 2251-178 could have a nonpower-law spectrum, but this is very unlikely since all active galaxies observed spectrally in the range 1-500 keV have power-law spectra or are best fitted by power laws.

d) The spectral index is otherwise constrained to be $\alpha \gtrsim 1.6$, which is consistent with the general range of active galaxies' indices of roughly 1.4 - 2.0, and moreover fits in with the trends appearing within this range. Zamorani et al (1981) have found a distinct broad-band spectral difference between radio-loud and radio-quiet quasars, in that they have correlated X-ray to optical luminosity ratios, L_x/L_{opt} , which are high and low respectively. (Here, 'radio-intensity' is defined relative to optical intensity, i.e. radio-loud quasars have high L_{rad}/L_{opt} ratios.) Thus radio-loud quasars are also X-ray-loud, and might be expected to have different, and probably harder, X-ray spectra than the radio-quiet and X-ray-quiet quasars. For a sample of mostly radio-loud quasars, Zamorani et al found an average of $\alpha = 1.4 - 1.5$, and HEAO-1 measurements by Worrall et al (1979) on the archetypal radio-loud quasar 3C 273 gave a similar value of $\alpha = 1.41 \pm 0.02$. However, another HEAO-1 and OSO-8 observation, on the radio-quiet quasar 0241+622, showed a

significantly different slope of $\alpha = 1.9 \pm 0.3$ (Worrall et al 1980). The LAPAD measurement of $\alpha \geq 1.6$ for MR 2251-178, another radio-quiet quasar, implies a similar significantly steeper spectrum than the radio-loud range. So two classes of X-ray emission from quasars seem to be indicated: radio-loud quasars' strong emission with hard spectra ($\alpha = 1.4 - 1.5$), and radio-quiet quasars' weak emission with soft spectra ($\alpha = 1.9?$). This has consequences for calculations of the fraction of the X-ray background accounted for by the integrated emission of distant quasars, since a substantial proportion of them, the radio-quiet ones, would not be significant contributors. In addition, spectral observations of Seyfert galaxies by Mushotzky et al (1980) show that they have power-law spectra with slopes characteristically in the range $\alpha = 1.6 - 1.7$. As yet, the number of accurate X-ray spectral measurements of active galaxies is small, particularly of the radio-quiet quasars since they are weaker X-ray emitters, but different characteristic spectra are emerging for the various types. However, it will require detailed observations of several more active galaxies to build up a precise picture, particularly of whether there are indeed different characteristic slopes for the two quasar populations.

5.4 Nova Ophiuchi 1977

This X-ray and optical nova peaked on 1977 August 10 after a very short rise time of 2 d. The Ariel-5 SSI was fortunate in being able to observe it for 25 d covering the rise, peak and fall-off to $\sim \frac{1}{3}$ maximum intensity (Watson, Ricketts & Griffiths 1978). A month after its peak, it was observed by two HEAO-1 experiments, narrowing the 1° Ariel-5 error circle down to two possible $1'$ -sized positions, in one of which an optical nova was located on plates taken at the Anglo-Australian Telescope (Griffiths et al 1978). In the optical, the star had brightened by a factor of 100, from 21^m to 16^m , while in the X-ray, its flux had

increased from below the level of previous surveys' sensitivity (~ 1 milli-Crab) to ~ 3500 milli-Crabs, a factor of at least several thousand. (1 Crab-unit corresponds to the X-ray intensity of the Crab Nebula.) The new X-ray source was given the catalog designations H1705-25 and 3A 1705-250, and the optical counterpart given the title Nova Ophiuchi 1977 and the variable star name V2107 Oph. An X-ray light curve for the first month is given in Watson, Ricketts & Griffiths (1979), but longer-term observations have been much sparser. Table 5-5 is a summary of those published to date, though care must be taken in comparisons of fluxes from different energy ranges as they depend on the nova's spectral shape relative to the Crab's, which probably evolved with time.

Table 5-5. Journal of X-ray observations of H1705-25

<u>Observatory</u>	<u>Date</u>	<u>Approx. Flux</u> (milli-Crabs)	<u>Energy</u> (keV)	<u>Ref.</u>
Uhuru	1971-1973	< 1 (2σ)	2-6	1
Ariel 5	1977 Aug 8	< 50 (2σ)	2-18	1
Ariel 5	1977 Aug 10	3500 (Peak)	2-18	1
Ariel 5	1977 Sep 1	1000	2-18	1
HEAO-1	1977 Sep 10	1000	1-13	1
HEAO-1	1977 Sep	250	13-25	2
HEAO-1	1977 Sep	250	80-180	2
HEAO-1	1978 Sep	25	80-180	2
LAPAD	1981 Dec 2	35	16-48	3

References: 1 = Watson, Ricketts & Griffiths (1979), 2 = Matteson (1982),
3 = this work.

The LAPAD observation was gained during the 1981 flight's two drift scans across the galactic center region. A total of 1500 s of on/off-source data covering the periods 1981 December 2 03:04 to 03:18 and 03:58 to 04:11 UT was obtained, together with 6000 s of nonsource

background counting which was used to determine the background level more accurately. Figure 5-6 shows the spectral points with a best-fit power law of index $\alpha = 3.3$, compared with the $\alpha = 2.4$ spectrum obtained by Wilson & Rothschild (1983) at high energies a month after maximum. The total level of significance for these points is 4.6σ . A reduced χ^2 of 4 resulted from the fit to the offset-angle distribution (see section 4.1.5) for the lowest energy, but because there were acceptable values of ~ 1 for the higher energies, it is unlikely that the overall detection is spurious. However, the error in the lowest energy's flux level may be larger than that shown in Figure 5-6, which is from counting statistics alone.

H1705-25 is thought to belong to the class of 'classical', high-luminosity X-ray transients, the best-known example of which is 3A 0620-003. Members of this class are probably eccentric-orbit binaries consisting of a low-mass dwarf star and a neutron star with accretion disk. Griffiths et al (1978) enumerate four characteristic features of this class of nova, which H1705-25 seems to satisfy:

- a) Increase in X-ray intensity by a factor of ~ 100 , rise time of a few days, decay time constant of tens of days, and no variability on short time scales — H1705-25's X-ray intensity increased by ~ 3000 with a rise time of 2 d and a decay time constant of ~ 10 d.
- b) Soft X-ray spectrum with $kT \approx 2$ keV — H1705-25 had a $kT \approx 3$ keV.
- c) An almost featureless blue optical continuum in the early stages — the nova star (after 40 d) had a smooth spectrum which peaked at 420 nm and showed one weak He II emission line.
- d) An L_x/L_{opt} ratio of ~ 100 — H1705-25 had a ratio of at least 100.

However, H1705-25 does show some nonstandard features, in that it had a double maximum, with peaks 2 d apart, and was followed by an irregular decay scheme. But the main difference seems to be indicated by the data from HEAO-1 and LAPAD on its long-term history. Whereas

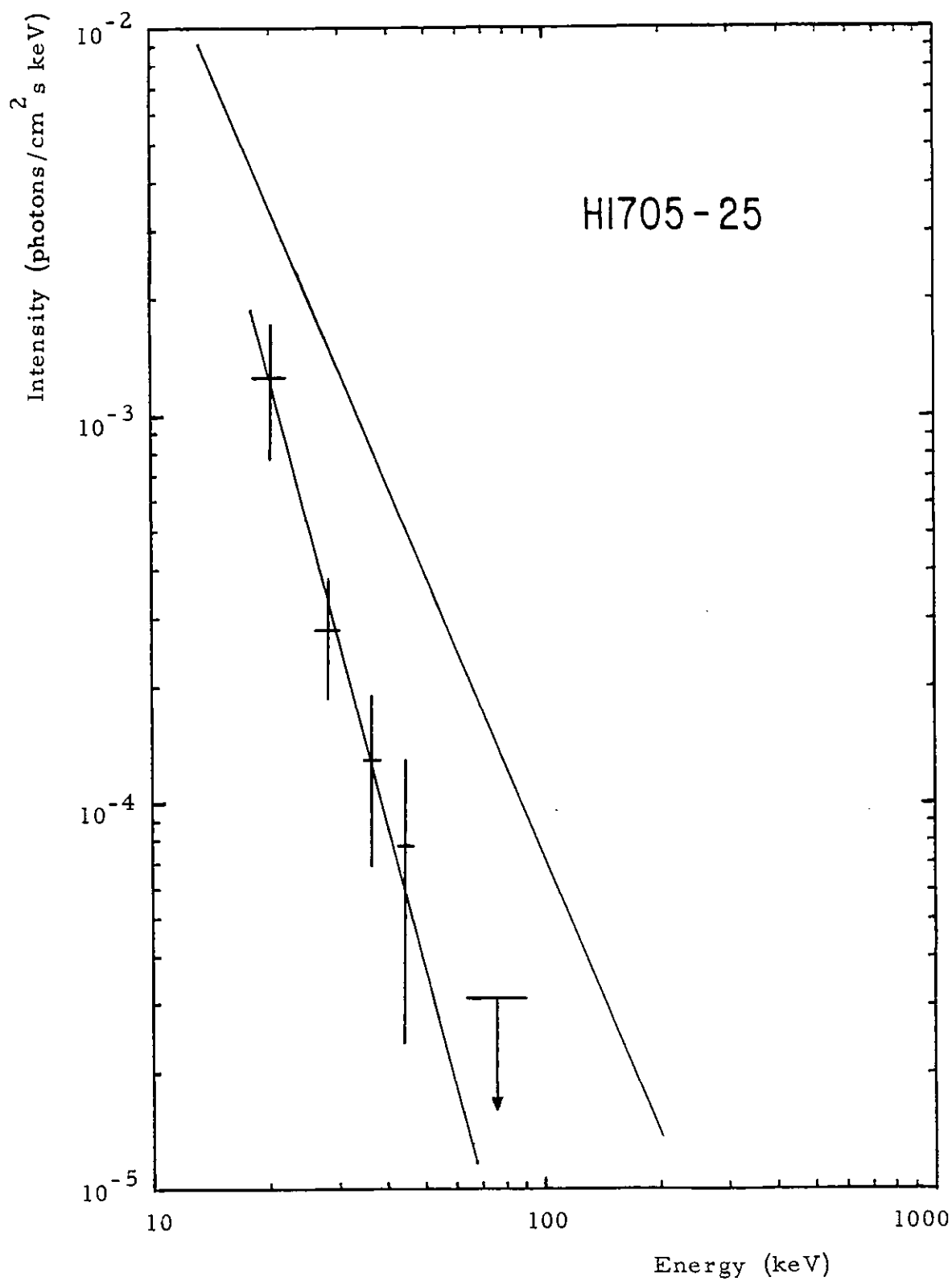


Figure 5-6. The $\alpha=3.3$ spectrum obtained for H1705-25 by LAPAD, 4 yr after maximum, compared with the $\alpha=2.4$ HEAO-1 spectrum one month after maximum (upper line — Wilson & Rothschild 1983).

3A 0620-003 faded within six months to below detection thresholds ($<10^{-6}$ of peak intensity), H1705-25 seems to have become a relatively permanent X-ray source, with flux levels $\sim 10^{-2}$ of peak intensity, as measured 1 and 4 yr later. Alternatively, the long-term X-ray behavior could be explained by some kind of flaring or recurrent transient activity in the source, like that observed in 3A 0535+262. This latter transient is perhaps more similar to H1705-25 than 3A 0620-003, as it is still detectable more than six years after its initial outburst (see Hameury et al (1983) for the most recent observation and a journal of detections).

5.5 The Galactic Bulge Sources GX5-1 and GX3+1

These two sources are both fairly typical members of the low-mass binary or galactic bulge class of X-ray emitters. The characteristics of the class are: soft X-ray spectra, usually low-temperature thermal bremsstrahlung with kT 's of 2-10 keV; no pulsations or eclipses in the X-ray emission; high X-ray to optical luminosities, L_x/L_{opt} , an aspect of their faint optical counterparts; optical spectra devoid of normal stellar absorption lines; X-ray burst activity and irregular variability on all time scales. Not all members share all these properties however, and there is some middle ground between the bulge sources and the pulsars. Because of their soft spectra, the bulge sources have almost exclusively been studied at low X-ray energies, so the LAPAD observations are some of the first above 20 keV.

5.5.1 GX5-1

GX5-1 (= 4U 1758-25 = 3A 1758-250) is one of the brightest bulge sources after Sco X-1, its existence being known from some of the earliest rocket-flight observations of the galactic center region. It was subsequently studied by the Uhuru, ANS, Ariel-5, and SAS-3 satellites. Many attempts have been made to identify GX5-1 with counterparts at other

wavelengths as its X-ray error circle has been reduced. The best position so far comes from a combination of lunar occultation, SAS-3 RMC and HEAO-1 MC results, with an uncertainty of 5" (Bradt & McClintock 1983). A weak point-like radio source was detected by Braes, Miley & Schoenmaker (1972), which is almost certainly associated with GX5-1, as it lies within the error circle and is similar to those associated with several other bulge sources. In the optical, the best candidate is a 12^m blue star, though this association is less conclusive. Uhuru satellite spectral observations by Jones (1977) show reasonable fits to the 2-20keV data by either a power law with $\alpha = 2.5$ or thermal bremsstrahlung with $kT = 6$ keV; Parsignault & Grindlay (1978) using ANS, similarly found $\alpha = 2.8$ or $kT = 3.3$ keV for their fits; and Mason et al (1976) found $kT = 3 - 8$ keV for various observations with the Copernicus and Ariel-5 satellites. As well as spectral variability, GX5-1 exhibits some irregular intensity variability, though less than most galactic sources (Forman, Jones & Tananbaum 1976), its maximum to minimum flux ratio being ~ 3 (Bradt & McClintock 1983), but it shows no regular periodicities (van der Klis & Rappaport 1983). The only previous hard X-ray measurements of GX5-1 are those by Ricker et al (1976) over the range 17-30 keV, which in conjunction with the low-energy fluxes, also give $\alpha = 2.8$ or $kT = 7$ keV.

During the 1981 flight's scans of the galactic center region, an 800 s on/off-source observation was obtained covering the period 1981 December 2 04:51 to 05:07 UT. An extra 1500 s of nonsource background counting was used to determine the background level more accurately. Source signal was detected in the range 20-75 keV, probably the highest ever. The unfolded spectral data points are plotted in Figure 5-7. Owing to the reasons discussed in section 5.6, there may be a systematic underestimation of the low-energy points, which may be at least partially responsible for the unusually hard spectrum obtained. However, using the spectral points as they stand, various spectral fits were tried, the

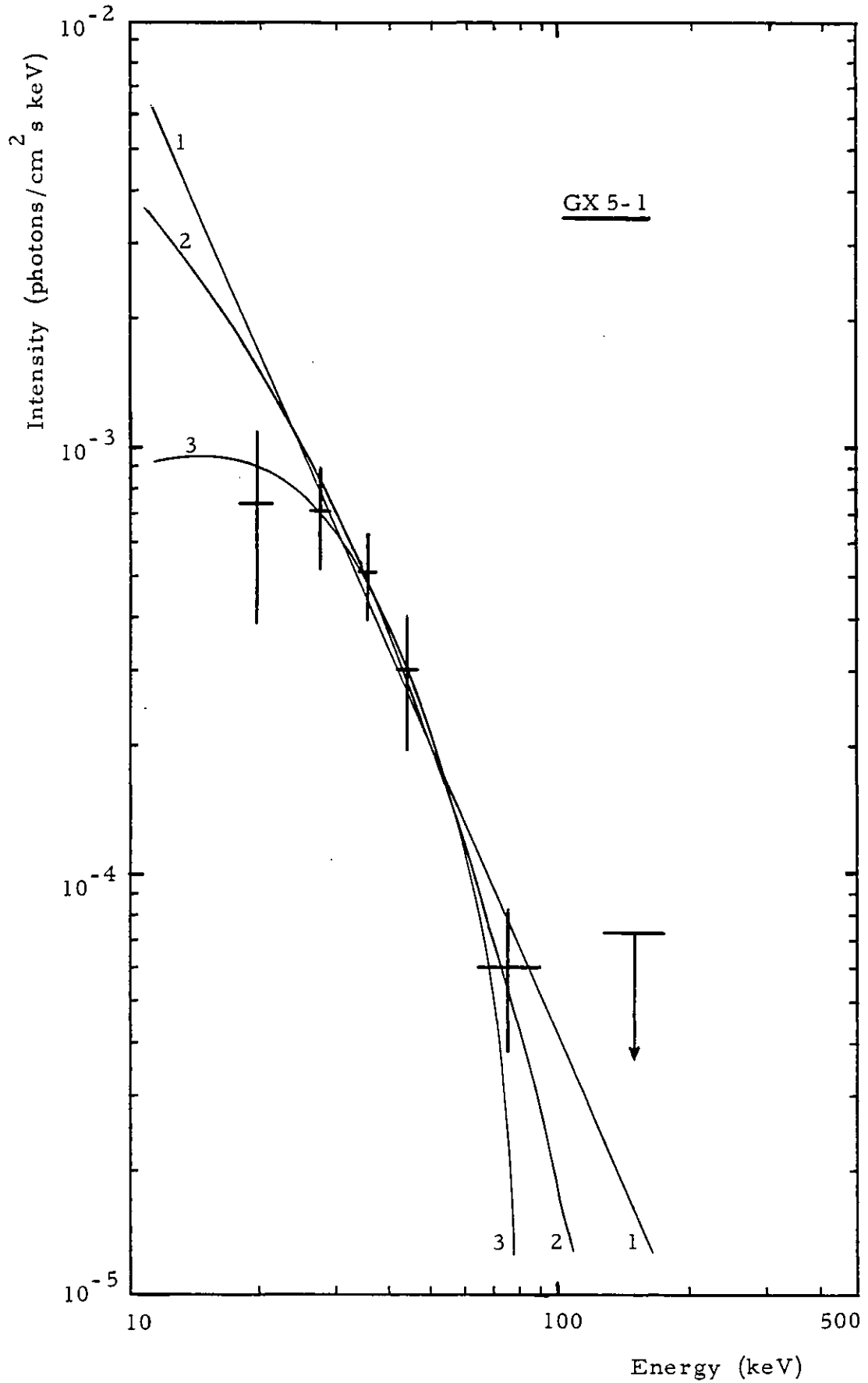


Figure 5-7. The three best-fitting models to the GX5-1 spectral points: (1) power law of index $\alpha = 2.2$, (2) TB with $kT = 29$ keV, (3) black body with $kT = 9.5$ keV.

results of which are given in Table 5-6.

Table 5-6. Results of model fits to the GX5-1 spectral points

<u>Spectral type</u>	<u>Parameter value</u>	<u>$\chi^2/\text{d.o.f.}$</u>	<u>Confidence</u>
Power law	$\alpha = 2.2 (+0.6, -0.7)$	2.6	5 %
TB (exc. Gaunt)	$kT = 29 (+26, -10) \text{ keV}$	2.2	9 %
TB (inc. Gaunt)	$kT = 40 (+70, -16) \text{ keV}$	2.3	7 %
Black body	$kT = 9.5 (+3, -2) \text{ keV}$	1.5	21 %
Modified Thomson	$E_H = 170 (+100, -50) \text{ keV}$	2.2	9 %

Notes. The spectral formulae are as defined in equations 4.17, 4.18 and 4.19, and the modified Thomson-scattering spectrum is given by

$$\frac{dN}{dE} = A E^{-1} \left[1 + \tau_0 \left(\frac{E}{E_H - E} \right)^2 \right]^{-1} \quad (5.1)$$

where E_H is the cyclotron energy, and τ_0 is the optical depth to scattering, set equal to 10 after Boldt et al (1976).

As is apparent from the table, power-law and thermal bremsstrahlung models do not give an adequate fit to the spectral points, nor does the modified Thomson-scattering model invoked by Boldt et al (1976) and Coe et al (1981) to fit the spectra from the binary pulsars Her X-1 and SMC X-1 respectively. The best fit, although not a particularly good one, is given by the black-body model, so this was used to unfold the data points, even though its shape is not consistent with the soft X-ray flux levels. A two-component model might give a better fit, but one has not yet been attempted. The various models' spectral shapes are shown in Figure 5-7 for comparison with the data points.

More-valuable information comes from a comparison of these data points with the fluxes measured at low energies, shown in Figure 5-8. The range of intensities implied by the Uhuru satellite's measurements is

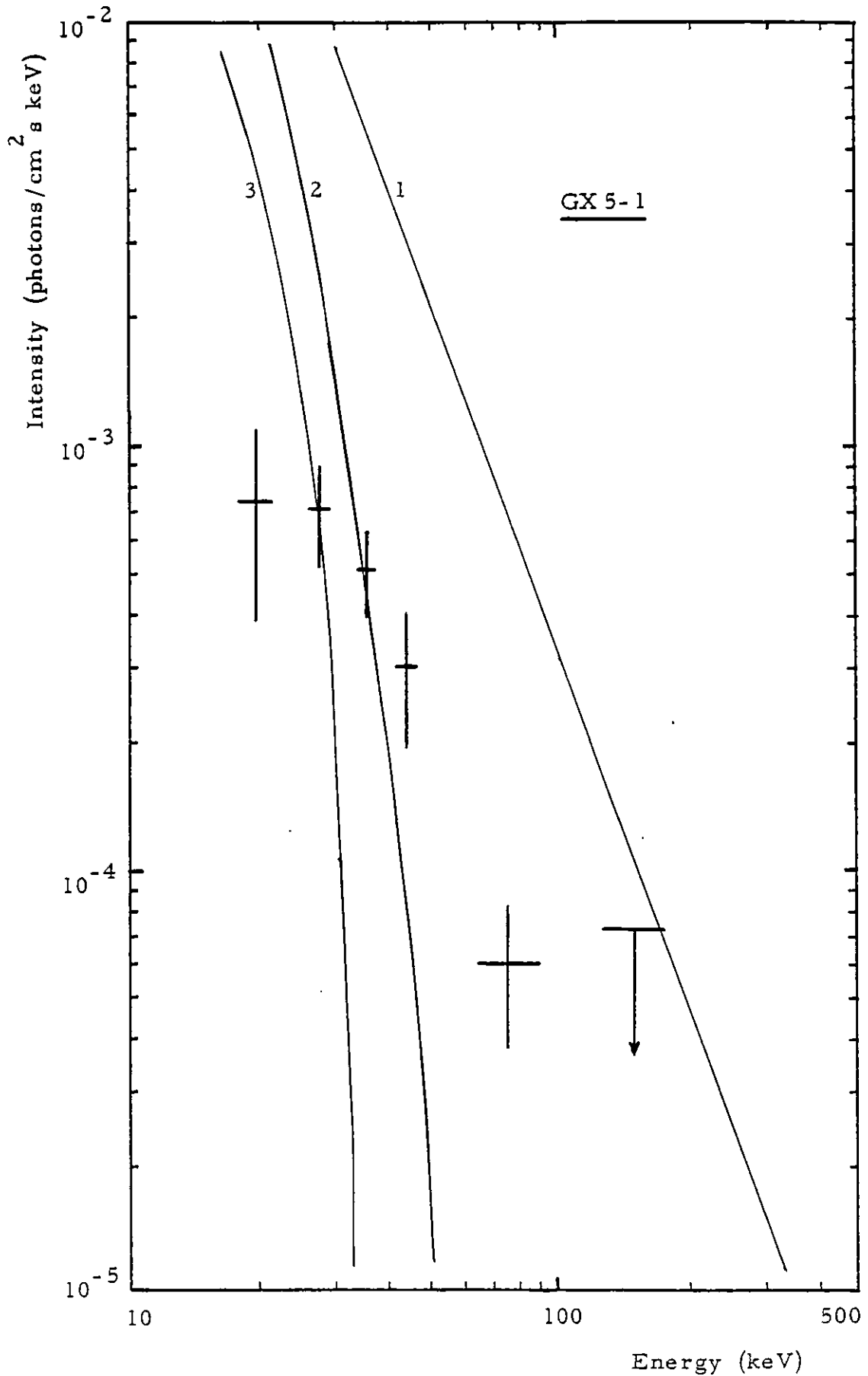


Figure 5-8. The spectral points for GX5-1 compared with extrapolations of low-energy measurements: (1) steepest power-law fit observed of $\alpha = 2.8$, (2) TB with $kT = 5.6$ keV, (3) TB with $kT = 3.3$ keV.

indicated by three low-energy spectral extrapolations: TB curves with $kT = 3$ and 6 keV to represent the range of observed temperatures, and the steepest power-law fit found, of index $\alpha = 2.8$. An overall power-law spectrum would seem to be excluded, as it requires high-energy fluxes much greater than those observed, which is not surprising, since none of the bulge sources are fitted better by power laws than TB in the low-energy range alone. The TB curves give intensities of the order found, but do not model the distribution of the high-energy points adequately. This could be explained either by a high temperature and underestimation of the LAPAD low-energy points, or by a lower temperature and some kind of high-energy excess or hard tail as has been claimed for other bulge sources, e.g. Sco X-1 and GX349+2 by Greenhill et al (1979). Further work is necessary on the galactic center observation before the former possibility can either be excluded or corrected for. However, the LAPAD data taken in context do indicate a basic exponential or thermal bremsstrahlung model for the emission from GX5-1.

5.5.2 GX3+1

GX3+1 (= 4U 1744-26 = 3A 1744-265), although only about a third of the apparent intensity of GX5-1, has some interesting features which make it worth studying. Like GX5-1, it was first detected from early rocket flights, and has been observed by several satellites. It also remains unidentified with an optical object, despite its very small, $4''$ error box from lunar occultations (Janes et al 1973), though it has a weak point-like radio counterpart. Spectrally, it is almost identical to GX5-1 — Jones (1976) fitted $\alpha = 2.5$ power-law or $kT = 6$ keV TB models to the range 2-20 keV observed with the Uhuru satellite, and Parsignault & Grindlay (1975) found $\alpha = 2.2 - 3.2$ or $kT = 3 - 5$ keV with ANS. However, it differs from GX5-1 in its variability. Forman, Jones & Tananbaum (1976) showed that it is one of the most variable sources on

time scales less than a day; its intensity varies by a factor ~ 10 assessed over all time scales (Bradt & McClintock 1983). It recently seems to have gone into a state of lower average intensity at about half its mid-1970s flux, as observed by Makishima et al (1985) with the Hakucho satellite, who also report the onset of X-ray burst activity (not previously detected in GX3+1), which they suggest is associated with its low luminosity state.

Exposure to GX3+1 was also achieved during the 1981 galactic center region scans, for 600 s of on/off-source rocking covering the period 1981 December 2 04:38 to 04:49 UT. No signal above background was detected, so only upper limits to the source flux in our energy range can be calculated. These are plotted in Figure 5-9, and compared with extrapolations of the low-energy flux levels and spectra. The range of intensities measured by Ariel 5 in the range 2-10 keV is indicated, with a similar box at half the level to correspond to the lower fluxes seen by Makishima et al. The factor of two in intensity in fact has relatively little effect at high energies due to the steep slope, the TB temperature being a more important parameter. An overall power-law shape can almost certainly be excluded by the 16-48keV upper limit, as it lies below an extrapolation of the steepest observed power-law fit, with index $\alpha = 3.2$, to the lowest of the range of low-energy fluxes. Like GX5-1, this is not surprising, since no bulge source has been found to have a power-law spectrum before. TB models give a more promising means of reconciling the low-energy flux levels and the LAPAD high-energy upper limits. TB temperatures $\lesssim 5$ keV seem to be required to fit the data, which are well within the 3-6 keV measured from previous observations. (These inferences about both power-law and TB models assume that there is no high-energy cut-off, since none have been reported for bulge sources, although this may reflect their low intensity at high energy.) Unfortunately, the LAPAD upper limits provide little information as to whether GX3+1 was

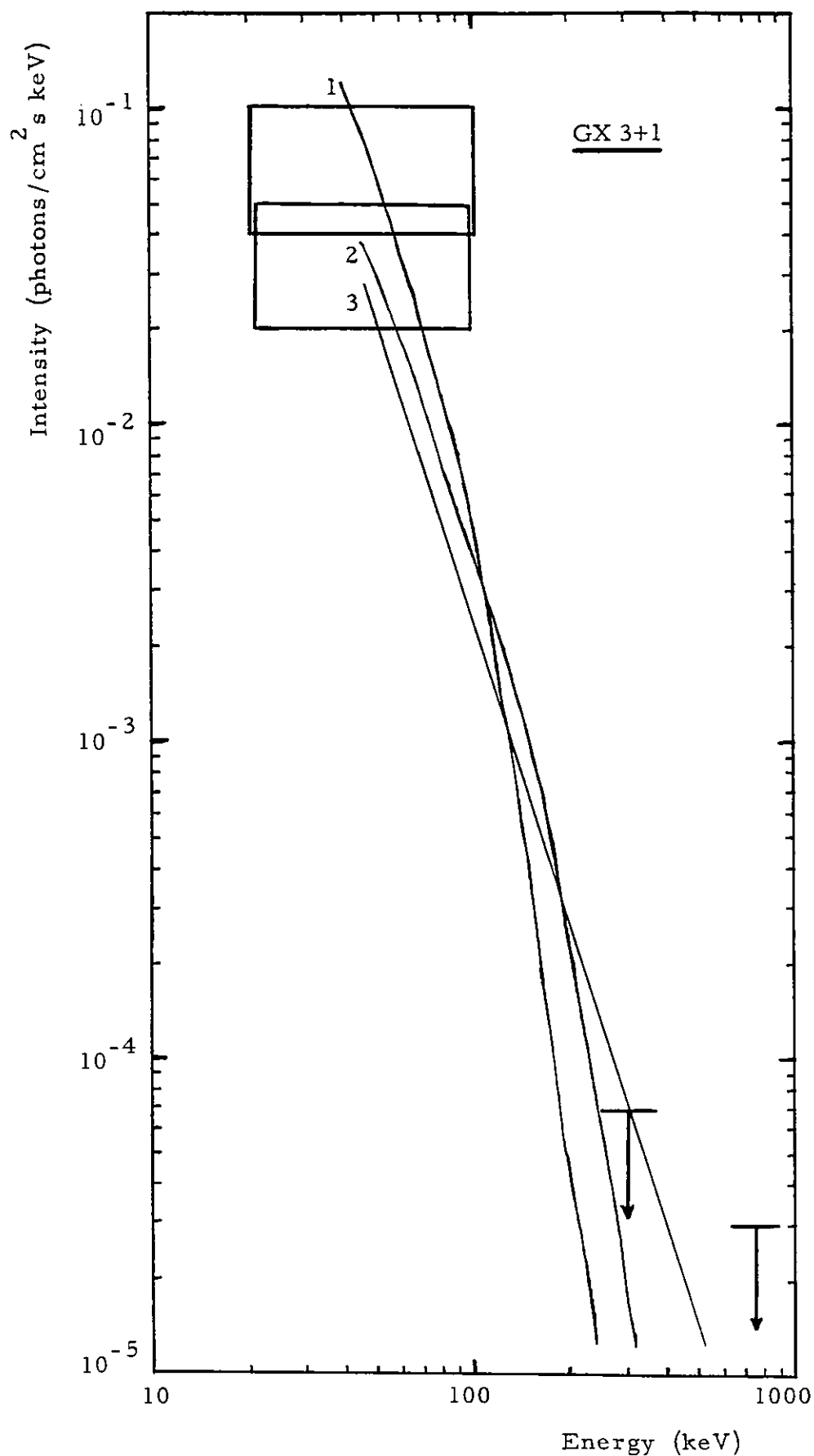


Figure 5-9. Upper limits for GX3+1 compared with extrapolations of low-energy measurements (boxes): (1) TB with $kT = 3$ keV, (2) TB with $kT = 6$ keV, (3) power law with $\alpha = 3.2$.

still in the low luminosity state reported by Makishima et al, or whether it had returned to its earlier, brighter state.

5.6 The Binary Pulsar GX1+4

There are many X-ray sources in the galactic center region, but as the majority have soft spectra, there are only a few bright sources at hard X-ray energies. The two brightest and most permanent are GCX, the X-ray source coincident with the galactic center itself, and the binary pulsar GX1+4 (= GX2+5 = 4U 1728-24 = 3A 1728-247). Wide-field observations of the galactic center region with balloon-borne detectors were made in the late 1960s, but it was not until the 1970 flight of Lewin, Ricker & McClintock (1971) that the discrete source GX1+4 was identified. They observed it again in 1972 (Ricker et al 1976), matching it with the low-energy source 3U 1728-24.

The first of these observations indicated that the flux might be regularly modulated with a period of ~ 140 s, which was confirmed by White et al (1976a) and Becker et al (1976), although there was a discrepancy between their results about whether this represented the full period of the source or half the period of a double-pulsed cycle. It was quickly realised that the pulse period was changing rapidly, spinning up at a rate of $\sim 2\frac{1}{2}$ percent a year, the fastest of any pulsar except 3A 0535+262. The most recent observation of the period was ~ 110 s in 1980 April, found by Ricketts et al (1982) with Ariel 6. The single-pulse or double-pulse question still lacks a firm answer, although several more recent reports of differences between alternate pulses seem to indicate that the ~ 230 s double-pulse period is the fundamental (Koo & Haymes 1980; Strickman, Johnson & Kurfess 1980; Doty, Hoffman & Lewin 1981 (ambiguous evidence); Kendziorra et al 1982). GX1+4 has a very complex X-ray spectrum. The 1-50keV Ariel-6 spectra of Ricketts et al (1982) show multicomponent structure within that range, including 7keV

iron-line emission. Their overall spectra could not be fitted by simple TB, power-law or blackbody models, but a multitemperature black body with $kT_{\text{max}} \approx 7$ keV gave a reasonable fit, as did an $\alpha = 1.0$ power law over the limited range 4-30 keV. At low energies, the 2-20 keV spectrum of Jones (1976) obtained with the Uhuru satellite could be fitted by a power law of index $\alpha = 1.2$, but not by a TB model for $kT < 20$ keV; Parsignault & Grindlay (1978) with the similar ANS detector over the range 1-28 keV found $\alpha = 1.2$ or $kT > 30$ keV fits for one observation, and $\alpha = 1.6$ or $kT = 12 \pm 8$ keV for another. For high-energy measurements, both power-law and TB models have given reasonable fits with parameter values ranging widely: $\alpha = 2.4 \pm 0.7$ (Lewin, Ricker & McClintock 1971) to $\alpha = 4.1 \pm 0.3$ (Dennis et al 1980), and $kT = 19 \pm 4$ keV (Dennis et al) to $kT = 41 \pm 8$ keV (Kendziorra et al 1982). Dennis et al (1980) found that a TB model gave an acceptable fit to their high-energy data (confidence level = 35%), whereas their best power-law fit was not acceptable (confidence level = 3%). GX1+4 exhibits unusually large spectral variability, Ricketts et al (1982) found that the spectral shape and structure varies significantly with pulse phase, particularly at the high-energy end of their range (> 20 keV); the low-energy spectral cut-off due to hydrogen absorption varies on time scales of less than a day (Becker et al 1976); and the overall spectrum shows large changes in the long term (measurements and references above). However, GX1+4 has less variability in intensity — the 3A catalog of Warwick et al (1981) indicates a maximum to minimum ratio for the time-averaged flux of < 2 , and Bradt & McClintock (1983) give a ratio of ~ 7 for all time scales.

Glass & Feast (1973) were the first to be successful in the search for counterparts to GX1+4 at other wavelengths. Scanning the 2' error box from observations with the Copernicus satellite, they found a bright infrared source near the center, corresponding to a 19^m star with an unusual optical spectrum. A finding chart is given with the SAS-3 RMC

X-ray position report in Doxsey et al (1977). Detailed optical spectrophotometry of this star by Davidsen, Malina & Bowyer (1977) showed that it has a very rich emission-line spectrum in the visible, dominated by a massive H α emission line, and is heavily reddened by interstellar absorption ($A_V \approx 5^m$, corresponding to a distance of ~ 10 kpc). They identify it as a member of the rare class of symbiotic stars, calculating that it consists of an M6 red giant with a smaller, hotter, blue companion. The emission lines show that, in addition, it is surrounded by an envelope of gas, possibly arising from its stellar wind, which is photoionised by the X-ray emission to produce the rich emission-line spectrum. GX1+4 is the only X-ray source to be identified with such a system, as well as being one of the very few binary X-ray pulsars not to be associated with a massive O- or B-type star, which makes it one of the most interesting galactic X-ray sources.

GX1+4 was observed on both scans of the galactic center region on the 1981 flight, for a total of 1500 s in the on/off-source rocking mode covering the period 1981 December 2 03:29 to 03:43 and 04:22 to 04:35 UT. In addition, another 6000 s of nonsource background data was used to determine the background level more accurately. The unfolded data points for the time-averaged spectrum are shown in Figure 5-10. They seem to indicate some kind of peak at ~ 30 keV, and since this is an extremely unusual feature, it is important to examine the data more carefully to check that it is not spurious. There are at least four possible ways of underestimating the source flux at the low-energy end, which would produce the effect of an increase in flux with energy:

a) If there were an unknown transient source with a soft spectrum near to GX1+4, which was included in the background level determination, it would decrease the apparent size of the source flux preferentially in the lower-energy channels. This is unlikely since the peak is still evident when using background counts obtained only within 3° of GX1+4,

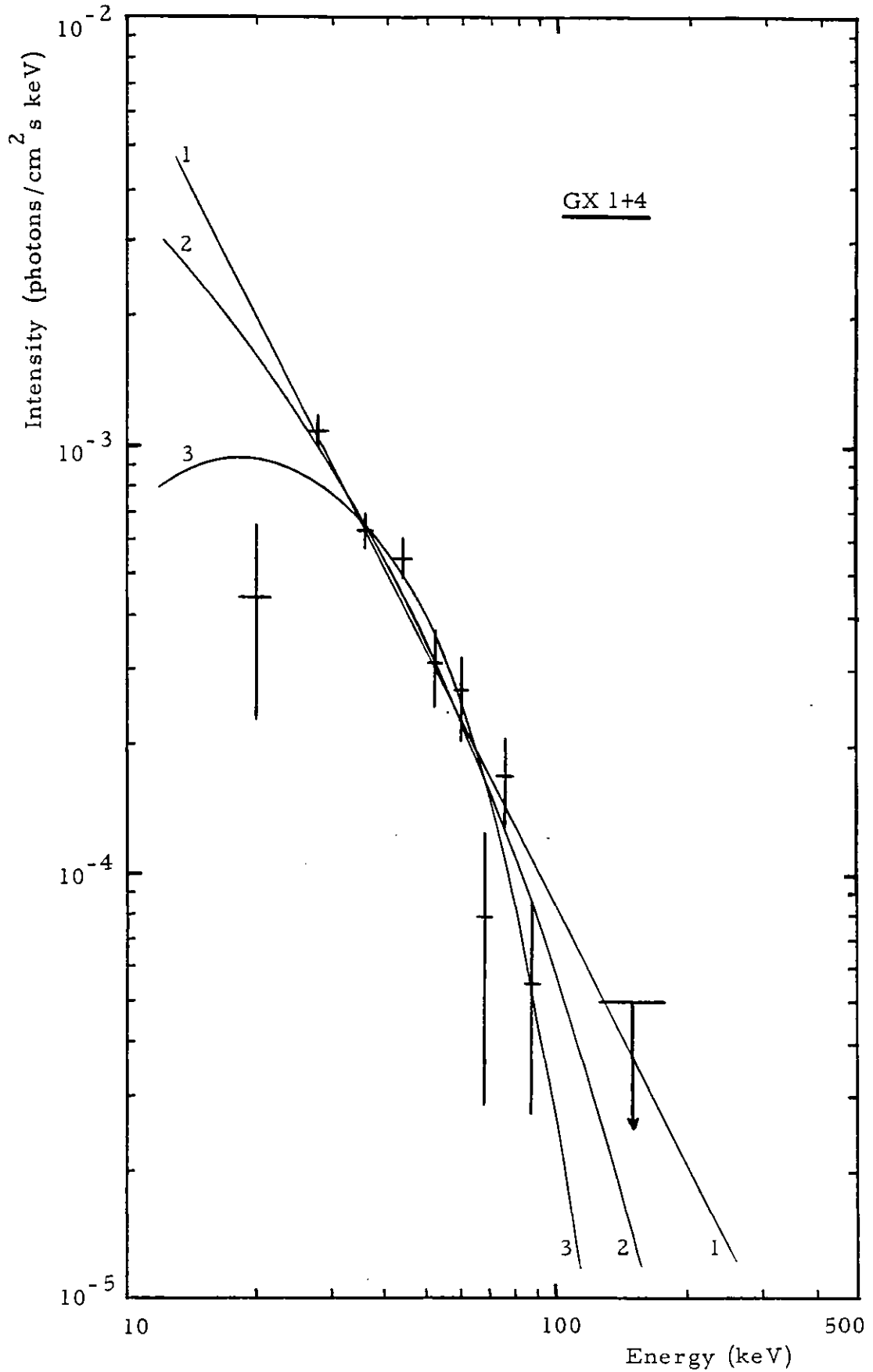


Figure 5-10. Three fitted models to the GX1+4 spectral points: (1) power law of index $\alpha = 1.9$, (2) modified Thomson scattering with $E_H = 250$ keV, (3) black body with $kT = 12$ keV.

and the fit to the source offset-angle distribution is good for the whole observation.

b) If the amount of residual air at the balloon float altitude was underestimated, this would not increase the low-energy fluxes relative to the high-energy fluxes during the unfolding process as much as they should have been increased. There was ~5% discrepancy between the measurements of residual air pressure *by* the University of Tasmania and NSBF instruments, and the lower value has been used. To check this possibility, another unfolding was done for the higher pressure, but there was negligible difference to the low-energy cut-off. It would thus take a very large mismeasurement of the air pressure to account for all of the peak, and the good results obtained for the unfolding of the 1981 Sco X-1 spectrum (see section 5.2) suggest that the air pressure measurement was reasonably accurate.

c) The choice of model used to unfold the spectrum affects the increase of the low-energy points relative to the high-energy points. The one actually used was the black-body model, because it gave the best fit (see Table 5-7) and should therefore produce the best unfolded spectrum. Since the black-body fit was poor (confidence level = 2%), there may be a better model for GX1+4's complex spectrum, which could make the peak less significant. Unfolding using the other models did make the peak less significant, although none removed it.

d) There may be some error left in one of the computer programs or the unfolding technique, which has the effect of creating this peak. However, the analyses of the Sco X-1 spectra are performed by virtually identical programs and methods, so this seems unlikely. Despite this evidence against the peak being an artifact of the data analysis, it is still a possibility that requires further and more detailed examination in the future. In the meantime, it will be cautiously treated as being real in the following discussion of the spectrum.

Five model fits to the spectral data points were tried, with the results shown in Table 5-7. None of the models gave a reasonable fit, mainly due to their inability to produce a sharp enough peak. The model spectra are shown in Figure 5-10 in comparison with the data points. It would seem to require a more complex model to fit the spectrum adequately — the multitemperature black-body model of Ricketts et al (1982) would be one possibility to try. This result is at odds with other recent high-energy observations of GX1+4, for example Kendziorra et al (1982) who found a good fit with a 41keV TB model, and Dennis et al (1980) who found a good fit with $kT = 19$ keV.

Table 5-7. Results of model fits to the GX1+4 spectral points

<u>Spectral type</u>	<u>Parameter value</u>	<u>$\chi^2/d.o.f.$</u>	<u>Confidence</u>
Power law	$\alpha = 1.9 \pm 0.3$	3.3	0.2 %
TB (exc. Gaunt)	$kT = 47 (+22, -12)$ keV	2.7	0.8 %
TB (inc. Gaunt)	$kT = 80 (+70, -27)$ keV	3.0	0.5 %
Black body	$kT = 12.2 \pm 1.5$ keV	2.3	2 %
Modified Thomson	$E_H = 250 (+90, -50)$ keV	2.5	1.5 %

Note. The spectral model formulae are as defined in equations 4.17, 4.18, 4.19 and 5.1.

Regarding the peak at ~ 30 keV in the LAPAD spectrum, there may be similarities in other published observations. Ricketts et al (1982) found a peak in the energy spectrum at ~ 20 keV at one phase of the pulse period, which would be roughly equivalent to a slight downward slope in the photon spectrum up to ~ 20 keV. Ricker et al (1976) found that a much larger peak in the time-averaged spectrum at ~ 20 keV is implied by their data points when taken in conjunction with the low-energy flux measurements of the Uhuru satellite, which would be equivalent to a flat

photon spectrum or peak between 4 and 20 keV (though their measurements may be partly contaminated by emission from GCX, which was also in their field of view). In addition to these, the data of Maurer et al (1982) show an emission feature at ~ 40 keV (or absorption feature at ~ 30 keV), but only if their power-law fit is valid. The LAPAD spectrum's peak may be related to one of these effects. .

Looking at the overall spectrum, the failure of the modified Thomson-scattering model to give a significantly better fit, compared with the good agreement found with it to other binary pulsars' spectra (e.g. Her X-1, Boldt et al 1976), may reflect the difference between GX1+4 and the other binary pulsars. Watts (1983) has plotted the power-law indices against spectral constants for all the observations of GX1+4, and found that the two quantities are related by an exponential function. The LAPAD observation's values of $A \approx 0.6$ and $\alpha \approx 1.9$ fall on this curve, within errors, which would tend to confirm that the underlying spectrum is consistent with previous observations. Watts has also developed a source model for GX1+4 based on the Comptonisation of an initial TB spectrum, which explains this index-constant relationship for a power law, and the tendency of the various power laws to pivot about a particular energy, E_p . Watts calculates $E_p = 44^{+18}_{-12}$ keV for GX1+4. The LAPAD power-law fit is plotted in Figure 5-11 together with those from three other recent observations, and appears to show such behavior.

In conclusion, the GX1+4 spectrum from LAPAD seems to be fundamentally consistent with previous observations, except for the cut-off below ~ 30 keV. Reasonable TB and power-law fits could probably be found to the data above 30 keV, as have been for other observations of the source. The reality of this cut-off needs to be investigated further before reliance can be placed on it. In addition to the four lines of investigation suggested above, it would be valuable to see if this cut-off is related to the pulse phase or is otherwise time dependent, and to check

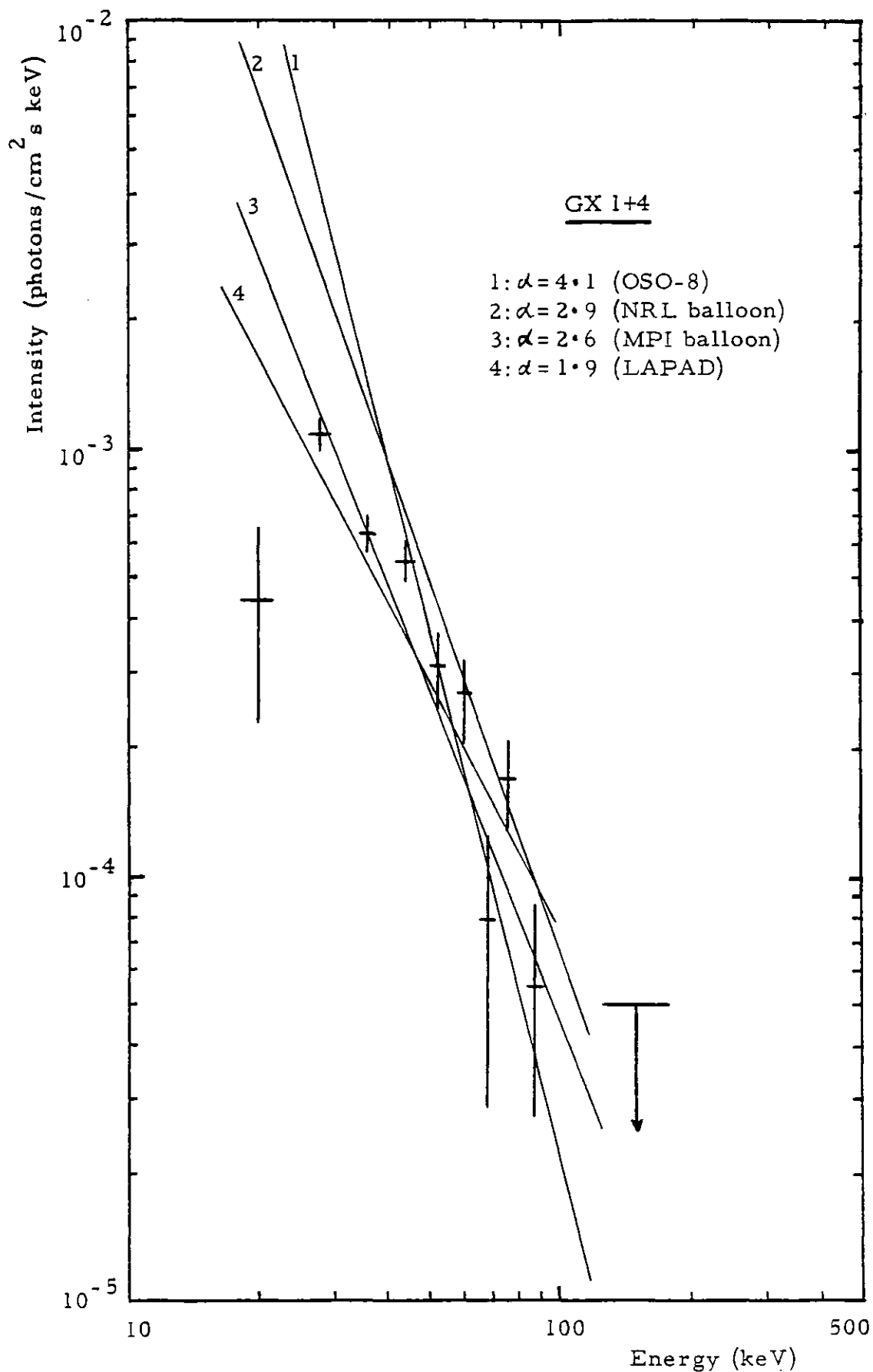


Figure 5-11. The best-fit power law to the LAPAD observation compared with those from other recent observations: (1) Dennis et al 1980, (2) Maurer et al 1982, (3) Kendziorra et al 1982, (4) this work.

to see how variable the total emission was during the ~ 1 h of the observation, which may cause distortion of the time-averaged spectrum. At the very least, a flattening of the spectrum below 30 keV is indicated, if not a complete turnover. Further analysis of this observation should prove a valuable way of studying this unusual, and perhaps unique, X-ray source.

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