An Investigation of Soft X-Ray Imaging and Polarimetry.

by

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March 1989

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Declaration

I hereby declare that no part of this thesis has been previously submitted to this or any other University as part of the requirements for a higher degree. Work described here was conducted by the undersigned except for the contribution of colleagues indicated in the text.

John E. Lees
March 1989
Abstract

This thesis includes work on both microchannel plate X-ray detectors and X-ray polarimetry, which although essentially distinct, have a common link through X-ray photocathodes. The source(s) of the background noise count rate in microchannel plates are investigated. Various noise mechanisms assessed include outgassing, cosmic rays, field emission, internal radioactivity, ion feedback and thermal emission. Experimental measurements are compared with calculations from a Monte Carlo model based on the assumption that radioactive decay (by beta emission) of elements within the microchannel plate glass is the major source of dark noise.

The performance of Caesium Bromide as an X-ray photocathode for enhancing the quantum detection efficiency of microchannel plates is reported and compared with that of Caesium Iodide.

A new type of microchannel plate configuration, a Sandwich Plate, consisting of three standard microchannel plates bonded in permanent contact is examined for use as an X-ray photon counting detector. This investigation includes a study of the correlation between gain reduction with increased count rate and the size of the illuminated area.

An evaluation is made of Galileo Long Life (L²) Microchannel plates operated in pulse counting mode with special emphasis on the stability of the gain as a function of abstracted charge. Further evidence for radioactivity as the major source of background noise is obtained; L² plates contain different radioactive isotopes compared to the ‘standard’ (Mullard) microchannel plate glass.

The design and performance of a new type of polarimeter, a Photoemission Polarimeter, for use in soft X-ray astronomy is presented. The polarimeter utilises the linear polarisation sensitivity in the photoemission from a CsI photocathode.

Possible sources of instrumental modulation are evaluated by comparing experimental measurements with calculations from a Monte Carlo model. The sensitivity of the photoemission polarimeter is compared with X-ray polarimeters presently used in X-ray astronomy.
Dedication

To Mum and Dad and all my family and friends
for their endless encouragement.

Acknowledgements

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Special thanks go to my supervisor, George Fraser, for his patience, inspiration and excellent supervision, and to Jim Pearson for passing on his enthusiasm for experimental work. I gratefully acknowledge the highly stimulating discussions with both of them which have contributed greatly to making the past three and a half years immensely exciting and very enjoyable.

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I gratefully acknowledge the assistance given to me by Mullard Ltd\(^1\) and my two industrial supervisors, Ron Field and Jim Smith, both whom helped to make my visits to Mitcham very interesting and trouble free. Many thanks to Richard Emptage for giving up so much of his time and helping to make my Mullard visits highly productive.

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---

\(^1\)Now called: Philips Components Ltd. Mitcham, New Road, Mitcham, Surrey CR4 4XY.
List of Publications

Some of the experimental results reported in this thesis have been incorporated in the following papers. The chapters to which these papers refer are given in brackets.

1. 'Dark Noise in Microchannel Plate X-Ray Detectors',
   G.W. Fraser, J.F. Pearson and J.E. Lees,

2. 'Caesium Bromide X-Ray Photocathodes',
   G.W. Fraser, J.F. Pearson and J.E. Lees,

3. 'Operating Characteristics of Sandwich Microchannel Plates',
   J.F. Pearson, J.E. Lees and G.W. Fraser,

4. 'Evaluation of Long Life (L²) Microchannel Plates for X-Ray Photon Counting',
   G.W. Fraser, J.F. Pearson and J.E. Lees,

5. 'A New Polarimeter For Soft X-Ray Astronomy: Measurement of Vectorial Effects in the X-Ray and UV Photoemission from Caesium Iodide',
   G.W. Fraser, J.E. Lees and J.F. Pearson,
   To be submitted to Nuclear Instruments and Methods in Physics Research A (Chapter 6).

6. 'Advances in Microchannel Plate Detectors',
   G.W. Fraser, J.F. Pearson, J.E. Lees and W.B. Feller,
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Chapter 1

Introduction

1.1 Microchannel Plate Imaging Detectors

Microchannel plates have found application in many areas, e.g., in image intensifiers, high temperature plasma diagnostics, accelerator mass spectrometry and fast oscilloscopes. This thesis, however, concerns their use in imaging X-ray detectors for astronomy.

Microchannel plate detectors have been used on a number of highly successful astronomical missions including the Einstein and EXOSAT X-ray observatories. Their continuing importance in imaging and for spectrometer readouts is reflected in their selection for several future X-ray astronomy experiments including the ROSAT Wide Field Camera (WFC) and the Advanced X-ray Astrophysics Facility High Resolution Camera (AXAF HRC).

Reviews of microchannel plate manufacture and operation have been given by many authors, including Wiza (1979), Timothy (1981) and Fraser (1984). Discussion of the performance of microchannel plate X-ray detectors and reviews of all the other major instruments used in X-ray astronomy can be found in ‘X-ray Detectors in Astronomy’, G.W. Fraser (in press). This wealth of coverage obviates the need to cover these areas in detail here.

Figure 1.1 illustrates the main features of MCP operation and the three plate configurations commonly found in detectors used for X-ray astronomy. The incident photon interacts with the top of the channel and generates secondary electrons which escape into the vacuum where they are accelerated by the large applied potential difference across the plate. These electrons drift across the channel and strike the opposite channel wall releasing more electrons which undergo the same process repeatedly. A large cloud finally leaves the plate to be collected by the readout element. The output charge pulse normally contains $10^5$ to $10^8$ electrons and the resultant pulse height distribution has a gaussian type shape.

The X-ray quantum detection efficiency of a bare MCP is very low ~ 10%. Detection efficiencies can be increased by the deposition of appropriate photocathode materials. This technique has been shown to give enhancements of ~ $x\ 5$ over the bare plate detection efficiencies. At present CsI is recognised as the best photocathode for the soft X-ray region. A new MCP photocathode material, CsBr, has been tested (Chapter 3) and has been shown to more efficient than CsI in the 20 to 100 Å wavelength range. The relevance of this increased efficiency is discussed by comparing
Figure 1.1: Configurations of high gain MCPs (Timothy 1985).


the detection efficiencies of CsI and CsBr coated MCPs with the requirements of the AXAF HRC and Low Energy X-Ray Transmission Grating Spectrometer.

Noise in any detector can be a major problem and this is especially true of detectors used in X-ray astronomy where the incident flux can be low (~1 count per square centimetre corresponds to a very bright source). Once the signal is maximized, further increases in signal to noise, and hence in the detector sensitivity, can be obtained only if the intrinsic background noise can be substantially reduced. Chapter 2 describes an investigation undertaken to find the mechanism(s) responsible for the dark noise in microchannel plates. Various noise mechanisms studied included the effect on the background noise of cosmic rays interacting within the microchannel plate glass, the contribution arising from radioactive decay of elements forming the glass material and desorption of gas from the channel walls. Other mechanisms investigated were electric field induced emission, thermal emission and ion feedback. A Monte Carlo model, developed at Leicester, based on the assumption that internal radioactivity associated with the MCP glass is the major source of MCP dark noise, was found to be in very good agreement with the experimental measurements.

Telescopes used in the soft X-ray region employ grazing incidence mirrors. Figure 1.2 illustrates the interaction geometry where each nested mirror consists of two sections which have paraboloid or hyperboloid geometry. Incident X-rays reflect once from each section and converge to form a cone of half angle $\theta$ at the focal plane. For example, the mirror design for the ROSAT WFC involves grazing angles of ~7.5° resulting in the X-rays interacting with the MCP at $\theta \sim 30°$ (Barstow et al. 1985). As the detection efficiency of MCP is a function of X-ray incidence angle the front plate usually has zero degree bias channels to give an uniform response with azimuthal angle (although for AXAF the front plate will probably have a bias angle > 8° see chapter 3).
Figure 1.2: X-ray interaction geometry with a Wolter type grazing incidence telescope. (Pearson 1984).

In addition to enhancing the detection efficiency other MCP parameters must be optimised to achieve the best results from an imaging detector. It is important that the gain of the MCP is constant across the plates active area. Chapter 4 describes a new type of microchannel plate, the Sandwich Plate, which was found to have excellent gain uniformity over the 22 mm diameter test area. These new plates also demonstrated good gain stability with high count rates and led to the discovery of a previously unreported connection between gain reduction with increased count rate and the size of the illuminated area.

The gain of microchannel plates is known to degrade with extended use. This drop in gain is usually associated with the amount of abstracted charge removed from the MCP. For detectors operated in high flux environments, e.g. in fusion research, this gain reduction can limit the useful life-time of the detector. The magnitude of the incident fluxes encountered in X-ray astronomy tend to be low although the expected life-time of the detector can be quite long (AXAF has been designed to operate for at least 15 years). Although gain reduction can be partially compensated by an increase in bias voltages across the plates a more satisfactory solution would be MCPs which had an intrinsically longer life. Chapter 5 discusses gain decay with abstracted charge and presents measurements made on various types of MCPs comparing their performance in accelerated life tests, including results from Galileo's Long Life (L²) MCPs.
1.2 Polarimetry

X-ray astronomy is severely disadvantaged, when compared to astronomy performed at other wavelengths, by not being able to measure the linear polarisation (degree and direction) of the collected radiation. At present only one positive X-ray polarisation measurement has been made (Novick et al. 1972, Weisskopf et al. 1978) giving a value for the polarisation $P$, from the Crab Nebula, of 19%. The importance of measuring X-ray polarisation has been emphasized by many authors (Rees 1975, Novick 1975 and Mészáros et al. 1988). A positive detection of X-ray polarisation coupled to presently available spectral and temporal information would give a much better understanding of the mechanisms responsible for the production of the detected X-rays. At present there is no instrument which can routinely measure the X-ray polarisation with sufficient sensitivity although the need for one is great.

Chapter 6 introduces a new type of X-ray polarimeter, the photo-emission polarimeter, based on vectorial effects in the grazing incidence X-ray photoemission from CsI. Present X-ray polarimeters are reviewed and some of the astrophysical mechanisms which produce polarised X-rays are discussed.

The results obtained, both in the soft X-ray and for a broad UV wavelength band, indicate that this type of polarimeter may form the basis of a sensitive, broad-band, high modulation, imaging polarimeter for soft X-ray astronomy.
Chapter 2
Background Noise in Microchannel Plates

2.1 Introduction

This chapter concerns the investigation of the source(s) of background noise in microchannel plates. Prior to this investigation there had been considerable speculation in the literature as to the nature of the MCP dark noise. Various mechanisms had been proposed including field emission (Henry et al. 1977), cosmic ray interactions (Timothy 1981), ion feedback, thermionic emission and internal radioactivity (Fraser et al. 1985).

The understanding and reduction of the MCP background noise is especially important for astronomical X-ray detectors where the incident count rates can be very low (a typical count rate being 1 count cm\(^{-2}\) s\(^{-1}\)). MCPs in other applications, for example as ion detectors for carbon dating (Friedman et al. 1988), would also benefit from a reduction in the MCP dark noise.

Each of the mechanisms mentioned above were investigated, the results of which are presented in the following sections. Section 2.5 discusses complementary noise reduction techniques.

2.2 General Characteristics of Background Events

The pulse height distribution (PHD) for photon detection is markedly different from the PHD obtained for background noise alone. Figures 2.1 a and b show typical PHDs obtained from MCPs operated in high gain mode suitable for X-ray photon counting. Incident photons are normally detected near the top of a channel releasing photoelectrons and subsequent secondary electrons which will undergo the full amplification of the MCP chevron. This results in a peaked pulse height distribution having a gaussian type shape. The peak (modal) gain \(G_e\) and the full width half maximum (FWHM) of the resulting distribution depends on the operating characteristics of the MCPs.

As can be seen from figure 2.1 b the noise distribution has a quasi-exponential shape with an excess of events in the 0.5 \(G_e\) - \(G_e\) range. Background events can also be seen to extend out to twice the modal gain. This shape can be explained if the noise sources are distributed uniformly throughout the MCP since background events would then be seen at all possible gains.

In order that noise count rates from different detector configurations can be compared the
lower level discriminator, \( d \), must always be related to the peak signal gain \( G_g \), since an absolute value of the lower level discriminator has no physical significance. The output charge is a rapidly varying function of the depth, from the input surface of the MCP stack, at which the event is initiated. The peak gain therefore has been taken as a charge marker for front surface interactions.

### 2.3 Detector Characteristics

All the following measurements were made in the Leicester Vacuum Test Facility (Pearson 1984) with operating pressures in the \( 2 \times 10^{-7} - 5 \times 10^{-6} \) mbar range. Each detector mode consisted of two MCPs in a chevron arrangement with an inter-plate gap of 160 \( \mu \)m. The bias voltages across the front plate (\( V_F \)), inter-plate gap (\( V_G \)) and the rear plate (\( V_R \)) could be independently varied. The readout element consisted of two orthogonal graded-density grids and a reflector plate (Smith et al. 1982). X-rays were generated using an electron bombardment source with an SiC coated anode and filters (1\( \mu \)m macrofol for C-K (0.28 keV), 1\( \mu \)m Ag for Si-K (1.74 keV) X-rays) to obtain the desired energies. The X-ray beam had an angular divergence of \( \pm 0.16^\circ \) which resulted in a spot size of \( \sim 5 \) mm diameter on the MCP surface. Count rates for the X-ray PHDs were \( \sim 200 \) counts per second with the angle of incidence to the channel axis being 10\(^\circ\) for Si-K and 20\(^\circ\) for C-K.

All MCPs used in these measurements were Mullard plates with a channel diameter of 12.5 \( \mu \)m, channel pitch 15\( \mu \)m, open area (\( A_{open} \)) 63% and diameter 36 mm. The active area determined by the inner diameter of the annular rear electrode was 7.1 cm\(^2\). Channel bias angle \( \theta_B \) and the channel length (\( L \)) to diameter (\( D \)) ratio are given for each plate in Table 2.1. The MCPs were incorporated into four distinct detector configurations, designated Modes A - D and detailed in Table 2.1.

<table>
<thead>
<tr>
<th>Mode</th>
<th>( L/D )</th>
<th>( \theta_B ) (degrees)</th>
<th>Serial No.</th>
<th>( L/D )</th>
<th>( \theta_B ) (degrees)</th>
<th>Serial No.</th>
</tr>
</thead>
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<td>DD002/2</td>
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<tr>
<td>C</td>
<td>80:1</td>
<td>13</td>
<td>DD002/6</td>
<td>80:1</td>
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</tr>
<tr>
<td>D</td>
<td>120:1</td>
<td>0</td>
<td>AB414/5</td>
<td>80:1</td>
<td>13</td>
<td>DD002/5</td>
</tr>
</tbody>
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Table 2.1: Detector Modes A - D characteristics
Figure 2.1: X-ray and Noise PHDs.

( a ) X-ray pulse height distribution,

( b ) Dark noise PHD with the same MCP bias voltages.
2.4 Investigation of MCP Noise Mechanisms

2.4.1 Time Dependent Noise

MCPs appear to have two distinct types of background noise sources; one which is time dependent, the other time independent. The dark noise measurements of Whiteley et al. (1984) show noise count rates decreasing with time under vacuum leaving an irreducible but stable noise count rate two days after pumpdown. Given the large surface area of a MCP (~200 cm² per cm² detector area) a possible explanation of the time dependent noise is that ions and/or neutrals released as a result of outgassing of the channel walls initiate detectable avalanches.

To investigate this further the Mode A detector was exposed to a variety of atmospheres with measurements being made of the subsequent changes in the noise count rate. The detector was subjected to the following conditions:

(a) 24 days exposure of the MCPs to humid laboratory air.

(b) 2 hours exposure to laboratory air.

(c) 80 hours exposure to a dry nitrogen environment.

Noise measurements were made after obtaining the required operating pressures (after ~20 hours pumping time).

Figure 2.2 illustrates the observed changes in noise count rate after the first long exposure to lab air. After initial re-activation the plates exhibit a large excess of low-charge noise events. The inset shows the decay as a function of time with the noise count rate reaching a plateau after ~60 hours. During the initial period erratic noise bursts were evident, although the overall noise decays with a $\frac{1}{2}$ time of ~6.5 hours.

After the second (2 hour) exposure to lab air the initial noise count rates were only slightly higher ($\overline{N}(0.05 \text{ Gc})=0.42 \text{ cm}^{-2} \text{s}^{-1}$ compared with 0.39 cm$^{-2}$s$^{-1}$ from figure 2.2) than the plateau value previously reached after ~160 hours under vacuum.

Figure 2.3 a-d illustrates the decay of noise spots (after 2 hours exposure to lab air) over a period of one week. The insets show a section through the image indicating the relative intensity of the 'hot spots'. Note that the charge acceptance threshold has been increased between figures c and d indicating the relative brightness of the longest-lived noise spots is much decreased by rejecting very low charge events.

After exposure to a dry nitrogen environment the noise count rate was found to be constant after pumpdown.

On considering the results from all three exposures they confirm the initial premise of two distinct noise mechanisms: one time dependent, which appears conditional on the environmental history of the MCP and identifiable with local outgassing of the channel surface (water vapour and/or oxygen being a particular problem); the second, a stable residual noise mechanism not dependent on pumpdown time.
Note that the voltages were continuously applied during the above measurements and that the outgassing could be expected to have a longer time constant if the bias voltages were off. Without the bias voltages applied the effect of electron scrubbing and the heating effect of the MCP strip current would be absent. Therefore to achieve the quick demise of the noise count rate due to outgassing it can be recommended that the MCPs be activated whenever acceptable operating pressures are obtained.

The following subsections concern the investigation of the mechanism responsible for the time independent noise.

### 2.4.2 Cosmic Rays

One of the proposed noise sources in MCPs is the effect of cosmic ray interactions (Timothy 1981). The passage of cosmic rays through a MCP will cause ionisation tracks with the possible detection of the resultant electrons.

Wolfendale (1963) states that the total cosmic ray intensity at sea level (varying with angle, \( \phi \), from the vertical) has the form:

\[
I(\phi) = I_0 \cos^2 \phi
\]  

(2.1)

where \( I_0 = 1.14 \times 10^{-2} \text{ cm}^{-2}\text{s}^{-1}\text{steradian}^{-1} \). It can be shown that the variation in cosmic ray count rate per unit area with angle of detector rotation from the vertical will have the functional form:

\[
N_{cr} = Q I_0 \frac{\pi}{4} (1 + \sin^2 \phi)
\]

(2.2)

where \( Q \) is the detection efficiency of the MCP for cosmic rays.

Measurements were made with the Mode A detector at the two extreme positions obtainable with the Test Facility configuration, \( \phi = 10^\circ \) and \( \phi = 45^\circ \). No significant change in the count rate was detected.

Using the above equations and the estimated detector efficiency for cosmic rays (63% Fraser et al. 1988b, Siegmund et al. 1988), the expected noise count rates due to cosmic rays are

\[ N_{cr}(45^\circ) = 8.5 \times 10^{-3} \text{ counts cm}^{-2}\text{s}^{-1} \] and \[ N_{cr}(10^\circ) = 5.8 \times 10^{-3} \text{ counts cm}^{-2}\text{s}^{-1} \].

Recalling that the noise count rates for well outgassed plates was 0.3 - 0.4 counts cm\(^{-2}\)s\(^{-1}\) the expected contribution of the cosmic rays is seen to be very minor (\( \sim 3\% \)) in comparison with the overall noise count rate.

Siegmund et al. (1988) measured the cosmic ray induced events in a Z plate by coincidence methods using a plastic scintillator well. They measured the cosmic ray event component in the vertical (\( N_{cr}(0) = 0.00848 \text{ counts cm}^{-2}\text{s}^{-1} \)) and the horizontal (\( N_{cr}(90) = 0.0157 \text{ counts cm}^{-2}\text{s}^{-1} \)) positions. Even for the maximum event position (\( \phi = 90^\circ \)) the contribution to the overall noise count rate was only 4%. Both our measurements and those of Siegmund et al. concur that cosmic rays are not a major source of dark noise in Mullard MCPs.
Figure 2.2: Noise count rate decay $N(d)$ as a function of time under vacuum for Mode A.
Filled circles - 16 hours, crosses - 20 hours, diamonds - 22.5 hours and squares - 80 hours after initial pumpdown. Inset - decay of noise count rate with time, $d = 0.2 G_c$ where $G_c$ is the Si-K modal gain.

![Graph](image)

Figure 2.3: Noise images obtained after a 2 hour exposure to lab air.
Each image contains 6500 events. $V_F = V_R = 1240$V, $V_G = +200$V
(a) 22 hours after pumpdown. Imaging threshold, $d = 0.03 G_c$, $N(d)=0.42$ cm$^{-2}$s$^{-1}$.
(b) 44 hours after pumpdown. Imaging threshold, $d = 0.03 G_c$, $N(d)=0.27$ cm$^{-2}$s$^{-1}$.
(c) 140 hours after pumpdown. Imaging threshold, $d = 0.03 G_c$, $N(d)=0.25$ cm$^{-2}$s$^{-1}$.
(d) 140 hours after pumpdown. Imaging threshold, $d = 0.4 G_c$, $N(d)=0.19$ cm$^{-2}$s$^{-1}$.
The calculated change in noise count rates for the two measured angular positions \( N_{cr}(45°) - N_{cr}(10°) \) is of the order of \( 2.7 \times 10^{-3} \) counts \( \text{cm}^{-2} \text{s}^{-1} \) was at the limit of this detector's sensitivity. Appendix A reports a measurement of the cosmic ray contribution on a modified detector incorporating low noise MCPs.

### 2.4.3 Thermal Emission

The lead glass in MCPs is well known to have a large negative temperature coefficient of resistance, 1 - 2% per degree centigrade. That this will lead to gain variations with changes in temperature has been reported for both MCPs (Seigmund et al. 1985) and CEMs (Smith 1969).

Consideration of the relevant material properties would however appear to rule out thermal emission as a major source of MCP noise. The emission current density from a cathode with a work function \( \phi \) (eV) is

\[
J = 1.2 \times 10^{-6} T^2 \exp\left( \frac{-\phi}{kT} \right) \text{amps m}^{-2}
\]

where \( T \) is the temperature in degrees kelvin and \( k \) is Boltzmann's constant. Assuming that the MCP glass is an intrinsic semi-conductor then the thermionic work function can be expressed as \( (E_g + E_a)/2 \) where \( E_g \) is the valence to conduction band gap energy and \( E_a \) the electron affinity. The band gap can be assessed from the UV quantum efficiencies of uncoated plates, Fraser (1983) gives a value of \( \sim 10 \) eV. As \( kT = 0.025 \) eV at room temperature this leads to a negligible thermionic noise count rate contribution.

Measurements of the dark noise count rate for the Mode A detector were made as a function of temperature over the limited range 17 - 31°C. The temperature was changed by altering the lab air conditioning and using the MCP resistances as indices of the detector temperature. Twenty four hours were allowed to elapse between measurements letting the detector reach thermal equilibrium before measuring the noise count rate. The front plate resistance changed from 576 to 460 MΩ and the rear plate from 560 to 430 MΩ as the ambient temperature increased from 17 to 31°C. Given that the temperature coefficient of resistance is 2% per °C the resistive changes correspond to detector changes of 11 - 13 °C.

No significant change in the noise count rate occurred over this temperature range. Figure 2.4 compares Mode A measurements with similar measurements made by Seigmund et al. (1988) which cover a temperature range of -15° to 22°C. Although the value of the integral background noise count rates is slightly different both sets of data show no variation of the dark noise with temperature change. Henry et al. (1977) have also reported that the noise count rate did not vary when the temperature of their chevron was reduced to -30°C.

Taken together these results agree that thermal emission does not contribute significantly to the MCP dark noise.
Figure 2.4: Variation of noise count rate with temperature.


2.4.4 Field Emission

It has been proposed by Henry et al. (1977) that a significant contribution to the MCP dark noise arises from field emission from channel defects. If this was a major noise source then the count rate would be expected to vary with the bias voltages \( V_F, V_G, \) and \( V_R \), given that the electric field strengths along the channel length and across the inter-plate gap are typically 1 kV/mm.

Fraser et al. (1985) have argued that the specific field-dependent mechanism proposed by Henry et al. can be disregarded. They argue that channel defects will have a creation probability proportional either to the number of channels or unit channel surface area. This would then lead to a noise count rate dependent on either \( V_F \) or \( V_R \) for a constant plate thickness \( L \). Their measurements on MCPs with 8 and 12.5 micron diameter channels revealed no significant difference in dark noise count rate.

Measurement of the noise count rate \( N(d) \) as a function of bias voltages were made for Mode A and B detectors. Figure 2.5 illustrates the change in \( N(d) \) as the bias voltages were varied, \( V_G \) held constant. The peak gain varies over the range 3.9 pC (\( V_F = 1120V, V_R = 1240V \)) to 13.6 pC (\( V_F = V_R = 1320V \)). As can be seen the count rates tend to converge at low discriminator thresholds indicating that the overall dark noise is not dependent on bias voltages. Note however that the maximum noise count rate, for discriminator levels > 0.8 \( G_C \), corresponds to the minimum peak gain. This correspondence is contrary both to the Monte Carlo model of Fraser et al. (1987a) and measurements of Siegmund et al. (1988). Similar behaviour was found for Mode B (figure 2.6) and by varying the inter-plate gap voltage (figure 2.7). A reason for the measured differences between our data and Siegmund's may be due to differences in gain profiles of chevron and Z stack MCP detector configurations. That the Monte Carlo model does not predict this effect reflects the necessary simplified treatment of the statistics of the avalanche multiplication process.

These differences aside, both measurements on the Mode A and B detectors and the the Z stack of Siegmund et al. agree that the integral noise count rates appear independent of the field strengths within MCP detectors.

2.4.5 Ion Feedback

Ions forming in the inter-plate gap and transported to the high gain input of the front MCP have been suggested as a mechanism for background noise. Figure 2.7 illustrates the change in noise count rate as the inter-plate voltage, \( V_G \), was varied from -50V to +200V. For all values of \( V_G \) the noise count rate tends to converge at low discriminator thresholds indicating that ion feedback does not contribute significantly to the MCP dark noise. The maximum in the noise count rate for discriminator levels at \( \sim G_c \) reflects the variation in peak gain with interplate gap voltage. These results are in agreement with measurements reported by Fraser et al. (1985) for an inter-plate gap voltage varying from -100V to +200V. Similarly Siegmund et al. (1984) found no change in the noise count rates, (for a Z plate detector), with variation in operating pressure in the \( 2 \times 10^{-5} \)
- 9x10⁻⁷ mbar range.

Taken together the above measurements indicate that ion feedback is not a major source of MCP dark noise.

2.4.6 Radioactivity

All the mechanisms, (excluding outgassing), considered so far have failed to account for the measured intrinsic MCP dark noise. The report of Henry et al. (1977) that cosmic rays and 'other forms of natural radioactivity' accounted for less than 5% of the measured background seemed to rule out radioactivity as a possible noise source. The measurements reported here and elsewhere (Fraser et al. (1987a), Siegmund et al. (1988)) however, confirm the hypothesis (Fraser et al. 1985), that radioactivity is the major source of MCP background noise.

The lead glass used in the manufacture of MCPs contains ~6.5% by weight of potassium. ⁴⁰K exits in naturally occurring potassium at a level of 0.0118% and has a half life $T_{0.5}$ of 1.28x10⁹ years ($=4.04x10^{16}$ seconds). The decay routes of ⁴⁰K are:

(a) $\beta$ emission; 1.31 MeV; 89.4% probability  
(b) $\gamma$ emission; 1.46 MeV; 10.6% probability

The number of disintegrations per second $n_k$ can be calculated using:

$$n_k = \left( \ln 2 \right) \left( \frac{F_r F_m N_a}{A_m} \right) \left( \frac{\rho \pi D^2 L (1 - A_{open})}{4} \right)$$

(2.4)

where $F_r$ is the amount of the radioactive isotope in the naturally occurring element; $F_m$ the fraction of the element in the material; $N_a$ Avogadro's number; $A_m$ the atomic weight of the isotope; $\rho$ the element density (3.3 gm.cm⁻³ for Mullard glass); $A_{open}$ the open area fraction; $D$ the diameter of the MCP and $L$ the MCP length. For most plates detailed in Table 2.1 $L = 1$ mm.
Figure 2.6: Variation of noise count rate as a function of bias voltages, Mode B.

Figure 2.7: Variation of noise count rate as a function of the inter-plate gap voltages.
Mode A detector, $V_F = V_R = 1240V$, $V_G = -50V$ $G_e = 1.4pC$; $V_G = +200V$ $G_e = 8.1pC$. 
\[ A_{open} = 0.63 \] and \( D = 36 \text{ mm} \). Therefore for a single plate:

\[
n_k = 2.5 \text{ s}^{-1} = 0.25 \text{ cm}^{-2} \text{s}^{-1}.
\]

MCPs have an detection efficiency for an external source of MeV gamma rays of around 2% \((\text{Timothy and Bybee 1979})\). Therefore assuming the detection 'self efficiency' for the \( \gamma \) rays is of this order they can be discounted as a major source of MCP noise events. An attempt was however made to detect the gamma rays using a calibrated Na(Tl) scintillator. Long integration times were used both for the laboratory background and the MCPs plus background (1.2\times10^6 seconds) but no significant peak was detected at 1.46 MeV. Siegmund \textit{et al.} (1988) have measured the radioactive decay from a MCP (Mullard MCPs) using a germanium well counter and detected the \( \gamma \) decay from the \( ^{40}\text{K} \) and 352 keV \( \gamma \) rays from \( ^{226}\text{Ra} \) which they attribute to trace Uranium (0.9 ppm).

Bateman (1977) has reported an external efficiency of up to 59% for 2 MeV electrons. An estimate of the \( \beta \) self efficiency, \( Q_\beta \) would therefore, obviously be of interest. A model using Monte Carlo techniques was developed by G.W. Fraser (Fraser \textit{et al.} 1987a) to determine a value for \( Q_\beta \). For MCPs with \( L = 1 \text{ mm} \) and \( D = 12.5 \mu\text{m} \) as detailed in Table 2.1, the predicted self efficiency \( Q_\beta \) was 0.87. The expected integral event rate, \( n_n(0) \), as a result of \( ^{40}\text{K} \) decay (emission probability = 0.894) for a single MCP is then:

\[
n_n(0) = 0.894 n_k Q_\beta = 1.95 \text{ s}^{-1} = 0.195 \text{ cm}^{-2} \text{s}^{-1}
\]

For MCPs with length-to-diameter ratios of 120:1 (\( L = 1.5 \text{ mm} \)) \( Q_\beta \) equals 0.92. The model also accurately describes the shape of the noise pulse height distribution which was found to be a superposition of a peaked single channel PHD and an exponential PHD from the extended \( \beta \) tracks. The calculated distribution for the beta rays gives track lengths extending out to 3.1 mm. Further discussion of track lengths will be found in section 2.5.

Measurements were made to find the relative noise contributions of the front and rear plates. The contribution of the rear MCP can be found by reducing the front plate bias voltage to zero whilst leaving \( V_G \) and \( V_R \) unaltered. Measurements were made on Mode A as follows:

\[
V_F = 1240\text{V}; V_G = 200\text{V}; V_R = 1240\text{V}; N(0.05G_\varepsilon) = 0.37 \text{ cm}^{-2} \text{s}^{-1}
\]
\[
V_F = 8\text{V}; V_G = 200\text{V}; V_R = 1240\text{V}; N(0.05G_\varepsilon) = 0.0002 \text{ cm}^{-2} \text{s}^{-1}
\]

Reducing all bias voltages to zero, the noise count rate arising in the electronics was found to be similar to the noise value measured for \( V_F = 8\text{V} \). These measurements indicate that only noise events initiated in the front plate will be significant and that avalanches started in the inter-plate gap or in the rear plate receive insufficient gain to be detected above the lower discriminator threshold. The betas produced by the decay of \( ^{40}\text{K} \) in the rear plate can however reach the front plate and thereby generate detectable noise events.
From equation 2.4 it can be seen that the number of disintegrations per second is proportional to the MCP thickness L. Now if the internal radioactivity is the main source of MCP noise, plates of the same thickness should follow a common noise curve. Also MCPs of greater thickness would be expected to show a larger noise count rate. Measurements were made on the Modes A, B, C (front plate thickness 1 mm) and Mode D (front plate thickness 1.5 mm). Figure 2.8 illustrates the variation of the noise count rate for changes in the Mode D bias voltages. Note the ‘high’ noise associated with the lowest voltage settings corresponds to a front plate not having reached full saturation (voltage required to fully saturate a 120:1 plate = \( \sim 1520\) V). The comparison between Mode D and the three other detectors clearly shows a variation in the noise count rates with MCP thickness as expected for radioactive decay being the main source of noise. The noise variation in the detectors containing a 80:1 front plate can be seen to be converging to a common value at low discriminator thresholds. The spread in the data at higher levels is modest (14% at 0.1G\(_e\)) and can be attributed to the variation of the individual MCP outgassing rates.

The solid curves indicated on figure 2.8 are calculated noise count rates using the model discussed above. For Modes A, B, and C:

Counts initiated in the front plate from \( K^{40} \) decay (section 2.4.6) .................................................. 0.195 cm\(^{-2}\)s\(^{-1}\)
Counts initiated from cosmic rays (section 2.4.2) ............................................... 0.0057 cm\(^{-2}\)s\(^{-1}\)
Counts initiated in the rear plate ................................................................. 0 cm\(^{-2}\)s\(^{-1}\)
Assuming that half of the betas originating in the rear plate initiate noise events in the front plate with 100% efficiency then:
Counts initiated by betas from the rear plate ................................................. 0.11 cm\(^{-2}\)s\(^{-1}\)
Therefore the total noise count rate \( N(0) \) ............................................... 0.31 cm\(^{-2}\)s\(^{-1}\)

For Mode D the only the first term changes due to the increased thickness of the 120:1 plate (\( Q_d \) also increases) giving \( N(0) = 0.42 \) cm\(^{-2}\)s\(^{-1}\). Both these integral noise count rates are in good agreement with the measured data as illustrated in the above figures.

## 2.5 Noise Reduction Techniques

Considering the results presented in the previous section it can be concluded that radioactivity in the MCP glass is the major source of background noise. It follows that two noise reduction techniques are then possible.

For MCPs without any radioactive constituents the major source of noise will be cosmic rays after the plates have been fully outgassed. By using plastic scintillator around the MCP, a five-sided coincidence could be used to reduce cosmic rays and/or particle induced noise. The second method, which does not require radioactive free MCPs, involves rejection of particle events on the basis of their extended track signature. An investigation of the latter method was undertaken with
Figure 2.8: Comparison of all four detector modes with normalised to the Si-K peak gain.

Curve (i) calculated noise count rates, L/D = 120:1, D = 12.5 μm, 1500V for comparison with measurements for Mode D.

Curve (ii) calculated noise count rates, L/D = 80:1, D = 12.5 μm, 1200V for comparison with measurements for Modes A, B and C.
a simple partitioned anode.

Figure 2.9 shows a schematic of the anode which was constructed from copper plated PCB board (electrodes E1 and E2) mounted onto a stainless steel back-plate (E3). The dotted circle describes the active area covered by the Mode D detector with the ‘fingers’ of electrodes E1 and E2 being 3 mm wide, separated by 1 mm gaps. The anode was positioned 2 mm from the rear MCP in order to minimise the diameter of the charge cloud resulting from single channel events. Both the bias voltages across the inter-plate gap and the rear plate to anode gap were maximised to help achieve a small diameter spot. Electrodes E1, E2, and E3 were connected to a coincidence unit (Ortec 418A) and the coincidence rate, defined as fraction of events producing signals on both electrodes E1 and E2 was measured as a function of the lower level discriminator setting. Measurements were made for both the noise and full face X-ray illumination. The latter gave a calibration for spreading of single channel events and of recorded events caused by charge induced onto each electrode (the capacitance between electrodes E1 and E2 was found to be ~20 pF).

Figure 2.10 illustrates the results obtained over a period of nine days for both the noise and the X-rays. That the coincidence rates for the noise and the X-rays at low level discriminator (LLD) settings appear to be identical may be attributed to the effects of induced charge. When the LLD is increased the X-ray coincidence rate rapidly decays whereas the events from the noise tracks continue at a level of ~5% (in agreement with the Monte Carlo model, curve (a) figure 2.10).

The above results have shown that track length recognition is a valid method for noise reduction although this anode is only sensitive to the longer track lengths and limited to detection of tracks in the Y direction. The solid curve (b) shown in figure 2.10 represents the predicted coincidence rates for an anode with narrower fingers (1 mm). By using a multi-amplifier crossed grid readout sub-millimetre track lengths would be detectable in both dimensions and should be quite effective for noise reduction.

2.6 Conclusions

The main conclusions to be drawn from the work presented in this Chapter is that there are two distinct sources of MCP dark noise:

(a) due to the decay of radioactive constituents of the MCP glass and
(b) outgassing of the MCPs with the plate environmental history playing an important role.

Confirmation of radioactivity as the major dark noise mechanism has lead two manufacturers (Philips Components and Galileo Electro-optics) to vigorously research the production of radioactive free MCP glass. Production of MCPs without radioactive components should lead to a reduction in background noise such that Cosmic Rays become the dominant noise mechanism. Further reduction of the dark noise would then entail the use of noise reduction techniques discussed above.

Low dark noise plates would certainly lead to an increase in sensitivity for ground based
Figure 2.9: Partitioned charge collecting anode.
Mode D plate voltages $V_F = 1450\,\text{V}$, $V_G = 400\,\text{V}$, $V_R = 1250\,\text{V}$, plate-anode voltage = 600V.

Figure 2.10: Coincidence rate as a function of the coincidence counting threshold, LLD.
Diamonds - C-K X-ray illumination, open circles - noise day 1, filled circles - noise day 2, crosses - noise day 5, squares - noise day 9. The top scale indicates the calculated percentage of all noise counts with output charges greater than a given LLD threshold.
detectors. Consideration of the importance that low noise MCP would have for detectors used in satellite experiments must include the effects of in orbit noise sources. The conclusions reported by Fraser et al. (1987a) are that direct particle interactions can be discounted (assuming these can be dealt with by the techniques of section 2.5) but that radioactivity induced in the plates by trapped protons in the satellites orbit would ultimately determine detector sensitivity.

For the High Resolution Camera (HRC) on the Advanced X-ray Astrophysics Facility (AXAF) production of very low noise MCPs has the potential to increase the instrument's sensitivity by factors of at least two.

The recent developments from the continuing investigation of MCP dark noise have been included in Appendix A.
Chapter 3
CsBr as a MCP Photocathode

3.1 Introduction

Microchannel plates have been used as the focal plane detectors for many imaging X-ray Astronomy satellite experiments, including the successful Einstein and EXOSAT missions. The most important advantage that MCPs have over other types of imaging detector is their ability to produce distortionless X-ray images with very high spatial resolution, due to the small diameter of the microchannels.

The X-ray quantum detection efficiency (QDE) of the bare MCPs is, however, very low (1 -10%) when compared with other types of detectors, for example, gas proportional counters which have detection efficiencies of almost unity. To increase the detection efficiency of the MCP a photocathode material is used either in reflection (deposited onto the surface of the front microchannel plate) or in transmission (deposited onto a thin substrate). For the soft X-ray energy band and the rigours of satellite borne detectors the reflection photocathode is the preferred method, and the one considered here. Earlier X-ray detectors used MgF₂ as a photocathode giving factors of 1.1 -1.6 enhancement of the QDE over bare MCP values (Henry et al. 1977). For the soft X-ray energy range, greater improvements in the MCP detection efficiency have been obtained using an coating of CsI evaporated directly onto the MCP surface (Fraser and Pearson 1984). The increased efficiency of CsI in the XUV and soft X-ray bands has resulted in its adoption as the photocathode material for MCPs to be used on the ROSAT Wide Field Camera and AXAF HRC experiments.

The work reported in this chapter compares the soft X-ray quantum detection efficiencies of microchannel plates coated with CsI with that of MCPs coated with CsBr.

3.2 Photocathode Properties

The use of CsI as a photocathode on MCPs has been widely reported by many authors (Martin and Bowyer 1982, Fraser and Pearson 1984, Barstow et al. 1985 and Simons et al. 1987). This breadth of investigation reflects the importance of CsI as a photocathode material for coating MCPs for X-ray and XUV astronomy. She Yong-zheng et al. (1985) reported relative photocurrent
measurements from normal density CsI and CsBr transmission photocathodes which indicated that CsBr was the more efficient photocathode in the 8.3 - 44.7 Å range. Since the 8.3 - 44.7 Å band is of interest for X-ray astronomy, a study of the detection efficiency of CsBr as a potential photocathode for MCPs was initiated.

Table 3.1 compares the physical properties of CsBr with those of CsI. As can be seen from the table CsBr has a melting point similar to CsI indicating that the coating techniques used for CsI (Whiteley et al. 1984) would be suitable for coating CsBr. To allow direct comparison with the CsI efficiency measurements of Fraser and Pearson (1984) their preparation and coating techniques were adopted for the deposition of the CsBr onto the MCP surface.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (gm/cm³)</th>
<th>Effective Atomic Number</th>
<th>Melting Point (°C)</th>
<th>Boiling Point (°C)</th>
<th>Solubility (gm/100gm H₂O)</th>
<th>Solubility (at 25 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsBr</td>
<td>4.44</td>
<td>47.5</td>
<td>636</td>
<td>1300</td>
<td>124</td>
<td>a</td>
</tr>
<tr>
<td>CsI</td>
<td>4.51</td>
<td>54.0</td>
<td>621</td>
<td>1280</td>
<td>92</td>
<td>b</td>
</tr>
</tbody>
</table>

Table 3.1: Physical properties of CsBr and CsI, (Fraser et al. 1987b).

(a) Interpolated from data at 0, 90 °C.
(b) Interpolated from data at 0, 61 °C.

3.3 Detector Characteristics

The MCPs used in this investigation were operated in a chevron arrangement with measurements being made in the Leicester Vacuum Test Facility (Pearson 1984). Both front and rear MCPs were Mullard type H36 TT plates with channel diameter D = 12.5 μm; length-to-diameter ratio L/D = 120:1 and channel pitch p = 15 μm. The inter-plate gap, 100 μm, was determined by the double sided electrode made from copper covered Kapton PCB. The channel bias angle, θ, measured from the MCP normal, was 0° for the front plate and 13° for the rear MCP. Image readout was by orthogonal graded density grids and a reflector plate. Noise count rates were ~1 count cm⁻²s⁻¹ above a lower level discriminator setting of 0.2 pC. Plate resistances over the measurement period were ~756 - 800 MΩ for the front plate and ~850 - 890 MΩ for the rear plate. These MCPs were geometrically identical to the MCPs used in the CsI efficiency measurements of Fraser and Pearson (1984).

3.4 Coating Method

Microchannel plates received from the manufacturer are known to contain a lot of water vapour absorbed on the channel surfaces. As CsBr is an hygroscopic material the excess of water vapour
must be removed to prevent degradation of the photocathode over a period of time due to the absorption of this water. Therefore, prior to coating the front MCP underwent a vacuum bake at 275°C for 48 hours. After bakeout the plate was always handled in a dry nitrogen atmosphere or with DN2 flowing over the plate surfaces.

Evaporation of the photocathode material was from a Molybdenum boat with the photocathode surface thickness being monitored by an Edwards FTM 4 quartz crystal thin film thickness monitor. The coating angle, α, was chosen by careful alignment of the MCP centre with respect to the coating boat position. As the coating angle controls the amount of material deposited on the channel walls, for a given surface thickness, the angle was set at 4° following the procedure used for coating CsI. Then by depositing 14000 Å on the MCP surface a channel wall thickness of ~350 Å for the first five channel diameters gradually decreasing to < 100Å at a depth of 15 channel diameters (Pearson 1984) can be achieved. This profile presents sufficient thickness of CsBr to usefully absorb all the X-ray energies used in this study. To approximate an even coating around the channel walls the MCP was rotated during coating (~ 1 Hz).

As a final preparation the MCP was heated under vacuum to 100°C, as it has been found (Pearson 1984) that coating onto a hot substrate increased the storage life of the photocathode. Heating was followed by a 10 minute glow discharge clean. The ion bombardment from the glow discharge removes any remaining contamination giving a clean surface for the CsBr to adhere to. The CsBr was deposited at a temperature of 100 ° ± 5 °C and a coating rate of ~20 - 40 Å s⁻¹.

One half of the MCP, radius 15 mm, was coated with CsBr whereas the other half was left bare allowing bare plate and coated plate efficiencies to be measured for each X-ray energy of interest.

3.5 Quantum Efficiency Measurements

3.5.1 X-ray Energies

The X-ray energies used in the efficiency measurements were generated using an electron bombardment anode source. Each energy was obtained by coating the anode with the appropriate material then using a filter to remove lower energy contamination. Table 3.2 details the X-ray lines, the filters and the coating materials used in this study.

Using this configuration, the purity of the X-ray lines (with the exception of the Boron line) should be high with any contamination coming from the Bremsstrahlung generated X-rays, most of which will be removed by the filters. The Boron line was generated using an anode voltage of 500V, implying a maximum in the Bremsstrahlung photon intensity distribution at ~50 Å (Agarwal 1979). As measurement of the relative intensities of the Bremsstrahlung and the B-K X-rays was not possible, it must be assumed that there is some wavelength contamination but that the B-K line is dominant.
<table>
<thead>
<tr>
<th>Line</th>
<th>keV</th>
<th>Å</th>
<th>Filter</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-K</td>
<td>0.18</td>
<td>67</td>
<td>None</td>
<td>Boron Nitride</td>
</tr>
<tr>
<td>C-K</td>
<td>0.28</td>
<td>44.7</td>
<td>Macrofol</td>
<td>Silicon Carbide</td>
</tr>
<tr>
<td>Cu-L</td>
<td>0.93</td>
<td>13.3</td>
<td>4 μm Al</td>
<td>None</td>
</tr>
<tr>
<td>Al-K</td>
<td>1.49</td>
<td>8.3</td>
<td>20 μm Al</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Si-K</td>
<td>1.74</td>
<td>7.1</td>
<td>1 μm Ag</td>
<td>Silicon Carbide</td>
</tr>
</tbody>
</table>

Table 3.2: X-ray lines, filters and anode material used in the detection efficiency measurements.

3.5.2 Reference counter

Measurement of quantum detection efficiencies on MCPs requires the use of a reference detector, with known detection efficiency at all wavelengths of interest, to measure the incident X-ray flux. The reference detector used in this study was a single wire, thin window gas proportional counter. The window consisted of stretched carbon coated polypropylene supported by a wire mesh. Mesh transmission for all X-ray energies used was 0.46 while the gas detection efficiencies were 100% for all X-ray energies except Si-K which was 99.2%. The proportional counter gas was an Argon-Methane mix being P50 (50% argon, 50% methane) for B-K and C-K and P10 (90% argon, 10% methane) for the other X-ray energies. This counter could be moved in and out of the X-ray beam as required.

3.5.3 Efficiency Measurement Techniques

The MCP detection efficiencies were obtained by measuring the X-ray count rates over three consecutive periods of 30 seconds duration for each angle of interest. The first and last sampling was from the proportional counter with the middle period measuring the MCP count rate. The MCP efficiency \( Q \) was then calculated using:

\[
Q = \frac{2N_m Q_{pc} T_p T_w}{(N_{n1} + N_{n2})/(T_p) \sec \theta}
\]

where \( N_m \) is the MCP X-ray count rate and \((N_{n1} + N_{n2})/2\) is the average proportional counter (PC) count rate. \( \theta \) is the angle of X-ray incidence, \( Q_{pc} \) is the PC quantum detection efficiency, \( T_p \) the transmission of the carbon coated polypropylene PC and MCP windows and \( T_w \) the transmission of the PC window support mesh. \( N_m \) and \( N_n \) are taken from the 30 second count rates with the PC/MCP noise count rates removed. Averaging of the PC count rates allows the X-ray source count rate to be determined to within ~1%. As the PC remains fixed as the MCP incidence angle is changed an allowance must be made for the variation of path length through the MCP polypropylene window; this accounts for the \( \sec \theta \) variation associated with \( T_p \) in equation 3.1.

The analysis of the errors which contribute to the MCP efficiency (Pearson 1984) are directly transferable to the measurements made during this study.
The error associated with the MCP detection efficiency, $Q$, is the sum of the errors from each of the individual parameters of equation 3.1. The errors in the PC and MCP count rates are dependent on counting statistics and the stability of the noise count rates of both the PC and the MCP. Noise count rates for both the PC and the MCP were very stable allowing their error contribution to be ignored ($\ll 1\%$). Therefore the contribution to the error from the MCP count rate was found to be $\sim 1 - 4\%$ with the latter figure pertaining to B-K because of the lower incident X-ray flux obtainable from the source for this line.

The counting error associated with the PC count rate was found to be $\sim 1\%$ for B-K, and slightly less for the other X-ray energies.

The error in the polypropylene window transmissions were of the order of one percent attributable to variation in the thickness of the stretched polypropylene. A similar value for the error was found (Pearson 1984) for the PC mesh transmission and this was assumed here. For the X-ray energies under consideration the calculated value for the proportional counter gas efficiencies $Q_{pc}$ was found to be negligible.

Considering all contributions the overall error for the MCP detection efficiency $Q$, was between 5 - 7% for the B-K measurements and $\sim 4\%$ for the other energies.

### 3.5.4 Results

Before coating and prior to the vacuum bake the two plates were tested as a chevron pair. The chevron gave suitable gains and pulse height full width half maxima appropriate for pulse counting. Efficiency measurements were made on the two halves of the MCP, using C-K and Si-K X-rays, as a function of incidence angle. These measurements were compared with the detection efficiencies made on the bare half of the MCP after it had undergone a vacuum bake and been through the coating procedure. No significant differences were found in their detection efficiencies indicating that the vacuum bake and the subsequent processing had no effect on the bare plate characteristics.

Measurements of the quantum detection efficiencies were made on both the bare and CsBr coated halves of the MCP as a function of incidence angle. Figures 3.1 a - e illustrate individually the dependence of the MCP efficiency with incidence angle and collectively as a function of the incident photon energy. For direct comparison the measurements of the detection efficiency of a CsI coated MCP (Fraser and Pearson 1984) and the bare plate efficiencies are plotted for each X-ray energy. Figures 3.1 d and e show that the CsBr is a more efficient photocathode ($\sim x 2$ at large angles) than CsI. Note that the peak efficiencies, at these wavelengths, approach the open area of the MCP (63%). Comparing the measurements of figures 3.1 a - e with the results reported by She Yong-zheng et al. both data sets agree that CsBr is more efficient than CsI for C-K X-rays (44.7Å). However at the shorter wavelengths (8.3 and 13.3 Å) the pulse quantum efficiency measurements (measured in reflection) of this study contradict the transmission photocurrent data of She Yong-zheng et al. which reported that CsBr was more efficient than CsI for these wavelengths.
Figure 3.3 illustrates the calculated linear absorption coefficients (Fraser et al. 1987b) for both CsBr and CsI. Comparing the wavelength dependence of the large angle detection efficiency ratio $Q(\text{CsBr})/Q(\text{CsI})$ with the ratio of calculated linear absorption coefficients $\mu(\text{CsBr})/\mu(\text{CsI})$ it can be seen that they follow a similar trend, since for increasing wavelength (5 - 50 Å) there are two cross-overs corresponding to the cross-overs in the efficiency measurements. For example, at Si-K which is below the Bromine LII and LIII edges in wavelength, the CsBr efficiency and the linear absorption coefficient are slightly greater than that for CsI. Figure 3.3 indicates that for wavelengths greater than 20 Å using CsBr affords a distinct increase in efficiency, this being confirmed by the measurements of figures 3.1d and e.

Taking the correspondence between the absorption coefficients and the detection efficiencies further, measurements by Cardona et al. (1970) would then suggest that CsBr will be more efficient than CsI out to 100 Å.

One of the major astronomical satellite experiments of the 1990's is the Advanced X-ray Astrophysics Facility (AXAF) due for launch around 1996. The focal plane imaging detector, the High Resolution Camera (HRC), utilizes two large area (10 x 10 cm$^2$) MCPs in a chevron configuration with the front MCP coated with CsI for increased detection efficiency. In the light of the above work it is of interest to compare the HRC detection efficiency for CsI with that of a hypothetical HRC coated with CsBr.

The HRC has been designed to operate in two distinct modes:

- direct imaging over an energy range, 0.1 - 8 keV
- as a readout for a low energy transmission grating spectrometer, 0.1 - 4 keV.

For AXAF, the cone angle of the telescope beam ranges from 2 - 4° (Murray and Chappell 1985). MCP detection efficiencies can change rapidly over this angular range ($\sim 5$ for C-K X-rays). By using a front MCP with biased channels, say 13°, the incident angle range is then 9 - 17° and the detection efficiency variation is much less severe, while the absolute efficiencies are only slightly reduced.

Figure 3.4 compares the quantum detection efficiency of CsI and CsBr as a function of energy for the two extreme incident angles, 9° and 17°. As discussed above, the dominance in detection efficiency between CsBr and CsI changes with energy, reflecting the influence of the various absorption edges. Over the 1.5 - 4 keV range CsBr can be expected to be the slightly more (30% compared with 27%) efficient, whereas CsI will dominate in the 4 - 8 keV band (figure 3.3). In between 1.5 and 0.6 keV CsI again exceeds CsBr by a factor of $\sim 1.2$ in efficiency. However, over the range 0.12 - 0.6 keV the dominance of CsBr is overwhelming with increases in efficiencies of between 1.5 and $\sim 2 \times$ depending on angle and energy.

Whether CsBr should be considered as a photocathode for the entire 0.1 - 8 keV energy range depends on which of the above energy ranges are deemed most likely to yield important astrophysical results. Consideration of the optimum photocathode for the HRC must also reflect
Figure 3.1: Measured quantum detection efficiency as a function of X-ray incidence angle.

(a) Si-K X-rays, 7.1 Å. Filled circles - CsBr coated MCP, open circles - bare MCP and crosses - CsI coated MCP.

(b) As fig. (a); Al-K X-rays, 8.3 Å.

(c) Cu-L X-rays, 13.3 Å.
Figure 3.2: Measured quantum detection efficiency as a function of X-ray incidence angle.

(d) C-K X-rays, 44.7 Å. Filled circles - CsBr coated MCP, open circles - bare MCP and crosses - CsI coated MCP.

(e) As fig. (d); B-K X-rays, 67 Å.
Figure 3.3: Calculated linear absorption coefficients as functions of X-ray wavelength for:
CsI (full curve), CsCl (dash curve), CsBr (dotted curve). Vertical lines indicate positions of
named absorption edges (Fraser et al. 1987b). Arrows indicate wavelengths at which the CsBr
efficiency measurements were made.
its use as the readout for the low energy transmission grating spectrometer. A review of the spectrometer given by Brinkman et al. (1985) details some of the instrument's requirements. The spectrometer covers the wavelength region between 2 and 140 Å. One stated mode of operation, used when observing sources where wavelengths beyond 70 Å are not of interest, would clearly benefit from using CsBr as it is much more efficient (between 1.5 and \( \sim 2 \times \) depending on angle and wavelength). Consideration of the 2 to 70 Å region shows that CsBr is more (and in the 20 to 70 Å region much more) efficient over \( \sim 80\% \) of this wavelength band than CsI.

A case against using CsBr is that at present it has not undergone the same extensive testing, with regard to stability with time and vibrational stability, as has CsI.

### 3.6 Conclusion

The above report has shown that CsBr is a suitable photocathode for improving the quantum detection efficiency of MCP detectors. It was shown that CsBr is comparable with CsI for ease of coating and over the limited time under study just as stable. That CsBr can compete in quantum detection efficiency as a MCP photocathode was indicated by the comparison with CsI for the AXAF HRC. As a photocathode for use in the 20 - 100 Å range CsBr was shown to be clearly exceed CsI in efficiency.

Further investigation over a larger wavelength band, especially the AXAF range, coupled with a study of the photocathode stability with time, would allow a more definite assessment to be made of its suitability for use with MCPs in astronomical detectors.
Figure 3.4: Comparison of AXAF quantum detection efficiencies for CsI and CsBr as a function of X-ray energy.

CsBr - Crosses - $\theta = 9^\circ$, circles - $\theta = 17^\circ$.
CsI - squares - $\theta = 9^\circ$, triangles - $\theta = 17^\circ$. 
Chapter 4
Sandwich Plates

4.1 Introduction

A Sandwich plate is a new arrangement of MCPs developed by Mullard Ltd, which is capable of giving good, high gain performance in a photon counting detector.

A Sandwich plate consists of three MCPs, in a Z stack configuration, permanently bonded together and is thus similar in concept to the (two stage) laminated MCP reported by Henke et al. (1978). The bonded configuration has advantages over the more common single curved-channel MCPs, chevrons and Z stacks (Timothy 1981; Fraser 1984; Siegmund et al. 1985). The main advantage of sandwich plates is that they can be manufactured from the standard, straight channel (length-to-diameter ratio, L/D, of 40:1) MCPs used in mass market image intensifiers. The use of production line MCPs to make a single sandwich plate contrasts with the complexity required to produce a curved channel microchannel plate. MCP Chevrons and Z stacks are normally operated either with individual high voltage supplies for each plate or with a single voltage supply and the plates in direct contact. The latter option requires the MCPs to be ideally flat to prevent gain variation over the plate area arising from variations in inter-plate gap thickness (Armentrout 1985a). The sandwich plate geometry with its mechanical simplicity and single high voltage, potentially overcomes the difficulties inherent in the operation of multi-plate stacks.

By bonding three MCPs together Mullard have produced a ready made pulse counting detector which has reduced the required handling, mechanical and electrical difficulties normally encountered with building multi-plate detectors. This may encourage the wider use of MCPs for pulse counting purposes.
4.2 Sandwich Plate Production

The two sandwich plates tested at Leicester (produced as part of my CASE award involvement at Mullard Mitcham) were manufactured from production-line MCPs which had undergone Mullard’s standard etching and reduction processes. The geometry of the component plates is described in Table 4.1.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>36 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness L</td>
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</tr>
<tr>
<td>Channel diameter D</td>
<td>12.5 μm</td>
</tr>
<tr>
<td>L/D</td>
<td>40:1</td>
</tr>
<tr>
<td>Channel pitch</td>
<td>15 μm</td>
</tr>
<tr>
<td>Bias angle</td>
<td>15°</td>
</tr>
</tbody>
</table>

Table 4.1: MCP specifications.

Earlier work at Mitcham (R. Emptage, private communication) had shown that Indium, with a melting point of 156.6°F, was the optimum bonding metal. Each MCP surface to be bonded was coated with Indium using an Edwards 19 inch evaporation system. The coating system was designed to restrict penetration of the Indium down the channels to a depth of one channel diameter. Evaporation always took place at pressures of less than $5 \times 10^{-6}$ torr; the coating thickness was typically 1000 Å.

Each component plate was examined prior to assembly for faults and the position of any defects recorded. The plates were then aligned with the maximum angle between their channel axes to eliminate ion feedback (figure 4.1). A pressure plate was applied to the stack during the final bonding process to ensure good contact between the surfaces and to prevent bowing of the plates. After bonding the input and output surfaces of the sandwich multiplier were Nichrome electroded.

Twenty one MCPs were used to make seven sandwich plates, two of which were rejected because of poor bonding. Each successfully fused sandwich plate was examined in the Mullard MCP test facility. A bias voltage of 2 kV was applied to each plate and the input flooded by electrons from a wire grid/filament assembly. Visual inspection of output uniformity was achieved by imaging the output electrons onto a fluorescent screen. Two of the seven sandwich plates produced were selected as having the best gain uniformity and the minimum number of noise spots. The noise spots on each plate corresponded to previously observed defects in the component plates. One of the remaining sandwich plates was given a vacuum bake at 350°F to assess the stability of the bond. No weakening of the bond was discovered.

The two selected plates were subsequently tested using the Leicester Vacuum Test facility (Pearson 1984). Results are described in the following sections.
4.3 Gain Measurements

The two sandwich plates, hereafter designated A and B, had very similar resistances, typically \( \sim 150 \, \text{M}\Omega \) at a bias voltage of 2300 V. Gain measurements were made using C-K (0.28 keV) and Si-K (1.74 keV) X-rays. A typical pulse height distribution is shown in figure 4.2. Representative pulse height distributions contained \( \sim 10^5 \) counts with \( \sim 750 \) counts in the peak channel. Output count rates \( N_m \), were \( \sim 480 \) counts s\(^{-1}\) for C-K and 100 counts s\(^{-1}\) for Si-K. The illuminated area was 14.5 mm\(^2\) at the centre of each plate.

4.3.1 \( G_c( x ) \)

The gain variation across the plate was measured by moving the detector along the x axis relative to the fixed X-ray beam and sampling the gain at 2 mm intervals on the MCP surface. Figures 4.3 a and b show the measurements of gain and FWHM as a function of radial position; \( x = 25.5 \, \text{mm} \) corresponds to the centre of each plate. When compared with previously reported measurements for chevrons (Fraser and Pearson 1984) and Z stacks (Armentrout 1985b), plate A in particular has very good uniformity.
Figure 4.2: A typical PHD from a Sandwich Plate.
C-K X-rays; \( G_c = 0.37 \) pC; \( V_0 = 2200 \) V; FWHM = 64% (arrowed).

Figure 4.3: Gain (a) and FWHM (b) as a function of position of X-ray incidence.
C-K X-rays for an illuminated area of 14.5 mm². Circles plate A \( V_0 = 2200 \) V.
Crosses plate B \( V_0 = 2300 \) V.
4.3.2 $G_c(V_0)$

Peak (modal) gain $G_c$, (fig. 4.4a) and pulse height Full Width Half Maximum (FWHM) $\Delta G_c/G_c$ (fig. 4.4b) were measured as functions of the bias voltage $V_0$. Peak charge gains of 0.8 pC (single electron gain of $5 \times 10^6$) were recorded using Si-K X-rays at $V_0 = 2400$ V. Such values are similar to those expected from single curved channel MCPs (Timothy 1981) and laminated plates (Henkel et al. 1978), but much lower than those obtained ($> 3$ pC) using chevrons (Fraser and Pearson 1984) or Z stacks (Siegmund et al. 1985). The lowest sandwich plate FWHM ($\sim 50\%$) compares favourably with those of all the other MCP geometries. As can be seen from figure 4.4b the FWHM has not reached a plateau value normally associated with optimised saturated MCPs. Also the slope of the gain curve $G_c(V_0)$ figure 4.4a has not changed indicating that saturation is not total. A further increase in gain and a decrease in FWHM could therefore be anticipated for larger bias voltages. No attempt was made to increase the bias voltages further since the sandwich plates, being prototypes only, could not easily be replaced if damaged.

4.4 Background Noise

The background noise of the sandwich plate was measured with an applied voltage of 2200 V. All events with charges above a lower level discriminator of 0.05 pC (electron gains of $3.1 \times 10^5$) were recorded.

Initial investigation showed that there were noise spots at the edge of the plate dominating the background count rate (figure 4.5a). These noise spots were correlated with the position of known defects in the component MCPs observed during manufacture of the sandwich plates. By reducing the rear electrode inside diameter from 30 mm to 24 mm the majority of these noise spots were masked off.

The background noise was then continually monitored over a period of twenty one days allowing the plates to completely outgas. The sequence of noise images figures 4.5b-d show noise spots, presumably related to outgassing, disappearing over this period of time. Referring to figure 4.5d there is a 'ring of noise' which was first thought to be an artefact of the imaging electronics but was later attributed to $\beta$ emission from the macor detector body as described in the Appendix. Using electronic imaging discrimination the noise count rate from a central area was investigated. The limiting noise count rate per unit area was $0.17 \pm 0.03 \text{ cm}^{-2} \text{ s}^{-1}$. The main cause of error in this measurement stems from the calibration of the electronic plate scale (mm/channel). The background noise, assuming that the radioactive decay of $^{40}$K is the dominant source of dark noise was calculated using the model of Chapter 2. The number of disintegrations per second $n_k$ is given by:

$$n_k = \left( \ln 2 \right) \left( \frac{F_r F_m N_0}{A_m} \right) \left( \frac{\rho \pi d^2 L (1 - A_{\text{open}})}{4} \right)$$
Figure 4.4: Gain (a) and FWHM (b) as a function of $V_o$.

Open circles C-K; open squares Si-K - plate A. Filled circles C-K; filled squares Si-K - plate B.
where the symbols are as defined in Chapter 2. For the sandwich plate the front MCP length $L$ is 0.5 mm giving a value for $n_k$ of 0.123 cm$^{-2}$ s$^{-1}$. The $\beta$ self-efficiency, $Q_\beta$, was calculated to be 0.74. The contribution from the middle and rear plates is (following from Chapter 2) 0.11 cm$^{-2}$ s$^{-1}$. When the contribution arising from cosmic rays is also included, the noise count rate (for events over a lower level discriminator of 0.1 G$_e$) is calculated to be 0.17 cm$^{-2}$ s$^{-1}$. The good agreement between the measured and calculated noise count rates confirm the assertions made in Chapter 2 that the decay of radioactive $^{40}$K is the main source of background count rate in MCPs.

Figure 4.5: Decay of Sandwich plate noise spots over a 21 day period.
(a) Active area 7.1 cm$^2$, (b - d) active area 4.5 cm$^2$. 
4.5 High Count Rate Performance

Sandwich plate gain and FWHM as functions of count rate, (figures 4.6 a and b) were investigated using both C-K X-rays and 2540 Å radiation from a Mercury discharge lamp. The sandwich plate bias voltage was 2300V. Measurements were made using three different spot sizes. A stainless steel mask, 100 μm thick with a 1 mm diameter hole sited directly in front of the sandwich plate provided an illuminated area of 0.79 mm². Secondly, the full face illuminated area was 380 mm². Thirdly, by introducing a collimating hole into the test beam a reduction in illuminated area to 14.5 mm² could be achieved.

Figure 4.6 (a) shows that the maximum count rate per unit area is a function of the size of the illuminated area, independent of the energy of the incident radiation. Measurements from both C-K and 2540 Å incident radiation have been plotted together in figure 4.6. Pulse pile up in the electronics was negligible in these measurements reducing the measured peak gain by only 1.5% at the highest count rates.

Eberhardt (1981) postulates that each activated channel has a lateral capacitance associated with it due to the surrounding quiescent channels (see figure 4.7). He calculates that this lateral capacitance is 50 times larger than the capacitance of a single channel to ground. It is reasonable to assume that the lateral capacitance associated with a group of active channels should be proportional to the circumference of the excited area while the combined effect of single channel capacitance to ground will be proportional to the area of the excited region. The effective capacitance, and hence the maximum charge available per event, at high count rates, will therefore decrease as the active area increases, as observed. Thus, the highest count rates per unit area are achieved when, over the plate as a whole, the ratio of quiescent channels to active channels is largest. At low count rates there will be many unexcited channels within the illuminated region and all beam sizes will give the same gain.

Comparisons between the sandwich plate high count rate performance and other MCP geometries reported in the literature are complicated by this dependence on beam size since the illuminated areas used are seldom given. The high count rate stability of the sandwich plate is compared with a chevron, incorporating MCPs with similar geometrical specifications, in the following chapter.

4.6 Quantum Detection Efficiency

The angular dependence of the X-ray quantum efficiency of microchannel plates is well known (Fraser and Pearson 1984; Siegmund et al. 1985). The quantum efficiency of the sandwich plate was measured using the same experimental techniques as described in Chapter 3 for CsBr coated NCPs. For MCPs with bias angle θ₀ equal to zero, the dependence is simply a function of the X-ray incident angle θ measured with respect to the channel axis. Figure 4.8 shows a typical quantum
efficiency curve for C-K X-rays on an uncoated zero-degree bias angle plate. When, however, the channel bias angle is non-zero, the channel axis is not perpendicular to the MCP surface and the orientation of the bias direction in azimuth relative to the beam direction must then be considered when making efficiency measurements.

Let the angle between the incident X-ray beam and the MCP normal be $\gamma$ and the phase angle between the plane of X-ray incidence and the plane containing the channel axis and the plate normal be $\psi$ (figure 4.9). Consider only rays passing through the centre of the channel mouth. From the Cosine Rule ($c^2 = a^2 + b^2 - 2ab\cos C$) we have when applied to triangle ABC:

\[(CA)^2 = (\sin \theta_B)^2 + (\cos \theta_B \tan \gamma)^2 - I^2 \sin \theta_B \cos \theta_B \tan \gamma \cos \psi\]  \hspace{1cm} (4.1)

applying the Cosine Rule to triangle AOC gives:

\[(CA)^2 = \left(\frac{\cos \theta_B}{\cos \gamma}\right)^2 + I^2 - \frac{2I^2 \cos \theta_B \cos \theta}{\cos \gamma}\]  \hspace{1cm} (4.2)

equating equations 4.1 and 4.2 and solving for $\cos \theta$ gives:

\[\cos \theta = \cos \theta_B \cos \gamma + \sin \theta_B \sin \gamma \cos \psi\]  \hspace{1cm} (4.3)

Quantum efficiency measurements were made on Sandwich plate A using C-K and Si-K X-rays at two different phase angles ($\psi = 40^\circ$ and $110^\circ$), the results of which are shown in Figures 4.10 a
Figure 4.7: Most probable configuration of electron flow in Sandwich plates with one activated channel in the front plate, Eberhardt 1981.

and b. The characteristic 'dip' of quantum efficiency observed with zero degree bias angle plates is absent. Since no 'dip' was observed the effective X-ray incident angle must have always been greater than 5° (figure 4.8). Using the angle transformation equation 4.3 for \( \theta \) and the given phase angles (40°; 110°) the expected efficiencies at these phase angles were calculated from zero degree bias angle data (Fraser and Pearson 1984). On comparison the quantum efficiency of the sandwich plate was found to be lower than that measured for the chevron arrangement of Fraser and Pearson (1984). Multiplying by a factor of 1.45 for C-K and 1.1 for Si-K brings the sandwich plate efficiencies into good agreement with the measurements on the zero degree chevron multiplier. Since the factor is energy dependant, some contamination of the sandwich plate MCPs may have occurred.

Figure 4.8: Bare plate quantum efficiency - C-K.
Let OC be equal to l
BC = l \cdot \sin \theta_a
BA = l \cdot \cos \theta_a \cdot \tan \psi
\frac{OA}{\cos \gamma} = \ldots

Figure 4.9: Geometrical construction for the derivation of the transformation equation.
OB is the normal to the MCP surface, X-rays are incident along AO, where O is the centre of a channel.

4.7 Conclusions

Measurements on the two prototype sandwich plates have shown that they are a viable arrangement for pulse counting detectors. Improvements in the sandwich plate gain and FWHM should be possible when the optimum bias voltage (optimised for each stage by resistance matching the component MCPs) and bonding material thickness has been determined. Reduction in the background noise count rate would be obtained if sandwich plates could be made from low noise glass MCPs (as discussed in Chapter 2).

Sandwich plates by virtue of their low (stage) resistance have been shown to have a good high count rate performance. Since there is no interplate gap between component plates their construction geometry (one active channel in the front plate, three and seven channels activated in the middle and rear MCPs respectively) allows direct comparison with Eberhardt's model of gain reduction. A detailed investigation of MCP gain, for different plate geometries, as a function of count rate will be undertaken at a future date.
Figure 4.10: Sandwich plate quantum detection efficiencies.
C-K circles, Si-K squares. Angular scale at top shows calculated values of the incidence angle, \( \theta \).
Solid curves, 1 - C-K, 2 - Si-K efficiencies predicted from Fraser (1984) divided by 1.45 and 1.1 respectively.
Chapter 5
L² Plates and Life Tests

5.1 Introduction

All microchannel plates tend to suffer gain degradation during their active lifetime. While this is a widely reported phenomena, the reasons for the gain decay are not properly understood. The gain decay of a MCP has been found to be a function of the total abstracted charge per unit area and can be a serious problem for MCPs used in detectors which are required to operate for many years, for example detectors in X-ray satellite experiments. This gain reduction can, however, be partially compensated for by using an adjustable high voltage supply. In trying to reduce the gain decay in image intensifier MCPs, Galileo Electro-Optics have produced a new type of MCP designated the Long Life Microchannel Plate (L²MCP Cortez and Laprade 1982). Besides reduced gain fatigue, the manufacturer also claimed the plates had a lower intrinsic background noise count rate, as compared with ‘standard’ MCPs.

Three of the Long Life MCPs, received gratis courtesy of Galileo Electro-Optics, were tested and their basic operating characteristics evaluated. The gain stability of the plates was also evaluated and compared with the performance measured for various other types of MCPs.

5.2 Operating Characteristics

5.2.1 Detector Characteristics

The geometrical characteristics of the three solid border MCPs are given in Table 5.1. The three MCPs were used in three chevron pairs, hereafter designated detector Modes A, B and C, with the plate arrangements as given in Table 5.2.

The inter-plate gap width was 160 μm and the effective active area as defined by the inner diameter of the rear electrode was 2.27 cm². Two X-ray energies C-K (0.28 keV) and Si-K (1.74 keV) were used for all measurements with the X-ray beam collimated to produce an illuminated plate area of 14.5 mm². All measurements were made using the Leicester Test Facility (Fraser and Pearson 1984). Plate resistances were measured, in vacuo at pressures < 1.4 ×10⁻⁷ mbar, as a function of bias voltage. Figure 5.1 shows the resistances decreasing with increasing voltage as predicted by the resistive heating model of Pearson et al. 1987.
Outside diameter 32 mm
Active diameter 25 mm
Thickness L 0.4 mm
Channel diameter D 10 μm
L/D 40:1
Bias angle $\theta_B$ 12°
Open area ratio $A_{open}$ 0.63

Table 5.1: Characteristics of the Long Life MCPS.

<table>
<thead>
<tr>
<th>Detector Mode</th>
<th>Front Plate</th>
<th>Rear Plate</th>
</tr>
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<tr>
<td>A</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.2: Long Life detector modes: plate combinations.

5.2.2 $G_c (V_F, V_G, V_R)$

The peak gain $G_c$ and pulse height Full Width Half Maximum (FWHM) characteristics were investigated, for each detector mode, by independently varying the bias voltages across the front plate ($V_F$), interplate gap ($V_G$) and rear plate ($V_R$). Measurements were taken at the plate centre $x = 25$ mm with signal count rates $N_m < 500$ counts s$^{-1}$. Figure 5.2 a-f illustrate the variation measured with Mode A. Measurements for Mode B and Mode C are illustrated in figures 5.3 a-f and 5.4 a-f respectively. Direct comparison between modes is complicated by the fact that the component plates may not all have come from the same batch (the serial number of plate 2 being significantly different from that of plates 1 and 3). A further complication is that prior to examination of Mode B its front MCP (plate 3) had been used as the rear MCP of Mode A which had undergone a full life test. Qualitatively however, all modes have similar characteristics and the best peak gain of $\sim 6$ pC and FWHM $\sim 60\%$ is remarkable for a chevron consisting of two 40:1 MCPs. Optimizing the voltages for each mode produced peak gains and FWHMs fully comparable with use in a pulse counting detector.
Figure 5.1: Variation of MCP in vacuo resistance with bias voltage at room temperature (~20° C) for each of the three L2 plates. Circles plate 1, crosses plate 2 and squares plate 3.

Figure 5.2: Variation of modal gain $G_e$ and pulse height FWHM ($\Delta G_e/G_e$) with applied voltages for Mode A. Circles - C-K X-rays and squares - Si-K X-rays.
Figure 5.3: Variation of modal gain \( G_c \) and pulse height FWHM (\( \Delta G_c/G_c \)) with applied voltages for Mode B. Circles - C-K X-rays and squares Si-K X-rays.

Figure 5.4: Variation of modal gain \( G_c \) and pulse height FWHM (\( \Delta G_c/G_c \)) with applied voltages for Mode C. Circles - C-K X-rays and squares Si-K X-rays.
5.2.3 $G_c(\ x\ )$

The gain uniformity across the microchannel plates was measured by moving the detector along the $x$-axis, relative to the fixed X-ray beam, and sampling the gain at 2 mm intervals on the plate surface. Measurements were made on Modes A and C, these are illustrated in figures 5.5 a, b and 5.6 a, b respectively. Pronounced non-uniformity was seen in both modes being radial for Mode A and increasing from one side of the detector to the other for Mode C. The reason for this variation is unknown although it may be due to variation of the inter-plate gap width (Armentrout 1985a). Alternatively, since the component MCPs were not all from the same batch, the possibly different processing may have affected the gain uniformity.

![Figure 5.5](image)

Figure 5.5: Variation of peak gain and FWHM with beam position $x$ for Mode A.
Circles Si-K, squares C-K X-rays, the vertical broken lines indicate the plate centre. $V_F = 950\,V$, $V_G = 600\,V$, $V_R = 1000\,V$.

5.2.4 $G_c(\ N_m\ )$

The count rate capability of the Long Life microchannel plates was investigated using C-K X-rays as the incident radiation. Mode A measurements were made using an illuminated area of $14.5\,\text{mm}^2$ at the plates centre whereas full field ($227\,\text{mm}^2$) X-ray illumination was used for Modes B and C.

The effect on the modal gain of increasing count rate is illustrated in figure 5.7. Modes A and
Figure 5.6: Variation of peak gain and FWHM with beam position $x$ for Mode C. Circles Si-K, squares C-K X-rays, the vertical broken lines indicate the plate centre. $V_F = 950\,\text{V}$, $V_G = 600\,\text{V}$, $V_R = 1000\,\text{V}$.

C show similar trends whereas Mode B (which included a life tested MCP Section 5.2.2) can be seen to be stable up to $6 \times 10^2 \text{ counts mm}^{-2} \text{ s}^{-1}$. In the limit the gain suppression characteristics of all three modes is very similar with the gain of each mode ultimately limited by the recharge current supply of the rear MCP as discussed in section 4.5. Initial gain depression occurs in Modes A and C when the pulse current (output count rate times peak gain) is $\sim 1\%$ of the standing current (bias voltage $V_R$ divided by the MCP resistance). Gain depression does not occur in Mode B however until $\sim 3\%$ of the standing current is abstracted. That Mode B should exhibit an extended gain plateau must be attributed to the life tested plate used as the front MCP of Mode B, since Modes B and C shared the same rear plate. The early onset of gain depression for Modes A and C can be explained by the higher gain of their front MCPs compared with the already depressed front plate gain of Mode B. For certain applications the gain plateau shown by Mode B may be more important than the lower gain. Thus, 'burning in' a chevron pair then interchanging the plates is a possible method of achieving gain stability over a reasonable range of input count rates. The pulse height FWHM of Mode A increased from $120 - 140\%$ with increasing count rate whereas the FWHMs for Modes B and C remained essentially constant ($\sim 85\%$).

Figure 5.8 illustrates the count rate performance of Mode A compared to the Sandwich Plate
of the previous chapter. Direct comparison can be made between the two data sets since the resistance/stage of each detector is similar (\( \sim 50 \text{ M}\Omega \)). Both sets of measurements were made using C-K X-rays and an illuminated area of 14.5 mm\(^2\). The gains were normalised to their low count rate values, (3.88\( pC \) for the Long Life chevron and 0.37 \( pC \) for the Sandwich Plate). Gain suppression in Mode A is seen to be more acute, for example at 0.75 \( G_e \) level the Sandwich Plate was operating at count rates an order of magnitude higher. Initial gain depression, however, occurs for both detectors when the pulse current is \( \sim 1\% \) of the standing current. This indicates that both detectors have similar charge abstraction limits. Since the available current supply limits the high count rate operation, the advantage then lies with the detector giving the smaller output charge. The difference in count rate performance of the detectors figure 5.8 can therefore be attributed to the higher operating gain (larger output charge) of the chevron, which had a low count rate peak gain \( \sim 10 \) times higher than the Sandwich Plate.

Further investigation of gain dependence on count rate for various plate types and geometries will be carried out at a future date.

![Graph](image)

Figure 5.7: Variation of modal gain with output count rate, \( N_m \) for detector Modes A, B and C. Operating voltages: Mode A - \( V_F = 950\text{V}, V_G = 600\text{V}, V_R = 1000\text{V} \). Modes B, C - \( V_F = 1050\text{V}, V_G = 600\text{V}, V_R = 950\text{V} \).

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Figure 5.8: Comparison of the variations of normalised gain with output count rate.
Circles - Sandwich plate, squares - Mode A, peak gains normalised to 0.37 pC and 3.88 pC respectively.

5.2.5 \( G_\theta(\theta) \)

Figures 5.9 a, b illustrates the variation of peak gain and FWHM as the angle, \( \theta \), between the X-ray beam and the MCP normal is changed. As can be seen the peak gain and FWHM remain relatively constant until the incident angle is such that the X-rays are interacting far down the channels. The broken vertical lines indicate (1) the angular position adopted for all previous measurements and (2) the point of closest alignment between the beam direction and the channel axis. Relative efficiency measurements (figure 5.10) were used to determine the channel bias angle \( \theta_B \). The angle \( \theta_B \) is found from the angular position of the 'dip' and the known MCPs normal direction. The depth of the dip is an indication of the MCP phase angle, \( \psi \), (section 4.6). Measurements were made on all three Modes (\( x = 25.5 \) mm); results from Modes A and B only are shown in figure 5.10. No dip was observed for Mode C which indicates that the phase angle was such that the X-ray incidence angle was always greater than 5 degrees.
Figure 5.9: Variation of modal gain and FWHM with X-ray incident angle $\theta$ for Mode A. Si-K X-rays, $V_F = 950\, \text{V}$, $V_G = 600\, \text{V}$, $V_R = 1000\, \text{V}$.

Figure 5.10: Relative efficiency measurements for Detector Modes A and B for C-K X-rays. Mode A - $V_F = V_R = 1000\, \text{V}$, $V_G = 200\, \text{V}$. Mode B - $V_F = 1050\, \text{V}$, $V_G = 600\, \text{V}$, $V_R = 950\, \text{V}$. 
5.3 Background Noise

Our model for the dark noise in MCPs (Chapter 2) indicates that the main source of noise (in defect free and completely outgassed plates) is due to the decay of radioactive elements in the plate glass. Following from the manufacturers claim that the L² plates were low noise and potassium free (B. Laprade, private communication), it was hoped that these plates would have a low intrinsic background noise count rate. However, after letting the plates completely outgas the noise count rate was found to be > 0.5 counts cm⁻²s⁻¹. This is much higher than that expected (0.14 cm⁻²s⁻¹) from standard Mullard MCPs (containing 6% by weight of potassium) of the same geometry.

The reason for the higher noise count rate lies with the fact that L² plates contain rubidium (Galileo Electro-Optics patent 1983 - probable glass type 6). Naturally occurring rubidium contains 27.83% radioactive ⁸⁷Rb (whereas ⁴⁰K is only present as 0.0018% of all potassium atoms) with a half-life of 5x10¹⁰ years. ⁸⁷Rb is a beta emitter with the betas having a maximum energy of 0.274 MeV. Therefore the presence of rubidium in MCP glass (for the same percentage weight) would have a proportionally larger effect than potassium. Assuming the Long Life glass is type 6 of the patent (containing 3.48% by weight of rubidium oxide therefore 3.18% rubidium), then using the model of Chapter 2 the calculated number of disintegrations from rubidium is \( n_b = 1.58 \text{ cm}^{-2}\text{s}^{-1} \). Assuming \( \beta_s \) with maximum energy traversing homogeneous MCP glass results in a maximum range for the betas of 0.17 mm. Since the maximum beta range is less than the channel plate thickness the contribution of the rear plate to the dark noise is negligible (unlike the potassium case). Glass density was taken as 4 gm cm⁻³ with the plate thickness being 0.4 mm. The \( \beta \) self efficiency, \( Q_\beta \), of the MCP was calculated to be 0.80, although since \( Q_\beta \) also refers to the maximum energy range a more likely value would be ~0.5. Assuming \( Q_\beta = 0.5 \) the calculated intrinsic background count rate will be \( N_n(0) = 0.79 \text{ cm}^{-2}\text{s}^{-1} \). This is in good agreement with the noise measured for all three detector Modes.

Figure 5.11 illustrates the noise count rate per unit area as a function of the lower level discriminator threshold, \( d \), normalised in each case to the peak gain of the detector. The measurements of figure 5.11 were made without the presence of localised noise spots as can be seen from the insert, which is a typical noise image obtained from Mode B. The similarity of the noise curves of each mode indicate that the internal radioactivity (present in the same amount in plates of the same geometry and glass type) is the main source of the observed dark count rate.

5.4 Life Tests

Detector Modes A and B were used to investigate the improvement in the gain stability with abstracted charge implicit in the microchannel plates Long Life designation. Accelerated life tests were performed on both these detector modes using C-K X-rays. The entire active area was illumi-
nated with the abstraction rate initially around $2 \times 10^4$ counts s$^{-1}$ increasing to $2 \times 10^5$ counts s$^{-1}$ during the latter part of each test. The count rate, however, was always reduced to 6000 counts s$^{-1}$ when the gain was measured. Life testing for both Modes continued until 0.1 C cm$^{-2}$ had been abstracted. Peak gain and pulse height FWHM were measured as functions of the abstracted charge per unit plate area.

At the conclusion of the tests the gains, in photon counting mode of the two detectors ( figure 5.12 ), had fallen to approximately half their initial values. The FWHM for Mode A increased from an initial value of 128% to 208% while the Mode C FWHM changed from 157% to 196%. Both Modes exhibit gain plateaux beyond 0.01 C cm$^{-2}$, a result very similar to that reported by Cortez and Laprade ( 1982 ) for electron stimulation of a single Long Life MCP.

Many gain lifetime measurements have been published for MCPs of different geometries and for plates produced by various manufacturers. Figure 5.13 illustrates representative measurements obtained by Malina and Coburn ( 1984 ), Whiteley et al. ( 1984 ), and Matsuura et al. ( 1985 ). The measurements of Malina and Coburn were obtained using chevron detectors of the same channel geometry ( $D = 25 \mu$m, $L/D = 40:1$ ) but incorporating plates from a variety of manufacturers. The data sets show a large scatter in relative gain for any given charge abstraction level. Similar variation between plates of the same geometry and glass type has also been reported by Sande et al. ( 1977 ) and by Rees et al. ( 1980 ). The MCPs used in the Whiteley et al. measurements had a

Figure 5.11: Noise count rate as a function of discriminator threshold. Circles - Mode A, crosses - Mode B, squares - Mode C. Solid line - calculated noise count rate. The insert is a noise image from Mode B.
length-to diameter ratio of 120:1; that these plates appear to suffer a more rapid gain decay may indicate that lifetime depends on the L/D ratio of the MCP.

Figure 5.14 compares the Long Life plates with MCPs of similar geometry which have recently been used in life-time evaluations. The Mullard plates (tested at Leicester) are seen to follow a similar trend to the L^2 MCPs. Curve (i) represents data (Matsuura et al. 1985) for MCPs manufactured by Hamamatsu, which have undergone a new process, whereas curve (ii) represents measurements on plates produced by an older method. In comparison, all three different 'new' plate types show an increase in gain lifetime which possibly reflects an preoccupation by all manufacturers to produce longer life plates. The physical reasons for the decrease in MCP gain life-time are as yet still unknown, although Sandele et al. (1977) suggest that the decay is caused by the removal of the electron sources through reaction with an intrinsic population of poisoning species. An alternate possibility is that the MCP semi-conducting surface is spoiled by vacuum contaminates, eg. carbon.

5.5 Conclusion

Long Life plates have been shown to be suitable for use in photon counting detectors giving adequate pulse height distributions, FWHM and gain characteristics. Although background count rate are disappointingly high, when compared with standard MCPs, this investigation has shown that changing the glass composition does affect the noise. MCPs with different glass composition have since been tested and the results are noted in the Appendix.

The advantage of the increased gain stability of the L^2 plates for detectors used in X-ray astronomy is easily out weighed by the increase in background noise. Astronomical X-ray detectors experience incident fluxes which are low and their expected operating life-times usually modest. For example, $4 \times 10^9$ counts cm$^{-2}$ corresponds to an average count rate of $\sim 100$ counts cm$^{-2}$ s$^{-1}$ for one year, a flux and duration typical of satellite borne X-ray and UV astronomy experiments (Malina and Coburn 1984). The successful Einstein HRI MCP detector only required one voltage adjustment in two years of operation. Gain decay will be a greater problem for ground based detectors, eg. spectrometers used in fusion research, where the input fluxes tend to be higher.

Therefore, unless Long Life plates can be manufactured without using radioactive components they do not represent an improvement over standard MCPs at present used in detectors for X-ray astronomy experiments.
Figure 5.12: Modal gain as a function of abstracted charge.
Mode A - circles and Mode C - squares.

Figure 5.13: Relative MCP detector gain as a function of abstracted charge per unit area.
Lifetest data of Malina and Coburn (1984): Circles - Galileo MCPs, Squares - Mullard MCPs, Crosses - Varian MCPs (absolute values of the initial gain lie in the 0.53 - 0.94 pC range). Lifetest data of Whiteley et al. (1984) Diamonds - Mullard, MCPs initial gain 3.2 pC. Full curve - lifetest on Hamamatsu MCPs, old production process (1985).
Figure 5.14: Relative MCP detector gain as a function of abstracted charge per unit area.
Filled circles - L^2 Mode A, Open circles - Mode C. Squares - chevron of Mullard D = 12.5 μm, L/D = 40:1 MCPs, initial gains lie in the 2.5 - 3.5 pC range. Hamamatsu MCPs - curve (i) new production process, curve (ii) old process.
Chapter 6
X-ray Polarimetry

6.1 Introduction

Since the beginning of X-ray astronomy in the early 1960's, there has been tremendous progress in the number of sources discovered and in the models used to describe the underlying physical mechanisms. Many of the advances have been due to the increasingly sophisticated detectors used on such satellite missions as Einstein and EXOSAT. At present however, measurements of astronomical X-ray emitting objects are confined to two independent parameters, spectra and time variability. The possibility of doubling the number of independent parameters lies with the measurement of the polarisation (direction and degree) of the detected X-rays. This increase from two to four parameters would allow greater discrimination between the models proposed for the emission processes.

The importance of X-ray polarisation measurements for astrophysics has been emphasized by many authors (Rees 1975, Novick 1975 and Mészáros et al. 1988) but to date only one positive detection has been made. This measurement was made on the Crab Nebula (Novick et al. 1972, Weisskopf et al. 1976, 1978) and yielded an X-ray polarisation P=19% (at the 18 σ level). Hughes et al. (1984) have analysed data from various X-ray sources observed using the polarimeters on the OSO 8 satellite; their results are all in the form of upper limits on the possible detected polarisation. Silver et al. (1978) have reported a marginally significant detection (3% at 2.6 keV) for Cyg X-1 and weak upper limits for the accretion powered pulsars Her X-1 (60%) and Cen X-3 (14% Silver et al. 1979). The dearth of polarisation measurements leaves X-ray astronomy lacking information readily available to optical and radio astronomers.

In Section 6.2 the astrophysical production of X-ray polarisation and the significance of polarisation measurements with respect to different types of source is reviewed. Section 6.3 reviews the instruments which have been used in X-ray polarimetry. The remaining sections describe a new type of polarimeter, and its relevance for astronomical research.
6.2 Astrophysical Review

Polarised X-rays are expected whenever emission occurs by a non-thermal process. Measurement of the degree, direction and energy dependence of the polarisation would provide information on the non-thermal electron distribution and possible magnetic field configurations responsible for the polarised emission. The more common examples of polarised emission processes are: (a) synchrotron radiation, (b) linear bremsstrahlung occurring from mono-directional electrons impinging on an atmosphere, (c) emission from asymmetrical hot plasmas with densities such that significant scattering occurs, (d) pulsar emission.

Strongly linearly polarised X-rays are expected to be emitted by the synchrotron (magnetic bremsstrahlung) process from a flux of accelerated relativistic electrons trapped in a quasi-homogeneous magnetic field (Landecker 1972). The trapped electrons spiral around the magnetic field lines radiating X-rays with the electric vector perpendicular to the magnetic field. This direction of the electric vector is independent of the energy of the emitted X-rays. It is this production mechanism which is generally accepted for the continuum emission from the Crab Nebula since the detection of X-ray polarisation is consistent with measurements made in the radio and optical wavelengths.

Polarised X-rays will be produced from linear bremsstrahlung as a result of high energy electrons colliding with a cool dense atmosphere. These X-rays would be linearly polarised with the direction of polarisation dependent on the X-ray energy. Low energy X-rays will be polarised perpendicular to the plane formed by the incident electron beam and the resultant X-ray beam. High energy photons however, will be polarised parallel to this plane. This reversal of the state of polarisation is characteristic of linear bremsstrahlung (Novick 1975).

Weakly polarised X-rays, produced by thermal bremsstrahlung, are expected from a spherically asymmetrical isothermal hot plasma where the density of the electrons is sufficient to produce significant internal Thomson scattering. No polarisation would occur if the source was spherically symmetric; detection of weakly polarised X-rays would therefore constrain any model used to describe the source.

Linearly polarised X-rays are expected from both accreting X-ray pulsars and rotation powered pulsars (Mészáros et al. 1988). Suggested emission processes include cyclotron radiation from the accreting material, X-rays generated by thermal processes near the stellar surface and synchrotron radiation (Rees 1975, Mészáros et al. 1988). In all cases the X-rays are expected to be strongly linearly polarised with maximum polarisations of ~80%.

The importance of the X-ray polarisation can best be illustrated by specific astrophysical examples. Extra-galactic sources such as Active Galactic Nuclei (AGN) emit much of their radiation by X-rays. At present it is not clear if the radiation is thermal or non-thermal or whether it arises from a disk, a torus, a quasi-spherical flow or a jet (Mészáros et al. 1988). Various combinations of the emission mechanisms can be used to create models which fit the
two parameter (energy and time) data available. Where the models do differ significantly is in their prediction for the degree of X-ray polarisation. These range from less than a few percent (asymmetrical plasmas), 2% - 10% for disks to greater than 10% - 20% for jets. Measurement of the X-ray polarisation would therefore discriminate conclusively between the proposed models.

Measurement of the X-ray polarisation may be the most conclusive method of deciding that an object is a black hole (Rees 1975, Novick et al. 1985, Mészáros et al. 1988). Current models of black hole candidates such as Cygnus X-1 propose that the X-rays emanate from a surrounding accretion disk. The X-rays are expected to linearly polarised due to electron scattering in the disk. Relativistic effects associated with the strong gravitational field extending into the disk (the Lense-Thirring effect - 'the dragging of inertial frames') would cause a rotation of the polarisation direction which would be dependent on the X-ray energy. This expected dependence arises as the higher energy photons are emitted from smaller radii and hence stronger gravitational fields. Rotation of the plane of polarisation, if detected, coupled with an inferred mass greater than three solar masses would give overwhelming evidence for a black hole (Mészáros et al. 1988).

These examples and various others reported in the literature (Landecker 1972, Novick et al. 1985, Mészáros et al. 1988) agree that polarisation measurements have the potential to shed light on many astrophysical problems. The need for an instrument with broad band capability and suitable sensitivity is obvious if routine X-ray polarisation measurements are to become a reality.

6.3 Polarimeter Review

6.3.1 Statistical Limitations

An ideal polarimeter for linearly polarised radiation would have 100% transmission in the pass axis and zero transmission in the perpendicular axis. Real polarimeters however, have less than 100% transmission in the pass axis and a finite transmission in the 'zero' axis. Accordingly a modulation factor $M$ is defined from the count rate modulation measured for 100% polarised radiation as

$$M = \frac{C_\perp - C_\parallel}{C_\perp + C_\parallel}$$

where $C_\perp$ and $C_\parallel$ are the signal counts when the pass axis is parallel and perpendicular to the polarisation vector respectively. The measurement of the polarisation is then given by

$$P = \frac{1}{M} \left( \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}} \right)$$

for a source with polarisation $P$ and $C_{\text{max}}$ and $C_{\text{min}}$ being the maximum and minimum signal count rates respectively.

All polarimeters, due to photon counting statistics, will measure a positive result for an unpolarised source (Novick 1974). Novick (1974) defines the minimum detectable polarisation as
\[ P(99\%) = \frac{3}{MS} \left( \frac{2(S + B)}{T} \right)^{\frac{1}{2}} \]  

where \( S \) is the signal counting rate, \( B \) the background count rate, \( T \) the observing time and \( M \) the modulation factor defined previously. If measured \( P > P(99\%) \) then the polarisation detection is regarded with 99% confidence as being real and not due to statistical fluctuations in the signal from an unpolarised source.

6.3.2 Polarimeters

X-ray polarimetry has been extensively reviewed by Novick (1974) where various potential polarisation mechanisms were evaluated for use in astronomy. Photoelectric polarimeters, Secondary Fluorescence polarimeters and Borrmann-effect polarimeters were all found to be unsuitable for X-ray astronomy. Two types of instrument, the Bragg crystal polarimeter and the Thomson scattering polarimeter, were also considered and both were shown to have sufficient sensitivity for X-ray astronomy.

Thomson Polarimeter

Polarised X-rays which undergo photon-electron scattering in a scattering block, figure 6.1 a, are preferentially scattered orthogonally to the incident photon electric field vector (Landecker 1972). The angular dependence is proportional to \( \sin^2 \phi \), where \( \phi \) is the angle between the polarisation vector of the incident photon and the propagation vector of the scattered photon (figure 6.1 b). This scattering is almost energy independent for photon energies above the binding energy of the electron and below the electron rest-mass energy. The energy range of the polarimeter is limited by the photo-electric absorption in the block at low energies and the decrease in flux with increasing energy of celestial X-ray sources. Since photo-electric absorption competes with the scattering process a low Z material must be used. The most commonly used material is metallic Lithium which gives an effective low energy cutoff of the polarimeter of about 4 keV (Novick et al. 1985).

The design for a Thomson scattering polarimeter proposed for the X-ray Multi-Mirror (XMM) mission by Novick et al. (1985) envisaged a 1.5 cm diameter by 5 cm long metallic Lithium cylinder encased in a Beryllium sheath. The expected values of minimum detectable polarisation were quoted as 0.5% to 2.5% in the 4 - 10 keV band for a one day observation time for any of the ~ 30 brightest galactic X-ray sources.

Figure 6.1 a shows a schematic diagram of a Thomson scattering polarimeter where the detectors surrounding the scattering block are proportional counters. The polarimeter is rotated about the line of sight and the polarisation is detected from the modulation of the detector counting rates. The modulation factor for this type of polarimeter is > 30% for 100% polarised incident radiation. This low modulation factor is a consequence of the large solid angle subtended by the proportional counters. The Thomson scattering polarimeter however has the advantage of
measuring polarisation over a broad energy range (\( \sim 4 - 10 \) keV as proposed for XMM).

Bragg Crystal Polarimeter

X-ray polarisation can be detected by utilizing a Bragg crystal orientated at 45° to the incident flux (Novick 1974, Novick et al. 1985). The crystal will reflect only those X-rays that are polarised perpendicular to the plane of incidence and have energies \( E_n \) which satisfy the Bragg condition for 45° reflection

\[
E_n = \frac{nhc}{d\sqrt{2}}
\]

where \( d \) is the lattice spacing, \( n \) is the diffraction order, \( h \) is Planck's constant and \( c \) is the velocity of light. Since the energy bandwidth of nearly perfect crystals is extremely small (\(< 1 \) eV), they are very inefficient for stellar X-ray sources. This small bandwidth can be greatly increased by using mosaic crystals which reflect a larger range of photon wavelengths then being simultaneously reflected by the crystal.

Mosaic crystals consist of disordered arrays of very small crystals. Each crystal will strongly reflect energies which satisfy the Bragg condition but will pass, with only negligible absorption, photons which do not fulfil the Bragg condition.

Figure 6.2 illustrates the design of a Bragg crystal polarimeter which uses a multiwire proportional counter to detect the reflected X-rays. The crystal surface is curved to focus the X-rays onto the small volume detector. This focusing reduces the size of the proportional counter that would be required for a flat mosaic crystal and hence reduces the detector area sensitive to background noise. The background noise is further reduced by using pulse-height analysis, rise-time discrimination and anticoincidence techniques. Background reduction is required to improve the sensitivity of the instrument (6.3) but also to reduce the possibility of false polarisation produced by variations in the background.

Both theoretical and experimental studies (Novick 1975) have shown that graphite mosaic crystals are the primary choice for a crystal analyser at energies \( \geq 1 \) keV. The first order energy for graphite occurs at 2.6 keV (bandwidth \( \sim 0.32 \) keV for a mosaic crystal surface), with second and third orders at 5.2 and 7.8 keV respectively.

Rotating the polarimeter about the line sight of a 100% polarised source would produce a modulation, for the curved surface design, of 96%. The signal counting rate, for a polarised source, will be modulated at twice the detector rotation frequency. The amplitude of the modulation yields the fractional polarisation \( P \) and the phase the position angle of the electric vector. Note this modulation value is about a factor of three larger than the modulation obtainable from the Thomson scattering polarimeter.

Extension of the Bragg crystal polarimeter method to X-ray energies less than 1 keV requires the use of artificial crystals, since no natural crystals exist with sufficiently high reflectivity at the lower energies. These artificial crystal are produced by depositing alternating layers of high and
Figure 6.1: (a) A schematic of a Thomson scattering polarimeter, (b) the angular variation of the X-ray scattering (Landecker 1972).
low density materials with periodic spacing $\sim 10$ Å. The choice of layer spacing and materials determines the wavelength band that will be sampled by any polarimeter using these multilayers. Novick et al. (1985) proposed multilayers which would sample X-rays at 0.26, 0.52 and 0.93 keV thereby giving reasonable coverage of the 0.1 - 1 keV region.
6.4 Photoemission Polarimeter

6.4.1 Introduction

This section discusses the design and operating characteristics of a new type of polarimeter, the photoemission polarimeter. The development of the instrument was based on unpublished measurements by Oba et al. (private communication) on the photoemission of CsI as a function of X-ray incidence angle for the S and P polarisation states. Consideration was also given to the MCP VUV polarisation sensitivity reported by McConkey et al. (1982), Tome et al. (1984), both papers emphasizing the pronounced dependence of the sensitivity on the radiation incident angle.

A schematic of the photo-emission polarimeter is shown in figure 6.3. X-rays generated by the electron bombardment source are collimated before impinging on a polarising crystal. After reflection the X-rays are both energy defined, by the Bragg condition, and linearly polarised perpendicular to the plane of incidence formed by the incident and reflected X-ray beams. The reflected beam then passes through a carbon coated polypropylene filter before striking the photocathode surface. The electrons generated by the incident X-rays are focused toward the Channel Electron Multiplier (CEM) by a negatively biased wire mesh. The incident angle, \( \theta \), can be changed by rotating the photocathode plate/CEM assembly. The whole photocathode plate/CEM assembly can also be rotated 360° about the beam line. The signature of photocathode polarisation sensitivity is a modulation in CEM count rate with a 180° period.

As originally conceived the polarimeter was to be illuminated by certain specific X-ray lines collimated to produce a small spot on the photocathode surface. The desire for a small illuminated area was a consequence of the fore-shortening of the photocathode at small X-ray incidence angles and the requirement to present an incident beam of uniform intensity in the plane of the polarimeter.

In practice however, this approach had to abandoned as the incident flux at the polarimeter was insufficient for good counting statistics. Contributing factors to the low incident flux included the limitations of the X-ray source, the crystal reflectivity and the solid angle reduction as a result of the narrow collimation.

Since the X-ray flux from the source was limited the collimation was changed such that more of the Bragg crystal was illuminated by the X-ray beam. As a consequence of decreasing the collimation the X-ray beam incident on the crystal became divergent. The main criterion for the intensity profile of the X-ray beam in the plane of the polarimeter was that it be radially symmetric about the axis of rotation, preventing any beam anisotropies producing spurious modulation. This requirement could not be fulfilled using line generated X-rays since the narrow wavelength range of the X-ray line and the vertical spatial extent of the fully illuminated crystal would have resulted in a very asymmetric (almost rectangular) beam profile at the polarimeter. Since a rectangular profile is not radially symmetric this would have resulted in a modulated count rate as the polarimeter...
Figure 6.3: Schematic of the photo-emission polarimeter.
was rotated about the X-ray beam. To achieve the correct intensity distribution from the crystal using a divergent incident beam, the X-rays incident on the crystal should ideally have a uniform intensity at all wavelengths. The Bragg condition would then, when taken over the full spatial extent of the crystal and accounting for the angular divergence of the beam, select out the desired wavelength band to produce the necessary intensity distribution.

Although an X-ray beam of uniform intensity at all wavelengths could not be produced with the present X-ray source an approximation to the required profile could be obtained by using Bremsstrahlung instead of line generated X-rays. The peak of the Bremsstrahlung intensity distribution was used to approximate the flat wavelength intensity profile required. The validity of this approximation and its relevance to the measured polarisation are discussed in a later section.

6.4.2 X-rays, Polarising Crystals and Filters

X-Ray Generation

X-rays are produced using a heated tungsten filament positioned above a copper anode. Electrons emitted from the filament are attracted to the anode which can be biased using an emission stabilize high voltage supply, variable over a 300 to 4000 V range.

The photon intensity distribution for the generated Bremsstrahlung radiation is given by (Agarwal 1984)

\[ I_p(\lambda) = \frac{C}{\lambda^2 \lambda_{\text{min}}^2}(\lambda - \lambda_{\text{min}}) \]  

(6.5)

where \( I_p(\lambda) \) is the photon intensity as a function of wavelength \( \lambda \), \( C \) a constant and the minimum generated wavelength \( \lambda_{\text{min}} \), is given by

\[ \lambda_{\text{min}} = \frac{12.4}{V_A} \text{Å} \]  

(6.6)

where \( V_A \) is the anode voltage in kilovolts. To find the peak of the intensity distribution as a function of wavelength, equation 6.5 is differentiated and set to zero. Solving for \( \lambda_{\text{max}} \) the wavelength of maximum photon flux and then equating with equation 6.6 gives

\[ V_A = \frac{24.8}{\lambda_{\text{max}}} \]  

(6.7)

this determines the correct anode voltage needed to maximize the photon intensity for a particular wavelength.

Two collimation holes were used to restrict the size of the beam incident on the crystal. The initial collimation was a 1 mm diameter hole positioned 30 mm in front of the centre of the anode. A 10 mm diameter hole situated a further 90 mm in front of the first hole provided the final collimation.

Figure 6.4 illustrates the stability of the X-ray source over times greater than the measurement duration time (average \( \sim 1200 \) seconds). The three plots are representative of the source stability for all crystals, anode voltages and both filters. As can be seen there are no fluctuations present.
which could lead to a modulation of the detected count rate of twice the instrument's rotation frequency. The 'ramp' illustrated in two of the plots can be attributed to general change in count rate with time related to material being laid down and burnt off of the anode. The presence of the ramps will lead to the count rate at the start and finish of a rotation scan being different. This however can be corrected at the analysis stage, as discussed later.

Polarising Crystals

The wavelengths used in this investigation were determined by the requirement to cover the soft X-ray range and the availability of suitable crystals with good reflectance. The available range of anode voltages for the X-ray source power supply further constrained the X-ray energies studied to a ~ 0.17 to 2.7 keV range. Of the crystals available (obtained from Quartz and Silice) the following four were chosen to fulfil the above requirements: Lead Stearate (PbSt), Rubidium Acid Phthalate (RbAP), Ammonium Dihydrogen Phosphate (ADP) and Germanium (Ge). Details of each crystal are given in Table 6.1 where 2d is the double atomic spacing and n is the order number. All wavelengths shown have been calculated for the Bragg angle, $\theta$, being 45°.

Each crystal was supplied mounted into a 30 by 40 mm standard Philips crystal-holder. When
Table 6.1: Characteristics of the polarising crystals.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>2d (Å)</th>
<th>n</th>
<th>λ (Å)</th>
<th>keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbSt</td>
<td>100</td>
<td>1</td>
<td>70.7</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>35.4</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>23.6</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>17.7</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>14.1</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>11.8</td>
<td>1.05</td>
</tr>
<tr>
<td>RbAP</td>
<td>26.12</td>
<td>1</td>
<td>18.5</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>9.20</td>
<td>1.35</td>
</tr>
<tr>
<td>ADP</td>
<td>10.648</td>
<td>1</td>
<td>7.53</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.76</td>
<td>3.29</td>
</tr>
<tr>
<td>Ge</td>
<td>6.50</td>
<td>1</td>
<td>4.60</td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.30</td>
<td>5.40</td>
</tr>
</tbody>
</table>

used with the polarimeter the crystal-holder was installed into a rotatable mount fitted with an angular positioning scale. The crystal angle could then be positioned to ±0.25°. To ensure that the crystal face was perpendicular to the plane of incidence formed by the incident and reflected X-ray beam alignments were carried out using a clock gauge and mechanical positioning pins.

A stainless steel pin was used to coalign the centre of the anode, inner collimating hole, outer collimating hole and the crystal centre. A second alignment pin was mounted onto the polarimeter, concentric with the azimuthal axis of rotation, which was then translated until the second pin was aligned, at right angles, with the crystal centre. This linear position at which this occurred, 5300 steps from the right hand limit of the motion, will be referred to as the mechanical centre (MC). The crystal holder was then adjusted using shims and a clock gauge until the crystal face was perpendicular to both alignment pins. The vertical crystal alignment was then within 0.5° of the perpendicular plane. This alignment procedure ensured that the X-rays incident on the crystal would be reflected through the centre of the photocathode and that the 'optical axis' and the polarimeter rotation axis were coincident. Any misalignment of the optical axis and the rotation axis will produce a spurious modulation with a 360° period.

As discussed in the previous section the anode voltage should ideally be set to ensure the required wavelength for each crystal (namely the first order wavelength) matches the maximum of the Bremsstrahlung intensity distribution. While this was achievable for both RbAP and ADP, the required voltages could not be generated for the measurements made with PbSt and Ge. When the PbSt crystal was in use, the anode voltage was set at 1.0 keV (compared with the 0.35 keV required to optimize for λ = 70.7 Å), as the X-ray source filament could not stand the necessary
current required to achieve reasonable count rates at the lower operating voltage. Operating with
1 keV on the anode the Bremsstrahlung wavelength range extends down to 12.4 Å and therefore
the PbSt crystal will now reflect the first five orders ( Table 6.1 ). In practice, however, the
low reflectivities for the higher order wavelengths preclude any significant contamination of the
resultant distribution at the polarimeter. The shape of the Bremsstrahlung intensity curve at
70.7 Å for an anode voltage of 1 keV still approximates the desired flat incident beam profile.
The anode voltage used when the Ge crystal was installed was 4.0 keV, due to the limitation of
the X-ray source power supply. Although again, this is not the ideal value for maximum photon
intensity, the Bremsstrahlung intensity distribution still fulfills the necessary requirements of not
being a rapidly changing function at the wavelength region of interest.

A model was developed by G.W. Fraser to calculate the intensity distribution of the X-ray
beam in the polarimeter plane for a variety of system parameters. Comparison of the results
obtained from the model and the experimental measurements are given in a later section.

Each of the four crystals can be thought of as a piece of dielectric material which will therefore
polarise all radiation to a certain degree.

UV radiation, generated by the X-ray source, will be partially polarised after reflection from
Bragg crystal. The degree of polarisation is dependent on the incident UV wavelength and the
crystals optical constants. This property was used, with an appropriate filter, to analyse the
polarimeter's response to broad band UV radiation.

The UV radiation reflected from the Bragg crystals will not, unlike the reflected X-rays, be
100% polarised perpendicular to the plane of incidence. An estimate of the magnitudes of the
perpendicular $R_p$ and parallel $R_p$ reflectivities can be calculated using Fresnel's equations and the
relevant optical constants. The two Fresnel equations are ( Zombeck 1980 )

$$R_p = \frac{a^2 + b^2 - 2a \cos \theta + \cos^2 \theta}{a^2 + b^2 + 2a \cos \theta + \cos^2 \theta}$$  \hspace{1cm} (6.8)

and

$$R_p = R_p \left( \frac{a^2 + b^2 - 2a \sin \theta \tan \theta + \sin^2 \theta \tan^2 \theta}{a^2 + b^2 + 2a \sin \theta \tan \theta + \sin^2 \theta \tan^2 \theta} \right)$$  \hspace{1cm} (6.9)

where $\theta$ is the angle of incidence ( angle from normal to surface ) and

$$2a^2 = (n^2 - k^2 - \sin^2 \theta)^2 + 4n^2k^2)\frac{1}{2} + (n^2 - k^2 - \sin^2 \theta)$$  \hspace{1cm} (6.10)

and

$$2b^2 = ((n^2 - k^2 - \sin^2 \theta)^2 + 4n^2k^2)\frac{1}{2} - (n^2 - k^2 - \sin^2 \theta)$$  \hspace{1cm} (6.11)

where $n$ is the refractive index at a given wavelength and $k$ the extinction coefficient.

Using the values for $n$ and $k$ given in table 6.2 for Germanium, ( Potter 1985 ), the two
polarisation components can then be calculated. The values for the optical constants are for a
freshly cleaved crystal face which our crystal is certainly not but are used as a first order estimate.
The band-pass for UV measurements is determined by the transmission $T(E)$ of the sapphire
window and the unpolarised quantum detection efficiency $Q(E)$ of the photocathode. Figure 6.5
shows the product TQ for the CsI photocathode which displays a peak at ~ 1550 Å (8 eV). Using the values given in the table the degree of polarisation \( P_s \) is then

\[
P_s = (1 + z)^{-1} = 0.667 \quad \text{where} \quad z = \frac{R_g}{R_s}
\]  

(6.12)

Thus modulation factors obtained from \( \phi \) scans (UV only) should be multiplied by a factor

\[
\frac{1 + z}{1 - z} = 3.0
\]

(6.13)

to take into account the fact that the UV is not fully polarised. A similar correction factor should also be applied to the UV data obtained using the RbAP crystal although no data for the optical constants of this crystal were available.

<table>
<thead>
<tr>
<th>( \lambda ) (Å)</th>
<th>n</th>
<th>k</th>
<th>( R_g )</th>
<th>( R_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5794</td>
<td>1.924</td>
<td>0.63</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>1770</td>
<td>1.0</td>
<td>1.8</td>
<td>0.58</td>
<td>0.336</td>
</tr>
<tr>
<td>1650</td>
<td>0.63</td>
<td>1.6</td>
<td>0.55</td>
<td>0.303</td>
</tr>
<tr>
<td>1460</td>
<td>0.92</td>
<td>1.4</td>
<td>0.496</td>
<td>0.246</td>
</tr>
</tbody>
</table>

Table 6.2: Optical constants for Germanium. Potter (1985)

Figure 6.5: The variation of the UV transmission \( T(E) \) of the sapphire window and the unpolarised quantum efficiency \( Q(E) \) of a CsI photocathode as a function of the energy of the incident radiation.
Filters

Two filters were used during this investigation, a carbon coated polypropylene (CCP) window and a Sapphire window. The transmissions of each, for the wavelengths of interest, are given in Table 6.3.

The CCP window was made from stretched polypropylene (C₂H₂ ~ 1 μm thick) mounted on a 150 mm diameter ring and dip coated with carbon (~ 0.1 μm thick). The transmission values given in Table 6.3 were derived by Monte Carlo methods for C, C₂H₂ thickness' obtained from small sample absorption data. Carbon coating produces a conducting layer allowing the filter to be grounded which prevents stray electrons/ions reaching the photocathode surface and also acts as filter for UV radiation.

A standard UHV sapphire viewport was used as a filter to define a band pass in the UV wavelength range. For UV measurements the sapphire filter was positioned directly in front of the second collimation hole and the CCP filter was removed. The sapphire window has a band pass (Table 6.3) over a ~ 1500 to 55000 Å range but the CsI photyield essentially goes to zero at 1800 Å (Martin and Bowyer 1982). Therefore measurement of the polarisation response using the sapphire filter essentially cover the UV range of ~ 1500 to 1800 Å.

As a check on the integrity of the CCP filter to block the band pass defined by the sapphire window, both these filters were installed at the same time. The resultant count rate was not significantly different from the background count rate of the detector, thereby confirming the effectiveness of the CCP filter for the UV/optical wavelength region. This was found to be essential as the polarimeter was shown to have a high sensitivity to polarised UV radiation.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Transmission %</th>
<th>Wavelength Å</th>
<th>Crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCP</td>
<td>48.7</td>
<td>70</td>
<td>PbSt</td>
</tr>
<tr>
<td></td>
<td>52</td>
<td>18</td>
<td>RbAP</td>
</tr>
<tr>
<td></td>
<td>93.8</td>
<td>7.3</td>
<td>ADP</td>
</tr>
<tr>
<td></td>
<td>98.6</td>
<td>4.6</td>
<td>Ge</td>
</tr>
<tr>
<td>Sapphire</td>
<td>~ 80-90</td>
<td>2500-55000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>~ 35</td>
<td>1500</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Characteristics of the Filters.

6.4.3 Photoemission Polarimeter

This sub-section describes the design and operating characteristics of the photo-emission polarimeter (a photograph of the instrument is included overleaf).

Two photocathode materials were used for the measurements reported here, CsI and Aluminium. The photocathode plate consisted of a 70 mm diameter stainless steel substrate with the
relevant material evaporated onto the surface (photocathode active area ~60 mm). Evaporation of the CsI (99.9% pure 'Spectrosol'; BDH Chemical Ltd) followed an similar procedure to that described in Chapter 3 for CsBr, with the exception that the CsI was deposited onto the stationary substrate at room temperature, ~23°C. The coated thickness of the CsI was 1620 Å, deposited at ~25 Å s⁻¹.

Aluminium was evaporated using a tungsten filament and 99.5% pure aluminium wire to give a 1066 Å coating. This coating was also deposited onto a stationary substrate at room temperature but at a coating rate of ~12 Å s⁻¹.

Both the photocathodes were examined using a Scanning Electron Microscope with representative micrographs shown overleaf. The surface of the CsI coating (top micrograph) shows the granular structure associated with evaporation of alkali halides. From the scale given, the individual grains can be seen to be approximately 2000 Å in size. Similar results have been reported by Chappell et al. 1987 for coatings of CsI on various substrates. For coatings of similar thickness to ours Chappell et al. report that depositions produced, under similar conditions to those described above, exhibit a strong preferred direction for crystal growth. Stevels and Schrama de Pauw (1974) also discuss the resultant orientation of crystal planes as a function of substrate temperature (for CsI:Na evaporations). The significance of a preferred crystal growth direction will be discussed later.

The micrograph of the Aluminium deposition shows no granular structure, the markings being a feature of the underlying substrate.

The wire mesh-cone, with a mesh transmission of ~40.5%, was connected to the photocathode plate assembly. Figure 6.6 illustrates the count rate as a function of the common photocathode/mesh voltage. For all measurements reported here this voltage was maintained at -100 V and enabling the mesh to act as a electrostatic lens.

A CEM (Mullard CEM type B419bl/01) was chosen as a detector for the focused electrons since connection and signal processing is much simpler than would be required using an imaging MCP detector. A further advantage of the CEM is its small size which keeps the overall dimensions of the polarimeter to a minimum. Operating voltages for the CEM were 2 keV for all X-ray measurements and 2.1 keV for the UV measurements. The necessary increase in CEM voltage for the UV measurements reflects the lower photoyield of CsI (and hence lower CEM gain) for UV radiation. In order to minimize background the CEM was enclosed in an aluminium screening box and data obtained using an elevated lower level discriminator of 0.5 pC.

The photocathode/mesh assembly could be rotated to give X-ray incident angles, θ, between 5 and 50°. Independently of this angular movement, the photocathode assembly could also be rotated 360° about the beam line (φ direction). Due to the restrictions imposed by the necessary connecting HT and signal wires each scan in the φ direction could rotate through 360° only. For a subsequent measurement the assembly was always reversed back to the original starting point before a further scan was undertaken. One further independent motion was available, allowing
Scanning Electron Micrographs of the photocathode surfaces.
The CsI photocathode (top micrograph) shows the granular structure associated with the evaporation of alkali halides. Whereas the Al surface (bottom micrograph) does not show any pronounced structure (the dark spot was attributed to contamination on the substrate). The gross lines are also intrinsic to the substrate surfaces.
Figure 6.6: Count rate as a function of the photocathode/mesh voltage $V_p$.

The polarimeter to be traversed across the beam line. This was used to investigate the intensity profile of the incident X-ray beam. All three motions were made by using stepper motors inside the vacuum chamber and controlled externally by a BBC micro-computer. This external control reduced the necessity to let the vacuum chamber up to atmosphere thereby potentially degrading the CsI photocathode.

The polarimeter, the X-ray source, polarising crystal and the filter assembly were all housed in the same vacuum chamber. The chamber was evacuated using a cold trapped diffusion/rotary pump system giving operating pressures of $< 2 \times 10^{-6}$ millibar. The output signal after suitable amplification was fed into a Canberra multichannel analyser (MCA). The MCA was used in two modes, either for pulse height analysis or to bin the count rate as a function of time. The latter mode was used for rotation about the beam, to give the count rate as a function of rotation angle, $\phi$.

The presence of a significant magnetic field inside the mesh-cone could lead to a signal count rate which would mimic polarisation by inducing a modulation at twice the rotation frequency. Measurements were made, using an Hall probe, both inside the mesh-cone (during azimuthal rotation of the cone assembly) and outside the vacuum chamber. A field of $\sim 4 \times 10^{-5}$ T, consistent with the Earth's magnetic field, was found for both locations. If spurious magnetic focussing was the sole mechanism generating the $180^\circ$ periodicity we would expect a constant $p$-type modulation, a situation contrary to our measurements (section 6.7).

The various operating modes for the photoemission polarimeter are summarised in tables 6.4.
and 6.5.

<table>
<thead>
<tr>
<th>Filter Mode</th>
<th>Name</th>
<th>Sapphire Window</th>
<th>Carbon coated polypropylene (CCP)</th>
<th>Bandpass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X-ray</td>
<td>No</td>
<td>Yes</td>
<td>Defined by Bragg X-ray reflection</td>
</tr>
<tr>
<td>2</td>
<td>UV</td>
<td>Yes</td>
<td>No</td>
<td>Defined by sapphire transmission and photoelectric threshold of CsI</td>
</tr>
<tr>
<td>3</td>
<td>Open</td>
<td>No</td>
<td>No</td>
<td>Defined by Bremsstrahlung cutoff and photoelectric threshold of CsI</td>
</tr>
<tr>
<td>4</td>
<td>Test</td>
<td>Yes</td>
<td>Yes</td>
<td>Null</td>
</tr>
</tbody>
</table>

Table 6.4: Photoemission polarimeter operation: energy selection.

<table>
<thead>
<tr>
<th>Carriage Mode</th>
<th>Name</th>
<th>Variable</th>
<th>Limits</th>
<th>Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x-scan</td>
<td>linear position</td>
<td>-30 - 16 mm</td>
<td>5.3 μm</td>
</tr>
<tr>
<td>2</td>
<td>φ scan</td>
<td>azimuthal angle</td>
<td>-90° - 270°</td>
<td>0.015°</td>
</tr>
<tr>
<td>3</td>
<td>θ scan</td>
<td>grazing angle</td>
<td>5° - 50°</td>
<td>1.8°</td>
</tr>
</tbody>
</table>

Table 6.5: Photoemission polarimeter operation: photocathode motions.

### 6.5 Linear Scans

The X-ray (UV) beam profile was mapped by traversing the polarimeter perpendicular to the incident radiation. The incident angle, $\theta$, was constant at 23° and the polarimeter moved from $x = -30$ mm to 16 mm. Table 6.6 details the polarimeter conditions used for linear scan measurements with figures 6.7 illustrating the measured profiles.

With the polarimeter positioned at $x = -30$ mm the photocathode lies outside the Bragg reflected beam. Inspection of the profiles (figures 6.7) shows that the detector count rate at this position is non-zero and is different for each crystal. The source of this noise, measured at this position, can be attributed to fluorescence emanating quasi-isotropically from the crystals, and striking the photocathode surface resulting in detection by the polarimeter.

For example, the bremsstrahlung radiation incident on the RbAP (1.5 keV) crystal is below the L shell fluorescence threshold for Rb in energy, resulting in the low recorded background count rate compared with, for example, Ge. The differences in background (table 6.6) for $\phi = -90°$ and $\phi = 90°$ arises from the more favourable acceptance geometry for the fluorescence for the latter angle. The condition reverses when the polarimeter is at the other extreme linear position.
\((x = 16 \text{ mm}, \text{see figures 6.7})\), where now the geometry favours \(\phi = -90^\circ\).

The solid line shown on each of the figures 6.7 is the modelled fit from the Monte Carlo model. Curves a and b illustrated in figure 6.7a are for assumed photocathode diameters of 60 and 50 mm respectively with the latter being the better fit. The reduction in active area, from that discussed in subsection 6.4.3 (60 mm) is a result of the angular dependence of the transmission for the mesh-cone. Curve fitting was more accurate for scans with low background noise count rates. In all curves it appears that the maximum count rate lies near the 5700 step position indicated by the vertical dotted line. The asymmetry of the scans can be attributed to differences in acceptance geometries for the fluorescence as the polarimeter traverses the beam, being more dominant for \(x=16 \text{ mm and } \phi = -90^\circ\).

Figures 6.7b shows the variation of the maximum and minimum incident angles of the photocathode, due to the divergent beam, as a function of linear position. As can be seen the variation, at any given position, is never greater than \(~4^\circ\).

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Crystal</th>
<th>(\phi = -90^\circ)</th>
<th>(\phi = 90^\circ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>RbAP</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>X-ray</td>
<td>PbSt</td>
<td>160</td>
<td>80</td>
</tr>
<tr>
<td>X-ray</td>
<td>RbAP</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>X-ray</td>
<td>ADP</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>X-ray</td>
<td>Ge</td>
<td>93</td>
<td>144</td>
</tr>
<tr>
<td>UV</td>
<td>Ge</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Open</td>
<td>RbAP</td>
<td>115</td>
<td>2570</td>
</tr>
</tbody>
</table>

Table 6.6: Background count rate per 5 s bin \((N_b)\) and maximum signal to noise ratio \((N_{\text{max}} - N_b)/N_b\) from linear scans extremity, \(x = -30 \text{ mm, grazing angle } \theta = 23^\circ\).
Figure 6.7: Counts per channel as a function of linear position.
(a) PbSt (b) variation of maximum and minimum X-ray angles incident on the photocathode versus linear position (c) RbAP (d) ADP (e) Ge.
6.6 Alignment

As discussed in subsection 6.4.2, the polarimeter was initially aligned mechanically using alignment pins which ensured that the crystal face was perpendicular to the plane of incidence. A further adjustment however, was necessary to ensure that the centre of the radiation was incident on the crystal at 45° and further, that the polarimeter rotation axis was coincident with the centre of the reflected beam. This adjustment was required to ensure (figure 6.8a) that the X-ray incident angle on the photocathode, \( \theta \), was constant as the polarimeter azimuth angle, \( \phi \), was changed.

With the polarimeter positioned at the mechanical centre (MC), a series of \( \phi \) scans were accumulated ('open system mode' table 6.4), each for a different crystal angle, \( \alpha \). Symmetry in the \( \phi \) scans (\( C(\phi) = C(-\phi) \)) will be achieved when the incident angle \( \theta \) remains constant during rotation about the azimuth and hence indicating the desired alignment conditions have been satisfied. Further series of scans were taken at linear positions either side of the MC. As can be seen from figure 6.8a, small rotations from \( \alpha = 45^\circ \) result in deviations from the constant \( \theta \) condition. Figure 6.8b illustrates the effects of small rotations of the crystal from the optimum 45° on the shape of the \( \phi \) scans. The use of inverted commas indicates the reading on the crystal holder's angular scale which, since '45.25°' was found to be the best alignment, implies an offset of 0.25° in the scale from the nominal zero. The linear position for this scan was 5100 steps and subsequently all the measurements presented here were made with the polarimeter at this position.

Following the discussion in section 6.5, which determined the the linear position for maximum count rate (the optical centre of the beam), to be 5700 steps, choosing to make subsequent measurements at 5100 steps may appear contradictory. Two reasons governed the final choice, the first being that measurements made with the crystal fixed ('45.25°') and the linear position perturbed about the MC resulted in little difference to the \( \phi \) scan shape. Secondly the noise associated with fluorescence can be expected to be less at 5100 steps when compared with the polarimeter positioned at 5700 steps (figures 6.7).

Monte Carlo correction files were generated to establish what \( \beta_4^\circ \) (angle between crystal plane and the normal to the plane of incidence) actually was. The distribution chosen for re-analysis was taken at a linear position of 5100 steps, \( \theta = 23^\circ \) using 0.67 keV X-rays. Figure 6.9a illustrates the correction files for the 5 tilt angles chosen whereas figure 6.9b shows the data after the correction files were applied. \( \sigma \) is the rms deviation between corrected the data and a curve with the form of equation 6.16 - the 'signature' of polarisation. Figure 6.9 shows that the best fit corresponds to \( \beta_4 = 0^\circ \), confirming that the crystal was perpendicular to the plane of incidence.

Figure 6.10 illustrates the calculated intensity distribution in the plane of the polarimeter's linear motion. The distribution is for reflection from a PbSt crystal, ideally aligned (\( \alpha = 45^\circ, \beta_4 = 0^\circ \)). Further calculations show that, for all energies, departures of \( \alpha \) and \( \beta_4 \) from their ideal settings, results in a shift of the position of maximum intensity by 4.65 mm/degree in x and 3.3 mm/degree in y, respectively.
During final analysis of the data corrections were made, computed from the Monte Carlo model, to account for the differences in calculated count rates between the 5700 step, 'optical centre' (OC), and the measurement position, 5100 steps.

Figure 6.8: Diagrams for alignment of the Bragg crystal (RbAP).
(a) Diagrams illustrate the change of incident angle, $\theta$, with different crystal angle, $\alpha$. (b) Variation of $\phi$ scans with crystal angle, $\alpha$.
Figure 6.9: Vertical crystal tilt simulations.
(a) Monte Carlo generated correction factors, (b) effect of correction factors on $\phi$ scan. RbAP X-ray $\phi$ scan, linear position- 5100 steps, $\theta = 23^\circ$.

Figure 6.10: Calculated intensity distribution in the plane of the polarimeter’s linear motion. The dotted lines indicates the width of the photocathode presented to the beam for an incident angle, $\theta = 10.4^\circ$. 
6.7 Results

The modulation factor can be measured by two independent methods, (a) by keeping the X-ray incident angle, $\theta$, fixed and rotating the polarimeter around the polarised beam, or (b) by fixing two orthogonal azimuthal angles, $\phi$, and then varying the incident angle, $\theta$.

Measurements were made at four discrete X-ray energies (0.17, 0.67, 1.65 and 2.7 keV as defined by the Bragg crystals) and in a UV band centred on 8 eV. Although the majority of the investigation is concerned with the response of CsI photocathode, measurements were also made using an Aluminium photocathode for comparison.

Figure 6.11 illustrates the form of the measurements and the various methods employed for analysis of the data. The following subsections describe the data reduction methods used in the analysis of all $\phi$ scan measurements.

6.7.1 Geometrical Correction Factors

A Monte Carlo model was used to calculate the variation of the incident flux at the photocathode surface. This model takes into account variations due to the geometric configuration of the photocathode at various angles and its relation to the beam profile. Other factors include the variation of the quantum detection efficiency of the photocathode and the changes in the mesh-cone transmission as a function of incident angle $\theta$.

The structure of the wire mesh was measured using a travelling microscope (pitch = 110$\mu$m, wire diameter = 40$\mu$m). These dimensions give, for a planar mesh and normal incident radiation, a transmission $\Gamma_0$ of 40.5%. For angles greater than $\psi_{\text{max}} = 68.4^\circ$, with $\psi$ measured from the normal to the mesh, the transmission is zero. The effective transmission $T_0$ of the conical mesh when at right angles to the beam is then

$$ T_0 = \frac{2}{\pi} \Gamma_0^{\frac{1}{2}} \int_0^{\psi_{\text{max}}} (1 - (1 - \Gamma_0 \sec \psi)) d\psi $$

which gives $T_0 = 0.236$. Therefore for our mesh-cone the modified transmission as a function of $\theta$ is given by

$$ T(\theta) = T_0^{\frac{1}{2}} (1 - (1 - T_0^{\frac{1}{2}} \sec(\frac{\pi}{4} - \theta))) $$

6.7.2 Correction for Slopes

When the polarimeter has been rotated through $360^\circ$ in the $\phi$ direction the photocathode is in the same physical position. Therefore the measured count rate should be the same for $\phi = 0^\circ$ and $\phi = 360^\circ$. Inspection of some of the raw data show a discrepancy from this ideal which in some part can be attributed to variations in the X-ray source stability. In all cases this can be corrected by dividing the data by a linear calibration file having a small slope. The data analysis suite allows the trial of various gradients, with the choice of the best fit being a mixture of visual judgement and reducing the Fourier Transform amplitude $A_1$ to a minimum.
A correction file, generated by the Monte Carlo model, which accounts for all the above system variables (e.g. figure 6.11b) was initially applied to the raw data before further analysis was carried out.

### 6.7.3 Curve Fitting

If photocathode sensitivity to polarisation is present, the detected count rate for polarised X-rays will be modulated at twice the instrument's rotation frequency and the ideal curve will have the form

\[
C(\phi) = C_p \cos^2(\phi + \Delta\phi) + C_s \sin^2(\phi + \Delta\phi)
\]  

(6.16)

where \(C_p\) is the count rate at \(\phi = 0^\circ\) or \(180^\circ\), \(C_s\) the count rate at \(\phi = -90, 90,\) or \(270^\circ\) and \(\Delta\phi\) allows for a phase offset (expected mechanical induced phase offset). After some manipulation we obtain:

\[
C(\phi) = \frac{1}{2}(C_p + C_s) + \frac{1}{2}(C_p - C_s) \cos 2(\phi + \Delta\phi)
\]  

(6.17)

The first term is the mean of the data set and \(\frac{1}{2}(C_p - C_s)\) is the amplitude of the modulation. To fit this curve to the corrected data the two parameters \(\frac{1}{2}(C_p - C_s)\) and \(\Delta\phi\) are adjusted until the minimum rms deviation between the theoretical curve and the measured data is found. The amplitude is incremented in steps of 1% of the mean up to an upper limit of 50%. This limit was chosen, from inspection of the raw data, to reduce the computation time. The phase shift \(\Delta\phi\) is incremented in one degree steps from -90 to 89 degrees. A theoretical curve is then calculated for each parameter pair and the minimum deviation of the data from this curve is then evaluated. This process is iterated until the two parameters which give the overall minimum rms deviation are found. The modulation factor is then calculated from the fitted curve's amplitude and the known mean. An example of the curve fitting is given by the solid line shown in figure 6.11c.

### 6.7.4 Reduction of C(\phi) data sets by the method of Doyle et al.

A different approach to obtaining the modulation factor uses the method of Doyle et al. (1978). An estimation of the phase offset, \(\Delta\phi\), is necessary to correct the \(\phi\) scale prior to straight line fitting, (obtained from curve fitting analysis). A brief outline of this method is now given.

For a X-ray beam striking the polarimeter plane after reflection from the crystal (assumed 100% polarised), the modulation factor of the polarimeter is given by

\[
M = \frac{(C_s - C_p)}{(C_s + C_p)}
\]  

(6.18)

where \(C_s\) and \(C_p\) are defined as above. As discussed previously the expected form of the modulated data is given by equation 6.17 therefore by plotting \(C(\phi)\) against \(\cos 2(\phi + \Delta\phi)\) the modulation factor can be obtained from the ratio of the intercept and the gradient. The four quadrants of the 360°\(\phi\) scans are now mapped into range (-1, 1) of \(\cos 2\phi\) (figure 6.11d). Linear regression of the
resultant plot gives values for the gradient and the intercept and hence the modulation factor. If the modulation is 'P' type rather than 'S' type the slope changes sign.

6.7.5 Analysis by the method of Discrete Fourier Transforms.

After application of the corrections outlined above in subsections 6.7.1 and 6.7.2 the data is analysed using a Discrete Fourier Transform routine, ( a standard NAG routine ). The resulting analysis produces values for the amplitudes of zeroth ( A_0 ), first ( A_1 ), second ( A_2 ) etc. component frequencies and their corresponding phases. Using the values of A_0 and A_2 the modulation factor can be calculated. This method of analysis requires no knowledge of the phase difference etc. and therefore gives a independent estimate of the modulation factor which can be compared with the value obtained by the method of Doyle et al. Similarly the phase differences obtained from the two methods can also be compared to evaluate the self consistency of the data analysis techniques.

Misalignment of the optical axis and rotational axis in a rotating polarimeter gives rise principally to spurious modulation with a 360° period ( Weisskopf et al. 1972 ). The magnitude of the ratio A_1/A_0 then gives a measure of the system alignment whereas A_1/A_2 gives an measure of the strength of the polarisation signal compared to the instrumental modulation.

Figure 6.11: $\phi$ modulation data and analysis methods.
(a) Raw X-ray data using RbAP crystal with $\theta = 23^\circ$. (b) Correction file generated from the Monte Carlo model. (c) The solid line indicates the theoretical curve fit. (d) Modulation factor determined by the method of linear regression.
6.7.6 X-ray Measurements

Figure 6.12a illustrates the variation in modulation factor, M, as a function of incident angle, θ, for the X-ray energies 0.17, 1.65 and 2.65 keV (crystals PbSt, ADP and Ge). The modulation factors for 0.17 and 2.65 keV X-rays are seen to be qualitatively similar, both having a maximum value of ~12%. Both data sets were also found to be approximately S type modulated, i.e. maximum count rates occurring closer to the angles f = −90, 90 and 270° than f = 0, 180° (figure 6.11). Measurements using the ADP crystal, however, show the modulation factor changing sign indicating that the photocathode is more sensitive to S polarised X-rays at small θ but P sensitive at larger angles. None of the other X-ray data sets show such a distinct change of sign, although the θ-scan photoyield data, figure 6.16, indicates a possible change for high (θ > 30°) incident angles.

Figure 6.13 illustrates the response of CsI to 0.67 keV X-rays (RbAP). Here the maximum modulation, ~22%, is almost a factor of two larger than the other X-ray modulation factors (figure 6.12). A possible explanation for the lower modulation factors lies with the background count rates caused by fluorescent emission from the crystals, as previously noted in section 6.5. Differentiating between fluorescent emission and Bragg reflected radiation was not possible in our detector. In an attempt to evaluate the effect of the fluorescent emission three of the θ scans (θ = 23°) were re-analysed after subtraction of a constant background, estimated from the values given in table 6.6. The lowest values were taken for each crystal and it is obvious that the assumption of a constant background level is an oversimplification of the true spatial distribution. Table 6.7 compares the modulation factors obtained with and without the background subtraction.

Using this over simplified background subtraction has resulted in an increase of M for all X-ray energies. Therefore the modulation factors for all other X-ray data reported here, since they are not background corrected, must be viewed as lower limits.

From equation 6.3 it can be seen that for a source of known polarisation a quantity called the Minimum Detectable Modulation (MDM) can be defined as

\[
MDM(99%) = \frac{3}{PS} \left( \frac{2(S+B)}{T} \right)^{\frac{1}{2}}
\]

The MDM was calculated for each data set and is displayed (or given) in the relevant figures. All measured modulation factors, with the exception of two higher angle (θ = 32 and 37.4°) Ge data

<table>
<thead>
<tr>
<th>Crystal</th>
<th>M_5</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbSt</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>ADP</td>
<td>0.06</td>
<td>0.053</td>
</tr>
<tr>
<td>Ge</td>
<td>0.085</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 6.7: Comparison of modulation factors with and without the background subtraction. M_5 is the modulation factors with subtracted background and M as given in figure 6.12a.
points, are above the MDM limit indicating that they are not produced by statistical fluctuations. The high value of MDM for Ge is a result of the high background count rate, taken from the average of the values obtained in the linear scan mode (table 6.6).

All the X-ray measurements using the CsI photocathode were found to have a phase shift away from the pure S type modulated form. This effect can be seen to be dependent on both the incident angle and the X-ray energy. Why a phase shift occurs can be explained if the CsI photocathode has a preferred polarisation axis, orientated in a different direction from the 'mechanical' axis of the crystal/polarimeter system. The preferred crystal growth discussed in section 6.4.3. may be the physical reason that would account for a CsI polarisation axis.

The uncertainty in the measured phase offset, Δφ, is dependent on the total number of detected counts, N, and on the modulation factor, M, such that

\[ \delta \phi(3\sigma) \sim \frac{2.1}{M(Nt)^{0.5}} \]  

(6.20)

where t is the integration time. The uncertainty in our measured angles are shown by the error bars on the appropriate figure. That the uncertainty, on some of the measurements, were quite large reflects either the low total accumulated counts (esp. Al data) or small measured modulation factors.

In order to evaluate the effect of deliberately introducing instrumental polarisation the scans were taken at 200 step intervals between 4500 and 6500 step linear positions. Figure 6.15a illustrates the change in modulation factor as a function of linear position. The increase in modulation factor as a function of distance from the OC is at present believed to be a consequence of the change in effective grazing angle, θ, with linear position (see figure 6.7 earlier). θ decreases towards x = 4500 steps; M is known (below) to increase with decreasing θ. The presence of grating-like structure on the CsI cathode surface would conceivably produce more rapid changes in local grazing angle with x.

Figure 6.15b shows the change in phase shift with x, which further supports the belief that a polarisation axis exists for the CsI photocathode. The position for the phase shift to go to zero can be interpreted as the beam positioned on the centre of the photocathode since the effect of the polarisation axis will be at a minimum at this position.

Figure 6.15c displays the variation of the 'goodness of fit' parameter σ (described above), as a function of x. As can be seen the fits for all the data sets are consistent indicating the measured modulation factor variation has not been caused by the analysis routines.

Figure 6.13 compares the measurements made on the CsI with those for an Al photocathode using 0.67 keV X-rays. The CsI photocathode is seen to have higher modulation factors at lower incident angles. The counting statistics, however, on the Al data were rather poor reflecting the lower (~10 times) detection efficiency of Aluminium photocathodes. That the Al modulation factors are higher than those found for the X-ray data shown in figure 6.12 may again reflect the influence of the background due to fluorescent emission apparent for the crystals used to obtain
these X-ray energies. Even though the Aluminium photocathode has a comparable modulation factor to CsI, its low quantum detection efficiency rules out its use for X-ray astronomy.

Figure 6.13c compares the variation of phase shift with incident angle for CsI and Al and indicates that for this incident X-ray energy the phenomenon is only associated with the CsI photocathode. That the CsI has a different surface structure from Al which would account for this effect seem plausible when the micrographs of subsection 6.4.3 are considered.

Figure 6.12: X-ray φ scan polarimetry measurements. Filled circles Ge, open circles ADP, squares PbSt. For clarity, MDM values are not displayed on the graph; MDM for Ge is 0.037, ADP 0.033 and PbSt 0.019.

Figure 6.14 illustrates unpublished measurements made by Oba et al. of the modulation factor, M, for CsI, Al photocathodes and reduced lead oxide (PbO) glass at four X-ray energies. All the data show an increase in (S-type) modulation factor as the grazing angle decreases. The measurements of Oba et al. do not cover the same low angle region as our data but do show the same trend over common angles. Our measurements, do however, confirm that the vectorial photoemission effect is present at energies higher than those used in their study.

Figure 6.16 illustrates measurement of the relative photoyield for CsI as a function of incident angle for two orthogonal φ settings. All graphs show the P polarised response decreasing and the S polarisation photoyield increasing, as θ tends to grazing incidence values. Measurements
Figure 6.13: Comparison of the X-ray data obtained from the CsI and Aluminium photocathodes. Crystal RbAP, 1.7 keV X-rays. Filled circles - aluminium photocathode; open circles - CsI photocathode. The two horizontal lines on figure a are the calculated MDM for each photocathode.

made by Lukirskii et al. 1964 on a CsI photocathode using 0.18 and 0.53 keV X-rays are shown for comparison (figures 6.16a and b) with our data. Their data was obtained using X-rays monochromated by a diffraction grating giving radiation of unknown polarisation state. The Lukirskii et al. measurements using 0.18 keV X-rays are in very good agreement with our data (0.17 keV). Their other data set, while having a similar trend, is not in such close agreement with our measurements. Presumably the divergence in the data sets can be accounted for by the difference in the X-ray energies used.

An explanation of the measurements presented above requires that materials have a different response for S and P polarised incident radiation at soft X-ray energies. Fiebelman (1976) has shown that surface optical properties of all materials differ for S and P polarisations. Afanas’ev et al. (1988) have shown that the angular distribution of emitted X-ray photoelectrons is highly dependent on the polarisation state of the incident radiation. They further conclude that a photoelectron can retain its initial polarisation dependent direction if the energy loss of the electron travelling through the crystal is small.

Whether the underlying physics governing the process which accounts for the measurements...
Figure 6.14: Modulation factor as a function of grazing angle θ. Oba et al. private communication. Filled circles: 1500 Å CsI, vacuum evaporated on Ni substrate. Open circles: thermally oxidised Al evaporated on Ni substrate. Crosses: reduced lead oxide glass (PbO).

Presented above is a surface or bulk dominated effect still needs to be determined. Further planned measurements may, however, resolve these questions.
Figure 6.15: Variation of modulation factors versus linear position.
(a) Modulation factor, (b) phase shift, (c) goodness of fit parameter $\sigma$ as a function of steps from RH limit. RbAP crystal, 0.67 keV X-rays, $\theta = 23^\circ$. Mechanical Centre - MC, Optical Centre - OC.

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Figure 6.16: Relative photoyield versus X-ray incident angle.
Filled circles - \( \phi = -90^\circ \) (nominally S), open circles - \( \phi = 0^\circ \) (nominally P), crosses - average 'unpolarised' photoyield. Squares - data from Lukirskii et al. (1964), normalised to our data at 40°. (a) 0.17 keV X-rays, Lukirskii et al. 0.18 keV. (b) 0.65 keV X-rays, Lukirskii et al. 0.53 keV. (c) 1.65 keV X-rays, (d) 2.65 keV X-rays.
6.7.7 UV measurements

Measurement of the modulation factor as a function of UV incidence angle was made using radiation reflected from the RbAP and the Ge crystals for the CsI photocathode only. Figure 6.17 illustrates the photocathode response to the partially-polarised UV radiation. Maximum modulation factors are, for both crystal reflections, ~27%, higher than the maximum value obtained in X-ray measurements. When the correction factor discussed in section 6.4.2 is considered, values of the true modulation factor for fully polarised UV exceed 80% at θ = 10.4°. The UV data has a peak modulation at approximately θ = 20° unlike the X-ray data which varied almost linearly with incident angle in the range of angles considered. Further differences between the UV and X-ray measurements can be seen in the shape of the raw UV data which was found to be more P type modulated. The relationship between the phase shift and incident angle for UV measurements is also markedly different from the X-ray case being more akin to the Al photocathode response.

The close similarity of the two UV data sets, seen in all measurements (figures 6.17a-d, may indicate that the optical constants, at 8 eV, of both crystals are very similar (no optical constants were available for RbAP).

Figure 6.17: Comparison of UV data obtained using the RbAP and Ge crystals.
Filled circles Ge, open circles RbAP. The horizontal line in figure a represents the MDM for both data sets.
Measurements were made of the relative photoyield measured for UV reflected from the Ge crystal; these are illustrated in figure 6.18a. Modulation factors calculated from the relative photoyield data, after correction for the phase shift, are shown in figure 6.18. Good agreement between modulation factor measured using both methods has been obtained for higher angles. The divergence of the modulation factors at small \( \theta \) values can be attributed to the low count rate in the relative photoyield measurements at small grazing angles. The geometric corrections at small angles (\(< 10^\circ\)) are relatively large making the overall error in the modulation measurements larger than those due to the statistical counting error.

![Figure 6.18: UV data as a function of \( \theta \).](image)

(a) Relative photoyield versus X-ray incident angle \( \theta \). (b) Modulation factors calculated from relative photoyields: filled circles - without correction for phase shift; open circles - corrected for phase shift. Crosses - modulation factors from figure 6.17.
6.8 $G_c(\phi, E)$

Measurements were made of the peak gain, $G_c$, as a function of energy for two orthogonal settings of the azimuthal angle, $\phi$. The X-ray incident angle, $\theta$, was held constant at 23° whereas the azimuthal angle was either $\phi = -90^\circ$ (nominally S) or $\phi = 0^\circ$ (nominally P). Gain measurements were made using the four X-ray energies, at the linear position of 5100 steps with a constant CEM voltage of 2000 V.

Figure 6.19 illustrates the variation of peak gain with X-ray energy for the two azimuthal positions. As can be seen the gain measured at $\phi = -90^\circ$ is always greater than for $\phi = 0^\circ$, consistent with the photocathode being more 'sensitive' to S polarised X-rays.

Two coupled factors are responsible for the peaked shape of the gain curve. For CsI photocathodes, Fraser and Pearson (1984) found that the most probable number of emitted secondary electrons increases with energy, over the 0.1 to 3 keV range. These secondary electrons have, however, a decreasing probability of escaping into the vacuum as the mean depth of X-ray absorption increases, since their escape length is only ~215 Å. Therefore as the X-ray energy increases the number of emitted secondaries increases and hence the gain goes up. This continues until the higher energy X-rays start to interact deeper than the electrons' escape length, which then results in a drop in gain. These two effects, when combined, qualitatively explain the resultant peak in the gain curve.

![Figure 6.19: Peak gain as a function of X-ray energy. Opened circles: $\phi = -90^\circ$, Filled circles: $\phi = 0^\circ$.](image)
6.9 A Polarimeter for X-ray Observations

At the time of writing (Jan 1989) an instrument based on the results of the work presented here is being proposed for the ESA X-ray Spectroscopy mission, XMM. This section compares the instrument’s calculated sensitivity with that of a 'standard' graphite crystal/multiwire proportional counter polarimeter (Novick et al. 1988).

The parameter of interest is the Minimum Detectable Polarisation (MDP), as defined previously (equation 6.3). For a photocathode incident angle of $8^\circ$ we have measured in the laboratory (refer to figure 6.16).

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>0.165</th>
<th>0.67</th>
<th>1.65</th>
<th>2.70</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>0.40</td>
<td>0.30</td>
<td>0.20</td>
<td>0.30</td>
</tr>
</tbody>
</table>

As a first approximation, an average value of $M=0.3$ was used for broad band (0.1 - 5.0 keV) MDP calculations.

For a polarimeter in the optical path of a telescope of effective area $A(E)$, preceded by a UV filter of transmission $T(E)$ and observing a source of flux $dN/dE$ counts cm$^{-2}$s$^{-1}$keV$^{-1}$ the source count rate, $s$, in counts s$^{-1}$ is given by

$$s = \int_0^{\infty} A(E)T(E)Q(E) \left(\frac{dN}{dE}\right) dE$$

(6.21)

where $Q$ is the unpolarised quantum detection efficiency of the photocathode. When calculating the MDP it was assumed that the transfer efficiency of the photoelectrons to the MCP detectors and the probability of subsequent detection were both unity.

The value of the background count rate, $b$, will depend on the details of the electron optics and the demagnification factor achieved from the photocathode surface to the focus of the MCP detectors. As an estimation for the background, the image area on the detector was assumed equal to 2.9 cm$^2$ and the background rate per unit area was assumed equivalent in the XMM case to that of the EXOSAT CMA detectors i.e. 1.38 cm$^{-2}$s$^{-1}$. Then $b_{\text{max}} = 4$ counts s$^{-1}$. We know, however that $\sim 60\%$ of the latter figure is attributable to internal radioactivity in the CMA MCPs (Chapter 2). Using the low noise MCPs now under development would give, therefore, a reduction to $b \sim 1.6$ counts s$^{-1}$. Addition of graded shielding will reduce this figure further, as will the opportunity, uniquely in an MCP detector, to use pulse height analysis to reduce particle background (each particle will activate, in general, one channel; X-ray events will be characterised by the prompt arrival of many photoelectrons, each into a different channel). Assuming by these two techniques a background rejection factor of $\sim 90\%$ gives $b_{\text{min}} \sim 0.1$ counts s$^{-1}$. Until a photoemission polarimeter incorporating an imaging detector is actually built, it is not possible, as in gas detectors, to express the background count rate in a spectral form, the values of $b_{\text{max}}$ and $b_{\text{min}}$ were both used in all broad band calculations.
Figure 6.20 illustrates the calculated MDP as a function of source count rate given in milliCrabs (where the count rate from the Crab Nebula is expected to be \( \sim 7140 \text{ counts s}^{-1} \)). The source spectrum used was that of the Crab Nebula with an observing time of \( 1 \times 10^5 \text{ s} \). Also shown is the MDP calculated for the graphite crystal polarimeter as part of the Stellar X-Ray Polarimeter proposed for the Spectrum-X-Gamma Mission (Novick et al. 1988). The X-ray optics of XMM and Spectrum-X-Gamma have similar collecting areas. The photoemission polarimeter is more than an order of magnitude more sensitive and could potentially detect the 19% polarisation of the Crab Nebula in as little as 5 minutes. Similar calculations have been carried out for various X-ray sources and all confirm the potential of the photoemission polarimeter as an stellar X-ray polarisation detector.

The combination of good sensitivity and the ability to detect X-rays over a broad-band (\( \sim 0.1-5 \text{ keV} \)) makes the photoemission polarimeter an unique instrument capable of significantly advancing the understanding of many X-ray generating mechanisms.

![Diagram showing calculated sensitivities (MDP) for the Photoemission Polarimeter proposed for XMM as a function of source count rate for a Crab-like source. The MDP was calculated using: \( b_{\text{min}} \) - solid line and \( b_{\text{max}} \) - dashed line and an observing time of \( 1 \times 10^5 \text{ seconds} \). The dotted line indicates the MDP calculated for the graphite crystal polarimeter (2.6 keV) proposed for the Spectrum-X-Gamma Mission (Novick et al. 1988).]
6.10 Conclusions

The work presented in this chapter has shown that a vectorial effect exists for X-ray and UV photoemission from CsI photocathodes.

X-ray measurements of the relative photoyield as a function of incident angle were shown to be in agreement with data, from an earlier study using CsI, by Lukirskii et al. Our measurements on CsI confirm that the vectorial effect found by Oba et al. also exists for the 0.1 to 3 keV soft X-ray range. The confirmation afforded by the results of these other groups to our own data allow us to conclude that the polarisation sensitive photoemission of CsI is both a real and potentially a very important advance in X-ray diagnostics.

The broad band sensitivity of this effect was shown to be of great benefit when considered for a soft X-ray polarimeter for astronomical observations. Section 6.9 illustrated the advantage of an instrument designed around the polarised response of a CsI photocathode over existing methods used in X-ray polarimetry.

Whether a polarimeter incorporating the vectorial effect can be utilized for ground based X-ray diagnostics is at present unknown.

Measurement of a very pronounced polarisation dependence for the UV photoemission from CsI photocathode, in agreement with Zetner et al. 1984, can also be seen to have a large potential both in astronomical and ground based measurements. Although our present measurements were confined to a narrow UV bandwidth, further study over a broader energy range and on different types of photocathodes should allow the development of an instrument capable of investigating many polarisation dependent mechanisms.

That there are many questions still to be answered about the underlying physical mechanisms of the vectorial effect does not detract from the diagnostic potential its utilization may realise.
Chapter 7

Conclusions and Future Developments

7.1 Conclusions

The work in this thesis has reported various advances in the physical understanding and operational use of microchannel plate X-ray imaging detectors. A new type of soft X-ray polarimeter has been shown to offer a significant improvement over existing polarimeters currently used for soft X-ray astronomical observations.

The results presented in Chapter 2 concluded that two independent mechanisms, radioactivity within the glass and outgassing of the MCPs, could account for the majority of the background noise count rate measured in defect-free plates. Confirmation of our noise model has lead to a joint Leicester University and Philips project to develop a new type of MCP glass, free from radioactive contaminates, which will reduce the MCP dark noise to the level of the cosmic ray background.

Assuming these plates are suitable for photon counting their use in X-ray imaging detectors will result in a significant improvement in instrument sensitivity. As a corollary of our collaboration on the AXAF project, Philips are planning to produce large area MCPs from very low noise glass. If these are successful they will be incorporated into the AXAF HRC, resulting in a significant increase in detector sensitivity. The availability of very low noise plates may find many applications outside the immediate area of astronomy, since MCPs are now widely used in a variety of measuring instruments. One specific application, where very low noise MCPs should allow an increase in instrument response, is their use in accelerator mass spectrometers where the sensitivity is at present limited by the background noise of the microchannel plates (Friedman et al. 1988).

Comparison of CsBr and CsI photocathodes has shown that CsBr displays a significantly higher quantum detection efficiency over the 20 - 100 Å wavelength band. When the detection efficiency of CsBr is considered over the wavelength region (2 to 140 Å) proposed for the AXAF HRC and the low energy transmission grating spectrometer, the analysis of Chapter 3 concludes that CsBr would be a better choice of photocathode material. While other factors, like material stability with time, need to be considered, a strong case for adoption of CsBr as the prime photocathode can be made.

Chapters 4 and 5 have shown that two new types of MCP, the Sandwich plate and the L² plate, have characteristics suitable for photon counting. Both types have properties that mark
them out as improvements over conventional MCPs. Sandwich plates displayed their suitability for the investigation of the gain reduction with increasing output count rate. Their remarkable gain uniformity across the plate surface gives them an obvious advantage over standard chevron and Z stacks. L^2 plates demonstrated that changes in the MCP glass composition can effect the dark noise and gain life-time characteristics of the manufactured MCPs. As a result manufacturers (esp. Philips and Galileo Electro-Optics) are presently trying to produce low noise glass without degrading the other desirable MCP properties.

Measurements were presented for soft X-rays which demonstrated that photoemission from CsI and Al was dependent on the polarisation state of the incident radiation. The photoemission polarimeter reported in this thesis has been shown to be a very sensitive instrument for the measurement of polarised radiation both in the soft X-ray and UV energy ranges. The need for a polarimeter to investigate the astronomically important soft X-ray range (0.1-5 keV) was discussed and comparison of the photoemission polarimeter with the present instruments used in this area of research illustrated the advance in sensitivity possible using detectors designed around this effect.

At the time of writing, an instrument utilizing the vectorial photoemission effect has been proposed by a Leicester University led (Principal Investigator: G.W. Fraser) international consortium for inclusion on the ESA XMM satellite facility.

### 7.2 Future Development

Further research is required in all the areas reported in this thesis, with important advances for X-ray Astronomy expected from continued development of both low noise MCPs and the new field of photoemission polarimetry.

Reduction of the background noise count rates in MCPs to cosmic ray levels has still to be achieved. The most recent measurements reported by Feller et al. (1989) for the latest low noise Galileo MCPs have noise count rates \( \sim 25\% \) lower than measurements previously made on Galileo's first batch of low noise plates (Fraser et al. 1988b). This continuing development can be seen to be pushing the dark noise count rates toward the Cosmic Ray limited level.

Assuming MCPs can be manufactured which have dark noise count rates at the level of the cosmic ray background, plastic scintillators used in coincidence will permit a further reduction of the MCP detector noise. Reduction in detector noise will be significant both for MCPs used in specific imaging configurations, such as for the AXAF HRC and for their eventual use in photoemission polarimeters where a low background count rate increases the detector's sensitivity. At present (February 1989) Leicester University are awaiting the arrival, from Philips, of the first radioactive free MCPs.

Further work needs to be undertaken to determine the relationship between gain decay with increasing count rate and the size of the illuminated area. This effect reported primarily for
sandwich plates has been recently confirmed on a MCP chevron detector (Fraser et al. 1988b). It therefore appears to be a general phenomena which would affect any high count rate detector which incorporates MCPs. Continuation of this work requires the development of a suitably controlled high count rate source and design of various 'masks' to allow the determination of the precise size(s) of the illuminated area on the MCP. The results of such an investigation may affect the calibration of MCPs used in such instruments as high count rate spectrometers.

Another important line of work is the further investigation of X-ray photocathodes primarily for use in the photoemission polarimeter. Various coating parameters (e.g., substrate temperature, coating thickness and coating rate) which affect the structure of the deposited layer will be investigated. This evaluation will be very important in helping to determine the physical process(es) behind the vectorial effect.

Future investigations connected with polarimetry include determining the cause of the phase shifts apparent in the CsI measurements but absent in the Al data, extending the energy range to cover 2-10 keV X-rays and reduction of the background to improve the instruments sensitivity. Instrumental improvements can be made in areas such as the electron collection optics and system alignment which will reduce possible spurious modulation effects. A further improvement entails replacing the CEM with an MCP detector thereby introducing the advantages of being able to image the photocathode area illuminated by the X-ray beam (provided the electron optics allow a good photocathode-to-MCP mapping).

Use of the synchrotron source at Daresbury in collaboration with the Leicester University Condensed Matter Physics group has been planned to utilize the advantages of such a source and overcome the limitations of our present test facility. The main advantages, apart from the beams' known polarisation would the increase in intensity, beam collimation and the availability of wide range of wavelengths, all which would help to increase our understanding of the underlying physics of the vectorial photoemission effect.
Appendix

A.1 Background Noise Review

The aim of this appendix is to review the latest noise results thereby giving a more complete account of the dark noise investigation. Appendix A.2 discusses measurement of the cosmic ray contribution to the dark noise as detected directly by a MCP detector incorporating low noise plates.

Chapter 2 concluded that two main mechanisms could account for observed MCP noise count rates. The first, being noise due to the MCPs outgassing, where it was found that the plates history, with special reference to water vapour and/or oxygen, gave a noise count rate which decayed with time. The radioactive decay of $^{40}$K, ( or $^{87}$Rb ), with the emission of $\beta$ rays, within the MCP glass was confirmed as the second noise mechanism. The noise count rate was shown to be independent of field emission, thermal emission and ion feedback. Cosmic rays were found not to be a major source of noise and would only become significant on the complete removal of the radioactive materials used in MCP glass manufacture.

Recent measurements (Fraser et al. 1988) have been made on MCPs which were manufactured from Galileo's new low noise glass formulation ( $^{40}$K and $^{87}$Rb 'free'). These plates have the same dimensions as the Long Life Plates ($L^2$) of Chapter 5 and were operated as a chevron pair in the same detector body as the $L^2$ plates.

As a part of the noise investigation it was found that the ceramic (Macor) body of the detector was contributing to the overall noise count rate. The reason for the ceramic contributing to the noise lies with the fact that Macor contains ~8.5% by weight of K$_2$O. The beta emission from the decay of $^{40}$K interacts with the MCPs and produces noise counts. The betas from Macor surrounding the MCPs can only penetrate the MCPs outer edges which accounts for the ring of noise reported in the discussion of Sandwich Plates (Chapter 5). Discovery of this 'extra' noise source does not invalidate our previous conclusions. In fact since this noise source contributes predominantly low charge events at the $N_m < 0.1$ cts cm$^{-2}$s$^{-1}$ level its presence improves the agreement between the measured and the calculated noise count rates of Chapter 2.

Before further measurements were made, with the Galileo 'low noise' MCPs, Macor parts were replaced by a low activity plastic PCTFE ($C_2F_3Cl$; trade name Kel-F). Background noise measurements with the 'low noise plates' using the low activity detector body gave a noise count rate of $N(0.05G_e) = 0.070 \pm 0.005$ counts cm$^{-2}$s$^{-1}$. Note that this count rate is an order of magnitude lower than that measured for the $L^2$ plates.

Although this noise count rate value is certainly the lowest recorded for plates of this geometry it is still higher than that expected using the noise model of Fraser et al. (1987a). Various mechanisms were investigated to account for this discrepancy (eg. Cosmic rays, outgassing etc.).
All these were eventually discounted (Fraser et al. 1988b), the mystery eventually being resolved when an assay of the MCP glass found both Rubidium and Potassium contamination. The contamination level easily accounted for the ‘extra’ noise count rate. A second batch of ‘low noise plates’ (L/D = 80:1), with the radioactive contaminates supposedly removed, were tested at Leicester and measurements indicated a background noise count rate of \( N(0) = 0.1 \text{ cts cm}^{-2} \text{s}^{-1} \) (Feller et al. 1989). Now since dark noise count rate scales with front plate thickness (as discussed in Chapter 2), this gives \( N(0.1 \overline{G}_e) \sim 0.05 \text{ cts cm}^{-2} \text{s}^{-1} \) a reduction of \( \sim 25\% \) from that found for the first ‘low noise plates’. However, this is still higher than the expected cosmic ray limited count rate \( \sim 6 \times 10^{-3} \text{ cm}^{-2} \text{s}^{-1} \). Once again contamination of the MCP is suspected and investigations are taking place to find the possible sources.

Table 1 summarizes some of the noise measurements made on the various MCPs which have been tested at Leicester. The lower level discrimination setting, \( d \), is the same \( (0.1 \overline{G}_e) \) for all the noise count rates tabulated.

<table>
<thead>
<tr>
<th>Plate Type</th>
<th>Front MCP</th>
<th>( N(d) ) cts cm(^{-2})s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mullard</td>
<td>80:1</td>
<td>0.30</td>
</tr>
<tr>
<td>Mullard</td>
<td>120:1</td>
<td>0.43</td>
</tr>
<tr>
<td>Sandwich Plate</td>
<td>40:1</td>
<td>0.17</td>
</tr>
<tr>
<td>( L^2 ) Plates</td>
<td>40:1</td>
<td>0.60</td>
</tr>
<tr>
<td>Low Noise Plates (Macor body)</td>
<td>40:1</td>
<td>0.10</td>
</tr>
<tr>
<td>Low Noise Plates (PCTFE body)</td>
<td>40:1</td>
<td>0.062</td>
</tr>
<tr>
<td>Low Noise Plates (second batch)</td>
<td>80:1</td>
<td>0.087</td>
</tr>
</tbody>
</table>

Table 7.1: Comparison of noise count rates for various MCP types.

**A.2 Cosmic Rays**

The high noise count rates of the MCPs used in Chapter 2 prevented a measurement of the cosmic ray contribution to the MCP background as a function of orientation angle. Fraser et al. (1988b) have succeeded in directly measuring this variation using the Low Noise MCPs. Using the notation of Chapter 2 the MCP was rotated from \( \phi = 0^\circ \) to \( 64^\circ \). The difference in the measured noise count rates from cosmic rays for this change in detector angle is

\[
N(0.1 \overline{G}_e) = (3.54 \pm 0.75) \times 10^{-3} \text{ cm}^{-2} \text{s}^{-1}
\]

That the contribution of the cosmic rays to the MCP dark noise could now be measured directly can be seen as a consequence of the lower overall MCP noise count rates of these low noise plates as compared with the MCPs used in Chapter 2. The limiting cosmic ray count rate for MCPs operated at \( \phi = 0 \) is \( \sim 6 \times 10^{-3} \text{ cm}^{-2} \text{s}^{-1} \) (Fraser et al. 1988b) and reduction of the dark noise to this level should be achievable for radioactive free plates.
## Reference Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bull.Acad.Sci.USSR</td>
<td>Bulletin of the Academy of Sciences of the USSR physical series</td>
</tr>
<tr>
<td>Philips Res.Repts.</td>
<td>Philips Research Reports</td>
</tr>
<tr>
<td>Phys.Rev.</td>
<td>Physical Review</td>
</tr>
<tr>
<td>Proc.SPIE</td>
<td>Proceedings of the Society of Photo-optical Instrumentation Engineers</td>
</tr>
<tr>
<td>Space Sci.Rev</td>
<td>Space Science Reviews</td>
</tr>
</tbody>
</table>
References

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(1972) L1.
NAG Ltd. Wilkinson House, Jordan Hill Road, Oxford, United Kingdom, OX2 8DR.
Mission' Private communication.
Quartz and Silice, 8, Rue D'Anjou, 75008 Paris.
763.
An Investigation of Soft X-Ray Imaging and Polarimetry  
John Ernest Lees

Abstract

This thesis includes work on both microchannel plate X-ray detectors and X-ray polarimetry, which although essentially distinct, have a common link through X-ray photocathodes. The source(s) of the background noise count rate in microchannel plates are investigated. Various noise mechanisms assessed include outgassing, cosmic rays, field emission, internal radioactivity, ion feedback and thermal emission. Experimental measurements are compared with calculations from a Monte Carlo model based on the assumption that radioactive decay (by beta emission) of elements within the microchannel plate glass is the major source of dark noise.

The performance of Caesium Bromide as an X-ray photocathode for enhancing the quantum detection efficiency of microchannel plates is reported and compared with that of Caesium Iodide.

A new type of microchannel plate configuration, a Sandwich Plate, consisting of three standard microchannel plates bonded in permanent contact is examined for use as an X-ray photon counting detector. This investigation includes a study of the correlation between gain reduction with increased count rate and the size of the illuminated area.

An evaluation is made of Galileo Long Life (L^2) Microchannel plates operated in pulse counting mode with special emphasis on the stability of the gain as a function of abstracted charge. Further evidence for radioactivity as the major source of background noise is obtained; L^2 plates contain different radioactive isotopes compared to the 'standard' (Mullard) microchannel plate glass.

The design and performance of a new type of polarimeter, a Photoemission Polarimeter, for use in soft X-ray astronomy is presented. The polarimeter utilises the linear polarisation sensitivity in the photoemission from a CsI photocathode.

Possible sources of instrumental modulation are evaluated by comparing experimental measurements with calculations from a Monte Carlo model. The sensitivity of the photoemission polarimeter is compared with X-ray polarimeters presently used in X-ray astronomy.