MICROCHANNEL PLATES IN ASTRONOMY AND PLANETARY SCIENCE

Thesis submitted for the degree of
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by

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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 requirement for a higher degree. The work described herein was conducted solely by the undersigned except for those colleagues and other workers acknowledged in the text.

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27th March 2006
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Abstract

Since their declassification in the late 1960s microchannel plates (MCPs) have been used as detectors for X-ray and extreme ultraviolet (EUV) astronomy, offering a unique sensitivity in the EUV waveband. The post 1990 era, however, has seen a universal, and unexplained, reduction in EUV quantum efficiency (QE). An analysis of microchannel plate glass composition has recorded variations in along channel composition for the first time. These observations may provide insight into the lost QE problem and present a way forward for the development of future EUV missions.

Although originally developed as photon detectors MCPs have more recently been applied as low mass X-ray optics for X-ray astronomy and planetary science, where fluorescent X-rays from planetary surfaces yield information on surface composition. The Mercury Imaging X-ray Spectrometer (MIXS), on the BepiColombo mission to Mercury, will have two instrument channels, both of which use MCP optical elements. The optimisation of the high spatial resolution imaging X-ray optics of MIXS-T is described and the novel MCP collimator geometry for the high throughput MIXS-C channel is introduced for the first time. The performance of both channels at Mercury is predicted.

An in situ investigation into the effects of the International Space Station space environment on MCP optics has led to the serendipitous discovery of nanometre scale dust particles in near Earth space and the realisation of filmed MCPs as extremely sensitive cosmic dust detectors. Analysis of the exposed samples and evaluation of the discovery are presented and possibilities for future dedicated experiments are explored.

Microchannel plates continue to be an important technology in astronomy and planetary science. This thesis describes developments in traditional MCP applications and the introduction of new ones, all of which will lead to unique measurement capabilities and significant scientific advancements.
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LIST OF PUBLICATIONS

Some of the results reported in this thesis and other results obtained by the author during the preparation of this thesis have been incorporated into the following publications. The chapter to which a paper relates is indicated in parenthesis.


2. J.D. Carpenter, G.W. Fraser and T.J. Stevenson, Nanometre scale dust detection on the ISS using thin aluminium film, *Proceedings of the fourth European Conference on Space Debris*, at the European Space Operations Centre, Darmstadt, Germany, 657-660, 2006. (Chapter 6)

3. J.D. Carpenter, T.J. Stevenson and G.W. Fraser, Damage and contamination to aluminium filmed microchannel plates exposed on the outside of the International Space Station, Submitted to *The Journal of Spacecraft and Rockets*, 43, 1, 194-199, 2006. (Chapter 6)


5. J. D. Carpenter, T. J. Stevenson, G. W. Fraser and A. Kearsley, Nanometre scale films as dust detectors, *proceeding of The Workshop on Dust in Planetary Systems*, Kauai, Hawaii, 26th – 30th September, accepted February 2006 (Chapter 6)

6. Various technical reports for the Mercury Imaging X-ray Spectrometer consortium (Chapters 3-5).
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CHAPTER 1

Microchannel Plates in Astronomy and Planetary Science

1.1 Introduction

Microchannel plates are descended from the continuous dynode electron multiplier, which was developed independently, in the 1960s, by the Metallurgical Institute of the Academy of Sciences in the former Soviet Union (Oschepkov et al., 1960), the Benedix Corporation in the United States (Goodrich and Wiley, 1962) and Mullard research laboratories in the United Kingdom. Arrays of microscopic multipliers could, it was realised, be used as position sensitive and photon counting detectors and microchannel plates (MCPs) were conceived. The early development of these detectors was for military use in “night vision” applications (Schagen, 1971) and MCPs became a classified technology.

Since declassification in the late 1960s (Ruggieri, 1972) microchannel plates have become invaluable as photon and particle detectors for the scientific community. In X-ray astronomy, MCP detectors have been used extensively in instrumentation such as the High Resolution Imager on Einstein, the first dedicated X-ray observatory (Giacconi, et al., 1979), and the High Resolution Camera on the Chandra X-ray observatory launched in 1999. Other missions with MCP based instrumentation include Exosat, Rosat, EUVE, and HST.

More recently MCPs have become the basis for low mass, grazing incidence X-ray/UV optics, ideal for applications in space based astronomy and planetary science (Martin, 1999). The Lobster-ISS X-ray telescope (Fraser et al., 2002) and Mercury Imaging X-ray Spectrometer (MIXS), on Europe’s BepiColombo mission to Mercury, will be the first space instruments to use MCP optics, and both are intended for operation within the next decade. The development of these optics has led to the serendipitous realisation of MCPs as highly sensitive detectors of interplanetary dust and space debris, with sensitivity to particle diameters almost two orders of magnitude smaller than previously flown detectors.

1.2 Microchannel Plate detectors

Single channel electron multipliers (CEMs), like that shown in Figure 1.1, are tubes made from a resistive material whose secondary electron emission properties have been optimised to provide a large number of low energy secondary electrons following interactions with a primary photoelectron. Ionisation at the
channel entrance excites secondary electrons, which are then accelerated parallel to the channel axis by an electric field. These electrons eventually strike the channel walls where they excite further secondary emission. The number of electrons in the avalanche multiplies exponentially along the channel to produce a detectable pulse at the channel’s end. The channel must be evacuated sufficiently that the mean free path of the electrons is of the same order of magnitude as the flight paths required. Microchannel plate detectors are composed of arrays of $\sim 10^7$ microscopic CEMs (Fraser, 1989).

The signal gain of a CEM is dependent on the channel’s aspect ratio (the ratio of channel’s length $L$ to its diameter $D$) and not its absolute diameter (Adams and Manley, 1966) so it is possible to reduce the channel dimensions, and stack channels together to form arrays with no loss of gain. Such arrays can be coupled with a position sensitive readout to allow imaging.

![Diagram of electron avalanche](image)

**Figure 1.1.** The electron avalanche along a typical channel electron multiplier. Gains of $\sim 10^4$ are typical for a single incident event. The potential difference across the detector is typically 1.5-4 kV.

The first imaging readouts based on arrays of CEMs were produced by stacking together many individual channels into arrays (Wiley and Hendee, 1962 and Somer and Graves, 1969). The requirement for “night vision” (Schagen, 1971), in military applications, eventually led to a new process for manufacturing arrays of microscopic CEMs, by the drawing and etching of lead glass, described in Chapter 2, and the production of the first MCPs.

A typical MCP detector consists of two or three MCPs stacked one above the other in a “doublet” or “triplet” arrangement to provide an increase in gain. The channel axes of both MCPs will normally have a bias angle of between 6° and 13° relative to the normal to the front surface of the plate and microchannels of alternate plates will be orientated in a chevron configuration as shown in Figure 1.2. This chevron arrangement minimises the noise contribution to images due to ion feedback, which occurs when ions, after liberation from the microchannel surface, travel in a direction opposite to the electrons and initiate further avalanches in the MCP. The earliest accounts of two stage multipliers are given by Parkes and Gott (1971) and Colson et al. (1973).
Figure 1.2. A typical stacking configuration for a two stage “doublet” MCP detector with the bias angles arranged in a chevron to prevent ion feedback and reduce image noise.

Despite having some advantages over solid state detectors (e.g. high photon count rates), MCPs have largely been superseded by detectors, such as charge coupled devices (CCDs), as the detectors of choice for astronomy in the X-ray band from ~250 eV to a few tens of keV. This is due largely to the lack of intrinsic energy resolution exhibited by MCPs for which it is inappropriate to assign a representative $\Delta E$ value, though two colour photometry is possible (Fraser, 1989). Solid state detectors have a high intrinsic energy resolution, with a typical $\Delta E$ of ~200 eV but tend to have low quantum efficiencies (QE) in the Extreme Ultraviolet (EUV) waveband, from ~30 eV – 250 eV. In EUV astronomy therefore MCPs remain the detector of choice.

1.2.1 Applications of MCP detectors in the extreme ultra-violet waveband

When used in conjunction with an energy dependent dispersion element such as a diffraction grating or multilayer normal incidence grating (Bannister et. al., 1999) MCPs can be used as highly sensitive spectrometers due to their high spatial resolution. New developments in Vernier readouts for MCPs have enabled their measured spatial resolution to approach the theoretical limit at channel pitch of the MCPs (Lapington et al., 1998). The JPEX sounding rocket experiment (Bannister et al., 1999) used a combination of high resolution progressive geometry Vernier readout, 6µm diameter pore MCPs and multilayer normal incidence gratings to provide unprecedented spectral resolution in the Extreme Ultraviolet ($\lambda/\Delta \lambda=4700$ measured at 235 Å (52.8 eV)).

The quantum efficiency (QE) of MCP detectors in the EUV waveband has typically been measured to be >8% (Kowalski et al., 1986; Hemphill et al., 1997; Jelinsky 1996; Bannister et al, 2000) but recent MCP detectors have been found to have EUV QEs <5%. No notable change in QE is observed for photons with soft X-ray energies >250 eV (Bannister, 2001). This loss of QE has serious consequences for EUV astronomy but the underlying mechanism for this loss of QE is unknown. Chapter 2 describes an investigation into the “along channel” composition of MCPs, using energy dispersive X-ray fluorescence spectroscopy. The results of this investigation indicate a possible mechanism for the loss of QE and a way forwards in restoring their EUV performance.
1.3 Microchannel plate optics

The interaction of X-rays with matter is governed by the complex refractive index $n$, defined as

$$n = 1 - \delta - i\beta,$$

(1.1)

where $\delta$ and $\beta$ are called the refractive index decrement and absorption index, whose origins are described in Chapter 5. The real part of the refractive index is typically very close to unity and so the refraction angles between media are very small. Conventional refractive lenses would therefore require very long focal lengths in order to focus X-rays. X-rays are also heavily attenuated during transmission through a lens material and resultantly almost all flux is lost. For this reason refractive optics are impractical for applications to X-rays and so reflection is the preferred means of X-ray focussing. Normal incidence reflectivities however are very low for X-rays and thus grazing incidence reflection is used in most X-ray optical systems such as microscopes and telescopes (Underwood, 1978; Willingale, 1984).

Conventionally, grazing incidence X-ray optics have been made from highly polished metallic mirrors, which are generally used in one of two optical geometries. The first of these was originally conceived by Kirkpatrick and Baez (1948) but was first proposed as a suitable optical system for X-rays by Schmidt (1975). This optical system is illustrated in Figure 1.3. Angel (1979) later derived an optical geometry, inspired by the eye of the squat lobster, in which separate, flat, orthogonal planes, used to approximate the Kirkpatrick-Baez lens geometry could be brought together in the form of a single, small, square channel. An array of these square channels could then be used as a telescope, and if the axes of these channels were normal to the surface of a sphere of radius $R$ then a telescope with a maximum theoretical field of view of $4\pi$ sr could be constructed. This optical arrangement has come to be known as the Lobster’s eye optic and is illustrated in one plane in Figure 1.4. The focal plane of a lobster’s eye optic is the surface of a sphere with centre of curvature coincident with that of the optic, but with a radius of curvature of $R/2$. MCPs with square microchannels and which have been slumped into sections of a sphere of radius $R$ can be used to provide this lobster’s eye geometry. Images produced by an MCP lobster’s eye lens were first reported by Fraser et al. (1993).

Unlike a true Kirkpatrick-Baez system, the reflecting surfaces of the microchannels are not ellipsoidal but flat. The channels are short enough, however, that the resultant broadening of the focus is small. It has been by shown by Chapman et al., (1991) that a lens employing channels of length $L$ will produce a depth of focus equal to $2L$. 
A slumped MCP optic in a lobster’s eye configuration obeys the lens equation (Chapman et al., 1991),

\[
\frac{2}{R} = \frac{1}{L_I} + \frac{1}{L_S},
\]

where \(L_I\) is the distance from the optic to the focus and \(L_S\) is the distance from the optic to the X-ray source.

To date all X-ray telescopes have used a reflection geometry based on coaxial, confocal sections in optical arrangements first proposed by Wolter (1952a and 1952b). In the most frequently employed geometry (type I of three proposed by Wolter) X-rays are focussed by successive reflections from the inside surfaces of first a paraboloid of rotation and then a hyperboloid of rotation illustrated in Figure 1.5. Wolter type I optical systems for space applications were first demonstrated during sounding rocket
flights in 1977 (Rappaport et al., 1979) and have since been employed by X-ray observatories including Exosat, Einstein, Rosat, ASCA, XMM-Newton and Chandra. To obtain high effective areas the optics are comprised of multiple macroscopic mirror shells, which in the majority of cases are highly polished, metal coated, metal or ceramic structures nested concentrically. These mirror modules are expensive to fabricate and have large masses. Foil mirrors have been employed on observatories such as ASCA, in a conical approximation to the Wolter Geometry.

A single conic section at grazing incidence has a very small effective area and so concentric shells are used. Such a nested shell Wolter type I optic of the type used on the XMM Newton X-ray observatory is shown in Figure 1.6a. This optic has a diameter of 700 cm and consists of 58 nested mirror shells. Three such optics are employed by XMM-Newton, each with a mass of 425 kg (de Chambure et al., 1999).

MCP optics can also be applied in a conic approximation to a Wolter type I grazing incidence optic by using successive reflections in two square pore, circular packed MCP optics shown in Figure 1.6b (Willingale et al., 1998). The microchannel packing and lens geometry of such an optic is shown in Figure 1.7. The MCPs are slumped and stacked such that concentric rings of microchannels form conic approximations to the true Wolter geometry. Figure 1.6b shows a square pore, radially packed MCP optic. MCP Wolter optics have a narrow field of view and a resolution which is limited by the flat wall approximation to the Wolter geometry. This telescope geometry is examined in detail in Chapter 4. By reducing the separation of the concentric mirror shells to the micrometer scale the number of shells employed can be very large resulting in large effective areas from small geometric areas and small masses. This mass and area saving, coupled with the high available effective areas make MCP Wolter optics ideal for planetary missions.
The development of MCP Wolter optics has been supported by the ESA Technology Research Programme (TRP) since 1996 (ESA internal report, 1995). X-ray imaging in the laboratory with microchannel plate Wolter optics, produced as a result of the ESA TRP, has been reported by Willingale et al. (1998) and the first instrument to use these new optics will be the Mercury Imaging X-ray Spectrometer (MIXS) on the European BepiColombo Mission to Mercury.

A figure of merit $F$ can be defined for an X-ray telescope as the ratio of effective area in cm$^2$ to mass in kg (Fraser, 1997). For a conventional X-ray telescope $F \sim 1-10$, whilst for a lobster’s eye MCP X-ray telescope $F \sim 1000$. For an MCP Wolter optic $F \sim 200$. A typical MCP optic will have a channel diameter of 20µm, so a large number of channels can be packed within a given optic area providing a large collecting/reflecting area whilst maintaining a very low mass. MCP optics, in both optical configurations,
therefore offer a significant mass advantage over conventional X-ray telescopes. This makes such optics ideal for space applications, where high performance is required but mass is at a premium, particularly to planetary science, where conventional X-ray optics have been impractical and prohibitively expensive.

1.3.1 Applications of MCP X-ray optics

The development of MCP optics for X-ray imaging has generated new research possibilities in astronomy and planetary science. Some of these possibilities will be realised in the next decade on missions for which MCP optics are a key technology.

1.3.1.1 All sky observing

The wide field of view and low mass of MCP optics in a lobster’s eye configuration can be used to image the entire sky in X-rays (Fraser et al., 2002). An instrument of this type is being developed to provide all sky X-ray imaging from a Local Vertical Local Horizontal (LVLH) orbital platform such as the International Space Station (ISS) where the same spacecraft faces are always nadir, ram and wake pointing.

Originally intended as an external payload for the European Columbus module of the ISS, Lobster uses six separate modules of MCP optics in a lobster’s eye configuration. Each of these modules has a field of view (FOV) of 27° x 22.5° providing a total instantaneous FOV of 162° x 22.5° (Fraser et al., 2002). As the ISS orbits the Earth every 90 minutes the instrument FOV sweeps out the entire sky. Figure 1.8 shows Lobster in place on the ESA Columbus Module of the ISS. Lobster may eventually form part of the payload for a free flying spacecraft owing to uncertainties in the construction timetable of the ISS, and the availability of other flight opportunities.

![Figure 1.8. The Lobster all sky X-ray monitor, in the centre of the image, as an attached payload on the Columbus module of the ISS.](image-url)
1.3.1.2 Planetary remote sensing

The low mass (~0.5kg) and large collecting area (~100cm²) provided by MCP Wolter optics make them ideal for planetary missions where they can be used to image fluorescent X-ray emission from airless planetary bodies and where mass minimisation is essential. In the inner solar system fluorescent emission from surfaces results from excitation by incident solar coronal X-rays and solar wind particles. Spectroscopy of surface fluorescence from orbiting instruments yields information on the elemental composition of a body’s surface by the identification and quantification of elemental spectral lines. Mercury, the Moon, Comets and Asteroids are all suitable targets for this technique, within the inner solar system (Clarke and Trombka, 1997a) although charge transfer from solar wind particles is the most likely source of emission from comets (Krasnopolsky, 1997). X-ray detection from orbit and elemental mapping was demonstrated at the Moon by Apollo 15 and 16 (Adler et al., 1972a,b,c) and the asteroid 433 Eros (Trombka et al., 2000). Instrumentation is currently in operation at the Moon (Grande et al., 2001) on Smart-1, is in transit to Mercury (Starr et al., 2001) on MESSENGER and was applied to asteroid 1998 SF36 (Itokawa) on Hyabusa (Okada et al., 2000). None of these instruments has an imaging capability and all must instead rely on collimators to limit their field of view. The future application of MCP optics will permit true X-ray imaging of planetary surfaces for the first time and unprecedented (>200m) surface resolution compared with that achieved by collimated instruments (>40km).

The first mission to use MCP optics for planetary remote sensing will be the European Space Agency’s BepiColombo mission to Mercury, whose launch is intended for 2013. BepiColombo’s X-ray spectrometer has been baselined as a two channel instrument, the Mercury Imaging X-ray Spectrometer.
(MIXS), comprising an imaging telescope (MIXS-T); using MCP optics in a Wolter type I configuration, and a novel slumped MCP collimator (MIXS-C). The geometrical design of the MIXS-C collimating geometry channel is described in Chapter 3, and the Wolter type I optical geometry is described in Chapter 4, which goes on to describe the optimisation and performance of the combined MIXS instrument and its predicted performance at Mercury. MIXS-T’s configuration is illustrated in Figure 1.9.

1.4 Dust and debris detection

MCP optics in space will be covered by a thin Al film, to reduce their thermal absorptivity. To investigate effects on the optics of exposure to the external ISS environment, in preparation for Lobster, representative samples of MCP optics, bearing thin Al films were attached to the ISS exterior for two years, retrieved and returned to the University of Leicester for analysis. Analysis of the samples has given insight into the contamination and deterioration of MCP optics in the ISS environment. A study into contamination effects is reported in Carpenter et al. (2006) and is not included in this thesis. In addition, the thin film is highly sensitive to impacts by interplanetary dust and space debris particles and therefore acts as a passive dust detector. Analysis of holes in the exposed films has revealed a new population of nanometre scale dust and debris particles in Low Earth Orbit, which is beyond the detection limit of previous dust and debris experiments. The development of future, optimised, passive experiments and a compact, low mass, active detector based on this nanofilm technology will allow the extension of current particle size distributions by more than an order of magnitude. The analysis of the returned MCP optic witness samples in terms of dust and debris impacts is described in Chapter 5 with a description of an active detector concept based on the thin films but with the addition of an active readout.

1.5 Overview of the thesis

The following chapters describe work carried out by the author towards the degree of PhD in the period September 2002 – June 2005.

Chapter 2 describes an investigation into the along channel surface composition of MCP detectors using energy dispersive X-ray spectroscopy. This investigation reveals structure in the along channel composition of MCP detectors, which may be related to the reduction in MCP quantum efficiency in the extreme ultra violet, which has blighted EUV astronomy in the post 1990 era. In this chapter the experimental design, Scanning Electron Microscope (SEM) operation, and data analysis was all carried out by the author.

Chapter 3 describes the process of X-ray fluorescence from planetary surfaces and the mechanisms for using observations of X-ray fluorescence to determine surface composition. This chapter introduces an equation describing the X-ray flux from a surface as a function of the incident solar spectrum, surface composition and the angles of incidence for X-rays and observation. This is a development on an equation presented by Clark and Trombka (1997). The derivation of an equation to more accurately represent the fundamental parameters was carried out by the author with input from G.W. Fraser.
Chapter 4 describes the design of a novel collimator geometry for application to observations of extended X-ray sources like planetary surfaces. The collimator design has particular relevance to the BepiColombo mission to Mercury for which it has been adopted as a high throughput X-ray channel on the Mercury Imaging X-ray Spectrometer. The collimator uses MCPs in a slumped configuration to provide a high X-ray throughput, which is independent of X-ray energy, whilst having important advantages over the collimator geometries which have been applied previously to planetary remote sensing. The concept, design, definition and modelling of this collimator is the original work of the author.

Chapter 5 describes the optimisation of the collimated MIXS-C and imaging MIXS-T channels for BepiColombo and predicts their performance at Mercury. The MIXS-T MCP optics are modelled using a Monte Carlo raytrace model, originally developed by G.Price and A.Brunton and modified by the author to account for the varying geometries of the instrument and optic coatings. Absorption and quantum efficiency calculations have been carried out by the author. A model of surface fluorescence due to incident solar coronal X-rays is then used to predict the X-ray flux from Mercury. The model has been developed by A. King, P. Warren and A. Brunton and subsequently modified by the author to use the modified fluorescence equation and the various compositional models of Chapter 3. The calculated X-ray fluxes are folded through the predicted effective areas for both instrument channels to quantify and predict the instrument’s performance during the BepiColombo mission. A subsequent comparison of modelled fluorescence from the Moon with real observations by the Chandra X-ray observatory is then presented to demonstrate the validity of the flux model used in the calculations. The modification of the raytrace model, application for MIXS optimisation, modification and application of the fluorescence model, modelling of Chandra observations and modelling of the slumped collimator in the context of MIXS has all been carried out by the author. The derivation of the grasp equations and the technique applied for the calculation of grasp from raytraced effective areas and vignetting curves are also the author’s own work.

Chapter 6 describes an analysis of MCP optics exposed to the space environment on the ISS, initially to assess the effects of the environment on the optics. Impact features in the 60 nm thick films are described and flux values determined for the nanometre sized particles detected by the MCPs during the exposure. This serendipitous method of dust detection has unprecedented sensitivity and offers a means of extending the range of dust measurements in the solar system by more than an order of magnitude. Preliminary work towards the development of an active dust detector, which is based on the thin film technology, is then described. All post-flight analysis of the samples including Field Electron Gun (FEG) SEM imaging (compositional and residue analyses have been carried out with support and facilities of Anton Kearsley and the Natural History Museum, London), data analysis, flux modelling, realisation of filmed MCPs as dust detectors and development of the active detector concept in this chapter have been carried out by the author.
In the final chapter conclusions are drawn from the work described in the thesis and possibilities for MCP technology in astronomy and planetary science in the near and more distant future is discussed.
CHAPTER 2

Compositional Analysis of Microchannel Plates Using Energy Dispersive X-ray Fluorescence Spectroscopy

2.1 Introduction

Recent MCP detectors have been found to have disappointing quantum efficiency (QE) (~1-5% (Bannister, 2001)) at Extreme UltraViolet (EUV) wavelengths between 100 and 1000 Å (120-12eV) compared to plates from the pre 1990 Extreme Ultra-Violet Explorer (EUVE) and Rosat Wide Field Camera era (~8-20% (Kowalski et al., 1986; Hemphill et al., 1997; Jelinsky et al., 1996; Bannister et al., 2000)). The cause of this, apparently global and manufacturer independent, (Jelinsky et al., 1996 Siegmund et al., 1996) change in efficiency is presently unknown, but is most likely to be due to changes in the surface chemistry of the processed MCPs.

Photons entering a microchannel interact with the glass of the channel wall via the photoelectric effect. The resulting photoelectron and/or Auger electron (electrons stimulated by a fluorescent X-ray released from an inner shell following photoionisation) may escape into the microchannel accompanied by the ejection of one or more secondary electrons. The mean energy required to excite one secondary photoelectron in MCP glass is 10 eV and the escape length in MCP glass is just 33 Å (Fraser 1983). The most probable number of electrons to escape into a microchannel is always one, regardless of photon energy (Fraser and Pearson, 1984), and as a result MCPs have very little intrinsic energy resolution in the soft X-ray band.

![Diagram of Photon at normal incidence to the front surface of an MCP with channel bias angle \( \theta \).](image)

Figure 2.1. Photon at normal incidence to the front surface of an MCP with channel bias angle \( \theta \).

The soft X-ray QE of MCPs is examined theoretically by Fraser (1982) and experimentally by Pearson (1984). For energies of less than ~8 keV interactions between photons and the MCP glass typically occur within a few µm of the channel surface, dependent on grazing angle. For EUV photons incident normally
on an MCP detector with a bias angle $\theta$, shown in Figure 2.1, the characteristic interaction depth beneath the surface has an upper limit at

$$d_i = \mu^{-1} \sin(\theta),$$

(2.1)

where $\mu$ is the linear absorption coefficient derived from the complex refractive index and described in Chapter 5. For a typical MCP bias angle of 5° the interaction depth ~70 Å for 100 eV photons.

**Figure 2.2.** Secondary electron yield as a function of primary electron energy for normal incidence on to MCP glass, from Hill (1973).

In general, for soft X-rays and EUV photons, QE decreases with increasing energy because the photon absorption depth increases and the probability of electrons escaping is reduced (Fraser, 1989). Figure 2.2 shows the secondary electron yield from MCP glass as a function of primary electron energy for normal electron incidence from Hill (1976). As photon energy is increased there is a decreased probability that an electron avalanche will result from an initial photon strike. A first order approximation is to assume that the outcome of the avalanche is wholly determined by the first collision of the photoelectron batch with the channel walls (Smith and Pounds, 1968). An additional effect for EUV photons is an increased probability of reflection from the microchannel surface at grazing incidence compared with X-rays. Figure 2.3 shows reflectivity as a function of grazing angle from silica (as an approximation to MCP glass) for 50 eV, 100 eV and 500 eV photons. The increased probability of reflection upon first strike with the channel walls, for EUV photons, may result in electron liberation occurring further along the microchannel’s length.

Some possible explanations for the reduced QE at EUV energies and not for soft X-rays are as follows:

- The quantum efficiency reduction has occurred following a change in bulk MCP glass composition. Different MCP manufacturers, however, use different MCP glass compositions but have experienced similar losses of QE and so this mechanism seems unlikely.
- Some change in the MCP manufacturing process has resulted in a compositional change at very shallow depths into the glass surface, where EUV photons are likely to interact. This change has
resulted in decreased secondary electron yield at these depths. X-rays by virtue of their increased energy, relative to EUV photons, will interact at greater depths and are therefore largely unaffected.

- By virtue of the increased reflection probability at grazing incidence, compared with X-rays, EUV photons interact further along the microchannel following an initial reflection. A change in the along channel elemental composition may then result in a reduced QE at these energies.

![Figure 2.3](#) 

*Figure 2.3. Reflectivity as a function of grazing angle from silica for 50 eV, 100 eV and 500 eV photons calculated for a semi infinite surface by the X-ray reflectivity calculator (http://www-cxro.lbl.gov/optical_constants/).* 

An investigation has been carried out into the composition of microchannels in a number of “high efficiency” and “low efficiency” MCPs. A Philips XL30 scanning electron microscope (SEM), in the Engineering Department at the University of Leicester, was used to provide X-ray fluorescence spectra and hence elemental compositions. These spectra were recorded with an Oxford ISIS 310 Si(Li) light-element analysis detector. Variations in the X-ray spectra as a function of channel length from both sets of MCPs are described in this Chapter and may provide insight into the nature of the “lost efficiency” problem.

### 2.2 MCP Manufacture and Electron Emission

MCP manufacture is a complex process and the resultant glass chemistry is not perfectly understood. Any observed differences in the composition of glass from MCPs with good and poor QE will have implications for manufacturing processes. There follows a summary of the manufacturing process based on a Mullard (now Photonis SAS, Brive) internal report by *Smith (1994)*, and previous observations of MCP glass composition.

Microchannel plates are made from a cladding glass type developed to provide a specific conductivity and secondary electron emission coefficient. The main stages of manufacture of MCPs from this glass in a
‘two draw’ process are shown in Figure 2.4. Initially a cylinder of cladding glass and a core made from acid soluble core glass are manufactured, such that the soluble core fits closely into the cladding tube. This core prevents collapse and distortion of the channels during the later fusion stages. The core and cladding glasses must have compatible thermal expansion and viscosity coefficients, and diffusion (mixing of the two glass types at their interface) must be minimised.

Once assembled this billet, approximately 35 mm in diameter, is slowly drawn vertically through an oven. The cladding collapses onto the core and the diameter of the composite fibre is reduced to around 0.8mm. The oven temperature is closely controlled and air turbulence is avoided.

The emerging fibre is then cut into lengths, which are stacked into a hexagonal mould. The mould is heated, causing the fibres to fuse into a single hexagonal array, which is drawn for a second time. This produces a hexagonal multifibre, approximately 0.85 mm in diameter, with channels containing the acid soluble glass, between 3.2 and 25 µm in diameter, depending upon the MCP requirement.

![Figure 2.4. Processes in microchannel plate manufacture (courtesy Photonis SAS, Brive)](image)

A number of multifibre lengths are then stacked into a hexagonal glass capsule and fused under vacuum so that the cladding glass flows to fill the small spaces between the fibres. This results in a single solid
glass composite boule, which is sliced either perpendicular to the channels or at an angle to introduce a bias to the channels.

The slices are then ground to the required size and shape, polished and acid etchant is used to remove the soluble glass cores. In the case of MCP detectors (but not MCP optics) the remaining glass plates are then baked in a hydrogen atmosphere at around 633 K to reduce the surface and produce a resistive layer with the required secondary emission characteristics. For MCP detectors, metallic electrodes (usually nichrome, Ni$_7$Cr$_3$Fe$_3$) are vacuum deposited on to the polished faces of the plates where they act as electrodes, connecting all of the channels in parallel.

For large MCPs (>46 mm diameter) a ram-fusion technique is employed. Here, multifibres are stacked and a mould is placed on an anvil in an oven and a close fitting top plate is inserted. At the required temperature the ram is used to put the multifibres under pressure and fuse them together.

The surface chemistry of microchannel plates is highly dependent on the etching and hydrogen baking processes (Hill, 1973; Siddiqui, 1977; Then and Pantano, 1990). Since the surface chemistry governs the electron emission characteristics of the microchannel it is possible that a subtle change in this process has occurred, changing the surface chemistry of MCPs and causing a reduction in QE at EUV energies.

### 2.2.1 MCP glass and secondary electron yield

The bulk composition of microchannel plate glass can be described by the pseudo molecule Si$_{30}$O$_{82}$Na$_5$K$_7$BiPb$_5$ (calculated using percentage by mass data for Phillips 3502 glass from Fraser, 1982) with a low abundance of Ba. The addition of lead, bismuth, sodium and potassium to silicate glass provides the required conduction and secondary electron emission (SEE) properties, of particular interest here. QE is dependent on the secondary electron yield (SEY) (Smith and Pounds, 1968), which is dependent on the work function and inelastic mean free path of electrons in the glass (Then and Pantano, 1990), which are in turn dependent on the glass’s composition. Secondary electron emission (SEE) only occurs from a region extending to depths of 10s to 100s of Angstroms and is therefore highly dependent on the surface composition and not that of the bulk glass.

Previous workers have shown that, after etching and reduction in hydrogen, the composition of MCP glass at shallow depths can depart considerably from the bulk formula (Then and Pantano, 1990; Hill, 1976; Siddiqui, 1977). At depths extending to a maximum of ~5 µm there is a semi-conducting medium in which reduction of PbO during hydrogen baking produces Pb metal within the glass. Above this region is a layer in which Pb is depleted. In glass containing K this only appears after both etching and then hydrogen baking. In glasses containing Cs, instead of K, hydrogen baking alone appears sufficient to produce this layer (Then and Pantano, 1990). The Pb depleted region has been found to extend to depths of 100 Å – 200 Å in MCP detector glass (Siddiqui, 1977). The reflectivity of MCP optics has been found to fit a model of X-ray reflectivity in which the MCP glass was modelled as a layer of silica 350 Å – 400
Å thick on a substrate with a standard MCP composition. Finally a surface region, still depleted of Pb and extending to around 10 nm, is rich in alkali species, in particular potassium. These are drawn from 20 nm-50 nm below, where they are found to be depleted. Figure 2.5 shows the different compositional layers in MCP glass.

Alkali metals are added to the glass in order to give it the required softening and annealing temperatures. Their abundant presence at the surface, however, particularly for K, will have a strong influence on the electron yield. K is an electropositive metal, which is readily ionised to form a dipole at the surface, reducing the potential barrier across the surface and resulting in an increased escape probability and higher SEY (Hill, 1973).

Also observed at the surface (to a depth of 0.2 – 0.5 µm) is hydrogen, which enters the glass during the reduction process and whose presence at the surface has been shown to increase SEY (Then and Pantano, 1990). Other contaminants detected at the surface include C, S, and Ca (Hill, 1973). Any Ca, Ba and Al detected in the MCPs will have originated in the core glass and migrated into the MCP (Fairbend, 2005).

The composition and structure described here has been deduced by previous workers from analysis of bulk microchannel plate glass samples using ion-scattering spectroscopy (ISS), secondary ion mass spectroscopy (SIMS) and Auger electron spectroscopy (AES). The samples analysed, however, were not MCPs but bars cut from the bulk glass and subsequently processed chemically in the same way as an MCP. The structures in composition observed in these glass bars may differ from those of actual MCPs, as a consequence of processes, not directly related to the chemistry of chemical etching or hydrogen reduction, but to the geometry of the microchannels themselves. For example a fluid, such as an etchant or hydrogen gas, flowing through a microchannel will have values of velocity, temperature and density which vary along the channel length and are functions of the scale and geometry of the microchannel and

---

**Figure 2.5. Diagram of the different layers in etched and reduced MCP detector glass.**
the initial properties of the flow as it enters (Agarwai et al. 2001; Roy et al., 2003). Rates of reaction can therefore vary along a microchannel’s length and produce a surface composition which varies along the channel length. Subsequently the SEE characteristics will also vary along the channel length.

The distinct compositional layers described occur through a combination of etching and reduction in hydrogen. If any change in surface composition can be correlated with the QE change then this may indicate that modifications to either the etching or reduction processes are responsible for that change. A programme to regain EUV sensitivity in MCPs could then be undertaken. Comparison of new compositional data from MCP microchannels, with that of previous workers, from MCP glass, may also reveal compositional changes resulting from the MCP geometry.

2.3 Energy dispersive X-ray spectroscopy of cleaved MCP fragments

2.3.1 Measurement of elemental abundance ratio profiles

Fragments of MCP detectors i-v in Table 2.1 were cleaved, by scoring and cracking, to expose their microchannels. Plates iii-v are considered “high efficiency” (>=8 %), plates i and ii, “low efficiency” (<8 %) at incident angles of less than 25° to the channel axis at a wavelength of 584 Å.

<table>
<thead>
<tr>
<th>MCP</th>
<th>year of manufacture</th>
<th>Pore diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i)AXAF FH003-5</td>
<td>1990</td>
<td>12.5</td>
</tr>
<tr>
<td>ii)JPEX DH001-D-1</td>
<td>1998</td>
<td>6</td>
</tr>
<tr>
<td>iii)WFC 344-3</td>
<td>~1985</td>
<td>12.5</td>
</tr>
<tr>
<td>iv)AB414-1</td>
<td>1981/2</td>
<td>12.5</td>
</tr>
<tr>
<td>v)277D-2</td>
<td>~1980</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2.1. Format, manufacturer and date of manufacture of the MCPs studied. All MCPs were manufactured by Photonis, SAS (formally Mullard) and have aspect ratio of 120:1.

Energy Dispersive fluorescent X-ray (EDX) spectra were obtained from ten points along the lengths of microchannels of each fragment using a 15 kV electron beam accelerating voltage. For some microchannels, debris from the cleaving process prevented data from being taken at the very ends of the microchannels and the number of data points along the channel was reduced. The electron spot size is much smaller than the channel diameter in each case but the precise diameter is not known. The SEM electron beam spot is typically several nanometres in diameter.
X-ray spectra were recorded in two configurations for each MCP. In the original Configuration 1 the long axes of the microchannels are orientated at approximately 45° to the detector in the x-z plane shown in Figure 2.6a. This Configuration was better suited to the measurement of distances along the channel lengths with the SEM software as the microchannel long and perpendicular axes ran parallel to the SEM’s default stage axes. In this configuration however it was noted that count rates were generally low and could vary significantly at different locations. The low fluxes were believed to result from occultation by the channel wall of the line of sight from the spot under analysis to the detector. Variability in the count rates was taken to be the result of variations in the height of the channel wall along a channel’s length. Figure 2.7 shows a SEM image of a section of cleaved microchannel plate. No data were taken where excessive occultation by the wall was likely. To account for any affect this geometry may have had on the detected fluxes, data were later taken in Configuration 2, in which the microchannels were aligned with the detector in the in the x-z plane, as shown in Figure 2.6b.
X-ray emission lines were identified and the number of events under each elemental peak estimated. To a good approximation the line intensity is proportional to the product of the fluorescent yield and the elemental concentration. Thus, dividing the counts under a peak by the fluorescence yield for the given element gives a measure of the element’s concentration.

SiO$_2$ forms the glass structure; it was assumed that the absolute Si abundance everywhere in the glass was constant. For this reason, the number of counts for each elemental line is expressed as a fraction of the number of counts in the Si peak at the same location and then scaled to a peak value of one. This normalisation process allows for comparison of different spectra, removing any variations in the number of counts resulting directly from changes to the measurement geometry. This has been the approach traditionally used to remove geometrical effects from X-ray fluorescence (XRF) observations of planetary surfaces (Clark and Trombka, 1997a), where, as with MCP glass here, elemental abundances are expressed after normalisation to Si.

The elements expected in the MCP glass are: O, Na, Si, Al, K, Ca, Ba, Bi and Pb, with Ni, Fe and Cr expected from the electrode material. Normalised relative abundances of the elements to silicon, taken along the microchannels were then combined to produce along channel abundance profiles for MCPs with both “good” and “poor” QE at EUV energies.
2.4 Relative abundance profiles

![Figure 2.8](image)

**Figure 2.8.** A representative spectrum taken from inside the entrance of an MCP i (Table 2.1) microchannel, uncorrected for fluorescent yield. Electron beam accelerating voltage was 15 kV and integration time was 100 s. See Chapter 3 for details on X-ray nomenclature.

The main lines observed were the K-shell emission lines of oxygen, sodium, aluminium, silicon, calcium and potassium as well as the L shell lines from barium and the M-shell emission from lead and bismuth. In some spectra, traces of carbon were observed, which was assumed to be a contaminant (Hill, 1973).

Figure 2.8 shows a representative spectrum from the entrance to MCP i. The integration time for each spectrum was 100 s.

In Configuration 1 each MCP displayed apparently periodic variations in the abundance of elements along microchannels. Figure 2.9 shows the Configuration 1 along channel profiles relative to Si-K for Na-K, O-K, K-K and Pb-M for MCP iii. In Configuration 2 count rates were observed to be generally higher and far more consistent as functions of position along a microchannel. The structure and periodicity in the along channel elemental profiles produced in Configuration 1 were found to be reduced or absent in the profiles produced in Configuration 2. Figure 2.10 shows the along channel profiles produced in Configuration 2 for MCP iii.

Where elemental profiles have been taken with Configuration 1 some elements can be separated into groups, whose profiles show similar structure. Na and O form a pair, both of which have K-line X-ray lines with energies lower than Si-K and which share almost identical profile shapes. Another pair, K and Pb, whose K-line (and M-line for Pb and Bi) energies are greater than Si-K and which also share profiles with similar shapes but with opposing phase to those of Na and O. This pairing applies to all the MCPs examined, although there is variation in the profile shape. The profile of Al also varies as a function of microchannel length but in a manner inconsistent with the other elements. The Al-K line is believed to be dominated by Al in the SEM structure and not by Al in the MCP glass and is therefore an artefact. Ba is present only in small quantities; introducing large uncertainties in the relative abundances measured, and
is not shown. In Configuration 2 variations in the along channel profiles of Pb and O remain small while for the highly mobile Na and K surface species the along channel abundance is more variable, but reduced from that observed in Configuration 1.

Figure 2.9. Along channel profiles for MCP (iii) in Configuration 1.

Figure 2.10. Along channel elemental profiles for MCP(iii) in Configuration 2.

2.5 Occultation and relative abundance

The large scale structure observed in along channel elemental profiles was only observed where microchannel walls were orientated so as to provide some obstruction in the line of sight between the detector and the spot under examination. This configuration also led to a general reduction in X-ray count
rate. Normalising to silicon should remove any geometrical effects resulting from this occultation and result in profiles whose shapes match those taken in Configuration 2, but this was not found to be the case, suggesting that there is some energy dependency to the flux reduction following occultation. This is supported by the groupings of the low energy O and Na profiles and the higher energy Pb and K profiles, which appear out of phase with each other in Configuration 1.

![Figure 2.11. SEM Secondary Electron image of the spot on MCP iii at which spectra were taken with various angles of orientation towards the detector. Surface charging has resulted from the repeated exposure to the electron beam. This can be seen as a bright spot indicating surface charging around the location from which spectra were taken.](image)

To quantify the effect of obstruction of line of sight on spectra from the same position, spectra were accumulated from a single location along an MCP iii microchannel as the fragment was rotated through 180° in 13 increments. By doing this, occultation by the microchannel wall was varied between its minimum (microchannels orientated towards the detector in x-z) and its maximum (microchannels orientated perpendicular to the detector in x-z). The walls are expected to be ~ 12.5 µm in height (half the channel diameter). The position of the examination spot was the same in each case at the very centre of the microchannel as viewed from above with the SEM’s secondary electron imager. Surface charging around the spot under observation became evident in secondary electron images after repeated exposure to the 15 keV electron beam and is visible after completion of the measurements in Figure 2.11 as a bright area. Charging may have affected the local composition of the MCP glass and particularly the abundances
of the highly mobile Na and K atoms.

**Figure 2.12.** The geometry of the MCP channels in the SEM.

The geometry of a measurement in both x-z and y-z planes is shown in Fig 2.12 for the case where the microchannel’s axis subtends an angle $\theta$ in the x-z plane and an angle $\Phi$ in the y-z plane to the line connecting the examination spot and X-ray detector. If a microchannel has a diameter $2r$, the cleaved walls of a microchannel have a height $r$ and the centre of the examination spot is the origin ($x=0$, $y=0$, $z=0$) then a line defining the summit of the channel wall can be described by the equations

$$x = r$$
$$y = r$$

and the line connecting the X-ray detector and examination spot is defined by the equations

$$y = z \tan \Phi$$
$$x = z \tan \theta$$

The point P at which the line of sight from the detector to the spot grazes the channel wall (i.e. line of sight becomes unobscured by the wall) occurs at

$$\theta = \Phi$$

For this experiment the region in which the line of sight is unobscured, and for which X-ray fluxes will be large compared with the fluxes at other angles, will have a full width half maximum equal to $2\Phi$.

### 2.6 Line intensities with varying occultation

Figure 2.13 shows the variation in counts for the principal elements observed, during 100 s integrations, as a function of angle as MCP (iii) was rotated through 180°. The number of counts has been scaled to a peak value of one for each element and not normalised to silicon. A low number of counts were observed for the Na-K line which resulted in large uncertainties and so values for Na-K have not been shown here.
Figure 2.13. Counts scaled to a peak value of one for certain observed X-ray lines as a function of orientation with respect to the X-ray detector in the SEM. Also shown are the normalised abundance ratios of O/Si and Pb/Si as a function of orientation.

The general effect of the occultation is to produce minima in the X-ray flux which rises sharply to a peak as the channel walls are orientated towards the detector as described in Section 2.5. The FWHM of the peaked region is 45° corresponding to a line of sight grazing angle of 22.5°. The individual responses of the elemental lines differ. With no occultation the normalised intensity of all the observed lines approaches 1. The K-K intensity can be seen to fall off more rapidly beyond this than other lines. This may result from the retreat of K from the surface in reaction to the build up of charge following repeated electron bombardment. A similar effect may explain the low count rates for Na.

In the region of occultation the lines diverge. While the higher X-ray energy Si-K, Pb-M, and K-K X-ray lines are grouped closely together, the lower energy O-K line maintains a slightly higher relative intensity. Figure 2.13 also shows the normalised ratios of O/Si and Pb/Si. The O/Si ratio shows a general increase in value in the region of occultation with a decrease in value where occultation is completely removed. In contrast occultation has no clear effect on the Pb/Si ratio.

2.7 Origins of the along channel profiles

The X-rays detected after emission from the surface spot under analysis provide information on the glass composition at the depth at which they were generated. The probability that a detected X-ray originated at a given depth is a function of the energy lost by the electron beam and the escape probability of the X-rays from that depth.
The empirical continuous slowing down approximation (CSDA) (Burke et al., 1977) for electron ranges in materials can be used to calculate the range of electrons in MCP glass. The CSDA range \( R_s \) in g cm\(^{-2}\) is given by

\[
R_s = k(E + b)^n,
\]  

(2.5)

where \( E \) is electron energy in keV,

\[
n = 1.715 - 1.698 \times 10^{-3} Z,
\]  

(2.6)

where \( Z \) is the atomic number of the surface into which electrons are penetrating,

\[
b = 0.6868 - \frac{0.7121}{\rho}(2.659 \times 10^{-2} Z + 1),
\]  

(2.7)

where \( \rho \) is the material density in g cm\(^{-3}\) and

\[
k = \frac{R_{s,10}}{(E + b)^n},
\]  

(2.8)

where \( E \) is the electron energy in keV and \( R_{s,10} \) is the electron range for 10 keV electrons in the material in units of g cm\(^{-2}\) (which are used here by convention) given by,

\[
R_{s,10} = 6.824 \times 10^{-6} Z + 2.566 \times 10^{-4}
\]  

(2.9)

Assuming a uniform composition described by the pseudo molecule in Section 2.2.1, which has a mean \( Z \) of 13.95, a CSDA range of 2.1 \( \mu \)m is calculated for 15 keV electrons. X-rays must therefore originate less than 2.1 \( \mu \)m from the surface. An integrated flux of X-rays generated at all depths between 0 and 2.1 \( \mu \)m will be observed at the detector. The X-ray flux contribution from a given depth is a function of the X-ray escape probability at that depth.

Beer’s law gives the intensity of X-rays \( I \) at a given distance \( x \) in a material as

\[
I = I_0 e^{-\mu x},
\]  

(2.10)

where \( I_0 \) is the intensity of X-rays before attenuation by the material and \( \mu \) is the linear absorption coefficient calculated from the tabulated values of Cromer and Lieberman (1970), to be 2811 cm\(^{-1}\) for K-K X-rays in MCP glass and 25061 cm\(^{-1}\) for O-K X-rays. The probability \( P \) of an X-ray escaping from a depth \( x \) in a material is given by

\[
P = e^{-\mu x}.
\]  

(2.11)

The X-ray escape probability for K-K X-rays from a depth of 2.1 \( \mu \)m is calculated to be 0.55. Consequently a contribution to the observed K-K flux will be from the bulk glass. The majority of secondary electron yield occurs <10 nm from the surface (Then and Pantano, 1990) but this region is too shallow to be isolated by this EDXS technique. An electron beam with energy <2.3 keV would have a penetration depth appropriate to this important region but would not provide fluorescence from most of the elements of interest.
Measurements of Pb-K and K-K X-rays are therefore dominated by fluorescence from the bulk glass but for O-K and Na-K X-rays this is not the case. Figure 2.14 shows the X-ray escape probability curves of K-K and O-K X-rays from MCP glass. Measurements of the O-K and Na-K X-ray flux will be dominated by emission from close to the surface. Changes observed in the O-K and Na-K lines may indicate a wider compositional change including elements for which the X-ray flux is dominated by emission from the bulk glass and for which small changes at the surface will not be observed.

![Graph showing escape probability with depth for O-K and K-K X-rays in MCP glass calculated with Equation 2.11 for an MCP glass composition given in Section 2.1.1.](image)

Figure 2.14. Escape probability with depth for O-K and K-K X-rays in MCP glass calculated with Equation 2.11 for an MCP glass composition given in Section 2.1.1.

The profiles may be a result of a change in composition of one of the layers in the MCP glass near to the surface or may be the result of changes to the thickness of the individual layers as a function of along channel position. To determine a probable mechanism for the generation of the observed profiles a programme of modelling is needed to investigate the different options. The energy loss of electrons through scattering and the subsequent generation of X-rays by fluorescence as a function of depth is a complex process, best modelled through a Monte Carlo approach. Such a study is beyond the scope of this chapter but may provide a future mechanism for investigation.

The change of line intensity, of fluorescent X-ray lines observed in Configuration 1, due to obscuration of the fluorescent X-ray flux by the channel wall has been shown to have an energy dependency. Lower energy X-rays from MCP glass show a decreased intensity loss when obscured by the cleaved microchannel wall. The O-K line shows an increase in relative intensity of approximately 30% compared with that of higher energy Si-K, Pb-M, and K-K X-rays. This increase in relative intensity for O-K may
result from an increased probability of reflection from the microchannel wall or may result from secondary fluorescence following interactions of higher energy X-rays with the channel walls. These variations in relative intensities of elements of different energies and for different extents of occultation suggests that the structures observed in the Configuration 1 relative abundance profiles, were in fact artefacts of the changing shape and height of the occulting microchannel wall and are not related to a change in the along-channel composition of the MCP glass. Only profiles obtained in Configuration 2 can therefore be considered. In these profiles periodic structure, all be it reduced from that in Configuration 1, is still observed, particularly for the highly mobile alkali metal Na.

**Figure 2.15.** Along channel profiles of the Na/Si counts ratio for all five MCPs. MCPs with good QE are red. MCPs with poor QE are blue.

**Figure 2.16.** Along channel profiles of the K/Si counts ratio for all five MCPs. MCPs with good QE are red. MCPs with poor QE are blue.
Figures 2.15 and 2.16 show the along channel count ratios of Na/Si and K/Si measured in Configuration 2 for all five MCPs. MCPs with high QE are red those with low QE are blue. No correlation can be made between the along channel profiles made in this Configuration and the MCP quantum efficiency. Periodic and helicoidal structures of pure Si crystals have also been observed in SEM images of MCP microchannels by the manufacturer Photonis, SAS (Brive) and an example image is shown in Figure 2.17. They are a common side effect of subtleties in a sol-gel process during manufacturing but their formation is poorly understood. The structures observed independently here in the Configuration 2 measurements may have a similar origin. It may be that even when the silicon crystalline structures are successfully avoided a similar process affects the channel composition. The formation of the crystalline structures is one of the biggest problems affecting deep pore etching processes. Recent work by Siegmund et al. (2005) has indicated that some QE can be recovered by a reduction in the etch time following a reduction in the lengths of the microchannels used.

Additional support for an along channel composition related origin for the QE loss comes from Bannister (2001) who presents pulse height distributions (PHDs) for the J-PEX detector MCP (MCP ii) at a wavelength of 256 Å. When the MCP QE was measured at normal and reversed orientations (ie. the MCP QE was measured, the MCP was turned around and the QE was measured again) the QE was not recovered by turning the MCP around although subtle changes in the PHD shape were observed. This, it was inferred, suggested inhomogeneity in the channel wall composition connected with the poor QE.

If the observed structure is related to those generated during the sol-gel process and shown in Figure 2.17 then the sampling in the experiment is unlikely to have had sufficient spatial density (measurements are separated by too great a distance) to resolve any such structure, which in Figure 2.7 has a period of ~D/4 (~3 µm). The sample period used in the experiment was ~12D. A future study may benefit from measurements made with an increased spatial density.

Figure 2.17. Periodic and helicodal silicon crystal structures in an MCP microchannel with period ~D/4, where D is channel diameter (image used courtesy of Photonis SAS, Brive).
2.8 Conclusions and further work

Variations in the along channel surface composition of MCPs have been observed for the first time using energy dispersive X-ray spectroscopy and is most evident for the alkali metal Na. The structure observed in these profiles appears periodic and may be related to periodic crystalline structures which can sometimes form during deep pore etching of the MCPs. The loss of MCP QE at EUV energies may be related to this compositional structure. The profiles observed here cannot be correlated with the QE loss but it is likely that there is insufficient spatial resolution to do so. Changes in surface composition will affect the secondary electron emission characteristics of the MCP glass, on which the QE is strongly dependent. The alkali metals Na and K are important in determining MCP QE as they form dipoles at the glass surface and reduce the potential barrier across the surface, increasing secondary electron yield. Changes in the concentration of elements, producing X-rays with higher energies than Na-K may be less pronounced because their X-ray flux will be dominated by fluorescence from the bulk glass.

Changes in the along channel composition may affect the EUV QE by altering the composition at intermediate channel depths, where by virtue of an increased probability of reflection, secondary electron emission for EUV photons is likely to take place, beginning the electron avalanche and dictating the MCP QE.

A future study may use increased spatial resolution to investigate the structure of the compositional inhomogeneity and may use complementary analysis techniques such as Auger electron spectroscopy (AES), which addresses surface and depth analysis, ion-scattering spectroscopy (ISS) for surface analysis, and secondary ion mass spectroscopy (SIMS) for depth profiling. ISS and SIMS have a key advantage over EDXS and AES in that an electron beam, which can potentially affect the surface being studied, is not employed. In addition SIMS allows the detection of hydrogen, the presence of which has been shown to impact upon SEY (Hill, 1973).

All of the MCPs used in this investigation, have been operated as photomultipliers. Electron bombardment, on the walls, during MCP operation and from the SEM electron beam may change the surface glass composition and influence the results of this study. Much of the work described by previous authors used Auger electron spectroscopy of microchannel plate glass (Hill, 1973 and Siddiqui, 1977) and the uncertain influence of electron bombardment lends uncertainty to their results. Changes in surface composition, structural modification, generation and/or annihilation of electronic effects, electrical charging and heating are all potential problems (Then and Pantano, 1990).

The EDXS technique described here gives a new method for the analysis of MCP composition. Structure has been observed in the along channel elemental composition of MCPs, which may offer insight into the origin of the lost QE. An understanding and subsequent application of this to MCP manufacture offers a potential way forward in solving a problem which has blighted EUV MCP detectors for the last decade.
CHAPTER 3

X-ray fluorescence from Mercury

3.1 Introduction

Figure 3.1. Apollo 15 and 16 map of the Aluminium/Silicon Abundance ratio for equatorial regions of the day side of the Moon obtained from X-ray fluorescence measurements made from orbit (image used courtesy of NASA).

As the innermost planet in the solar system, Mercury represents an extreme case of planetary formation. A knowledge of the planet’s history is essential to understanding the formation and evolution of the inner Solar System (Clark and Trombka, 1997b). Despite Mercury’s importance it remains the least explored of the planets (apart from Pluto, which is widely accepted to be a Kuiper belt object and not a planet), having been visited by just one mission, Mariner 10, which made observations of during three flybys in 1974 and 1975 (Murray, 1975). Two new missions to Mercury, the US MESSENGER spacecraft (Santo et al., 2001); launched on 3rd August 2004 and due to enter Mercury orbit in March 2011, and the European BepiColombo spacecraft (Anselmi and Scoon, 2001); intended for launch in 2013 and expected to arrive at Mercury in 2017, will provide a significant increase in data on the planet, which will allow major advances in our understanding of the innermost planet and the formation and history of the inner Solar System. Both of these missions use X-ray fluorescence spectroscopy to generate maps of surface elemental composition from orbit around the planet. These data can be used to address key questions on Mercury’s evolution and the processes which have modified its surface (Clark and Trombka, 1997b).
X-ray fluorescence spectroscopy (XRF) has been used as a tool for the remote sensing of atmosphereless planetary bodies since the 1970s, when X-rays from the lunar surface were observed from the orbiting Apollo 15 and 16 service modules (Adler et al., 1972a,b,c and 1975). The resultant X-ray spectra were used to generate maps, like that shown in Figure 3.1, of elemental abundance ratios for Mg/Si and Al/Si, which were used as indicators of rock type. Maps were only produced for equatorial regions following the service module’s ground track and observations were necessarily limited to the solar illuminated hemisphere as solar coronal X-rays provided the excitation source (Adler et al., 1972b). The detectors used were gas proportional counters (GPCs) and the surface resolution was selected by a collimator, which limited the detector’s field of view (FOV). The technique has since been used for measurements of the surface of asteroid 433 Eros by the Near Earth Asteroid Rendezvous (NEAR) mission (Trombka et al., 2002), of asteroid Itokawa by the Japanese Hyabusa mission (Okada et al., 2006) and of the Moon by the D-CIXS experiment on SMART-1 (Grande et al., 2001). These instruments and their energy resolutions are discussed in Chapters 4 and 5.

3.2 X-ray fluorescence from planetary bodies

![Figure 3.2. Fluorescent X-rays are emitted from elements as outer electrons decay to fill vacancies created in inner electron shells following photoionisation by X-rays.](image)

The primary mechanism for producing X-ray fluorescence from planetary bodies in the inner solar system is excitation by solar coronal X-rays, though fluorescence can also be induced by bombardment by charged particles. X-rays incident on atoms in the surface excite photoelectron emission from inner electron shells. Electrons from outer shells decay to fill the vacancies as illustrated in Figure 3.2. The potential energy lost by the outer electrons as they decay to lower energy levels is emitted as fluorescent X-rays. The fluorescent X-rays can either escape from the atom or excite further “Auger” electron emission from outer shells. The efficiency of fluorescent X-ray emission is weak compared with Auger electron emission. The energies of X-rays emitted from an element are defined by the changes in energy levels. Fluorescent X-rays from any given element are labelled according to the inner shell from which the primary photoelectron originated, denoted as K,L,M,N, and the number of shells above that, from which the decaying electron originated; denoted as $\alpha$ for one, $\beta$ for two, $\gamma$ for three etc. The X-ray frequencies ($\nu$) for series vary with the atomic number $Z$ of the element according to Moseley’s law,
\[ \nu^2 = K(Z - k), \tag{3.1} \]

where for each spectral series \( K \) and \( k \) are constants for all elements.

Only atmosphereless bodies within approximately 3AU of the Sun are subject to solar X-rays of sufficient intensity to allow practical observations of fluorescent X-ray emission (Adler and Trombka, 1970, Adler et al., 1972a). X-ray fluorescence spectroscopy as an observation technique is therefore limited to observations of the Moon, Mercury, asteroids and comets in the inner solar system, although cometary X-ray emission is generally believed to result primarily from charge exchange between ions in the solar wind and cometary gas (Cravens, 1997). Note, however, that X-ray fluorescence has also been observed by the Chandra X-ray observatory from the surfaces of Io and Europa in the Jovian system (at ~5AU). In these cases, fluorescence is believed to be induced by bombardment of the satellite surfaces by energetic (> 10 keV) H, O, and S ions (Elsner et al., 2002). To date, spectroscopy of these X-ray fluxes, to obtain compositional information about Europa and Io, has not been possible, although it is believed that emission is dominated by the K shell emission from oxygen in both cases.

The intensity of solar induced X-ray fluorescence from a planetary surface at different energies is highly dependent on the solar X-ray spectrum and total intensity. Solar X-ray output can change by several orders of magnitude in energy and overall intensity and is highly variable over time scales of minutes. Solar X-ray variability is illustrated by data from the Geostationary Operational Environmental Satellite (GOES) illustrated in Figure 3.3. The solar X-ray spectrum is also dominated by low energy X-rays with a typical decrease in flux of 3 to 4 orders of magnitude over the range 1-10 keV for most solar states. Figure 3.4 shows the decrease in flux as a function of energy for three solar flare states, M1, C1 and B1. As solar flare state increases there is a general increase in hard X-ray emission. The primary X-ray energy required to produce secondary fluorescence increases with the atomic number of the target element. The energy of primary radiation must be greater than the energy at the absorption edge of an element in order to liberate a photoelectron prior to the generation of a fluorescent X-ray. An increase in solar state is associated with an increase in total X-ray output and the mean energy of the solar spectrum and therefore results in an increase in X-ray emission from planetary surfaces, particularly for high Z elements for which a higher energy incident flux is required. Consequently, a sun-pointing solar X-ray spectrometer is required in addition to any surface-pointing X-ray spectrometer to allow analysis of the detected surface spectrum with respect to the exciting solar spectrum.
Figure 3.3. Geostationary Operational Environmental Satellite (GOES) X-ray data from 2\textsuperscript{nd} – 5\textsuperscript{th} November 2003 showing orders of magnitude increases in X-ray intensity over time scales less than hours (www.sec.noaa.gov).

Figure 3.4. Power law data fits of Truscott et al. (2000) to the mean solar X-ray spectrum in M1, C1 and B1 flare states. Flare states are defined by the total X-ray power output. See Chapter 5 Section 5.5.1 for flare state definitions.

The relationship between the fluorescent X-ray intensity from a surface, which is incident on a collecting area, $I_{\text{line}}$ (in photons / cm\(^2\) s), and the illuminating source intensity $I_0(E)$ can be derived from fundamental physical parameters. From Beer’s law the probability $P(x)$ of absorption of an X-ray with energy $E$ in a material with a linear absorption coefficient $\mu(E)$ is given by

$$P(x) = 1 - \exp\left(-\left(\frac{\mu(E)}{\rho}\right)x\right),$$

(3.2)

Where $(\mu(E)/\rho)$ is the mass absorption coefficient. The probability $dP$ that an X-ray is absorbed at a depth between $x$ and $x+dx$ is therefore
\[ dP = \rho \left( \frac{\mu(E)}{\rho} \right) \exp(-\mu(E)x)dx . \]  

(3.3)

The total flux \( f \) of X-rays with intensity \( I_0(E) \), incident at an angle \( \alpha \) to the surface normal, which are absorbed at a depth between \( x \) and \( x+dx \) is given by

\[
f = \int_{\alpha}^{\infty} I_0(E) \rho \left( \frac{\mu(E)}{\rho} \right) \exp \left( -\frac{\mu(E)x}{\cos \alpha} \right) dE ,
\]

(3.4)

where \( E_{\text{abs}} \) is the energy at the absorption edge of the \( i \)th element in the material. If \( w_i \) is the fluorescence yield (probability that absorption will result in fluorescence) for a given emission series and \( p_i \) is the probability that an absorbed X-ray will be absorbed by the \( i \)th element in a material, \( p_{\text{line}} \) is the probability that absorption is associated with a given line and \( g \) is a weight fraction for a given line within an emission series (e.g. \( K\alpha \) or \( K\beta \)), then the fluorescent X-ray intensity \( dI \) into \( 4\pi \) steradians from a depth between \( x \) and \( x+dx \) is given by

\[
dI(E) = w_i f p_i p_{\text{line}} g .
\]

(3.5)

If the partial mass absorption coefficient for the \( i \)th element is \( (\mu(E)/\rho)_i \) and the weight fraction of that element in the material is \( C_i \) then \( p_i \) can be given by the expression

\[
p_i = \frac{C_i \left( \frac{\mu(E)}{\rho} \right)_i}{\left( \frac{\mu(E)}{\rho} \right)}
\]

(3.6)

The probability \( p_{\text{line}} \) can be expressed in terms of the jump ratio \( r \), the ratio of the linear absorption coefficients across the absorption edge associated with the line of interest as \( \text{(Minardi and Borrea, 1996)} \)

\[
p_{\text{line}} = \frac{r-1}{r}.
\]

(3.7)

The fluorescent X-ray flux \( dI_{\text{det}}(E) \) which escapes from this element to the surface and is then incident upon a collecting area at an angle \( \beta \) to the surface and subtending a solid angle \( d\Omega \) is

\[
dI_{\text{det}}(E) = w_i g f C_i \left( \frac{\mu(E)}{\rho} \right)_i \rho \left( \frac{r-1}{r} \right) \exp \left( -\left( \frac{\mu(E)_{\text{line}}}{\rho} \right)_i \frac{x}{\cos \beta} \right) \frac{d\Omega}{4\pi} .
\]

(3.8)

Substituting equation 3.4 gives the intensity \( I_{\text{line}} \) of X-rays from all depths, for a given emission line of the \( i \)th element in a material, incident on the collecting area

\[
I_{\text{line}} = \frac{d\Omega}{4\pi} w_i g C_i \left( \frac{r-1}{r} \right) \int_{E_{\text{abs}}}^{\infty} I_0(E) \left( \frac{\mu(E)}{\rho} \right)_i \rho(E) \exp \left[ -\left( \frac{\mu(E)}{\cos \alpha} + \frac{\mu(E)_{\text{line}}}{\cos \beta} \right) x \right] dEdx
\]

\[
= \frac{d\Omega}{4\pi} w_i g C_i \left( \frac{r-1}{r} \right) \int_{E_{\text{abs}}}^{\infty} I_0(E) \rho \cos \alpha \frac{\left( \frac{\mu(E)}{\rho} \right)_i}{\mu(E) + \frac{\mu(E)_{\text{line}}}{\cos \beta}} dE
\]

(3.9)
Line emissions calculated from Equation 3.9 are combined with a scattered X-ray background flux. Coherent scattering occurs when X-rays are scattered from their incident direction by bound electrons, with no loss of energy. This scattered contribution to the detected signal for a given line must be removed to determine the line fluxes. Incoherent Compton scattering, in which energy is lost to electrons in the surface, is negligible compared with coherent flux for X-ray energies below approximately 10 keV for low Z elements (e.g. carbon) and 100 keV for high Z elements (e.g. gold) and can therefore be neglected in these calculations (Michette 1993). The coherent contribution to the detected X-ray intensity \( I_c \) is shown by King (2000) to be

\[
I_c = \frac{0.00239I_o \rho}{\mu(E)} \sum_{i=1}^{N} f_i^2 \left( \frac{C_i}{W_i} \right),
\]

where \( N \) is the number of elements in a material, \( W_i \) is the atomic weight of the \( i \)th element and \( f_i \) is the atomic scattering factor described in Chapter 5.

X-ray fluorescence provides a measure of the composition of the first few microns of a planet’s surface. Churning up of the surface by small meteorite and micrometeoroid impacts, or “impact gardening” however, produces a surface composition which can be representative of that of the first few metres of the regolith.

### 3.3 Measuring X-rays from Mercury

Mercury has an average density of 5.4 g cm\(^{-3}\), similar to that of the other terrestrial planets. The small radius and mass of Mercury, when compared to the other terrestrial planets, however, results in reduced gravitational forces on its interior and a resultant reduction in compression. Accounting for and removing the effect of gravitational compression allows the determination of an “uncompressed density”, which serves as a much better indicator of a planet’s composition. Mercury’s uncompressed density of 5.3 g cm\(^{-3}\) is large when compared with the other terrestrial planets (Strom and Sprague, 2003). Earth’s uncompressed density for example is 4.0 g cm\(^{-3}\). Various models describing the formation and evolution of Mercury have been proposed, with different resultant compositions (Morgan and Anders, 1980; LPSI, 1980; Fegley and Cameron, 1987; Goettel, 1988). The predicted surface compositions for nine of these models are given in ESA’s BepiColombo Science requirements document and are shown in Table 3.1. Comparison of measured and theoretical surface compositions can be used as an indication of the planet’s true origins. A modelled X-ray spectrum from Equations 3.8 and 3.9, calculated for the refractory rich model composition of Table 3.1 is shown in Figure 3.5.
<table>
<thead>
<tr>
<th>Model</th>
<th>Na</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
<th>Fe</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chondrite(^1)</td>
<td>0.059</td>
<td>25.0</td>
<td>4.7</td>
<td>35.0</td>
<td>0.0062</td>
<td>3.9</td>
<td>0.24</td>
<td>0.045</td>
<td>2.7</td>
<td>0.12</td>
<td>0.034</td>
</tr>
<tr>
<td>Equilibrium condensation (EC)(^2)</td>
<td>0</td>
<td>30.0</td>
<td>7.1</td>
<td>30.3</td>
<td>0</td>
<td>6.4</td>
<td>0.36</td>
<td>0</td>
<td>0.04</td>
<td>0.19</td>
<td>0.053</td>
</tr>
<tr>
<td>EC with usage of feeding zones(^2)</td>
<td>0</td>
<td>30.3</td>
<td>5.3</td>
<td>33.4</td>
<td>0</td>
<td>4.9</td>
<td>0.27</td>
<td>0</td>
<td>0.03</td>
<td>0.14</td>
<td>0.040</td>
</tr>
<tr>
<td>Dynamically mixed(^2)</td>
<td>0</td>
<td>35.4</td>
<td>3.5</td>
<td>32.3</td>
<td>0</td>
<td>3.0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>Collisionally differentiated(^2)</td>
<td>0</td>
<td>40.5</td>
<td>0</td>
<td>32.3</td>
<td>0</td>
<td>1.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Vapourisation(^3)</td>
<td>0</td>
<td>25.6</td>
<td>13.4</td>
<td>23.8</td>
<td>0</td>
<td>10.8</td>
<td>0.52</td>
<td>0</td>
<td>0</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Refractory-rich(^4)</td>
<td>0</td>
<td>25.7</td>
<td>12.3</td>
<td>24.2</td>
<td>0</td>
<td>11.3</td>
<td>0.53</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Intermediate(^4)</td>
<td>0.45</td>
<td>26.0</td>
<td>3.9</td>
<td>31.9</td>
<td>0</td>
<td>3.9</td>
<td>0.17</td>
<td>0</td>
<td>2.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Volatile-rich(^4)</td>
<td>1.0</td>
<td>23.8</td>
<td>2.4</td>
<td>33.4</td>
<td>0</td>
<td>2.2</td>
<td>0.10</td>
<td>0</td>
<td>11.2</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1. Percentage by number of elements for nine models of Mercury’s formation taken from the ESA Science requirements document for BepiColombo

\(^1\)Morgan and Anders, 1980; \(^2\)Chapter 4, Basaltic volcanism on the terrestrial Planets, 1980; \(^3\)Fegley and Cameron, 1987; \(^4\)Goettel, 1988.)
The actual surface composition of Mercury remains a mystery. The Mariner 10 spacecraft carried no instruments capable of measuring elemental abundances, mineral or rock types. All measurements of Mercury’s composition to date have been made from Earth by observing the solar spectrum reflected from Mercury in the infrared – ultraviolet waveband and by recalibrating Mariner 10 images of the surface in narrow wavebands. Comparisons between these reflected spectra and measurements made in the laboratory and at the Moon can provide an indication of surface composition. All of these measurements have led to the surprising conclusion that Mercury’s surface is depleted of iron, even though Mercury’s large density and magnetic field imply that iron is a major constituent of the planet’s composition (Strom and Sprague, 2003). This is primarily inferred by Mercury’s high albedo compared to the Moon, low radio reflectivity, and most importantly the reduced size, compared with other terrestrial planets and the Moon, of an absorption feature between 900 and 1000 nm, caused by electron transition in the Fe$^+$ ion when iron is bound to oxygen in a silicon lattice. Only measurements of iron X-ray emission lines can determine categorically whether or not iron is present and in what abundance.

The dominant landforms on Mercury are impact craters produced by impacts by asteroids, comets and meteoroids. These craters are often associated with large amounts of ejecta, which can be observed as rays extending out from the crater and impact melts often observed as a sheet on the crater floor. Craters provide access to materials from depths of many metres and therefore provide a sample of the underlying regolith (Melosh, 1989). In addition, impact melts and ejecta contain elements from the original impactor, which can be used to yield information on the impactor’s composition and origins. X-ray spectroscopy of impactor residues in small craters found on retrieved spacecraft surfaces is a commonly used technique and is discussed on the nanometre scale in Chapter 6.
The role of volcanism in the evolution of Mercury’s surface is another key area for investigation. Large smooth plains have been observed by Mariner 10 on the surface, with a reduced density of impact features. These surfaces must have been formed recently by comparison with intercrater plains, where significant cratering is observed. It has been deemed most likely that these smooth plains came about as a result of volcanism (Murray et al., 1974) although no volcanic constructs have been identified. This may however be a result of the poor spatial resolution of the Mariner 10 images. The variation in albedo between these regions and the surrounding highlands is markedly reduced from that observed on the Moon. Knowledge of surface composition is essential if a volcanic origin is to be confirmed.

Throughout its formation and evolution Mercury will have experienced very high temperatures given its close proximity to the Sun. It is likely that there will be an overall depletion of elements with low boiling temperatures, such as Na (boiling point at 1156K) and K (boiling point at 1032K). Elements with higher boiling temperatures, such as Al (2792K) and Ca (1757K) are likely to be more abundant (Lewis 1988).

Measurements of fluorescent X-rays from the uppermost few microns of the surface can be combined with complementary measurements by other instruments operating at different wavelengths. Gamma ray spectra provide compositional information extending to depths of approximately one metre (Reedy, 1978) while infrared and ultra violet spectra provide mineralogical information. A combination of spectroscopic measurements at different wavelengths has been employed extensively on the Moon (Heiken et al., 1991) and can allow differentiation of basaltic rocks, formed by volcanism, and other types of rocks in the surrounding terrain.
CHAPTER 4

A Slumped MCP Collimator for Planetary Remote Sensing

4.1 Introduction

All of the instruments to have made measurements of X-ray fluorescence from planetary surfaces to date have used detectors whose fields of view (FOV), and the resultant size of a surface element, were selected by a collimator. A schematic diagram of a typical collimated instrument is shown in Figure 4.1. An X-ray collimator is normally an array of parallel channels whose aspect ratio (length $L$ divided by diameter $d$) defines the angular limit for which incident photons can be transmitted onto the underlying detector. Collimators are conventionally of a planar geometry and are placed directly in front of the detector. The detector and collimator are necessarily identical in area and the angular resolution of the instrument is equal to the FOV (i.e. there is no true imaging capability).

![Figure 4.1. Schematic diagram of a planar collimator. The FWZM field of view ($\theta_{col}$) of the collimator is defined by its aspect ratio ($L/D$).](image)

The first application of the technique for planetary remote sensing was on the Apollo 15 and 16 service modules and since Apollo several planetary missions have employed X-ray spectrometers to determine surface compositions. The X-ray and Gamma Ray Spectrometer (XRGS) on the Near Earth Asteroid Rendezvous (NEAR-Shoemaker) spacecraft (Goldsten et al., 1997 and Trombka et al., 2002), which visited asteroid 433 Eros in 2001, and the X-ray Spectrometer (XRS) on the MESSENGER spacecraft (Starr et al., 2001), launched on August 2nd 2005, en route to Mercury, with an expected insertion into Hermetian orbit in March 2011, are essentially identical. The technology in both cases is similar to that of the Apollo spectrometers (Adler et al., 1972a, b, c) in that all use collimated gas proportional counters (GPCs) as their X-ray detectors. A review of GPC detector operation is given by Fraser (1989). Both the NEAR-XRGS and the MESSENGER-XRS instruments have an intrinsic GPC energy resolution of ~ 850eV FWHM at 5.9 keV (Starr et al., 2001) and, as was the case for Apollo before them, proper separation of the K shell emission from Mg, Al and Si is not possible. Instead three separate detectors are
employed with 25µm Be windows, two of which bear additional thin Mg or Al filters. The Mg filter attenuates the Al line and to some extent the Si line, while the Al filter attenuates the Si line. In the bare detector the Si line is most prominent. The resultant signal at each detector is the contribution from each of the three lines modified by the absorption properties of the filters. Three simultaneous equations are therefore obtained, which can be solved to give the line intensities. The K lines of S, Ca, Ti and Fe are separated sufficiently in energy that the GPCs can resolve them without this step (*Clark and Trombka, 1997a*). A major disadvantage of this technique is the major loss of flux necessitated by absorption in the filters.

The D-CIXS instrument on Smart-1 (*Grande et al., 2001*) and the instruments on the Japanese spacecraft Hyabusa (*Okada et al., 2000*) and Selene (*Okada et al., 2002*) have utilised semiconductor detectors for the first time. Semiconductors provide an intrinsic spectral resolution which is improved from that of the traditional GPC approach so there is no need for filtering to resolve spectral lines; giving these instruments access to greater X-ray fluxes. The improved spectral resolution arises because Fano factors (*Fano, 1947; Alkhazov et al., 1967*) in semiconductors are several times less than for gases. The Fano factor $F_\alpha$ is defined by

$$\sigma^2 = F_\alpha N$$  \hspace{1cm} (4.1)

where $\sigma^2$ is the variance in the number of electrons $N=E/w$ produced in the initial localised charge cloud generated by a photon of energy $E$ incident in a material with an average energy, $w$, required to create a secondary ion pair. For a typical GPC gas (e.g. argon or xenon) $F_\alpha \sim 0.17$ and $w \sim 25$ eV. For a typical semiconductor (e.g. silicon or germanium) $F_\alpha < 0.1$ and $w \sim 3$ eV (*Fraser, 1989*). X-ray photons in semiconductor detectors therefore produce more charge carriers than in gas detectors and there are smaller statistical fluctuations in the number of charge carriers produced.

The mass and expense of the grazing incidence X-ray optics, used in X-ray astronomy and described in Chapter 5, have inhibited their use on planetary missions but the development of low mass MCP optics will lead to the introduction of imaging X-ray instruments for planetary missions in the future (*Bavdaz et al., 2002; Price et al., 2001; Martin et al, 1999*). In Chapter 5 MCP optics and their application to planetary remote sensing on the BepiColombo mission to Mercury are described. Despite offering angular resolutions of approximately 1 arcminute, compared with collimator resolutions of several degrees, practical limits to optic sizes can result in a low X-ray throughput when compared to collimated instruments. In addition, the X-ray reflectivity of grazing incidence optics falls off with energy, leading to reduced effective areas at higher energies. X-ray fluxes from planetary surfaces are typically very low and the response of MCP optics to the emission lines of some key elements of interest for planetary science (e.g. Fe-K at 6.4 keV) is poor. Observations over a large spectral range are also required to allow the determination of absolute elemental abundances. High instrument throughput across a wide range of energies is therefore important for planetary remote sensing and to this end collimated instruments, for
which the transmission of X-ray flux on to a detector is independent of energy, will continue to be important for planetary missions.

A traditional planar collimator geometry is not optimal for observing planetary surfaces. A geometry in which collimator and detector are separated, and for which there is a reduction in detector area relative to the collimator area, will have a reduced minimum detectable flux, a reduced background, will place a reduced thermal load on cooling systems and will require less radiation shielding. These benefits are described in more detail in sections 4.1.1 to 4.1.4.

4.1.1 Minimum detectable flux

The sensitivity of a photon detecting instrument can be defined by the minimum signal flux from a source which it can distinguish from the background. This is referred to as the minimum detectable flux $F_{\text{min}}$ and can be calculated for a collimator observing an extended source such as a planetary surface in terms of various instrument parameters.

An isotropic flux $F$ (in units of photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$) of fluorescent X-rays at a discrete energy (in keV) from an extended source is incident on a collimator with an area $A_{\text{col}}$ which has an underlying detector with geometric area for photon detection $A_{\text{det}}$, energy resolution $\delta E$ and Quantum Efficiency $\xi$. All photons transmitted through the collimator are subsequently incident on the detector. The collimator has a FOV of $\Omega$ steradians and the transmission of the collimator as a function of angle is defined by the function $T(\theta)$. The collimator will have a mean transmission $\overline{T}$ (between 0 and 1) over its FOV. The collimator will also have an open area fraction $T_0$, which results from the finite thickness of the collimator channel walls (i.e. photons incident at $0^\circ$ cannot pass through this part of the collimator), which further reduces the total transmission. The detected X-ray signal is accompanied by a background X-ray flux, due to scattering from the surface under examination, which is denoted as $F_{\text{scat}}$ (in units of photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$). The detector also has an intrinsic background $B_i$ (units of counts cm$^{-2}$ s$^{-1}$ keV$^{-1}$). The geometric area for the intrinsic background is $A_i$. We assume here for simplicity that $A_i = A_{\text{det}}$. If the instrument is allowed to integrate flux for a time $t$ then the detected signal $A$ is given by

$$A = F\xi A_{\text{col}} T_0 \overline{T} \Omega t. \quad (4.2)$$

The detected background $B$ is given by

$$B = (B_i A_{\text{det}} t \delta E + F_{\text{scat}} \xi A_{\text{col}} \Omega T_0 \overline{T} t \delta E) \quad (4.3)$$

The ratio of the signal to the standard deviation of the background is denoted as $S$ and can be expressed as

$$S = \frac{F\xi A_{\text{col}} T_0 \overline{T} \Omega t (\delta E)^{-\frac{1}{2}}}{\sqrt{B_i A_{\text{det}} t + F_{\text{scat}} \xi A_{\text{col}} \Omega T_0 \overline{T} t}} \quad (4.4)$$

and the minimum detectable flux $F_{\text{min}}$ for a given value of $S$ (typically taken to be a factor of 3-5) is given by

$$43$$
\[ F_{\text{min}} = \frac{S\sqrt{\delta E (B_{A_{\text{det}}} + F_{\text{scat}} \xi A_{\text{col}} \Omega T_q \bar{T})}}{\xi A_{\text{col}} T_q T \Omega \sqrt{t}}. \] (4.5)

A geometry in which the detector’s area is reduced from that of the collimator results in a reduced value of \( F_{\text{min}} \) and it is therefore an advantage when measuring low fluxes. The introduction of detectors with an improved energy resolution \( \delta E \) will also lead to a reduced minimum detectable flux.

4.1.2 Contribution of X-ray emission from the collimator to the instrument background

Cosmic radiation, X-rays from the planetary surface and incident charged particles will all strike the collimator material and induce secondary X-ray and charged particle emission which will contribute to the instrument background (Grande et al., 2003). This secondary emission will occur into \( 2\pi \) steradians from a radiating point on the collimator. The fraction of emitted X-rays which are intercepted by a detector of area \( A_{\text{det}} \), separated from the collimator by a distance \( d \), is proportional to the solid angle subtended by the detector to the radiating point on the collimator, which is approximately \( A_{\text{det}}/d^2 \). This contribution to the background is therefore reduced significantly by increasing \( d \) and reducing \( A_{\text{det}} \), further improving signal to background and reducing \( F_{\text{min}} \).

4.1.3 Thermal

Solid state X-ray detectors must be maintained at low temperatures to reduce their intrinsic noise; thus some system for cooling is required. A reduced detector area places a smaller thermal load on any cooling system as there is a reduced volume of material to cool. In addition an increase in \( d \) and reduction in \( A_{\text{det}} \) reduces the thermal flux incident on the detector, as a result of thermal radiation from the collimator or thermal barrier films on the collimator face. As in Section 4.1.2 the detector’s radiative coupling with these surfaces will be dependent on the solid angle subtended by the detector at a point on the radiating surface and is therefore proportional to \( A_{\text{det}}/d^2 \). Although this radiative heat transfer dominates the heating of a detector there is an additional heating which is intrinsic to the device as a result of potentials applied for charge transfer. This contribution to heating is small compared with radiative coupling but scales approximately linearly with detector area.

4.1.4 Radiation Shielding

A major problem for semiconductor detectors, which are usually silicon, is their susceptibility to damage by radiation. The D-CIXS Si swept charge device, was believed to have a reduced susceptibility to radiation damage compared with standard CCD devices, operates near room temperature (Grande et al., 2003), and has an energy resolution given as \( \sim 200 \) eV between 0.5 keV and 10 keV (Grande et al., 2001). It has since been shown by Holland et al. (2004) that the claims of radiation hardness are unfounded and prepublication spectra, measured by D-CIXS at the Moon, indicate a severe reduction in spectral resolution following radiation damage sustained during a prolonged passage through the Van Allen radiation belts en route to the Moon. A smaller detector located deeper within the spacecraft requires reduced radiation shielding with resultant reduction in instrument mass.
Solid state detectors have introduced an improvement factor of approximately 4 in the spectral resolution available to X-ray astronomers (Fraser, 1989); however, their introduction to orbital planetary X-ray instrumentation has been slow, due in part to the limitations of standard collimator geometries as outlined above. This chapter introduces a novel slumped collimator geometry which allows the separation of collimator and detector and reduces the area requirement of the detector as a fraction of collimator area with a minimal loss of throughput, allowing the practical application of semiconductor detectors to collimated X-ray instruments on planetary science missions for the first time.

4.2 Flat collimators

For a diffuse source, such as the fluorescent X-ray flux from a planetary surface, the key parameter in determining sensitivity is the grasp ($G$) (units of cm$^2$ sr), which quantifies the instrument throughput and is given by the product of the collimators FOV, $\Omega$, in steradians and the mean effective area over the FOV $A_{eff}$, given by

$$A_{eff} = A_{col} \bar{T} T_0,$$

where $A_{col}$ is the geometric area of the collimator, $\bar{T}$ is the mean transmission of the collimator over the field of view and $T_0$ is the collimator’s open area fraction.

4.2.1 Collimator grasp

The one dimensional transmission function of a parallel channel collimator is

$$T(\theta) = 1 - \frac{\theta}{\theta_{col}},$$

for $\theta < \theta_{col}$ otherwise $T=0$, where $\theta_{col}$ is the maximum angle relative to the channel axis at which a ray can be transmitted (shown in Figure 4.1). $\theta$ is the angle of incidence of a given X-ray relative to the channel axes. The triangular transmission function, for a collimator with a FOV of 12° ($\theta_{col} = 6°$) is shown in Figure 4.2. The collimator’s grasp $G$ is given by the integration of Equation 4.7 between the limits of $\pm \theta_{col}$ and multiplied by the on axis effective area,

$$G = T_0 A_{col} \int_{-\theta_{col}}^{\theta_{col}} 1 - \frac{\theta}{\theta_{col}} d\theta$$

$$G = T_0 A_{col} \theta_{col}. $$
This transmission function can be extended to describe a three dimensional collimator system by introducing a component in $\phi$, orthogonal to $\theta$, to give a transmission function

$$T(\theta) = \left(1 - \frac{|\phi|}{\phi_{col}}\right) \left(1 - \frac{|\phi|}{\phi_{col}}\right),$$

(4.10)

The effective area of the collimator as a function of angle is given by the transmission function multiplied by geometric area and open area fraction. Figure 4.3 shows the effective area as a function of angle for a collimator with a format like that shared by two of the three D-CIXS collimator facets with $\theta_{col} = 6^\circ$ (0.105 rad), open area fraction $T_0 = 0.64$ and geometric area $A_{col} = 8 \text{ cm}^2$ (McBride and Castiglione, 2001). The remaining D-CIXS facet has $\theta_{col} = 4^\circ$ but is otherwise identical. The effective area peaks on axis with a value $T_0A_{col}=5.6 \text{ cm}^2$. Integrating this transmission function between the angular limits $\pm \theta_{col}$ and $\pm \phi_{col}$ and multiplying by $T_0$ and $A_{col}$ produces the three dimensional grasp of a planar collimator:

$$G = T_0 A_{col} \theta_{col} \phi_{col}.$$

(4.11)

The grasp calculated for a single $12^\circ$ FOV D-CIXS collimator facet is $G = 0.05 \text{ cm}^2 \text{ sr}$. The grasp of the three combined D-CIXS facets is 0.101 cm$^2$ sr.
4.2.2 Detector Plane

In a conventional planar collimated instrument the detector is located directly behind the collimator and has the same area ($A_{\text{det}} = A_{\text{col}}$). As described in Section 4.1 there are advantages to be gained by separating the collimator and detector elements by some distance $d$. If the collimator’s side length $l_{\text{col}}$ remains constant then to intercept all transmitted X-rays the instrument would require a detector with sides of length ($l_{\text{det}}$) given by

$$l_{\text{det}} = l_{\text{col}} + 2d \tan \theta_{\text{col}},$$

resulting in a detector area,

$$A_{\text{det}} = A_{\text{col}} + 4d^2 \tan^2 \theta_{\text{col}} + 4l_{\text{col}}d \tan \theta_{\text{col}}.$$

The imaging X-ray telescope for the Mercury imaging X-ray Spectrometer (MIXS) intended for the BepiColombo mission to Mercury, described in Chapter 5, will have an additional collimated channel to provide a high throughput of X-rays. A geometry proposed for this channel used a collimating hole in the centre of the X-ray optic as shown in Figure 4.4. X-rays are transmitted onto an extended detector in the telescope focal plane. The distance $d$ is equal to the telescope focal length which will can be assumed to be equal to the side length of the spacecraft bus, which was originally given as 0.7 m (See Chapter 5 for a detailed description of MIXS, instrument focal length and the BepiColombo mission to Mercury). For a detector-collimator separation distance of 0.7 m a planar collimator geometry would require a detector with an area of 516 cm$^2$, to match the collimator footprint in the detector plane. Such a detector size would have excessive data processing requirements, have a high value of $F_{\text{min}}$, would prove challenging to cool and be expensive to fabricate. Any attempt to separate a collimator and detector, in a planar...
geometry will result in large values of $A_{det}$ with resultant disadvantages for the instrument. Such solutions are therefore impractical. An improved geometry will allow separation of the collimator and detector, while minimising the detector area. If the detector area can be reduced to less than the area of the collimator then this would have an advantage over conventional collimated instruments for the reasons outlined in Section 4.1.

Figure 4.4. A possible collimator geometry for the Mercury Imaging X-ray Spectrometer in which an MCP optic is complimented by a collimator at its centre.

4.3 A Slumped Collimator

Figure 4.5 illustrates the geometry of a collimator which has now been shaped such that it forms a section of a sphere with radius $R$. All of the channel axes are orientated toward the centre of curvature. From this point on this is referred to as a “slumped” collimator geometry. The slumped collimator has a side length $2l_{\text{max}}$ and the angle $l_{\text{max}}/R$ is denoted as $\theta_{\text{max}}$. The position of an individual channel on the collimator can be denoted by either a length $\pm l_{\text{chan}}$ from the collimator’s centre or an angle $\pm \theta_{\text{chan}}$ from the collimator axis. The aspect ratio of the collimator defines the acceptance angle of a single channel $\theta_{\text{col}} = \arctan(D/L)$ (Figure 4.2). The angle of incidence of an X-ray is denoted as $\pm \theta$. A detector at an axial distance $R/2$ from the collimator has a side length $l_{\text{max}}$. In this configuration every channel axis, when extended to the detector plane, is intercepted by the detector and the fraction of the transmitted flux from a single channel arriving at the collimator is always $> 0.5$. The fraction from a channel on the collimator axis equals 1.
Figure 4.5. Geometry of a slumped collimator with slump radius $R$, and collimator angle $\theta_{\text{col}}$.

### 4.3.1 1D collimator grasp

The transmission function of a single channel at angular position $\theta_{\text{chan}}$ on a slumped collimator in 1D shown in Figure 4.5 is given by

$$T(\theta) = \begin{cases} 1 - \frac{|\theta - \theta_{\text{chan}}|}{\theta_{\text{col}}} & \text{for } \theta < \theta_{\text{col}}, \\ 0 & \text{otherwise} \end{cases}$$

for $\theta < \theta_{\text{col}}$, otherwise $T=0$. The transmission function for a collimator with $\theta_{\text{col}} = \theta_{\text{max}} = 6^\circ$ is shown in Figure 4.6. The collimator’s grasp can be expressed in terms of the mean transmission $\overline{T}$ over the collimator’s FOV as

$$G = 2T_{\text{chan}} \overline{T_{\text{col}}} (\theta_{\text{max}} + \theta_{\text{col}}),$$

where $\pm \theta_{\text{max}}$ denotes the positions of the microchannels at the collimator’s extremities and $2(\theta_{\text{max}} + \theta_{\text{col}})$ is the Full Width Zero Maximum (FWZM) FOV of the collimator. The transmission function $T_{\text{chan}}(\theta)$ of a single channel is equivalent to that of a flat collimator (Equation 4.9) and the mean transmission $\overline{T_{\text{chan}}}$ relative to an individual channel’s axis between $-\theta_{\text{col}}$ and $\theta_{\text{col}}$ is therefore 0.5. The FOV of a single channel as a fraction $F_{\text{chan}}$ of the total FOV of the collimator is

$$F_{\text{chan}} = \frac{\theta_{\text{col}}}{\theta_{\text{col}} + \theta_{\text{max}}},$$

A geometry is adopted here in which $\theta_{\text{max}} = \theta_{\text{col}}$ resulting in a value of 0.5 for $F_{\text{chan}}$. The mean transmission $\overline{T}$ of the entire collimator is the product of the mean transmission of a single channel and the FOV of that channel as a fraction $F_{\text{chan}}$ of the total collimator FOV, which here gives a value of $\overline{T}$ equal to 0.25.
Figure 4.6. 1D Transmission of a slumped collimator where $\theta_{col} = \theta_{max} = 6^\circ$.

Figure 4.6 shows a slumped collimator transmission curve with a FWZM at $\pm 12^\circ$ and Full Width Half Maximum (FWHM) at $\pm 6^\circ$. The effective area ($A_{eff}$) at a given angle is the product of the geometrical area, the open area fraction and the transmission. The mean effective area multiplied by the FOV gives the grasp. If the FOV is taken over the FWHM shown in Figure 4.6 between $-6^\circ < \theta_{ray} < 6^\circ$ (the FOV of a flat collimator with an identical $L/D$) then the 1D grasp $G$ is found to be 0.554 cm rads. Over the FWZM FOV ($-12^\circ < \theta_{ray} < 12^\circ$) the total grasp $G$ equals 0.664 cm rad. The FWZM FOV can be restricted and more closely approximate that of a flat collimator by increasing the aspect ratio $L/D$. The transmission function of a slumped collimator as above, but with $L/D=20$ is shown in Figure 4.7.

With $L/D=20$ the FWZM viewing angle is restricted to $\pm 8.6^\circ$ but with the adverse result that there is an overall reduction in effective area at all angles and a subsequent loss of grasp. This reduction in transmission can be minimised by limiting the FOV with a profiled collimator geometry which is discussed in Section 4.5.
4.3.2 2D Grasp

Extending the transmission function into two dimensions the transmission in $\phi$, the angular direction orthogonal to $\theta$, is introduced,

$$T(\theta, \phi) = \left(1 - \frac{|\theta - \theta_{\text{chan}}|}{\theta_{\text{col}}} \right) \left(1 - \frac{|\phi - \phi_{\text{chan}}|}{\phi_{\text{col}}} \right),$$

(4.17)

and the grasp is given by

$$G = 4T_0 \bar{T}(\theta, \phi) A_{\text{col}} (\theta_{\text{max}} + \theta_{\text{col}}) (\phi_{\text{max}} + \phi_{\text{col}}).$$

(4.18)

The mean collimator transmission is given by the product of the mean transmission of a single channel, in $\theta$ and $\phi$ over the FWZM FOV of the whole collimator, and the fraction $F_{\text{cha}}$ in $\theta$ and $\phi$, where

$$F_{\text{cha}} = \frac{\phi_{\text{col}} \theta_{\text{col}}}{(\theta_{\text{col}} + \theta_{\text{max}}) (\phi_{\text{col}} + \phi_{\text{max}})}.$$

(4.19)

The calculated mean transmission for the given geometry is 0.0625. The effective area ($A_{\text{eff}}$) as a function of $\theta_{\text{ray}}$ and $\phi_{\text{ray}}$ is shown in Figure 4.8, where the collimator’s geometric area $A = 64$ cm$^2$, $l_{\text{max}} = \pm 4$ cm, $R = 40$ cm, open area fraction $T_0 = 0.7$ and $L/D = 10$. These values are chosen to coincide with a previously suggested geometry for a Mercury orbiting instrument based on the D-CIXS concept. Again the mean off-axis effective area across a selected FOV, multiplied by that solid angular FOV gives the collimator grasp for a given angular range.

The grasp values over angular ranges for which formulae are not presented here have been calculated by a computational method in which $T(\theta, \phi)$ is calculated at points across the collimator face for values of $\theta$ and $\phi$ within a defined angular range. These values are then averaged to provide a value of $\bar{T}$ which is then applied to the given expressions for $G$ to provide grasp values within these ranges. This
computational method also allows the introduction of variations in aspect ratio across the collimator face or “profiling”, which is described in Section 4.4. Grasp values calculated by raytracing X-rays through this collimator geometry using a modified version of the Monte Carlo code described in Chapter 5 are shown in Table 4.2 and compared to the values obtained from this geometrical model.

Over the FWHM FOV (-0.1< θ_{ray} <0.1 rad and -0.1< φ_{ray} <0.1 rad) the grasp G calculated from the geometrical model equals 0.309 cm² sr, and over the FWZM FOV (-0.2< θ_{ray}<0.2 and -0.2< φ_{ray}<0.2) G equals 0.444 cm² sr. The grasp of a planar collimator with equivalent collimator area, open area fraction and aspect ratio is 0.448 cm² sr. A slumped geometry therefore results in a minimal reduction in collimator throughput compared with a planar collimator of equivalent dimensions.

![Figure 4.8. 2D effective area vs angle for a slumped collimator where l_{max}= 8cm, R=40 cm and L/D=10.](image)

### 4.3.3 Detector Plane

Section 4.1 demonstrates that it is advantageous for a collimator to use as small a detector as possible. A detector at axial position R/2 in the geometry outlined above will require a side length equal to that of the collimator to acquire all transmitted rays despite the collimator-detector separation. This in itself is an advantage over conventional collimated instruments. The slumped geometry has the added advantage of allowing a significant reduction in detector size with little loss of signal.

If a detector is placed at axial coordinate R/2 and has a side length equal to half that of the collimator, then every collimator channel axis will be intersected by the detector, providing θ_{max} = θ_{col} as indicated in the previous sections. Some rays will however miss the detector, reducing the instrument’s grasp and resulting in a loss of signal. If θ_{chan} is a channel’s angular position and θ is now measured from the channel axis, and not the collimator axis, then for a channel with angular position θ_{chan}>θ X-rays with an
incident angle $\theta > 0$ will miss the detector, after passing through the collimator, if $\theta < \theta_{\text{chan}} - \theta_{\text{col}}$ and $\theta_{\text{col}} > 0$. If $\theta_{\text{chan}} < 0$ then transmitted X-rays will miss the detector after passing through the collimator if $\theta > \theta_{\text{chan}} + \theta_{\text{col}}$. The transmission function of a single channel is equivalent to that of a flat collimator. The shaded region in Figure 4.9 represents X-rays transmitted by a single 1D channel at $\theta_{\text{chan}}$ which do not hit the detector for the $\theta_{\text{chan}} < 0$ case. The fraction of rays incident on a given channel, which are transmitted but are not incident on the detector can be determined by calculating the ratio of the shaded region of the transmission function, and the integrated transmission function over all angles.

**Figure 4.9.** Transmission function of a single channel with angular position $\theta_{\text{chan}}$, relative to the central axis of the collimator for the case where $\theta_{\text{chan}} < 0$. The incident X-ray angle $\theta$ is measured relative to a line parallel to the axis of the given channel. The shaded area indicates transmitted rays, which are not incident on the detector following transmission.

For a single channel at position $\theta$ the triangular shaded area $A_n$ in Figure 4.9 is the product $\theta_{\text{chan}} T(\theta)/2$. Substituting Equation 4.7 we obtain the expression for $A_n$

$$A_n = \frac{\theta_{\text{chan}}}{2} \left(1 - \frac{\theta}{\theta_{\text{col}}}\right), \quad (4.20)$$

where $\theta = (\theta_{\text{col}} - \theta_{\text{chan}})$ giving

$$A_n = \frac{\theta_{\text{chan}}^2}{2\theta_{\text{col}}}. \quad (4.21)$$

The fraction of transmitted rays striking the detector $F_1$ is therefore

$$F_1 = 1 - \frac{A_n}{A_{\text{total}}}, \quad (4.22)$$

where $A_{\text{total}}$ is the transmission function in Figure 4.9 integrated over the FWZM FOV which is equal to $\theta_{\text{col}}$. The fraction of photons from a given channel that hit the detector, $F_{\text{channel}}$, is therefore
\[ F_{\text{channel}} = 1 - \frac{\theta_{\text{chan}}^2}{2\theta_{\text{col}}^2}. \] (4.23)

Because of the symmetry of the collimator the fraction \( F_{\text{hit}} \) of photons hitting the detector after transmission through all of the collimator channels can be determined by integrating \( F_{\ell}/\theta_{\text{col}} \) over half of the collimator,

\[
F_2 = 1 - \frac{\int_{0}^{\theta_{\text{max}}} \frac{\theta_{\text{chan}}^2}{\theta_{\text{col}}^2} d\theta_{\text{chan}}}{\int_{0}^{\theta_{\text{col}}} \theta_{\text{chan}} d\theta_{\text{chan}}} = 1 - \frac{\theta_{\text{max}}^2}{6\theta_{\text{col}}^2}, \tag{4.24}
\]

where \( \theta_{\text{max}} = \theta_{\text{col}} \) and \( F_{\text{hit}} \) is therefore equal to \( \frac{5}{6} \). The fraction \( F_2 \) for both hemispheres must be identical due to the collimator symmetry and so this value represents \( F_2 \) for the entire 1D collimator. This can be extended into 2D to include a \( \phi \) component, and so represent a real collimator, by squaring the solution, again due to the collimator’s symmetry. The resultant value for the total fraction of rays passing through the collimator which are then subsequently incident on the detector \( F_{\text{hit}} \) is \( \frac{25}{36} \) or \( \sim 0.7 \). Raytracing of this geometry with a modified version of the model described in Chapter 5 also produces a fraction \( F_{\text{hit}} \) of \( 0.7 \). Table 1 shows the fraction of rays incident on different detector areas for a collimator-detector separation distance of \( R/2 \), obtained by raytracing.

<table>
<thead>
<tr>
<th>Detector side length/collimator side length ratio</th>
<th>( F_{\text{hit}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>0.62</td>
<td>0.87</td>
</tr>
<tr>
<td>0.75</td>
<td>0.95</td>
</tr>
<tr>
<td>0.88</td>
<td>0.996</td>
</tr>
</tbody>
</table>

*Table 4.1. Fraction of transmitted X-rays incident on detectors of different sizes at \( R/2 \).*

### 4.4 Profiling

![Figure 4.10](image_url)

*Figure 4.10. A linearly profiled collimator for which the channel aspect ratio changes with constant gradient from the collimator centre towards its extremities.*

To profile a collimator is to vary the aspect ratio \( L:D \) and therefore the angle \( \theta_{\text{col}} \) as a function of a channel position \( (\theta_{\text{chan}}, \phi_{\text{chan}}) \). By doing this it is possible to increase \( F_{\text{hit}} \) and restrict the viewing angle whilst minimising the loss of grasp which results from a universal increase in \( L:D \). Optimisation of the profiling function is essential to ensure a minimal loss of detectable flux. A linearly profiled collimator,
for which channel diameter varies with a constant gradient from the collimator’s centre to its extremity, is
shown in Figure 4.10. \( G \) for a collimator with this geometry is calculated to be a factor of 0.37 that of a
non-profiled collimator by the computational method indicated in Section 4.3.2 with the addition that the
angle \( \theta_{\text{col}} \) is recalculated for each position on the collimator to provide the profile.

Table 4.2 compares the grasps of a flat collimator of the D-CIXS format, a non-profiled slumped
collimator and slumped collimators with different profiling functions. In each case it is assumed that the
channel diameter remains constant while the channel length is altered in the manner specified by the
function shown in the table. \( L/D \) is varied from 10 at the centre of the collimator to 20 at its edge. For
slumped collimators \( \theta_{\text{max}} = \theta_{\text{col}} \) on the collimator axis. A slumped collimator has a grasp comparable with
that of a flat collimator with the same dimensions but allows the use of a detector with half the side
length. Profiling results in a significant reduction in grasp but restricts the FOV.

<table>
<thead>
<tr>
<th>Profiling function type</th>
<th>FWZM (radians)</th>
<th>Grasp over full view (cm(^2)sr)</th>
<th>Ray traced grasp over full view (cm(^2)sr)</th>
<th>Grasp over ( \pm 0.1 ) radians (cm(^2)sr)</th>
<th>Ray traced grasp over ( \pm 0.1 ) (cm(^2)sr)</th>
<th>FWHM (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat collimator (D-CIXS format, all facets)</td>
<td>0.1</td>
<td>0.101</td>
<td>0.097</td>
<td>0.101</td>
<td>0.097</td>
<td>0.05</td>
</tr>
<tr>
<td>Flat collimator ( 2l_{\text{max}} = 8 ) cm</td>
<td>0.1</td>
<td>0.448</td>
<td>0.411</td>
<td>0.448</td>
<td>0.411</td>
<td>0.05</td>
</tr>
<tr>
<td>Slumped non profiled ( 2l_{\text{max}} = 8 ) cm</td>
<td>0.2</td>
<td>0.444</td>
<td>0.425</td>
<td>0.309</td>
<td>0.297</td>
<td>0.1</td>
</tr>
<tr>
<td>Slumped Linear profiled ( 2l_{\text{max}} = 8 ) cm</td>
<td>0.15</td>
<td>0.164</td>
<td>-</td>
<td>0.140</td>
<td>-</td>
<td>0.09</td>
</tr>
<tr>
<td>Slumped Square profiled ( 2l_{\text{max}} = 8 ) cm</td>
<td>0.15</td>
<td>0.277</td>
<td>-</td>
<td>0.226</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Slumped Sin profiled ( 2l_{\text{max}} = 8 ) cm</td>
<td>0.15</td>
<td>0.182</td>
<td>-</td>
<td>0.158</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Slumped Tan profiled ( l_{\text{max}} = 4 ) cm</td>
<td>0.15</td>
<td>0.234</td>
<td>-</td>
<td>0.194</td>
<td>-</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 4.2. Comparison of grasps for a flat collimator and slumped collimators with different profiling
functions (open area fraction \( \sim 0.7 \) and \( D = 100 \) \( \mu \)m for the square channels in all cases apart from the
D-CIXS format collimator). A square profile is a power law profile defined by Equation 4.25 where \( n=2 \).
4.4.1 4th power profiling

The profile selected for a slumped collimator should provide the required reduction in instruments FOV whilst minimising the loss of flux that must result from the application of an increased anywhere on the collimator. In Table 4.2 various profile types are compared and shown to introduce different reductions in instrument grasp. It is important therefore to identify an optimum profile type that minimises this loss of grasp.

For the same \( L/D \) a slumped collimator has a larger FOV than a flat collimator, although the contribution from rays at angles greater than \( \theta_{\text{col}} \) to the overall signal is small. The maximum obtainable grasp of a slumped collimator will occur in the non-profiled case. The ideal profile will be one for which the aspect ratio approximates that of the non-profiled case towards the centre of the collimator, before rapidly increasing towards the extremities to limit the acceptance angle of these channels. Such a profile can be described by a power law of the form

\[
L' = (L_2 - L_1) \left( \frac{\theta_{\text{chan}}}{\theta_{\text{max}}} \right)^n + L_1
\]  

(4.25)

Where \( L_1 \) is the channel length on the collimator axis, \( L_2 \) is the channel length at the collimator’s edge, \( \theta_{\text{max}} \) is the position of the collimator’s edge, \( \theta_{\text{chan}} \) is the position of given channel and \( n \) is the power law index.

The advantage of a power law over some other types of function is demonstrated initially by the success of the square profiling function \((n=2)\) when compared to the other profiling forms in Table 4.2. With each increasing power the area approximating a non-profiled collimator will become larger; the increase in aspect ratio towards the extremities will become more rapid and will occur closer to the collimator’s edge. With each increase in power there will also be an increase in grasp whilst the collimator acceptance angle will remain unchanged (providing the maximum aspect ratio remains the same in all cases). Beyond some power the acceptance angle will begin to rise as the aspect ratio rise occurs close enough to the collimator’s edge that the acceptance angles of channels close to the edge can exceed that required.

Simulating profiles for \( n=1-5 \) it was found that grasp did indeed increase with power law index. The range of aspect ratios used in this case was 10:1 to 20:1. For \( n = 2, 3 \) and 4 profiles the detector side length \( l_{\text{det}} \) required for \( F_{\text{hit}} = 1 \) is 6 cm; for \( n=5 \) \( l_{\text{det}} = 6.2 \) cm. For \( n>4 \) it was found that the FWZM FOV of the collimator began to increase. The transmission of the \( n=4 \) and \( n=5 \) cases was simulated using the geometrical model and the resultant plots in 1D are shown in Figures 4.11 and 4.12. The grasp and acceptance angle values in the two cases are compared in Table 4.3.
<table>
<thead>
<tr>
<th>Regime</th>
<th>FWZM FOV (°)</th>
<th>FWHM of response (°)</th>
<th>Grasp over full view (cm²sr)</th>
<th>Grasp over ±0.1 radians (cm²sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat collimator 2l_{max} = 8 cm</td>
<td>5.73</td>
<td>2.86</td>
<td>0.446</td>
<td>0.446</td>
</tr>
<tr>
<td>N=4</td>
<td>8.59</td>
<td>5.84</td>
<td>0.335</td>
<td>0.259</td>
</tr>
<tr>
<td>N=5</td>
<td>8.88</td>
<td>5.84</td>
<td>0.351</td>
<td>0.267</td>
</tr>
</tbody>
</table>

Table 4.3. Grasps and acceptance angles and FWHM for l^4 and l^5 profiling regimes.

Profiling of the collimator with an n=4 function gives the required FOV restriction while offering the maximum possible grasp to within a reasonable approximation. Acceptance angles can be limited further by increasing the maximum aspect ratio to 50:1. This has little effect on grasp as the large aspect ratio only affects a small region on the collimator. 1D transmission functions for an n=4 profiled collimator with maximum aspect ratio of 50:1 can be seen in Figure 4.13. The effective area in the 2D case is shown in Figure 4.14. In this case acceptance angle is reduced to 7.4° whilst the FWHM becomes 5.67° and grasp is reduced to 0.20 cm² sr over 6° and 0.225 cm² sr over the full view. The shape of an n=4 profiled collimator is shown in Figure 4.14.

![Figure 4.11](image1.png)

**Figure 4.11.** Transmission of a 1D n=4 profiled slumped collimator with L/D from 10:1 to 20:1.

![Figure 4.12](image2.png)

**Figure 4.12.** Transmission of a 1D n=5 profiled slumped collimator with L/D from 10:1 to 20:1.

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The viewing angle of the collimator can be limited further by reducing D for the square channel’s diameter, thus increasing the aspect ratio of every channel; this, however, results in an appreciable loss in grasp. A universal reduction in aspect ratio will result in an increase in grasp but also increases the acceptance angle.

**Figure 4.13.** Grasp for a 1D n=4 profiled slumped collimator with aspect ratios ranging from 10:1 on the collimator axis to 50:1 at its edge.

**Figure 4.14.** 2D effective area of an n=4 profiled collimator with aspect ratios ranging from 10:1 on the collimator axis to 50:1 at its edge.
Figure 4.15. Shape of the front (top) and rear (bottom) faces of a 4th power profiled slumped collimator with aspect ratios from 10:1 to 50:1. The distance axis is the height d above the detector plane. The front face is identical to that of a non-profiled slumped collimator and channel axes run perpendicular to this surface. The rear face varies from that of a slumped collimator by the given power law function.

4.5 MCPs as collimators

Collimators in X-ray astronomy and planetary science have traditionally been made from beryllium, aluminium or stainless steel. Collimators on the European EXOSAT X-ray observatory, however, were produced from lead glass by the same drawing and fusion manufacturing process as MCPs (Fraser, 1989). EXOSAT was operated in a highly eccentric, near polar orbit between May 1983 and May 1986. In a laboratory setting MCPs have been demonstrated as collimators for X-rays of energies less than 8 keV (Yamaguchi et al., 1987) and terrestrial instrumentation utilising the collimating properties of MCPs have been proposed (Skala, 2000). Kent et al. (2000) have suggested that on planetary missions low Z elements such as oxygen and silicon, which are the prime constituents of MCP glass (see Chapter 2), will interact with high energy cosmic rays resulting in X-ray fluorescence, indistinguishable from the source under observation, which will essentially blind the detector. For this reason the collimator on D-CIXS (Grande et al., 2003; Kent et al., 2000), whose dimensions and geometry are comparable with those of an MCP (D=168 µm, L=1.8 and 2.4 mm) and which has FWZM half angles of 6° and 4°, was manufactured from gold plated copper in a square channel microarray structure (McBride and Castiglione, 2001). This high Z coating material was used in order to avoid any contamination of the detected signal. It may be, however, that interactions of cosmic rays with the Gold coating may cause Au-M line fluorescence at 2.12 keV, which will contaminate the detected signal. Experience on EXOSAT, where MCP type collimators (Hoffman, 1975) operated successfully in deep space, would suggest that concerns over signal contamination by fluorescence from the MCPs may be unfounded.

For the slumped collimator geometry, MCPs have a distinct advantage over other collimator materials because they already have a heritage as slumped optics (Price, 2001) and in particular as “Lobster’s eye” X-ray optics introduced in Chapter 1 (Angel, 1979), whose geometry is similar to that of the slumped
collimator geometry introduced here. The output from an MCP collimated instrument will therefore contain two components. The first will be an energy independent diffuse background consisting entirely of collimated X-rays. The second component will be focussed after grazing incidence reflection from orthogonal channel walls. The geometry described here is optimised for collimation, though the focussed component may be used to increase the grasp of the collimator for low energy rays and low grazing incidence angles. Complications are introduced however as this component will have its own energy and angle dependent response. Contributions from both collimated and focussed components must be identified and separated in order to determine abundance ratios and ultimately absolute abundances. If required the focussed component can be removed by increasing the surface roughness of the microchannel walls by an etching process as was the case for EXOSAT, where the MCP collimators were bathed in hydrogen fluoride to reduce the inherent reflectivity of the MCP channel walls (Abbey, 2005).

4.6 Conclusions

X-ray measurements of planetary surfaces have conventionally been made by instruments with an X-ray detector whose field of view is limited by a collimator with a planar geometry and triangular transmission function. Although the majority of these instruments, from Apollo to the present day, have used gas proportional counter detectors a new generation of instruments from Europe and Japan are employing solid state detectors for the first time. The planar collimator geometry however has remained the same in all cases but is not optimal for measurements of extended sources.

A slumped collimator geometry provides a grasp which is comparable with that of a planar geometry but allows the separation of collimator and detector and a reduction in the detector area/collimator area required by a factor of 4. This separation and size reduction reduces an instrument’s minimum detectable flux and has specific advantages for solid state detectors in terms of detector heating, radiation exposure and the cost of detector fabrication.

The slumped geometry has an increased full width zero maximum field of view compared with a planar collimator and will therefore have a reduced surface resolution if the field of view is defined by the full width zero maximum. The full width half maximum field of view of the slumped collimator is equal to the full width zero maximum of a planar collimator and can be used to define the field of view as the contribution at larger angles is small. If required the field of view of a slumped collimator can be limited by profiling to alter the aspect ratio as a function of position on the collimator face.

Owing to their heritage as X-ray collimators on EXOSAT and their development as slumped X-ray optics with similar geometries to that described here, square channel MCPs are ideal as collimators for an instrument with a slumped collimator geometry. The intrinsic X-ray reflectivity of the channel surfaces, unless reduced through etching, leads to a focussed component, with advantages in terms of soft X-ray flux but which will cause difficulties for elemental abundance determination. A future study to quantify the relative magnitudes of these two components, as a function of angle and energy, and the ease of
separation of these two components for composition calculations may be required for future instrument optimisation. Here it has been assumed that detected fluxes contain no reflected component (i.e. the microchannels have a high surface roughness).

The slumped collimator geometry is a new instrument design for the remote sensing of X-rays from planetary surfaces from orbit. It has a particular application to extreme radiation and thermal environments and has been adopted as a high throughput channel for the Mercury Imaging X-ray Spectrometer (MIXS) on the BepiColombo mission to Mercury, which is described in detail in Chapter 5.
CHAPTER 5

The Mercury Imaging X-ray Spectrometer

5.1 Introduction

The Mercury Imaging X-ray Spectrometer (MIXS) is a key instrument in the science payload of BepiColombo’s Mercury Polar Orbiter (MPO), one of two spacecraft which make up the BepiColombo mission; the other being the Japanese Mercury Magnetospheric Orbiter (MMO). The MIXS instrument has two channels: MIXS-C is a high throughput collimated channel based on the geometry described in Chapter 4, and MIXS-T is an imaging X-ray telescope providing 2 arcminute angular resolution using MCP Wolter optics. The two MIXS channels are shown together in Figure 5.1. MIXS-T is derived from the earlier HERMES imaging spectrometer proposal to ESA (Owens et al., 2001). In this Chapter the optimisation of both MIXS channels is described and the overall performance of the MIXS instrument at Mercury is predicted. The global composition maps produced by MIXS will have a spatial and spectral resolution superior to that achieved by any orbital X-ray spectrometer on any previous planetary mission.

Figure 5.1. Schematic overview of MIXS showing both the imaging and collimating channels (from the MIXS Science and Technology Plan., 2004).

All previously flown instruments for X-ray fluorescence observations from orbit rely on collimators to restrict their FOVs and have no imaging capability as the collimator’s acceptance angle defines the angular resolution. Maps of a surface are produced by the combination of separate spectral measurements, which are later combined. The D-CIXS instrument on SMART-1 has three collimator facets, one with an 8° FOV and two with 12° FOVs (Grande et al., 2001). Such fields are typical for collimated X-ray spectrometers of this type and result in large surface footprints, placing severe limits on the spatial resolution of elemental composition maps. The XRS on NASA’s MESSENGER mission to Mercury uses
a 12° Be-Cu honeycomb collimator which, when coupled with the highly elliptical MESSENGER orbit, results in a surface footprint of approximately 3000 km at apoherm (15193 km) (Starr et al., 2001). At this spatial resolution the entire planet essentially subtends one image pixel. At periherm (200 km) the footprint is reduced to 40 km but this resolution is only available for 15 minutes in each 12 hour orbit. A characteristic crater size in the Hermetian highlands is 120 km (Strom and Sprague, 2003), so the MESSENGER XRS will therefore only resolve inter-crater features on this scale for a small fraction of its orbit. To resolve structure and inter-crater compositional variations X-ray spectra with a surface resolution of less than 120 km are required throughout the orbit. A resolution of less than 1 km will approach that of instrumentation imaging at complementary wavelengths such as the optical and the infrared for which surface resolutions of between 50 and 500 m are required (ESA Science requirements document for BepiColombo, 2004). MIXS-T will have an unprecedented surface resolution of 200 m at periherm.

The collimated gas proportional counters (GPCs) of the Apollo 15 and 16 era produced Al/Si and Mg/Si abundance ratios for equatorial regions of the Moon (Adler et al., 1972), which were used to identify highland and maria rock types. One benefit of the ratioing process was believed to be the removal of any signal changes resulting from physical variations in the regolith such as surface roughness (Clark and Trombka, 1997a) but it was also a necessity as an insufficient range of elemental line energies were observable with these instruments to allow the determination of absolute abundances. The dependence of the intensity variation of emission lines of different energies owing to irregularities in the surface geometry was deemed to be weak by the team developing the instrument and ratioing was expected to remove geometric influences on the signal (Adler et al., 1972a, b, c, Starr et al., 2000). Okada et al. (2002 and 2004) present results which suggest that for observation angles other than normal incidence the detected intensity of fluorescent X-rays from a surface with micron scale surface roughness, comparable with a planetary or asteroidal surface, will vary with energy. The energy dependence makes this ratioing process alone unreliable as a means of determining rock types at large observation and illumination angles. Okada et al. (2004) concludes that this effect is sufficient to change the meteoritic analogue of asteroid 433 Eros (meteorite type to which 433 Eros can be likened) as determined from Mg/Si and Ca/Si ratios measured by the collimated GPC X-ray spectrometers on NEAR-Shoemaker (Trombka et al., 2002). For nadir observations of large objects such as Mercury, the observation angle across the FOV ~ 0 and so roughness is unlikely to significantly affect the energy distribution of the outgoing flux. The incident angle of incoming solar X-rays will vary across a hemisphere, however, with a resultant variation in the fluorescent flux observed from orbit.
5.2 MCP Wolter optics for MIXS-T

5.2.1 Wolter optical geometries

For any optical system to form an image it must satisfy the Abbe sine condition, that for each ray of a parallel beam from a source at infinity

\[ \frac{h}{\sin \theta} = F, \]  

(5.1)

where \( h \) is radial distance from the optical axis, \( \theta \) is the angle subtended by the ray’s final path relative to its incident path and the focal length \( F \) is a constant for all rays. Wolter (1952a,b) showed that successive grazing incidence reflections from a paraboloid and then a confocal and coaxial hyperboloid, shown in Figure 5.2, will approximately satisfy the Abbe sine condition.

Wolter proposed three possible reflection modes for grazing incidence focusing using this optical geometry. In Type I images are formed after single consecutive internal face reflections at the paraboloid and then the hyperboloid. Type II focuses by means of an internal face reflection at the paraboloid followed by an external face reflection at the hyperboloid. Type III uses an external face reflection followed by an internal face reflection.

Mathematical treatments of the Wolter type I geometry are given by Mangus and Underwood (1969) and VanSpeybroek and Chase (1972) and Michette (1993). If an incoming X-ray strikes the paraboloid at \( P_1(x_1, y_1, z_1) \) and the hyperboloid at \( P_2(x_2, y_2, z_2) \) then, in the \( x=0 \) \((y,z)\) plane shown in Figure 5.2, the mirror surfaces are generated by the equations,

\[ y_p(z) = \sqrt{p(2z + p)}, \]  

(5.2)
for the paraboloid where the factor $p$ is defined as

$$\begin{align*}
p &= F_1P_1 - z_1 \\
\text{and}
\end{align*}$$  \hfill (5.3)

and

$$y_h(z) = \sqrt{\frac{b^2(z-e)^2}{a^2} - b^2}$$  \hfill (5.4)

for the hyperboloid where

$$a = \frac{1}{2}(F_1P_2 - F_2P_2)$$  \hfill (5.5)

and the eccentricity $e$ is given by

$$e^2 = a^2 + b^2.$$  \hfill (5.6)

The path of a ray through a Wolter type I imaging system is illustrated in Figure 5.2. By considering the incident and reflected angles of rays at each of the two mirrors an expression for the focal length of the telescope $F = F_2$ in terms of the lens radius $R_0$, measured from the intersection of the two mirrors to the optical axis, and the total angular change in ray direction, $\alpha_2$, or the incidence angle of the ray, $\alpha_1$, can be derived; provided that at the mirror boundary the incident angles on both the hyperbola and the parabola are equal \textit{(VanSpeybroek and Chase, 1972)}. The Focal length $F$ is given by the expression

$$F = \frac{R_0}{\tan \alpha_2} = \frac{R_0}{\tan 4\alpha_1^*},$$  \hfill (5.7)

where $^*$ denotes reflections at the paraboloid-hyperboloid boundary. If this mirror boundary condition is met then the collecting area and short wavelength X-ray reflectivity are maximised for a given diameter to focal length ratio, with little loss of angular resolution. In addition it can also be shown that at the interface between the two mirrors the angle subtended by the tangent to the parabola and the optical axis ($\theta_p^*$) and the tangent to the hyperbola and the optical axis ($\theta_h^*$) are related by,

$$\theta_h^* = 3\theta_p^* \text{ \textit{(VanSpeybroek and Chase, 1972)}.}$$  \hfill (5.8)

### 5.2.2 MCP conic approximations to Wolter geometry

A conic approximation to the Wolter geometry employs two cones, whose angles satisfy the conditions required for Equation 5.7 to be valid and for which Equation 5.8 must therefore apply at the interface between the two cones. If the conic section is provided by an MCP microchannel then the lengths $L_{\text{parab}}$ and $L_{\text{hyperb}}$ are small and deviation from an ideal conic section will also be small. \textit{Price (2001)} gives a detailed description of the microchannel conic approximation to Wolter imaging systems, which is summarised here.

In an MCP Wolter optic the two consecutive MCPs are slumped such that their faces form sections of spheres with radii $R_1$ and $R_2$ to provide the necessary conic sections. From Equation 5.18 the relationship between the two slump radii is

$$R_1 = 3R_2$$  \hfill (5.9)
By analysing the path of rays through such an optical arrangement a lens equation for the system can be derived as

\[
\frac{1}{L_I} = \frac{2}{R_i} - \frac{2}{R_i} - \frac{1}{L_S},
\]

where \( L_I \) and \( L_S \) are the image and source distances respectively, for a Wolter Type I optical arrangement. The MCP will only approximate a Wolter type I optic if the ray reflected from the internal surface of the first optic (i.e. that facing the optical axis) is then incident on the internal surface of the second.

### 5.2.3 Profiling

![Figure 5.3. Profile shape of an MCP Wolter optic defined by Equation 5.11 (after Price, 2001).](image)

The effective area of an MCP optic to on axis sources can be increased substantially if the aspect ratio of microchannels is varied as a function of position on the optic. For the ideal Wolter system every ray will undergo only one reflection in each optic. For an MCP Wolter optic Willingale (1994) derives the profile for both front and rear optics to be

\[
\frac{L}{D} = \frac{R_i}{\sqrt{x^2 + y^2}} = \frac{3R_2}{\sqrt{x^2 + y^2}},
\]

where \( x \) and \( y \) are the distance of a given microchannel from the optical axis. The profile of an MCP Wolter optic is shown in Figure 5.3.

### 5.3 Monte Carlo raytracing of MCP optics

The performance of MCP optics can be modelled using Monte Carlo raytracing. A Monte Carlo approach allows the observation of artefacts resulting from various reflection modes which are not focussing (e.g. single reflections in only one MCP optic), effective area determination and the generation of synthetic images. The effective area of an MCP optic is governed by its open area fraction, the geometrical area for X-ray interaction at grazing incidence and by physical equations governing X-ray interactions with the reflecting surfaces.

In a Monte Carlo raytrace model, a single ray is followed through the optical system. Each time the ray interacts with the MCP the physical equations governing the processes of reflection and absorption are used to calculate the probability of an event occurring (e.g. reflection at a given surface). A random number generator is used together with these event probabilities to determine the onward path of the X-ray. Repeating this process for a statistically significant number of rays allows the prediction of the bulk
performance of the X-ray optic. By changing the physical properties of the materials used and the
geometrical parameters of the MCPs, the optics can be optimised for a given application.

5.3.1 Raytrace model structure

The raytrace model described here was originally designed to model the performance of the first
generation of square packed, square pore MCP optics, which could only achieve point to point focussing
(Brunton, 1994), and later the slumped Lobster’s eye optics (Brunton et al., 1997) described in Chapter 1.
It was later modified by Price (2001) to model MCP Wolter optics and to operate into the hard X-ray (>10 keV) region. The model is based on a system using vector coordinates to describe the passage of rays
through the optical system. This coordinate system has a Cartesian origin \( x = y = z = 0 \) defined at the
centre of curvature of the first slumped MCP optic, shown in Figure 5.4. The optical axis of the system is
the \( z \) axis. A ray’s starting point is defined by a Cartesian coordinate \( a \), and its direction is given by a unit
vector direction \( b \). A magnitude scalar \( t \) extends the path of the ray. The uninhibited path \( r \) of a ray is
therefore given by

\[
r = a + bt. 
\]

\[ \text{Figure 5.4. The coordinate system of the raytrace model, the x axis is in the plane of the paper.} \]

Rays are generated at a source and are incident on the optic within specified area and angular constraints,
which are source specific. Rays from infinity are modelled by setting their angular divergence equal to
zero and setting the source emission area equal to the geometrical area of the MCP optic. The interception
of the ray with the optic’s front is defined where

\[
r.r = R_{\text{slump}}^2. 
\]

Having defined the optic’s geometrical parameters, open area fraction, multifibre size and packing
geometry, it can be determined whether or not an incident ray enters a channel or strikes the interchannel
web. At interception with the front face of the MCP optic the probability that the ray enters a channel is
calculated and the Monte Carlo process determines whether or not it enters. If a ray enters a channel then
the channel co-ordinates are recorded before the channel is transformed onto the optical axis by rotation
about the origin. This transformation allows the reflectivity subroutine which follows to remain
 universally applicable to all rays. For X-rays incident on the interchannel web the probability of transmission of the ray through the MCP glass into an adjacent channel is calculated. For X-ray energies of less than ~5 keV this calculation is superfluous as there is a very high probability of absorption. For hard X-rays with energies up to 100 keV transmission becomes important as X-rays can pass through the glass and enter adjacent microchannels. The transmission calculation is described in Section 5.3.2.

Upon entering a channel the point of interception and angle of incidence of the ray with the channel wall is determined and the probability of reflection from the channel wall is then calculated. If the Monte Carlo process deems that the ray is reflected then any deviations from the specular direction are determined according to the surface roughness of the microchannel wall. The ray vector is then changed to

\[ \mathbf{r} = \mathbf{c} + s \mathbf{d}, \]

where \( \mathbf{c} \) is the point of reflection and for specular reflection (Figure 5.5) the unit vector \( \mathbf{d} \) is given by

\[ \mathbf{d} = 2 \hat{n} \cos \theta_{\text{inc}} + \mathbf{b} \]

Where \( \hat{n} \) is the unit normal to the microchannel wall and \( \theta_{\text{inc}} \) is the incident angle of the X-ray measured from the surface normal given by

\[ -\hat{n} \cdot \mathbf{b} = \cos \theta_{\text{inc}}. \]

The path of the ray is followed until it is incident on another surface where the process is repeated or leaves the first MCP. Upon incidence at the second MCP the process is repeated. Eventually the X-ray becomes extinct or is incident on the detector plane, where it is registered. This process is repeated for a statistically significant number of rays.

**5.3.2 X-ray transmission**

When an X-ray is incident on the MCP interchannel web there is a probability that it will be absorbed by the MCP glass. The probability of X-ray absorption is dependent on the complex refractive index of the material, given by Equation 1.1 as

\[ n = 1 - \delta - i\beta. \]

The coefficients \( \delta \) and \( \beta \) are the refractive index decrement and the absorption index, which are given by

\[ \delta \]
\[ K_f = \frac{\delta}{2 \pi} \]  
\[ \beta = K f_2 \]  
where
\[ K = \frac{r_0 \lambda^2 N_A}{2 \pi} \rho, \]  
\[ r_0 \] is the classical electron radius (given by \( e^2/4\pi \varepsilon_0 m_e c^2 = 2.8179 \times 10^{-15} \text{m} \)), \( N_A \) is Avogadro’s number, \( A \) is the atomic number of the material and \( \rho \) is the material density. The factors \( f_1 \) and \( f_2 \) are the atomic scattering factors which have been calculated from quantum mechanical models for electrons around an atom of given \( Z \) (Cromer and Liberman, 1970, Henke, 1981).

From the complex refractive index the linear absorption coefficient, \( \mu_{ab} \), can be calculated,
\[ \mu_{ab} = \frac{4 \pi f \beta}{\lambda}, \]  
where \( \lambda \) is the X-ray wavelength. Beer’s law gives the change in intensity, \( I \), for an X-ray beam with distance into a material, \( t \),
\[ I = I_o e^{-\mu_{ab} t}. \]  
The probability, \( P_{\text{trans}} \), of transmission for a single X-ray through a thickness of MCP glass \( t \) is therefore
\[ P_{\text{trans}} = e^{-\mu_{ab} t}. \]  
The values for \( \mu_{ab} \) used in this thesis are calculated from the tabulated scattering factor values of Cromer and Liberman (1970) using the routine Xopt (Willingale, 1994).

5.3.3 X-ray reflectivity

In Chapter 2 the composition of MCP detector glass is examined and is shown to have a multi layer structure close to the microchannel surface. MCP optic glass is identical in bulk composition to detector glass but does not undergo reduction in hydrogen and as a result differs in composition close to the microchannel surface. Experimental investigations into the reflectivity of MCP glass have shown that bare glass MCP reflectivity is in good agreement with the modelled reflectivity of a lead/bismuth depleted glass MCP layer, \(~150 \text{ Å}\) thick, upon a substrate with the MCP glass bulk composition of Chapter 2. Reflective metal coatings, deposited onto the microchannels to increase reflectivity, are modelled as 150 Å layers on a substrate of bulk MCP glass.

The X-ray reflectivity is determined in the raytrace model by an evaluation of the Fresnel equations at the boundary between two media (Henke, 1981) by the Rex algorithm (Crabb et al., 1993). The multi layer reflectivity is also calculated by Rex using the formulae of Parratt (1954) which gives the reflectivity coefficient at the plane, parallel interface between two homogenous layers \( n \) and \( n-1 \) as
\[ R_{n-1,n} = a_{n-1}^4 \left( \frac{R_{n,n+1} + F_{n-1,n}}{R_{n,n+1} F_{n-1,n} + 1} \right) \]  
Where the layer \( n+1 \) is a vacuum in this case and
\[ F_{n-1,n} = \frac{f_{n-1} - f_n}{f_{n-1} + f_n} \]  \hspace{1cm} (5.24)

and

\[ f_n = \left( \phi^2 - 2\alpha_n - 2i\gamma_n \right)^{\frac{1}{2}} \]  \hspace{1cm} (5.25)

where \( \phi \) is the X-ray grazing angle. The coefficients \( \alpha \) and \( \gamma \) are given by \( \delta/2 \) and \( \beta/2 \) respectively and define the complex dielectric constant

\[ k = \alpha + i\gamma. \]  \hspace{1cm} (5.26)

The factor \( a_n \) is the amplitude reduction factor defined as

\[ a_n = \exp\left(-i\frac{\pi f_d d_n}{\lambda}\right) \]  \hspace{1cm} (5.27)

where \( d_n \) is the thickness of the \( n \)th layer.

### 5.3.4 Surface roughness

The surface of a microchannel is not perfectly smooth and will not therefore produce perfect specular reflection. The roughness of the microchannel surface is accounted for in the raytrace model by the modification of the coefficient \( F_{n-1,n} \) by a Debye-Waller factor (Beckmann and Spizzichio, 1963) to

\[ F'_{n-1,n} = F_{n-1,n} \exp\left(-\frac{1}{2} \left( \frac{4\pi\sigma \sin \theta}{\lambda} \right)^2 \right), \]  \hspace{1cm} (5.28)

where \( \sigma \) is the rms roughness of the surface. The deviation of the angle of reflection from the specular direction is determined according to a Gaussian distribution whose root mean square magnitude in radians is given by

\[ \psi_{\text{scatter}} = \frac{\lambda}{\tau \sin \phi}, \]  \hspace{1cm} (5.29)

where \( \tau \) is the correlation length of the surface roughness, which is assumed to have a sinusoidal height distribution (Willingale, 1994).

### 5.4 The Mercury Imaging X-ray Spectrometer (MIXS)

MIXS combines the high X-ray collection efficiency of MIXS-C across a wide range of energies, allowing statistically significant flux detection for a wide range of line energies and for all solar states, with sub-km spatial resolution provided by MIXS-T for soft X-rays during medium to high solar states. Both channels require shielded, radiation hard, solid state detectors as Mercury is expected to be a high radiation environment and fluxes of energetic protons is expected to be high. An energy resolution of approximately 200 eV is required to allow proper separation of spectral lines from elements key to an understanding of the planet, given in Table 3.1, between 0.5 and 2 keV. X-ray imaging with MCP Wolter type I optics has been reported by Willingale et al. (1998) and Price (2001). The application of these optics for remote sensing at planetary bodies has been described by Bavdaz et al. (2002).
Figure 5.6. Comparison of flat and slumped collimators. R is the slump radius of the slumped collimator.

MIXS-C employs a spherically slumped MCP collimator instead of a conventional planar collimator (Figure 5.6). This collimator configuration provides a collecting power comparable with that of a flat collimator whilst allowing the use of a smaller detector which is physically separated from the collimator. This collimator geometry and its advantages over conventional collimator designs for planetary remote sensing are described in detail in Chapter 4. The extended collimator length also allows the detectors for both MIXS channels to share similar detector planes and a common design. For MIXS these detectors are nominally mosaics of four radiation hard, GaAs active pixel arrays (Owens et al., 2002; Bavdaz et al., 2002) with 32 x 32 ~300 µm square pixels, which are cooled to a temperature of approximately -10 °C. A carbon fibre telescope tube acts as additional shielding from background X-ray fluorescence and from the spacecraft structure (MIXS Science and Technical plan., 2004).

### 5.4.1 Imaging channel

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>1m</td>
</tr>
<tr>
<td>Front MCP slump radius</td>
<td>4m</td>
</tr>
<tr>
<td>Rear MCP slump radius</td>
<td>4/3m</td>
</tr>
<tr>
<td>Channel diameter</td>
<td>50µm</td>
</tr>
<tr>
<td>Channel Pitch</td>
<td>55µm</td>
</tr>
<tr>
<td>Channel Length</td>
<td>5000µm</td>
</tr>
<tr>
<td>Microchannel coating</td>
<td>Ni or Au (150Å thickness)</td>
</tr>
<tr>
<td>Core diameter at centre of radially packed optic</td>
<td>6mm</td>
</tr>
<tr>
<td>FOV</td>
<td>1° half angle</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2 arc minutes (optic)</td>
</tr>
<tr>
<td>Detector</td>
<td>GaAs active pixel array (4cm)</td>
</tr>
</tbody>
</table>

Table 5.1. Key parameters for the original HERMES telescope concept (Owens et al., 2001).

The original imaging X-ray spectrometer proposed for BepiColombo was called HERMES (Owens et al., 2001). The MCP optics proposed for HERMES were not optimised and in this section the telescope is optimised to enhance the science return of the instrument and practicalities of the design. Table 5.1 gives
values for key parameters of the optics in the original HERMES proposal. The optic is an MCP Wolter optic made from radially packed square pore MCPs. The optic diameter is 21 cm.

5.4.1.1 Microchannel surface coating
MCP optics are manufactured from unreduced silicon lead glass (Chapter 2), from which X-ray reflectivity rapidly falls off as energy is increased above ~2 keV. For most practical applications and in particular for planetary measurements, where detection of the Fe-K X-ray emission line, at 6.4 keV, may be required, it is important to extend this energy range. Coating the microchannel walls with high reflectivity and low surface roughness metal films, can significantly increase the effective area and the energy range of these optics (Peele et al., 1998; Willingale et al., 1998; Martin et. al., 1999). The coating material must be selected on the basis of its own reflectivity versus energy profile and the position of its absorption edge. For MIXS-T the requirement is to maximise the effective area ($A_e$) of the optic at energies corresponding with X-ray emission from the key elements given in Table 3.1.

The Raytracing model described in Section 5.3 has been used to investigate the performance of the MIXS-T MCP optic for different coating materials. The optic parameters used were those given in Table 5.1, but with different coating materials. A root mean square surface roughness of 10 Å is assumed and the MCP microchannels are modelled as being perfectly aligned. The calculated effective area, $A_e$, as a function of energy for bare glass, nickel, gold and iridium channel coatings is shown in Figure 5.7. The coating is assumed to be 150 Å thick in each case. Uncoated glass is modelled as a bilayer with a 150 Å surface layer of lead/bismuth depleted MCP glass on a substrate of bulk MCP glass (Brunton et al., 1999). Figure 5.7 also shows the emission energies of the K series X-ray emission lines of some key elements of interest in the context of observations of Mercury. By selecting Ir as the coating of choice the energy range of the instrument is extended significantly and $A_e$ is increased at all energies above 1 keV. There is a small loss of effective area below 1 keV compared to bare glass. Although effective areas for Ni are in general greater for most elements of interest shown in Figure 5.7, the improvement in effective area at Fe-K is significant enough that Ir has been deemed to be a preferential coating. A programme to test the reflectivities of coated MCP optics using the Daresbury Synchrotron Radiation Source (SRS) is ongoing and some preliminary results have been obtained (Nussey, 2005). Note that the coated MCPs investigated by Nussey are early production samples, and a programme to optimise the coatings is currently underway (Fairbend, 2005; Aaltonen et al., 2004). The primary driver for the choice of coating for MIXS-T will in fact be the maturity of the coating technology and the quality of the coatings produced, though the energy of secondary fluorescence emission from the coating is also a factor in their selection. The results of the reflectivity studies made to date indicate that iridium is the coating with the highest quality.
Figure 5.7. Variation of effective area with energy for the HERMES format optic with different coatings. Other MCP format variables remain the same as in Table 5.1.

5.4.1.2 Focal length and profiling

Figure 5.8. Variation of effective area with energy curves for profiled and non-profiled, iridium coated, MCP Wolter optics for the telescope with different focal lengths. a-e indicate Ir absorption edges $M_I-M_V$: $a=2.040$ keV; $b=2.116$ keV; $c=2.551$ keV; $d=2.909$ keV; $e=3.174$ keV. Energies of the K-shell fluorescence emission for key elements are also shown.
The proposed BepiColombo spacecraft bus has a depth of 70 cm (ESA-SCI(2000)1) compared with a nominal baseline focal length for the optic of 1m (Owens et al., 2001). This adds difficulty to accommodation of the optic in the spacecraft and requires that the telescope be extended beyond the edge of the spacecraft. The focal length of the optic can be altered to match the bus depth by altering the slump radii of the front and rear MCPs in accordance with Equations 5.9 and 5.10 but as focal length is reduced grazing incidence angles are increased. This reduces the probability of reflection and effective area is reduced. The modelled effective area curves for Ir coated optics with focal lengths of both 70 cm and 1 m are shown in Figure 5.8. Reducing the focal length from 1 m to 0.7 m results in ~30% decrease in on axis effective area arising from the increased grazing angles required. This reduction in effective area is significant and will result in a significant loss of flux. This unacceptable especially at higher energies (e.g. Fe-K at 6.4 keV) where X-ray fluxes and effective area are both low. Thus a system to maintain a 1 m focal length is preferred. A reduction in focal length should be avoided and a 1 m focal length is assumed in all further calculations.

Altering the aspect ratio of the MCP as a function of distance from the optic centre, or “profiling”, according to Equation 5.11, increases the effective area by maximising the probability of a reflection occurring in a channel for an on axis X-ray. The curves in Figure 5.8 compare the on-axis effective area with energy for a profiled optic and a non-profiled optic with a 100:1 channel aspect ratio. Profiling results in a peak increase in effective area of approximately 450%. Figure 5.8 also shows the influence of the Ir M-edges (Thompson et al., 2001) between 2.04 and 3.174 keV on $A_e$ at the energies of fluorescent lines from Ca, Ti and Fe.

5.4.1.3 Core diameter

The MCP optic will have a non-focussing, opaque central core. This core has a nominal diameter of 6 mm following Bavdaz et al. (2002), Owen et al. (2001) and Price (2001). The final diameter of this central core is not yet defined but will be dependent on the support requirements for the optic. It has been suggested that the diameter should be extended by up to ~15 mm to allow for the structure to support the mosaic of MCPs which will make up the optic (Pearson, 2004). The resultant change in effective area is shown in Figure 5.9. The larger core size has a negative effect on effective area, reducing the effective area by approximately 10% below 1 keV and by approximately 5% for energies beyond the Ir absorption edge. Minimisation of the core diameter is required but this will be constrained primarily by practical support requirements the details of which are yet to be determined.
Figure 5.9. Variation of effective area with energy for a profiled, Ir coated, MIXS-T optic with core diameters of 6 mm and 15 mm. Other variables describing the optic format are as in Table 5.1.

5.4.1.4 Microchannel diameter

Figure 5.10. Variation of effective area with energy of the baseline optic (50 µm pore side length, 55 µm pitch and 21 cm diameter) and an “optimised optic” (20 µm pore diameter, 22 µm pitch and 21 cm optic diameter).
The nominal square pore diameter for both front and rear MCPs is 50 µm with a pitch of 55 µm, and the nominal diameter of the optic is 21 cm following Price (2001) and Bavdaz et al. (2002). To achieve a 2 arcminute angular resolution at 1 m the instrument must have a full width half maximum focus in the focal plane of less than $F \tan(2 \text{arcminutes}) = 582 \mu m$. This is also the minimum pixel size required for a pixelated focal plane detector. Raytracing shows that the nominal 50 µm microchannel side length MCP format has a FWHM focus of approximately 800 µm corresponding to a 2.75 arcminute resolution, and not the sub 2 arcminute resolution required. A reduction in pore diameter to 20 µm, whilst holding the open area fraction constant, is found to increase the resolution of the telescope to ~400 µm in the detector plane, corresponding to an angular resolution of 1.38 arcminutes. Comparable resolutions have already been achieved in prototype MCP Wolter optics with 10µm channel diameters (Price et al., 2002). In true optics the resolution will be limited by microchannel misalignments. A recent ESA Technology Research Programme at Photonis SAS (Brive) has sought to minimise the problems of channel misalignment and so perfectly aligned channels have been assumed in these simulations.

Figure 5.10 compares a 1m focal length, profiled, Ir coated optic with a 15 mm diameter core size and 50µm diameter microchannels, with a similar telescope using an optic with 20 µm diameter pores. A significant increase in effective area is observed across all energies for the latter design. A reduction in pore size reduces the lengths of microchannels and increases their number. In doing so the conic approximation of the MCP to the Wolter geometry is improved leading to an increase in effective area.

5.4.1.5 Off axis vignetting and detector size

The off axis vignetting function is given by the effective area at an off axis angle $\theta$ as a fraction of the on axis effective area. The vignetting function calculated by raytracing for the profiled optic with a 1m focal length is shown in Figure 5.11 including a 6th order polynomial approximation to the vignetting function at 2500 eV. The HERMES telescope’s FOV was stated to be 2°, for which there must be an appreciable effective area at 1° off axis. Figure 5.11 shows the off axis vignetting function of the MIXS-T optic simulated by raytracing 100000 rays through a profiled 210 mm diameter optic with a 15 mm diameter core and 20 µm side length pores on a 22 µm pitch. The surface coating is 150 Å of iridium with a 10 Å rms surface roughness. The effective area is dominated by flux within 0.5° of the optical axis. The FOV may therefore be reduced to 1° to achieve a reduced focal plane size with a minimal loss of detected flux. The area under the curve in Figure 5.11 within 0.5° of the optical axis is 79 % of the total within 1° at 0.5 keV increasing to 96 % at 5 keV. Reducing the focal plane to 1° may prove optimal for MIXS but the remaining calculations here assume a 2° FOV in order to maximise the observed flux.
Also shown in Figure 5.11 are 6th order polynomial approximations to the vignetting function $V(\theta)$ at each energy. The fluctuations in the vignetting functions shown in Figure 5.11 result from statistical variations in the Monte Carlo raytrace model and are not real. It is therefore justified to apply polynomial smoothing functions for the following analyses. The polynomials are, for 500 eV;

$$V(\theta) = 1.696\theta^6 - 3.0613\theta^5 + 11.309\theta^4 - 17.753\theta^3 + 13.849\theta^2 - 5.5098\theta + 1.0898,$$

for 1 keV;

$$V(\theta) = 1.0979\theta^6 - 7.3117\theta^5 + 18.822\theta^4 - 24.149\theta^3 + 16.478\theta^2 - 5.9385\theta + 1.0815,$$

for 2.5 keV;

$$V(\theta) = 2.384\theta^6 - 13.788\theta^5 + 31.664\theta^4 - 36.751\theta^3 + 22.761\theta^2 - 7.3488\theta + 1.0865,$$

for 5 keV;

$$V(\theta) = 4.157\theta^6 - 22.37\theta^5 + 47.875\theta^4 - 51.806\theta^3 + 29.818\theta^2 + 8.7888\theta + 1.1102.$$  

For a 2° FOV the detector plane must be large enough to view the focus generated by sources at infinity, both on axis and at 1° off axis. The off axis distance in the detector plane of a ray incident with an off axis angle of 1° is equal to $F\tan2^\circ = 3.5$ cm. Figure 5.12 shows the raytraced positions of foci in the detector plane resulting from three sources at 0 °, 0.5 ° and 1 ° off axis. A detector with a 4 cm side length and 16 cm² area is sufficient to provide a 2° FOV. If a 1° FOV is adopted in the detector plane then a detector of side length 2 cm and area 4 cm² is sufficient. Accepting a MIXS-T FOV of 1° rather than 2° will therefore allow a reduction in the required focal plane detector area by a factor 4, with little loss of flux. This will allow the use of a single 32x32 pixel GaAs active pixel sensor in the detector plane instead of the mosaic of four originally proposed.
The coma in Figure 5.12 is the result of rays undergoing a single reflection in the second MCP (even-odd reflections) only. The fraction of rays in the coma for the 0.5° off-axis case is approximately 14 % of those in the focus, rising to approximately 33 % in the 1° off-axis case.

![Raytraced image of the telescope (focal length 1m) detector plane for point sources at infinity, 0°, 0.5° and 1° off axis.](image1)

**Figure 5.12.** Raytraced image of the telescope (focal length 1m) detector plane for point sources at infinity, 0°, 0.5° and 1° off axis.

5.4.1.6 MIXS-T performance

![Graph showing variation of on axis effective area for MIXS-T as a function of energy including a 21 cm diameter, profiled MCP optic with perfectly aligned 20 µm wide pores, a 150 Å thick Ir coating with 10 Å rms surface roughness, an 80 nm Al optical filter, a GaAs detector with a 100 µm depletion depth and varying GaAs substrate dead layer thickness.](image2)

**Figure 5.13.** Variation of on axis effective area for MIXS-T as a function of energy including a 21 cm diameter, profiled MCP optic with perfectly aligned 20 µm wide pores, a 150 Å thick Ir coating with 10 Å rms surface roughness, an 80 nm Al optical filter, a GaAs detector with a 100 µm depletion depth and varying GaAs substrate dead layer thickness.
The effective area curves presented thus far assume a 100 % efficient filter and detector. Figure 5.13 introduces the response of an 80 nm thick Al optical filter and a GaAs detector with a 100 µm depletion layer. The thickness of the detector dead layer, in which incomplete charge collection occurs, is varied between 0.01 µm and 0.1 µm. The design goal for these detectors is 0.05 µm.

5.4.2 Collimating channel

The high spatial resolution and narrow FOV of MIXS-T is complemented by MIXS-C’s lower angular resolution but larger collecting power. The aspect ratio of the MIXS-C microchannels is chosen to provide the required acceptance angle for the energy independent “straight through”, collimated component of the flux. The collimated channel’s large collecting power, quantified by the grasp which is defined in Chapter 4, compared with that of the imaging channel, ensures global coverage at low spatial resolution for all levels of solar activity. The collimator’s grasp is also independent of energy, providing a greater number of counts at all energies and hence improved statistics in measurements of X-ray emission lines and the resultant calculated surface elemental abundances. This is of particular use for surface elements emitting X-rays at energies greater than 2 keV for which MIXS-T’s effective area is low.

5.4.2.1 Collimator geometrical parameters

The BepiColumbo Spacecraft bus is nominally a cube with a 70 cm side length and it is assumed that cooling of the detectors for both channels will be provided by a single cold finger in the focal plane of the telescope. Both channels must have the same pointing direction and should use GaAs detectors of identical format. The width of the square MCP collimator is 8cm and the “focal” length of the collimator is selected to be 50 cm, 20 cm shorter than the bus length and requiring an MCP slump radius of 1 m. The 20 cm shortfall in length can be made up by the introduction of a cold shelf shown in Figure 5.1 (MIXS Science and Technical plan, 2004). Lengthening the collimator reduces both the FOV and the collimator grasp. A 50 cm collimator length is a trade off between maintaining the high grasp of an \( R = 40 \) cm collimator calculated in Chapter 4 and accommodation within the spacecraft. The detector is nominally a 4cm mosaic (half the collimator side length) of four 32x32 pixel GaAs active pixel arrays, identical to that used for the telescope. Matching the aspect ratio of the collimator to the subtended angle of the 8cm diameter slumped MCP at its centre of curvature gives an L/D of 25:1. The effective area of the MIXS-C collimator, as a function of off-axis angle, is shown in Figure 5.14. The FWHM of the curve is 4.6° and the FWZM is 9.2°. Both FWHM and FWZM can potentially be used to define the collimator’s FOV.
Figure 5.14. Effective area with off axis angle for the collimated channel accounting for the 4 cm detector size. The energy response of the detector is not accounted for.

The 4cm detector utilised by MIXS-C is too small to cover the complete “focal plane”. The fraction of transmitted rays hitting the detector for this collimator geometry is shown in Chapter 4 to be 0.7. Figure 5.14 shows the raytraced off axis effective area of the collimated channel, accounting for the detector’s size, but neglecting the detector’s energy response. The MIXS-C FWHM FOV is now 5.2°. The FWZM FOV is now 9.2°.

In its final configuration MIXS-C has an 8 cm side length square MCP collimator with square microchannels, which have an aspect ratio of 25:1. The MCP slump radius is 1m and the instrument has a 4cm side length mosaic of GaAs active pixel array detectors centred on the collimator axis at a distance of 50 cm from the collimator.

5.4.2.2 MIXS-C Effective Area

The flux of X-rays transmitted by a collimator is not energy dependent and so variations in the effective area with energy are due entirely to the instrument’s filter and detector. The filter and detector are assumed to be GaAs arrays identical to those on MIXS-T. Figure 5.15 shows the on axis effective area as a function of energy for MIXS-C incorporating these elements. The absorption of each layer is calculated from Beer’s law with the linear absorption coefficient calculated as described in Chapter 4.
Figure 5.15. On axis effective area as a function of energy for MIXS-C with 8 cm diameter collimator, 25:1 aspect ratio channel, 1 m slump radius, 80 nm Al filter and a 4 cm GaAs detector with 100 µm thick active region and 500 Å dead-layer thickness. The detector is located 50 cm from the collimator. The Ga, As, Ir and Al absorption edges combine to produce the sharp drop in effective area above 1 keV.

5.4.3 MIXS-T and MIXS-C Grasps

For an instrument with a circular FOV the solid angular element \( d\Omega \) subtended by an element \( d\theta \) at an off-axis angle \( \theta \) is given by

\[
d\Omega = 2\pi d\theta
\]

and the off axis effective area \( A(\theta) \) is

\[
A(\theta) = A(0)V(\theta),
\]

where \( A(0) \) is the on axis effective area and \( V(\theta) \) is the vignetting function. The instrument grasp \( G \) is therefore given by

\[
G = 2\pi A(0) \int_{\theta_{\text{max}}}^{0} \theta V(\theta) d\theta,
\]

where \( \theta_{\text{max}} \) is the off axis angle at the limit of the FOV. From Equations 5.30 to 5.33 we obtain equations for MIXS-T, for 0.5 keV

\[
\theta_{\text{max}} \int_{0}^{\theta_{\text{max}}} \theta V(\theta) d\theta = 0.0212\theta^8 - 0.437\theta^7 + 1.885\theta^6 - 3.551\theta^5 + 3.462\theta^4 - 1.885\theta^3 + 0.545\theta^2,
\]

for 1 keV;

\[
\theta_{\text{max}} \int_{0}^{\theta_{\text{max}}} \theta V(\theta) d\theta = 0.137\theta^8 - 1.045\theta^7 + 3.137\theta^6 - 4.83\theta^5 + 4.12\theta^4 - 1.98\theta^3 + 0.541\theta^2
\]
for 2.5 keV
\[
\int_{0}^{\theta_{\text{max}}} \theta V(\theta) d\theta = 0.294\theta^3 - 1.97\theta^7 + 5.277\theta^6 - 7.35\theta^5 + 5.96\theta^4
\]
\[-2.45\theta^3 + 0.543\theta^2
\]
for 5 keV
\[
\int_{0}^{\theta_{\text{max}}} \theta V(\theta) d\theta = 0.52\theta^3 - 3.196\theta^7 + 7.98\theta^6 - 10.36\theta^5 + 7.454\theta^4
\]
\[-2.93\theta^3 + 0.555\theta^2
\]
where \(\theta\) is in degrees. If \(G'\) is defined as the ratio
\[
G' = \frac{G}{A(0)} = 2\pi \int_{0}^{\theta_{\text{max}}} \theta V(\theta) d\theta
\]
then Figure 5.16 shows \(G'\) as a function of energy determined from Equations 5.37 to 5.41 for MIXS-T taking a 1° maximum off axis angle at the extreme of the FOV and converting from units of degrees\(^2\) to steradians by multiplying by the factor \(\pi^2/180^2\). Also shown is a power law approximation to \(G'(E)\) above 1 keV. In the calculations that follow \(G'\) is assumed to diverge from a power law below 1 keV and this region is treated separately as a linear extrapolation to the 0.5 keV data point. The accuracy of this approximation must be checked in future work by modelling the vignetting function at a larger number of energies, particularly below 2.5 keV. Where \(E\) is energy, the power law approximation for \(G'\) is
\[
G' = 0.0001E^{-0.8058}
\]
\[
\text{Figure 5.16. } \text{G' as a function of energy calculated from Equations 5.38 to 5.40 and a power law best fit approximation to the trend above 1 keV.}
\]
The Grasp as a function of energy for MIXS-T is now calculated from the product
\[
G(E) = G'(E)A(E),
\]
where $A(E)$ incorporates both the detector and filter responses and is shown in Figure 5.13. The MIXS-C grasp is calculated from Equations 4.18 and 4.24 and then modified by the energy dependant detector response and filter transmission of Section 5.4.2.2. The calculated grasps of both MIXS-T and MIXS-C are shown as a function of energy in Figure 5.17.

![Figure 5.17. Grasp as a function of Energy for MIXS-T and MIXS-C including theoretical detector and filter responses.](image)

5.5 Instrument performance at Mercury

By predicting solar input, calculating surface coverage over the entire mission and applying the model of surface X-ray fluorescence introduced in Section 3.2, the performance of MIXS at Mercury has been predicted. The number of detected X-rays for elemental emission lines of interest at Mercury has been predicted for both channels, assuming the surface compositions predicted by the refractory-rich and volatile-rich models of planet formation which are given in Table 4.1.
5.5.1 Solar input

**Figure 5.18.** Solar activity cycle, estimated from sunspot number for the last two 11 year solar cycles (from MIXS Science and Technology plan., 2004).

<table>
<thead>
<tr>
<th>Flare State</th>
<th>1-8 Å power range (Wm$^{-2}$)</th>
<th>Fraction of year in state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;1x10$^{-5}$</td>
<td>1996 (1988)</td>
</tr>
<tr>
<td>X</td>
<td>1x10$^{-5}$ – 1x10$^{-4}$</td>
<td>0.00001 0.00007 0.0004</td>
</tr>
<tr>
<td>M</td>
<td>1x10$^{-6}$ – 1x10$^{-5}$</td>
<td>0.0001 0.0007 0.006</td>
</tr>
<tr>
<td>C</td>
<td>1x10$^{-7}$ – 1x10$^{-6}$</td>
<td>0.0045 0.017 0.014</td>
</tr>
<tr>
<td>B</td>
<td>&lt;1x10$^{-7}$</td>
<td>0.07 0.3 0.9</td>
</tr>
<tr>
<td>Quiet Sun</td>
<td></td>
<td>0.93 0.68 0.08</td>
</tr>
</tbody>
</table>

**Table 5.2** Fraction of time measured in various flare states during years analogous to possible years of operation for BepiColombo at Mercury (data recorded by GOES 1-8 Å).

BepiColumbo is expected to operate at Mercury somewhere between 2018 and 2020. Taking sunspot number as a measure of solar activity and continuing the cyclic trend in the data shown in Figure 5.18, it is predicted that BepiColumbo will arrive at Mercury around solar minimum (MIXS Science and Technology plan., 2004). Table 5.2 gives the percentage of the nominal one year mission time that X, M, C and B flare solar states can be expected based on the assumption that solar activity at this time will be similar to that recorded between 1996 and 1998. High activity (C, M and X states), will result in high levels of fluorescence and will allow high resolution imaging of the surface by MIXS-T. These solar flare states are expected for approximately 1 % of the mission (MIXS Science and Technology plan, 2004). Such a statistical approach does not however allow for single large events such as the X-class flare of November 2003 (Liu et al., 2004).
5.5.2 Surface coverage

Figure 5.19. Change in the argument of periherm (ω). Yellow line is the plane of the ecliptic. The orbit marked in green has an argument of periherm \( \omega_1 \), the orbit marked in blue occurs at a later stage in the mission and has an argument of periherm \( \omega_2 \). The sub-satellite latitude at the two periherm points is different as the argument of the periherm has precessed. In this case, exposure times will be different for northern and southern hemispheres (image used courtesy of N. Bannister).

The surface coverage achieved by MIXS, assuming a 1° FOV over a nominal one year mission has been estimated by Bannister (2006) by solving Kepler’s equation for the published orbital parameters for the BepiColumbo Mercury Polar Orbiter (MPO) (ESA-SCI(2000)1), folding in a triangular approximation to the calculated off axis vignetting function of MIXS-T and the cosine of the angle of incidence for solar X-rays. This solution accounts for the precession of the argument of periherm, defined as the angle, in the plane of the satellite’s orbit, between the ascending node of the orbit and the periherm point, measured in the direction of the satellite’s orbit and shown in Figure 5.19. The resultant coverage map for MIXS-T during a one year nominal mission is shown in Figure 5.20 including only dayside observations, neglecting any measurements possible through particle interactions with the surface and accounting for the changing incident angle of solar X-rays.

Both MIXS instrument channels will achieve global coverage but the increased throughput of MIXS-C ensures that elemental maps of limited resolution but improved counting statistics are obtained for the entire surface. The average pixel exposure time for MIXS-T between ±70° of Mercury’s equator is \(~200 \) s. Assuming a worst case scenario in which adjacent observations do not overlap the observation time for a 2° FOV is 400 s. Removing the triangular vignetting function assumed by Bannister (2006) in this model using Equation 5.36 results in an increase to 1200 s of observation time.
Figure 5.20. Hammer-Aitoff projection showing the coverage time accumulated over Mercury’s surface by MIXS-T for the one-year nominal mission calculated by Bannister (2006). The coverage map accounts for a triangular approximation to the vignetting function and the cosine of the solar incidence angle. Variations in colour scale represent various accumulated observation times for each surface pixel.

### 5.5.3 Predicted fluxes and composition

The predicted solar state and resultant spectra calculated by the method introduced in Chapter 3 have been used to calculate the Fluorescent X-ray fluxes from the surface into $2\pi$ steradians. Solar X-rays are assumed to be at normal incidence to the planet’s surface and a sub-solar nadir view is assumed for the observations (equivalent to equatorial observations). The number of X-rays detected for each elemental line of interest and for each solar state, within a single geometrical footprint, are calculated from synthetic spectra of the type shown in Figure 3.5. The detected X-ray flux $F_{\text{line}}$, at an emission line at an energy $E_{\text{line}}$, for which fluorescent X-rays have an intensity $I_{\text{line}}$ (photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$) for an instrument with a grasp at the energy of the line $G(E_{\text{line}})$ and footprint dwell time $t$ is given by

$$F_{\text{line}} = I_{\text{line}} G(E_{\text{line}}) t, \quad (5.43)$$

The total flux detected by an instrument with a finite energy resolution $\Delta E$, including both line and continuum X-rays is given by

$$F_{\text{det}} = \int_{E_1}^{E_2} (I_{\text{line}} + I_{\text{cont}}(E)) G(E) t dE, \quad (5.44)$$

where $I_{\text{cont}}(E)$ is the continuum flux in photons/(cm$^2$ s keV), $E_1=E_{\text{line}}-\Delta E/2$ and $E_2=E_{\text{line}}+\Delta E/2$; $\Delta E$ for a GaAs active pixel array is assumed to be 200 eV at all energies as this is the resolution required for separation of the spectral lines of interest at Mercury. The pixel dwell time for MIXS-T at apoherm is 39 s and at periherm is 5.4 s. The dwell time for MIXS-C is 165.29 s at apoherm and 22.98 s at periherm (Bannister 2006). The surface area under observation will increase with the square of altitude, whilst the flux from a given area will decrease with the square of altitude. The total detected flux from the surface is therefore independent of altitude.
If a residual charged particle background is assumed to be in line with that experienced by the XMM-Newton X-ray telescope at 0.026 cm$^2$ s$^{-1}$ (Lumb, 2002) and the focal plane arrays for both channels have an area of 16 cm$^2$ then for $5\sigma$ detection of planetary emission more than 20 detected events are required at apoherm and more than 7.4 events are required at periherm, from a given footprint for MIXS-T. For MIXS-C more than 41.5 counts are required at apoherm and more than 15 are required at periherm.

Simulated spectra in counts s$^{-1}$ as a function of energy for MIXS-T and MIXS-C for B1, C1 and M1 solar flare states and assuming surface compositions in line with the refractory rich and volatile rich models of formation are shown in Figures 5.21 – 5.24. The lines are shown as Gaussian peaks with a FWHM energy resolution of 125 eV to approximate the energy resolution of the detectors, though a poorer energy resolution is likely. The predicted line and continuum fluxes detected for a single footprint measurement at apoherm and periherm, for M1, B1, C1 and solar quiet flare states are given in Tables 5.3 and 5.4 for MIXS-T and in Tables 5.5 and 5.6 for MIXS-C.

**Figure 5.21.** Synthetic X-ray spectrum of counts per second as a function of energy detected by MIXS-C for the volatile rich model of Mercury’s formation and different solar flare states. A 125 eV detector FWHM energy resolution for the GaAs active pixel array is assumed.
Figure 5.22. Synthetic X-ray spectrum of counts per second as a function of energy detected by MIXS-C for the refractory rich model of Mercury’s formation and different solar flare states. A 125 eV detector FWHM energy resolution for the GaAs active pixel array is assumed.

Figure 5.23. Synthetic X-ray spectrum of counts per second as a function of energy detected by MIXS-T for the volatile rich model of Mercury’s formation and different solar flare states. A 125 eV detector FWHM energy resolution for the GaAs active pixel array is assumed.
Figure 5.24. Synthetic X-ray spectrum of counts per second as a function of energy detected by MIXS-T for the refractory rich model of Mercury’s formation and different solar flare states. A 125 eV detector FWHM energy resolution for the GaAs active pixel array is assumed.

Combining the mean observation time and the fluxes calculated for each solar state with the fraction of time expected in each solar state from Table 5.2 the mean spectrum from a surface pixel obtained by integrating across the MIXS-T FOV is calculated and shown in Figure 5.24 assuming operation at Mercury in 2020. The calculated mean altitude is 994 km (Bannister 2006) and resulting in a mean surface footprint size of 35 km.

Figure 5.24. Calculated spectrum from a mean 35 km surface pixel obtained by MIXS-T for two models of Mercury composition. A 125 eV detector FWHM is assumed.
<table>
<thead>
<tr>
<th>Model</th>
<th>Refractory Rich</th>
<th>Volatile Rich</th>
</tr>
</thead>
<tbody>
<tr>
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<td>M1</td>
<td>C1</td>
</tr>
<tr>
<td><strong>Flare state</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>L</strong></td>
<td><strong>C</strong></td>
<td><strong>L</strong></td>
</tr>
<tr>
<td>O K</td>
<td>60670</td>
<td>566</td>
</tr>
<tr>
<td>Mg K</td>
<td>15176</td>
<td>66</td>
</tr>
<tr>
<td>Al K</td>
<td>3154</td>
<td>17</td>
</tr>
<tr>
<td>Si K</td>
<td>3364</td>
<td>5</td>
</tr>
<tr>
<td>Ca K</td>
<td>175</td>
<td>0</td>
</tr>
<tr>
<td>Ti K</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Fe K</td>
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<td>0</td>
</tr>
<tr>
<td>Ca L</td>
<td>534</td>
<td>736</td>
</tr>
<tr>
<td>Ti L</td>
<td>70</td>
<td>763</td>
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<tr>
<td>Fe L</td>
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<td>575</td>
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Table 5.3. Calculated line (L) and continuum (C) counts by MIXS-T for a geometrical footprint during single observations at apoherm for both the refractory rich and volatile rich models of formation.

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<thead>
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<th>Model</th>
<th>Refractory Rich</th>
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<tr>
<td></td>
<td>M1</td>
<td>C1</td>
</tr>
<tr>
<td><strong>Flare state</strong></td>
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<td></td>
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<td><strong>C</strong></td>
<td><strong>L</strong></td>
</tr>
<tr>
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<td>Si K</td>
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</tr>
<tr>
<td>Ti K</td>
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<td>0</td>
</tr>
<tr>
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<td>0</td>
</tr>
<tr>
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<tr>
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<td>105</td>
</tr>
<tr>
<td>Fe L</td>
<td>0</td>
<td>79</td>
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Table 5.4. Calculated line (L) and continuum (C) counts by MIXS-T for a geometrical footprint during single observations at periherm for both the refractory rich and volatile rich models of formation.
<table>
<thead>
<tr>
<th>Flare state</th>
<th>Model</th>
<th>Refractory Rich</th>
<th></th>
<th>Volatile Rich</th>
<th></th>
</tr>
</thead>
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<td>A9</td>
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<td>L</td>
<td>C</td>
<td>L</td>
<td>C</td>
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<td><strong>O K</strong></td>
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<tr>
<td><strong>Mg K</strong></td>
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<tr>
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<tr>
<td><strong>Si K</strong></td>
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<td>14522</td>
<td>20</td>
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<tr>
<td><strong>Ca K</strong></td>
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</tr>
<tr>
<td><strong>Ti K</strong></td>
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<td>24</td>
<td>115</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td><strong>Fe K</strong></td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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<td><strong>Ca L</strong></td>
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<td>6864</td>
<td>381</td>
<td>423</td>
<td>1123</td>
</tr>
<tr>
<td><strong>Ti L</strong></td>
<td>655</td>
<td>7132</td>
<td>56</td>
<td>496</td>
<td>79</td>
</tr>
<tr>
<td><strong>Fe L</strong></td>
<td>0</td>
<td>6635</td>
<td>0</td>
<td>557</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 5.5.** Calculated line (L) and continuum (C) counts by MIXS–C for a geometrical footprint during single observations at apoherm for both the refractory rich and volatile rich models of formation.

<table>
<thead>
<tr>
<th>Flare state</th>
<th>Model</th>
<th>Refractory Rich</th>
<th></th>
<th>Volatile Rich</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M1</td>
<td>C1</td>
<td>B1</td>
<td>A9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L</td>
<td>C</td>
<td>L</td>
<td>C</td>
</tr>
<tr>
<td><strong>O K</strong></td>
<td>78755</td>
<td>735</td>
<td>6639</td>
<td>54</td>
<td>10347</td>
</tr>
<tr>
<td><strong>Mg K</strong></td>
<td>44180</td>
<td>192</td>
<td>5336</td>
<td>21</td>
<td>1240</td>
</tr>
<tr>
<td><strong>Al K</strong></td>
<td>10527</td>
<td>57</td>
<td>1380</td>
<td>6</td>
<td>257</td>
</tr>
<tr>
<td><strong>Si K</strong></td>
<td>13959</td>
<td>22</td>
<td>2019</td>
<td>2</td>
<td>304</td>
</tr>
<tr>
<td><strong>Ca K</strong></td>
<td>2776</td>
<td>8</td>
<td>654</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td><strong>Ti K</strong></td>
<td>75</td>
<td>3</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Fe K</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Ca L</strong></td>
<td>692</td>
<td>954</td>
<td>52</td>
<td>58</td>
<td>156</td>
</tr>
<tr>
<td><strong>Ti L</strong></td>
<td>91</td>
<td>991</td>
<td>7</td>
<td>69</td>
<td>11</td>
</tr>
<tr>
<td><strong>Fe L</strong></td>
<td>0</td>
<td>922</td>
<td>0</td>
<td>77</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 5.6.** Calculated line (L) and continuum (C) counts by MIXS–C for a geometrical footprint during single observations at periherm for both the refractory rich and volatile rich models of formation.

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5.5.4 Validation of fluorescence calculations

To validate the X-ray fluxes predicted for MIXS, X-ray spectra of the Moon, made by the Chandra X-ray observatory (Wargelin et al., 2004) and shown in Figure 1 have been compared with synthetic spectra modelled for the same observing geometry. The observations were made in July 2001 using the I2 and I3 front illuminated chips of the Advanced CCD for Imaging Spectroscopy (ACIS) instrument (Garmire et al., 2003).

The fluorescence model has been used to estimate the line fluxes (photons per unit lunar surface area per unit time into $2\pi$ sr) for solar flare state, which is based on solar activity measured during the observations by GOES. The lunar composition is assumed to be uniformly that of lunar mare basalt (Truscott et al., 2000). The calculations assume that the illuminated lunar surface is perfectly smooth, neglecting the factor of ~2 that may be introduced by surface roughness (Okada et al., 2002 and 2004). The geometry of the observations is summarised in Table 1, which gives the inputs for the modelled data. The geometry is an approximation to the true geometry from that illustrated by Wargelin et al. (2004) (accurate values for observation angles are not given). The QE(E) assumed is the pre launch QE of the I1 CCD from the Chandra Science data centre. The mean effective area for a single Chandra I CCD, over its FOV is assumed to be approximately 0.8 times the on axis value stated in Table 1. The solar flare state measured by GOES during July 2001 was variable between B1 and C1 background states. The model is in good agreement with the Wargelin et al. data if the flare state is approximated as having Truscott et al. C1 flare like properties below 0.6 keV and B1 flare like properties above 0.6 keV.

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined I2 and I3 observation time (s)</td>
<td>8063</td>
</tr>
<tr>
<td>Peak ACIS-I Effective area (cm$^2$)</td>
<td>600</td>
</tr>
<tr>
<td>Solid angle subtended by a single chip (sr)</td>
<td>5.9x10$^{-6}$</td>
</tr>
<tr>
<td>Solar state</td>
<td>B-C flare variable</td>
</tr>
<tr>
<td>Lunar surface composition</td>
<td>Mare Basalt</td>
</tr>
<tr>
<td>Mean angle of observations (º)</td>
<td>45</td>
</tr>
<tr>
<td>Mean angle of incident solar X-rays (º)</td>
<td>45</td>
</tr>
</tbody>
</table>

*Table 5.7. Inputs to the X-ray fluorescence model.* $^1$Wargelin et al. (2004); $^2$Chandra Science Web Site, http://cxc.harvard.edu/; $^3$GOES on line data archive, http://sec.noaa.gov/ftpdir/warehouse/2001/; $^4$Truscott et al. (2000). I2 and I3 are two Chandra detectors used for the observations.

The number of counts observed for the Chandra observation is given explicitly only for O-K X-rays as ~1300 counts. The predicted total number of detected O-K photons is 1788. Figure 5.25 shows the data from Wargelin et al. (2004) for the observation. Figure 5.26 shows the data predicted by the model for the observation assuming a detector FWHM energy resolution of 100 eV at all energies. Differences between the two can easily be attributed to surface roughness effects (Okada et al., 2002 and 2004) or to the
approximated lunar composition, viewing geometry and incident solar X-ray flux. The mean vignetting over the FOV is ~0.9.

**Figure 5.25.** X-ray spectrum of the Moon taken by the Chandra X-ray observatory (from Wargelin et al., 2004).

**Figure 5.26.** Simulated X-ray spectrum of the Moon taken by the Chandra X-ray observatory.

### 5.6 Conclusions

X-ray fluorescence spectroscopy is an invaluable tool for the remote sensing of atmosphereless planetary bodies in the inner Solar System. The technique allows the determination of surface elemental composition from orbit and the generation of global elemental composition maps. Such maps of Mercury will place constraints on possible formation mechanisms and the evolution of the planet. An understanding of processes which define Mercury’s history will enhance our understanding of the formation and evolution of the solar system as a whole.
Previous orbital measurements of fluorescent X-rays have been made using collimated proportional counters whose spatial and spectral resolution is severely limited. The Mercury Imaging X-ray Spectrometer uses MCP Wolter optics to provide fine spatial resolution through true imaging, during periods of high solar activity, and an MCP collimator, with a slumped geometry and guaranteed global coverage, at lower spatial resolution but at all energies of interest and regardless of solar state. The surface resolution achieved will always be less than a few tens of km and under appropriate conditions can be less than 200 m. This is a three order of magnitude increase in achievable resolution when compared with the resolving capability of the X-ray spectrometer on MESSENGER, whose surface resolution is just less than the planet’s diameter for most of its orbit.

The detectors for both MIXS-C and MIXS-T are identical radiation hard GaAs active pixel arrays (Owens et al., 2002), providing much improved spectral and spatial resolution when compared to GPC detectors. The slumped collimator geometry separates the collimator and detector planes and reduces the required detector size allowing the practical introduction of these detectors. Factors affecting the performance of both instrument channels have been optimised to produce the maximum Effective area possible and maximise the science return of the instrument. Key parameters determined for both instrument channels are given in Tables 5.8 and 5.9.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel diameter</td>
<td>20µm</td>
</tr>
<tr>
<td>Channel Pitch</td>
<td>22µm</td>
</tr>
<tr>
<td>Channel Length</td>
<td>Profiled</td>
</tr>
<tr>
<td>Microchannel coating</td>
<td>Ir</td>
</tr>
<tr>
<td>Core diameter</td>
<td>15mm</td>
</tr>
<tr>
<td>FOV</td>
<td>2° (possible reduction to 1° if required)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>&lt;2 arc minutes</td>
</tr>
<tr>
<td>Detector</td>
<td>32x32 pixel GaAs active pixel array</td>
</tr>
<tr>
<td>Filter</td>
<td>Al (80 nm)</td>
</tr>
</tbody>
</table>

*Table 5.8. Variables and values for the imaging channel after optimisation (MIXS-T). Other values remain the same as those in Table 5.1.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collimator type</td>
<td>Microchannel plate</td>
</tr>
<tr>
<td>Packing</td>
<td>Square pack, square pore</td>
</tr>
<tr>
<td>Slump radius</td>
<td>1m</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>25:1</td>
</tr>
<tr>
<td>Detector position</td>
<td>50cm from MCP collimator</td>
</tr>
<tr>
<td>Detector type</td>
<td>2x2 32x32 pixel GaAs active pixel arrays (4cm mosaic)</td>
</tr>
<tr>
<td>FOV</td>
<td>9.2° FWZM</td>
</tr>
<tr>
<td>Pore diameter</td>
<td>40µm</td>
</tr>
<tr>
<td>Open area fraction</td>
<td>0.7</td>
</tr>
<tr>
<td>Profiling</td>
<td>No</td>
</tr>
<tr>
<td>Filter</td>
<td>Al (80 nm)</td>
</tr>
</tbody>
</table>

*Table 5.9. Variables and values for the collimating channel (MIXS-C).*
The detected fluorescent X-ray fluxes from key elements at Mercury have been predicted by modelling the flux from the surface for different compositions and solar states and then combining the resultant line fluxes with the calculated instrument effective areas and grasps. The signal from the surface will be dominated by O-K X-rays but will also contain significant number of X-rays from key elements of interest for studies of Mercury. MIXS-C will provide statistically significant measurements of these spectral lines for all solar states at low resolution, while MIXS-T provides higher spatial resolution for some solar states. For M and X flare states MIXS-T may provide true imaging of the surface. For low solar states integration times for MIXS-T can be increased with a loss of spatial resolution.
CHAPTER 6

Detecting Interplanetary Dust and Space Debris with Filmed MCPs

6.1 Introduction

The basic optical unit of the proposed Lobster-ISS X-ray telescope (Fraser et al., 2002) is a square pore MCP optic which, in order to reduce its absorptivity $\alpha$, bears a thin (~10 nm) aluminium barrier film over the channel entrances. Filmed MCPs were originally developed as ion barriers for night vision intensifiers (Williams et al., 1991).

![Diagram of ISS components]

Figure 6.1. Mounting location of the samples on the outer surface of the Docking Compartment No. 1 "Pirs" (image courtesy of Kayser-Threde GmbH and RKK Energia, Moscow)

Between 2002 and 2004 two aluminium-filmed circular-pore MCP witness samples, manufactured by Photonis SAS (Brive, France), were flown on the International Space Station (ISS). They were exposed to the space environment on the Russian docking module (Pirs) for 756 days as part of the X-ray Mirror Expose Experiment (Hofer, 2004). The location of this experiment on the ISS is shown in Figure 6.1. The ram, wake, zenith and nadir directions are true for a standard ISS local vertical local horizontal (LVLH) attitude. This deployment, an opportunity made possible by collaboration with Keyser-Threde GmbH (Berlin) and the Max-Planck-Institut für Extraterrestrische Physik (Garching), was intended to evaluate the long-term effects of the ISS environment on the thermal properties of MCP optics. The experiment is shown in situ on the ISS in Figure 6.2.
After return to the University of Leicester, the samples were examined to determine (i) the effects of contamination and erosion on the film absorptivity and emissivity which are described in Carpenter et al. (2006) and are not included in this thesis and (ii) the effects of particle collisions, reported in this chapter.

Most in-situ measurements of the near-Earth dust environment have been made using retrieved surfaces and foils. Active sensors, detecting impact ionisation plasmas or the flashes of light associated with hypervelocity impacts (Auer, 2001) have also been flown. In the case of retrieved foils and surfaces the measured parameter is a hole or crater diameter, $D_h$. Previously flown foils, with thicknesses in excess of 1 µm, have been sensitive to particles with diameters $d_p > 0.1$ µm. In Sections 6.2 and 6.3 below it is shown that MCPs such as those exposed on the ISS, with film thicknesses more than one order of magnitude less than a typical free-standing foil, provide access to previously inaccessible dust distributions.

The results of the analysis presented here may have significant implications for the understanding of interplanetary dust and space debris and lead to future dedicated cosmic dust experiments based on the filmed MCP technology. The development of an active detector based on the thin film technology could offer a simple, inexpensive means of detecting nanometre scale particles in the near Earth environment and throughout the solar system.

### 6.2 Filmed MCPs

The retrieved MCP samples bear a very thin (60 nm, monitored with a crystal balance during the deposition process) aluminium film coating on one face, which is supported by the lead silicate glass inter-channel web between hexagonally packed 12.5 µm diameter microchannels. This film is applied by evaporation on to a lacquer, which is then floated on to the MCP before being baked away, leaving the Al film (Fairbend, 2005). The rectangular MCP samples and their Macor support are shown after their return to Leicester in Figure 6.3. The exposed area analysed was circular, 12 mm in diameter and over the examination hole of sample 1. The exposure time was calculated to be $6.5 \times 10^7$ s.
Figure 6.3. Retrieved, filmed MCP samples and their Macor support. Sample 1, with the aluminium film on its external face, is the exposed sample analysed here. Sample 2 has the aluminium film on its internal face so the solid angle exposed to space is reduced by the 40:1 aspect ratio of the microchannels.

Although the main pre-flight interest in these films was on their properties as thermal control layers for MCP X-ray telescopes, they are also highly sensitive micrometeoroid detectors. McDonnell and Sullivan (1992) present an empirical formula describing the maximum foil thickness $F_{\text{max}}$ that an impacting particle with known properties can perforate, also called the ballistic limit,

$$\frac{F_{\text{max}}}{d_p} = 1.272 d_p^{0.056} \left( \frac{\rho_p}{\rho_{Fe}} \right)^{0.476} \left( \frac{\sigma_{Al}}{\sigma_t} \right)^{0.134} v^{0.806}. \quad (6.1)$$

In the equation $d_p$ is the diameter of the impacting particle, $\rho_p$ is its density, $\rho_t$ is the density of the foil and $\rho_{Fe}$ and $\rho_{Al}$ are the densities of iron and aluminium; $\sigma_{Al}$ and $\sigma_t$ are the tensile strengths of aluminium and the target material respectively and $v$ is the velocity of the impactor. McDonnell and Sullivan define $F_{\text{max}}$ when the hole diameter $D_h$ is equal to the foil thickness. It should be noted however that this definition is not universal; other equations such as that of Gardner et al. (1997) define $F_{\text{max}}$ where $D_h = 0$.

Almost all ballistic limit equations have been determined through microparticle accelerator experiments. Equation 6.1 has been determined using micron scale iron spherules impacting at velocities of 1-16 km s$^{-1}$ onto foils with thicknesses of the order of microns. It may not be justified to apply this equation to nanometre scale evaporated films, where impact mechanics may be quite different, but no data exists for impacts on such foils. Currently available empirical relationships can therefore give only a first order indication of the potential impact properties of these films.

Using Equation 6.1, the minimum particle size required to perforate a 60 nm thick Al film is ~23 nm at a velocity of 20 km s$^{-1}$, and ~9 nm at 70 km s$^{-1}$. These velocities are chosen because they represent peaks in
the velocity distribution of interplanetary dust particles impacting on the Long Duration Exposure Facility (LDEF) (McDonnell et al., 2001). Such particles are almost two orders of magnitude smaller than those detected by previously flown foils.

Nanometer scale particles have been detected in streams from the Jovian and Saturnian systems (Grün et al., 2001) where acceleration by the large magnetic fields to velocities of around 100-300 km s\(^{-1}\) provide even very small dust particles with sufficient energy to be detected by the Cassini spacecraft’s cosmic dust analyser (Srama et al., 2004). In the near Earth environment such particles will have greatly reduced collision energies and will have been undetectable by foils with thicknesses on the micrometer scale or any other previously flown instrumentation.

Particles in near Earth Space can also originate from man’s activities in space. These debris particles can be ejecta from larger impacts on other spacecraft surfaces, flakes of paint from surfaces, which have become brittle following exposure to atomic oxygen, fragments from spacecraft explosions and collisions, slag from solid rocket motors, Al\(_2\)O\(_3\) dust particles, also ejected by solid rocket motors and droplets of NaK coolant ejected from the retired soviet RORSAT spacecraft nuclear reactors (Kessler et al., 1997). The velocities of these populations are in general less than those for the natural micrometeoroid background making small particles more difficult to detect.

### 6.3 Characterisation of the exposed nanofilm

Scanning electron microscopy (SEM), using a Phillips XL30 SEM in the engineering department at the University of Leicester, was used to determine the size distribution of holes in the retrieved samples. Figure 6.4 shows an SEM image of holes in the film; one hundred and thirty three such images were acquired and analysed, covering a total area of 2.75 \(\text{mm}^2\), or approximately 3% of the total sensitive area after accounting for the 63% open area fraction of the microchannel array. All images were obtained with an electron accelerating voltage of 1.5 kV. At higher accelerating voltages the electron range in aluminium is much greater than the film thickness and the film becomes less visible.

SEM images like Figure 6.4 were analysed using the ImageJ analysis package\(^2\), which was used to identify holes, calculate their area and determine their circularity, \(c\), given by \(4\pi \text{hole area}/\text{perimeter}^2\). A \(c\) value of 1.0 indicates a perfect circle while a value approaching zero indicates an increasingly elongated or freeform shape. A circularity filter was applied in order to discriminate against irregularly shaped holes, which are less likely to have resulted from hypervelocity impacts, and holes close to the interchannel web.

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\(^2\)(http://rsb.info.nih.gov/ij/)
Hypervelocity impacts tend to produce approximately circular holes in foils for particles with diameters similar to or smaller than the film thickness, although holes can become increasingly elongated with increased angle of incidence (McDonnell and Gardner, 1998). Experience with impacts on thicker foils exposed to dust and debris populations in orbit has indicated that holes with $D_h < 10f$, where $f$ is foil thickness, tend to be highly circular while irregularly shaped holes can result from particles with $d_p >> f$, which punch through the film leaving an impression of the particle’s cross section (McDonnell and Gardner, 1998). Large holes with sizes approaching the channel diameter, and holes occurring close to the channel walls, are likely to be distorted by the interchannel web and will be non-circular. For the very smallest holes ($D_h < 500 \text{ nm}$), approaching the image resolution, the calculated circularity is unreliable because the hole size approaches the area of a single image pixel. Of the SEM sample, of 2323 holes, 2222 had circularity $c > 0.5$, 1216 had $c > 0.8$. The variation of mean circularity with hole diameter is shown in Figure 6.5.

Circularity tends to decrease as particle diameters become significantly larger than the film thickness and the diameters of the resulting holes increase. The circularity tends to 1 as diameter goes to zero except for the smallest holes for which the circularity filter is likely to be incorrect as hole diameters approach the image resolution, introducing errors in the circularity value for very small holes. As hole diameters approach that of the circular microchannel diameters the circularity increases following a minima at $D_h = \text{microchannel diameter}/2$. This results from the microchannel walls limiting the size of the holes in the film.
Figure 6.5. Mean circularity $c$ of holes in the film as a function of diameter.

Conventional SEM imaging had insufficient resolution to image holes smaller than ~500 nm and was therefore only suitable for resolving impact damage by particles with ballistic limits, $F_{\text{max}}$, much greater than that of the film thickness. Subsequent images obtained with a newly commissioned Field Electron Gun Scanning Electron Microscope (FEGSEM), in the Department of Engineering at the University of Leicester, allowed the resolution of holes with diameters close to the film thickness and therefore close to the particle detection limit of the films. Figure 6.6 shows a FEGSEM image obtained with an accelerating voltage of 2 kV of a hole in the film with a diameter of ~100 nm. This feature has a morphology typical of the larger impact holes observed in thicker foils, a raised rim and regular shape. The particles which generated these holes must be smaller than the hole diameter. These impact holes are the smallest hypervelocity impact features ever imaged, generated by the smallest particles of dust/debris ever detected in near Earth space.

Figure 6.6. FEGSEM image of one of the smallest holes observed in the Al film.
The improved resolution of FEGSEM imaging has also allowed the observation of craters in the interchannel web, which were previously unobservable in SEM images. An example crater is shown in Figure 6.7. These craters would be more challenging to observe on bare glass but the contrast between the glass and the overlying film allows the craters to be observed. Observation of the craters lends confidence to an impact origin for the holes. Insufficient craters have been observed however to provide a crater size distribution and a measurement of impactor flux independent of that obtained from the hole size distribution.

Impact holes which are much larger than the film thickness have variable morphologies. Some, like that shown in Figure 6.8, are elliptical. For these features the ratio of the major and minor axes of the ellipse may be used as a measure of the particle’s incident direction. Irregularly shaped dark features around the impact hole may indicate subsurface damage caused during the impact. Other impact features are more irregular in shape, like that in Figure 6.9. These holes may be generated by particles with diameters much greater than the film thickness and serve as a record of the particle’s shape. Alternatively they may be the result of the ultimate spallation of film material following the subsurface damage observed in Figure 6.8. The lack of a clearly raised rim for these holes may indicate that they have been generated by slow particles and irregularity may result from stress relief in the film. Figure 6.9 shows aspects of all of these morphologies and may represent an impact at the boundary between different hole types. Figure 6.10 is a stereo image of an elliptical hole at the interface between the open area of a channel and the interchannel web. No experimental data exists on the impact effects on thin films or on the nanometre scale. It is possible that impact effects on the nanometer scale are significantly different from those on larger scales and so accurate determination of particle properties and discrimination between hypervelocity and slow impacts is not possible.

![Figure 6.7. An impact crater in the interchannel web.](image)
Figure 6.8. An elliptical hole in the film

Figure 6.9. An irregularly shaped hole in the film.
6.3.1 Particle flux

Previous workers have determined the size distribution of interplanetary dust particles by comparison of observed hole and crater sizes in space exposed surfaces with empirical hole and crater growth relationships based on experimental microparticle accelerator test data (McDonnell et al., 2001). Most of the resultant data available to date indicate a minimum interplanetary dust particle diameter $d_p \sim 0.1 \, \mu m$. The new data presented in this chapter indicate that this roll-off may be an artefact of previously used detection techniques.

Figure 6.11 shows the size distribution of holes in the MCP nanofilm with $c > 0.5$, obtained through analysis of both SEM from FEGSEM images. The $c$ values was selected because it was found through inspection that this circularity could be used to select morphologies of interest. A roll off in the population is observed towards the resolution limit of each imaging technique. The fluxes are calculated from the hole number density by assuming an isotropic distribution of particles throughout the exposure. If the observed holes are the result of a single event, such as secondaries resulting from a larger impact elsewhere on the ISS or particles ejected during progress docking procedures, then the calculated flux values are no longer valid but the hole size distribution remains so.
Figure 6.11. Impactor flux density as a function of hole diameter $D_h$ measured with the SEM and with the FEGSEM ($\text{circularity} > 0.5$). Also shown are statistical errors in the data.

The Carey-McDonnell-Dixon (CMD) formula (Carey et al., 1985) can be used to relate the diameter of an impacting particle to the diameter of the resulting hole for foils with microscopic thicknesses but can be extrapolated to the nanometre size regime to give an indication of the size of impacting particles. Where $D_h$ is hole diameter, $d_p$ is particle diameter, $v$ is the velocity in km s$^{-1}$, $f$ is the foil thickness, $\rho_f$ is the density of the foil material and $\rho_p$ is the density of the particle the CMD equation is expressed as

$$\frac{D_h}{d_p} = 1 + 2.9 \left( \frac{\rho_f}{\rho_p} \right)^{0.6} \left( \frac{f}{d_p} \right)^{0.3} \left[ \frac{1}{1 + 2.9 \left( \frac{\rho_f}{\rho_p} \right)^2 \left( \frac{f}{d_p} \right)^{2 - n}} \right],$$

(6.2)

where $n$ is given by

$$n = \begin{cases} 2 < v < 20 \text{ km s}^{-1} : 1.02 - 4 \exp(-0.9 v^{0.9}) - 0.003(20 - v) \\ v \geq 20 \text{ km s}^{-1} : 1.02 \end{cases}.$$  

(6.3)

The particle size as a function of hole diameter in a 60 nm Al film for different particle velocities and assuming a particle density of 1 g cm$^{-3}$ is shown in Figure 6.12 determined from the CMD equation. Typical space debris velocities are $< 10$ km s$^{-1}$, while dust particles can have velocities of 10s of km s$^{-1}$.
Figure 6.12. Particle diameter $d_p$ as a function of hole diameter $D_h$ in a 60 nm Al film calculated from the CMD equation, for different impact velocities and assuming a particle density of 1 g cm$^{-3}$. Values in the legend are velocities in km s$^{-1}$.

For $D_h = 0.4$ µm (the smallest hole size observed with the SEM) in a 60 nm thick aluminium film, and adopting an impacting particle density of 1 g cm$^{-3}$, the CMD formula indicates a particle diameter $d_p = 100$ nm at 5 km s$^{-1}$ or $d_p = 35$ nm at 20 km s$^{-1}$ impact velocity. At 100 nm the CMD equation predicts particle diameters of 33 nm and 13 nm for these velocities. These values represent typical velocities for space debris and IDP populations. The CMD equation has severe limitations near to the ballistic limit and it may again be unjustified to extrapolate this empirical formula to the nanometer scale but it is used here to give a first order approximation to $d_p$.

Other hole growth equations exist (Gardner et al., 1997; Maiden et al., 1963; Sawle, 1969; Nysmith and Denardo, 1969) of which only that of Gardner et al. (often referred to as the GMC equation) and the CMD equation attempt to characterise hole growth near marginal impacts. Of these two equations the GMC equation is more reliable close to the ballistic limit but its particle density dependence is scaled to data from Horz et al. (1994) for hole growth in 3000 – 10000 µm foils. The GMC equation is therefore extrapolated here to the nanometer scale.

The cumulative flux of holes in the nanofilm was calculated to be 35 m$^{-2}$ s$^{-1}$. From McDonnell et al. (2001) the spatial density $n$ of particles, assuming an isotropic and homogeneous incident flux is given by $n = 4F/\nu$, which, assuming a mean velocity of 20 km s$^{-1}$, gives a spatial density of 7x10$^{-3}$ m$^{-3}$ for particles with diameters greater than ~25 nm in the ISS environment. This compares with a previously determined spatial density of particles with diameters >10 µm in the ISS orbit of ~1x10$^{-8}$ m$^{-3}$ (Liou et al., 2002). This calculation provides an order of magnitude estimate for the number density of an impactor population and does not account for the geometry of the surrounding space station structure or any directional bias associated with a dust or debris population. Figure 6.13 shows the measured cumulative flux of holes in the exposed nanofilm along with the hole fluxes in foils of different thicknesses on the MicroAbrasion Package (MAP) experiment carried on the Long Duration Exposure Facility (LDEF) (McDonnell and
The LDEF spacecraft carried 57 separate experiments to investigate the near Earth space environment. It had a near cylindrical structure and was deployed by the Space Shuttle Challenger in 1984. LDEF’s equatorial orbit and attitude were such that the same spacecraft faces maintained the same pointing vectors relative to the orbital plane (i.e. space/zenith, nadir, North, South, East and West). After 5.7 years in orbit LDEF was retrieved and the various surfaces and experiments were examined and form the basis of much of our current understanding of the near Earth interplanetary dust environment (McDonnell et al., 1993). There is an almost two order of magnitude increase in sensitivity over the LDEF foils. The trend line is a power law continuation of the North, South and Space MAP data, which are likely to be the best approximation to the exposed film’s pointing history.

Measurements of impacts on returned spacecraft surfaces and theoretical models of the natural meteoroid background and debris populations have been combined to produce ESA’s Micrometeoroid And Space debris Terrestrial Reference model MASTER. MASTER provides predictions of fluxes of impactors on spacecraft in different orbits as a function of particle properties and populations. The smallest particles which can be modelled by MASTER are 1µm in diameter. The most recent version of this model, MASTER 2005 (Oswald et al., 2005), has been used here to model the micrometeoroid and debris fluxes on a flat plate on the ISS with a pointing direction identical to that of the returned MCP samples. The ISS orbit is modelled with a semi major axis of 6725.65 km, an eccentricity of 9x10⁻⁴, an inclination of 51.6°, a right ascension of ascending node of 199.76° and an argument of perigee of 274.3°. The pointing direction of the samples is 40.5 degrees to the right of wake for an LVLH attitude (the negative x-axis in the ISS coordinate system). Although the intended attitude for the ISS is LVLH during construction and for the majority of the exposure period the ISS has flown in an attitude in which the x-axis is perpendicular to the orbital plane (X-POP). In X-POP attitude the negative ISS x-axis always has a
direction which has a positive solar component so that power generation by the solar panels is optimised throughout orbit without them being moved. MASTER 2005 is not able to recreate an X-POP pointing history and so the pointing history of the samples is approximated by assuming a solar orientated attitude where the negative x-axis is always Sun pointing and the samples have a pointing direction of 40.5° right ascension (RA) and 0° declination (Dec) in a coordinate system where the Sun has coordinates RA = 0°, Dec = 0°.

The diameters, masses and velocities of the particles incident on the thin films cannot be accurately inferred from the observed impact damage at present and so a direct comparison with existing particle diameter and mass distributions may not be justified. A new feature in MASTER 2005 however is the application of Equation 6.1 to determine the ballistic limit $F_{\text{max}}$ for each impacting particle as a function of its mass, diameter and velocity. This allows the cumulative flux of holes as a function of foil thickness to be predicted for the MCP sample’s exposure history using a MASTER 2005 simulation. This prediction can be compared with the cumulative flux of particles observed in the 60 nm film. This comparison is shown in Figure 6.14.

![Figure 6.14](image.png)

**Figure 6.14.** Cumulative flux of holes in aluminium foils of varying thicknesses for surfaces in an ISS orbit and with equivalent pointing direction to that of the MCP films during the exposure as predicted by the MASTER 2005 model of space debris and natural meteoroid fluxes. Also plotted is the cumulative flux of particles measured on the MCP nanofilm.

$F_{\text{max}}$ values are shown for $F_{\text{max}} > 10 \, \mu\text{m}$. Because the MASTER 2005 population is for particles larger than 1 $\mu\text{m}$ $F_{\text{max}}$ values close to this value will be unreliable. The MASTER 2005 population rolls off at $F_{\text{max}}$ values below 0.1 mm. The roll off may be an artefact in the data from which MASTER 2005 is derived. For the hole size distribution shown in Figure 6.11 there is a roll off towards the limit of each analysis technique. A roll off is observed to occur for particles smaller than ~1 $\mu\text{m}$ because the force
dominating particles in this size regime is radiation pressure and particles can be removed from orbit. For particles approaching the nanometre scale however the Lorenz force dominates and so the dynamics will be significantly different. It may therefore be the case that a dense population of particles in this size regime exists in near Earth space despite the observed roll off in density of the sub micron population. If the general trend in the data before the roll off is continued to an $F_{\text{max}}$ value of 60 nm then the seemingly very large cumulative flux of $1.1 \times 10^9 \text{ m}^{-2}\text{ yr}$ in the nanofilm is compatible with the increased sensitivity of the thin films to small particle impacts.

The separate populations of particles with $F_{\text{max}} > 10 \mu\text{m}$ can be separated to reveal their relative contributions. Figure 6.15 shows the relative contributions by natural micrometeoroids and space debris calculated using MASTER 2005. The population is dominated by the natural population. If the data point provided by the nanofilms is a true extrapolation of the general trend to the nanometre scale then this flux measurement may be dominated by a new population of nanometre scale natural dust particles.

Figure 6.15. Contributions by the natural micrometeoroid and orbital debris populations, to the MASTER 2005 cumulative flux, as a function of $F_{\text{max}}$ predicted for the MCP samples.

6.4 Particle incident directions

The flux of particles on the ISS will in general be homogeneous across the sky with an enhancement towards the ram direction and a reduced flux in the wake direction. Shadowing by the Earth will produce zero flux from directions intercepted by the Earth. The particle flux as a function of elevation and azimuth, with respect to the ISS velocity vector and local horizontal plane, for particles with diameters greater than 1 $\mu\text{m}$ impacting on a random tumbling plate in the ISS orbit, calculated using MASTER 2005 is shown in Figure 6.16. The figure shows zero flux in Earth pointing directions and a general flux enhancement towards the ram direction. Directions with very high flux densities correspond with debris fluxes related to specific orbits. If the nanoparticle flux observed by the thin films retrieved from the ISS
is an extension of the >1 μm population then the distribution of incident directions is likely to be aligned with this population.

**Figure 6.16.** Particle flux as a function of impact azimuth and elevation with respect to the local velocity vector and horizontal planes.

The morphologies of impact holes in thin foils can be used to infer the incident directions of particles. For a perfectly spherical particle with a diameter $d_p > 10f$ at grazing incidence on a thin foil the aspect ratio of the major axis $L$ and minor axis $D$ of the elliptical hole produced following an impact will be related to the incident angle $\phi$, measured from the normal to the surface, by the relation $D/L = \cos \phi$ (McDonnell and Gardner, 1998). This relationship cannot account for irregular morphologies which are believed to be produced by irregularly shaped particles which punch out their cross sections from the foils.

An arbitrary number of 174 images of randomly selected holes were analysed using imagej. For each hole the circularity and area were calculated. For holes with $c > 0.5$ a best fit ellipse was generated to match the hole morphology. The ratio of major and minor axes of each ellipse was then used to infer an incident angle for the particles. Figure 6.17 shows the incident particle flux, scaled to a peak value of 1, as a function of inferred incident angle. Also shown is the scaled particle flux as a function of incident angle for natural, debris and total populations calculated by MASTER 2005 for the population with $d_p > 1$ μm. The peak in the observed nanoscale population corresponds with the peak in the modelled natural population but has a much narrower angular distribution. The general angular distribution more generally approximates that of the debris flux neglecting the most significant debris peak between ~22-38°. The major contributions to the debris population are Solid Rocket Motor dust and ejecta.
Figure 6.17. Flux scaled to a peak value of 1 as a function of off-axis angle inferred for the ISS exposed film and calculated for a surface, with a pointing history approximating that of the films, for natural and debris particle populations.

From the major axis of a hole’s best fit ellipse two possible azimuthal angles of incidence in the plane of the surface and parallel to the ellipse major axis, can be inferred. The angle of incidence $\phi$ and the azimuthal angle $\theta$ can then be combined to infer an incident direction. Figure 6.18 shows the incident direction inferred for particles, which generated those holes in the sample of 174 whose circularities were greater than 0.5, plotted over a hemispherical view of the ISS as seen from the samples. The data is shown in Figure 6.18a and b for a hole threshold of $D_h > 0.4 \mu m$ and in c and d for all particles. Figure 6.18a and c show all of the incident directions that can be inferred from the ellipses taking both possible azimuthal values. Figure 6.18b and d show the directions selected such that they can be attributed either to the ISS structure or to the negative x-axis of the ISS.
Figure 6.18. Inferred incident direction of the impacting particles on the nanofilms shown over a hemispherical view of the ISS as seen from the samples (hemispherical view used courtesy of Boeing). In a and b a hole diameter threshold of 0.4 µm is applied and c and d all hole diameters are used. In a and c all possible directions are shown (i.e. all particles are shown twice). In b and d directions are selected to coincide with significant directions with respect to the space station structure. The space station modules in the figure point along the negative x-axis of the space station.

The close alignment of the population with both the ISS structure and the negative x axis of the ISS strongly indicate that the particle population which produced the impacts in the film is local to the ISS. Those particles associated with the structure are most likely to be secondary ejecta particles following larger impacts on the ISS. The rear of the Zvezda module on the ISS at the extreme of the ISS negative x axis is the docking location for the Progress capsule. Particles released during thruster firings by Progress during docking manoeuvres are therefore the most likely source of these holes. Aluminium surfaces from the Shuttle Plume Impingement Flight Experiment (SPIFEX) show impact craters produced by high-speed propellant droplet impacts with \( d_p \) values ranging from 1-20 µm (Soares et al., 2002). Such a mechanism may be the source of some of the holes observed in the filmed MCPs.

This incident direction indicated will also be close to the mean solar direction observed by the particles over the two year exposure in an X-POP attitude. It is possible that beta meteoroids, meteoroids accelerated on hyperbolic orbits out of the solar system by radiation pressure (Whipple, 1976; Wehry and Mann, 1999) are the cause of this directionality given the direction relation to the solar direction, although beta meteoroids have a minimum possible diameter of ~100 µm. Natural particles with diameters smaller than ~100 nm will be charged in the space environment, will have trajectories dominated by the Lorenz...
force and will interact with the Earth’s electromagnetic field. A review of the dynamics of charged dust particles in the solar system is given by Horyani (1996). The observed directionality may also be an artefact of the technique used to infer direction, which has not been calibrated.

6.5 Impactor residues

The analysis of residues left on foils by impactors is another useful tool for the separation and identification of debris and dust populations. Studies of impactor residues have been carried out extensively on returned space-exposed surfaces using EDXS and SIMS.

Difficulties arise in residue identification around impact features in filmed MCPs owing to the complex composition of the underlying MCP glass (Chapter 2), which includes most elements of interest for impact studies. X-ray spectra from the impacted aluminium film also contain a contribution from the glass within the walls of the underlying microchannel as the high electron-accelerating voltages required to excite elements of interest cause electrons to penetrate the film and excite fluorescence from the glass below. Analyses carried out on retrieved solar cells from the Hubble Space Telescope (HST) have demonstrated that impactor residues can be identified on complex substrates (Kearsley et al., 2005). By comparing spectra from locations on a sample, with and without impact features, and with an equivalent geometry with respect to the X-ray detector, changes in the peak heights of key elements can be interpreted as evidence for the presence of residues. Such an approach removes the geometrical effects, shown in Chapter 2 to be important for EDXS analysis on the microchannel scale. High resolution elemental mapping is also available as a standard EDXS technique and can be a valuable tool in the observation and identification of impact residues.

A study has been carried out using the SEM at the Natural History Museum in London to identify possible residues in the Al film using EDXS and elemental mapping. If the observed impact features are largely generated by particles with diameters of 10s of nanometers then residues will be small. Despite this some potential impact residues have been observed.
At accelerating voltages >20 kV and using backscattered electron (BSE) imaging, faint outlines of some holes in the film have been resolved and around three of these holes apparent residues have been observed. Backscattered electrons are detected after ~180° deflections following impacts with atoms in the sample under analysis and BSE imaging is well suited to finding residues and localised contaminants as it is highly sensitive to variations in atomic number. A backscattered electron image of one of these impact sites is shown in Figure 6.19. Two spectra were taken from the region around the hole from a similar area within the same microchannel using an electron beam energy of 20 keV. The spectra from both sites are compared in Figure 6.20 after normalisation to the Si-K peak.

Over the apparent residue there was an excess of aluminium when compared with the background region of film. Other elements observed are consistent with the background spectrum. Elemental mapping also shows an excess of aluminium in the residue. Figure 6.21 shows a map of Al-K X-rays from the area surrounding the impact feature shown in the BSE image of Figure 6.19. The background contribution from the microchannel walls and Al-K X-rays from the overlying film are observed with a high density of Al-K X-rays from the residue. Similar maps for other elemental lines show no significant structure related to the residue.
Aluminium residues are generally associated with impacts by oxidised aluminium spherules with diameters of ~1 µm, which are used in solid rocket motors (Cofer et al., 1989). It can therefore be speculated that aluminium spherules may be responsible for the few impact sites observed to have residues like the one described. It is perhaps more likely that the observation of Al excess has resulted from material vaporised from the film during impact and then re-deposited or which has remained around the impact site on the underside of the film. Al residues in other space exposed surfaces such as HST retrieved arrays (Kearsley et al., 2005) have been found to contain variable and often very minor quantities of oxygen. It is believed that this variation arises from the variable combustion of the Al particles in solid rocket motor exhaust (Hörz et al., 2002).

Given the rarity of these residues in comparison with the overall number of holes (estimated to be <0.1% of the total sample) they cannot be considered representative of the wider population of impact features. These results do, however, indicate that residues of impacting particles may be detectable. Attempts to detect smaller residues by using longer integration times of hours to days have not been successful. SIMS is a more sensitive, but destructive, technique for residue analysis. A programme of sample analysis using a SIMS Attachment to a Focussed Ion Beam (FIB) at Imperial college, London is underway and is likely to allow a more detailed compositional analysis and detection of any residues present to provide insight into the impactors’ origins.

**Figure 6.20.** Comparison of the residue and background spectra of Figure 6.16 showing an aluminium excess in the region around the impact site.
Figure 6.21. Al-K X-ray line elemental map of the region around the impact site imaged in Figure 6.19 showing a large excess of aluminium in the residue.

6.6 Future nanofilm exposure experiments

This experiment has demonstrated filmed MCPs as passive detectors of interplanetary dust and space debris with unprecedented sensitivity. Analysis of impact holes in the films has revealed a previously unobservable nanometre scale particle population in the ISS environment, though the precise origins of this population have not yet been established. A future exposure, optimised for particle detection, would best allow the identification of the particulate populations as either micrometeoroids from interplanetary space or sub-micron space debris. Such an experiment may use films of differing thicknesses and pointing directions in a manner similar to the MAP experiment on LDEF. MCP films can be manufactured with thicknesses as small as 40 nm (Fairbend, 2005). An experiment consisting of a number of detectors with different film thickness and the same pointing characteristics would provide valuable insight into the ballistic limits of the impactors and place limits on the properties of observed particles. It may be that the exposed film surfaces need not be large; analysis of the ISS exposed films indicates approximately 3 impacts per minute for each 1 cm² surface area. It may be however that the high spatial density of holes is in fact the result of single events such as docking procedures or secondary ejecta from large impacts elsewhere on the ISS. If this is the case then much larger areas may be required to ensure detection of nanometre scale natural dust particles.

This technique relies on the return of samples from orbit and is therefore limited to exposure on manned spacecraft in LEO and sample return missions. No time resolution or directional information is available and the analysis of impact sites requires detailed post-flight investigation. The addition of an active element to provide information on time and position of impacts would be a major advantage for any future exposure. Clusters of events with small or zero time separations, likely to result from secondary impacts, can then be identified and holes can be correlated with the pointing direction of the surface at time of impact. Temporal and directional information allows the separation of debris impacts (which are
often clustered and dominated can be highly directional) and interplanetary dust populations. An ideal experiment would use multiple detectors with multiple pointing directions, whose fields of view were unobscurred by structures that may provide a source of secondary particles. An active detector would also be suitable for use on missions where the experiment is not returned allowing the large cost of retrieval to be removed and extending the measurement technique to unmanned missions in both near Earth and deep space orbits. Nanometer-scale dust populations could then be detected throughout the solar system.

One possible active readout solution uses the transmission of light by impact holes in the film. The high reflectivity of the undamaged Al film significantly reduces the transmission of radiation from an external light source, such as an LED, onto a position sensitive detector on the non-filmed side of the MCP. Photons passing through holes will produce a localised increase in illumination on the detector. The change in intensity is a function of the hole size, which is in turn a function of impactor cross-section, density and velocity. A possible arrangement for such a detector is shown in Figure 6.22. The high flux obtainable in the small particle size regime allows for a very small detector area. If larger areas are required then multiple detectors can be employed.

![Figure 6.22](image)

*Figure 6.22. Possible format of an active MCP nanofilm detector. The total light flux incident on the front face of the film $I_o$ is equal to the sum of the reflected and transmitted fluxes $I_r$ and $I_t$. The photon intensity under a single microchannel after the generation of a hole ($I_{t2}$) as a fraction of the pre-impact intensity ($I_{t1}$) is given by

$$\frac{I_{t2}}{I_{t1}} = \frac{A_{hole} + (1 - R)(A_{channel} - A_{hole})}{(1 - R)A_{channel}}, \quad (6.4)$$

Where $A_{hole}$ is the area of the generated hole, $A_{channel}$ of the microchannel, and $R$ is the reflectivity of the microchannel at the selected wavelength. This equation assumes that the wavelength selected is sufficiently small that it can be transmitted unimpeded through the hole generated. A disadvantage of the technique is that the smallest hole resolvable is defined by the wavelength of light selected as photons with wavelengths greater than the hole diameter will not be transmitted.
Another disadvantage of this technique is that detecting the generation of a hole does not directly yield information on the velocity or mass of a particle. If hole sizes can be determined from the signal increase then impactor properties can only be determined by comparison with simulations of impacts and microparticle accelerator experiments yet to be carried out.

An alternative solution may be to observe the impact flash generated as a hypervelocity impact occurs. The light flash from impacts on solid targets has been utilised for dust detection on sounding rocket experiments (Berg and Meridith, 1956) and on the VeGa 1 and 2 and Giotto Spacecraft (Kissel, 1986). The advantage of light flash detection is that the maximum light intensity and total light energy are both unique functions of the impactor mass and velocity (Friichtenicht, 1965, Gehring et al., 1966, Rollins and Jean, 1968, Eichhorn, 1976, Burchell et al., 1996) and the rise time of the impact flash is a function of velocity (Eichhorn, 1975). Light flash observations therefore have the potential to provide detailed information on particle properties and the lower detection limit is defined by the photon counting ability of the detector and not by the wavelength. In addition the flash, which lasts for approximately 100 µs, can be time resolved into two parts; the first of which results from the primary impact and the second results from impacts by secondary particles. The determined relationships have been for particles incident on semi infinite surfaces where complete annihilation has occurred and not for thin film or foil impacts where the output may be significantly reduced as complete annihilation of the impactor may not occur. In addition it is the flash component on the rear side of the film which is observed in this case; a component which has not been measured before.

### 6.6.1 Selection of operating waveband

The reflectivity of the film, the size of the impact holes and the detector quantum efficiency will define suitable wavebands for operation of the detector system. Aluminium has high reflectivity across the infrared-visible-ultraviolet range (Bennett et al., 1962) but reflectivity measurements of Al films on MCPs have not been made before. The reflectivity of a non exposed Al film on an MCP, identical to those flown, was measured with a Perkin Elmer Lambda series UV-VIS spectrometer using an RSA-PE-20 accessory to provide the optical geometry illustrated in Figure 6.23. The Integrating sphere allows the simultaneous measurement of both specular and diffuse reflection.

The measured reflectivity, from infrared to ultra-violet wavelengths, of a 60 nm Al film on an MCP similar to that exposed on the ISS is shown in Figure 6.24. The reflectivity of the Al film is determined by comparison with a standard sample of known reflectivity.
Figure 6.23. Optical setup of the reflectivity measurements provided by a RSA-PE-20 accessory. M1, M2 and M3 are flat mirrors and the beam is transmitted onto the sample through apertures in the transmittance port and integrating sphere. The sample beam is incident on the sample at an angle of 8° to the normal and is provided by a Perkin Elmer Lambda series UV-VIS spectrometer, which also measures the integrated reflected signal.

Figure 6.24 shows a high reflectivity across all wavelengths, but the narrow peak at 694 nm has not been observed in data from standard Al films published by previous workers (Bennett et al., 1962). Although the sample intervals used in previous studies were sufficiently large that such a narrow peak may not have been observed, it is possible that the peak is an artefact of the measurement technique employed here. The peak has also been observed by this technique for measurements made of Al films evaporated onto glass slides but not for other metal films or a highly polished thick Al mirror, although structure in the reflectivity profile is seen in this last case. Similar peak shapes are observed as a result of surface plasmon resonance (SPR) (e.g. Bussjager and Macleod, 1995) but using different measurement techniques and illumination geometries. SPR is a phenomenon associated with thin films and at very specific wavelengths and incident angles, and via media with a refractive index of less than 1 (e.g. glass). Although SPR usually manifests as a minimum in reflectivity it can manifest as a peak under very specific conditions. SPR may be the origin of the observed peak in Al reflectivity although the probability that the described measurements were made under conditions appropriate to the production of an SPR peak is small. Further investigation is required to identify the origin of the peak and the possibility of SPR.
Figure 6.24. Measured IR-UV reflectivity for a 60 nm Al film on an MCP identical to the ISS exposed samples.

The minimum hole diameter resolvable by the detector is defined by the wavelength of the light, which is selected to provide a high ratio $I_2/I_1$. The peak at 694 nm must be regarded as anomalous until further investigations can establish its true nature. The illuminating wavelength must also be less than the size of the holes under observation. Photons with wavelengths longer than the hole diameter will not be transmitted. Transmission of light with wavelength $\lambda$ through apertures with diameter $D < \lambda$ has been observed and even amplified through arrays of apertures using SPR to enhance the transmission (Ghaemi et al., 1998) but is a technique unlikely to be of use here given the specific wavelength and angle requirements.

A trade off must be made between reflectivity, the minimum resolvable hole size and the quantum efficiency of the readout detector. Assuming an operating wavelength of 300 nm and adopting the reflectivity of Figure 6.24 the value $I_1/I_2$ as a function of hole diameter ($D_h$) from Equation 6.14, assuming circular holes and neglecting diffraction limitations is shown in Figure 6.25.
Figure 6.25. The fractional change $(I_1/I_2)$ photon intensity under a single 12.5 µm diameter filmed microchannel after the generation of a hole as a function of hole diameter $D_h$ calculated from Equation 6.4 and assuming circular holes.

If impact flashes are to be detected then the detection wavebands should coincide with the peak in emission of the incident particles. Temperatures associated with hypervelocity impacts are generally in the region of 2500 K to 5000 K, determined from experimental studies with particle accelerators (Eichhorn, 1976) by assuming that the light emissions was that of a black body radiation curve, which was found to peak between 150 and 300 nm. Eichhorn (1975) was able to establish cratering characteristics by observation of the light emission between 300 and 700 nm. A light detector will require high quantum efficiency at these wavelengths. The precise relationships between velocity, mass and light emission will need to be investigated for the specific size regime and detector properties of the instrument described here to allow detailed information on impact properties to be determined. The rise times for these peaks are velocity dependent and are typically between 10 µs and 100 µs (Eichhorn, 1976). The precise origin of the light flash is believed to result from emissions by a jet of shocked material initiated from either the target or the particle depending on the shock properties of these materials and the particle velocity (Ang, 1990).

6.6.2 Optical arrangement

Direct contact of the detector with the back of the MCP is one possible arrangement (Figure 6.22). The particles under observation have previously been undetectable and are therefore unlikely to pose a significant damage risk to pixels. The collimating MCP limits the maximum angle of incidence for particles impacting directly on the detector to 0.6° following perforation of the film (for a standard $L/D=120$ MCP), although secondary particles from the film and microchannel walls will be incident on the detector. Particles at grazing incidence to the channel walls may also be deflected in a direction parallel to the walls as has been found to occur for grazing incidence X-ray optics (Meidinger et al., 1990).
Variability in secondary impacts following the initial impact with the film may lead to measurement uncertainties.

The MCP walls also provide an optical advantage; radiation incident on the walls will, in general, be reflected back into the MCP, ensuring a concentration of flux over the area directly under a given microchannel. Losses at the channel wall are likely to be small. Internal reflection within the channels can be increased by coating the inside surface of a microchannel with a reflective metal coating similar to those used for X-ray optics and described in Chapters 4 and 5 to create an integrating cylinder.

### 6.6.3 Selection of detector

One readout option for the active nanodust detector may be a CMOS active pixel detector, which is available off the shelf at low cost. CMOS detectors also have good radiation hardness compared with CCDs (Hopkinson, 2000) and are therefore well suited to applications in space. Permanent effects on single pixels are introduced by atom displacement by incident radiation but the readout mechanism does not require pixel transfer, as is the case for CCDs, and so single damaged pixels can be isolated. Pixels with diameters similar to those of the MCP microchannels will allow detection of localised light intensity changes. In addition such pixellated detectors can provide good time resolution allowing the identification of pointing direction and multiple events resulting from dust or debris clouds. A disadvantage with CMOS sensors is the high noise typical in signals which may prevent accurate identification of small signal changes.

A candidate device is the Fill Factory STAR1000, which is designed for use in the space environment. The STAR1000 has 15 µm×15 µm pixels, which approximate the diameter of a conventional MCP, and a peak quantum efficiency of 30 % at 600 nm falling to ~10% at 400 nm (Star1000 data sheet, Fill Factory, Mechelen, Belgium).

Alternatively a CCD detector may be used although such detectors will require cooling and are highly susceptible to radiation damage. Displacement of atoms in the Si lattice by incident radiation can create potential wells within pixels in which charge, transferred through that pixel can be trapped (Janesick et al., 1989). Although CCD’s in general have a poor UV quantum efficiency (<10 % below 300 nm) they can be coated with high refractive index dielectrics to reduce the UV reflectivity of the pixel surfaces and thus optimise their UV performance. QE as high as 75 % can be achieved at 250 nm (CCD47 data sheet, E2V Technologies, Chelmsford, UK). Low QE is not an important factor here however as the intensity of the illuminating LED can be increased to compensate for a poor detector response. By running a CCD in frame transfer mode, where each frame is integrated and read out as an image, and subtracting the previous frame from each preceding frame, changes in signal will be detected.

If a UV light flash is to be detected then in a frame transfer mode the integrated energy of the flash will be recorded and read out from the area underneath the impacted microchannel. If run in “photodiode” or
“time resolving” mode (Abbey, 2005), where pixels are continuously transferred and all spatial resolution is lost, then a time resolution for an isolated event on the detector area of 10-20 µs can be achieved providing ~15 flash measurements during an impact event. This mode has a power requirement of ~10-100 mW compared with a power requirement for frame transfer mode of <1 mW.

6.7 Discussion and conclusions

The detection of dust and debris particles in space by a filmed MCP has been demonstrated by in-situ measurements of the ISS environment. The particle diameter detection limit of the 60 nm Al films, calculated by extrapolation of empirical formulae for the perforation limit of aluminium foils, is approximately 15-20 nm for particles with velocities typical for interplanetary dust particles, more than an order of magnitude smaller than for previous experiments. The particle fluxes, inferred from measurements of the spatial density of holes, are consistent with the extrapolation of existing data and models to this new size regime.

As with most evaporated films, it is likely that our MCP films are highly stressed (Fairbend, 2005) and will have a crystalline structure with a scale comparable with the diameters of particles at the ballistic limit. In addition, any oxidised surface layer will have a significant effect on the mechanical properties of the film, which are poorly understood. Hence the response of our films to impacts may differ substantially from the response measured in studies of thicker aluminium foils. It cannot be assumed, therefore, that the existing equations connecting \( D_h \) and \( d_p \) apply in the case of the current thin film samples, though the formulae so developed were from hypervelocity impacts in a wide range of foils with thicknesses from 10 µm to 100 nm and dimensional scaling, albeit weak, was incorporated into the expressions (McDonnell, 2005). A programme of research will be required to verify the relationships and perhaps develop new relationships connecting particle diameter \( d_p \), particle density \( \rho_p \), target density \( \rho_t \), velocity \( v \) and hole diameter \( D_h \) for these much thinner films.

There is a strong possibility that impactor species other than naturally occurring interplanetary dust may have contributed to the observed hole distributions. The observed impacts may result from secondary ejecta from larger impacts elsewhere on the ISS; such enhancements have been previously reported (Mandeville et al., 1999; Rival et al., 1999), though there is little evidence of damage from the much larger particles that would also be the product of such events. Ejecta need not come from surfaces in the line of sight; particles with \( d_p < 1 \mu m \) can have orbital lifetimes of the order of a day, whilst particles with \( d_p < 10 \mu m \) can have lifetimes of around one year, and so secondary particles can impact with non line-of-site surfaces after several ISS orbits (Mandeville et al., 1999). The spatial density of ejecta in the ISS orbit is expected to be \(~10^{-13} m^{-3}\) for \( d_p = 10 \mu m \) particulates and \(~10^{-12} m^{-3}\) for those with \( d_p = 1 \mu m \) (Bariteux and Mandeville, 2002). The domination of space debris over the interplanetary dust population at size regimes \( d_p < 10 \mu m \) (McDonnell et al., 2001) suggests that our observed holes may be generated by debris. The fluxes of these particles have been measured in LEO by experiments incorporating a range of
foil thicknesses on a variety of spacecraft (McDonnell et al. 1996). The measured fluxes are orders of magnitude less than that described here and are for particles with \( d_p > 1 \) \( \mu \)m. More recent measurements of impactor fluxes by the active detector DEBIE on the Belgian led PROBA mission (Schwanethal and McBride, 2004) have recorded fluxes of between \( 5.6 \times 10^{-4} \) m\(^{-2}\) s\(^{-1}\) and \( 6.5 \times 10^{-4} \) m\(^{-2}\) s\(^{-1}\) for particles with \( d_p > 1.9 \) \( \mu \)m; a factor of \( 10^4 \) less than that experienced by the MCP nanofilm.

If the impact holes in the thin aluminium film result from man-made debris, then this debris must be from either a high density population of particles with diameters sufficiently small that they have been undetectable by previous experiments, or the flux of particles impacting on the sample was orders of magnitude higher than that detected for previous experiments in similar orbits and on the ISS.

Generation of the observed, high circularity, holes by processes other than impact is unlikely. Vibrations and acoustic stress on the films during launch of the manned Soyuz carrier will have been small. Atomic oxygen will oxidise the film uniformly and across the entire film area, which in any event will be almost entirely oxidised soon after deposition on the MCP. Other sources of damage are likely to affect the wider surface area, including the interchannel web, unlike the localised effects of impacts; such extended regions of damage are not observed, and while thermal-cycling over the ISS orbit could potentially induce damage to the film, this would be expected to produce tears in the film rather than the observed holes. Similar films made from carbon and supported by micromeshes have been tested extensively for space applications and found to survive thermal, acoustic and vibrational testing (McComas et al., 2004).

A thermal cycling test on MCP film samples has been carried out to provide further insight into film behaviour. After 24 hours of cycling in nitrogen in an Environmental Design thermal cycling unit in the Space Research Centre at the University of Leicester, between –70 \( ^\circ \)C and 100 \( ^\circ \)C, no damage was observed on the film samples when observed with an SEM. This temperature range is not fully representative of the in orbit temperature variations but represents the full range achievable with this equipment so some uncertainty remains.

Future experimental work will investigate impacts on these thin films, particularly by nanometre to micrometre scale impactors. This programme may use aluminium particles with diameters of between 80 nm and 100 nm (provided by Qinetiq Nanomaterials Ltd, Farnborough, UK) accelerated by the Van de Graaff microparticle accelerator at the Open University, Milton Keynes, UK to determine the characteristics of hypervelocity impacts on filmed MCPs. Particle size and velocity selection is not available with this facility. Alternatively these particles may be fired from a light gas gun facility at the Open University or the University of Kent at Canterbury, at velocities \( \sim 6 \) km s\(^{-1}\). The Van de Graaff accelerator at the Max Plank Institute for Nuclear Physics, Heidelberg may accelerate particles as small as 10 nm at speeds greater than 10 km s\(^{-1}\), although the particles with diameters smaller than \( \sim 50 \) nm cannot be controlled at the moment.
Further realisation of this new technique and the discovery of this new small particle population could be achieved by future passive exposures and by an ‘active’ version of the detector through the addition of a readout solution, able to measure and record impacts in real time. The MCP detector would then become suitable for use on any platform, allowing mapping of dust distributions from spacecraft throughout the solar system. It is vital to obtain measurements from outside of Low Earth Orbit. At low altitudes debris populations are high and it may be that very small natural particles, which are dominated by the Lorenz force will be unable to travel through the magnetosphere.

Readout solutions may use optical transmission by holes in the nanofilm, resulting from particle impacts or the detection of the UV flash associated with the impacts. Such a detector will provide pixellated impact position and time resolution, and may yield mass and velocity information. Further work needs to be carried out to determine the optimal readout mechanism for an active nanoscale dust detector.

Whether the high impact fluxes described here are due to natural dust or man made debris, the detection of nanometre scale impacts by the 60 nm aluminium film represents an order of magnitude improvement in the sensitivity of instrumentation designed for the detection of dust in space.
CHAPTER 7

Conclusions and Further Work

Microchannel plates have been an invaluable technology for the detection of X-rays, EUV photons and charged particles during four decades of space missions. More recently MCPs have been developed as X-ray optics and may form the basis of future detectors for interplanetary dust and space debris research. The preceding chapters have described developments in MCP technology as detectors, collimators, optics and finally cosmic dust detectors. These developments have contributed significantly to the state of the art, led to new applications of MCPs and opened new areas of research for scientific discovery.

7.1 MCP detectors for EUV

The reduction in EUV quantum efficiency in modern MCPs, which has inhibited EUV astronomy since the early 1990s, may be due to changes in the along-microchannel surface composition of these MCPs, observed here for the first time. Along channel composition profiles have been observed through the novel application of energy dispersive X-ray spectroscopy provided by a scanning electron microscope. Surface composition affects the secondary electron emission characteristics of MCP glass, which in turn defines MCP QE. Compositional changes at intermediate channel depths may result in a loss of QE for EUV photons but not for X-rays, as the former has an increased probability of reflection at the channel entrance and is likely to interact with the glass at these channel depths.

Variations in glass composition are likely to result from some subtle changes in the manufacturing process. The stages in manufacture most likely to be associated with these changes are associated with flow of fluids in the microchannels and sol-gel processes. The mechanics of fluids along channels with microscopic dimensions are complex and can vary considerably from flows in macroscopic pipes. The temperature, velocity and pressure of a fluid can vary considerably with position along the channel, and the position dependencies can be affected by the properties of the fluid at the channel entrance. A change in fluid properties at a given point along a channel resulting from small changes in the properties of the fluid entering the channel may alter the reaction rate with the channel walls and vary the surface composition producing the observed compositional variations and reducing the QE.

An experimental programme is underway to investigate MCP QE further by testing the QE of a number of MCPs with good electron detection efficiencies. It is reported by the manufacturer Photonis, SAS that such plates should have improved EUV QE if the reduction is due to variations in composition at depths of ~three channel diameters. Modelling of fluid flows along microchannels may allow the investigation of fluid flows as possible origins of the observed structure in along-channel composition.
The study described in Chapter 2 has provided a way forwards towards solving the mystery of the lost QE and regaining historical detector performance for future applications. Such a programme of QE recovery is essential for EUV astronomy, a subject whose future may depend on the results of this work.

7.2 MCP optics and collimators for planetary remote sensing

The Mercury Imaging X-ray Spectrometer (MIXS) on the European BepiColombo mission to Mercury will detect and image solar X-ray induced fluorescent X-rays from the surface of the planet. Analysis of these X-rays will provide detailed information on Mercury’s surface elemental composition allowing its history and evolution to be inferred and leading to an increased understanding of the formation of the solar system as a whole. MIXS will have two instrument channels, an X-ray telescope (MIXS-T), using an MCP Wolter optic, whose optimisation has been described in this thesis to provide sub-km surface resolution during high solar activity, and a non-imaging slumped MCP collimator (MIXS-C), introduced for the first time in Chapter 3, to provide high X-ray throughput regardless of solar state and access to X-ray lines with energies greater than 5 keV. This two channel approach guarantees the production of global elemental abundance maps at ~40 km resolution regardless of solar state whilst providing an unprecedented surface pixel size of 200 m if solar conditions are favourable, maximising the science return. The resultant elemental maps will only reveal the composition of the surface few microns of the planet but can also indicate the composition of the underlying regolith as a result of “impact gardening”.

The next few years will see the development of a laboratory programme to test and construct the technologies required for MIXS, the construction of test models of the instrument and the eventual flight to Mercury, beginning in 2013 with arrival at Mercury in 2017.

MIXS may be followed by other similar instruments applying the same technology to investigate the compositions of other bodies in the Solar System. In the outer solar system fluorescent X-ray emission from atmosphereless bodies in the Jovian and Saturnian systems is believed to result from bombardment by highly energetic magnetospheric ions. The power emitted in soft X-rays from Io and Europa is observed to be 1.5-2 MW (Elsner et al., 2002), approximately 20 times greater than from the Moon whose soft X-ray emission is 0.07 MW (Schmitt et al., 1991; Kamata et al., 1999) and so imagers similar to MIXS are ideal instruments for future missions to the two gas giant systems. Jupiter and Saturn themselves are emitters of X-rays as a result of interactions between their ionospheres and the solar wind (Metzger et al., 1983), bremsstrahlung radiation (Gladstone et al., 2002), resonant scattering of solar X-rays and ion precipitation from the ring current (Waite et al., 1994; Maurellis et al., 2000; Gladstone et al., 2002; Ness et al., 2000). In addition the plasma torus around Io is also a major emitter of bremsstrahlung X-ray emission. The work described in this thesis will result in the realisation of an instrument which will revolutionise our view of the innermost planet, advance our understanding of solar system formation and may eventually be applied to exploration of the Saturnian and Jovian systems.
7.3 MCPs as interplanetary dust detectors

Nanometer scale aluminium films, applied to the faces of MCP optics as thermal barriers, have been demonstrated as highly sensitive detectors of impacting interplanetary dust and space debris with sensitivities two orders of magnitude greater than previously flown detectors. An analysis of a filmed MCP, which was exposed to the external environment of the International Space Station has revealed a high density, and previously unobservable, nanometer scale dust population. The origins of this population are currently unclear. It may contain contributions from both natural dust and man made debris. Further analysis of the samples with advanced microanalysis techniques may allow the identification and isolation of natural and artificial contributions to this population through the detection of trace elements in impactor residues.

A programme of detector calibration using controlled impacts from particle accelerators is essential in order to properly quantify the impacts that have been observed. Although no accelerators available can accelerate or control particles close to the ballistic limit of this detector the Van De Graaff accelerator at the Max Plank Institute in Heidelberg can accelerate 50 nm iron particles to high speeds and other accelerator facilities are working towards developing ten nanometer scale particle capabilities.

The ISS sample exposure experiment was not optimised as a dust or debris experiment. A future optimised experiment would allow improved confidence in the results presented here and provide additional information on nanometer dust fluxes for different environments and exposure characteristics such as pointing direction and film thickness. Passive exposure experiments are limited to manned vehicles in LEO, and this environment cannot be assumed to be representative of the conditions in higher orbits and in deep space. To observe the wider dust environment it will be necessary to produce an active sensor with equivalent sensitivity to that demonstrated by the filmed MCPs.

A detector concept based on the transmission of light by holes in the film and the detection of the UV flash associated with high velocity impacts has been presented. Such a sensor could be used to map the nanometer scale dust populations encountered by any platform. The development of this detector requires laboratory calibration of particle impacts on thin films and the associated UV flash and verification of the proposed readout technique using a Van de Graaff dust accelerator. Modelling of impacts on nanometer scales using molecular models and hydrocodes may provide additional insight into the physics of submicron impacts and thin films and a subsequent decoding of impact morphologies to determine properties of the impacting particles.

7.4 Final comments

After four decades of service as detectors for space science MCPs continue to be an important technology. From their beginnings as X-ray and EUV detectors MCPs are still the detectors of choice for EUV astronomy and have been adapted as optics for X-ray astronomy and planetary remote sensing, providing unprecedented elemental mapping resolution. MCPs have been demonstrated in this thesis as
highly sensitive detectors of interplanetary dust and space debris particles, for the first time, and have led to the discovery of a hitherto undetectable dust population in near Earth Space. Over the next forty years MCPs will find use as scientific detectors throughout the solar system and will continue to be a vital technology for astronomy and planetary science.
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