A study of x-ray bursts with EXOSAT
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Chapter 2

The EXOSAT Medium Energy instrument

2.1 Introduction

The European X-ray observatory *EXOSAT* was operational from May 1983 to April 1986. It was launched into a highly eccentric orbit ($e \sim 0.93$) with a 90.6 hr period and an apogee distance of 191,000 km. This rather non-standard orbit had its origin in the initial main goal of the mission, i.e. determination of accurate positions of X-ray sources through lunar occultations. The orbit chosen maximized the number of sources occulted by the moon. In the long period of time between the first ideas about the satellite and its launch (almost 15 years), detection techniques in X-ray astronomy developed rapidly. In the period 1971-1977, six X-ray observing satellites (*Uhuru*, *Copernicus*, *Ariel V*, *ANS*, *SAS 3* and *HEAO 1*) were launched which were highly successful and had an increasing capability for determining accurate source positions. When X-ray imaging optics became feasible, the originally planned instrumentation of the satellite was changed, and two imaging telescopes were included. At the time of launch, the lunar occultation mode was still supported, but eventually only one attempt was made to determine a source position with this technique. What remained, however, was the highly eccentric orbit and it was this feature of the *EXOSAT* mission that proved to be of high scientific value: the long orbital period of the satellite allowed uninterrupted observations for up to $\sim 76$ hours, enabling for the first time the monitoring of source variability on long time scales. This led to important new discoveries, e.g. the short time scale variability in extra-galactic sources ($10^3 - 10^4$ s; Lawrence et al. 1985) and the determination of orbital periods of low-mass X-ray binaries and cataclysmic variables. In the field of X-ray bursters, the topic of this thesis, it became possible for the first time to make extensive studies of the recurrence behaviour of X-ray bursts, since the sources could be monitored for long uninterrupted intervals without the chance of missing bursts due to Earth occultations.

The instrumental configuration of *EXOSAT* consisted of the following three experiments:

1. Two Low Energy (LE) imaging telescopes, covering the 0.05-2 keV photon energy band, used in conjunction with either a Channel Multiplier Array (CMA) or a Position Sensitive (proportional counter) Detector (PSD). The CMA had a circular field of view with a diameter of $2^\circ$, an on-axis angular resolution of $\sim 15$ arc seconds, and no energy resolution. A choice of five filters was available for
broad band spectroscopy, and a transmission grating could be inserted behind each telescope for medium resolution spectroscopy. The PSD had an energy resolution \( \Delta E/E \) (FWHM) = 44\( E^{-0.5\%} \) (E in keV), and an angular resolution of \( \sim 45'' - 180'' \), depending on energy.

2. A Medium Energy (ME), large area (\( \sim 1500 \text{ cm}^2 \)) proportional counter array, consisting of 8 Argon-filled chambers (sensitive in the 0.5-30 keV band) and 8 Xenon-filled chambers (sensitive in the 5-55 keV band). The instrument provided spectral and temporal data, with a selectable time- and spectral resolution. The field of view was 45' x 45' FWHM.

3. A Gas Scintillation Proportional Counter (GSPC), sensitive in the 2-40 keV range, with \( E/\Delta E \sim 9 \) at 6 keV and a geometric area of \( \sim 160 \text{ cm}^2 \). The field of view was 45' x 45' FWHM.

For the study of X-ray bursts a high time resolution is needed in order to follow accurately the rapid evolution of bursts in time. At the same time, the spectra accumulated in these short time bins should be statistically significant to enable the study of the spectral evolution of the bursts. Since the burst sources are relatively weak, these two objectives can only be realized with an instrument having a large geometric area. Therefore, the ME instrument is best suited for this task, and only data from this instrument have been used in this Thesis. In Section 2.2 of this Chapter, I give a description of the ME instrument. In Section 2.3, I describe in some detail the calibration of the ME instrument and the methods used to analyse the data, in particular the data on X-ray bursts.

2.2 The Medium Energy Instrument

The ME instrument (Turner et al. 1981) contained eight proportional counters in four pairs. Each counter, depicted schematically in Fig. 2.1, consisted of two gas cells: an Argon-filled cell, sensitive in the 0.5 – 30 keV energy range, on top of a Xenon-filled cell, sensitive in the 5 – 55 keV range. Between the cells was a 1.5 mm beryllium window. The entrance windows to the Argon cells were made of beryllium with a thickness of 32\( \mu \text{m} \) for two detectors, and 62\( \mu \text{m} \) for the other six. The Argon cells had two layers of anode wires, with one layer of cathode wires in between. The Xenon cells had three layers of anode wires, with two layers of cathode wires in between. In front of each counter a collimator was mounted in the form of a lead glass microchannel plate. This collimator gave a square field of view of 45' x 45' FWHM. The collimator response (see Fig. 2.2) was triangular with a 7' flat top. The energy resolution of the detectors was given by:

\[
\frac{\Delta E}{E} = \frac{54}{\sqrt{E}} \% \quad \text{(Ar)} \\
\frac{\Delta E}{E} = \frac{34}{\sqrt{E}} \% \quad \text{(Xe)} \quad \text{(E in keV)}
\]

(2.1)

Background rejection was accomplished by anti-coincidence techniques and pulse rise time discrimination, giving a rejection efficiency of \( \sim 99\% \).
2.2. The Medium Energy Instrument

Figure 2.1 Schematic cross section of a medium energy detector.

Table 2.1 Principal EXOSAT ME OBC modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Output</th>
<th>Time Resolution</th>
<th>No. of Energy Channels</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>HER4</td>
<td>spectral</td>
<td>2.5–10 s</td>
<td>128(Ar)+128(Xe)</td>
<td>det$^{-1}$, quad$^{-1}$, or half$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>intensity</td>
<td>31–250 ms</td>
<td>–</td>
<td>Ar+Xe added</td>
</tr>
<tr>
<td>HER5</td>
<td>spectral</td>
<td>0.13–4 s</td>
<td>64(Ar)+64(Xe)</td>
<td>half$^{-1}$; selectable channels</td>
</tr>
<tr>
<td></td>
<td>intensity</td>
<td>0.3125 s</td>
<td>–</td>
<td>Ar only</td>
</tr>
<tr>
<td>HTR3</td>
<td>intensity</td>
<td>4–16 ms</td>
<td>–</td>
<td>Ar and/or Xe added</td>
</tr>
<tr>
<td>HTR4</td>
<td>intensity</td>
<td>0.25 ms</td>
<td>1</td>
<td>selectable channel</td>
</tr>
<tr>
<td>HER6</td>
<td>intensity</td>
<td>typically 4 ms</td>
<td>1 or 2</td>
<td>selectable channels</td>
</tr>
<tr>
<td>HER7</td>
<td>intensity</td>
<td>typically 4 ms</td>
<td>1, 2 or 4</td>
<td>selectable channels</td>
</tr>
</tbody>
</table>

The eight detectors were mounted in pairs to form quadrants. A tilt mechanism could be used to offset half of the array by about 2° from the pointing direction to monitor the background.

Each detector provided data in 128 pulse height channels. Because of the limited capacity of the downlink from EXOSAT to the Earth ground station, the data were compressed by an On Board Computer (OBC). Many OBC programs (OBC modes) were available, each providing a different combination of time resolution and spectral...
resolution, and optionally combining the information of several detectors. Depending on the objectives of the observation, the investigator could choose up to three different ME OBC modes to run simultaneously. Table 2.1 gives details on the most important ME OBC modes. In our work we used mainly HER5 data from the Argon detectors in the spectral mode, giving information per half array (4 detectors) with a time resolution of 1 s, and spectral information in 64 channels. The time resolution could be increased to 0.3125 s, either at the expense of spectral information (by adding adjacent spectral channels), or at the expense of the time resolution of data from the Xenon detectors.

2.3 Data analysis techniques

2.3.1 Dead time correction

Dead time occurs both in the ME detector, the electronics associated with it, and in the OBC, the latter being the most important source. For our purpose (time resolutions $\geq 0.3$ s), the dead time of the detector and electronics can be neglected compared to that caused by the OBC. The OBC dead time depends on the total count rate in the detector and can be expressed in the dead time factor, i.e. the multiplication factor that should be applied to the recorded count rate to account for dead time. The easiest way to evaluate the dead time factor is by using the raw count rate of the detectors. This raw count rate, called the Qualified Events
(QE) rate, contains information from all Argon and Xenon detectors, provides no spectral information and is not processed by the OBC. Therefore, this count rate is not affected by OBC dead time; an analytical expression is available to evaluate the dead time factor from these Qualified Event rate (Andrews and Stella 1985). However, the QE rate of a single detector is sampled only once every 32 seconds, which makes the QE rate only suitable for the dead-time evaluation of constant or slowly varying signals. In the case of X-ray bursts, which show count rate variations of factors of \( \sim 10 \) on time scales \( \leq 1 \) s, the QE rate can therefore not be used to evaluate the dead time. In principle, instead of the QE rate, data could be used which contain information of all 128 spectral channels at a high time resolution and which have a low OBC dead time (e.g. HTR3 data; see Table 2.1). However, the HTR3 mode is only available in about half of the observations used in this thesis, and in some observations it contains only information from the Argon detectors and not from the Xenon detectors. To guarantee uniformity in our results, we decided to use only the HER5 data to evaluate the dead-time factor.

Evaluating the dead-time factor from the HER5 data poses the problem that in this mode only a certain preselected part of the spectral information is transmitted to Earth. Most of our observations use 64 out of 128 channels for both the Argon and Xenon detector. However, the counts detected in the other channels are essential because they are also processed by the OBC and thus contribute to the total dead time.

This problem is solved in the following way: The dead time of a piece of data just prior to the burst, when the emission of the source (including background) shows only small variations, is determined using the QE rate, which yields directly the ‘correct’ dead-time factor for this piece of data. This dead-time factor is then applied to the HER5 count rate of the combined Argon and Xenon detectors of the same piece of data. The resulting dead-time corrected HER5 count rate is lower than the QE rate. The difference, called \( C \), is the dead-time corrected count rate in the Argon and Xenon channels which are not transmitted to Earth in the HER5 mode. This quantity \( C \) is used throughout the burst in an iterative process to derive the dead-time factor. An initial estimate is made of the dead time of a piece of burst data (the ‘input’ dead-time factor) and the dead-time corrected HER5 count rate is evaluated using this estimate. The value of \( C \) is added to the result yielding the total dead-time corrected count rate in all channels. Based on this total dead-time corrected count rate, a dead-time factor (the ‘output’ dead-time factor) can be calculated, using the analytical expression mentioned above. This dead-time factor serves as a new estimate in the following cycle of the process. This process is repeated until the ‘input’ dead-time factor and the ‘output’ dead-time factor agree within a certain limit.

This method will only work if \( C \) is constant during the burst. This is indeed the case, as can be seen in Fig. 2.3 which shows an example of the evolution in time of the count rate of a burst in different channels of the Argon detector. Fig. 2.3a shows the count rate in Argon channels which are transmitted to Earth, while Fig. 2.3b shows Argon channels which are not transmitted to Earth in our HER5 observations. The count rate in these channels shows no trace of the burst which is clearly visible in Fig. 2.3b. The burst in this example is observed in HER4 mode (see Table 2.1), which is the only mode where all 128 channels are transmitted. The results will be
Figure 2.3 (a): raw (i.e. not corrected for dead time) count rate of a burst event in the Ar detector channels which are transmitted to Earth in our observations (channels 4–67, \( \sim 0.9 - 21 \) keV); (b): same as (a) for the summed count rate in channels 0–3 and 68–127 (\( \sim 0.5 - 0.9 \) keV and \( \sim 21 - 30 \) keV, respectively), which are not transmitted to Earth.
the same for the HER5 mode.

2.3.2 Binning of data

The 128 energy channels available from the ME detector result in an oversampled signal, for which the statistical errors on the data points in the different channels are not independent, making statistical tests in the data analysis worthless. Davelaar (1979) showed that the optimum bin width, extracting the maximum of information from the spectrum with sufficiently independent channels to justify the use of standard statistical tests, is 80% of the (energy dependent) standard deviation ($\sigma$) of the spectral resolution function (see Section 2.3.4) of the detector. Using this optimum bin size we rebinned the data in the energy range over which the detector energy channels are smaller than 0.8$\sigma$, and left the channel boundaries unchanged otherwise. As could be expected from the energy dependence of the spectral resolution function (see eq. 2.1), the data remain unchanged at low energies, whereas data at energies higher than $\sim 3$ keV have to be rebinned. The result is that the original 64, or 32, HER5 channels are rebinned to 38, or 28, channels, respectively. Although this procedure may result in undersampling of the signal at low energies, it is useless to rebin the data to bins smaller than the fundamental detector bin size, since this will yield no additional spectral information, and will result in data points which are statistically dependent by definition.

2.3.3 Background subtraction

A part of the events detected by the instrument have not come from the observed objects, but e.g. from cosmic-ray induced events, solar activity, the diffuse extragalactic X-ray background, or from events generated in the detector itself. All these events together are called the background. Most of these events are recognized as not being X-ray events by the background rejection system of the instrument (see Section 2.2). The characteristics of the remaining background (mainly diffuse X-ray background and solar activity) can be seen in Fig. 2.4, which shows a 'slew' observation for the two detector halves separately (i.e. the satellite is not pointed at a specific source but is moved from one source to another, observing 'empty' X-ray sky). The background can show flares on time scales of seconds to minutes (usually of solar origin) and long time variations on time scales of hours to days. From this figure it is clear that the two halves of the detector produce different background count rates. This poses a problem to the analysis of the data, because it is not possible to use the background count rate of one half of the ME as background for the other half. We therefore only subtract background information from source data obtained with the same half.

Two sources of background information have been used. The first source of background data is obtained from 'blank-field' observations, acquired by tilting one half of the detector array by $\sim 2^\circ$ to an empty part of the sky (see also Section 2.2). The second source of background data comes from the slewing of the satellite from or to another source at the beginning or end of pointed observations. This information is less reliable than the former type because of the possibility that the field of view of the observatory sweeps across some X-ray source. Whenever slew data are used in our analysis we have always carefully checked them for such accidental source detections.
Figure 2.4 Typical raw count rate during a slew observation in Half 1 (lower panel) and Half 2 (upper panel) of the Ar detector. The count rates in the two halves differ by $\sim 6$ counts/s. Typical small-scale background variations on times scale of a few minutes can be seen. At $t \sim 4800$s the field of view of the instrument swept past an X-ray source, which is visible as a peak in the count rate.
2.3. Data analysis techniques

During a large part of the observations used in this thesis both array halves were pointed at the source. At regular intervals one of the array halves was tilted to monitor the background for about 15 min, while the other half remained pointed to the source. This method has the advantage that most of the time the full detector area is pointed at the source to assure a high signal-to-noise ratio. The disadvantage of this method is that the data used for background subtraction is recorded at a different time as the source data, making the background subtraction sensitive to background variations. Also, small solar flares may occur unrecognized and influence the results. The same is true for the method using the slew data, which is always recorded only at the beginning or the end of an observation. In the specific case of our analysis, this disadvantage only applies to analysis of the persistent emission of the sources. In the case of bursts, the net burst emission is analysed, which means that the persistent emission (including background) has been subtracted from the burst emission. This persistent emission plus background is always taken from data recorded as closely as possible to the burst, assuring that long-term variations in the background do not seriously influence the results.

To show the importance of a correct background subtraction, we plot in Fig. 2.5 a typical background spectrum (dashed crosses) together with a typical raw (i.e. including background) persistent spectrum from the source 4U/MXB 1636-53 (solid crosses). At the peak of the persistent spectrum, the background attributes less than

![Figure 2.5 A typical X-ray background spectrum (dashed), together with a raw (i.e including background) persistent spectrum from the source 4U/MXB 1636-53 (solid). Above ~ 12 keV the persistent spectrum is completely dominated by the background.](image-url)
5% to the total counts. However, at energies ≥ 12 keV the persistent spectrum is completely dominated by the background, which makes the subtraction highly sensitive to small variations in background level. Careful examination of the background before selecting an appropriate stretch of data is therefore needed.

After the launch of the EXOSAT observatory, it was discovered that the particle background of the detectors depends on the tilt angle of the detector array. Using long-lasting blank-field observations with the detector halves at various offset angles, it was possible to evaluate the differences in background for different tilt angles. These so-called difference spectra have been used to correct the background spectrum before subtracting it from the source spectrum.

2.3.4 The detector response function

The dead-time corrected, background subtracted spectrum is still not the true source spectrum, since the detector treats photons of different energies differently, thereby altering the incoming source spectrum considerably. Because we only use data from the Argon detectors in this thesis, we will concentrate on the response function of these detectors. This response function is determined by the following characteristics:

*The effective geometric area*
The real geometric area of a detector is diminished by screening of the guard wires and by the collimator transmission.

*Detector absorption efficiency*
The probability of detecting a photon is energy dependent and is affected by absorption of photons in the entrance windows and other parts of the detector. The combination of effective geometric area and detector absorption efficiency is usually called the effective area. In Fig. 2.6a this effective area is shown as a function of photon energy for the full Argon detector array. The jump in the effective area at ~ 3 keV is due to an increase in the absorption efficiency caused by Ar K-shell electrons.

*Escape fractions*
A part of the photons above a certain energy level may be detected at lower energies. This is due to the fact that the incident photon may knock out an electron from the inner shells of an Ar or Xe atom in the detector gas. The atom will adjust its electron configuration, thereby emitting one or more secondary X-ray photons. These photons will either be reabsorbed in the gas or will escape from the counter. The energy of the escaped photons will not be registered by the instrument. The mean energy losses are 2.96 keV for photons with energies > 3.20 keV (Ar K-shell), 30.49 keV for photons with $E > 34.56$ keV (Xe K-shell) and 4.33 keV for photons with $E > 5.1$ keV (Xe L-shell). The influence of the Argon escape fraction can be seen in Fig. 2.6b, which shows the detector response after taking account of the effective area and the escape fraction.

*Spectral distribution function*
Photons of equal energy will be detected in a range of neighbouring detector energy channels due to the limited energy resolution of the detector. This
2.3. Data analysis techniques

Figure 2.6 (a): The ME Argon effective area (full detector array). This comprises the effective geometrical area and the detector absorption efficiency. The jump near 3 keV is due to Ar K-shell absorptions; (b): As (a), but after including the influence of the escape fractions; (c): As (b), but after including the spectral distribution function of the detector; (d): The ME Ar electronic acceptance efficiency as function of energy; (e): The total ME Ar detector response function.
resolution is a function of energy and is determined by the FWHM of the energy resolution function. The influence on the detector response is illustrated in Fig. 2.6c.

*Electronic acceptance efficiency*

A certain energy dependent fraction of events is lost, due to the acceptance criteria used to discriminate between 'real' events and, e.g., background (other than X-ray background) events. In addition, some unexplained detector characteristics (especially at energies \( \leq 1.5 \) keV) have been compensated in the calibration matrix (see below) by incorporating them in the electronic acceptance. In Fig. 2.6d the electronic acceptance efficiency is shown as a function of energy. At energies below \( \sim 1.5 \) keV, the electronic acceptance efficiency decreases rapidly, while at energies below 0.7 keV the efficiency is not known and set equal to 1.0.

The combined effects of the above detector characteristics yield the final detector response function of the full Argon detector array, which is plotted in Fig. 2.6e.

The detector characteristics have been calibrated on basis of both pre-launch ground tests and in-flight tests. For in-flight tests, the spectrum of the Crab Nebula has been used, which has a well-established power-law shape with the following parameters: photon index \( \Gamma = 2.10 \pm 0.03 \), normalization constant \( C = 9.7 \pm 1.0 \) photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) (Toor and Seward 1974) and equivalent Hydrogen column density (see next Section) \( N_H = (3.45 \pm 0.42) \times 10^{21} \) cm\(^{-2}\) (Schattenburg and Canizares 1986). The results are combined to form the calibration matrix, which contains information
2.3. **Data analysis techniques**

![Graph of fitted colour temperature, $kT_c$, and fitted equivalent interstellar Hydrogen column density, $N_H$, for burst spectra from 4U/MXB 1636-53. See text for more details.](image)

**Figure 2.7** The relation between fitted colour temperature, $kT_c$, and fitted equivalent interstellar Hydrogen column density, $N_H$, for burst spectra from 4U/MXB 1636-53. See text for more details.

on how the detector responds to photons of different energies. The remaining systematic uncertainties in the detector response lead to an uncertainty of $\leq 1\%$ in this calibration matrix (Parmar and Smith 1984). Generally, this is taken into account by quadratically adding 1% of the observed counts to the statistical error in each channel. This method is formally not correct because it neglects the possible existence of a global bias on the signal. However, since we have no a priori knowledge of possible biases, the method is the best available and is therefore also used in our analysis procedure.

Especially due to the rapidly decreasing electronic acceptance at low energies ($\leq 1.5$ keV) it is not advisable to use data below this energy. We therefore used only data above $\sim 1.5$ keV in our analysis.

### 2.3.5 The interstellar absorption

On its way from the source to the observer, a fraction of the X-ray emission of the source is absorbed by interstellar matter. This absorption, which is most pronounced at energies below $\sim 3$ keV, has been incorporated in the analysis by expressing it in terms of the quantity $N_H$, defined as the equivalent column density of Hydrogen atoms which, for assumed heavy-element abundances, is needed to account for the observed absorption. For most X-ray sources the value of $N_H$ is not known. This
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poses a problem on the spectral analysis of the X-ray emission, because it is hard to disentangle the effects of variations in the shape of the spectrum (as formed in the upper layers of the neutron star) from the effects of a changing absorption in the vicinity of the source (e.g. due to mass loss). Moreover, if the interstellar absorption is treated as a free parameter in the fit procedure, small variations in the shape of the photospheric X-ray spectrum may be overlooked because they have been compensated by a variation in the value of $N_H$. This problem is illustrated in Fig. 2.7, where we plot the results of a series of test fits on spectra of bursts from the low-mass X-ray binary 1636-53 (see Chapter 3 of this thesis). The spectra are all fitted with a blackbody model with free parameters $kT$ (the colour temperature) and $N_H$. The resulting values of $kT$ and $N_H$ have been plotted against each other in Fig. 2.7. As can be seen in this figure, these parameters show a strong anti-correlation, and $N_H$ even becomes negative at high values of $kT$. Since negative $N_H$-values do not exist in nature, it is impossible that these variations in $N_H$ reflect real variations in the absorption between the source and the observer. A far more likely explanation is that the shape of the burst spectra shows small variations which are a function of the temperature. These small deviations from a pure Planckian shape are compensated in the fit procedure by variations in $N_H$.

The main goal of our work is a detailed study of the spectra of X-ray burst emission. In view of the above result we found it not advisable to treat the interstellar absorption as a free parameter in the spectral fits. We therefore used a fixed value for the equivalent hydrogen column density in all our fits to burst spectra. For the various X-ray sources studied in this thesis, these $N_H$ values have been derived using two different methods.

The first method uses an empirical relation, derived by Gorenstein (1975), between $N_H$ and the interstellar optical extinction, $A_v$, towards the source:

$$A_v[\text{mag}] = (4.5 \pm 0.3) \times 10^{-22}N_H[\text{cm}^{-2}]$$

Using this relation and values for the optical extinction found in literature, $N_H$ can be calculated. This method has the disadvantage that a value for the intrinsic colour index $(B-V)$ of the source must be known, which yields a value for $A_v$ through the well-known relation $A_v = 3.1 \times E(B-V)$, where the $E(B-V)$ is the difference between the observed colour index and the intrinsic colour index of the source. Because the optical emission of X-ray burst sources is completely dominated by emission from the accretion disk (see Chapter 1 of this Thesis), determination of the intrinsic colour index is not straightforward. Most authors assume an intrinsic colour index $(B-V) \approx 0.0$ for this type of sources (see e.g. Van Paradijs 1983).

If no suitable optical observation were available, $N_H$ has been derived from fits to the persistent X-ray spectrum of the source. As mentioned earlier, the fitted $N_H$-value might be influenced considerably by small deviations of the observed spectrum from the assumed spectral model. This method of determining $N_H$ is therefore only valid if the shape of the persistent spectrum is well-established.
2.3. Data analysis techniques

2.3.6 Spectral fitting

It is not possible to directly convert the detected spectrum to the source spectrum by means of the inverted calibration matrix, since the process of inverting this matrix is unstable. Therefore, modelling of the data is done in an iterative process in which a model spectrum, \( F(E) = CA(N_H)F(s, E) \) is folded through the ME response function, and compared with the observed count spectrum. Here \( F(s, E) \) is the model source spectrum with spectral parameters \( s \), \( A(N_H) \) is the interstellar extinction, and \( C \) is a geometric ‘dilution’ factor (incorporating the distance to the source). The model parameters \( C \), \( N_H \) and \( s \) are then varied in a fit procedure until the correspondence between observed and modelled spectrum is optimal according to some statistical test (usually a \( \chi^2 \) test). In Fig. 2.8 this procedure is depicted schematically. In each step of this diagram, the model spectrum is modified by one of the detector characteristics described in Section 2.3.4, resulting in the synthesis of a model count spectrum which can be compared with the actual observed count spectrum.

2.3.7 Some remaining calibration problems

After the work described in this Thesis had been carried out, we were informed by Dr. G. Hasinger of the Max-Planck Institut für Extraterrestrische Physik and Drs. F. Haberl and A. N. Parmar of the EXOSAT observatory that the following ME calibration problems have been discovered:

1. The detector gain shows position-dependent variations. As a result, a small fraction of the source counts is redistributed in the spectrum, and appears erroneously at high energies. About 0.1% of the total source counts appears above 30 keV. This fraction increases at lower energies, but is hard to estimate because more and more ‘real’ source counts appear at lower energies. Tests show that probably \( \sim 0.2\% \) of the total source counts appears erroneously above 20 keV and \( \sim 1\% \) appears between 10 and 20 keV.

As mentioned in Section 2.3.4, the ME instrument is calibrated using the spectrum of the Crab Nebula in such a way that fits to this spectrum yield the correct parameter values (see Section 2.3.4). This means that the excess counts at high energies are compensated in the calibration, but only for spectra having this particular shape. Using this calibration on an arbitrary spectrum will introduce either an excess or a deficiency at high energies, depending on the detailed shape of the spectrum.

2. Spectra taken from the Crab Nebula show a high-energy excess when fitted with a power-law model using the values mentioned in Section 2.3.4 for the photon index, the normalization constant and the equivalent Hydrogen column density. This excess is due to non-linearities in the Analogue-Digital Converter (ADC) of the instrument, which introduce a ‘wiggle’ in the fit residuals around 3 keV. This ‘wiggle’ is compensated in the fit procedure at high energies, resulting in an apparent excess above \( \sim 10 \) keV of \( \sim 1\% \) of the total count rate in the spectrum.
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\[ f(E) = C \times A(N_H) \times F(s, E) \]

Binning \( E_j \), bin width \( \Delta E_j \); effective geometric area

Count spectrum in energy space counts \( s^{-1} \text{ bin}^{-1} \)

Absorption efficiency

Count spectrum in energy space corrected for detector absorption

Escape fraction

Count spectrum in energy space corrected for escape losses

Transformation energy \( \rightarrow \text{mV (channel)} \)

Count spectrum in mV space

Energy spreading; adding up all contributions from spreading in one bin

Count spectrum in mV space corrected for energy resolution

Electronic acceptance

Count spectrum that corresponds to \( f(E) \)

Comparison

Observed count spectrum

Statistical test

Not best fit change \( N_{H,s} \)

Best fit

\( N_{H,s} \) define source spectrum

Figure 2.8 Schematic summary of the spectral fitting procedure.
Again, the magnitude of this effect depends on the detailed shape of the fitted spectrum.

A new calibration will be distributed by ESTEC in the future, which will at least partly correct for these effects.

These two calibration problems are especially of importance for the results of Chapters 6 and 7 of this Thesis. In both Chapters a rough estimate of the effects of these calibration errors shows that they are relatively unimportant compared to the statistical uncertainties on the results (see Chapters 6 and 7 for details).

References

Parmar, A. N. and Smith, A.: 1984, *EXOSAT Express* 6, 28