X-Ray Observations of the Impulsive Phase of Solar Flares with the Yohkoh Satellite

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Abstract

This thesis starts with an overview of the physics of the solar corona, concentrating on X-ray emission and the plasma dynamics associated with the impulsive or rise phase of solar flares.

The Yohkoh satellite is described, with a section on each major instrument on board. Analysis techniques used in the thesis are then introduced, with a section of soft X-ray spectroscopy and on the application of the Maximum Entropy Method image reconstruction technique to data from the Hard X-ray Telescope on Yohkoh.

The instrumental effect known as fixed pattern noise is described, leading to a numerical model of the BCS digitisation process, which is used both to understand the limits of the detector, and to correct the data in a limited way. Alternative methods for the avoidance of fixed pattern noise are evaluated.

The analysis of a solar flare with unusually large soft X-ray blue shifts is then performed. Physical parameters of the plasma during the initial stages of the flare are derived, which are used in an energy balance calculation. Agreement is found between the energy in nonthermal electrons and that contained in the coronal plasma, supporting the nonthermal beam driven chromospheric evaporation theory of impulsive flares.

The location of superhot plasma in two impulsive flares and one hot thermal flare is then investigated. Superhot plasma is found to be located close to the chromosphere, and related to the nonthermal burst in the two impulsive flares. Superhot plasma in the hot thermal flare is distributed uniformly throughout the loop. The differences are explained as being due to the different energy transport processes active in each type of flare.
Chapter 1

Introduction

The Solar corona is visible at optical wavelengths as a bluish-white halo surrounding the sun during an eclipse. The corona lies directly above the chromosphere starting some 5000 km above the visible limb, and extends fairly uniformly outwards for several radii, often containing large scale radial streamer structures.

In the chromosphere the presence of strong hydrogen emission lines, particularly \( \text{H}\alpha \) (which is responsible for the distinctive red colour), made it relatively easy to determine the temperature \( \approx 10^4 \) K. However, it was not until Grotrian (1939) and Edlèn (1942) identified the coronal lines at 6374Å and 7892Å as forbidden transitions of Fe X and Fe XI, that the high temperature nature of the corona \( \geq 10^6\)K) became apparent. Explaining the creation and maintenance of such high temperatures, and in particular the steep temperature gradient that exists between the corona and the chromosphere, continues to present difficulties (Ionson, 1985; Parker, 1988; Hudson, 1994). Figure 1.1 shows profiles of the temperature and density as a function of height for a model of the upper layers of the solar atmosphere.

Plasma at coronal temperatures will produce black body radiation at soft X-ray (SXR) energies \(1-10 \text{ keV; Culhane, 1981} \) which, since it is absorbed by the earth’s atmosphere, can only be observed by rocket or satellite borne instruments. The existence of this radiation was first confirmed in 1948 by scientists at the U.S. Naval Research Laboratory (NRL), using photographic plates covered by a thin beryllium filter as a detector (Burnight, 1949). This early experiment was mounted in place of the warhead on a captured V2 Rocket and marked the start of the exploration of the X-ray corona.
This observation was repeated by subsequent sounding rocket flights. These first simple instruments were followed by increasingly complex experiments on the Orbiting Solar Observatory (OSO) and Orbiting Geophysical Observatory (OGO) series of satellites, as well as further sounding rockets. These spacecraft measured flare X-ray energy spectra and light curves using ionization chambers (OGO-3; Arnoldy et al., 1968) and scintillation counters (OSO-5; Kane et al., 1979 and OGO-5; Kane, 1969). Spectrometers, which were initially only capable of studying intensity fluctuations in EUV lines (OSO-1; Behring, 1970), progressed to make some of the first high resolution measurements distinguishing, and allowing the identification of, individual SXR spectral lines (OSO-6; Doschek et al., 1971). Observations were also made with low spatial resolution ($20''$) with X-ray and EUV spectroheliographs (OSO-7; Neupert et al., 1974).

The SKYLAB mission in 1973 was the first to carry a grazing incidence telescope capable of making images with high spatial resolution ($1''$; Vaiana et al., 1977) in the soft X-ray wavelength range. Observations from this telescope showed graphically that the corona was complex and magnetically dominated, with the coronal plasmas contained in loops and regions of closed field. SKYLAB also carried two UV spectrometers (SO82A, SO82B; Tousey et al., 1977; Bartoe et al., 1977) which observed excess (nonthermal) line broadenings and Doppler shifts during some solar flares, in-
indicating turbulence and mass motions in the flaring plasma (Doschek and Feldman, 1978). SO82B also found evidence of high densities \((10^{12}\text{cm}^{-3})\) in these plasmas from studies of Si III line ratios (Cheng, 1980).

SKYLAB was followed by the NRL P78-1 mission which was launched in 1979, making use of flight spares from the OSO-7 spacecraft. The SOLFLEX flat crystal spectrometer (Doschek, 1983a) on P78-1 found significant nonthermal line broadenings and blueshifts, similar to those observed by SKYLAB, on almost all the flares observed (Doschek et al., 1979; Doschek, 1983b).

The NASA Solar Maximum Mission (SMM) was launched a year after P78-1, and carried a range of instruments including the; X-ray Polychromator (XRP; Acton et al., 1980), Hard X-ray Burst Spectrometer (HXRBS; Orwig et al., 1980), Hard X-ray Imaging Spectrometer (HXIS; Van Beek et al., 1980) and UV Spectrometer and Polarimeter (UVSP; Woodgate et al., 1980). Major advances made by SMM instrumentation included the imaging of high energy X-rays \((8''\times 8''\text{ up to } 30\text{keV})\) by HXIS and full spectrum observations at rapid cadence (up to 0.5s) made possible by the XRP Bent Crystal Spectrometer (XRP/BCS). The intentionally wide spectral coverage of the combined set of SMM instruments (Bohlin et al., 1980) was further complemented by an active collaboration with ground based instruments.

In 1981 the Japanese Hinotori satellite was launched, carrying a soft X-ray spectrometer of comparable spectral resolution to XRP/BCS, and a Hard X-ray Imager \((15''\times 15''\text{ up to } 40\text{keV})\). Data from both SMM and Hinotori provided key insights in many areas, including particle acceleration, soft X-ray blueshifts, flare energy transport, and Coronal Mass Ejections (see Kundu and Woodgate (1986) for a comprehensive set of reviews covering results from both spacecraft).

The data upon which this thesis is based were taken by the Yohkoh spacecraft, launched on 30th August 1991 from Japan. Yohkoh carries 4 major instruments; the Soft X-ray Telescope, the Hard X-ray Telescope, the Bragg Crystal Spectrometer and the Wide Band Spectrometer. The spacecraft and instruments are described in detail in chapter 2.
1.1 Coronal Structure

The SKYLAB images showed that most of the hot coronal material is contained within magnetic loop structures or other closed regions of magnetic field. This is not surprising, given the density and temperature profiles shown in figure 1.1.

The containment of plasmas by magnetic fields is governed both by the relative strengths of the magnetic and gas pressures and by the resistivity of the plasma to the diffusion of the magnetic field through it.

From Tandberg-Hanssen and Emslie (1988), the ratio of the gas pressure to the magnetic pressure (plasma \(\beta\) value) for a two fluid (electron and ion) gas is:

\[
\beta = \frac{16\pi nkT}{B^2}
\]

where \(n\) is the electron density, \(T\) is the temperature, \(k\) is the Boltzmann constant and \(B\) is the magnetic field strength. In the photosphere and lower chromosphere the plasma beta value is high, but in the corona where the densities are much lower, the beta value is much less so that the magnetic field shapes the plasma.

From Mariska (1992) the magnetic diffusion equation is:

\[
\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \frac{\eta c^2}{2\pi} \nabla^2 B
\]

where \(v\) is the velocity, \(\eta\) is the resistivity, and \(c\) is the speed of light. The first term on the R.H.S. describes how the plasma convects the magnetic field and the second describes the collapse of the field via the plasma resistivity. The ratio of the convective to diffusive terms is the magnetic Reynolds number \((R_m)\), and describes the degree of resistance of the plasma to relative motions of the magnetic field;

\[
R_m = \frac{\mid \nabla \times (v \times B) \mid}{\frac{\eta c^2}{2\pi} \nabla^2 B} \approx \frac{4\pi vl}{\eta c^2}
\]

with the approximation based on the assumption that the magnetic field varies over a scale length of \(l\).

For coronal plasma \(R_m \approx 10^6l\), which for typical distance scales found in the corona is much greater than 1 \((\approx 10^9-10^{10};\ \text{Low}\ 1985)\). Magnetic diffusion is therefore a negligible effect, with the consequence that the field lines and plasma are strongly interlocked. This together with low \(\beta\) conditions in the corona means that the magnetic fields both define and contain the hot plasma very effectively, and so allows the study of magnetic structures via soft X-ray images of the trapped plasma.
The coronal field remains anchored in the photosphere at its footpoints, where high $\beta$ conditions prevail, with the result that the coronal magnetic field is swept around with the convective and differential rotational motions of the solar surface (Parker, 1983; Parker, 1988). This electrodynamic coupling between the corona and photosphere leads to a stretching, twisting and shearing of the coronal field (Ionson, 1985; Parker, 1987b). The resulting nonequilibrium (with respect to a potential field) state is the normal situation for the corona (Low, 1985; Strong, 1994) and is balanced by constant dissipations or reconnections (via spontaneous tangential discontinuities) to less stressed, lower energy states (Parker, 1972).

Significant amounts of energy can be released when the coronal field reconnects (Hudson 1991). On a small scale this "nanofiaring" (Parker, 1987a) may be a candidate for the source of coronal heating (Parker, 1988), by transferring work done on the footpoints directly into heat in the corona at an estimated rate of $10^7$ erg cm$^{-2}$ s$^{-1}$ (Parker, 1983). This model still has its difficulties (Hudson, 1994), as recent studies still find a shortfall between the numbers of nanofiare events required by the model, against those extrapolated from observations of active region transient brightenings (Shimizu, 1995). It is generally accepted however that when this process happens catastrophically, sufficient energy can be released to power a solar flare (Spicer, 1977; Priest, 1983).

### 1.2 Solar Flares

Solar flares are abrupt intense releases of energy, with typical durations ranging from a few minutes to several hours. The strength of a flare can be measured by the amount of energy that it releases in specific wavebands. The first widely used scheme was the Importance classification (IAU, 1955; IAU, 1966), which rates flares by both the size (in millionths of a hemisphere) and the optical intensity (faint, normal or brilliant). A more quantitative measure has also been recently adopted, based on the 1–8Å SXR flux monitored by the GOES$^1$ spacecraft as part of a programme of continuous whole-sun observations. The GOES classes are given in table 1.1. The GOES class letter is normally suffixed with a number indicating the strength within the class, so that for example a GOES class of C5 means a flux of $5 \times 10^{-3}$ erg cm$^2$s$^{-1}$.

---

$^1$Geostationary Operational Environment Satellite
1.2. SOLAR FLARES

<table>
<thead>
<tr>
<th>GOES Class</th>
<th>flux (erg/cm²/s)</th>
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<tr>
<td>B</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>C</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>M</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>X</td>
<td>$10^{-1}$</td>
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Table 1.1: GOES Flare Classes (From Zirin, 1988)

1.2.1 Flare Types

The term "Solar Flare" covers a wide variety of energy releasing phenomena occurring in the solar atmosphere. In addition to flare classifications based on flare energy output, there exist several morphological classifications, which divide flares according to their appearance and evolution.

Early classifications were based on the appearance of a flare in particular wavelength ranges, for example; Hα (e.g. Bhatnagar, 1984; Zirin, 1983) and X-ray wavelengths (Pallavicini et al., 1977).

Bhatnagar describes, based on optical observations, five general flare classes ranging in size from large "two-ribbon" events to small compact impulsive flares associated with Field Transition Arches. Each type has its own characteristic pattern of Hα emission and evolution. For several of the classes a defining magnetic field topology can be assigned. Pallavicini et al. define a simpler classification, dividing X-ray flares into three types; compact flare loops (Type a), point like flares (Type b) and large diffuse flares (Type c), based on data from the SKYLAB mission.

A more detailed scheme proposed by Tanaka (1983) based on multi-wavelength observations, identifies five specific flare emission components and three major flare types; Hot Thermal (Type A), Impulsive (Type B) and Gradual-Hard (Type C). Each major flare type can be modelled as comprising one or more flare emission components, which are listed in table 1.2.

Statistical surveys show that most flares are Type B impulsive events. Kosugi et al. (1988) found that in a sample of 400 flares observed by SMM, 13 were Type C, 3 were Type A and the rest were Type B. Studies conducted by Sakao, (1994) and
### 1.2. SOLAR FLARES

<table>
<thead>
<tr>
<th>Component</th>
<th>Time Profile / Spectrum</th>
<th>X-ray &amp; Hα morphology</th>
<th>Origin / Flare Type</th>
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</thead>
<tbody>
<tr>
<td>Impulsive</td>
<td>Impulsive variability. Power law or exponential (E&gt;15keV)</td>
<td>SXR at footpoints and in low corona (source shrinks and shifts). High magnetic shear. Filament eruption. Irregular spread along inversion line → two-ribbon spread</td>
<td>Impulsive accelerations (energizations) in complexly sheared fields (Immediate decay). Impulsive phase of type B</td>
</tr>
<tr>
<td>Gradual-Hard</td>
<td>Spikeless broad peak(s) Power law (hard spectrum), hardening beyond peak</td>
<td>SXR extended at high corona. Stationary or shifts to higher altitudes. Large scale weak-sheared configuration. Filamentless region. Hα two ribbon spread at distance</td>
<td>Progressive accelerations across large scale fields. Type C &amp; gradual phase of type B</td>
</tr>
<tr>
<td>Hot Thermal</td>
<td>Gradual rise and fall. $T_e = 3 - 4 \times 10^7\text{K}$ (FeXXVI). Excess thermal HXR at 10-40keV.</td>
<td>Compact loops (progressive shift to higher altitudes). High $n_e \geq 10^{11}\text{cm}^{-3}$. Bright loops appear with short delay. Hα two ribbon spread</td>
<td>In-situ coronal heating. Complementary to impulsive component. Type A similar to gradual phase of type B</td>
</tr>
<tr>
<td>SXT thermal</td>
<td>Flux $\propto f^\gamma$ (impulsive component) dt (Type B). Gradual rise uncorrelated with Impulse (Type C). Upflows and nonthermal random motions ($T_e \geq 10^7\text{K}$)</td>
<td>Diffuse extended emissions with peaks at footpoints → loops. Two ribbon (extended) loops at later stages.</td>
<td>Evaporation &amp; in-situ coronal heating. Occurs in all flare types</td>
</tr>
<tr>
<td>Quasi-Thermal</td>
<td>Gradual variation. Background enhancements at 20-70keV</td>
<td>SXR extended in corona. Hα two ribbon (diffuse).</td>
<td>Nonthermal or thermal ($&gt; 5 \times 10^7\text{K}$). Gradual phase of type B. Background of types B and C.</td>
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Table 1.2: Five flare emission components. (Adapted from Tanaka, 1987)

Takakura <i>et al.</i>, (1984b), reach a broadly similar conclusion.

**Hot Thermal Flares (Type A)**

Hot thermal flare light curves show a gradual rise and fall in the energy range below 40keV. This flux is generated by a compact HXR source (<5000 km) located low (<6000km) in the corona (Tsuneta <i>et al.</i>, 1984). This source also generates strong emission in the FeXXVI lines, and is best fit by a hot thermal plasma with $T_e = 3 - 4 \times 10^7\text{K}$ below 40keV and a soft power law above 40keV with $\gamma \geq 8$ (Tanaka, 1987). Densities derived from the source size and FeXXVI emission measure are high ($> 10^{11}\text{cm}^{-3}$; Tanaka <i>et al.</i>, 1982). Any impulsive component is weak compared to type B flares, with radio and microwave emissions being very weak or non-existent.
1.2. SOLAR FLARES

(Tsuneta et al., 1984; Kosugi et al., 1994).

Impulsive Flares (Type B)

Impulsive flares follow a similar evolutionary pattern to the example shown in Figure 1.2. The flare light curve can be broadly divided into three phases; Impulsive, Gradual and Decay.

The impulsive phase consists of rapidly varying spikes in the hard X-ray light curve, occurring at low coronal altitudes. Images at higher energies (> 30keV) often show a double source structure (Hoyng et al., 1981), which have been identified as being the loop footpoints (Duijveman et al., 1982). These footpoints have been observed to be cospatial with white-light emission (Hudson et al., 1992) and Hα emission (e.g. Wülser et al., 1994), vary simultaneously (Sakao et al., 1994), and be located on opposite sides of the magnetic neutral line (Sakao et al., 1992). A recent observation of a weaker impulsive phase loop-top source, which varies similarly to the more dominant footpoint sources, has been made for a limb flare (Masuda, 1994). This source is thought to be directly related to a primary energy release mechanism (Masuda et al., 1994).

At lower energies (< 30keV) a slowly varying component is observed to appear, situated between the two footpoints (Antonucci et al., 1985; Inda-Koide, 1994), becoming more pronounced during the impulsive phase. During the gradual phase of the flare this component dominates. The timing, duration and spectral type of this type of source point to a thermal origin, with calculated temperatures of 10–20MK (Doschek et al., 1986). During the decay phase of the flare, this thermalised plasma gradually cools by conduction and radiation (and in some cases enthalpy flow, as material drains from the coronal loop).

Impulsive phase energy spectra above 30keV show either a single power law dependence (e.g. Frost, 1969);

\[ I(E) = I_{20} \left( \frac{E}{20} \right)^{-\gamma} \]  

for a normalisation at 20keV, or a double power law with a break in the 60-600 keV range (Kane and Anderson 1970; Frost and Dennis 1971; Lin and Schwartz, 1987):

\[ I(E) = \begin{cases} 
I_{20} \left( \frac{E}{20} \right)^{-\gamma_1} & E \leq E_b \\
I_{20} \left( \frac{E_b}{20} \right)^{-\gamma_2} \left( \frac{E}{20} \right)^{-\gamma_1} & E > E_b 
\end{cases} \]  

(1.4)
Figure 1.2: Type B flare lightcurve for the flare of 15 November 1991. This flare was observed at a range of soft and hard X-ray wavelengths by the Yohkoh and GOES satellites. Note the dominance of the impulsive component at high energies and the increase in the gradual component at progressively lower energies. The small spikes on the GOES Lightcurve at 22:36:30 and 22:37:50 are instrumental in origin.
where $E_b$ is the break energy. During the impulsive phase the spectrum often follows a “soft-hard-soft” type behaviour, with the values of $\gamma$ lower during the peaks of the impulsive bursts (Dennis et al., 1981; Dennis, 1985). During the gradual phase the spectrum softens and becomes thermal.

**Gradual-Hard Flares (Type C)**

Gradual hard flares are long enduring events with broad peaks in both the HXR and microwave light curves. They show little or no impulsive variation (Dennis, 1985). The source size is large ($> 20''$; Takakura et al., 1983; Takakura et al., 1984a), located high in the corona ($> 5 \times 10^4$ km; Kosugi, 1994) and has a hard power law spectrum ($\gamma = 2.5 - 4$; Takakura et al., 1984b). As the flare evolves, the spectrum becomes progressively harder (Kai et al., 1985). SXR temperatures derived from FeXXV are low ($< 25$MK), and appear uncorrelated with the HXR peaks (Tanaka, 1987).

### 1.3 Chromospheric Evaporation

Models attempting to describe Type B solar flares normally include the process of Chromospheric Evaporation. In most cases it plays a central role in the evolution of the flare.

Chromospheric evaporation, or ablation, was first proposed by Neupert, (1968) as a way of explaining the differences in the numbers of electrons involved in the flare process determined from microwave observations, compared with the numbers of electrons calculated from observations of the FeXXV line flux seen by the third Orbiting Solar Observatory (Neupert 1967).

The mismatch between the calculated electron populations from the two sets of data indicated that different plasmas were responsible for each type of emission. Neupert proposed that the soft X-ray emitting material was of chromospheric origin. In this model, during the initial stages of a flare, the chromosphere would be heated by some mechanism to several million Kelvin and expand upwards into the corona. This ablated plasma would emit the soft X-rays seen by OSO-III. As the microwave burst preceded the soft X-ray emission, it was suggested that the heating mechanism might be a result of energy transfer from the high-energy electrons that emitted the microwaves hitting the chromosphere.
1.3. CHROMOSPHERIC EVAPORATION

The chromospheric evaporation mechanism provided a good solution to the problem of creating sufficiently high densities in the corona to match the observations. Alternative ways to create the necessary quantities of flaring plasma relied on the condensation of pre-existing coronal plasma. This seemed unlikely (Hudson and Ohki, 1972), mainly due to the requirement for large volumes of coronal plasma to collapse on relatively short timescales, for which there was no observational evidence (Ohki, 1975).

Direct observational support for chromospheric evaporation can be summarised into three major strands; Plasma mass motions, Momentum balance and Energy balance.

1.3.1 Plasma Mass Motions

The detection of blue-shifts in the soft X-ray lines of FeXXIV by SKYLAB (Widing, 1975), in addition to excess spectral line broadening previously discovered by lower resolution spectrometers (Grineva et al., 1973) indicated the existence of mass motions during the initial impulsive phases of some flares. Later observations from SKYLAB, (Widing and Cook, 1987), P78-1 (Doschek et al., 1980) and SMM (Antonucci et al., 1982) confirmed this conclusion. These observations were seen as additional strong evidence for the chromospheric evaporation theory, as the most likely interpretation was that these blue-shifts were the signature of upflowing evaporated plasma, and that the excess, or nonthermal, line broadening was due to turbulence.

Surveys of both the SMM (Antonucci et al., 1984) and Yohkoh data sets (Mariska et al., 1993) both found that blueshifts of the major emission component by up to 100 km/s early in the impulsive phase were common. For a sample of 219 flares Mariska et al. found that the average radial motion was about 58 km/s, and confirmed the existence of the centre to limb variation first reported by Antonucci and Dennis, (1983). The gradual decrease in line of sight velocity with increasing longitude from the central meridian found by Mariska et al. follows the computed centre to limb dependence for constant velocity radial flows. This is strong evidence that the observed blue shifts are due to a systematic radial upflow of flare plasma.

The spectrometers on SMM also allowed the temporal evolution of soft X-ray blueshifts to be followed in detail. Doschek et al., (1986), stated that blueshifts were observed simultaneously with hard X-rays with energies above 25keV, suggesting a
causal relationship between the hard X-ray burst and the occurrence of soft X-ray blueshifts. Furthermore, the magnitude of the blueshifts was largest at the start of the impulsive burst, and decreased steadily throughout the impulsive phase. Antonucci et al., (1982) found that the blueshifted plasma component became undetectable by the time the soft X-ray light curve peaked. Subsequent analysis found that there was in fact a correlation between the decrease in the line of sight velocity and the rate of increase of the soft X-ray emission for a small sample of flares (Antonucci and Dennis, 1983). Recent higher resolution studies using combined Yohkoh and Compton Gamma Ray Observatory (CGRO) data, whilst confirming the general close correlation between the onset of soft X-ray blueshifts and the hard X-ray burst (Doschek et al., 1996), have however found some evidence for soft X-ray blueshifts occurring in advance of the hard X-ray impulse (Culhane et al., 1993; Plunkett and Simnett, 1994).

1.3.2 Momentum Balance

Hα red asymmetries are a common feature of flare spectra. Tang, (1983) found that 92% of a sample of 60 flares observed in Hα had a red asymmetry. Similar results were found by Ichimoto and Kurokawa (1984), who concluded that the red asymmetry typically appeared at the onset of a flare, and that the most likely cause was a redshift caused by downward moving chromospheric material. It was also further noted that there was good temporal co-incidence between the downward motions seen in Hα and the blueshifts seen in soft X-rays, and in a manner similar to that observed for the SXR blueshifts, the Hα redshifts abruptly increased at the onset of the Soft X-ray flare and became undetectable by the peak of the flare light curve.

The chromospheric evaporation theory predicts that momentum should be conserved between the plasma seen in soft X-rays flowing up into the corona, and the downflowing chromospheric material seen in Hα (Fisher et al., 1985b; Fisher, 1987). Momentum balance for the entire flaring area was confirmed for several flares using X-ray spectrometer data from SMM (Zarro et al., 1988; Canfield et al., 1990). Wülser et al. (1994), by using a combination of image and spectrometer data from Yohkoh and Mees Solar Observatory, also found agreement for the flare of 15th November 1991, using spatially resolved soft X-ray and Hα observations to verify momentum balance for each individual footpoint, showing that the blueshifted coronal material and the
redshifted chromospheric material originated at the same location.

### 1.3.3 Energy Balance

Antonucci *et al.* (1984) examined the conditions under which the increase in emission of the stationary plasma component was consistent with the observed plasma upflows, based on an approach described by Antonucci *et al.*, (1982). This method allows the calculation of the energy in the soft X-ray emitting plasma by requiring that the increase in mass (assuming a constant loop volume) observed in the stationary plasma be entirely supplied by material ablated from the chromosphere. By integrating the enthalpy and kinetic energy flows over the duration of the impulsive phase and accounting for losses by conduction and radiation, a total energy for this plasma component was calculated. Antonucci *et al.*, (1984) compared this derived energy with that deposited in the chromosphere by energetic non-thermal electrons, for several flares, and found that the nonthermal electrons contained sufficient energy to account for the observed soft X-ray emission.

### 1.3.4 Problems with Chromospheric Evaporation

The evidence presented above was not considered to be completely conclusive (Doschek, 1990; Feldman, 1991; Feldman *et al.*, 1994). Criticisms levelled at the arguments presented in favour of chromospheric evaporation at the SMM Workshops (Doschek *et al.*, 1986) and in subsequent papers (Doschek, 1990; Feldman *et al.*, 1994) focussed on the limitations of the available observations, as well as mismatches between numerical simulations of the different flare models and the raw spectral data.

Doschek (1990) summarised the objections to both the early momentum balance results and the energy balance calculations by suggesting that the lack of spatial resolution of the existing observations allowed such latitude in determining volumes and footpoint areas that the value of the agreements found was questionable. The case for improving the momentum balance argument was addressed by Wülser *et al.* (1994), who found equal momentum balance within well constrained error limits as described above. Improving the energy balance argument by including more accurate spatially resolved observations is described in chapter 5 of this thesis.

Feldman (1991) used measurements of coronal to photospheric abundance variations as an additional argument to support the conclusion that chromospheric evap-
oration did not provide the flare plasma. Feldman et al. (1994) also described evidence that appeared to contradict the chromospheric evaporation hypothesis, extending the work of Acton et al. (1992) by presenting new observations of a class of compact looptop events with little indication of any associated loop filling.

Other observations which have been used as a counter argument to chromospheric evaporation, like the relative timings of the onset of hard and soft X-ray emission (Feldman et al., 1982; Zarro et al., 1995), the existence of a strong stationary SXR component at the start of a flare, before the start of HXR emission, (Doschek, 1990; Cheng et al., 1994), the presence of soft X-ray blueshifts before the onset of the hard X-ray burst (Simnett, 1991; Plunkett and Simnett, 1994; Cheng et al., 1994; Culhane, 1996), and an observed lack of correlation between the integral of the hard X-ray light curve and the soft X-ray light curve (Feldman et al., 1982; Feldman, 1990), are not levelled at the Chromospheric Evaporation theory in itself, but are instead mainly directed at the numerical simulations of particular solar flare models (primarily nonthermal beam models) which include it as a principal process.

The next section outlines some of the principal impulsive solar flare models, and reviews the major points of both supporting and discrepant observational evidence.

1.4 Impulsive Flare Models

The canonical model for compact impulsive flares evolves, at least conceptually, through three distinct stages (Underwood et al., 1978);

1. Primary energy release with resulting energetic particle acceleration and/or hot plasma ($10^7$K) creation.

2. Transport of energy to the chromosphere with possible ablation of chromospheric material.

3. Flare plasma cooling (decay).

In the first stage energy is thought to be released in the corona by fast magnetic reconnection (Brown et al., 1994; Tsuneta, 1995; Priest, 1983), probably at the loop top (Figure 1.3; Shibata, 1996; Emslie, 1983; Hirayama, 1974) related to observed plasmoid or filament ejection (Shibata et al., 1995), the relaxation of magnetic shear in an arcade (Sakurai et al., 1992), or internally to the loop itself (Spicer, 1977). Some
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Numerical models have also included a primary energy release site at the base of the coronal loop near the chromosphere (Wu et al., 1981; Antonucci et al., 1987), but this geometry does not seem to be borne out by time correlation of the HXR light curves for each footpoint (Sakao, 1994).

For the second stage, simple flare models can be broadly divided into two categories based on the energy transport mechanism employed: Thermal or Non-Thermal (Acton et al., 1982). Hard X-rays can be generated by the free-free process in hot ($> 10^8$) plasmas or by the collisional interaction of a nonthermal population of accelerated electrons with the ambient coronal plasma (Thin-Target emission), or the chromosphere (Thick-Target emission).

In Thermal models the energy released by reconnection heats plasma in the coronal part of the loop. The flare energy is then transferred down to the chromosphere by a thermal conduction front, where the deposited energy drives the upflow of plasma, termed “gentle evaporation” (Schmieder et al., 1987; Fisher et al., 1985c). Nonthermal models transport energy to the chromosphere using streams of high energy electrons which are accelerated by the reconnection process (Benz et al., 1994; Vlahos, 1989), although a case has also been made for high energy protons (Simnett, 1986).
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Energy transported by these nonthermal electrons is also deposited in the chromosphere, again driving the upflow of plasma, sometimes explosively, depending on the incident energy flux (Fisher et al., 1985c).

This upflowing material emits the blueshifted soft X-rays seen in the CaXIX and FeXXV spectral lines. As the flare progresses, the coronal loop fills from the footpoints. On reaching the top of the loop the ablated plasma slows and becomes stationary, so that by the end of the evaporative phase, the loop is full of essentially stationary plasma with temperatures of the order of $1 \times 10^7$K, and with electron densities of $10^{11}$ to $10^{12}$ cm$^{-3}$ (Li et al., 1989).

During the decay phase the heated plasma gradually cools, mainly by thermal conduction back to the chromosphere (Culhane et al., 1970; Zaumen and Acton, 1974) with additional contributions from radiation (Priest, 1982; Machado, 1991) and enthalpy flow (Veck et al., 1984).

1.4.1 Nonthermal Electron Beam Models

In nonthermal beam flare models energy is transported from the primary release site high in the corona by a beam of fast (>20keV) electrons (Brown et al., 1981; Fisher et al., 1985a). These energetic electrons descend along the field lines emitting microwaves by the gyrosynchrotron process.

On reaching the chromosphere, the incident electrons penetrate to average densities of $10^{12}$ to $10^{13}$ cm$^{-3}$ (Hudson, 1972) where they are rapidly stopped by interactions with the ambient plasma, simultaneously emitting hard X-rays by electron-proton collisional bremsstrahlung. As the X-ray emitting region is optically thin to hard X-rays for densities of less than $10^{17}$ cm$^{-3}$, the incident electron power law energy spectrum can, at least in principle, be reconstructed from observations of these emitted X-rays (Brown, 1971; Hudson, Canfield and Kane, 1978). For a power law hard X-ray spectrum;

$$\Phi = AE^{-\gamma} \quad (1.6)$$

the distribution of electron energies is, for a thick target;

$$\frac{dN_e}{dE} = 3.3 \times 10^{33} \gamma^2 (\gamma - 1)^2 B \left(\gamma - \frac{1}{2}, \frac{3}{2}\right) AE^{-\delta} \Delta t \quad (1.7)$$

which is equation 4. of Lin and Hudson (1976), with a modification for the presence of heavy elements suggested by Hudson, Canfield and Kane (1978). $B(x, y)$ is the
Beta function, and $\delta = \gamma + 1$. The power deposited by electrons above a cutoff energy of 20keV is then;

$$P_{20} = 1.6 \times 10^{-9} \int_{20}^{\infty} E \frac{dN_e}{dE} \frac{dE}{dt} dE$$

The deposited energy heats the chromospheric plasma, raising it to coronal temperatures. The response of the corona and chromosphere to thick target heating has been modelled, and compared with observations, by many authors e.g. MacNeice et al. (1984); Nagai and Emslie, (1984); Fisher et al., (1985a,b,c); Mariska, Emslie and Li, (1989); Antonucci et al., (1993).

The velocity of the upflowing hot material is dependent on the electron energy flux, with a lower threshold for ‘explosive' evaporation, and a maximum upflow velocity of $v_{up} \leq 2.35c_s$, where $c_s$ is the sound speed in the evaporated plasma. Explosive evaporation occurs when the chromosphere is unable to radiate the flare energy deposited (Fisher et al., 1985c). Below this threshold, 'gentle' evaporation occurs, where material is ablated off the chromosphere at a much slower rate (Fisher et al., 1985a). In the case of explosive evaporation, the high pressure region in the chromosphere which drives the upward flow of plasma also drives an equal and opposite downward motion in the chromosphere (Fisher et al., 1985b; Fisher, 1987) visible as Hα redshifts of between 50-100km/s (Fisher, 1989).

1.4.2 Observational Evidence

Observational evidence for the presence of nonthermal electron beams in solar flares is widespread. This section summarises some of the important supporting arguments in favour of electron beams as an energy transport process.

Hard X-ray Images

Hard X-ray observations from SMM indicated that the sources of emission during the impulsive phase often had a double structure (Hoyng et al., 1981). Higher resolution images from the Hard X-ray Telescope on Yohkoh have confirmed and extended the SMM results (Kosugi, 1994).

Sakao et al. (1996) found that at high energies (>33keV) hard X-rays typically formed a double source structure, whereas lower energy hard X-rays (14-23keV) originated from the apex of the coronal loop (Sakao et al., 1992). The double sources were
on opposite sides of the magnetic neutral line, and were observed at the ends of the soft X-ray loops seen in the low energy band (14-23keV), and Soft X-ray Telescope. Sakao et al. further discovered that hard X-rays emitted from the footpoints vary simultaneously, that the weaker source of the two is located in the stronger magnetic field region and has a softer spectrum. That hard X-rays are predominantly emitted from the footpoints was also confirmed by Matsushita et al., (1992), who found that the average height of hard X-ray sources decreased with increasing energy. These observations all indicate that nonthermal electrons accelerated near the loop top, and subject to magnetic mirror effects near the footpoints, are the cause of the hard X-rays in these flares, which are emitted by thick target interactions in the chromosphere.

**Microwave, Hard X-ray and γ-Ray Correspondence**

The strong correlation between impulsive microwave and hard X-ray emission has been recognised for some time (Covington and Harvey, 1961; Crannell et al., 1978) holding down to timescales of a fraction of a second (Dennis, 1988). As the microwave spectrum also does not match that expected from a thermal source (Takakura, 1967; Švestka, 1976), the suggestion was made that the same population of accelerated electrons were responsible for both the impulsive hard X-ray and microwave burst (Neupert, 1968; Dennis, 1988), with the nonthermal electrons causing microwave emission by both the gyrosynchrotron process and the excitation of Langmuir waves in the coronal plasma (Tandberg-Hanssen and Emslie, 1988). Microwave observations also lend support to the thick target model of hard X-ray emission, as the number of electrons involved in the emission derived from microwave observations matches the number derived from hard X-rays, assuming a thick target (Hudson, 1972). For a thin target model of hard X-ray emission the number of electrons calculated is a factor of $10^3$-$10^5$ more than is calculated for the microwave emission (Švestka, 1976).

The correlation of peak hard X-ray and γ-ray fluxes has also been confirmed to within about a second (Forrest and Chupp, 1983) for some flares. This has implications for the acceleration processes (Ramaty and Murphy, 1987; Benz, 1987), since the extension of impulsive variability for the electron bremsstrahlung continuum up to γ-ray energies and the inclusion of γ-ray lines (which are generated by nuclear interactions between high energy ions with ambient nuclei) implies that both electrons
and ions are accelerated simultaneously to high energies (Trottet, 1996). In a similar way the rapid variability in the hard X-ray and microwave lightcurves, down to timescales of a few hundred milliseconds (Benz, 1985; Vilmer et al., 1994; Dennis, 1988) constrains energy transport models still further (Trottet, 1996) and seems to imply a "microburst" or fragmented energy release, for which there may be additional evidence from studies of soft X-ray blueshifts in SMM data (Doyle and Bentley, 1986).

**Neupert Effect**

The 'Neupert Effect' (Hudson, 1991) refers to the tendency of the integral of the hard X-ray light curve to match the impulsive phase soft X-ray light curve (Neupert, 1968). The presence of the Neupert effect is dependent on the flare type, with about 80% of a sample of 66 type B (Impulsive) flares showing a strong correlation between the differential of the soft X-ray light curve and the hard X-ray burst (Dennis and Zarro, 1993). However, contrary observations of flares in which the existence of this effect (Feldman et al., 1982) is undetectable have also been made. For these types of events it was suggested by Dennis (1988) that the reason for the variance in results lay in the existence of different flare types. This conclusion was reinforced by the poor correlation found by Dennis and Zarro, (1993) for type C (Gradual Hard) flares.

The existence of this effect, and the recent related discovery of impulsive behaviour in the soft X-ray footpoint light curve (Hudson, 1994) are also evidence for thick target energy deposition by nonthermal electrons with subsequent evaporation of chromospheric material into the corona, as the same electrons are responsible both for the hard X-rays and the simultaneous heating of the soft X-ray emitting plasma (Dennis, 1991; Hudson, 1994).

**1.4.3 Problems with Nonthermal Beam Models**

Nonthermal electron beam models are not without their problems. As has been pointed out by Feldman (1991) and Feldman et al. (1994) many of the cited items of observational evidence do not apply to flares that are not type B Impulsive, implying that other processes must be active. There are also significant theoretical objections to the idea of a large scale beam of nonthermal electrons propagating through the solar corona (Knight and Sturrock, 1977) or chromosphere (Matthews et al., 1996).
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As the nonthermal beam is an electric current it must be neutralised by an accompanying, and cospatial for an intense beam, return current in order to be stable against disruption caused by a self-induced magnetic field (Brown, 1991; Winglee et al., 1988).

The details of the beam stability, generation of return currents, and the effects on the particle dynamics of plasma waves and instabilities have not yet been properly addressed by the current generation of numerical simulations (Mariska, 1996). Small scale particle simulations of the propagation of electron beams, accelerated by quasi-static electric fields, have indicated that these effects are likely to have significant impact on the propagation of a nonthermal beam (Winglee et al., 1991a).

There is also observational evidence that contradicts some of the predictions of the simple nonthermal beam models. Two major points are the presence of a significant stationary plasma component in soft X-rays at the flare onset, and the existence of weak blueshifts before the start of the hard X-ray burst. The existence of a strong stationary plasma component seen in soft X-rays at the start of the flare was reported for SMM data by Doschek et al. (1986) and McClements and Alexander (1989), who pointed out that this conflicted with electron beam numerical simulations, which predicted that the blueshifted component should dominate at the start of the flare (Mariska, Emslie and Li, 1989; Antonucci et al., 1993). This is unlikely to be a detector sensitivity effect as suggested by Antonucci et al., as the existence of a dominant stationary plasma component, right at the start of the flare has been confirmed for a large sample of flares using the more sensitive instruments on Yohkoh (Mariska et al., 1993; Cheng et al., 1994).

One of the implicit predictions of the nonthermal beam model that is also not in agreement with the observational data, is that of the timing of the onset of the hard X-ray burst and the occurrence of blueshifts in the soft X-ray ion spectra. The nonthermal beam model predicts that, since plasma is ablated by the deposition of energy from the energetic electrons responsible for the production of the hard X-ray burst, then the blueshifts, and indeed the stationary component, seen in soft X-rays must follow the initial hard X-ray emission. In a sample of 35 flares observed by Plunkett and Simnett (1994), 14 had delays of more than 15s between the onset of blueshifted emission and the first hard X-ray burst. Similar results are obtained by Cheng et al. (1994) and Zarro et al. (1995). Self consistent modelling of these observations is difficult within the context of a pure electron beam model, and requires the
introduction of some method of preheating the plasma, for example by thermal conduction from a source in the corona before the start of the hard X-ray burst (Mariska, 1995; Emslie et al., 1992).

1.4.4 Thermal Models

Thermal flare models rely on thermal conduction along the magnetic field lines to transport heat from a primary energy release site in the corona to the chromosphere. In this model hard X-rays are generated thermally at the primary energy release site, and the heat transported to the chromosphere via a thermal conduction front (Cheng et al., 1983) or shock front (Wu et al., 1981) ablates plasma which emits in soft X-rays (Fisher, 1989).

Thermal models explain power-law hard X-ray bursts by proposing that the primary energy release heats a region of coronal plasma to about $10^8 - 10^9$K. If the plasma contains a degree of non-isothermality then the spectrum that is produced is practically indistinguishable from a power law (Brown, 1978). This is an efficient means of creating hard X-ray emission (Brown et al., 1981) as 100% of the electron energy goes into production of hard X-rays. Models of thermal energy release and conductive transport (Brown, Melrose and Spicer, 1979) or adiabatic compression and expansion (Crannell et al., 1978), while explaining the general characteristics of impulsive hard X-ray bursts down to timescales of a few seconds face difficulties in explaining the recent results on rapid hard X-ray variability with time scales of a few hundred milliseconds or less. Likewise a recent numerical simulation by Li et al. (1993) found that, contrary to observations, the hard X-ray lightcurves at a range of energies $> 30$keV did not peak simultaneously, which was interpreted as evidence in favour of the nonthermal model.

Numerical simulations of thermal flare models (Cheng et al., 1983; Antonucci et al., 1987) have been more successful at modelling the evolution of soft X-ray blueshifts via 'gentle evaporation' than comparable nonthermal beam models (Antonucci et al., 1992; Schmieder et al., 1994; Antonucci et al., 1993). Thermal conductively driven evaporation has also been positively identified in a number of flares as being the process most likely to be responsible for the observed soft X-ray blueshifts (Canfield and Gunkler, 1985; Zarro and Lemen, 1988; Wülser et al., 1994; Schmieder et al., 1987).

Thermal models naturally explain some of the problems that beset nonthermal
beam models, such as the existence of a strong stationary component in soft X-rays at the start of the flare and the relative weakness of the blueshifted component. However, the containment of the high temperature plasma required by the thermal model is problematic (Brown et al., 1981), as is explaining the direct evidence for electron beams cited above, like the hard footpoint spectra reported by Sakao et al. (1992).

1.4.5 Hybrid models

Hybrid models combine both in situ heating of coronal plasma and the generation of energetic particle beams to explain the stationary thermal emission at the start of the flare and the nonthermal signatures discussed above. This has been accomplished in a simple fashion by modifying existing nonthermal beam models, for example via the addition of coronal preheating (Emslie et al., 1992), or by the addition of conduction from an additional thermal source in the corona (Tanaka, 1987).

More complex hybrid models have also been based on reconsiderations of the basic particle acceleration processes. Winglee et al. (1991a) considered quasi-static electric fields as an acceleration process. These fields, combined with wave particle interactions, create a nonthermal population of electrons with a broken power law spectrum similar to that observed by Lin and Schwartz (1987), and heat the ambient plasma to soft X-ray emitting temperatures.

DC electric fields as an acceleration process, and the consequent field aligned current, have been studied in detail by Holman (1985), Tsuneta (1985) and Holman et al. (1989). In this model electrons are both bulk heated by Joule heating and for sufficiently energetic electrons, accelerated to many times the thermal velocity via a runaway process. The proportion of electrons accelerated out of the Maxwellian distribution is dependent on the ratio of the accelerating electric field to the Dreicer field value, given by Zarro et al. (1995) as;

$$E_D = 7 \times 10^{-8} \left( \frac{n_e}{T_e} \right)$$  \hspace{1cm} (1.9)

If the electric field is sub-Dreicer, then the fraction of electrons that are nonthermally accelerated are those which have a velocity \(v\) such that;

$$v \geq \left( \frac{E_D}{E} \right)^{\frac{1}{2}} \left( \frac{kT_e}{m} \right)^{\frac{1}{2}}$$  \hspace{1cm} (1.10)

The process is a runaway process, since the electron collisional drag is a decreasing
function of electron velocity. This acceleration process has the advantage of creating both a power law spectrum electron beam with a sharp cut off corresponding to the potential drop over the acceleration distance (Tsuneta, 1995), and a hot thermal source in the corona.

Tsuneta, (1995) describes a process for the rapid creation of field aligned currents as a result of the magnetic reconnection outflow which has been observed in limb flares (Tsuneta, 1996; Shibata et al., 1995). When the reconnection outflow reaches the field at the top of the soft X-ray loop, viscosity induced shear flow around flux bundles drives a time varying charge separation, and generates a field aligned current. Current closure for the space charge so generated occurs in the chromosphere, where the electron gyrofrequency becomes comparable to the collision frequency. Since the shear flow around flux bundles is orientated randomly, oppositely directed current channels would be created giving rise to both a zero net current and explaining the presence of hard X-ray sources at both ends of the loop. The acceleration of particles by the electric field in a flux bundle would stop either when the reconnection outflow ceases (Tsuneta, 1995), or by a quenching process, as the evaporated chromospheric plasma raises the mean electron density, inhibiting electron runaway by raising the value of the Dreicer field (Zarro et al., 1995).

Observational support for the DC electric field model has been found by Benka and Holman (1992), Zarro et al. (1995) and Kucera et al., (1996) who find that the DC field accounts consistently for the dominant stationary soft X-ray component, the relative timing of the hard X-rays and soft X-ray blueshifts, and also some previously unexplained low frequency gyrosynchrotron spectral features (Benka and Holman, 1992).
Chapter 2

The Yohkoh Spacecraft

The Solar-A satellite was launched from the Kagoshima Space Centre on August 30th, 1991. Following a tradition of the Institute for Space and Astronautical Science (ISAS) it was then given a new name – Yohkoh. Yohkoh has an almost circular orbit with an altitude of between 520 and 790 km, and an orbital period of about 97 minutes, of which 40 minutes typically are spent in spacecraft night.

The principal scientific objective of the Yohkoh mission is to study energetic processes related to solar flares in X-rays with a complementary and co-ordinated set of instruments. Specific topics include; pre-flare evolution of active regions, rapid plasma dynamics associated with flare onset, particle acceleration and storage, correlation of soft and hard X-ray sources as well as more general non-flare related studies of the general corona, coronal holes and X-ray bright points.

The Yohkoh satellite carries four main instruments; two X-ray telescopes, the Soft X-ray Telescope (SXT), the Hard X-ray Telescope (HXT) and two spectrometers, the Bragg Crystal Spectrometer (BCS) and the Wide Band Spectrometer (WBS). A diagram illustrating the layout of the spacecraft, from Ogawara et al., (1991) is shown in Figure 2.1.

The two X-ray telescopes and the Bragg Crystal Spectrometer are mounted on a central panel which acts as a common optical bench. The Wide Band Spectrometer is mounted directly on the sun-facing panel.

As the X-ray telescopes are capable of taking high resolution images, with a minimum pixel size of 5" for the Hard X-ray Telescope and 2.5" for the Soft X-ray Telescope, precise control over the pointing and attitude stability of the spacecraft is im-
Figure 2.1: The Yohkoh spacecraft and scientific instruments. The labels refer to the Wide Band Spectrometer set of instruments and are: SXS, Soft X-ray Spectrometer; HXS, Hard X-ray Spectrometer; GRS, Gamma-Ray Spectrometer; RBM, Radiation Belt Monitor. The top panel is sun facing. (From Ogawara et al., 1991)
The Yohkoh spacecraft is three-axis stabilized, using two dimensional fine sun sensors, a star tracker targeted towards Canopus, a geomagnetic sensor to provide pointing relative to the sun and the ecliptic, and an inertial reference unit using four gyro wheels to provide an internal reference. Signals from these sensors are processed by the attitude control processor (ACP) and changes in the spacecraft pointing made using momentum wheels, magnetic torquers and control moment gyros as the actuators. This microprocessor controlled attitude system provides a sub-arc second stability for long duration SXT exposures.

The on-board data processing (DP) hardware and software is complex, to cope with sophisticated instrument operation sequences, high data acquisition rates in flare modes and the relatively limited storage of the magnetic bubble data recorder (BDR, 10 MByte), as well as the scheduling of telemetry to ground stations. There are four operating states of the spacecraft; 'flare', 'quiet', 'night' and 'BCS-out', and three telemetry data rates; 'high', 'medium' and 'low' corresponding to rates of 32kbps, 4kbps and 1kbps respectively. The combination of the operating state and data rate is called the DP mode. The observing state will also dictate the telemetry rate, dependent on a set of internal thresholds.

Each DP mode has different telemetry assignments for each instrument, with transitions between modes controlled by flags, triggered either by the instruments themselves in the case of the 'quiet' to 'flare-high' or 'BCS-out' mode changes, by the Solar Aspect Sensor at the onset of spacecraft night, or by the DP unit itself using internal flare minimum timers and flare importance thresholds.

In continuous flare mode the BDR storage can be exhausted within 40 minutes. In addition, the BCS has the capability to acquire data faster than its allotted telemetry rate in certain observing modes. The excess data is absorbed by a 384 kbyte queue memory, which can be later flushed to the main data storage. Since the time between contacts with the down-link stations can exceed 40 minutes in some cases, older data will be overwritten by newer data. To avoid overwriting data like a flare observation with less interesting quiet mode data, a 'data importance' level is set for each data block in the recorder. Data with lower importance will not overwrite data with higher importance levels.

A complete description of the spacecraft, including its observing modes and capa-
2.1 Bragg Crystal Spectrometer

The Bragg Crystal Spectrometer (Culhane et al., 1991) flown on Yohkoh is similar in construction to the Bent Crystal Spectrometer flown on the Solar Maximum Mission (Rapley et al., 1977; Acton et al., 1980) and Hinotori (Kondo 1982). The instrument is divided into two spectrometers (BCS–A, BCS–B) and a data processing unit (BCS–E). Each spectrometer consists of two channels which share a common position sensitive (wedge-wedge) cathode, and front end electronics, but are electrically separated from each other by a cathode screen. The four channels consist of 255 bins and cover selected wavelength ranges of the ions FeXXVI, FeXXV (BCS–A), CaXIX and SXV (BCS–B). In practice, several of the physical detector bins at either end of the detector are occluded by the detector faceplate and therefore unused. For the BCS–B instrument the energy resolution is usually also reduced by a factor of two by double binning the observations in the grouper section of the BCS DP.

The spectrometers and front end electronics are mounted on opposite sides of the spacecraft central partition, as shown in Figure 2.2.

The main scientific objective of the BCS is to use high cadence observations of the line emission of the four ions to investigate problems in flare impulsive phase heating and plasma dynamics. Line emission spectroscopy provides values for the temperature, emission measure and plasma velocity, both directed and turbulent, which can be used to study the initial stages of the impulsive phase. Specific topics include the study of early heating, relative timing of soft X-ray emission and hard X-ray bursts, and the generation of the 'superhot' plasma component. Dynamical studies include the occurrence of plasma upflows related to chromospheric evaporation, and the apparent non-thermal or turbulent excess line width throughout the duration of the flare. In addition, abundance variations and continued decay phase heating can be investigated.

The bent crystal design uses curved crystals to diffract a range of wavelengths onto a position sensitive detector, according to the Bragg relation;

\[ n\lambda = 2d \sin \theta \]  

(2.1)

where \( \theta \) is the Bragg angle — the angle between the incident radiation and the crys-
Figure 2.2: Mounting arrangement of the two spectrometers. The spectrometers are mounted opposite each other on either side of the spacecraft central panel. The apertures are inset into the top sun-facing panel of the spacecraft below a thermal shield (not shown). (From Culhane et al., 1991).
tal lattice plane, \( d \) is the inter lattice spacing, and \( \lambda \) is the lowest harmonic which results. A bent crystal presents a range of the Bragg angle values to the incident radiation, as a function of distance along the crystal, and so diffracts a range of wavelengths onto the position sensitive detector. This method presents some notable advantages over a rotating flat crystal design, such as the FCS on SMM, since an observation of the whole spectral range covered by the spectrometer is taken simultaneously at data rates limited only by the detector sensitivity, without the need for a mechanical scanning system. This has an incidental benefit of eliminating all moving parts from the detector system.

This simultaneous readout of data across the entire spectral range removes the problem of a tradeoff of spectral coverage versus temporal resolution, and allows the study of very dynamic processes which occur during the impulsive phase of a flare. This method also ensures that temperatures derived by line ratio methods are more reliable than those from a scanning spectrometer, where the temperature of the emitting plasma may change significantly between the recording of each member of a diagnostic line pair.

This increased temporal resolution is gained at the expense of an absolute wavelength scale. The BCS is an uncollimated whole-sun instrument, and so the position of any given wavelength, and hence the actual wavelength range covered by each crystal is a function of the incident Bragg angle. The incident angle is dependent on the position of the emitting source relative to the optical axis of the spectrometer along the plane of dispersion. For the Yohkoh BCS the plane of dispersion is north-south, so the wavelength scale applied to a spectrum is a function of the latitude of the source and the spacecraft pointing. The design wavelength ranges for each channel, for a source located along the optical axis are given in table 2.1.

The BCS instrument has its own microprocessor which supervises the grouping and compression of data prior to passing to the spacecraft DP hardware. The BCS microprocessor has a 384 kbyte data queue which allows the instrument to operate in modes where data is acquired faster than can be transmitted to the spacecraft DP with the BCS’s allotted portion of the telemetry data rate. The excess is stored in the queue and passed to the spacecraft DP later using the ‘BCS-out’ mode. This delay can sometimes lead to a mismatch between the housekeeping data which is always output immediately and may result in difficulties in applying some instrumental cor-
2.2. HARD X-RAY TELESCOPE

<table>
<thead>
<tr>
<th>Channel</th>
<th>Ion</th>
<th>Wavelength (Å)</th>
<th>Bin Range</th>
<th>Sens. (SMM = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCS-A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>FeXXVI</td>
<td>1.7636-1.8044</td>
<td>212-28</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>FeXXV</td>
<td>1.8298-1.8942</td>
<td>224-36</td>
<td>9</td>
</tr>
<tr>
<td>BCS-B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>CaXIX</td>
<td>3.1631-3.1912</td>
<td>27-229</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>SxV</td>
<td>5.0160-5.1143</td>
<td>40-234</td>
<td>63</td>
</tr>
</tbody>
</table>

Table 2.1: BCS Instrument parameters. The quoted sensitivities for the first three channels are with respect to the SMM-BCS instrument. The last channel is relative to the SMM-FCS scanning at 10 arc sec/sec.

2.2 Hard X-ray Telescope

The Hard X-ray Telescope (Kosugi et al., 1991, 1992) is a Fourier synthesis type telescope consisting of 64 bi-grid modulation sub-collimators. The HXT covers an energy range from 14 to 93 keV in four bands: LO (14-23 keV); M1 (23-33 keV); M2 (33-53 keV); HI (53-93 keV). In flare mode the telescope makes observations every 0.5s, with a resolution of 5" for a synthesis aperture of 126".

X-rays in the energy range covered by the HXT are produced by interactions between high energy electrons and ions (bremsstrahlung). The science goals of the HXT focus therefore on the confinement and generation of these high energy electrons. Topics include investigations of the location and mechanism of the acceleration sites, and the effect of the high energy electrons on the rest of the corona, and chromosphere.

The HXT is composed of three major sections, as shown in Figure 2.3. The collimator unit (HXT-C) is fixed to the spacecraft central panel, and maintains the two Fourier grid assemblies at a fixed separation and alignment. The two grid assemblies each hold the 64 sub-collimator plates, each of which has a different pitch and position angle. In addition the front grid plate holds the filters and lenses for the white light aspect system.

Each sub-collimator measures a spatially modulated photon count, using a Na(Tl) crystal and a photomultiplier tube located in the HXT-S section. Each sub-collimator uniquely modulates the signal based on the angle of incidence of the X-rays, approxi-
Figure 2.3: Layout of the HXT. The HXT consists of three major sections, the collimator (HXT-C), the detectors (HXT-S) and the control unit (HXT-E). The aspect system (HXA) runs along the central axis of the collimator and detector units. (From Kosugi et al., 1991).
mating a distinct spatial Fourier component. These observed spatial Fourier components can be reassembled into an image on the ground, using computer algorithms developed for the reconstruction of incomplete or noisy images like the Maximum Entropy Method (MEM; Gull and Daniell, 1978; Skilling et al., 1979) or CLEAN (Högbom, 1974). The typical spatial resolution for images deconvolved using this method, determined empirically, is about 5" for a typical synthesis aperture of 126", which is the fundamental angular period of repetition of the sub-collimator grids.

Data from all energy channels on the HXT are recorded at 0.5s time resolution only when the spacecraft enters flare-high mode. During quiet or low bit-rate flare modes only data from the LO channel at a time resolution of 2s are recorded by the DP. Data from all channels are stored for 4s independent of DP mode, so that data from the very early stages of a flare (before the flare flag has been activated by WBS or BCS) are not lost or overwritten, and can be recovered.

2.3 Soft X-ray Telescope

The Soft X-ray Telescope (Tsuneta et al., 1991) is a grazing incidence type reflecting telescope, which observes soft X-rays in the energy range 0.28–4keV (corresponding to a wavelength range of 3–60Å) at a maximum cadence of a few seconds. The telescope has a maximum resolution of 2.45" and a field of view of 42' x42'. Alongside the X-ray system is a small optical telescope which provides pointing and co-alignment information.

The SXT is similar to a telescope flown on the SKYLAB mission and makes images of magnetic structures in the corona by measuring the soft X-ray emission of heated plasma trapped in the coronal field. These observations provide information about the magnetic field topology, and the geometry and evolution of the flaring regions. The different filters used by the SXT allow the measurement of temperature and emission measure of coronal plasmas, in flares and active regions, giving important context information for the spectrometers and the HXT. The SXT can also provide images of the quiet corona and active regions on a regular basis, allowing synoptic studies, as well as studies of events like coronal mass ejections.

The SXT is a complex instrument, both mechanically and procedurally in terms of the wide range of observations possible. The mechanical system is shown in Fig-
The detector for both the soft X-ray and optical images is a Charge Coupled Device (CCD) with a resolution of $1024 \times 1024$ pixels. Each CCD pixel corresponds to an angular resolution of $2.45''$ (1 FR pixel), although in many observation modes CCD pixels are summed together to give resolutions of $4.9''$ (Half-Resolution (HR) pixel), or $9.8''$ (1 Quarter-Resolution (QR) pixel). Two filter wheels and a shutter are located in front of the CCD camera to allow the selection of different energy bands and exposure times. The rear filter wheel holds six X-ray filters and the front wheel holds optical and neutral density filters, as well as a flood lens which is used to mitigate the damage caused by X-rays to the CCD. The contents of the two filter wheels are given in table 2.2.

<table>
<thead>
<tr>
<th>Commanded Position</th>
<th>Front Wheel</th>
<th>Rear Wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>open</td>
<td>open</td>
</tr>
<tr>
<td>2</td>
<td>30Å at 4310Å</td>
<td>Al 1265Å</td>
</tr>
<tr>
<td>3</td>
<td>CCD Flood Lens</td>
<td>Al/Mg/Mn composite</td>
</tr>
<tr>
<td>4</td>
<td>Opal-glass diffuser</td>
<td>Be 119 μm</td>
</tr>
<tr>
<td>5</td>
<td>140Å at 4580Å</td>
<td>Al 11.6 μm</td>
</tr>
<tr>
<td>6</td>
<td>8.05% mesh</td>
<td>Mg 2.52 μm</td>
</tr>
</tbody>
</table>

Table 2.2: SXT Filter Summary. List of Filters mounted on the two SXT Filter wheels. The Rear wheel holds the X-ray analysis filters. From Tsuneta et al., (1991).
The X-ray mirror is of the glancing incidence type, composed of two hyperboloids of revolution. When combined with having the CCD 0.1mm forward of optimal central focus this configuration gives a good consistency of angular resolution across a wide field of view.

Images from the SXT consist of two types of data, partial frame images (PFI's) and full frame images (FFI's). FFI data is full sun data which requires the entire data area of the CCD to be written out to telemetry, and is taken with a relatively low cadence. FFI data is taken primarily in DP quiet mode. Partial frame images are taken at a faster rate and are a subset of the entire image, typically $64 \times 64$ pixels. When the spacecraft moves into flare mode the usual observing sequence is to take PFI's through a predefined set of filters, centred on the brightest point selected by the Automatic Observing Region Selection (ARS) function from a previous patrol image or FFI. During the rise of a flare the brightness can change by several orders of magnitude and this has to be accounted for by a corresponding shortening of the exposure time for a given filter. This is done by the Automatic Exposure Control (AEC) software.

SXT observing programs can be complex combinations of sequences of different filter and exposure settings. These sequences are held in tables in the spacecraft DP, and can be modified by real-time or stored commands.

### 2.4 Wide Band Spectrometer

The Wide Band Spectrometer (Yoshimori et al., 1991) observes across a wide energy range from soft X-rays to $\gamma$-rays. The WBS is composed of four instrument sets: the Soft X-ray Spectrometer (SXS), the Hard X-ray Spectrometer (HXS), the Gamma-Ray Spectrometer (GRS), and the Radiation Belt Monitor (RBM). The SXS, HXS and GRS instruments are mounted on the sun facing panel of the spacecraft. A summary of the WBS instrument set is given in table 2.3

The Soft X-ray Spectrometer is a gas filled proportional counter, divided into two sections (SXS-1 and SXS-2), which have different effective areas, to increase the overall dynamic range of the instrument. The SXS instruments produce both pulse count (PC) and pulse height (PH) data covering an energy range of 2–30keV. Two channel PC data is produced every 0.25s, and the 128 channel PH spectrum is produced every
Table 2.3: WBS Instrument Summary. Description of the energy channels and time resolution for each instrument. SXS-1 and SXS-2 refer to the two gas proportional counters, GRS-1 and GRS-2 to the two BGO scintillators. From Yoshimori et al. 1991.

2s. The SXS is also used as the flare mode trigger for the spacecraft.

The Hard X-ray Spectrometer detector is a NaI scintillator attached to a photomultiplier. It outputs 32 channel PH data every second covering the energy range 20–600keV. The HXS also produces PC data every 0.125s in two channels; HXS-PC1 (20-50 keV) and HXS-PC2 (50-600keV). HXS-PC1 can also be used as the flare mode trigger.

The Gamma-Ray Spectrometer is a pair of BGO scintillators coupled to photomultiplier tubes, covering the energy range 0.2–100MeV. The GRS output is separated into two channels, GRS-L (128 channels, 0.2–10MeV) and GRS-H (16 channels, 8–100MeV).

The Radiation Belt Monitor is not a primarily a scientific instrument, although together with the HXS instrument, it can record observations of cosmic γ-ray bursts. It is composed of a pair of detectors, a NaI scintillation detector and a Si detector mounted on a side panel of the spacecraft, perpendicular to the direction of the sun. When the count rate in the RBM exceeds a preset threshold the radiation belt passage alarm in the spacecraft DP is raised. This allows various scientific instruments to reduce their high voltage levels, to avoid damage.

2.5 Data Management

The raw Yohkoh telemetry is sent to the SIRIUS database upon receipt by the ground stations, where it is time-ordered and stored. The SIRIUS database is located on a mainframe at ISAS. This database is then reformatted into several separate files
for each individual instrument by an IDL program on a UNIX workstation at ISAS (Morrison et al., 1991). The intent of creating this secondary database is to allow the portability of the data across a wide variety of machines with different Operating Systems.

The use of IDL not only makes machine independence easy but also allows the use of complex data structures and the ability to re-use common routines across all of the instruments' data. To further that end, all the reformatted data files share a common file header and index structure, which is separated into generic and instrument sub-structures, so that any program which performs a generic function such as time conversion should work on each data file independent of the instrument. This approach removes unnecessary duplication of effort, and facilitates studies which use data from multiple instruments.

In addition to the primary data files, the reformatted database holds derivative databases such as observation logs, event logs and pointing logs. These files also share the same basic file format as the raw data files. This approach has also been carried through most of the data analysis routines, with the use of compounded structures, so that the reduced data index holds both the history and results of the analyses performed, while still retaining the core generic and instrument specific structures, so that functions which were designed to operate on the raw data sets may be applied to reduced data in the same way.

This advance planning of data formats and structures, together with the reuse of simple modular functions allows easy and rapid data analysis. The Yohkoh software tree provides many simple routines for manipulation of the data, which can be used to generate complex programs for specific tasks. This modular approach has the benefit that basic errors either due to programming bugs, or misunderstandings about the instrument are greatly reduced, as the basic functions have been written and tested by the instrument groups themselves, before being made available to the rest of the scientific team.

This type of planned approach to data analysis becomes more important as the amount and complexity of the data from instruments on future missions increases, and as integrated multiwavelength studies using data from many different sources become more frequent.
Chapter 3

Analytical Methods

In this chapter I describe the theory behind the basic analytical methods used in the following chapters. For the BCS instrument the process and assumptions involved in determining the thermodynamic state of a plasma from the emitted soft X-ray ion spectra are described. For the HXT instrument, an introduction to the Maximum Entropy Method (MEM) of image synthesis from incomplete or noisy data is presented.

3.1 BCS Data Analysis

Spectral line emission from a plasma is determined by the physical composition and thermodynamic state of the plasma, together with any dynamic processes operating upon it.

The analysis of spectra provided by crystal spectrometers usually takes one of two paths. One approach is to use the observations to determine the basic composition of the plasma in the corona by determining such parameters as elemental abundances and ionization fractions. The second approach is concerned with the calculation of macroscopic physical and thermodynamical properties, such as temperature, density, velocity and emission measure, normally by making some attendant assumptions about the plasma composition. As interpretation of observations of flares and other eruptive events normally relies on measurements of these physical and thermodynamical properties, the second approach is the method described here. The methods used to derive these plasma properties are to a large extent independent of the models used to explain the processes as a whole, and are described in the next section.
3.1. BCS DATA ANALYSIS

The normal method of extracting the information from the raw spectrum is to use an iterative fitting process. This process requires the repeated synthesis of theoretical or template spectra covering the spectral region to be fitted. These initially start out based on intelligent guesses at the starting values of the parameters to be fitted together with independently determined atomic data. For each iteration the theoretical spectrum is first convolved with instrumental response functions, then compared with the observed spectrum. The differences are then carried forward to the next iteration as modifications to the original fit parameters.

The BCS team has developed software to perform instrumental corrections and basic analysis on the data from the spectrometer. The data reduction sequence or 'pipeline' used in this thesis is shown schematically in figure 3.1. The BCS team written software is based on the reformatted database and data handling structures described by Morrison et al. (1991), and is implemented in the FORTRAN and IDL languages.

3.1.1 Soft X-ray Line Emission

When compared to the photosphere and solar interior, the physical conditions prevalent in the corona are those of relatively high temperatures and low densities. Typical coronal temperatures lie in the range $10^6 - 10^7 \text{K}$, with densities of the order of $10^9 \text{ cm}^{-3}$ for the quiet corona and $10^{11} - 10^{13} \text{ cm}^{-3}$ for flaring plasmas. Under these conditions most elements are highly ionized, and it is only those elements with a high atomic number that are able to retain any bound electrons at all. The dominant mechanism for both ionization and atomic excitation is by collisions with electrons. The ionization equilibrium is maintained by the reverse process of dielectronic capture, which is itself composed of the opposing processes of dielectronic recombination and autoionization. For allowed transitions the dominant de-excitation process is spontaneous radiative decay.

The Bragg Crystal Spectrometer observes at specific wavelength ranges corresponding to transitions of the helium-like ions of CaXIX ($\lambda_w = 3.1769 \text{Å}$), SxV ($\lambda_w = 5.03 \text{Å}$) and FeXXV ($\lambda_w = 1.8509 \text{Å}$), which have had all but the two innermost electrons stripped off, and the hydrogen-like FeXXVI ($\lambda_{Ly\alpha} = 1.778 \text{Å}$) with only one remaining bound electron. Typical spectra are shown in figure 3.2. For the helium-like ions four principal spectral lines are seen; the resonance line ($1s^2 \, 1S_0 - 1s2p \, 1P_1$),
Figure 3.1: BCS data reduction flowchart. Raw reformatted database files (BDA format) are first corrected for known instrumental effects, then spectrally calibrated and fitted. Intermediate file formats are denoted by rectangular boxes, programs and display software by rounded boxes. Software is attributed by initials. Unattributed software was written by the author of this thesis.
the quadrupole intersystem line \((1s^2 \, ^1S_0 \rightarrow 1s2p \, ^3P_2)\), the dipole intersystem line \((1s^2 \, ^1S_0 \rightarrow 1s2p \, ^3P_1)\), and the forbidden line \((1s^2 \, ^1S_0 \rightarrow 1s2p \, ^3S_1)\). These are commonly referred to as the w, x, y and z lines using a notation introduced by Gabriel (1972).

Figure 3.2: Example BCS Spectra. The lines are labelled according to the notation developed by Gabriel (1972). The small two bin wide features near the d13 line in the CaXIX spectrum, and between the y and k lines in the FeXXV spectrum, are an artifact of the incomplete removal of Fixed Pattern Noise, which is described in Chapter 4.

The He-like spectral regions shown in figure 3.2 have several diagnostically useful line ratios. Some of the best studied diagnostics are based on the ratios of a dielectronic satellite line to a principal line. An example is the temperature sensitive ratio of the Calcium \(n = 3\) (marked as d13) satellite transition to CaXIX resonance line intensity (Bely-Dubau et al., 1982b), which can provide temperature estimates independent of assumptions about the relative ion abundance or ionization equilibrium.

Dielectronic satellite lines arise as a result of a two step process involving an excited ion and a recombining electron. The first step is the capture of an energetic free electron by an ion, with some of the energy being used to simultaneously excite
one of the bound electrons, resulting in the formation of a doubly excited state. Once captured, the electron can either auto-ionize, effectively reversing the original capture, or it can radiatively decay to a stable configuration of the recombined ion stage. The proportion of the excited state population that undergoes radiative decay after a dielectronic capture is known as the radiative branching ratio. The excited bound electron (or spectator electron) acts to perturb the energy of the stabilising transition, depending on the energy level of the spectator, so that the emitted line appears as a satellite to the principal transition. The spectator electron state (denoted by $nl$) has a decreasing influence as the value of $n$ increases, due to a diminishing shielding effect. In the case of He-like ions, satellites to the resonance line are a result of these stabilising transitions to a Li-like electronic configuration. The branching ratio is dependent on the nuclear charge of the ion, approximately as $z^4$, and is taken to be $\approx 1$ for the ions with $z \geq 20$, which are observed by the BCS (Doschek and Feldman, 1987).

In the spectral regions covered by the BCS, dielectronic transitions are of the type $1s2pnl \rightarrow 1s^2nl$ where the spectator electron occupies an empty slot with principal quantum number $n = 2, 3, \ldots \infty$. The $n = 2$ group of satellites includes the $j$ and $k$ lines, and is well separated from the parent resonance line. As the value of $n$ increases, the shielding effect of the spectator electron on the $2p$ electron is decreased, and consequently the energy and wavelength of the satellite line approaches that of the parent resonance transition. For the CaXIX spectrum shown in figure 3.2 the d13 line ($n = 3$ satellites) is resolvable, but the $n \geq 4$ and higher satellites are blended with the resonance line. This blending serves to boost the intensity of this line, and must be accounted for when fitting. This can be done by means of an additional correction factor applied to either the basic collisional excitation coefficient to convert it into an effective collisional excitation coefficient (Gabriel, 1972), or directly to the intensity of the line itself (Mewe, 1987b). The expression for the altered line intensity can be written as:

$$I'_r = I_r (1 + \alpha (T)) \quad (3.1)$$

where $\alpha$ is the correction factor. Both methods are equivalent, but the formulation given in equation 3.1 is more convenient, particularly when used with pre-tabulated values of $\alpha$. An example set of curves for four He-like ions including CaXIX and FeXXV is shown in figure 3.3 taken from Mewe (1987b).
The following sections outline the derivation of a relation describing the flux emitted in a soft X-ray transition as a function of the plasma temperature and emission measure.

### 3.1.2 Coronal Optical Depth

In contrast to the solar interior, the corona is an optically thin environment for lines emitted at soft X-ray wavelengths. This can be demonstrated as follows.

For an emitting region of line of sight depth \( L_d \) the line centre optical depth is given by

\[
\tau_0 = n \, L_d \, \frac{\pi e^2}{mc} \, \frac{f}{\pi^{\frac{1}{2}} \Delta \nu_D}
\]  

(3.2)

where \( n \) is the number density of absorbing states, \( f \) is the emission oscillator strength of the transition giving rise to the spectral line, and \( \Delta \nu_D \) is the Doppler width of the line given by

\[
\Delta \nu_D = \frac{\nu_0}{c} \left( \frac{2kT}{M_{ion}} + v_{turb}^2 \right)^{\frac{1}{2}}
\]  

(3.3)
in which $M_{\text{ion}}$ is the mass of the ion, and $v_{\text{turb}}$ is the average turbulent velocity of the plasma, $T$ is the temperature, $\nu_o$ is the line centre frequency, and $k$ is the Boltzmann constant. Equation 3.3 contains two terms representing the thermal and non-thermal, or turbulent, contributions to the line width. Observations of spectral line broadenings also incorporate two further terms to account for the source width and instrumental resolution (Moorthy, 1993).

Performing this calculation for the CaXIX resonance line transition at 3.1769Å, which has an emission oscillator strength of 0.259 (TOPbase; Cunto et al., 1993) with typical flare values of electron density ($10^{11}$ cm$^{-3}$), and at a temperature of $10^7$K, which is close to the characteristic temperature of formation of the line, the opacity is,

$$\tau_o = 2.2 \times 10^{-12} L_d$$

(3.4)

This assumes a turbulent velocity of 20-60 km/s from studies of active regions (Saba and Strong, 1991). The number density of absorbing states has been approximated here by

$$n = 0.8 A_Z n_e \frac{n_{\text{ion}}}{n_Z}$$

(3.5)

The abundance ($A_Z$) of the element in the corona is that reported by Meyer (1985), and the ionization fraction of CaXIX at this temperature is taken from table IV of Arnaud and Rothenflug (1985).

Under these plasma conditions an optical depth of one would only be achieved for a line of sight emitting region thickness in excess of $10^{11}$ cm. This is much more than the dimensions of most observed loop geometries would allow for, and while it may be possible that such thicknesses of plasma may be present in exceptionally large limb flares, it can generally be assumed that the flaring plasmas are almost completely transparent to the soft X-rays generated within them. There are a few exceptions to this general rule however, for example the 15.015Å line of FeXVII. This transition, due to its large oscillator strength, often has a measurable discrepancy between the flux observed from a coronal source (active region or flare), compared to that expected, and thus can have a measurable opacity. This discrepancy is normally attributed to resonance scattering of the emitted flux from the heated region out of the line of sight by overlying cooler loops (Phillips et al., 1996).

This transparency to radiation also means that coronal plasmas are not in detailed radiative balance, nor are they in local thermodynamic equilibrium. Detailed
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Balance is present in the solar interior, and is the condition under which the radiation field is in equilibrium with the atomic excited states, so that each photon emitted by a spontaneous decay of an excited electron is locally balanced by an equivalent, but opposite photoexcitation. In the corona however most of the photons are not reabsorbed, but are instead lost from the system. In addition, photoexcitation is not the dominant excitation process, as the ambient radiation field emerging from the photosphere is low in energy when compared to the characteristic transitions of most ionization stages present in the corona. Observationally this is seen as a dark photosphere underlying the structures emitting soft X-ray photons in the corona.

3.1.3 Formation of Soft X-ray Spectra

For a given transition to the ground state from an excited level \(i\), the flux emitted for a unit volume is given by:

\[
   f_i = h\nu_i A_i n_i \quad (\text{erg cm}^{-2} \text{s}^{-1})
\]

(3.6)

where \(h\nu_i\) is the energy of the transition, \(A_i\) is the Einstein spontaneous radiative decay rate coefficient, and \(n_i\) is the number density of atoms in the excited level. As opacity can be neglected, the flux recorded at the earth from a given volume \((V)\) is

\[
   F_i = \frac{1}{4\pi R^2} \int \Delta V f_i \, dV \quad (\text{erg cm}^{-2} \text{s}^{-1})
\]

(3.7)

where \(R\) is the distance from the sun to the earth.

The quantity \(n_i\) can be expressed as the identity

\[
   n_i = \left(\frac{n_i}{n_{ion}}\right) \left(\frac{n_{ion}}{n_z}\right) \left(\frac{n_z}{n_H}\right) \left(\frac{n_H}{n_e}\right) n_e
\]

(3.8)

where \((n_i/n_{ion})\) is the relative population of the excited state, \((n_{ion}/n_z)\) is the fraction of the specific ion stage present, \((n_z/n_H)\) is the abundance of the element relative to hydrogen \((A_z)\) and \((n_H/n_e)\) is the abundance of hydrogen relative to the free electrons. Each term in 3.8 must be known for flux to be calculated correctly.

As mentioned above, in the corona due to the absence of a strong radiation field the dominant processes for both excitation and ionization are collisional. As the characteristic time scale for collisional ionization exceeds that for collisional excitation by several orders of magnitude (Mewe and Schrijver, 1978) the problem of calculating the flux emitted in a spectral line can be separated into two parts – calculation of
the ionization balance, and the calculation of the flux from a given ion stage. Mewe (1987a) gives approximate relations for the characteristic time for ionization equilibrium to be established for a variety of astrophysical plasmas. For solar flare plasmas the effects of transient ionization, where there is significant departure from equilibrium, are only important for large temperature changes occurring over timescales of less than the relaxation time of the plasma, which is given by;

\[
n_{e}t_{\text{rel}} \leq 10^{11} - 10^{12}
\]  

(3.9)

In solar flares, with densities of \(10^{11} - 10^{13}\) this relation gives relaxation times of a second or less. For rapidly evolving or compact events, with low densities, the effects of transient ionization may be important. Accounting for transient ionization requires a complete solution of the time dependent ionization balance equations. In most cases it is sufficient to assume that the plasma is in ionization equilibrium, and that the use of tabulated ionization fractions (Arnaud and Rothenflug, 1985; Landini and Montsignori-Fossi, 1990) which depend only on electron temperature is correct.

The third term in equation 3.8 represents the relative abundance of the element in the solar corona. Collections of coronal abundance values have been made by several authors, e.g. Meyer (1985) and Ross and Aller (1976). Whilst there is some evidence for variation of calcium abundance values from flare to flare derived using SMM XRP \(\text{Ca}XIX\) channel data (Sylwester et al., 1984), recent analyses with data from the Yohkoh BCS (Fludra et al., 1993), using a similar method, seem to contradict this finding, with little evidence for either a temperature dependency in the derived Ca elemental abundance, or for any significant variation in the measured abundance from flare to flare. This term is therefore assumed to be a constant.

The calculation of the intensity of a spectral line emitted by a given ion stage in the corona can be further simplified for many allowed transitions such as the resonance lines of He-like ions by the use of the ‘two-level atom’, or ‘coronal approximation’ (Elwert, 1952).

This approximation relies on the fact that only collisionally excited transitions between the ground state and the excited level responsible for the emitted spectral line are significant in forming the population of the excited state. The spontaneous radiative decay rate is several orders of magnitude larger than the collisional excitation rate. This imbalance in rates ensures that most ions are in the ground state
and that there is no significant population of more complex excited states. It also follows that any contributions to the population of an excited state by radiative cascades or collisionally induced transitions are negligible. Notable exceptions to this rule are some lines like the magnetic dipole or 'forbidden' transitions, for which collisional depopulation rates are comparable to spontaneous decay rates. As the collisional de-excitation rates for these states are a function of density, the ratio of one of these lines to an allowed transition can provide a density sensitive diagnostic (e.g. Gabriel and Jordan, 1969).

In the case of a two level atom, all excitations from the ground state to the excited level are matched by spontaneous radiative decays back to the ground state configuration. The emission rate, ignoring the flux contributions from blending of high order dielectronic satellites, is then;

\[ I = n_e n_g C_{g \rightarrow i} = n_i A_{i \rightarrow g} \text{ (photons cm}^{-3}\text{s}^{-1}) \]  

where \( C_{g \rightarrow i} \) is the collisional excitation coefficient. Substitution into equations 3.7 and 3.8 gives

\[ F_i = \frac{\hbar \nu}{4 \pi R^2} \int V C_{g \rightarrow i} \left( \frac{n_g}{n_{ion}} \right) \left( \frac{n_{ion}}{n_z} \right) A_z \left( \frac{n_H}{n_e} \right) n_e^2 dV \]  

As almost all the ions are in the ground state the term \( \left( \frac{n_g}{n_{ion}} \right) \) can be removed from the equation.

The collisional excitation coefficient can be expressed as a function of the effective collision strength for that transition \((\Upsilon)\), which is tabulated for many ions (e.g. for He-like ions see Dubau (1994)), and the statistical weight, or degeneracy of the state. From Harra (1993);

\[ C_{g \rightarrow i} = \frac{8.63 \times 10^{-6} \Upsilon_{gi}}{g_s T_i^{1/2}} e^{-\frac{bY}{kT_i}} \]  

(3.12)

The flux emitted in the spectral line is then;

\[ F_i = \frac{8.63 \times 10^{-6} \hbar \nu \Upsilon_{gi} A_z}{4 \pi R^2 g_s} \int V T_i^{-1/2} \left( \frac{n_{ion}}{n_z} \right) \left( \frac{n_H}{n_e} \right) e^{-\frac{bY}{kT_i}} n_e^2 dV \]  

(3.13)

The value of \( \left( \frac{n_H}{n_e} \right) \) the proton to electron ratio is approximated to be 0.8, based on the assumption that almost all of the free electrons are due to ionized hydrogen and helium. The temperature dependent terms in equation 3.13 are normally incorporated into the contribution function, or emissivity.

\[ G(T) = \left( \frac{n_{ion}}{n_z} \right) T_i^{-1/2} e^{-\frac{bY}{kT_i}} \]  

(3.14)
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Figure 3.4: Emissivities for the ions of SXV, CaXIX, FeXXV and FeXXVI.

Contribution functions for the He-like ions of FeXXV, CaXIX and SXV are shown in figure 3.4. If the plasma emitting the radiation is assumed to be isothermal, then the $G(T)$ function can be removed from the integral and the flux in the line becomes:

$$F_i = \frac{6.9 \times 10^{-6} h \nu \gamma g A_z}{4 \pi R^2 g_s} \int_V n_e^2 dV$$

(3.15)

where the quantity $\int_V n_e^2 dV$ is referred to as the emission measure of the emitting plasma. The line intensity is now a function of electron temperature and emission measure only.

3.1.4 Temperature Diagnostics

The equation for the flux in a spectral line, as described above, depends on three of the plasma parameters (temperature, density and volume) we would like to have unique values for. To get a unique solution, two of the parameters must be determined independently, so that equation 3.15 can deliver the third.

One method of determining the electron temperature is to exploit the tempera-
ture sensitivity incorporated in the $G(T)$ function, and take the ratio of two lines with different energies. This can be the ratio of two lines from different ions (Doschek, 1990) or two lines from the same ion, which avoids the problem of possible relative abundance variations. For the case of two lines from the same ion, if there are two levels $i$ and $j$ where the dominant rates are collisional excitation from the ground state and spontaneous radiative decay, then the ratio of emission rates (from Gabriel, 1991) is;

$$\frac{I_j}{I_i} = \frac{\gamma_{gj}}{\gamma_{gi}} \exp\left(-\frac{(E_j - E_i)}{kT_e}\right)$$ (3.16)

Which, neglecting the weak dependence on temperature of the $T$ term, is a simple function of temperature in the exponential. The energy difference between the two levels $(E_j - E_i)$ must be large for the ratio to be sensitive to variations in temperature, so the lines must be well separated in wavelength. If the lines must be well separated in wavelength, then this places a constraint (large spectral range) on any instrument for which this technique is to be used. This approach also may give incorrect results for regions of plasma with non-uniform temperatures and densities, as the different lines may be formed at different locations, giving a misleading diagnostic.

One useful technique which is not affected by these problems is to take the ratio of a dielectronic satellite line to the parent resonance line. These two lines are very close in wavelength, similar in intensity, and due to their way of formation, are unaffected by abundance or ionization balance variations. The temperature sensitivity of the ratio of intensities of a dielectronic satellite to a parent He-like resonance line is described in detail in Gabriel and Paget (1972) and can be demonstrated as follows.

The emission rate of a dielectronic satellite line is given by Gabriel and Paget (1972) and Bely-Dubau et al., (1982a) as;

$$I^d = n_e n_{ion} C^d$$ (3.17)

$$C^d = 2.06 \times 10^{-16} T_e^{\frac{7}{2}} g_s^{-1} e^{-\frac{E_d}{kT_e}} F_2(s)$$ (3.18)

$$F_2(s) = g_s A_s B^r$$ (3.19)

This follows the formulation of Gabriel (1972), by separating the temperature dependent and satellite dependent ($F_2(s)$) terms. Equation 3.17 is equivalent to equation 3.10 for the resonance line transition. The term $B^r$ in 3.19 refers to the radiative
branching ratio as described in section 3.1.1 and is defined by Mewe (1987b) as;

\[ B' = \frac{A_r}{(A_a + \sum_k A_k')} \]  

(3.20)

where \( A_a \) and \( A_r \) are the autoionizing and radiative decay rates, and the sum is over all possible final states.

Recalling equations 3.10 and 3.12 and applying the coronal approximation, we can write the ratio of the emissivity of the dielectronic satellite line to that of the resonance line as;

\[ \frac{I_d}{I} = 2.39 \times 10^{-11} F_2(s) \frac{e^{(E_{w} - E_d) / kT_e}}{T_e \gamma_{gi}} \]  

(3.21)

Combining this equation with the correction for high order dielectronic satellite line blending from equation 3.1 and excluding the constant terms (for any given dielectronic transition) gives the temperature dependence of the ratio for that transition;

\[ \frac{I_d}{I} \propto \frac{e^{(E_{w} - E_d) / kT_e}}{(1 + \alpha(T_e))T_e} \]  

(3.22)

This is a function of temperature only (again neglecting the weak temperature dependence of \( \gamma \)). This function is shown in figure 3.3 for the \( n = 2 \) to resonance line transition for several ions.

3.1.5 Emission Measure

The line ratios discussed above will give mean temperatures independent of the emission measure. Once the temperature is known, the emission measure can be recovered from equation 3.15. Separation of the electron density and the volume of emitting plasma is more difficult however. The electron density can be found by using a density sensitive line ratio, as mentioned above, or the volume can be estimated by using an instrument with sufficient spatial resolution. Both these methods rely on the assumption that the emitting volume is essentially homogeneous.

Density sensitive diagnostics in the X-ray spectrum for coronal conditions are usually based on the ratio of a forbidden line to an allowed transition (Doschek, 1987). For example for He-like ions, the density sensitivity of the \( z/y \) line ratio, which was discovered by Gabriel and Jordan (1969), arises from the increasing depopulation of the \( 1s2s^3S_1 \) level by electron collisions to the \( 1s2p^3P \) levels as the density increases.
Thus as the density increases the proportion of the $1s2s \, ^3S_1$ which decays radiatively, and so the intensity of the $z$ line, diminishes at the expense of the $y$ line. As the $z$ line radiative decay rate increases with atomic number while the collisional depopulation rate tends to decrease with increasing $Z$, so the lower limit of the range of densities for which this ratio is useful rises. For typical coronal densities the heaviest useful ion is MgXI. Figure 3.5 shows values of the $z/y$ ratio as a function of density for several ions.

![Graph showing ratios of forbidden and intersystem lines](image)

Figure 3.5: Ratios of the forbidden $(1s^2 \, ^1S_0 - 1s2s \, ^3S_1)$ to the intersystem $(1s^2 \, ^1S_0 - 1s2p \, ^3P_1)$ lines as a function of density for several coronal ions. (From Doschek, 1987)

The Yohkoh BCS does not cover the wavelength range of any of these lighter ions, and so it is not possible to make use of this technique, as the $z/y$ ratio for the lightest ion (Sxv) only becomes density sensitive for densities in excess of $10^{14}$ cm$^{-3}$ (Harra-Murnion et al., 1996). To extract an electron density from BCS observations requires an accurate estimate of the emitting volume from SXT or HXT images instead.

This estimate of the electron density can only be regarded as a lower limit, due to the implicit assumption of this method that the volume of emitting plasma seen in the HXT or SXT image is homogeneous. This is in practice unlikely to be the case.
3.2 HXT Data Analysis

The Hard X-ray Telescope can act both as a sensitive wide band spectrometer, and as a Fourier synthesis telescope. When used as a spectrometer all the signals from the individual sub-collimators are summed together for each energy band. This gives four energy bands centred at 18, 28, 43 and 73 keV, which can be used to fit single power laws or thermal model peak temperatures by using standard curve fitting techniques. This fitting requires knowledge about the spectral responses and effective areas of the sub-collimators for each energy band. These parameters must also be accurately determined for use by the image synthesis methods.

3.2.1 Image Analysis

The HXT is composed of 64 sub-collimators. Each sub-collimator has a simple non position sensitive detector, and measures one of a pair of complex Fourier components. The transmission function of each sub-collimator is triangular with respect to the hard X-ray incident angle. This arises as the front grid plate occults the rear grid plate with increasing X-ray incident angle. The 'sine' sub-collimators are similar to the 'cosine' sub-collimators but have transmission functions which are phase shifted by a quarter period (Figure 3.6). The sub-collimators are laid out in a circular manner to minimise the effects of any torsional distortion of the metering tube on the relative alignment between the front and rear grid plates.

Fourier Synthesis

The Fourier synthesis method using these sub-collimators works as follows. If the X-ray source intensity map \( B(x, y) \) is projected perpendicular to the line of sight with axes relative to the telescope of \( x \) and \( y \), then each sine-cosine sub-collimator pair will measure a different wavenumber \( k \) and position angle \( \theta \) relative to the \( x \) axis.

If \( x \) and \( y \) are normalised with respect to the fundamental wavenumber, then the transmission function for each cosine sub-collimator \( M_c(kr) \) is a function of the source map co-ordinate, the sub-collimator wavenumber and position angle. This can be expressed by a standard Fourier expansion in the natural polar co-ordinate sys-
3.2. HXT DATA ANALYSIS

\[ M_c(kr) = \frac{2}{\pi^2} \left( \frac{\pi^2}{8} + \cos(kr) + \frac{1}{9} \cos(3kr) \ldots \right) \]

\[ k = \frac{2\pi D}{p} \]

\[ r = x \cos(\theta) + y \sin(\theta) \]

where \( D \) is the inter-grid spacing along the metering tube, \( p \) is the grid pitch for the sub-collimator, and \( r \) is the distance along the perpendicular to the grid pattern in the source map (Kosugi et al., 1991). The modulation function for the sine sub-collimators \( (M_s(kr)) \) is similar to that for the cosine sub-collimator, but is shifted by a quarter wavelength, and can be written as;

\[ M_s(kr) = M_c \left( kr - \frac{\pi}{2} \right) \]

Equation 3.23 approximates a cosine function well, provided that the D.C. offset is subtracted, as the high order coefficients decrease rapidly in significance. In this case the observed count rate though one pair of sub-collimators approximates the
3.2. HXT DATA ANALYSIS

The spatial Fourier transform of the source map \( b(U, V) \).

\[
b(U, V) = b_c + i b_s \tag{3.27}
\]

\[
b_c(k, \theta) = A c \int B(x, y) M_c(k, r) \, dx \, dy \tag{3.28}
\]

\[
b_s(k, \theta) = A_s \int B(x, y) M_s(k, r) \, dx \, dy \tag{3.29}
\]

The parameter \( A \) is the effective area of the sub-collimator.

If the measurements were made at a sufficiently large number of wavenumbers and position angles, then the original sky map \( B(x, y) \) could be recovered from the observations by an inverse Fourier transform.

The HXT has fewer sine-cosine detector pairs than are needed to make a direct inverse transform feasible without producing significant noise and spurious signals in the recovered source map. The actual methods used to perform the inversion of the data therefore are those developed for the reconstruction of images from incomplete sets of measurements like CLEAN (Högbom, 1974) and the Maximum Entropy Method (Gull and Daniell, 1978; Skilling et al., 1979).

**Maximum Entropy Method**

Direct linear inversion of HXT data sets is not a practical method of producing images suitable for quantitative analysis, since the coverage of the complex component plane \( b(U, V) \) is incomplete. HXT images in this thesis were instead generated by using the Maximum Entropy Method (MEM). MEM allows image reconstruction by placing additional prior constraints on the solution. These constraints arise from information theory arguments, and result in a solution which ‘represents the most uniform intensity distribution which is consistent with the data’ (Skilling et al., 1979).

The idea behind deriving the most uniform, or “flattest” solution is to ensure that all the structure in the reconstructed image is ‘real’. Thus if a feature appears in the image, then we can be confident that there is significant evidence in the data to support its existence, and is therefore not due to the misinterpretation of noise. If this criterion were not to be applied then the reconstruction method may incorrectly show noise as a spurious signal.

The criterion of uniformity or smoothness can be also expressed as a minimisation of the information content of the image. Most implementations of MEM for photon counting applications (Willingale, 1981) define the configurational entropy of the
3.2. HXT DATA ANALYSIS

image as:

\[ S = - \sum f_i \ln f_i \]  

(3.30)

where \( f_i \) is the normalised flux in the \( i \)th pixel of the current source intensity map. The above expression assumes that the detectors are equally efficient. The configurational entropy here represents the negative information content of the image (Shannon, 1948).

The solution that minimises equation 3.30 in isolation is the grey map, which has no structure. In order to constrain the solution to be one that fits the data well, a measure of the goodness of fit of a given map to the data is required. In the case of the HXT, since the data is of good statistical quality, the \( \chi^2 \) statistic can be used:

\[ \chi^2 = \sum_{j=1}^{64} \frac{(b'_j - b_j)^2}{\sigma_j^2} \]  

(3.31)

where \( b_j \) are the observations, the sum is over all sub-collimators, and \( b'_j \) are the current estimates of the Fourier components. \( \sigma_j \) is the standard deviation of the original data set, which includes both systematic and statistical errors. For a good fit to the data the target value \( \chi^2 \approx N \), where \( N \) is the number of data points (64) is used.

The combination of these two criteria, plus conservation of flux, forms the objective function \( Q \) (Gull and Daniell, 1978).

\[ Q = - \sum_i f_i \ln f_i - \frac{\lambda}{2} \left( \sum_{j=1}^{64} \frac{(b'_j - b_j)^2}{\sigma_j^2} \right) + \mu \sum_j b'_j \]  

(3.32)

The factors \( \lambda \) and \( \mu \) are Lagrangian multipliers, allowing the relative weighting of the function between the goodness of fit to the data and the entropy (\( \lambda \)), and the conservation of flux across successive iterates (\( \mu \)).

Following Sakao (1994), this method can be applied to reconstruct an image in a given energy band of the HXT by taking the generalised form of equations 3.28 and 3.29 and adapting from a continuous integral over the source map to a sum over discrete pixels. For the \( j \)th collimator:

\[ b_j = A_j \sum_{x,y} B(x,y) M_j(k,r) \]  

(3.33)

For ease of computation, this can be reformulated in terms of a response matrix \( P_j(x,y) \), which includes the effective area, such that:

\[ b_j = \sum_{x,y} P_j(x,y) B_j(x,y) + n_j \]  

(3.34)
where \( n_j \) is an additional contribution of noise to \( b_j \) and;

\[
P_j(x, y) = A_j M_j(k, r)
\]

(3.35)

is effectively a transform of \( M_j \) into sky co-ordinates. Equation 3.34 is now in a form similar to equation 2 of Willingale (1981), who gives the iterative solution to equation 3.32 under these conditions as;

\[
f_i^{n+1} = (1 - \gamma)f_i^n + \gamma e^{-\mu_i^{n+1}} e^{-2\lambda^n \sum_j P_j \frac{(b_j^n - b_j)}{\sigma_j^2}}
\]

(3.36)

Here \( \gamma \) acts as a weighting function for the successive iterates, stabilising the convergence by controlling the 'memory' of the algorithm.

The reconstruction starts with the grey map as the initial input (\( \lambda = 0 \)). As the iteration proceeds the value of \( \lambda \) is increased periodically as the iterates converge on the end solution, giving increasing weight to the \( \chi^2 \) statistic over the smoothness criterion.

Since equation 3.36 is in a fractional form, once the iteration has converged to a solution, the final source map must be re-normalised to the value of the total flux to recover the source intensity map \( B(x, y) \). In the HXT software the total flux is calculated from the incident flux on the fanbeam sub-collimators (Sakao (1994)). In practice the deconvolution is slightly more complex than the process outlined here, which assumes that the input data \( (b_j) \) are all simple Fourier components, due to the presence of low wavenumber fanbeam elements which act to increase the quality of the reconstructed image for extended sources (Kosugi et al., 1991).
Chapter 4

Fixed Pattern Noise in Yohkoh/BCS

Detectors are subject to random errors, for example thermal noise in the electronics, and systematic errors which are usually relatively constant over long time periods. Random noise cannot be removed, but instead must be accounted for by the use of standard statistical data analysis techniques. However systematic errors can in some cases be removed from the data. This is particularly desirable if data quality is sufficiently reduced by the presence of systematic biases that the assumptions of gaussian or poissonian counting statistics, which underly almost all statistical analysis methods, become invalid.

The Yohkoh Bragg Crystal Spectrometer has a systematic variation as a function of position along the spectrometer, caused by errors in the digitisation process. The form of the variation is a function of the detector design, gain settings, and the incoming event energy distribution. In the case of the BCS this function creates a series of enhancements and depressions in the final position spectrum referred to as 'spikes', due to incorrect position coding of events. These spikes form a predictable pattern, which is known as 'Fixed Patterning', or 'Fixed Pattern Noise' (FPN). This chapter describes the work done by the author to characterise and model the Fixed Pattern Noise in the BCS detector, with the aim of correcting the most severe errors. The model was based around a computer simulation of part of the BCS event encoding electronics, combined with empirical parameters derived from pre and post launch calibration data.
The occurrence of FPN in detectors was known about before the launch of Yohkoh/BCS. A well studied example of FPN is the spectral camera on board the International Ultraviolet Explorer (IUE). The FPN on this instrument is a slowly varying function of time and temperature (Adelman and Leckrone, 1985). The fixed pattern noise in IUE can be corrected by the subtraction of a flat field image from the data, provided that the slow drift between the fixed pattern noise in the image and the reference flat field is accounted for properly (Linde and Dravins, 1988).

Flat field images do exist for the BCS, being taken as part of the regular instrumental calibration. However a numerical model of the fixed patterning described in this chapter has revealed that the IUE approach of subtracting a stored flat field is of limited use, although the general principle of subtraction of a normalised flat field is still valid. The approach adopted instead to correct the FPN was to create a model of the fixed patterning in the detector electronics, and use this to predict the expected flat field dynamically during data reformatting from the raw data files.

This calculated flat field can then either be used to directly remove the effects of fixed patterning via direct subtraction, or to act as a guide to data analysis programs for assigning low fitting weights to the bins which are worst affected. The calculated flat field spectrum is useful as it allows both remedial action on the real data, and easy comparison with End to End (ETE) and flight calibration test data. Such comparisons are also useful for monitoring the accuracy of the model with time.

Modelling the detector in detail requires some understanding of the basic processes that are carried out by the electronics in response to a detected event. The BCS is a gas proportional counter (Lapington et al., 1989) similar to those used on the Solar Maximum Mission. The next section gives an overview of the analogue encoding sequence of the BCS. A complete description of the instrument may be found in Trow, (1996).

4.1 BCS Event Encoding

The position sensitive element of the detector is a 'Wedge and Wedge', or 'Backgammon' cathode in a chamber filled with a Xe–Ar–CO₂ mixture. This type of detector works by dividing the charge from an event into two amounts, with the proportions being determined by the position of the event along the cathode (Allemand and
An event in the BCS is associated with the absorption of a soft X-ray photon by the detector gas, with the consequent ionization of gas atoms. The electrons created by the ionization are accelerated under a high voltage towards the anode wires. These electrons cause further ionization, resulting in a charge avalanche near to the anode (Trow et al., 1994). The amount of charge generated is proportional to the incident photon energy. A corresponding positive charge is registered on the cathode pattern. The cathode pattern splits the charge into two quantities, depending on the position of the event along the detector, referred to as the 'a' and 'b' charges. The relationship of these two charges is linear, and such that the original position of the event \( p \) can be determined by:

\[
p = \frac{a}{a + b}
\]  

(4.1)

The total charge of the event \( q \) is given by:

\[
q = a + b
\]  

(4.2)

The total charge is proportional to the energy of the incoming photon, and the detector gain. Over many events the charge collected on the anode forms the Pulse Height Distribution (PHD). A flow chart of the BCS analogue event encoding electronics for a single channel is shown in figure 4.1.

The cathode signals are initially processed by the front end electronics immediately adjacent to the detectors. The signals pass through several stages; charge sensitive preamplifiers, first stage pulse shaping and test circuitry, before being passed to the BCS-E unit. Here the signals are amplified further before reaching the Analogue to Digital Converters (ADCs). After digitisation the events are then accumulated, grouped and processed into the spacecraft telemetry stream by the BCS microprocessor.

Once the two wedge charges have passed through the pre-amplification stage, they can be digitised either before or after the charge division (to recover the event position), is performed. In general digital division is considered superior to analog division (Koike and Hasegawa, 1988), so the signals are digitised immediately after amplification.

There were several constraints placed on the design of the BCS (most particularly weight) that pose additional complications for event encoding. Although figure 4.1
4.1. BCS EVENT ENCODING

Figure 4.1: BCS electronics schematic

shows the encoding sequence for a single detector, each physical detector is in fact shared by two channels, separated internally by a cathode screen. The cathode event encoding electronics is therefore shared between two channels each having a different energy, although the anode electronics are separate for each channel. This has several consequences, of which two are directly relevant to the fixed patterning problem. The first is that the active range of the amplifiers and ADCs must cover the pulse height distributions for both channels. The second is that a high count rate in one channel (and consequent electronic deadtimes) affects the other channel equally.

Charge division is implemented in the lookup table (LUT) which takes the outputs from the ADCs, and returns an 8-bit number representing the position of the event. This is done in a lookup table, as opposed to a direct calculation for each event primarily for speed, but also allows modifications to the algorithm to be easily loaded during construction and testing. Since the fixed patterning is independent of the charge division method, the principles of the analysis performed here hold for both lookup tables and direct calculation methods. The BCS lookup table is a 512 by 512 byte memory that holds the previously computed result of the charge division for each possible combination of inputs from the ADCs. The same LUT is used by both of the detectors to encode events even though the ADCs for BCS-A are 9-bit and those
for BCS-B are 8-bit. In order to cover the same range as the BCS-A ADCs the outputs from the BCS-B ADCs are shifted up one bit, and bit zero permanently wired to logic 1.

The BCS lookup table also implements a stretching algorithm to match the range of output bins to the exposed part of the detector cathode. This arises from the layout of the beryllium window, which occludes the ends of the cathode. The stretched lookup table expands the occluded bins to four times the effective width of the in-window bins, effectively compressing the dynamic range of the digitised output position to more closely match that of the exposed cathode. If a linear table were used instead, then a significant proportion of the output spectrum would lie in the occluded bins, with the science data being concentrated into a smaller number of bins near the centre. This would lead to a loss of spectral resolution, compared to that possible from using a stretched lookup table.

The PHD is recorded by the Pulse Height Analyser (PHA) which is a 32 bin, 8 bit deep accumulator and is included in the housekeeping part of the BCS telemetry. The PHA can either record the PHD from each anode string in a 'round-robin' schedule, or it can be programmed to sample a particular channel continuously. The anode signals for each channel are independent and are used by the discriminators to pass or reject events depending on their energy. There are two discriminators per channel (upper and lower) which are set to pass only events that lie in the target PHD of the channel, and reject background events with energies above and below the allowed energy range.

### 4.2 Fixed Patterning

Equations 4.1 and 4.2 are a coordinate transformation from the wedge charges to the data coordinate system of position and energy. From Geesman et al., (1991), the analogue events (with input charges $a$ and $b$) are digitised by the ADCs to produce corresponding output values $(A$ and $B)$ such that;

\[
A - \frac{1}{2} \leq a < A + \frac{1}{2} \quad (4.3)
\]

\[
B - \frac{1}{2} \leq b < B + \frac{1}{2} \quad (4.4)
\]

Thus each 'area element', or $(A,B)$ address pair created by the quantization of
4.2. FIXED PATTERNING

the ADC output is equivalent to an integration over the input analogue PHD \( P(q) \).
Assuming that the occurrence of events is uniform along the detector (i.e. the PHD
is independent of position), then the probability of a given address pair as;

\[
P(A, B) = \int \int P(q) \, dq \, dp
\]

including the coordinate conversion in equations 4.1 and 4.2;

\[
P(A, B) = \int \int \frac{P(a + b)}{a + b} \, da \, db \approx \frac{P(Q)}{Q}
\]

where

\[
Q = A + B
\]

and the \( \frac{1}{a+b} \) term is the Jacobian of the coordinate transformation.

The reason for the change in form of the digitised PHD can be understood, if it
is remembered th at the density of addresses is linear in \((A, B)\) coordinates, but in­
creases linearly (for a given element \(Q, Q + dQ\)) with increasing energy. Thus, the
PHD of incoming events can be thought of as being spread more thinly with increas­
ing \(Q\), so that the probability for any individual address is proportional to \(\frac{1}{Q}\). The
relationship in equation 4.6 has been numerically verified for the BCS using the mea­
sured value of \(P(q)\) from the PHA and the results of the model described below.

Geesman et al., (1991) give the output position spectrum as;

\[
G(X) = \Sigma \frac{P(Q)}{Q} \times F(X, Q)
\]

where \(F(X, Q)\) is the number of addresses that satisfy the condition

\[
X = S \times \frac{A}{A + B}
\]

\(G(X)\) is the output position spectrum, the sum being taken over all valid values
of \(Q\), and \(S\) is a scaling factor. For the BCS LUT the scaling factor is 256. The fixed
patterning as a function of position is described entirely by the \(F(X, Q)\) term, since
\(P(Q)\) is independent of \(X\). A simple example is shown in the diagram in figure 4.2.

The thick lines represent two adjacent bins in \(X, Q\) space. The dots represent the
lookup table addresses \((A, B)\). The thin line encapsulates all addresses that return
the same value for the position \(F(X, Q)\). Although both bins have the same area,
due to the discrete nature of the lookup table they contain different numbers of ad­
dresses (15 & 16), and therefore have a different value of \(F(X, Q)\). If each address
4.2. FIXED PATTERNING

were stimulated evenly by an input flat field then there would be a discrepancy between the two bins, such that if each address was to receive 10 counts/second then one will register 150 counts per second, and the other 160 counts per second.

The occurrence of FPN can best be understood if a small lookup table is used as an example. For a 3 bit lookup table with a 3-bit output the results of summing $F(X,Q)$ over $0 \leq Q \leq 7$ are;

<table>
<thead>
<tr>
<th>BinNumber</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addresses</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>

If a flat field with respect to both the $X$ and $Q$ coordinates (so that the $P(Q)$ term can be ignored) is applied, then the output position spectrum from the lookup table will not be a uniform flat field, but will be the same as the $F(X,Q)$ function summed over the appropriate range of $Q$, shown above. A flat PHD is not realistic however, so both the $F(X,Q)$ and the $P(Q)$ functions need to be determined if the effect of fixed patterning on real data is to be accurately modelled and assessed.

The $F(X,Q)$ is a static property of the lookup table and ADCs. Once the number of bits of ADC output and the scaling factor $S$ is known, then the value of $F(X,Q)$ can in principle be easily calculated. It is also possible to derive empirical measures of uniformity solely based on these properties, provided the PHD has a simple enough form (Koike and Hasegawa, 1988). This approach was not taken due to the relatively complex nature of the BCS PHD.
4.2. FIXED PATTERNING

4.2.1 Determination of $P(Q)$

The event PHD ($P(q)$) is recorded by the Pulse Height Analyser. This is a 32 bin 8-bit deep accumulator, which at relatively low countrates suffers from roll-over. The PHD is a Pearson type 3 distribution but can be fitted quite successfully with a gaussian profile. Since the event PHD should be a function of the detector gain setting only (ignoring the effects of rate dependence of gain for the present), an average centroid and width can be derived for each channel by averaging the fits to many PHA spectra. The derivation of these ‘typical values’ will need to be repeated each time the high voltage settings are trimmed to compensate for the gradual loss of detector gain with age. However since, at the current steady rate of gain loss with time, this is only likely to be the case once every 12 years (Trow, 1992) this may not be too arduous a task.

Despite the PHA rollover it is possible to use active region and small flare data to determine the centroid and width of the PHD for the CaXIX and Sxv channels, and use M and X class flare data to determine the parameters for the two BCS-A channels. Repeated rollover in the PHA for the BCS-B channels at large countrates makes them useless, so the PHA readout can be altered from cycling between each channel to concentrate on the two BCS-A channels, upon triggering of a suitable flare flag. Likewise the default behaviour for small countrates can be altered to return data only from the BCS-B counters. Additional care has to be taken in the selection of PHA spectra, particularly at high countrates, to compensate for the effects of gain depression and germanium fluorescence.

Figure 4.3 shows the results of fitting several hundred suitable spectra taken from the flight data between November 1991 and February 1992 with a gaussian and linear background. The effects of gain depression are clearly visible in the increased scatter for the BCS-A channels. The averages for each channel, weighted by the $\chi^2$ value of the fit are listed in table 4.1. Note that channel numbers are zero-offset in calibration software.

The largest number of good data points were obtained from channel 3 (Sxv), which is reflected in the small errors listed for the centroid and FWHM. Using the values from channel 3, for which we are confident that we have good results, we can check the widths for the other channels, since the PHD FWHM is expected to scale
4.2. FIXED PATTERNING

Figure 4.3: Plot of fit results for 600 PHA spectra taken between November 1991 and February 1992.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Ion</th>
<th>Samples</th>
<th>Centre</th>
<th>Std Dev.</th>
<th>FWHM</th>
<th>Std Dev.</th>
<th>Exp. FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCS-A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>FeXXVI</td>
<td>28</td>
<td>19.183</td>
<td>0.249</td>
<td>2.52</td>
<td>0.399</td>
<td>2.50</td>
</tr>
<tr>
<td>1</td>
<td>FeXXV</td>
<td>91</td>
<td>18.887</td>
<td>0.259</td>
<td>2.68</td>
<td>0.224</td>
<td>2.55</td>
</tr>
<tr>
<td>BCS-B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CaXIX</td>
<td>223</td>
<td>19.01</td>
<td>0.184</td>
<td>3.51</td>
<td>0.223</td>
<td>3.34</td>
</tr>
<tr>
<td>3</td>
<td>SxV</td>
<td>258</td>
<td>17.698</td>
<td>0.083</td>
<td>4.26</td>
<td>0.128</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.1: Averaged PHA channel parameters.
where $K$ is a constant and $E$ is the energy of the ion. The last column in table 4.1 lists the expected values of FWHM based on channel 3 data using this equation. There is reasonable agreement for all channels except channel 2.

In order to use these values for the centroid and width from the PHA in the model they must be converted into units of $Q$ at the LUT. This is a clumsy procedure, since we measure the PHA off the anode, and the input to the LUT is amplified separately by the cathode electronics. This requires that the gains at each stage of the anode and cathode electronics be incorporated, as the centroid and width at the PHA are converted back to charges at the wedge, then forward through the cathode electronics to the ADCs and LUT. For each detector the conversion is:

$$Q = PHA \times \frac{4.25}{31} \times \frac{0.84 \times FE\text{edge} \times Shaping \times 511}{Atten_c \times Buffer_c \times Shaping_e \times FE\text{Anode} \times 4.25}$$

The subscript $c$ refers to fact that the gains are different for each PHA channel. The factor 0.84 arises from electrostatic factors related to the geometry of the detector. In effect the charge collected on the cathode is only 84% of that collected on the anode. The resulting PHD parameters in LUT coordinates $(X,Q)$ are listed in table 4.2.

As is expected the values for the PHD centroid on the lookup table are spaced further apart for the BCS-B ions, as they have a larger difference in energy than is the case for the BCS-A ions. As mentioned above, the requirement that both channels share the same cathode electronics places the pulse height distributions at either ends (in terms of $Q$) of the lookup table, where each channel is likely to be subject to different geometrical effects. For channel 2 (CaXIX) the top of the addressable range

<table>
<thead>
<tr>
<th>Channel</th>
<th>Ion</th>
<th>Energy (keV)</th>
<th>Centre $(Q)$</th>
<th>$1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCS-A</td>
<td>0</td>
<td>FeXXVI</td>
<td>6.97</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>FeXXV</td>
<td>6.7</td>
<td>335</td>
</tr>
<tr>
<td>BCS-B</td>
<td>2</td>
<td>CaXIX</td>
<td>3.9</td>
<td>493</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>SXV</td>
<td>2.4</td>
<td>309</td>
</tr>
</tbody>
</table>

Table 4.2: Ion PHD parameters in ADC coordinates.
4.3. **LOOKUP TABLE GEOMETRICAL EFFECTS**

is less than $1\sigma$ from the peak of the PHD, and for channel 3 (Sxv) the lower end of the PHD falls into a region with inaddressable bins at more than $1.4\sigma$ from the peak.

### 4.3 Lookup Table Geometrical Effects

The BCS lookup table has three distinct regions, separated by lines of constant $Q$. The first region is from $Q = 0$ to $Q = 255$. In a more general case the upper value of $Q$ is set by the number of output position bins (The scaling factor $S$ in equation 4.9). In this area of the lookup table the fixed patterning is most severe, as there is always less than one address per bin on average. This is equivalent to having at least one bin, or value of output position, for which there exists no address, or $A$, $B$ coordinate. For any counts to be recorded within a bin there must be at least one address in the table, for any given $Q$, that will return that bin number. For values of $Q$ that are less than 256 this is not true. Hence there will always be output bins that contain no counts, because they are not physically addressable. For the case of the BCS-B detector which has an 8-bit wide ADC the boundary is actually the same, even though only a quarter of the addresses can be accessed, since in the standard mode of operation for the BCS the output for both BCS-B channels is double binned down to an effective scaling factor of 128.

The second region is from $Q = 256$ to $Q = 511$. This is the usable area of the lookup table. Fixed patterning can be corrected if the values of $Q$ lie in this area. In the more general case the upper limit of $Q$ here is set by the maximum range of the ADCs. The severity of the fixed patterning decreases with increasing $Q$ up the table, as the number of addresses per bin increases.

The last region is from $Q = 511$ to $Q = 1024$. This region, which comprises 50% of the lookup table, is not strictly legally addressable, as the value of $Q$ should never exceed 511, which is the maximum range of the ADCs. However the BCS will only flag an illegal value of $Q$ if either one of the ADCs have an input that exceeds the maximum allowed range. This allows for a position dependence on pulse height, as an illegal value of $Q$ can be accepted as a valid event provided it falls towards the centre of the detector. Events of a similar energy falling towards the edges would exceed the maximum range of one of the ADCs, and the event would be marked as invalid, and rejected. This eventuality depends entirely on the gain settings, and hence the
position of the pulse height distribution in the lookup table. For the end bins events with energies larger than the maximum ADC output are rejected, since most of the charge is concentrated in either the $a$ or $b$ cathode, but accepted in the middle of the detector, where the charge is more equally divided between $a$ and $b$, so that each signal is less likely to individually exceed the ADC maximum. The higher the values of $Q$ the more pronounced the vignetting of the end bins, and the more of the range of the detector that will be affected. The BCS is fortunate however, in that the only channel potentially affected by this problem is the CaXIX channel. Alteration of the gains for BCS-B is not a viable option however if SXV is to have the peak of its pulse height distribution safely above the $Q = 256$ limit. The effect is restricted to the end bins of the detector, and this practically means that all the vignetting is contained almost entirely in the out of window bins, and is unlikely to cause significant loss of counts in all but the most extreme of data bins.

The other source of clipping of the PHD is the use of energy discriminators to reject unwanted energies, such as germanium. These operate in a position independent way, but can cause problems if areas of the detector become significantly gain depressed.

### 4.4 Numerical Model

The numerical model developed to correct fixed pattern noise works on a principle of simulating a uniform input as a function of position along the detector ($X$), but with the correct PHD synthesised from the default centroid and width values listed above. The result after summing over $Q$ and normalising is a ‘flat field’ that can be used as a correction to the data. This is a numerical solution of equation 4.8 with the $F(X, Q)$ term being supplied by the actual flight lookup table which is read into an array, and the $P(Q)$ term constructed on the fly. This numerical model actually uses a more complex two dimensional $P(Q)$ array (i.e. $P(X, Q)$), as there are position dependent modifiers to the basic $P(Q)$ function. The position dependent $P(X, Q)$ can be treated in the same way as a PHD that is independent of $X$, for the purposes of maintaining the simplifying assumptions in equation 4.6, by considering it as composed of a small number of separate $P(Q)$ distributions, each of which is valid over a given range of $X$, and is independent of $X$ over that range. However the position dependence of
4.4. NUMERICAL MODEL

\( P(X, Q) \) is important, making a numerical model the only practical solution to the problem of deriving a correction.

The numerical model uses both predetermined defaults and instrumental parameters from the telemetry stream where possible, in the attempt to create a result that mirrors the actual behaviour of the detector as closely as possible.

The program is composed of three distinct sections.

- **Variable preparation;** includes checking validity of high voltage settings, extraction of needed data items (e.g. SCA settings, ALL and LIM counters) from QS and DP_SYNC record structures, calculation of the germanium ratio.

- **\( P(X, Q) \) construction;** the flat field PHD is created for each address on the LUT accounting for gain depression, SCA clipping, and for BCS-A the inclusion of the germanium signal.

- **Summation;** the input PHD and the LUT are combined by summing over \( Q \) to produce the final flat field array, which is then normalised to produce the correction array \( (G(X)) \).

4.4.1 Sample Results

Results from the second stage of the program are shown in figures 4.4 and 4.5. The CaXIX \( P(X, Q) \) plot, which does not include any gain depression term, shows both the asymmetry of the \( \frac{P(Q)}{Q} \) function with increasing \( Q \), and the vignetting of the end bins for values of \( Q \) greater than 511. The FeXXV surface shows the inclusion of the germanium distribution (the rise towards high values of \( Q \)), and the operation of the upper discriminator, which acts to truncate the germanium distribution.

Application of the calculated distribution in figure 4.5 to flight data is shown in figure 4.6. The spikes in the spectrum are removed by dividing the raw data by the calculated fixed pattern array. The correction is most obvious for the spike at bin 128.

4.4.2 Germanium Fluorescence

The model includes the effect of germanium fluorescence on the BCS-A channels. Fluorescence is caused when high energy X-rays illuminate the Ge-220 crystals which
Figure 4.4: CαXIX $P(X, Q)$ distribution. Energy increases from the lower left hand corner to the upper right hand corner of the surface. The position axis is orthogonal to the $Q$ axis. $A, B$ coordinates run along the front and left edges.
Figure 4.5: FeXXV $P(X, Q)$ distribution. Axes as for figure 4.4.
Figure 4.6: FeXXV $G(X)$ function, and application to flight data. The corrected data is obtained by dividing the raw data by the calculated fixed pattern.
act as dispersive elements for BCS-A. The photons emitted by this mechanism have an energy of about 9.9keV, and directly illuminate the detectors causing a second higher energy peak in the PHD for each channel. For BCS-A the programmable energy discriminators can be used to reject photons with energy outside set upper and lower limits to remove the germanium contribution. This method is not totally effective however as the iron and germanium energy distributions overlap. The normal method is to place the discriminator at the estimated minimum in energy between the two distributions, to maximise the iron flux recorded, yet not allow too much germanium to contaminate the spectrum.

The flux due to germanium must be accounted for in the derivation of the LUT output PHD, as it will have a strong influence in removing fixed patterning due to its occurrence at relatively high values of Q. It will also modify the behaviour of the rate dependence of gain.

The parameters required to characterise the germanium contribution for use in the model are the centroid and width of the pulse height distribution and the ratio of the heights of the germanium and iron PHDs. Since the germanium PHD is not recorded by the PHA these parameters have to be estimated. The centroid is estimated by extrapolating the measured values from the centroids of FeXXV and FeXXVI given in table 4.2 up to 9.9keV. The width is estimated by applying equation 4.10 in the same was as was done for the other ions. The ratio of the height of the Ge PHD to either the FeXXV or FeXXVI PHD is slightly more complex to estimate, but can be done by making some assumptions and using the ALL and LIM counters saved in the DP_SYNC section of the telemetry.

If all the normal ion distribution (for example FeXXVI) occurs between the two SCA limits ($SCA_h$ and $SCA_l$), then the number of counts contained in a given spectrum will be;

$$A_n = H_n \sum_{SCA_h}^{SCA_l} e^{\frac{(i-m_n)^2}{2w_n^2}}$$

(4.12)

where $m_n$ is the centroid of the ion distribution, $w_n$ is the gaussian width, and $H_n$ is the height. This sum can be similarly written for the counts contained in the germanium PHD ($A_g$). The ratio of PHD heights can then be written as;

$$\frac{H_n}{H_g} = \frac{A_n \sum_n}{A_g \sum_g}$$

(4.13)

where $\sum_n$ represents the sum in equation 4.12. The sums for both the ion and ger-
manium PHDs were evaluated using the previously estimated centroids and widths by using the \texttt{GAUSSINT} procedure in IDL. The first term can be approximated by;
\[
\frac{A_n}{A_g} = \frac{LIM}{ALL - LIM}
\] (4.14)
since the counts that fall inside the SCA limits are recorded by the LIM counter, and all the counts that the detector registers within the time period covered by the current spectrum by the ALL counter. The ratio is time dependent, being a function of the incident hard X-ray flux on the crystals.

4.4.3 Rate Dependence of Gain

Rate dependence of gain, and consequent image distortions can be a severe problem in the BCS, mostly due to factors related to the detector geometry (Trow et al., 1994). As the name implies this effect is position dependent, and forms the second position dependent modifier to the basic $F(A, Q)$ function. The most important outcome of rate dependence of gain as far as the fixed pattern model is concerned is that the PHD is moved towards lower $Q$ at high countrates for certain bins only. This affects the calculation of $F(X, Q)$ for those values of $X$, making the fixed patterning within the affected area more severe. This position dependent gain depression is time dependent and difficult to estimate. An example calculation of the position dependent gain for the spectrum shown in figure 4.6 using the \texttt{GAINDEP} program (Trow, 1992) is shown in figure 4.7. This program calculates the charge per mm, using the supplied

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{rate_dependence_of_gain.png}
\caption{Calculated rate dependence of gain for example channel 1 (FeXXV) spectrum}
\end{figure}
spectral data as an estimate of the raw count rate, then calculates the relative gain in the bin using the following equation;

\[
\ln \left( \frac{g}{g_0} \right) = K_0 R + K_1 R^2
\]  

(4.15)

where \( R \) is the charge per unit length, \( g_0 \) is the nominal detector gain, and \( K_0 \) and \( K_1 \) are determined empirically.

The result of including the gain depression array in the calculation of \( P(X, Q) \) is shown in figure 4.8. This is the same \( P(X, Q) \) function as in figure 4.5, but with the germanium fluorescence and the lower SCA terms removed for clarity. The most intense bins generate the largest local depressions in gain, and hence will be the most subject to both flux loss by clipping at the lower SCA discriminator, and to more severe fixed pattern noise as the centroid moves to lower \( Q \).

Another problem associated with position dependent gain depression is that the recorded PHA spectrum will have an increased width, with a wing towards lower energies. If a significant fraction of the detector suffers from gain depression then the centroid of the PHD recorded will be shifted towards lower energies. This makes the use of the PHA spectra to gain the initial information about the PHD characteristics for each channel additionally complicated. As the gain depression profile has no lower threshold, picking a safe countrate limit for the PHA spectra whilst still gaining enough data points is tricky. This shows up as an increasingly non-gaussian profile in the PHA with a larger width than at lower rates, and accounts for most of the scatter in figure 4.3 for the high energy channels.

**4.4.4 Errors**

It is likely that the errors on the derived PHDs are large. Aside from the poor statistics for the high energy channels, the gains for each of the stages shown in equation 4.11 are only known to an accuracy of 3%. Calculation of the sensitivity of the model to an incorrectly derived PHD, in order to weigh the benefits of a successful correction against the probability of increasing the error, was carried out by simulating a range of simple PHDs with different centroids. Figure 4.9 shows the maximum deviation caused by fixed pattern noise as a function of \( Q \). The maximum deviation is expressed as a percentage. A maximum deviation of 100% means that the bin worst affected by fixed pattern noise will have a flux of zero, or twice that expected. As ex-
Figure 4.8: Inclusion of gain depression array in the calculation of $P(X, Q)$. The germanium fluorescence term and the lower SCA discriminator have been removed for clarity. The gain depression array was scaled before inclusion by a factor of 4 for display.
The results of applying the $G(X)$ from an incorrectly calculated PHD are shown in figure 4.10. This figure was generated by taking the tabulated centroid for each channel as the ‘true’ centroid, and calculating the corresponding $G(X)$. This ‘true’ fixed pattern was then divided by those calculated for a range of PHDs with different centroids, and maximum percentage error of the result calculated in the same way as for figure 4.9. In general the two BCS-A channels show reasonable tolerance for errors in the centroid position, with the maximum error as a result of a faulty correction being no worse than the error expected from the uncorrected fixed pattern (comparing with figure 4.9) over a wide range of $Q$. The BCS-B channels are less tolerant of mistakes, with centroid errors of more than 1σ in the SxV channel rapidly worsening the maximum error over that expected from an uncorrected flat field. It is likely that the differences between the shape of the curves for the SxV and CaXIX channels are due to the density of addresses in the vicinity of the ‘true’ centroids. Since SxV has a centroid which is at a relatively low value of $Q$
Figure 4.10: Maximum deviation as a function of $Q$ for a miscorrected flat field.
ber of addresses per bin is also low. Thus a small variation in $Q$ potentially leads to a large variation in $F(X, Q)$. All four channels show a similar behaviour within a few $\sigma$ of the true position.

### 4.4.5 Summary

A numerical model of Fixed Pattern Noise in the Yohkoh BCS has been described. The model works by synthesising the expected flat field pulse height distribution, including position dependent and rate dependent modifications to a characteristic PHD which have been derived empirically for each channel. The calculated flat field can be used to either directly remove fixed pattern noise from spectra by division or as a guide to the worst affected bins.

The conclusion drawn from figures 4.9 and 4.10 is that the fixed pattern correction is suitable for the BCS-A channels, and possibly the CaXIX channel, but not for the Sxv channel. Typical maximum errors (in the absence of significant gain depression of the PHD) for each spectral band are shown in table 4.3. These errors are the maximum errors expected. Neglecting gain depression, the entire noise pattern scales (approximately) with the maximum error, so this number can be used as a “measure” of how badly affected the output position spectrum will be. From inspection of figure 4.6 it can be seen however that only a few bins have a fixed pattern error which is of the same significance as the maximum error, so that for low maximum percentage errors, the errors on the vast majority of bins will be small.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Ion</th>
<th>Est. Max. Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCS-A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>FeXXVI</td>
<td>29</td>
</tr>
<tr>
<td>1</td>
<td>FeXXV</td>
<td>32</td>
</tr>
<tr>
<td>BCS-B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CaXIX</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>Sxv</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 4.3: Estimated Maximum FPN error as a percentage. (Thus an error of 50% would mean that the worst affected bin would have half the counts expected).

The effects of position dependent gain depression are poorly understood, and are likely to have a significant effect on the Sxv PHD due to the high count rates in this channel. It is therefore likely that the calculated PHD for this channel would be sufficiently incorrect to result in a worsening of the maximum error, rather than
 REMOVAL OF FIXED PATTERNING ERROR

4.5 Removal of Fixed Patterning Error

Techniques for the reduction or complete removal of fixed pattern noise require either special hardware or attempt to exploit geometrical properties of the lookup table. Methods involving redesigns of the coding electronics attempt to increase the density of addresses per bin in the lookup table, or restrict the pulse height distributions to the upper parts of the lookup table where the fixed patterning is least damaging. Methods that do not involve a hardware redesign are more limited in scope and either involve a reduction in resolution, or accept the fixed patterning. In the latter case software determines the parts of the detector in position space which are worst affected by the fixed patterning, and flag them according to some preset quality criterion.

4.5.1 Hardware Methods

Reduction of the effect of fixed patterning by using alternative electronics coding schemes is limited by the technology of Analogue to Digital Converters. There is a tradeoff between power, speed and the number of bits of digitisation. For applications where the type of the ADC is determined by such factors, only a few solutions present themselves. The first is the use of nonlinear ADCs in the positioning chain. There are several possible nonlinear transformations that can be used, of which the logarithmic ADC is one example. This will compress the input pulse height distribution into a narrower band on the lookup table. This band can be designed to lie in that part of the table with the largest density of addresses per bin.

An alternative approach is to use extension bits (Koike and Hasegawa, 1988). Extension bits are randomly generated numbers which replace the low \( n \) bits of the result from each ADC (which is shifted up by \( n \) bits), giving a final number of width \( N + n \), where \( N \) is the width of the ADC output. The resulting extended output from each ADC is then used to calculate the position, using equation 4.1. This is an ef-
fective method of increasing the density of addresses per bin without increasing the range of the ADCs. Koike and Hasegawa (1988), give the following empirical relation for 'perfect uniformity';

\[ N + n \geq M + m + 1 \]  

(4.16)

where \( M \) is the number of output position bits (\( M = \ln (S) \)), and \( m \) is a parameter that accounts for the percentage of the lookup table covered by the PHD. The PHDs for which this relation is valid are step functions in \( Q \) space. A PHD which is 1 in the upper 50% of the table and zero elsewhere has \( m = 1 \), one which is 1 in the upper 75% has \( m = 2 \) and so forth. Since static lookup tables can become very large with this method, dynamic computation of equation 4.1 is the only practical method of calculating the position. If \( m \) is approximately 3 for the BCS, then the above relation requires at least 3 extension bits for the suppression of fixed patterning. A static lookup table for this configuration with \( S \leq 256 \) would require 16 Megabytes of memory. However dynamic computation is generally slower than a static lookup table, and might limit the peak countrate.

4.5.2 Software Methods

Methods also exist to redesign the structure of the lookup table (Geesman et al., 1991) to minimise the fixed patterning by exploiting symmetry within the table. This symmetry is critically dependent on properties of the pulse height distribution as well as the scaling factor used in the lookup table. In the simple case fixed pattern noise is minimised if \( S \) is prime and the quantity \( \frac{P(Q)}{Q} \) is symmetrical about \( nS/2 \) where \( n \) is an integer.

Lookup tables modelled on this principle have been constructed and used as input to the numerical model. For the BCS, the closest prime number to the actual scale factor used in practice is 257. This gives two possible values of \( nS/2 \) in the second region of the lookup table; 257 and 385.5. The first is on the boundary of regions 1 and 2, and can be discounted.

Figure 4.11 shows the calculated \( G(X) \) for a symmetrical PHD centred at 385.5 using both (a) a standard lookup table and (b) a stretched lookup table similar to that used in the BCS. For the standard case the errors are much reduced with a maximum percentage error for the in-window bins of about 0.5%. The existence of deviations from the predicted perfect uniformity in (a) is due to the difference between
4.5. REMOVAL OF FIXED PATTERNING ERROR

Figure 4.11: $G(x)$ functions calculated using a prime lookup table and tuned PHD. a) standard lookup table, b) BCS style stretched lookup table.
a symmetrical $P(Q)$ and $P(Q)/Q$. To achieve perfect uniformity requires a skewed input PHD (of the form $qP(q)$), which may not be realistic requirement for real detectors. Figure 4.11b shows the result of using a lookup table that has been stretched in a similar way to that used in the BCS flight table. The PHD and scale factor of the table are identical to that used for figure 4.11a. The fixed patterning has a similar magnitude to that expected from the unmodified flight table, indicating that the conditions for uniformity are quite strict. Investigation of tolerance of the method to small departures from the ideal conditions shows a steady increase in maximum deviation from a minimum at $Q = 385.5$ to a 'standard' level of error at distances of approximately $\geq 2\sigma$. Thus the benefits conferred by exploiting symmetry are very dependent on the ability to tune the input PHD to lie in a narrow energy band.

Application of this technique to the BCS is not likely to be successful for several reasons. Since the cathode electronics for each detector are shared between two channels, tuning the gains to satisfy the symmetry criteria for the PHDs from both channels simultaneously is likely to he difficult. Even if the input PHDs could be tuned to lie precisely at the optimal points in the table any gain depression or significant germanium fluorescence would cause the fixed patterning to reappear, as these are asymmetric modifiers to the PHD. More importantly, the use of this technique would also require that a non-stretched lookup table be used, with a consequent loss of spectral resolution.
Chapter 5

Flare of 16 December 1991

The presence of blueshifts in soft X-ray spectra during the impulsive phase of solar flares has been used as evidence for bulk upflows of heated plasma, in support of the chromospheric evaporation theory (Antonucci et al., 1982; Antonucci and Dennis, 1983; Tanaka and Zirin, 1985). The nonthermal electron beam model explains the upflowing plasma as being material ablated off the chromosphere. The transport of energy from the flare ignition site to the chromosphere by a high energy beam of electrons leads to a very rapid heating of the chromospheric plasma. If the energy deposited is such that the heating and consequent plasma expansion timescale exceeds the hydrodynamic time scale, then the ablation of chromospheric material upwards into the coronal loop is explosive (Fisher et al., 1985b). Conservation of momentum also requires that plasma immediately below the ablation site be driven downwards into the chromosphere at speeds of 50-100 km/s to balance the matter flowing up into the corona (Fisher, 1987). The plasma which is driven downwards is much cooler than the plasma which is ejected upwards, and appears as a red-shifted region in Hα images of the chromosphere.

This model can be quantitatively tested by looking for conservation of energy between that contained in the nonthermal electron beam and the total energy of the evaporating soft X-ray emitting plasma (Antonucci et al., 1982), or by looking for momentum balance between the soft X-ray emitting plasma ejected into the corona and the Hα emitting material flowing downwards, (Zarro et al., 1988; Canfield et al., 1990).

Energy and momentum balance calculations for flares observed by SMM have
been criticised however as being too inexact, mainly on the related grounds of instrumen
trial resolution and filling factors (Doschek 1990). Improving the accuracy of
the momentum balance calculation by including better spatially resolved data has
been carried out recently by Wülser et al., (1994). This chapter addresses the case
for improving the energy balance calculation, following a similar analysis to that per­
formed by Antonucci et al., (1982) for an M2.7 flare observed by the Yohkoh satellite
on the 16th December 1991 at 04:56 UT, which occurred in active region NOAA 6961
at heliocentric coordinates N04 W45. The absence of simultaneous Hα observations
unfortunately prevented the use of a momentum balance calculation for this partic­
ular flare.

5.1 Observations

The closest SXT image of AR 6961 is shown in figure 5.1, which was taken about 10
minutes before flare onset through the thin aluminium filter. Because of the occur­
rence of a smaller flare (C7.4) about ten minutes earlier in a different active region
(NOAA 6972 at S12 E70), the spacecraft instruments were already in flare mode and
so the event at 04:56 UT was observed throughout its development. However the
partial frame mode response of the SXT was centred on the smaller event, so there
are no contemporary soft X-ray images for this flare. In addition, spectra from the
earlier flare caused some contamination of the earliest spectra for this event in the
lower energy BCS channels. This requires some care to eliminate in order to prevent
a false interpretation as a blueshift by the fitting programs.

As the spacecraft was already in flare mode, the Bragg Crystal Spectrometer (BCS)
and Hard X-ray Telescope (HXT) recorded the initial stages of this event at a high
data rate, with a cadence of 3s for the BCS and 0.5s for the HXT. The light curves for
this event are shown in figure 5.2 for the BCS and in figure 5.3 for the HXT channels.

In the highest energy channel of the HXT (HI) a simple hard X-ray impulsive
burst is registered with a total duration of \( \approx 30s \), a rise time of \( \approx 10s \) and a double
peak structure with a separation of \( \approx 4s \) between the peaks. The simple nature of
the burst is further emphasised by the 17GHz light curve obtained at the Nobeyama
Radio Observatory (figure 5.4). The peak in the HI channel coincides in time with the
Figure 5.1: Part of an SXT full frame image (FFI) showing AR 6961. This image was taken at about 04:43:52UT, about 10 minutes before the flare onset. This image was taken through the thin aluminium filter (3-50Å). Each HXR footpoint (From figure 5.11) is marked by the contour lines. Each pixel represents 9.84'
Figure 5.2: BCS light curves for the flare of 16th December 1991. The temporal resolution is 3s.
Figure 5.3: HXT light curves for the flare of 16th December 1991. The data have been binned down to the HXT major frame interval of 2s for clarity, and to match the time resolution of the BCS light curve (3s).
Figure 5.4: 17GHz Microwave emission recorded at Nobeyama Observatory (Data Provided by S. Enome). The small feature recorded at 04:46 UT is related to the flare in AR 6972. The time of the microwave peak correlates well with the HXR seen in HXT, although the time resolution is not sufficient to distinguish the individual sub peaks seen in the HXT data.
17GHz microwave burst recorded at Nobeyama, although the radio data lacks sufficient time resolution to confirm the correlation with the individual sub-peaks seen in the HXT data. The HXR spectral signature (Power Law) and time profile of this burst suggests that it is nonthermal in origin.

In the lower energy HXT channels the impulsive rise of the nonthermal burst and some of the fall is observed, after which a more gradual increase occurs. The intensity of this gradual rise in emission relative to the burst is a strong function of energy, being strongest in the LO (14-23 keV) energy HXT channel, with the HXT M1 channel (23-33 keV) showing a similar but less intense profile. This gradual phase emission is identified with thermal emission from a hot plasma. This light curve displays the characteristics of an impulsive flare (Type 'B' of Tanaka, (1987)) with some of the characteristics of a hot thermal flare (type 'A'). During the gradual phase a "superhot" plasma component is seen in the BCS FeXXVI and HXT LO channels, which is discussed separately in chapter 6.

An energy dependence can also be seen in the BCS channel light curves, with the higher energy channels, FeXXVI (E ≈ 6.9keV) and FeXXV (E ≈ 6.7keV), having proportionately shorter decay times than the lower energy channels, CaXIX (E ≈ 3.9keV) and Sxv (E ≈ 2.4 keV). The gradual rise and decay shown by the BCS and HXT low channels is characteristic of the heating and cooling of flare plasma.

5.1.1 Pre-Flare Background

The first step in the analysis was to assess the impact of both instrumental effects and preflare background on the observations.

Pre-flare background is an important consideration for the lower energy BCS channels (SxV and CaXIX), where there is a significant contribution from the earlier C class flare, and in the case of SxV additional background contribution from the other active regions on the solar disk. Because of the potential for confusion in SxV by spectra from these other sources on the disk, as well as the pronounced line narrowing instrumental effect present at the peak of the flare, data from the SxV channel were not used in this analysis.

In the CaXIX channel the spectra from the previous flare appear superimposed and offset to the short wavelength side of the rising M flare spectra. The secondary spectra are registered because the BCS is an uncollimated instrument with its dis-
5.1. OBSERVATIONS

<table>
<thead>
<tr>
<th>Time (UT)</th>
<th>M - Flare</th>
<th>C - Flare</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:55:42</td>
<td>42</td>
<td>16</td>
<td>38</td>
</tr>
<tr>
<td>04:56:06</td>
<td>154</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>04:56:12</td>
<td>220</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>04:56:18</td>
<td>292</td>
<td>14</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

Table 5.1: Gaussian fit results, significance of pre-flare spectrum

dispersion axis aligned in a North-South direction relative to the Sun. The intensities of the superimposed spectra are small however, as the earlier flare is in late decay phase by 04:56 UT.

In order to assess the importance of the superimposed spectra the relative intensity was estimated by fitting two Gaussian profiles to the combined CaXIX resonance line. The centre and width of the profile fitted to the superimposed C flare component were fixed at values derived from an earlier spectrum taken at 04:50:48 UT. The fit parameters for the M flare component were allowed to vary, with the width being calculated from the red side of the resonance line, and the centre of the profile fixed at the bin corresponding to the maximum countrate. As the fit was a simple Gaussian parametric fit, the region of the resonance line used excluded the d13/d15 satellites.

This approach is conservative, in that it will underestimate the intensity of the rising flare profile which is very asymmetric, due to the significant blueshifts, when compared to a Gaussian. The superimposed C flare profile will be more closely fitted by a Gaussian as the profile is nearly symmetrical. The results of this fitting process are given in Table 5.1.

It can be seen from the listed percentages that the contribution from the C-flare is negligible after 04:56:12 UT, and after 04:56:18 becomes of the same order as the counting statistics. The contribution for the first three spectra is important, as the extra flux contributed by the C flare to the blue wing of the M flare would bias the analysis of the velocity structure of the early impulsive phase.

The presence of the C flare spectrum was accounted for by excluding the first spectrum (04:55:42 UT) entirely from the subsequent analysis. This spectrum was not considered reliable due to the relatively large contribution from the C flare spectrum, and the low count rate in the M flare spectrum.

For the remaining two spectra the superposed spectrum was removed by subtrac-
tion. This was done by first calculating a scaling factor for each affected spectrum by fitting an inverse exponential to the decay of the C-flare (Bornmann, 1985). A suitable clean late spectrum from the C-flare was then scaled by this factor and subtracted from the combined CaXIX profile. Errors due to the differences in temperature between the scaled spectrum and the blended spectra are likely to be negligible, as the flare is cooling slowly, with no evidence in the C flare light curve of any continued heating.

The higher energy BCS channels are less affected by the cool pre-flare spectrum, and due to the design of the BCS, record the superimposed spectrum displaced to the red side of the M-flare spectrum. This means the resonance line blue wing is unaffected, although the derivation of plasma temperatures may be incorrect for the earliest FeXXV spectra. It was not considered worthwhile to subtract the superimposed spectra from the FeXXV channel, as there were other instrumental effects, mainly localised rate dependence of gain that prevented the reliable use of fitting programs for this channel.

5.1.2 Blue shifts

BCS spectra that show detail of the resonance line \((1s^2 1S - 1s2p^1P)\) profiles for the FeXXV and CaXIX channels are shown in figure 5.5. This figure illustrates the large blueshifts observed in spectra taken between 04:56:06 and 04:56:21 during the impulsive phase, (histograms) compared to a spectrum taken from much later in the flare decay phase (smooth lines) which has no significant blue asymmetry.

The assumption was made that the decay phase spectrum was emitted by stationary plasma (Antonucci et al., 1984), and so could be used to provide an absolute wavelength calibration. The spectra were taken with a 3s time resolution, but have been integrated to a 6s interval to improve the statistics early in the impulsive phase. The spectral range around the resonance lines has been expanded for both figures to emphasise that for both ions there is both a significant asymmetry, indicating a range of plasma velocities, and a shift of the peak of the emission, indicating that the majority of the plasma is in motion. From figure 5.5 it can also be seen that the proportion of plasma that is moving is much greater than that which is stationary. This observation is qualitatively in agreement with several numerical simulations of beam heated flaring loops undergoing explosive chromospheric evaporation (Antonucci et
5.1. OBSERVATIONS

Figure 5.5: BCS spectra from the FeXXV and CaXIX channels. The histogram style lines are early impulsive phase spectra that have been integrated for 6s, and scaled by the indicated factors. A late decay phase spectrum, integrated for 24s, is shown as a solid line. The region around the resonance lines has been expanded to show that the blueshifts are composed of two distinct features, an asymmetry and a peak shift.
Figure 5.6: Maximum blueshift velocities from FeXXV and CaXIX superimposed on HXT LO and CaXIX channel light curves

5.1. OBSERVATIONS

Figure 5.6 shows estimated maximum blueshift velocities derived from BCS spectra as a function of time for FeXXV and CaXIX. These velocities were derived by subtracting the continuum background from the spectrum, and applying the Doppler equation to the calculated half width of the resonance line at 10% of the peak flux. This particular method of calculating the upflow velocity was chosen, as it was found to be the most robust method of estimating the maximum velocity for all of the ions. Other methods, for example the spectral fitting technique used to derive a measure of the average upflow velocity (described in the next section), are much less sensitive to the maximum velocities in each ion. Furthermore, it was found that the use of this technique allowed the change in detector dispersion with count rate in the FeXXV channel to be accounted for relatively simply.

For FeXXV the tabulated dispersion for the channel was modified empirically to account for the effects of rate dependent gain depression (Trow et al., 1994). Figure 5.7 shows the calculated dispersion for two pairs of lines in the FeXXV channel. The dispersion calculated from the most widely spaced line pair (w, j) was taken to
represent the global change in dispersion (see figure 3.2 for line notation). The effect of rate dependence of gain on the CaXIX channel dispersion was much less severe, due to the isolated nature of the major lines.

Figure 5.7: Effects of rate dependence of gain on FeXXV channel dispersion. Panel (a) shows the dispersion calculated for the w, j line pair, and (b) for the w, x line pair. Panel (a) is more likely to represent the global change in dispersion for the channel, as the lines are widely separated. The shape of the dispersion curve in panel (b) is a result of the changing line intensities on either side of the x line as a function of temperature during the flare. The flux in the x line is therefore attracted first in the direction of the w line, and then in the direction of the r, j, z complex. This makes use of automatic fitting programs for FeXXV (which assume a linear dispersion) difficult for this particular event.

Figure 5.6 shows that the maximum velocities recorded by the FeXXV channel are much higher than those recorded in the CaXIX ion. The difference between the two channels is unlikely to be an artifact of an incorrect dispersion relation, as the expected error in velocity from this effect is of order 10 to 15%. The difference in velocities between the two ions, and between the velocities recorded in FeXXV during the impulsive and gradual phases is significantly larger than this value.

This velocity structure has been seen before in SMM studies, where a correlation between the maximum velocity and the increasing energy of the ion species was found (Antonucci et al., 1990). It is also obvious that the velocities recorded in the
FeXXV channel decay faster than those recorded in the CaXIX channel. This may be a simple consequence of the evaporation process, in that hotter plasma which is moving faster is more closely related to the evaporating region of the chromosphere, and will cool and slow down as it moves up into the loop. This is also suggested by the rapid decay of the FeXXV velocities to values similar to those from CaXIX after the end of the hard X-ray burst, when (according to the nonthermal beam model) the heating of the chromosphere ceases.

**BCS Spectral Fits**

BCS CaXIX spectra were fitted by a two component velocity model (Lemen et al., 1984; Fludra et al., 1989) during the rise phase of the flare. The FeXXV channel was not used in the analysis, as the uncertainty over the correct dispersion led to corresponding errors in the spectral fitting (see figure 5.7). The software used was the BCS analysis pipeline, which has been described earlier.

The fit results are shown for several rise phase spectra in figure 5.8. Most fitting parameters were allowed to vary freely, whilst others were subject to certain constraints. The central wavelength of the stationary component resonance line was fixed at a constant value which was determined from a decay phase spectrum, when it was assumed that all the plasma was stationary. The second component was fitted to the blue wing of the resonance line, and represents the moving plasma. This profile was allowed to vary in central wavelength, with the constraint that the width of this component was proportional to the separation between the two components.

This method of fitting gives values of electron temperature and emission measure for the stationary component along with average upflow velocity and emission measure for the second or moving component. For the purpose of fitting satellite lines, the temperature of the moving plasma was assumed to be the same as the temperature of the stationary plasma. These parameters are calculated for each spectrum throughout the duration of the flare, and are shown in figure 5.9. At the peak of the CaXIX light curve almost all of the emission observed is from the rest component and the blueshifted component is undetectable, based on a $\chi^2$ significance test. It was assumed that directed upflows have ceased at this time, and the model was changed to a single velocity component for the decay phase. The velocities for the upflowing component shown in figure 5.9 are not corrected, under the assumption of radial up-
Figure 5.8: BCS CaXIX channel spectra with fit results superimposed for several times during the flare. Histograms show the raw data, dotted lines show the fitted rest component, and the solid lines show the combination of the stationary and blueshifted components. The individual blueshifted components are not shown for reasons of clarity. The underestimation of the peak flux in the later spectra is caused by gain depression induced line narrowing.
5.1. OBSERVATIONS

flows, for the flare longitude. Early on in the course of the flare most of the plasma appears to be moving, with the ratio of the emission measures (moving to stationary) peaking at a value around 15 at 04:56:12 UT. Interestingly, the ratio of emission measures correlates well with the hard X-ray light curve, having both a similar rise and fall time, and peaking at approximately the same time as the hard X-ray burst. The peak emission measure from the upflowing plasma component occurs somewhat later at 04:56:30 UT and then decreases until the peak of the CaXIX light curve at 04:58:00 UT where it is minimal.

The fits in figure 5.8 show that that the two component model, whilst providing good results for the later stages of the impulsive phase, has difficulty in matching the shape of the earliest spectra. This difficulty could be resolved by the addition of a further velocity component moving at high velocities.

The inadequacy of a simple two component fit to blueshifted spectra in the initial stages of solar flares has been noted before (Antonucci et al., 1990), but the introduction of further plasma components causes problems by adding a new sets of free parameters to an already badly conditioned fitting problem, so the evolution of the high velocity plasma was studied by looking at the lightcurve of the emission in a range of bins. Figure 5.10 shows a lightcurve for the CaXIX channel, during the impulsive burst, for a range of wavelengths corresponding to Doppler shifts of 650 to 950 km/s. The flux in this velocity range is related to the hard X-ray burst, in a similar way to the velocities derived from the FeXXV spectra in figure 5.6.

The average blueshift velocity is much lower than this, as can be seen from the fitted upflow velocity for the two component model shown in figure 5.9, where the average is about 300 km/s. Blueshifted emission from plasma occupying the lower velocity ranges has a longer lifetime than that occupying the higher velocity ranges. Emission in the velocity range 650-950 km/s has vanished by 04:57:00 UT, whereas blueshifted emission at lower velocities is recorded until the peak of the CaXIX light curve at 04:58:00 UT. There is also a decreasing trend in the fitted velocities from the start of the impulsive phase to the point at which the second velocity component is no longer statistically significant.

This, together with the velocity information for FeXXV, leads to the conclusion that the high velocity component is directly related to the deposition of energy in the chromosphere. This velocity component appears to be hotter (preferentially emitting
Figure 5.9: BCS CaXIX fit results. Time series of parameters resulting from fits to the CaXIX channel using a two velocity component model. Each time step is 6s. The upflow velocities shown here are line of sight velocities, and have not been corrected for the heliocentric longitude of the flare.
Figure 5.10: CaXIX flux in velocity range 800 +/- 150 km/s, superimposed on the hard X-ray burst from the HXT HI (53-93 keV) channel. At higher velocity bands relative to the rest wavelength the correspondence between the blueshifts and the hard X-ray burst increases. The HXT light curve is shown at full 0.5s resolution.
in FeXXV), and disappears rapidly once the heating of the chromosphere is finished, assuming that the heating function is accurately modelled by the nonthermal burst.

5.1.3 Flare loop morphology

Although flare images from the Soft X-ray Telescope were not available for this event, the flare morphology has been studied using images from the Hard X-ray Telescope. HXT images for the 53-93keV channel (HI band) are shown in figure 5.11. Each image is related to a box on the HI band light curve. The horizontal width of the box represents the integration time of the image. To synthesise the HI band images longer accumulation times were needed than for the lower energy bands in order to obtain the required number of photon events through each sub-collimator.

The images show clearly that the emission is contained in two distinct compact regions which are identified as being the footpoints of the loop. The contours in each frame are the same and were produced by overlaying the 04:12:00 UT image with levels of 30, 60 and 90% of the maximum intensity in each frame. The secondary sources, and lobes on each footpoint have an intensity of 10% or less of the maximum intensity in each frame, and may be artifacts of the image deconvolution process (Kosugi et al., 1993). The two footpoints are separated from each other by ≈ 28″ or ≈ 21,000 km, and are active at these locations for the duration of the simple burst in the HI channel.

The impulsive burst time profile shows an interesting double peaked structure, with the first peak occurring at 04:56:07 UT, and the second at 04:56:11 UT. The light curves obtained by fitting a Gaussian source to each of the two footpoints in the MEM images are shown in figure 5.12a, with the results of a cross correlation analysis in figure 5.12b (Inda, 1993).

These figures clearly indicate that each footpoint has a very similar time profile, with a time lag of less than a second between both light curves. The long time separation of 4s between the two peaks in both light curves also precludes this being the signature of successive footpoint emission caused by any asymmetry in the location of the primary energy release site along the loop. Instead this structure in the light curve must be due to two successive energy releases, a modulation of some sort in the particle release, or due to a second separate loop flaring. However, the close synchronisation between the footpoint light curves throughout the double peak is strong
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Figure 5.11: HXT HI band images during the impulsive phase. Image integration time is indicated by the width of the box on the light curve. FOV is 126" by 126". The contours are 30, 60 and 90% of the peak brightness in the frame starting at 04:56:12. All images were created using the MEM method. The intensity of each image is normalised to the peak value in that image for the purposes of display.
Figure 5.12: The top panel (a) shows the HXT Gaussian model fitting light curves, from the M2 band (33-53keV) during the impulsive phase. The lower panel shows the cross correlation function between the two Gaussian sources. Figures kindly provided by M. Inda.
evidence that the footpoints are those of a single loop.

MEM images from the LO channel are shown in figure 5.13 in a similar way to those from the HI channel. The contour lines are once again the 30, 60, and 90% levels from the second HI channel image in figure 5.11, and show the limits of the footpoints. The source structure in the lower channels is more dynamic, with the emission being initially confined to the regions around the footpoints observed in the HI channel. As the flare progresses through the gradual phase the source becomes more elongated, and moves out along an arc, which it eventually fills. As the HXT LO light curve decays the source becomes more concentrated at a point between the two footpoints. Again there are smaller sites of emission in the images, but these mainly have intensities of less than 10% of the peak, and so may be discounted.

A vector magnetogram taken at Okayama Observatory is shown in figure 5.14. Co-alignment of the HXT images indicates that the footpoints lie on opposite sides of the magnetic neutral line, and that the flare occurred in the small north-south aligned loop. The HXT footpoints also match the locations of Hα flare emission points observed by Hida observatory. This small north-south loop can also be seen in the pre-flare SXT image in figure 5.1, with a few long loops which connect the two sunspots seen in optical images. The HXT footpoints are marked by the contour lines to a co-alignment accuracy of about 10". The pixel size of the SXT image is 9.84" however, so it is not easy to determine structures on the scale of the flaring loop.

These observations all provide evidence that the flare occurred in a single loop, with one footpoint on either side of the magnetic neutral line. Given the single loop nature of this event, it is reasonable to interpret the HI band images as showing the sites of thick target emission at the loop footpoints, and the LO band images as being due to a loop filling with hot plasma, and then cooling, predominantly by thermal conduction to the chromosphere. The asymmetry of the cooling plasma towards the end of the gradual phase may be due to line of sight effects, which would be consistent with orientation of the loop as inferred from the SXT and Okayama images. This filling of the loop from the footpoints is consistent with numerical models of nonthermal beam driven chromospheric evaporation (Reale and Peres, 1995; Feldman, 1990).
Figure 5.13: HXT LO images. Image integration time is indicated by the width of the box on the light curve. FOV is 126" by 126". The contours are at 30, 60, 90% of the peak brightness in the HI band frame starting at 04:56:12, as for figure 5.11. The intensity of each frame is normalised to the peak in that frame for the purposes of display.
Figure 5.14: Vector magnetogram taken at Okayama Observatory of AR 6961. The images used were co-aligned using the sunspots observed in white light by the SXT, and Hα by the ground based instruments. Magnetic field lines shown in this image were calculated under the assumption of current free magnetic fields by T. Sakurai. The flare occurred in the small north south aligned loop.
5.2 Energy Balance

In the following sections a loop model for the flare is constructed, based on structure determined from the images provided by the HXT. An energy balance calculation is then performed using the loop as a bounding volume.

5.2.1 Loop Model

Energy balance calculations require a model of the emitting region to provide a bounding volume, in order to correctly calculate the energy contained in the flare plasma. The lack of detailed information about the shape of the emitting region has led to two different approaches being taken in previous calculations. The first is to assume a geometry either based on a plausible magnetic field shape, such as a magnetic dipole (Wu et al., 1981), or a semicircular loop of constant cross-section (Antonucci et al., 1985). The second method is to use a cube determined by the spatial resolution of the instrument (Acton et al., 1982; Wolfson et al., 1983).

Klimchuk et al., (1992) have shown that for a sample of coronal loops the cross-section observed in soft X-rays by the SXT is relatively constant. This is in contrast to the force free picture of the coronal magnetic field diverging with altitude. As the coronal loops trace the magnetic field lines, they also should diverge with height and present an altitude dependent cross-section. This is not borne out by either general SXT observations, or the survey of Klimchuk et al., as most loops appear to have a relatively constant cross-section along their length. Whilst this raises important questions about the mechanisms of magnetic confinement in coronal loops, and the validity of the force-free approximation, it makes construction of models significantly easier.

For this calculation, a semicircular loop model was chosen as a bounding volume, taking the footpoint separation as an estimate of the loop diameter, and the area of the footpoints seen in the HXT as the loop cross-sectional area. The loop was assumed to be rigid, based on the absence of any discernible change of the magnetic field in pre and post flare SXT images of AR 6961.

The footpoint separation was 28", which becomes ≈ 30" or 22,000 km after correction for projection onto the line of sight. The line of sight correction equation for latitudes near the solar equator, is derived by resolving a length on the surface of a
Table 5.2: Physical parameters of the Flaring Loop. The footpoint separation has been corrected for line of sight effects using equation 5.2.

sphere into two components, and projecting each component separately onto the line of sight. For a length \( L_{\text{sol}} \) at heliocentric longitude \( \lambda \), at an angle \( \phi \) to the local N-S meridian, the projection onto the line of sight \( (L_{\text{obs}}) \) is given by

\[
L_{\text{obs}} = \sqrt{(L_{\text{sol}} \cos(\phi))^2 + (L_{\text{sol}} \sin(\phi) \cos(\lambda))^2}
\]

for values of \( L_{\text{sol}} \ll R \), the solar radius. This reduces to

\[
L_{\text{obs}} = L(1 - \sin^2(\phi) \sin^2(\lambda))^{\frac{1}{2}}
\]

where \( \phi \), the angle between the loop diameter and the N-S meridian is 25° and \( \lambda \), the heliocentric angle is 45° for this flare.

Physical parameters of the loop are given in table 5.2. The loop cross-section was derived from the the areas of the HXT HI band footpoints. Strictly, these images give an upper limit only, but other studies (Zarro and Canfield, 1989; Canfield et al., 1991) using coordinated \( \text{H}\alpha \) and X-ray data indicate that an area of \( 10^{17} \text{cm}^2 \) is a reasonable figure.

The measured area of the footpoints is a fairly constant function of energy. The area of the footpoints measured in the HXT LO (14-23 keV) channel is assumed to be a good approximation to the area of the footpoints at BCS energies (3-7 keV), although the 119\( \mu \text{m} \) Be filter of the SXT would have been preferable.

CaXIX cooling rates

The loop physical parameters can be verified using the observed cooling rate of the CaXIX emitting plasma. The initial rapid fall of temperature shown in figure 5.9 is suggestive of conductive cooling. A simple calculation using the peak emission measure also shown in figure 5.9, and the loop volume derived above results in an average density of about \( 3.7 \times 10^{11} \text{ cm}^{-3} \). At these densities thermal conduction along the field
5.2. ENERGY BALANCE

lines is a far more efficient loss mechanism than radiative cooling. Cooling via loss of enthalpy due to material condensing out of the loop (Veck et al., 1984) is unlikely as the emission measure is constant over the time period considered here.

The method used to investigate the cooling rate is a variation of that described by Culhane et al., (1970). The conductive loss rate (from Priest, 1982) is;

\[ q = -\kappa \nabla T \]  

(5.3)

where \( q \) is the heat flux, and \( \kappa \) is the thermal conductivity. This can be resolved along and across the field lines to give, (Spitzer, 1962; Spitzer and Härn, 1953);

\[ \kappa_\parallel = 1 \times 10^{-6} T^{\frac{7}{2}} \text{ (ergs sec}^{-1}\text{ cm}^{-1}\text{ K}^{-1}) \]  

(5.4)

and

\[ \kappa_\perp = 2 \times 10^{-16} N_e^2 T^{-\frac{1}{2}} B^{-2} \text{ (ergs sec}^{-1}\text{ cm}^{-1}\text{ K}^{-1}) \]  

(5.5)

assuming a fully ionised and thermalised hydrogenic plasma. Conductive heating across the magnetic field lines is dominated by positive ions, due to larger radius of gyration. For typical flare values of temperature, density and magnetic field strength, \( \kappa_\perp \ll \kappa_\parallel \) and the heat flux transverse to the field can be neglected. Approximating the local temperature gradient to the global gradient by

\[ \nabla T \approx 4 \frac{T - T_0}{L} \]  

(5.6)

where \( L \) is the loop length, so that \( (L/4) \) is an effective length, and \( T_0 \) is the ambient temperature of the chromosphere. In addition since the chromospheric temperatures are of the order \( 10^4 \text{K} \), and for ease of integration, \( T_0 \approx 0 \).

For a uniformly filled loop of constant cross section, the loss of energy by conduction through both footpoints is

\[ \frac{dE}{dt} = -8 \kappa_\parallel A \frac{T}{L} \]  

(5.7)

with \( A \) being the loop cross-sectional area, and \( E \) is the thermal energy content of the contained plasma. Substituting \( E = 3N_e kTV \) into equation 5.7 gives

\[ \frac{dT}{dt} = -\frac{8}{3} \times 10^{-6} \frac{T^{\frac{7}{2}}}{kN_e L^2} \]  

(5.8)

Integration gives

\[ T = \left( T_p^{-\frac{3}{2}} + \alpha t \right)^{-\frac{2}{3}} \]  

(5.9)
5.2. ENERGY BALANCE

Where $T_p$ is the peak temperature at time $t = 0$, and $\alpha$ is defined as;

$$\alpha = \frac{1.2 \times 10^{10}}{N_e \left(\frac{L}{2}\right)^2}$$

(5.10)

![Figure 5.15: CaXIX conduction cooling curve (solid line), superimposed on CaXIX channel decay phase temperatures.](image)

The temperature decay data are plotted in figure 5.15, with the best fit to equation 5.9, obtained by a standard gradient search curve fitting technique. The fit is better than an exponential and yields a best fitting value of $\alpha$ of $1.47 \times 10^{-20}$ cm.

The model loop has a length of $3.5 \times 10^9$ cm and a calculated peak electron density of $n_e = 3.6 \times 10^{11}$ cm$^{-3}$ from the observed emission measure and inferred loop volume. Using this value of $L$ in the expression for $\alpha$ gives an best fit electron density $n_e = 2.5 \times 10^{11}$ cm$^{-3}$ which is in reasonable agreement with the more directly determined value.

This provides an independent corroboration of the loop model physical dimensions to within an order of magnitude. A filling factor of close to 100% also eliminates the need for complex fine magnetic structures within the flaring volume (Wolfson
et al., 1983), and is similar to values from the SKYLAB spectroheliogram experiment, which found filling factors close to 100% for coronal flare plasmas above $10^6$K (Doschek, 1990).

This is in contrast to several SMM results (Wolfson et al., 1983; Wu et al., 1986; Linford et al., 1988) which require very small filling factors, on the order of 1% to reconcile observed emission measures with densities derived from density sensitive line ratios. This apparent discrepancy may be explained to a certain extent by the methods of assigning flare volumes, allied with the limited spatial resolution of the instruments used.

The conductive cooling curve shown in figure 5.15 underestimates the last few data points, as a consequence of the approximation ($T_0 \approx 0$) made in equation 5.6. Although the plasma within the loop should cool to chromospheric temperatures, in reality there is a heating source function to be accounted for, as the pre-flare loops within active regions can exhibit temperatures of the order of $5 \times 10^6$K (Hara et al., 1992). This steady state heating function, represented by an asymptotic temperature $T_0$ would act to increase the goodness of fit to the observed CaXIX temperatures, as well as the value of $\alpha$. This would also have the effect of increasing the derived density closer to the directly calculated value.

5.2.2 Nonthermal Electron Energy

Although the HXT is primarily an imaging instrument, it can be used as a 4 channel hard X-ray spectrometer when the events from all 64 sub-collimator/detector units are summed together. HXT spectra during the impulsive phase were fitted with a single power law model, with the intensity ($I_{20}$) and photon index ($\gamma$) as free parameters. The power law photon index was fitted by taking the ratios of the HI to the M2 bands and the M2 to M1 bands. The resulting count rate ratios were compared with the precomputed spectral response function (Inda, 1993). The normalisation intensity at 20 keV ($I_{20}$) was calculated by using the value of $\gamma$ to extrapolate the observed intensities in the M2 and HI channels to 20keV. The results of the spectral fitting are given in table 5.3, and some example fits are shown in figure 5.16. As each band has unequal width in energy space the data points shown have been corrected, using the detector response function, to show intensities per keV, rather than recorded counts.
5.2. ENERGY BALANCE

<table>
<thead>
<tr>
<th>Time (U.T.)</th>
<th>$\Delta t$ (s)</th>
<th>$I^{a}_r$</th>
<th>$\gamma^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:56:00</td>
<td>4</td>
<td>0.91</td>
<td>4.2</td>
</tr>
<tr>
<td>04:56:04</td>
<td>2</td>
<td>1.7</td>
<td>4.0</td>
</tr>
<tr>
<td>04:56:06</td>
<td>2</td>
<td>2.2</td>
<td>4.1</td>
</tr>
<tr>
<td>04:56:08</td>
<td>2</td>
<td>1.8</td>
<td>4.2</td>
</tr>
<tr>
<td>04:56:10</td>
<td>2</td>
<td>1.9</td>
<td>4.1</td>
</tr>
<tr>
<td>04:56:12</td>
<td>4</td>
<td>1.4</td>
<td>4.0</td>
</tr>
</tbody>
</table>

$^a$ Normalisation at 20 keV ($\times 10^2$ Photons s\(^{-1}\) keV\(^{-1}\) cm\(^{-2}\)).

$^b$ Power law index.

Table 5.3: HXT power-law model fits to the December 16\(^{th}\), 1991 flare spectra during the impulsive phase.

Figure 5.16: Spectral fits to the four HXT bands. Error bars assume simple Poisson counting statistics (Kosugi et al., 1992). Later spectra are successively displaced upwards by one dex. The solid curve is the fitted power law intensity spectrum. Data points have been corrected to show intensity per keV.
The expected flux from these fits when compared to the lower energy bands, overestimates the actual intensities recorded in each of the LO and M1 bands. The predicted flux for the M1 band is close to that observed, but the predicted flux for the LO band is far in excess of that observed. This may be due to either a double power law, with a steepening at higher energies, (Winglee et al., 1991b) or to a low energy spectral cutoff at an energy within the LO band. If the predicted LO channel flux is equated to that observed, assuming that the flux is limited by a spectral cutoff, then a simple calculation gives the cutoff energy as 20.5keV for the spectrum at 04:56:06 UT. This is consistent both with the result obtained by Wülser et al., (1994) for the 15th November 1991 flare, who found good agreement with the assumption that the incident power law spectrum for this event had a cutoff at about 20 keV, and also with some theoretical models (Mariska and Zarro, 1991).

The best fitting value of $\gamma$ does not vary appreciably during the impulsive phase, which is reflected in the similarity of the light-curves for the M1, M2 and HI bands. As the spectral index was so consistent a flare spectrum of the following form

$$I_E = I_{20}(E/20)^{-4} \text{[photons cm}^{-2}\text{s}^{-1}\text{keV}^{-1}]$$

was assumed for the duration of the impulsive phase, where $I_{20}$ is the flux at 20keV, derived from the observations, and $E$ is the photon energy in keV.

Integration of the thick target bremsstrahlung equation (Brown, 1971; Lin and Hudson, 1976), with the photon spectrum being described by an equation of the same form as 5.11 gives

$$\frac{d^2 N_e}{dE dt} = 3.28 \times 10^{33} b(\gamma) A E^{-(\gamma+1)}$$

(5.12)

where $b(\gamma)$ is the function

$$b(\gamma) = \gamma^2 (\gamma - 1)^2 B(\gamma - \frac{1}{2}, \frac{3}{2})$$

(5.13)

with $B(\gamma - \frac{1}{2}, \frac{3}{2})$ being the beta function.

The power deposited by electrons of energy $\geq 20$keV is given by Hudson, Canfield and Kane, (1978) as

$$P_{20} = 1.6 \times 10^{-9} \int_{20}^{\infty} E \frac{d^2 N_e}{dE dt} dE$$

(5.14)

Which when integrated, defines the relationship between the power deposited and
5.2. ENERGY BALANCE

the spectral flux at 20keV ($I_{20}$).

\[
\frac{P_{20}}{I_{20}} = 1.05 \times 10^{26} \frac{b(\gamma)}{(\gamma - 1)}
\]

(5.15)

Values of $b(\gamma)$ for a set of values of $\gamma$ are tabulated by the same authors. For this event, which has an average value of $\gamma$ equal to 4.0, the corresponding value of $b(\gamma)/(\gamma - 1)$ is 5.90.

The total energy deposited by non-thermal electrons during the impulsive phase of the flare can be calculated by applying equation 5.15 to each of the values of $I_{20}$ in table 5.3. The energy deposited in each interval is then just $P_{20} \delta t$. The sum over all of the intervals is the total energy deposited ($E_{nt}$), which is $1.51 \times 10^{30}$ ergs.

5.2.3 Plasma Thermal Energy

The procedure used to calculate the total thermal energy contained in the soft X-ray emitting plasma is a variant of that described by Antonucci et al., (1982), and Antonucci et al., (1984), using the loop model described above. The principal differences lie in the treatment of radiative and conductive losses from the upflowing plasma before assimilation into the stationary plasma component at the top of the loop.

The soft X-ray emitting plasma is separated into two distinct components, which are identified with those derived from the fitting process. The first component is composed of stationary isothermal plasma at the loop top, and the second is composed of upflowing plasma. The loop is assumed to be initially empty, gradually filling through the footpoints of cross sectional area $A (= 10^{17}$ cm$^2$). The high velocity component present during the hard X-ray burst is not considered in this analysis.

This is equivalent to the assumption by Antonucci et al., (1982) that the integral of the electron flow through the footpoints is equal to the increase in electron number in the loop during the evaporative phase. The condition that the loop be initially empty is equivalent to the assumption that mass of the evaporated plasma is much greater than that of the pre-existing coronal plasma, which may be subject to in situ heating.

The stationary plasma component is assumed to occupy the whole loop volume ($V$), whilst the upflowing plasma occupies a volume ($V'$), which is related to the upflow velocity ($v'$) given by

\[
V' = \int v' A \, dt
\]

(5.16)
where $\tau$ is the time elapsed since the start of the impulsive phase. The upflow velocity has been corrected for projection onto the line of sight, assuming that the upflow was originally radially directed, by multiplying by a factor of $\cos(\lambda)$ where $\lambda$ is the heliocentric longitude of the flare. For a longitude of 45° this increases the fitted upflow velocities by 1.4. There was an additional boundary constraint placed that $V' \leq V$.

The duration of the evaporation phase, for the purposes of the calculation, was determined by the occurrence of blueshifted plasma in the CaXIX channel. The disappearance of detectable blueshifts was approximately coincident with the peak of the CaXIX light curve, which was taken to delineate the end of the evaporative phase.

The thermal energy in the soft X-ray emitting plasma is the sum of the thermal energy of the stationary component, together with the losses by conduction and radiation from both stationary and upflowing plasma components.

$$E_{SXR} = E_{turb} + E_{therm} + \int_{\tau}^{\infty} (P_r + P_c) \, dt + \int_{\tau}^{\infty} (P'_r + P'_c) \, dt$$

(5.17)

where $P_r$, $P_c$, $P'_r$, and $P'_c$ are the radiative and conductive loss rates from the stationary and upflowing components respectively. The first two terms are,

$$E_{therm} = 3N_e k T_e V$$

(5.18)

$$E_{turb} = \frac{3}{2} m N_e V^2 v_{turb}$$

(5.19)

where $N_e$ is the electron density, $T_e$ is the electron temperature, $m$ is the mass of a proton (with the assumption of a hydrogenic plasma) and $v_{turb}$ is the turbulent velocity,

$$V_{turb} = \left( \frac{2 k (T_i - T_e)}{m_i} \right)^{\frac{1}{2}}$$

(5.20)

where $T_i$ and $m_i$ are the ion temperature derived from the spectral fits and the ion mass respectively.

The thermal and turbulent energies of the stationary component are calculated directly from the fitted parameters. The upflowing plasma temperature and electron densities are not directly determined parameters however, and must be estimated. The upflow electron density is derived from the second component emission measure using equation 5.16. The upflow plasma temperature is calculated by requiring that the increase in the stationary plasma component thermal energy is entirely due to the enthalpy and kinetic energy transported into the loop by the upflowing plasma
during the impulsive phase. This implicitly assumes that there is no in situ heating mechanism active in the loop. Thus for a time interval $\Delta t$

$$\Delta E_{\text{stat}} = 5N_e^l k T_r V'(\Delta t) + \bar{m} N_e^l v^2 V'(\Delta t)$$

(5.21)

where $\bar{m}$ is the average particle mass, and $V'(\Delta t)$ is the volume of material transported into the loop within $\Delta t$, from equation 5.16.

**Loss Mechanisms**

There are two important loss mechanisms. Radiative losses become increasingly dominant as the density increases above $10^{12}$ cm$^{-3}$. For the optically thin part of the solar atmosphere the radiative loss takes the form

$$P_r = N_e^2 Q(T)$$

(5.22)

The radiative loss function $Q(T)$ is a complex function of temperature (Cox and Tucker, 1969; Raymond and Smith, 1977), but can be approximated for temperatures above $10^6$ K (Priest, 1982) by;

$$Q(T) = 10^{-19} T^{-\frac{1}{2}} \text{ (ergs cm}^3\text{) (10}^6\text{ K} < T < 40 \times 10^6 \text{ K})$$

$$Q(T) = 2.5 \times 10^{-27} T^{\frac{1}{2}} \text{ (ergs cm}^3\text{) (40 \times 10^6 \text{ K} < T })$$

(5.23)

Thus for the stationary CaXIX emitting plasma using the first form of 5.23 the radiative loss term can be written as

$$P_r = 10^{-19} T_e^{-\frac{1}{2}} N_e^2 V$$

(5.24)

and correspondingly the loss term from the upflowing plasma as

$$P'_r = 10^{-19} T_e^{-\frac{1}{2}} N_e^l v^2 V'(t)$$

(5.25)

Below densities of $10^{12}$cm$^{-3}$ conduction to the chromosphere dominates as an energy loss mechanism for flare plasmas. The classical Spitzer-Härm conductivity (equation 5.4) for conduction along the magnetic field lines, where the heat flux is proportional to the local temperature gradient, is only valid for temperature gradients much less than the temperature scale height (Karpen and DeVore, 1987). The underlying assumption is that the plasma is thermalised, and that the mean free path of the particles is much less than the temperature scale height.
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The Spitzer-Härm conductivity equation was derived for an infinitesimal heat flow. Application of this equation to large global temperature gradients can produce excessively large, and incorrect values for the conductive flux. Parker, (1964) pointed out that there is in fact an upper bound to the classical heat flux, the free-streaming limit, which is obtained when all the electrons are moving in the direction of the temperature gradient at the electron thermal velocity.

\[
Q_c = \frac{3}{2} N_e k T_e v_{th} \quad (5.26)
\]

\[
v_{th} = \left( \frac{k T_e}{m_e} \right)^{\frac{1}{2}} \quad (5.27)
\]


A smooth transition from classical to saturated regimes in modelling codes is normally achieved by the use of a flux limiting function. Fisher, Canfield and McClymont define the conductive flux as

\[
F_c = \frac{F_{cl}}{1 + F_{cl}/F_{sat}} \quad (5.28)
\]

where \(F_{cl}\) is the classical flux and \(F_{sat}\) is the saturated flux limit,

\[
F_{sat} = \frac{N_e (k T_e)^{\frac{3}{2}}}{4 m_e^{\frac{1}{2}}} \quad (5.29)
\]

Consideration of the saturated flux limit is important for the stability of the superhot plasma component discussed in chapter 6, but as the classically calculated fluxes from both CaXIX emitting plasma components never exceeded 10% of the saturated flux given by equation 5.29, a conductive loss term for the stationary component of the form;

\[
P_c = 8 \times 10^{-6} A T_e^\frac{3}{2} \left[ \frac{T_e}{L} \right] \quad (5.30)
\]

and for the moving component,

\[
P'_c = 2 \times 10^{-6} A T_e^\frac{1}{2} \left[ \frac{T'_e}{L'} \right] \quad (5.31)
\]

\[
L' = \frac{V'(t)}{2A} \quad (5.32)
\]
was used here. As in section 5.2.1 the local temperature gradient has been approximated to the global gradient. \( L' \) is an effective length, and is calculated from the volume occupied by the upflowing plasma at a given time during the impulsive phase (Eqn 5.16).

### 5.2.4 Upflow Plasma Temperatures

Equation 5.21, which is used to derive the upflowing plasma temperatures implies a level of temporal resolution that can be misleading. Differential use of 5.16 together with 5.21 could yield temperatures for the upflowing plasma at the same time resolution as the observations. The minimum time interval required for the equation to be valid is dependent on the loop geometry. The underlying assumption that the increase in the stationary plasma component thermal energy is due to the enthalpy and kinetic energy carried in by the upflowing plasma is only valid for intervals that exceed the ‘absorption time’ of the transported energy into the stationary plasma. The absorption time includes the transit time of the upflowing plasma to reach the stationary plasma, which for uniformly filled loops translates to a characteristic ‘stopping distance’, and the equipartition time for equilibrium to be established between the upflowing material and the existing stationary plasma. The most important term for most cases will be the transit time.

Nonthermal beam models (Dennis, 1988; Reale and Peres, 1995), and observations of impulsive flares (Inda-Koide, 1994) indicate that loops fill from the footpoints, with the gradual generation of a stationary component near the loop top as the flare evolves. Based on this it was assumed that the average transit time for the upflowing plasma before it reaches sufficient density of stationary plasma to halt it will be a simple function of the loop length and upflow velocity. For the current energy balance calculation a transit time of about 60 seconds was used, based on an average upflow velocity throughout the rise phase of about 150-200 km/s. The energy equipartition time for two groups of particles with Maxwellian velocity distributions but differing kinetic temperatures \( T_f \) and \( T \) is given by Spitzer, (1940);

\[
t_{eq} = 5.87 \frac{AA_f}{N_fZ_f^2Z_f^2} \ln \Lambda \left( \frac{T}{A} + \frac{T_f}{A_f} \right)^{\frac{3}{2}} \text{ (sec)}
\]

(5.33)

where \( A, A_f \) are the masses of the particles from each population in a.m.u., \( Z, Z_f \) are the charges, and \( N \) is the number density of the field particles. \( \ln \Lambda \) is the Coulomb
logarithm which is tabulated by Spitzer (1962).

The value of $t_{eq}$ for protons in the flaring loop is $\approx 1$ s and a factor of $\sqrt{A_e/A_p}$ or $1/43$ less for electrons. This is much less than the transit time. The minimum time step for computation of the upflow temperatures in this flare was therefore set to be 60 s.

An average upflow temperature of $13 \times 10^6$ K was also derived by increasing the time step to match the evaporation time. The resultant average upflow temperature of $13 \times 10^6$ K is lower than that of the stationary component. This lower upflow temperature has been calculated in previous treatments where the temperature difference was dismissed as being within the bounds of error (Antonucci et al., 1982). This is quite likely, as a 20% decrease in the upflow velocity is sufficient to raise the derived average upflow temperature from 13 MK to 17 MK.

Uncertainty in the upflow velocities is due to two sources. The first is that although the assumption of radially directed upflows is statistically a good one (Moorthy, 1993), it is difficult without SXT images to discern whether this is true for this particular flaring loop. Since this flare is located at W45, the correction for projection onto the line of sight under the assumption of radial outflows, increases the upflow velocities by a factor 1.4. The second uncertainty over the measured upflow velocity stems from the poor fit of a simple two plasma velocity component model to the Ca XIX resonance line profile early in the impulsive phase.

### 5.2.5 Calculation Results

A program was constructed, based on the equations outlined above, taking as input the results of the spectral fitting shown in figure 5.9. The program calculated the terms in equation 5.17 for the duration of the evaporative phase.

For the stationary plasma component the final value of the thermal energy was $6.13 \times 10^{29}$ ergs. The total losses over the same period from both conduction and radiation were $5.0 \times 10^{29}$ ergs. The total thermal energy in the stationary plasma was $1.1 \times 10^{30}$ ergs. The stationary component thermal energy and losses are shown as a function of time in figure 5.17.

Conductive losses were dominant, accounting for about 42% of the total. The energy in turbulent motions was also calculated and was found to be negligible, accounting for only $9 \times 10^{27}$ ergs, or about 1% of the total. This is a similar result to
Figure 5.17: Stationary component cumulative thermal energy ($E_{th}$). The cumulative losses by conduction ($E_{Con}$) and radiation ($E_{Rad}$) are also shown. Radiation becomes more efficient as the density of plasma in the loop increases. The total thermal energy ($E_{SX}$) in the stationary component as a function of time is also shown.
that found by Antonucci et al., (1982).

The computed cumulative conductive and radiative losses for the moving plasma are shown in figure 5.18, together with the total stationary component thermal energy, and the cumulative sum of the all the terms \( E_{\text{tot}} \). The conductive and radiative energy losses from the moving component were calculated to be \( 3.1 \times 10^{29} \) ergs, and \( 2.8 \times 10^{28} \) ergs respectively. Conductive losses were once again the dominant term.

![Figure 5.18: Upflow component cumulative energy losses. Cumulative losses by conduction \( (E_{\text{Con}}) \) and radiation \( (E_{\text{Rad}}) \) are shown, along with the stationary component thermal energy \( (E_{\text{SXR}}) \). The curve \( E_{\text{tot}} \) is the sum of all terms.](image)

The total thermal energy in soft X-rays at the end of evaporation was \( 1.4 \times 10^{30} \) ergs, of which 22\% was contributed by losses from the moving component. This energy is in agreement with the energy supplied by non-thermal electrons during the impulsive burst \( (1.51 \times 10^{30} \) ergs), and demonstrates energy balance.
5.3 Conclusions

Evidence for a non-thermal beam heated impulsive flare, occurring in a single loop straddling the magnetic neutral line has been presented. A set of physical parameters for the flare loop have been derived from HXT images, and used to construct a realistic bounding volume for the flare, based on a semicircular loop of constant cross-section. This model loop is justified by consideration of the conductive cooling of the stationary plasma, which gives a filling factor of order unity.

Based on this model agreement is found between the energy supplied by non-thermal electrons in the impulsive phase ($1.5 \times 10^{30}$ erg), calculated from power law fits to the HXT, and that contained in the evaporating soft X-ray plasma observed in the CaXIX resonance line by the BCS ($1.4 \times 10^{30}$ erg).

Objections to this type of energy balance calculation have centred around two points (Wu et al., 1986). These are; the determination of the low energy cutoff of the hard X-ray spectrum, which has been criticised as being arbitrary (Simnett, 1986) and the low filling factor found in many SMM flare observations.

The filling factor for this loop is high, which is attributed to the realistic geometry obtained from the HXT images. Previous observations (Acton et al., 1982; Wolfson et al., 1983), have been limited by instrumental resolution and may have overestimated the volume occupied by the flaring plasma. This in turn leads to low filling factors. The problem of the low energy cutoff of the hard X-ray spectrum is more difficult to address, but there is evidence that the cutoff lies within the HXT LO energy band, in agreement with observations of other events.

Blueshifted plasma observed in the CaXIX resonance line is, in qualitative agreement with numerical models of nonthermal beam driven chromospheric evaporation, responsible for the majority of the emission in the earliest stages of the flare. In common with previous SMM observations (Antonucci 1989) there is significant emission at this time at blueshifts corresponding to directed velocities of $10^3$ km/s. As the flare progresses, emission in the CaXIX resonance line is quickly dominated by the stationary component.

HXT images in the LO channel of the HXT demonstrate loop filling by hot plasma during the gradual phase of the flare. Emission starts from plasma located close to the footpoints of the loop, and rises to fill the entire loop. As the gradual phase
light curve declines and the plasma cools, emission concentrates between the two foot­points, probably at the loop top, indicating conductive cooling through the loop foot­points as the dominant energy loss mechanism. This cooling model is independ­ently confirmed by the BCS observations.

In conclusion, the event of 16 December 1991 appears to be a simple impulsive event, adhering closely to the chromospheric evaporation model both morphologi­cally and energetically. It is interesting to find the expected predominance of blueshifted emission in the earliest stages of the flare, but interpretation and fitting of the velocity and temperature structure of this moving plasma poses problems, par­ticularly for the most extreme velocities, and may only be resolved by making model dependent assumptions about the velocity and temperature structure underlying the evaporation (Bornmann and Lemen, 1992).
Chapter 6

Superhot Plasma

The existence of superhot plasma (30-40MK) in some solar flares was first observed by Lin et al., (1981) and was subsequently confirmed by Takakura et al., (1983) and Tanaka, (1986). This superhot plasma is thought to be responsible both for the gradual emission below 40keV and for the FeXXVI line emission observed in these flares (Tanaka et al., 1982; Tanaka, 1987).

Tanaka, (1986) found for a sample of flares that the temperatures derived from FeXXVI spectra increased from 20MK to 31-40MK at the peak of the gradual phase. These temperatures were systematically higher than the temperatures derived from FeXXV spectra by 7-13MK. A second 'low temperature' group of flares with FeXXVI temperatures of between 22-27MK showed deviations from the FeXXV temperatures of less than 4MK. Recent work by Pike et al. (1996), based on a survey of 75 flares with significant FeXXVI emission with the Yohkoh BCS, has shown that there is a more continuous spread of flare types, with the difference between the FeXXV and FeXXVI temperatures being proportional to the temperature in FeXXV, rather than two distinct populations.

Superhot plasma is most often associated with type A compact flares, which show a suppression of the impulsive burst and associated microwaves (Tanaka, 1987). Spatially resolved observations of these types of flare show a compact source (Takakura et al., 1983; Tsuneta et al., 1984) located at the loop top (Kosugi et al., 1994). The loop top position is also required by thermal stability calculations based on observed temperature decay times for the superhot plasma (Tanaka, 1987). It is also thought that the superhot plasma created in these flares is due to the absorption of the flare en-
ergy by a relatively dense ambient plasma, which in most cases may be due to chromo-
mospheric evaporation caused by a prior event in either the same, or an adjacent
closely related loop. (Kosugi et al., 1994; Nitta et al., 1995).

The creation of superhot plasma in type B impulsive flares appears to follow a
different path to that in type A flares. Three flares are presented in this chapter,
two type B and one type A, all of which have a superhot plasma component. The
location, and lifetime of the superhot plasma appears to be different for the type B
flares to that found both for the type A flare studied here, and for other type A events
in the literature.

6.1 16 December 1991

The flare of 16th December 1991 produced significant thermal emission at superhot
temperatures during the gradual phase. This can be seen in the HXT LO channel
lightcurve in figure 5.3. In the BCS this was visible as line emission in the FeXXVI
channel.

During the gradual phase five spectra were recorded in the FeXXVI channel of the
BCS. The sum of these spectra is shown in figure 6.1. There is a significant instru-
mental background contribution, resulting from fluorescence excited by solar hard
X-rays in the germanium crystals which are the dispersive elements in the spectrom-
eter. The asymmetry to the background is a characteristic of the spectrometer geom-
etry. This is a similar spectrum to those observed by SMM (Parmar et al., 1981), and
Hinotori (Tanaka et al., 1982). The germanium fluorescence was subtracted by fit-
ting a straight line to the spectral background.

These spectra were used to calculate temperatures and emission measures for the
superhot plasma component. The spectral features include the two H-like resonance
line components (1s $^2S_{1/2} - 2p^2P$, marked as Ly$\alpha$ on figure 6.1) and the 1s$n_l$ - 2p$n_l$
satellite transitions which are due to dielectronic recombination (marked as 'J'). The
ratio of the main $n = 2$ satellite line intensity to that of the resonance lines is a strong
function of temperature (Dubau et al., 1981; Parmar et al., 1981).

The temperatures derived from this ratio have a peak value at about 40MK co-
temporal with the gradual phase peak in the HXT LO lightcurve, and are shown in
figure 6.2 superimposed on the HXT 14 - 23 keV lightcurve.
Figure 6.1: Integrated FeXXVI spectrum for the flare of 16th December 1991. The background is instrumental in origin. The lines marked as J and Fe II are the FeXXV dielectronic recombination line, and the inner-shell Kβ line (Phillips et al., 1994)
Figure 6.2: Temperatures from FeXXVI Lyα line ratios plotted against the HXT LO channel lightcurve as a reference.
These derived temperatures are comparable with those previously observed for superhot plasma components. The temperatures, and temporal relationship to the impulsive hard X-ray lightcurve bear more similarity to the original superhot event observed by Lin et al., (1981) than to the 'hot thermal' or type A events described by Tanaka (1987), which show suppression of microwave emission and hard X-ray bursts.

![Graph showing temperature and emission measures from thermal fits to the HXT LO and M1 channels, with a HXT LO channel light curve as a reference.](image)

Figure 6.3: Temperatures and emission measures from thermal fits to the HXT LO and M1 channels, with a HXT LO channel light curve as a reference.

Temperatures and emission measures derived from fitting a thermal continuum only model (Mewe et al., 1985) using the RAT2THERM program (which contains the scaling factors for the effective area and response of the HXT; Hudson, 1992) to the ratio of the HXT LO and M1 channel lightcurves during the gradual phase are shown in figure 6.3. These temperatures and emission measures agree quite well with the
Table 6.1: Comparison of BCS FeXXVI temperatures and emission measures with thermal fits to HXT LO and M1 channels.

<table>
<thead>
<tr>
<th>Time (U.T.)</th>
<th>BCS FeXXVI</th>
<th>HXT M1/LO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Te (x10^6K)</td>
<td>EM (cm⁻³)</td>
</tr>
<tr>
<td>04:56:27</td>
<td>37.3</td>
<td>6.0x10⁷</td>
</tr>
<tr>
<td>04:56:57</td>
<td>37.0</td>
<td>1.7x10⁸</td>
</tr>
<tr>
<td>04:57:27</td>
<td>29.6</td>
<td>5.4x10⁸</td>
</tr>
<tr>
<td>04:57:57</td>
<td>23.0</td>
<td>3.0x10⁹</td>
</tr>
<tr>
<td>04:58:27</td>
<td>21.8</td>
<td>3.2x10⁹</td>
</tr>
</tbody>
</table>

For both instruments the superhot temperatures at the peak of the HXT gradual phase are found to be between 30-40 MK with errors of +/- 5 MK. The progressive increase of the FeXXVI emission measure with time is due to either an increase in density or volume of the emitting plasma. As the plasma is cooling at the same time, it is more likely that the plasma is expanding up into the loop. This would be consistent with the observed chromospheric evaporation seen in the early stages of this flare.

6.1.1 Imaging the Superhot component

The morphology and evolution of this event is discussed in chapter 5, using HXT LO band images to trace the evolution of the hot thermal emission. As the MEM code used to deconvolve the images shown in figures 5.11 and 5.13 is flux conserving it is possible to calculate temperatures for specific features in the LO and M1 images by using a thermal model, in a similar way to that used to produce figure 6.3 from the raw lightcurves.

The images are the result of MEM deconvolution, so caution must be exercised in the selection of the regions to be used for temperature determination. The two criteria that must be met for reliable results are that the spatial extent of each region or feature must be larger than the point spread function (PSF) width of the instrument, and that the counts in the region must exceed 10% of the peak value in the image for an average integration time. As the PSF width of the HXT is about 5 arc sec, and the field of view 126 arc sec, the minimum feature size that can be safely used is 3x3 HXT pixels. Temperatures were derived from the ratios of the HXT LO
and M1 channels using the RAT2THERM program as for the whole detector case.

A conservative approach was taken. Three regions were chosen, centred around the north and south footpoints and the middle of the loop. These areas were made as large as possible, with the constraint that each box was separated by at least one PSF width from the adjacent regions. The position and extent of the regions chosen is shown in figure 6.4.

For each M1 band image the flux within each of the three regions was summed. LO band images were then accumulated for the duration of the M1 band image, and the flux in the same image regions totalled. A thermal model was then fit to the ratio of the two channels, giving the average temperature for each region. The results of this calculation are shown in figure 6.5. Error bars are shown for the loop centre points only (triangles), and represent the extremes from a 10% error in the flux.
values in both channels.

Figure 6.5: Temperatures for loop footpoints and centre. Results of HXT thermal fits to the three areas shown in figure 6.4, superimposed on a HXT LO channel light curve for reference. The symbols are; Diamonds – North footpoint, Squares – South footpoint, Triangles – Loop Centre. Error bars are shown for loop centre points only, and correspond to the extrema derived from a 10% error in both channels.

The temperatures in figure 6.5 are calculated for the loop centre box earlier in the progress of the flare than is the case for the loop footpoint temperatures. This delayed start was to ensure that any contamination of the thermal flux with non-thermal emission from the footpoints is avoided. The HI band images clearly show that nonthermal emission is contained within the footpoints, so derivation of loop centre temperatures at these earlier times are probably justified even though the impulsive burst is not quite finished. These early middle loop temperatures show a distinct heating to a peak of around 30MK, then a steady cooling to about 20MK at the end of the LO channel gradual phase.

The heating observed for the centre loop region, together with the rising post-burst light curve, is a signature of chromospheric evaporation. The temperatures
for the footpoints are initially much higher than those in the centre loop region, with values of 40MK during the peak of the gradual phase. These elevated temperatures are maintained in the footpoint boxes for about 30s, after which they join the loop centre temperature profile and cool steadily to 20MK at the end of the gradual phase. This persistent high temperature in the footpoints extends for 40s after the end of the nonthermal burst in the HI channel, which is several times the duration of the burst (FWHM ≈ 10s).

The temperatures derived for the footpoints are the same as those derived from the line ratios in the BCS FeXXVI channel, and show a very similar evolution (figure 6.2). The temperatures from both the HXT footpoint ratios and the FeXXVI channel decay at approximately the same time and rate from 40MK to 20MK.

This leads to the surprising conclusion that the superhot temperature component in this flare is concentrated in the region of footpoints, and hence from the loop geometry, near to the chromosphere. This is unlikely to be an artifact of nonthermal contamination from the impulsive burst, given both the duration of the elevated temperatures, which extend for long past the time the burst subsides, and the similar behaviour of the temperatures from the FeXXVI channel.

This is unusual in that all previous observations locate the superhot plasma at the top of the loop near the primary energy release site (Takakura et al., 1983; Kosugi et al., 1994). It may be that, in view of the timing and evolution of the emission relative to the hard X-ray impulsive burst and the small emission measure derived for this plasma, that the superhot component in this flare is the initial result of violent heating of the chromosphere at the base of the loop.

### 6.1.2 Thermal stability

A superhot plasma situated close to the chromosphere would lose heat by thermal conduction very rapidly. Previous authors have argued that observed lifetimes of superhot plasmas are only consistent with calculated conductive loss rates if the superhot plasma is situated near to the top of the loop, and subject to continued in-situ heating (Tanaka, 1987). This section assesses the thermal stability of the superhot plasma observed in the 16th December event, drawing on the loop model and discussion of loss mechanisms in the previous chapter.

From the analysis of the HXT images described above, it can be seen that the
superhot plasma is confined to the lower parts of the coronal loop. If it is assumed that this material occupies (as an upper limit) the lower half of each leg of the model loop described in section 5.2.1, then the maximum volume would be one half of that for the entire loop, or $1.75 \times 10^{26} \text{ cm}^3$. Thus for an emission measure of $2 \times 10^{48} \text{ cm}^{-3}$ at 04:56:57 UT, the lower limit for the electron density would be $1 \times 10^{11} \text{ cm}^{-3}$. This is comparable to the densities obtained for the CaXIX emitting plasmas in the previous chapter. The thermal energy contained in this material would then be $3 \times 10^{29} \text{ ergs}$.

The superhot plasma has a maximum lifetime of the order of 30 seconds, and would primarily lose energy by thermal conduction to the chromosphere, as was the case for the CaXIX emitting plasma. Application of the classical Spitzer-Härm thermal conductivity equation to this situation, in the same manner as was used for the CaXIX emitting component in the previous chapter (c.f. section 5.2.3 for the discussion of the validity of applying this equation to the CaXIX heat flux), is not correct in this case however, as the calculated heat fluxes would be an order of magnitude above the free-streaming limit (Parker, 1964, Karpen and DeVore, 1987). Instead the saturated flux limit of Smith and Auer, (1980) (see also Fisher, Canfield and McClymont, 1985a), which is one sixth of the free streaming flux limit, was adopted.

\[ F_c = \frac{1}{6} N_e k T_e \left( \frac{k T_e}{m_e} \right)^{1/2} \]  

(6.1)

The upper limit of the loss rate from the very hot material is $2 \times 10^{28} \text{ erg/s}$. Using the estimated energy given above yields a minimum lifetime of 15 seconds. This is within a factor of 2 of the observed temperature decay time for the north footpoint, and approximately equal to that observed for the south footpoint. Any mechanism that acts to inhibit thermal conduction will extend this lifetime and provide closer agreement. Possible mechanisms include hydrodynamically generated plasma turbulence (Bornmann, 1987) and the scattering of outflowing hot electrons by self generated ion-acoustic waves (Brown et al., 1981).

Alternative models for the stability of this very high temperature component require either continual heating after the hard X-ray burst has ended, or the formation of a plasmoid or other magnetic structure which isolates the hot material from conduction to the cooler chromosphere. There is no evidence of continued flare heating in either the lightcurves or in the CaXIX cooling curve (section 5.2.1). In the latter case the hot plasma would have to cool radiatively, which allows an estimate of the
electron density.

Integration of the radiative loss rate in equation 5.24, with the condition of no conductive losses gives a solution for the temperature;

\[ T = \frac{3}{2} \left( \frac{2T_p^3}{3} - \frac{10^{-19}n_e t}{3k} \right)^{\frac{2}{3}} \]  

(6.2)

where \( T_p \) is the peak temperature, and \( n_e \) is the electron density.

From figure 6.2 and table 6.1 the temperature gradient observed in FeXXVI and HXT LO gives an electron density of \( 5 \times 10^{12} \, \text{cm}^{-3} \). Taking the emission measure from the FeXXVI as \( 2 \times 10^{48} \) at 04:57 UT implies a volume occupied by this plasma of \( 8 \times 10^{22} \, \text{cm}^3 \). These values of density and volume are similar to those found by Linford and Wolfson (1988).

Both these scenarios would accommodate the observations, but the simpler explanation of the saturation of the conductive flux is preferred, as it requires electron densities which are similar to those observed in CaXIX, and does not require the simultaneous presence of complex magnetic structures in both legs of the loop to provide thermal isolation. It is also likely that turbulence will play a role in further reducing the conductive heat flux early in the evolution of the flare. This may account for the longer lifetime of the northern footpoint compared to the minimum lifetime for cooling by saturated conduction.

### 6.2 1 April 1992

This event occurred at S09W45 with GOES class M5. The active region that the event occurred in is shown in figure 6.6, which is a full frame SXT image taken about 20 minutes before the flare. The region is dominated by a large cusp shaped loop in the centre of the active region, which remains uniformly bright throughout the pre-flare and postflare phases. The flare occurs in a smaller loop to the south of the large loop. Light curves from each channel of the HXT are shown in figure 6.7, and a sequence of SXT partial frame images showing the evolution of the flare in figure 6.8.

The HXT light curves show that there is a well defined nonthermal burst which has finished by 00:55 UT. In the LO and M1 channels there is a significant gradual component that is thermal in origin. During this flare emission is recorded in the
Figure 6.6: Preflare active region. This image was taken by the SXT through the thin Al filter about 20 minutes before the flare. The region is dominated by several complex magnetic structures. The flare loop is situated to the south of the large cusp shaped loop.
Figure 6.7: HXT light curves for the flare of 1 April 1992. In a similar fashion to the 16 December 1991 flare, there is a very well defined impulsive phase corresponding to nonthermal emission, and a significant gradual phase in the HXT LO and M1 channels, which is thermal in nature.
Figure 6.8: Evolution of the 1 April 1991 flare as seen by the SXT in partial frame mode. Each image is related to the HXT LO band light curve. The emission gradually spreads along an arc as the flare progresses. Each image is scaled to the maximum in that frame.
BCS FeXXVI channel, but the spectra were not of sufficient quality to be used for temperature determination.

The presence of the bright cusp structure in the active region close to the flaring loop appears to have confused the SXT, so there are only 14 images which show the flaring loop itself, and these are all over exposed to some degree. The cusp structure appears to play no part in the flare, maintaining a constant level of brightness throughout the flare, consistent with pre and post flare full frame images.

6.2.1 Superhot Component Location

A similar procedure to that used on the 16th December 1991 flare was used to find the temperatures of the loop footpoints and centre. The regions used to define the loop centre and footpoint for this flare are shown in figure 6.9, superimposed on a HXT LO band image taken at 00:52:46UT.

Figure 6.9: Loop footpoint and centre regions for 1 April 1992. The grayscale image is an HXT LO band image taken at 00:52:46. The contours represent the footpoints of the loop as seen in the HXT M2 channel at 00:51:50UT, and the solid boxes the regions chosen for the loop footpoint and centre. The footpoint contours are 40, 60, 80 and 100% of the peak flux.
The temperatures derived for the south footpoint and the centre of the loop, using the regions determined from the HXT LO band and SXT partial frame images are shown in figure 6.10.

Figure 6.10: Temperatures derived for the south footpoint and loop centre in the 1 April 1992 flare. Symbols are: Triangles – Loop centre, Squares – South footpoint. Error bars are shown for loop centre points only, and correspond to the extrema derived from a 10% error in both channels, as for figure 6.5

It was unclear from the SXT images as to whether the north footpoint was partially obscured by the body of the flaring loop, due to the loop orientation. As it was not possible to maintain a separation of one HXT PSF width between the north footpoint region and the loop centre, temperatures were calculated for the south footpoint only. Figure 6.10 shows a similar evolution of the temperature to the 16 December 1991 flare, with high temperatures ($\approx$ 40MK) maintained in the region of the footpoints for some time after the end of the impulsive burst. After the peak of the gradual phase the footpoint temperatures then drop to the same temperature as the loop centre ($\approx$ 20MK).
6.2.2  Nonthermal Contamination

It can be seen from figure 6.7 that the nonthermal burst in this event is not as well defined as for the 16 December flare. This raises the issue of nonthermal contamination of the LO and M1 images used to calculate the temperatures for the different parts of the loop. The nonthermal burst appears to have finished by 00:54 UT from inspection of the HXT HI and M2 band light curves. However, both these channels are much higher in energy than the two channels used for deriving the footpoint temperatures. In order to assess the possibility of a residual nonthermal contamination of the lower energy HXT channels a spectral diagnostic developed by Gabriel and Phillips, (1979) was used.

This diagnostic relies on the fact that the FeXXV dielectronic satellite lines \( j \left( 1s^2 \, 1S + e \longleftrightarrow 1s2p^2 \, 2D_{5/2} \right) \) and \( d13 \left( 1s^2 \, 1S + e \longleftrightarrow 1s2p3p \, 2D_{5/2} \right) \) are excited by electron collisions in a narrow range of energies (less than the autoionization width \( 10^{-4} \) keV for each satellite). The ratio of these two satellite lines is temperature sensitive, as is the ratio of each to the resonance line \( \left( 'w', 1s^2 \, 1S + e \rightarrow 1s2p \, 1P + e \right) \). The resonance line however is excited by collisions with any electron having an energy above 6.701 keV. If the plasma is strictly Maxwellian in its energy distribution, the ratios of each of the dielectronic satellite lines to each other and to the resonance line should provide the same temperature. If there is a high energy tail to the electron population caused by the presence of a second nonthermal distribution of electrons at energies > 6.701 keV, then the temperatures derived from the ratio of the dielectronic satellites to each other will be different from that derived from the ratio of one of the satellites to the resonance line. There is an implicit assumption that the nonthermal energy distribution does not extend down to the excitation energies of the two satellite lines \( j=4.69 \text{ keV, } 1.8657 \AA; d13=5.81 \text{ keV, } 1.8526 \AA \). If there were a significant non-Maxwellian distribution extending down to these energies or below, then the temperatures from the ratios of the two dielectronic satellites would be affected. The dielectronic lines should (given a reasonable nonthermal distribution), be affected to a lesser degree than would be the case for the resonance line, due to the differing processes of formation. Given that most reported low energy spectral cutoffs are in the range from 5 keV upwards, it is unlikely that the other ions observed by the BCS would be affected.

Gabriel and Phillips, (1979) tabulate the ratios \( I_j/I_{d13}, I_j/I_w \) and \( I_{d13}/I_w \) as a
function of temperature. We can define a measure of the deviation from a purely thermal distribution \((D_{nt})\) as a simple ratio;

\[
D_{nt} = \frac{(I_{lw})_{\text{thermal}}}{(I_{lw})_{\text{observed}}}
\]  

(6.3)

Where the ratio \((I_{lw})_{\text{thermal}}\) is provided from extrapolating the observed \(j\) to \(d13\) line ratio (which measures only the thermal population) to that expected from the \(j\) to \(w\) line ratio, if there were no nonthermal contribution to the \(w\) line. As the relative proportion of nonthermal electrons increases, so the intensity of the \(w\) line increases in excess of that expected for the observed plasma temperature. A value of \(D_{nt} = 1\) indicates that the plasma is purely thermal, with positive values indicating an increasing departure from a Maxwellian distribution.

A program was written which calculated the intensities of the three lines by means of a simple parametric fit. This was justified, as the \(w\) line intensity \((I_w)\) used by Gabriel and Phillips, (1979) to calculate the ratios includes the contribution from all unresolved satellites within 0.001 Å of \(w\). The parametric fit to \(d13\) includes a substantial contribution from the \(d15\) satellite line at 1.8518 Å. The intensity of \(d13\) was estimated by using the satellite dependent \(F_2(s)\) terms tabulated by Phillips, (1993) to derive a correction factor. The correction factor included all strong satellites within 0.001 Å of 1.8526 Å. The results for this flare are shown in figure 6.11. The use of this program is complicated by the presence of large blueshifts. Application of this diagnostic to the flare of 16th December was unsuccessful for this reason.

The values of \(D_{nt}\) in figure 6.11 clearly show the presence of the nonthermal electron population during the burst, as compared with the M2 channel. This lends support to the conclusion based on the shape of the lightcurve alone, that the nonthermal burst has finished by 00:54 UT. Thus the elevated footpoint temperatures shown in figure 6.10 are unlikely to be the result of any nonthermal contamination of the footpoint region, compared to the purely thermal signal from the loop centre.

### 6.3 6 February 1992

This flare occurred at 03:20 UT at N05W82 on the solar limb. The flare was a hot thermal event, and was studied by Kosugi et al., (1994) using the HXT and SXT and
Figure 6.11: Departure from thermal distribution ($D_{nt}$) for flare of 1 April 1992. HXT LO and M2 band lightcurves are plotted as a reference. Deviations of greater than 1 indicate the presence of a nonthermal electron population.
by Sterling (1994) using the BCS. This event was chosen as it represents the 'traditional' superhot flare, to act as a control for the temperature determination method used in the two events described above.

The flare is closely related to a previous event which happened at 03:10UT, and which displayed strong microwave and hard X-ray emission, characteristic of a type B event. The main event, which is of interest here, occurred at 03:20UT in an adjacent loop to the north of the first flare. The HXT flare lightcurves are shown in figure 6.12, and show very little hard X-ray emission. The 17 GHz microwave emission recorded at Nobeyama is also very weak. During the peak of flare the BCS FeXXVI channel recorded a spectrum which became strong enough to derive a temperature of 30-40MK between 03:20UT and the time the instrument saturated (∼ 03:23UT).

![HXT lightcurves for 6th February 1992](image)

Figure 6.12: HXT lightcurves for 6th February 1992. The HI band is not shown, as the signal is non-existent at energies of > 50keV. There is little evidence of any impulsive burst.

The evolution of the flare is shown by several SXT partial frame images in fig-
6.4. **CONCLUSION**

Figure 6.13. The SXT images show a relatively uniformly bright loop throughout the duration of the flare. The remnants of the previous flare in the southern loop can also be seen gradually decreasing in intensity with time. HXT images in the M1 and M2 channels show a source which starts at the top of the loop then expands downwards during the early part of the flare (Kosugi et al., 1994), eventually occupying most of the loop by 03:25UT. A LO band image taken at 03:23 UT is shown in figure 6.14, along with the regions defining the footpoints and loop centre for this flare. The same loop asymmetry seen in the SXT images is visible, although the distribution of intensity through the loop is different, indicating that cooler plasma (visible in the SXT) is predominantly in the northern footpoint area, and that the hotter material (visible in the HXT LO band) is primarily at the loop top.

Temperatures derived for each of the regions in figure 6.14 are shown in figure 6.15. As expected from the HXT images, the temperatures for all three regions are similar. Each region has a temperature of between 30-35MK throughout the flare, with a very slight drop of mean temperature with time. The loop top location of the superhot component, derived using ratios of selected portions of the HXT images for this flare, is consistent with the conclusions of Kosugi et al., (1994). This provides a consistency check on the method used for the previous two events.

6.4 Conclusion

Analysis of the HXT images for both the 16th December 1991 and 1st April 1992 events has shown that superhot plasma at $\approx 30-40$MK is concentrated near the footpoints and not at the loop top where the plasma is much cooler (20MK). The superhot plasma loses energy on a timescale consistent with saturated thermal conduction, and appears to be related to the chromospheric evaporation process in an intimate way, given the position and temporal relationship to the non-thermal burst.

Tanaka (1987) notes that flares rich in the superhot component show a suppression of the impulsive burst and associated microwave emission. In Tanaka's classification scheme these are called Hot Thermal (type A) flares. The superhot component for these type A events is thought to be located at the loop top, and this is confirmed by observation.

Impulsive (type B) flares can also generate a superhot plasma component how-
Figure 6.13: SXT PFI for the flare of 6th February 1992. Each image is related to the HXT LO band lightcurve. Each PFI is 150'' x 150''. The flaring loop is the uppermost one in the images. The loop to the south gradually cools during the peak of the flare. The images were taken with the thin aluminium filter.
Figure 6.14: Loop Footpoint and Centre regions for 6th Feb. 1992. The grayscale image is a LO band image taken at 03:23 UT. The solid lines show the extent of the boxes used for calculating the temperature of the footpoints and the loop centre.
Figure 6.15: Temperatures for loop footpoints and centre for the flare of 06 Feb 1992. Res­ults of HXT thermal fits to the three areas shown in figure 6.14, superimposed on a HXT LO channel light curve for reference. The symbols are; Diamonds – North footpoint, Squares – South footpoint, Triangles – Loop Centre.
ever, and may show shorter cooling times for this component than the Hot Thermal type. Impulsive flares show a temporal relationship between the appearance of the superhot plasma and the impulsive burst, with the peak emission from superhot plasma occurring soon after the end of the impulsive burst, followed by a rapid temperature decay. Both type B events presented in this chapter have a similar temporal relationship between the impulsive burst, and the occurrence of a superhot plasma component to other observations of impulsive superhot flares (Lin et al., 1981).

It is therefore reasonable to make a distinction between the superhot plasma components generated in each of these flare types, based on the inferred differences in energy transport for each type. The dominant characteristic of type B flares is the occurrence of microwave emission and a hard X-ray burst, indicating particle acceleration processes. In many of these events the presence of soft X-ray blueshifts indicates that chromospheric heating and evaporation is also an active process. Type A events show an absence of these indicators of particle acceleration, implying in situ coronal heating.

The second distinguishing characteristic is the relative lifetimes of the superhot plasma components in each flare type. The superhot plasma component generated by impulsive flares is located at the base of the flare loop, near to the chromosphere, where it rapidly cools by (often saturated) thermal conduction. The close relationship to chromospheric evaporation would also explain the increase in emission measure of the superhot component with time deduced from the FeXXVI spectra. The lifetimes of these components are short, on the order of a few minutes. The superhot plasma component generated by type A flares is the result of continued in situ heating, and can last for a relatively extended period of time (Tanaka, 1987).

It is suggested that the superhot plasma observed in the flares of 16th December 1991 and 1st April 1992, and possibly in some others of the Impulsive type, is a direct result of the heating of the plasma ablated off during the chromospheric evaporation process. This is a different process to that which creates the superhot plasma in type A flares, which have provided the bulk of the spatially resolved observations of this component in the past.
Summary and Further Work

Fixed Pattern Noise in Yohkoh/BCS

The numerical model of the BCS Fixed Pattern Noise described in chapter four successfully predicts the expected flat field position spectrum produced by the detector for a wide range of input energy distributions. The model has been applied to the task of correcting flight data by incorporating the relevant detector effects as a series of perturbations to an average pulse height distribution. The average pulse height distribution for each channel was in turn empirically derived from flight and calibration data. The model is presently in use as part of the BCS data reduction pipeline software, being used to correct the spectral data prior to analysis. For the BCS the use of Night-Mode data, gathered periodically, will allow a long term check on the stability and accuracy of the average pulse height distribution, and allow any drifting of the detector parameters with time to be accounted for.

The logical extension of the fixed pattern model is to new detectors. Handling data in digital form from position sensitive detectors has great advantages, provided that the problems inherent in digital division are understood. Modelling of the digitisation process can help in reducing the impact of fixed pattern noise by allowing the easy evaluation of a given lookup table. Modelling of this sort can also assist in the evaluation of alternative schemes designed to reduce the impact of digital division errors.

Flare of 16 December 1991

Chromospheric evaporation appears to be an active process in most type B impulsive flares. The improved energy balance calculation presented in chapter five provides support for the nonthermal electron beam driven evaporation model. Close agree-
ment is found between the energy contained in the nonthermal electron beam, and that in the ablated soft X-ray plasma. The higher spatial resolution of the data used, which allowed more accurate estimate of the soft X-ray flare bounding volume, together with a more careful treatment of the upflowing plasma, yields a result which strongly supports the nonthermal beam hypothesis, and addresses several of the criticisms that have been levelled at this type of calculation in the past. There is scope for further improvement however. The analysis of the soft X-ray blueshifts could be improved by using the Velocity Differential Emission Measure (VDEM) of Newton et al., (1996). This would allow a more accurate treatment both of the detailed structure and evolution of high velocity upflows for each ion species, as well as of the mass and kinetic energy injected into the loop as a function of time. The increased accuracy of this technique, which is based on sounder physical principles than the rather arbitrary method of fitting a single average blueshifted component, should allow further refinement of the energy balance calculation. Use of VDEM will also eliminate the obvious inconsistencies seen between the real data and the fitted profiles in figure 5.8, leading to greater confidence in the values of the other fitted parameters.

The 16th December 1991 flare is not a typical flare. Although the nonthermal beam model is successful at describing this particular event, it is less successful for the majority of solar flares. Recent models of flare energy transport adopt a hybrid approach, with a combination of a nonthermal beam and thermal conduction driven evaporation. Extending energy and momentum balance calculations to include these different energy transport mechanisms would offer a quantitative observational test of the predictions of the new models.

Superhot Plasma

Impulsive flares which generate superhot plasma are few in number. Observations prior to Yohkoh were either spatially unresolved, or of type A hot thermal flares only. The flares analysed in chapter six seem to suggest that superhot plasma is generated in different locations, and by different mechanisms, depending on the type of flare. The relationship to the impulsive burst, and the location and lifetime of the superhot component in impulsive flares all strongly suggest that superhot plasma may be created by the same energy transport mechanism that drives the chromospheric
evaporation process.

The work in chapter six can be extended to a larger sample of both type A and type B flares with superhot components. Study of these extreme events with multiple instruments may provide useful clues about the different energy release processes active in each type of event. Evidence from combined studies of HXR footpoint motion seen by the HXT together with magnetogram and radio data by Sakao (1996) seems to imply a difference in the pattern of energy release for events occurring in each of the two major classes of flaring magnetic field geometry (The “Emerging Flux” and “Filament Lift-off” configurations). The generation of superhot plasmas may well provide a useful probe into how the morphology of the magnetic field affects flare energy release. The flares studied in chapter six, although a limited sample, do in fact separate into two distinct classes according to their magnetic field configuration, with the Type B Impulsive events being of the “Emerging Flux” type, and the Type A Hot thermal event being of the “Masuda” or “Filament Lift-off” type. Investigation of this relationship should produce clues to some of the fundamental differences between flare types. The database provided by the Yohkoh mission should be a rich source of candidate events for this type of study, particularly in conjunction with data from other space and ground based instruments.

The nonthermal electron energy diagnostic described in chapter 6 also offers possibilities for further development. Extension of the fitting method to cover more of the dielectronic satellite lines, by using a limited spectral synthesis technique will be considered as a method of improving the quality and reliability of the fitting process. Such a spectral synthesis approach could be applied separately to the resonance line (and perhaps other similar collisionally excited lines) and to the set of dielectronic lines, to yield even more robust estimates of the value of \( D_{nt} \) for a given spectrum. Such improved estimates would be invaluable as a guide to the validity of the temperature maps synthesised from the HXT images, as well as providing a useful check on the reliability of the plasma parameters (principally temperature) derived for the Iron channels by the standard fitting programs.

Finally the creation and thermal stability of superhot plasma at such low altitudes in the corona places severe constraints on flare models. Modelling such an extreme phenomenon should also act as a good test for numerical simulations.
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