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Nonthermal Hard X-ray Flux Saturation in Solar Flares

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ABSTRACT

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We use the unprecedented spectral and spatial resolution of RHESSI to explore the behavior of electrons and their associated currents in solar flares. Spectral images are used to determine an estimate of the effective surface area for the different independent substructures within each event. The incident electron spectra at those flaring footpoints are derived from the RHESSI photon spectra. We find that, over a wide range of flare X-ray magnitudes, the integrated photon flux above 20 keV asymptotically approaches a limiting value, suggesting a saturation of the photon production in flares. The inferred particle fluxes in the beam, together with this saturation limit, are used to determine the energy loss mechanism dominating the energetic particle transport in solar flares.
Acknowledgments

To my father Georges and my mother Josephine, my true guardian angels: you have managed to raise me in a war shattered country and severe social conditions, and made me what I am now. You have deprived yourselves from most if not everything and just focused all your time, energy and dreams on being perfect parents, I love you.

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Chapter 1
Introduction

1.1 History of Observations

The first recorded observation of the solar flare phenomenon was independently made by R.C. Carrington and R. Hodgson on September 1st, 1859. An intense brightening at a number of locations in a complex sunspot group that lasted a few minutes was witnessed while they were engaged in a routine survey of sunspots on the solar disk. This, as it turned out, was an example of a rare event called a white-light flare, where the optical continuum is enhanced considerably over the photospheric background. Over the subsequent century, flares were systematically studied with Hα observations at 6563Å, defining the flare phenomenon as a chromospheric manifestation. The Hα data led to general conclusions about the characteristic of flares (e.g. size, shape, lifetime, intensity).

In the 1960s and 1970s, with the introduction of spacecraft observations, our understanding of solar flares increased rapidly. Flares were observed over the entire detectable electromagnetic spectrum, from radio emission to γ-rays in excess of 100 MeV. Nearly all flares were found to occur in active regions with sunspots, with the frequency of flare occurrence increasing with the magnetic complexity of the sunspot group (Bell and Glazer, 1959; Dodson-Prince and Hedeman, 1970). This observation pointed to the importance of magnetic fields in the flare process. Solar magnetographs
helped compare flare positions with pre-existing magnetic structures (Bumba, 1958; Severny, 1958; Martres, 1966) with the result that flares were normally not found above the spot umbrae where fields are the strongest but in the surrounding penumbral regions (Švetska, 1961). In the 1960s, the Orbiting Solar Observatory (OSO) series of satellites allowed solar researchers to study for the first time detailed characteristics of flares at wavelengths inaccessible to ground-based observatories. In subsequent decades, a fleet of spacecraft have contributed significantly to our knowledge of solar flares e.g. NASA’s Skylab Apollo Telescope Mount (ATM, 1973), the International Sun-Earth Explorer 3 (1978), NASA’s Solar Maximum Mission (SMM, 1980), the Japanese Hinotori spacecraft (1981) and, more recently, a set of solar instruments helped collect a huge amount of solar data of which the Geostationary Operational Environmental Satellites (GOES, 1980), the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX, 1992), YOHKOH solar observatory (1991), the Solar and Heliospheric Observatory (SOHO, 1995), the Transition Region and Coronal Explorer (TRACE, 1997), and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI, 2002).

1.2 An Overview of Solar Flares

Solar flares are unquestionably associated with the rapid release of stored magnetic energy in the solar atmosphere (see Section 1.2.3). A large flare can release up to $10^{32}$ ergs of energy in a few minutes, over an area of $10^{18}$ cm$^2$ (roughly 190
arcsec$^2$ when viewed from Earth). Although this is an impressive amount of energy, it corresponds to only one-fortieth of a second of the normal solar radiative output, so that bolometrically, the contribution of solar flares to the total luminosity of the Sun is insignificant and so far unobservable. Solar flares are not as energetic as their stellar counterparts whose occurrences do show up in the light curves of the star (van den Oord, 1987). The energy available for release in a solar flare is stored in the stressed magnetic field of active regions. The stressed magnetic fields, detected as shear structures in the solar atmosphere, are evident for hours to days prior to the actual release of energy (Parker, 1975). It is not yet clear whether this shearing occurs as a result of photospheric motions on pre-existing unstressed fields or as the emergence of already stressed field from below the surface (Leka et al, 1996; Schmelz and Brown, 1992).

The basic building block for a flare model is an isolated magnetic flux tube rooted (line-tied) in the photosphere and extending into the corona. Flare modeling typically proceeds by one of two paths. In the direct, or forward-fitting approach, a pre-flare magnetic field plasma configuration is adopted and the physical equations governing particle production, particle transport and heating are solved to predict the subsequent evolution of the configuration following the initial energy release in the solar atmosphere. By contrast, inverse modeling attempts to infer details of the energy release process via relationships between flare observations at different wavelengths
and times. A combination of these techniques allows us to infer much about the physics of the flare phenomenon from the various radiative emissions which result as a by-product of the initial energy release.

![Diagram](image)

**Figure 1.1** Schematic drawing of radio and hard X-ray sources in a magnetic loop trapping energetic electrons (Aschwanden, Benz and Kane, 1990)
In fact, once the energy has been released, it is transported throughout the flare atmosphere to produce enhanced temperatures in both the corona and the chromosphere, and in turn, enhanced radiation signatures across the electromagnetic spectrum (Figure 1.1). Various mechanisms have been proposed to explain this transport of energy such as the propagation of accelerated nonthermal electrons and the diffusion of heat from the region of primary energy release.

In the study presented here, we focus on the specific problem of whether accelerated particle beams are physically capable of producing the detailed characteristics of the observed hard X-ray fluxes (Emslie, 1978). We analyze X-ray spectral images generated near the peak of hard X-ray flare, over a wide range of solar flare magnitudes, in order to understand the spectral and spatial properties of the hard X-ray emission and what they infer about the physics behind the original particle production and acceleration. We will explore the substructure in flares and inspect the stability of the down-flowing electron beam to understand whether Coulomb collisions, return currents, or both dominate the electron energy losses in the flaring solar atmosphere.

1.2.1 Flare X-ray Emission and Classifications

Flares produce enhanced emission across most of the electromagnetic spectrum. In this study, we are interested in analyzing X-ray emission from a number of solar flares observed by the RHESSI spacecraft (see Chapter 2). The X-ray emission is typically qualified as hard in the energy range 10-300 keV and soft below this range.
Figure 1.2  Lightcurve for the flare of July 17 2002 showing the pre-flare, impulsive and gradual phases (Solarsoft)
The time evolution of solar flares can essentially be described by three phases:

a. The pre-flare phase: this is a gradual brightening in soft X-rays, Hα and cm radio waves which lasts a few tens of minutes.

b. The impulsive phase: typically lasting less than 5 minutes during which the rate of energy release is maximal and the most energetic photons are observed. In our study, we select observing times for flares coinciding with this phase, where we find the peak of the measured hard X-ray flux (see Figure 1.2).

c. The gradual phase: can last tens of minutes with most of the energy being radiated as soft X-rays with a thermal (Maxwell-Boltzmann) profile.

Hard X-ray photons are produced via the Bremsstrahlung process when the accelerated electrons collisionally interact with ambient protons, predominantly in the chromosphere. The resulting hard X-rays are the direct signature of the impulsive phase of a flare. The first hard X-ray emissions from the Sun were detected by Peterson and Winckler (1959), in the range of 20-500 keV, using a balloon experiment. The observed hard X-ray emission was attributed to Bremsstrahlung emission of 0.05-1 MeV electrons stopping in the photosphere. Afterwards, many experiments measured spatially averaged hard X-ray spectra from solar flares and the general trend was that the energy spectra were consistently found to have a power law form, viz,

\[ I(\varepsilon) = A\varepsilon^{-\gamma} \text{ photons.cm}^{-2}.s^{-1}.keV^{-1}, \]  

(1.1)
where $\varepsilon$ is the photon energy and $\gamma$ is the spectral index (Kane, 1969; Frost, 1969). Generally $\gamma$ ranges between 2 and 8 (Dennis, 1988; Dulk, 1992). Frequently, a spectral break was observed at energies higher than 60 keV (Frost, 1969; Kane and Anderson, 1970; Frost and Dennis, 1971; Lin and Schwartz, 1981) and the energy spectra could be fitted with a double power law

\[
I(\varepsilon) = \begin{cases} 
A\varepsilon^{-\gamma_1} & \text{if } \varepsilon \leq \varepsilon_0 \\
A_0\varepsilon^{-\gamma_2} & \text{if } \varepsilon > \varepsilon_0 
\end{cases}
\]  

(1.2)

where $\varepsilon_0$ is the break energy and $A$ is a constant.

Flare soft X-ray emission spans the wavelength range of 1-10\AA, and contains a substantial fraction of the total radiated energy (Canfield, 1978). The electrons responsible for exciting both lines and continuum are generally thermal electrons with a temperature around $10^7$ K. Such temperatures are typically found in the coronal portion of the flaring structure; hence, soft X-rays are a particularly valuable tool for understanding flaring atmospheric conditions like temperature, density and velocity distributions.

Comparing flares of different sizes is complicated by the fact that emission at different wavelengths is not always proportional for different flares. However, some general characteristics can be found, and several classification schemes have been adopted. The objective of a flare classification is to categorize the various manifestations over a large dynamic range, in order to gain insight into the key physics of processes governing these transient phenomena. Solar flares are classified by importance mainly in
the optical, X-ray and radio regions of the electromagnetic spectrum.

The visible light classification uses the flare projected area in terms of the unit heliographic square degree at the center of the disk during the time of maximum brightness of the flare, where 1 square degree is equivalent to $1.476 \times 10^8$ km$^2$. Size classification alone, however, ignores the brightness of the flare. Therefore, a dual form for brightness and surface importance classification was adopted (IAU, 1966). This classification consists of a letter and a number, with the number describing the size of the area and the letter indicating whether the flare intensity is faint (f), normal (n) or brilliant (b). Table 1.1 shows the dual form for this classification.

<table>
<thead>
<tr>
<th>Corrected Area</th>
<th>Relative Intensity Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Degrees</td>
<td>Millionth of Hemisphere</td>
</tr>
<tr>
<td>&lt;2.06</td>
<td>&lt;100</td>
</tr>
<tr>
<td>2.06-5.15</td>
<td>100-250</td>
</tr>
<tr>
<td>5.15-12.4</td>
<td>250-600</td>
</tr>
<tr>
<td>12.4-24.7</td>
<td>600-1200</td>
</tr>
<tr>
<td>&gt;24.7</td>
<td>&gt;1200</td>
</tr>
</tbody>
</table>

Table 1.1  Hα flare classification scheme (Zirin, 1988)

The simplest and most commonly used classification is based on the global output of soft X-ray photons during a flare. This is usually provided by the Geostationary Operational Environmental Satellites (GOES), operated by the National Oceanic and Atmospheric Administration (NOAA). The GOES satellites are more commonly known for their weather and climate observations but they also have instruments to
Figure 1.3  GOES plot for the X 4.8 flare of 07/23/2002 (SolarSoft)

detect photons and particles from the sun. The X-ray Sensor (XRS), on board GOES, gives real time measurements of the solar X-ray emission in two channels, covering the X-ray ranges 0.5-3Å and 1-8Å (see Figure 1.3). The flare classification uses the 1-8Å data. Depending on the measured X-ray flux, flares are classified on a decadal scale as B, C, M or X according to the maximum measured flux at the Earth. These letters represent the order of magnitude of the X-ray flux as described in Table 1.2, and an associated numerical value indicates the multiple of the order of magnitude (e.g. an M4 flare is equivalent to a flare of 4x10^{-2} erg cm^{-2} s^{-1} maximum flux).

X-ray signatures were used to classify flares in ways that reveal certain aspects of the physics involved in the phenomenon. Time profiles of the flare emission at several frequencies (energies) enable us to divide flares into impulsive or gradual events and
<table>
<thead>
<tr>
<th>GOES Class</th>
<th>Intensity erg cm(^{-2}) s(^{-1})</th>
</tr>
</thead>
<tbody>
<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>
</tr>
</tbody>
</table>

Table 1.2  GOES Soft X-ray Flare Classification (Tandberg-Hanssen and Emslie, 1988)

into flares with hard and/or soft X-ray spectra. Pallavicini (1977) used Skylab data to study soft X-rays and classified them into compact flare loops, point-like flares and large diffuse flare loop systems.

Hard X-rays were classified by Tanaka (1983) into three categories, viz.

Type A: thermal flares, where very hot plasma (\(\approx 10^7\) K) produces a smoothly varying thermal X-ray emission. These tend to be small flares (\(\approx 5000\) km long loops) occurring at low altitude.

Type B: impulsive flares with plasma confined in long (>10\(^4\) km) sheared loops producing impulsive spikes or bursts in the X-ray time profile.

Type C: gradual flares occurring at high altitudes (\(\approx 5 \times 10^4\) km), whose plasma produces smooth long-duration X-ray profiles. The X-ray spectrum gradually hardens than softens again with time.

Types B and C are generally considered nonthermal X-ray sources with the particles responsible for emission being part of an accelerated population.
1.2.2 Flare Structure

Figure 1.4 Particle acceleration beneath the reconnection point and precipitation into the footpoints where hard X-ray emission occurs (Aschwanden, 1997)

In the simple loop model of a solar flare, free magnetic energy is dissipated in the current carrying loop by means of some undefined dissipation process (e.g. ohmic losses, wave-particle interaction), probably in the corona, where ambient densities are low and particle acceleration is likely to be most efficient. As a result, plasma is
heated to a high temperature, possibly in excess of $10^8$ K, and electrons and protons are accelerated to very high energies (>100MeV). Once accelerated, those energetic particles will travel along field lines and reach the loop footpoints in the solar chromosphere, producing hard X-ray and sometimes γ-ray emission (Figure 1.4).

Figure 1.5  Trace satellite image in 171Å showing arcade of post-flare loops in the X 28 mega-flare of November 4, 2003 (www.lmsal.com)

A compact flare takes place in a small loop structure in the lower corona, and the flare emission is largely confined to the plasma in the loop where it eventually dies away due to energy loss processes like radiation and conduction. On the other hand, the triggering seems to be similar to that of large flares, namely due to a large
scale eruption and reconnection of sheared magnetic fields (Sturrock, 1984; Machado, 1988).

By contrast, a two ribbon flare is mainly associated with an erupting prominence/filament, and the flare emission occurs in an arcade of post-flare loops along the prominence with the individual loop oriented more or less perpendicular to the long axis of the prominence (Figure 1.5). Emission also occurs at the feet of the loops, hence forming two ribbons on either side of the prominence. These ribbons of emission move apart as the flare progresses with larger and higher loops continuing to bridge them. The erupting prominence may eventually be confined or break away. In the latter case, we may witness what is known as a Coronal Mass Ejection (CME).

1.2.3 Energy Storage and Release

The energetic output of a flare ($\sim 10^{32}$ ergs over a period of tens of minutes) provides an effective first order constraint on the possible source of the released energy.

If we consider that coronal thermal energy above an active region is approximated by

$$E_{th} = 3nk_BT V,$$  \hspace{1cm} (1.3)

where for the corona, plasma density is around $n \approx 10^9$ cm$^{-3}$, a typical active region volume is $V \approx 10^{27-30}$ cm$^3$, and temperature $T \approx 3 \times 10^6$ K, we find $E_{th} \approx 10^{27-30}$ ergs, which is obviously several orders of magnitude lower than the observed energy release in a flare.
Similarly, for a coronal loop, the gravitational potential energy is given by

\[ E_{\text{grav}} = 3\rho ghV \simeq 10^{28}\text{ergs}, \tag{1.4} \]

which is a similar value to the thermal calculation and not sufficient to provide the energy output observed in a flare.

The only plausible source of energy for a flare is the magnetic energy available in the solar corona. In fact, for a field \( B = 10^{2-3} \text{G} \), the magnetic energy stored is

\[ E_{\text{mag}} \simeq B^2V/8\pi \simeq 10^{30-35}\text{ergs}, \tag{1.5} \]

which is sufficient to account for the flare observed energy. However, not all of this energy can be freely released. Since the ground state of magnetic fields is the potential or current-free state, only energy in excess of this state is free. Therefore, flares should occur in regions of non-potential field, where there are currents or where magnetic shear occurs.

### 1.3 Theoretical Hard X-ray Spectral Profiles

Hard X-ray emission in solar flares is produced in the energy range 10-300 keV. In the solar atmosphere, these photons are most likely produced by Bremsstrahlung between accelerated electrons and ambient ions. In this case, classical electrodynamics (Jackson, 1962) predicts that an accelerated electron will emit radiation throughout its acceleration, and Kramers (1923) derived an expression for the radiation rate in free-free transitions as a function of the acceleration of the electron. Billings
(1966) gave an expression for the electric field generated at a large distance \( r \) from an accelerated electron, namely,
\[
E = \frac{e \sin \alpha \, dv}{c^2 r \, dt}
\]  
(1.6)

where \( \alpha \) is the angle between the direction of the acceleration, \( dv/dt \), and initial direction of the electron. Now, the Poynting flux in the radiation is
\[
S = \frac{cE^2}{8\pi} + \frac{cB^2}{8\pi} = \frac{cE^2}{4\pi} = \frac{e^2 \sin^2 \alpha}{4\pi c^3 r^2} \left( \frac{dv}{dt} \right)^2
\]  
(1.7)

The rate of emission, or power, is found by integrating over a spherical surface \( \Sigma \) to give
\[
P = \int Sd\Sigma = \frac{2e^2}{3c^3} \left( \frac{dv}{dt} \right)^2 \text{ erg.s}^{-1}
\]  
(1.8)

Cross-sections for the Bremsstrahlung process were tabulated by Koch and Motz (1959). A convenient formula to use is the nonrelativistic, direction-integrated, Bethe-Heitler cross-section
\[
\sigma_B(\varepsilon, E) = \frac{7.9 \times 10^{-25} Z^2}{\varepsilon E} \ln \frac{1 + \left(1 - \frac{\varepsilon}{\varepsilon_0}\right)^{\frac{1}{2}}}{1 - \left(1 - \frac{\varepsilon}{\varepsilon_0}\right)^{\frac{1}{2}}} \text{ cm}^2.\text{keV}^{-1},
\]  
(1.9)

where \( \varepsilon \) is the photon energy of interest, \( E \) is the energy of the photon producing electron and the factor \( Z^2 \), the abundance weighted value of \( Z^2 \), is approximately 1.4 for solar conditions, \( Z \) being the atomic number of the scattering ion (Allen, 1973; Emslie, 1986a).

When the electrons have energies much larger than the mean thermal background energy of the plasma, we call this nonthermal Bremsstrahlung. On the other hand,
when the electrons are part of the distribution of a population of energetic electrons, we get *thermal Bremsstrahlung*.

### 1.3.1 Nonthermal Bremsstrahlung

The object is to calculate the hard X-ray Bremsstrahlung flux $I(\varepsilon)$ observed at the Earth in photons.cm$^{-2}$.s$^{-1}$.keV$^{-1}$.cm$^{-2}$, resulting from the injection of a beam of suprathermal energetic electrons with a differential energy spectrum $F(E_0)$ in electrons.cm$^{-2}$.s$^{-1}$.keV$^{-1}$, interacting with the ambient plasma over some flare area $S$. The emission is usually considered to be of two types, thin-target and thick-target (Brown, 1971). In the first case, no change to the injected spectrum occurs and the electrons lose very little energy per interaction. In the second case, all of the electrons are completely stopped, that is, thermalized in the target plasma. This may be due to Coulomb collisions of the electron with ambient electrons, or collective interaction with each other. Return currents (see Section 1.4) can also play a role in modifying the original injected spectrum.

The thin target scenario is applicable to electrons injected outwards through the corona, in cases where part of the target is observed, or even cases where target is obscured by the photospheric limb (Kane, 1979). It is also the case where observation sampling time is considerably lower than the energy loss time of the electron in an otherwise thick target. In all other cases, e.g. flare accelerated electrons interacting with the denser solar chromosphere, a thick target scenario is the best choice.
For the thick target case, the formula for \( I(\varepsilon) \) is

\[
I(\varepsilon) = \frac{S \Delta N}{4\pi R^2} \int_{\varepsilon}^{\infty} F(E)\sigma_B(\varepsilon, E) dE
\]

(1.10)

where \( R = 1 \text{ AU} \), \( \Delta N = \int_{\text{source}} n_p(s) ds \) is the column density of the source observed, \( n_p(s) \) is the ambient proton density as a function of the distance along the injected electron’s path and \( \sigma_B \) is the Bremsstrahlung cross-section from (1.9). In other words, the photon flux at a given energy is a result of the contributions, in the Bremsstrahlung process, of all the electrons above the photon energy weighed by the differential cross-section.

We assume the energy loss rate to be

\[
dE/dt = -\sigma_E(E)n_pv(E)E,
\]

(1.11)

where \( \sigma_E \) is the cross-section for the particle energy loss process.

Thus, over the lifetime of an electron, the number of photons emitted per unit energy, centered on photon energy \( \varepsilon \), by an electron of initial energy \( E_0 \) is

\[
m(\varepsilon, E_0) = \int_{t_1(E=E_0)}^{t_2(E=\varepsilon)} n_p(s(t))\sigma_B(\varepsilon, E(t))v(E(t))dt
\]

(1.12)

Changing the integration variable from \( t \) to \( E \), using (1.11), we get

\[
m(\varepsilon, E_0) = \int_{\varepsilon}^{E_0} \frac{\sigma_B(\varepsilon, E)dE}{E\sigma_E(E)}
\]

(1.13)

which has no dependence on the density distribution in the target, but is a ratio of Bremsstrahlung to energy loss cross-section. Thus, the Bremsstrahlung flux observed
at the Earth is found by integrating $m(\varepsilon, E_0)$ over the whole injected distribution $F(E)$, and assuming it occurs over a flare area $S$:

$$I_{\text{thick}}(\varepsilon) = \frac{S}{4\pi R^2} \int_{E_0=\varepsilon}^{\infty} F(E_0) m(\varepsilon, E_0) dE_0$$  \hspace{1cm} (1.14)

which, using (1.13), becomes,

$$I_{\text{thick}}(\varepsilon) = \frac{S}{4\pi R^2} \int_{E_0=\varepsilon}^{\infty} F(E_0) \int_{\varepsilon}^{E_0} \frac{\sigma_B(\varepsilon, E) dE}{E \sigma_E(E)} dE_0$$  \hspace{1cm} (1.15)

Adopting Coulomb collisions as the predominant source of energy loss, we have that,

$$dE/dt = (-C/E) n_p v,$$  \hspace{1cm} (1.16)

where $C=2\pi e^4 \ln \Lambda$ and typical values for the Coulomb logarithm $\ln \Lambda$ for solar conditions are in the range 20-30 (Rybicki and Lightman, 1979). From (1.11), we see that $\sigma_E(E)=C/E^2$ and the injected distribution equation becomes

$$I_{\text{thick}}(\varepsilon) = \frac{S}{4\pi R^2} \frac{1}{C} \int_{E_0=\varepsilon}^{\infty} F(E_0) \int_{\varepsilon}^{E_0} E \sigma_B(\varepsilon, E) dE dE_0$$  \hspace{1cm} (1.17)

Since the observed nonthermal photon spectra typically exhibit a power law form, we assume a source function of electrons of the form

$$F(E_0) = F_0 E_0^{-\delta},$$  \hspace{1cm} (1.18)

where $F_0$ is a normalization constant. Substituting into (1.17) yields,

$$I_{\text{thick}}(\varepsilon) = \frac{S F_0}{4\pi R^2 C} \frac{\kappa_{BH} Z^2}{\varepsilon} \int_{\varepsilon}^{\infty} E_0^{-\delta} \int_{\varepsilon}^{E_0} \ln \frac{1 + (1 - \frac{\varepsilon}{E})^{1/2}}{1 - (1 - \frac{\varepsilon}{E})^{1/2}} dE dE_0,$$  \hspace{1cm} (1.19)

where

$$\kappa_{BH} = \frac{8\alpha}{3} r_0^2 m_e c^2 = 7.9 \times 10^{-25} \text{ cm}^2 \text{ keV}$$  \hspace{1cm} (1.20)
The evaluation of the integral then readily gives

\[ I_{\text{thick}}(\varepsilon) = \frac{SF_0\kappa_{BH}Z^2B(\delta - 2, \frac{1}{2})}{4\pi R^2C(\delta - 1)(\delta - 2)}\varepsilon^{1-\delta}, \tag{1.21} \]

where \(B(a,b)\) is the standard Beta function

\[ B(a,b) = \int_0^1 x^{a-1}(1-x)^{b-1}dx = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)} \tag{1.22} \]

and \(\Gamma(a)\) is the gamma factorial function

\[ \Gamma(a) = \int_0^\infty e^{-x}x^{a-1}dx \tag{1.23} \]

with the properties

\[ \begin{align*}
\Gamma(a) &= (a - 1)\Gamma(a - 1) \\
\Gamma(1) &= 1
\end{align*} \tag{1.24} \]

This is a power law: \(I_{\text{thick}}(\varepsilon) = I_0\varepsilon^{-\gamma}\), where we see that

\[ \gamma = \delta - 1 \tag{1.25} \]

and

\[ I_0 = \frac{SF_0\kappa_{BH}Z^2B(\delta - 2, \frac{1}{2})}{4\pi R^2C(\delta - 1)(\delta - 2)} \tag{1.26} \]

An equivalent analysis for the thin-target flux yields \(I_{\text{thin}}(\varepsilon) = I_0\varepsilon^{-\gamma}\), where

\[ \gamma = \delta + 1 \tag{1.27} \]

and

\[ I_0 = \frac{S\Delta NF_0\kappa_{BH}Z^2B(\delta, \frac{1}{2})}{4\pi R^2} \tag{1.28} \]

In this case, the integral over electron lifetime is not performed by definition. Using (1.18), we can obtain the total electron flux (and similarly for the total photon flux) above a certain energy \(E_1\)

\[ F_1 = \int_{E_1}^{\infty} F_0E_0^{-\delta}dE_0 = \frac{F_0}{\delta - 1}E_1^{1-\delta} \tag{1.29} \]
and the energy flux above the same reference energy is

\[ U = \int_{E_1}^{\infty} F_0 E_0^{-\delta} E_0 dE_0 = \frac{F_0}{\delta - 2} E_1^{2-\delta} \]  

(1.30)

(Tandberg-Hanssen and Emslie, 1988).

1.3.2 Thermal Bremsstrahlung

Historically, thermal Bremsstrahlung was the first model proposed to explain the observed solar hard X-ray emission (Chubb, 1966). In this model, the Bremsstrahlung-producing electrons are part of a thermal distribution and only lose a small fraction of their energy in Coulomb collisions with ambient, cooler electrons. This permits a more energetically efficient process, involving fewer energetic electrons to produce the observed hard X-ray flux.

Consider a hot mass of gas with temperature \( T \approx 10^8 \text{K} \), such that \( \epsilon = kT \approx 10 \text{keV} \), and a Maxwellian distribution of speeds corresponding to a temperature \( T \) viz.

\[ f(v) = 4\pi \left( \frac{m}{2\pi kT} \right)^{3/2} n_e v^2 \exp\left(-mv^2/2kT\right) \]  

(1.31)

The corresponding energy distribution will be

\[ f_E(E) = f(v) dv/dE = \frac{2n_e}{\pi^{1/2}kT^{3/2}} E^{1/2} \exp\left(-E/kT\right) \text{ electrons.cm}^{-3}.\text{keV}^{-1} \]  

(1.32)

When these electrons interact with stationary ambient protons, with similar number density, the Bremsstrahlung emission at the Sun will be

\[ I(\epsilon) = n_e V \int_{\epsilon}^{\infty} f_E(E) v(E) \sigma_B(\epsilon, E) dE \text{ photons.s}^{-1}.\text{keV}^{-1} \]  

(1.33)
Integrating by parts, we find that

\[ I(\varepsilon) = D \frac{Q}{\varepsilon T^{1/2}} \exp(-\varepsilon/kT), \]  

(1.34)

where

\[ D = (8\pi m_e k)^{1/2} \kappa_{BH} Z^2 = 5.7 \times 10^{-12} Z^2 \quad \text{cm}^3 \cdot \text{s}^{-1} \cdot \text{K}^{1/2}, \]  

(1.35)

and

\[ Q = n_e^2 V \]  

(1.36)

Q is the emission measure of the source.

Observed flare emissions are comprised of a thermal and a nonthermal component and typically, a hybrid model of both thermal and nonthermal properties is necessary.

1.4 Beam Driven Return Currents in Flares

Emissions in solar flares occur when free magnetic energy is released in the corona in the form of energetic particles and/or bulk heating. In either case, this energy is transported through the low density corona to the chromosphere: the particles travel along the newly energized magnetic fields while the bulk heating leads to the propagation of a thermal conduction front (Sweet, 1969; Sturrock, 1974).

The favored mechanism for the hard X-ray production in a nonthermal flare is the acceleration of a beam of electrons (and/or ions) which then lose energy, primarily to collisions or ohmic losses. If we consider a flux \( F = 10^{18} \text{s}^{-1} \text{cm}^{-2} \) for the hard X-ray producing electron beam, and a typical beam length of \( 10^9 \text{cm} \) and cross-section, A, of \( 10^{18} \text{cm}^2 \), the energy in the self magnetic field of such a beam is \( \sim (eFA/c)^2 \times \text{beam} \)
length, which is typically 12 orders of magnitude greater than the pre-flare energy content of the active region magnetic field (Porter and Klimchuk, 1995).

In such a case, Alfvén (1939) and Lawson (1957) discovered a maximum current allowable for the beam to propagate. Currents in excess of the limit prevent the beam from propagating.

Consider the beam of charged particle to be a cylinder of radius $r_0$. The self magnetic field of such a beam is similar to that of a wire, viz,

$$ B = \begin{cases} \frac{\mu_0 l r}{2\pi r_0} & \text{if } r \leq r_0 \\ \frac{\mu_0 l}{2\pi r} & \text{if } r > r_0 \end{cases} \quad (1.37) $$

The radius of the particle orbit is then

$$ R = \frac{\gamma m v}{q B} \quad , \quad (1.38) $$

where $\gamma$ is the Lorentz factor, $m$ is the mass of the charged particle, $v$ the speed, $q$ the charge and $B$ is the magnetic field strength. The equation of motion of particles is found by setting

$$ \rho = -\frac{(1 + (dr/dx)^2)^{3/2}}{d^2r/dx^2} \quad , \quad (1.39) $$

where $\rho$ is the gyroradius and $x$ is along the direction of propagation of the beam. Alfvén (1939) found that a critical radius $r'$ exists such that if $R \geq r'$, the particles have figure of eight type orbits and so cease to propagate along the beam; and if $R \geq r'$, the particle orbit in the self magnetic field prohibits the propagation in the direction of the beam and thus the beam, as it is defined, cannot exist. There is a maximum
allowable current for which a beam can propagate when \( r' = r_0 \). The Alfvén-Lawson limit defining the maximum current for electrons to propagate is

\[
I_A = \frac{2\pi m_e \gamma v}{e \mu_0} = 1.7 \times 10^4 \beta \gamma \simeq 10^{3-4} A,
\]  

(1.40)

where \( \beta = v/c \) (Alfvén, 1939; Lawson, 1957).

Beam electrons which produce hard X-ray bursts above 20 keV in solar flares, must precipitate at a rate that sometimes exceeds \( 10^{38} \) electrons.s\(^{-1} \), requiring a current in excess of \( 10^{17} \)A, some 14 orders of magnitude greater than the limiting current defined by (1.40). However, if one allows for the presence of a strong guiding ambient magnetic field, larger than the self-magnetic field of the beam, so that the particle will spiral around inside the beam, the maximum current I allowed to flow in a cylinder of radius \( r_0 \) increases to

\[
I_A \leq \frac{2\pi r_0 B_{amb}}{\mu_0} \simeq 10^{12-13} A,
\]  

(1.41)

which is 4 orders of magnitude less than the current for electron fluxes inferred from hard X-ray observations.

The current limit specified in (1.41) is the net current in the loop system not just the current in the beam. Allowing for the charge displacement by the beam creates an electric field which redistributes the plasma electrons in such a way as to neutralize the original local charge build up. Moreover, the plasma magnetic fields do not vary considerably over timescales less than the magnetic diffusion time, which is generally much larger than the total impulsive phase in a flare (van den Oord, 1990).
So when the current in the plasma varies in magnitude, an inductive electric field will be created, driving a current in such a way as to counter the magnetic field variations on short timescales. Both these effects will result in creating a plasma electron current which will be narrowly co-spatial with the beam, ensuring that $I$ does not exceed $I_A$. Thus, the effect of an induced return current in the ambient particles is to make the net current small (Knight and Sturrock, 1977; Spicer and Sudan, 1984; Brown and Bingham, 1984). This return current is formed by thermal electrons that drift in the opposite direction to the initial electron beam with a drift speed given by

$$v_D = \frac{n_B}{n_p} v_b,$$  \hspace{1cm} (1.42)

where $n_B$ is the beam density, $n_p$ is the ambient plasma density and $v_b$ is the speed of the beam associated with its mean energy (LaRosa and Emslie, 1989; van den Oord, 1990, 1992).

The equation for the energy loss rate to ohmic dissipation in the return current is given by

$$\frac{dE}{dt} = \eta j v = \eta e^2 F_{tot} v,$$  \hspace{1cm} (1.43)

where $\eta$ is the plasma resistivity (assumed to be classical), $j$ the current density and $F_{tot}$ the total number of electrons in the beam. For a parent electron spectrum $F(E) = F_0 E^{-\delta}$, we have

$$F_{tot} = \frac{F_0}{\delta - 1} E_1^{\delta - 1},$$  \hspace{1cm} (1.44)

where $E_1$ is cutoff energy usually assumed to be around 10-20keV.
Equation (1.43) then becomes

\[ \frac{dE}{dt} = \eta e^2 v \frac{F_0}{\delta - 1} E_1^{1-\delta} \]  

(1.45)

The number of photons emitted per unit energy, centered on \( \varepsilon \), by an electron of initial energy \( E_0 \) becomes (from Equation (1.13))

\[ m(\varepsilon, E_0) = \int_{\varepsilon}^{E_0} \frac{n\sigma_B(\varepsilon, E)(\delta - 1)dE}{\eta e^2 E_1^{1-\delta} F_0} \]  

(1.46)

Since \( m(\varepsilon, E_0) \) is inversely proportional to \( F_0 \), (1.14) indicates that the resulting nonthermal photon flux is not dependent on the beam flux. When return currents dominate the energy losses, the observed nonthermal flux can only be used to determine the spectral index, \( \delta \), of the electron beam and the cutoff energy, but cannot say anything about the total number of electrons, since the return current induced is a result of all the electrons in the beam. Thus, in current dominated regime, any increase in the total number of electrons induces a proportional increase in the return current and consequently the ohmic losses, resulting in a limit to the photon emission.

In the research presented here, we utilize the unprecedented spectral and spatial resolution of the RHESSI hard X-ray observations to place limits on the photon, and by inference, the electron fluxes over a wide range of flare magnitudes. We then compare these fluxes to the physical limits implied by the discussion above in the presence of both Coulomb collisions and return currents. Chapter 2 gives a basic overview of RHESSI and the technique of spectral imagery. In chapter 3, we show
the results for a wide range of solar flare magnitudes. We conclude in chapter 4 with a discussion of the results and a discussion of future work related to our research.
Chapter 2
RHESSI: Instrumentation

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is a solar flare mission launched on February 5, 2002. Its primary scientific objective is to explore the basic physics of particle acceleration and energy release in solar flares. This is accomplished by high resolution imaging and spectroscopy with cooled germanium detectors, allowing the resolution of emission lines extending to nuclear γ-rays.

2.1 The RHESSI Hardware

RHESSI’s main function is high-resolution imaging at energies of 3keV through 20MeV and high-resolution spectroscopy. A set of 9 bi-grid rotating modulation collimators with FWHM resolutions ranging from 2.3" to 183" is used for this purpose. The spacecraft spins at 14.5-15 rpm, points within 0.1° of the solar center, weighs 130 kg and orbits at 38° inclination and 600 km altitude. It has a lifetime of about 10 years and an X-ray spectral resolution of 0.5-2keV. RHESSI (Figure 2.1) is controlled by the University of California at Berkeley and is a joint project of UCB, Paul Scherrer Institute (Switzerland) and NASA’s Goddard Space Flight Center. All RHESSI data is available online for scientific research (www.hessi.com). A technical description of RHESSI can be found in Lin et al. (2002,2003 and 2004), Dennis et al. (1996) and Hurford et al. (2002).
The solar aspect system on RHESSI consists of three identical lens filter assemblies mounted on the forward grid tray to form full-Sun images on three linear diode arrays mounted on the rear grid tray. Simultaneous exposures every 10 ms allow the precise locations of the solar limb to be obtained on the ground by interpolation.

Image reconstruction on the ground requires a knowledge of the relative roll. This is obtained using a star scanner that samples the roll orientation at least once every rotation. Measurement of only one star, averaged over a minute, allows the roll angle
to be determined to 2.7 arcmins.

Nine grids are mounted on a grid tray at each end of the telescope tube. The nine germanium detectors are positioned behind the nine grid pairs on the telescope. They convert incoming X-rays and γ-rays to pulses of electron current, with the amount of current measured directly proportional to the energy of the photon. Each germanium detector covers the entire hard X-ray to γ-ray energy range (up to 20 MeV). The grid pairs modulate the transmission of solar flare X-ray and γ-ray emissions through the detectors as the spacecraft spins around the axis of the telescope tube (Figure 2.2). This modulation is crucial to determining spatial information. In our study, we use the modulated count rates to construct images of solar flares in different energy bands.

Excessive photon flux, which can occur during very bright flares, is controlled by an dual attenuator system. Each attenuator is a set of 9 aluminum disks held in a lightweight frame. Each frame has two positions: one with the disks covering the detectors and one with the detector field of view completely clear. The attenuators are moved automatically in response to changes in the monitor rate counters in order to prevent saturation effects that might occur during periods of high count rates.

Analyzing RHESSI data is a delicate job. For this project, special care is needed in selecting specific flares and making sure that instrumental effects were minimal and acquisition settings were optimal.
**Figure 2.2** Front and rear grids modulating the signal that reaches the detector (Hurford et al., 2002)
2.2 Using RHESSI Data

RHESSI records every photon above a threshold energy of 3keV as a time-tagged event up to a maximum rate of approximately $10^6$s$^{-1}$. The telemetry data we can access contains photon event lists from each of the 9 detectors, with a time accuracy of 1$\mu$s. In this analysis, we interactively use IDL to run imaging codes compatible with the RHESSI software package. The latter is part of a SolarSoft system which retrieves RHESSI data from the Goddard Space Flight Center primary archive and processes it (Bentely and Freeland, 1998; Freeland and Handy, 1998).

To provide context for the RHESSI hard X-ray data, we utilize the full sun soft X-ray information from the GOES satellites. The GOES flare catalogue is an online daily archive of solar flares available to the public. It provides dates, times and soft X-ray fluxes of flare events wherever they occur on the Sun. We combine this with the RHESSI flare catalogue to search for common flares with characteristics of interest. The catalogue gives information on changes in the count rates consistent with flare signatures, including the start, peak and end times, peak count rate and total flare counts.

RHESSI level-0 data files are used to make useful plots like observing summary count rates (raw and corrected) to analyze the flare. Quicklook low resolution images of the flare in a defined energy range provide a determination of the flare location and a consistency check of the flare catalogue information, which can sometimes be
incomplete.

The field of view of RHESSI contains the whole solar disk. Spatial information such as flare location and hard X-ray source structure is provided by a detailed analysis of the signal modulation which results from the rotating collimator design. Because of the rotation of the spacecraft, signal modulations recorded on each detector vary as a function of the source (flare) position, spatial extent and intensity. Figure 2.3 explains the basic image reconstruction process:

Row 1 gives the theoretical modulations in a single detector, recorded for a single point source located away from disk center on the solar disk. When flux from the same source changes, the amplitude of the recorded modulations changes accordingly as seen in row 2. Row 3 shows how the modulations shift in the time axis (horizontal) when the angular position of the source varies. The change in the pseudo-period of the modulations indicates a change in the distance of the source from the rotation axis (row 4). Extended sources result in a shift of the modulation in the flux direction (vertical) as seen in rows 5 and 6: the larger the source, the smaller the observed modulation. Effectively, when dealing with real data, the observed modulations looks more like row 7, where a thorough mathematical analysis is required to deconvolve the recorded pattern into the multiple subsections described above. The RHESSI software analysis suite provides the necessary tools to deconvolve a modulation pattern like that shown in row 7.
Figure 2.3  Ideal rotating collimator modulations for multiple cases of sources on the solar disk (www.hessi.com)
Combining data from all the possible detectors increases the accuracy of the mathematical solution for the flare position, extent and flux distribution.

Several algorithms have been developed to reconstruct an image from the RHESSI modulation patterns. These have various strengths and weaknesses, a discussion of which is beyond the scope of this thesis. Aschwanden et al (2004) summarizes the effectiveness of these algorithms. We will be mostly concerned with the methods of Back Projection, CLEAN and PIXON.

Back Projection is the simplest and quickest way to get an image of the flare. It has limited use for resolving structure in the emission and is generally used simply to generate a full disk image of the sun in order to find or verify flare coordinates on the solar disk and to determine the correct times for subsequent imaging analysis. By multiplying the calibrated event list (detected counts) by the collimator modulation patterns, the Back Projection algorithm constructs a dirty map of the image (Schmahl and Hurford, 2003; Hurford et al, 2002).

The CLEAN algorithm sharpens the image produced via Back Projection by treating each bright pixel as an individual source. It first considers the pixel with highest counts, removes it from the original map and places it in a cleaned map of the flare. Then it iterates through the whole modified original map many times to obtain a representation of all potential sources. The flare map resulting from CLEAN is significantly sharper than that generated by Back Projection, although the resolution
depends on the collimators used in constructing the image.

PIXON image reconstruction tries to maximize the image resolution in locations where the information content of the data is high, but allows a degraded resolution when the count is low and there is little information. This very powerful method, explained by Puetter and Pina (1993, 1994) and Metcalf (1996), gives good noise suppression and good recovered photometry, but is very time consuming due to the construction of a PIXON map of pixel sizes. It is ideally suited for obtaining high quality images.

![Reconstructed image](image1.png)

**Figure 2.4** October 29 2003 flare imaged using Back projection (a, whole solar disk), CLEAN (b, 64"×64" subfield) and PIXON (c, 64"×64" subfield) techniques (Solarsoft)

Our technique uses Back Projection to generate a full or partial solar disk image and to check the flare preliminary parameters. Then, we use CLEAN to get a sub-image centered around the flare in order to verify the choice of fine position coordi-
nates, the availability of significant counts, the resolution and the image dimensions. Then, we use PIXON for spectral imagery since it produces the best photometry images. An example of results using these three techniques is given in Figure 2.4.

The spectral resolution provided by RHESSI combined with advanced image reconstruction algorithms such as PIXON, allow us to obtain precise measurements of the solar flare hard X-ray spectrum that we can directly invert to obtain information about the parent X-ray producing electrons at the Sun. RHESSI is a wonderful tool for understanding particle acceleration and energy release processes in solar flares.
Chapter 3
X-ray Spectral Imagery Using RHESSI

RHESSI data provides an excellent diagnostic capability for exploring high energy processes occurring in solar flares. However, to gain insight into the flare energy release, one must be able to relate the observed photon characteristics (flux, spectrum, time behavior, spatial distribution) to those of the particle populations responsible for these emissions. This requires and understanding of the particle transport and photon production physics in the flaring solar atmosphere. Together, the theoretical understanding, coupled with the experimental data analysis, provide new insight into the flare phenomenon.

3.1 Flare Data Analysis

In this work, we have selected ten flares for analysis (Table 3.1) spanning the GOES class range M 1.8 to X 17. Flares are selected if they satisfy the following criteria:

1. The events chosen are all significant flares with GOES X-ray fluxes larger than $10^{-2}\text{erg.cm}^{-2}\text{s}^{-1}$ (GOES class M1 or above).

2. The required observing times should fall within RHESSI daytime mode.

In fact, the number of potentially significant flares in the GOES database is huge. However, few of them (especially the X flares) coincide with
RHESSI day-time.

3. The flares should show some well defined substructures in the RHESSI images.

<table>
<thead>
<tr>
<th>RHESSI #</th>
<th>GOES Class</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2092002</td>
<td>M 1.8</td>
<td>09/20/2002</td>
</tr>
<tr>
<td>3042638</td>
<td>M 2.5</td>
<td>04/26/2003</td>
</tr>
<tr>
<td>2111802</td>
<td>M 7.4</td>
<td>11/18/2002</td>
</tr>
<tr>
<td>2071705</td>
<td>M 8.5</td>
<td>07/17/2002</td>
</tr>
<tr>
<td>2070352</td>
<td>X 1.5</td>
<td>07/03/2002</td>
</tr>
<tr>
<td>3110301</td>
<td>X 2.7</td>
<td>11/03/2003</td>
</tr>
<tr>
<td>2072301</td>
<td>X 4.8</td>
<td>07/23/2002</td>
</tr>
<tr>
<td>3110221</td>
<td>X 8.3</td>
<td>11/02/2003</td>
</tr>
<tr>
<td>3102929</td>
<td>X 10.</td>
<td>10/29/2003</td>
</tr>
<tr>
<td>3102825</td>
<td>X 17.</td>
<td>10/28/2003</td>
</tr>
</tbody>
</table>

Table 3.1 Flare list with dates, GOES satellite classification and RHESSI ID number

The RHESSI database contains hundreds of M class flares and a few X type flares. However, generating spectral images for these flares is a long process so we limited our analysis to 10 flares spanning the full range above M1.

The selection process for flares starts with inspecting the GOES satellites database for flares in the required range. Figure 3.1 shows a GOES plot for the case of the flare of September 20, 2002.

After this, an observing summary plot is generated using Solarsoft in IDL for each flare (Figure 3.2). This plot shows the time variation of emission for different energy bands and thus helps identify the different phases of the flare and pick the correct
timing for spectral imagery. We concentrate on times around the peak of the hard X-ray emission as we expect to detect the largest particle fluxes at this time.

Figure 3.1 GOES plot for the flare of 09/20/2002 (SolarSoft)

The summary plots are flagged for attenuator-state change, satellite night times, South Atlantic Anomaly passage and other complexities like photon pileup and decimation of data due to instrumental over-flood. Using these flags, a careful selection of imaging time intervals is made in order to ensure a good data set.

Once an appropriate time interval is selected, a Back Projection image is processed for the entire solar disk. This reveals the flare position relative to disk center in arc-seconds as measured from Earth.
Figure 3.2: Observing Summary Data plot for the flare of 09/20/2002, showing time variation of emission for different energy bins (Solarsoft)
Figure 3.3  Reconstructed CLEAN image for the the flare of 09/20/2002 (Solarsoft)

We then apply the CLEAN algorithm to generate a magnified image of the flare (Figure 3.3) as a consistency check on the Back Projection inferred coordinates and to provide information on the extent and complexity of the hard X-ray structures. CLEAN is used for this purpose because it is fast and reasonably reliable. We are interested in looking at detailed substructures in the flare. Our final spectral images are generated using the PIXON algorithm (Section 2.2).

After flare specifications (e.g. time interval, energy range, image dimensions and resolution) are confirmed, spectral images of the flare for the required times and covering the range 6-100keV are generated using the PIXON algorithm (Figure 3.4).
Figure 3.4  Reconstructed Pixon (128×128 arcsec$^2$) images a) 8-10keV, b) 10-12keV, c) 12-14keV, d) 14-16keV, for the flare of 09/20/2002 (Solarsoft)

The better photometry of the PIXON reconstructions (see Alexander and Metcalf, 1997) is required since we are interested in analyzing the detailed substructures in the flare. An image is generated for each 2keV interval of emission. While PIXON is computationally intensive, it is the best image reconstruction code available for the RHESSI data.
3.2 Total Structure Analysis

Due to the lack of good spatial resolution at hard X-ray energies prior to RHESSI, spectra from solar flares were limited to whole flare studies, with little or no spatial information. For comparison with earlier results, we focus in this section on calculating and analyzing the total thermal and non-thermal energy fluxes for the flares listed in Table 3.1 as well as the total hard X-ray flare area observed in each case using RHESSI. In the following section, we perform a more comprehensive study, isolating individual substructures.

3.2.1 Spectral results

Figure 3.5 shows the observing summary data plot for the flare of July 23, 2002. The impulsive phase of the flare starts around UT 00:27 when the photon counts in the energy bands above 25keV suddenly increase, in contrast to the gradual increase of soft X-ray energy bands. The peak of hard X-rays is defined between UT 00:28 and 00:30. All RHESSI imaging algorithms require integration time intervals corresponding to at least half a revolution of the spacecraft about its axis (directed towards the center of the solar disk). Spectral imagery of this flare using PIXON needs a 12 second integration time corresponding to \(~3\) revolutions of the spacecraft. Pixon-generated images consist of photon counts spatially distributed in a \(128\times 128\) arcsec\(^2\) field of view. The data cubes will be analyzed to infer the total effective area of the flare and the corresponding photon fluxes.
Figure 3.5  Observing Summary Data plot for the flare of 07/23/2002, showing time variation of emission. The peak of hard X-rays can be identified between UT 00:28 and 00:30 (SolarSoft)
To estimate accurately the total effective area of the flare, a spectral image in the range 30-40 keV is selected for each flare. Then, we analyze this image to understand the spatial distribution of counts. This will help in showing which part of the image is the true representation of the flare extent. To illustrate this, Figure 3.6 shows our analysis for a 30-32keV energy bin image for the flare of July 23 2002. The PIXON reconstruction is shown in A, while the effective part of the image from which we calculate the area is shown in B. This area defines the locations of significant photon fluxes in the original PIXON image. Typically, flare area for hard X-ray was implied rather than measured. However, the algorithm we developed spatially analyzes the images and calculates flare areas. This will be discussed in Section 3.3.

![Figure 3.6](image)

**Figure 3.6**  A) Reconstructed Pixon image (64×64 arcsec², 30-32keV energy bin) for the flare of 07/23/2002  B) Map showing effective flare area (SolarSoft)

Figures 3.7 and 3.8 show the data from spectral imagery of the flares of September 20, 2002 and July 23, 2002 (Figures 3.4 and 3.6). Each data point on the graph
represents the photon flux calculated from a single PIXON-generated image.

Figure 3.7 Spectrum of the flare of September 20, 2002, with fits to the thermal and non-thermal parts

Those images consist of photon counts spatially distributed over the flare area. Photon counts are read and processed for the whole structure and the total effective area of the flare is calculated using the map of Figure 3.6B, thus determining the total photon counts and photon fluxes in the whole flare structure at the peak of hard X-ray emission.

Plotting X-ray flux variation with energy gives a spectrum that agrees with the theoretical analysis of Section 1.3. Indeed, an isothermal profile (T\sim3.5\times10^7\ K)
Figure 3.8  Spectrum of the flare of July 23, 2002, with fits to the thermal and non-thermal parts

is clear in the range 4-20 keV in accordance with (1.34), whereas above 25keV, a nonthermal profile (Equation 1.21) provides the best fit for the data. This shows that in these flares, the hard X-ray emission is due to both thermal (dominating at low energies) and nonthermal Bremsstrahlung (dominating at higher energies). The former being related to a hot mass of plasma while the latter is related to the downward flow of beam electrons as seen in Figure 1.1.

The fitted spectra are then integrated to compute the total thermal photon and energy fluxes above 3keV and the total nonthermal photon flux above 20keV for each flare. Results for all the flares of Table 3.1 are shown in Figure 3.9. Results are
Figure 3.9  Total thermal (diamonds) and nonthermal (asterisks) photon fluxes for the flares of table 3.1 plotted against the total thermal energy compared to the thermal energy flux, showing the magnitude of the flare.

Note that the total thermal photon flux rises linearly on a log scale with rising total thermal energy, as a direct consequence of Equation (1.34). The nonthermal flux has a slower increasing trend. The nonthermal emission, is usually more localized in parts of the flare, while the thermal emission can be detected throughout the total flare volume.

Emslie (1980) showed that the nonthermal photon spectrum becomes independent of the total electron flux when it crosses a certain limiting flux. The critical electron flux was found to be $10^{19}$ electrons.cm$^{-2}$.s$^{-1}$, which can be related to an upper limit
in the nonthermal photon flux of $10^{-15}\text{photons.cm}^{-2}.\text{s}^{-1}.\text{cm}^{-2}$ above 20keV. All the data points in Figure 3.9 fall below this limit.

### 3.2.2 Flare Area Dependence

In the preceding section we categorized our flares by their total thermal energy and demonstrated that the photon fluxes defined as thermal and nonthermal from the spectra, increased as the flare gets larger. A key factor in determining the flux is the area over which the emission is produced.

In an analysis of UV versus hard X-ray fluxes in solar flares, Kane, Frost and Donnelly (1979), concluded that larger flares are primarily characterized by larger areas over which electron precipitation occurs, such that a large increase of the total energy in the precipitating electrons constitutes only relatively small increase in the precipitating energy flux.

The spatially resolved spectra available from RHESSI allows us to address this issue directly. Figure 3.10 shows the variation of total flare area with total thermal energy for the flares listed in Table 3.1.

In contrast to the assertion of Kane et al (1979), Figure 3.8 shows that an increase of $\sim$ a few hundreds in the flare radiative output (i.e. as we go to larger and larger flares) corresponds, in the maximum case, to only an increase of a factor of 5 in the flare area. Thus, larger flares are in fact not simply scaled by an increase in area, but exhibit an increase in the photon flux.
Figure 3.10  Total flare area plotted against total thermal energy for the flares of table 3.1

3.3 Substructure Scale Analysis

So far, the spectral analysis for the flare as a whole has provided some insight into the relationship between thermal and nonthermal emissions and their dependence on flare magnitude. However, when dealing with the whole flare, nothing can be said about the substructures, and therefore the distribution of the flux. The advent of RHESSI enables us to spatially resolve individual sources and thereby address the beam-driven photon production on more physically relevant scales.
3.3.1 Identifying Substructures

In solar images, a flare is recorded as a relative increase in brightness with respect to the background. While compact flare models show a loop structure in the lower corona anchored at footpoints in the chromosphere (Figure 1.1), many flares show ribbons associated with arcades of post flare loops that vary in size and complexity (see Figure 1.5) throughout the flare duration (Zirin, 1988).

The sensitivity and spatial resolution of RHESSI, coupled to the excellent photometry of the PIXON image reconstruction technique, allows us to identify multiple structures in the hard X-ray emission from flares. At the higher hard X-ray energies (>25keV), these structures are most likely loop footpoints, i.e. the touchdown locations of flare loops in the chromosphere. With the ability to isolate these structures, we can understand solar flares in their real aspect rather than just studying the total emission from the whole structure. In other words, rather than determining the average fluxes, we can find the actual spatial distribution of the hard X-ray flux and consequently, the regions of different injected electron spectra.

As discussed in the previous section, the total effective area of the flare is determined using a spectral image in the range 30-40 keV. Analyzing this image leads us to understand the spatial distribution of counts. To generate Figure 3.6B, a thorough analysis of the spatial distribution of counts enables us to set a threshold to filter out the background from the respective spectral images of the flares in Table 3.1.
Figure 3.11  3D representation for Figure 3.7A, showing small unlocalized substructures removed on the right extrusion (SolarSoft)
Here, background describes a small fraction of counts that PIXON was not able to allocate to a given substructure: the count rates are so low that to converge, the PIXON algorithm bins over a large area pixel, therefore compromising the area determination. Figure 3.11 shows a 3D extrusion of Figure 3.6, the small noise features (better seen in the projection on top) at the base of the substructure group in the left extrusion are removed in the right, showing the effective map for the flare.

We have developed an automated technique which finds substructures in the RHESSI images and provides quantitative feedback on their brightness, spectrum and size.

The basic process in identifying substructures starts with defining a non zero pixel in the effective image, then searching for all spatially related pixels around it. Two pixels are spatially related if they are adjacent in any direction and are thus considered to be part of the same substructure and sampled in the same map. After this, the substructure is removed from the original map. The process is repeated until all nonzero pixels in the original map are sampled.

The object of this process is to divide a single energy binned image into maps of each of the independent substructures. These maps will later be used as anchors for the locations of substructures to compute their respective areas and determine the photon counts.

Thus, for each isolated event composing the flare, we can determine the photon,
and subsequently the electron fluxes over the whole energy range for which there are adequate counts. The next step follows a similar approach to the previous section: spectral plots and total fluxes for thermal and nonthermal components for each substructure are generated in order to explore the distribution of photon fluxes attainable in flares.

<table>
<thead>
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<th>Date</th>
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<th>Substructures</th>
</tr>
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<tbody>
<tr>
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<td>1</td>
</tr>
<tr>
<td>04/26/2003</td>
<td>M 2.5</td>
<td>1</td>
</tr>
<tr>
<td>11/18/2002</td>
<td>M 7.4</td>
<td>1</td>
</tr>
<tr>
<td>07/17/2002</td>
<td>M 8.5</td>
<td>2</td>
</tr>
<tr>
<td>07/03/2002</td>
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<td>7</td>
</tr>
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<td>10/29/2003</td>
<td>X 10</td>
<td>4</td>
</tr>
<tr>
<td>10/28/2003</td>
<td>X 17</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3.2 Flare list with number of subflares identified

Table 3.2 shows the number of significant substructures identified in the effective images for each flare.

We notice that the larger the flare, the more substructures that can be identified. While this is a result of the increased magnetic complexity and bigger areas of large flares, it is also an artefact of the PIXON reconstruction which better resolves structures when there are more counts.
3.3.2 Analysis of Substructures

After identifying the different independent substructures for the list of flares in Table 3.1, a spectral plot similar to Figure 3.5 is generated for each individual map. Figure 3.12 shows the different substructures identified for the X10 flare of October 29, 2003. This flare is part of the Halloween events of 2003 which is a set of the largest flares ever recorded.

The image in (A) corresponds to the 30-32keV energy bin and UT 20:42:06 to 20:42:16 time interval. (B) shows a map of the different discernable substructures. Each one is then mapped as an independent event in panels (1), (2), (3) and (4).

Figure 3.12  Reconstructed Pixom map (B) for the multiple substructures identified in the case of the flare of 10/29/2003 (A), together with automatically generated maps of the different independent substructures 1,2,3 and 4 (Solarsoft)
The map shows four coherent substructures. An individual spectral analysis is then made by calculating the photon counts in every image corresponding to the location of the substructure in the map, calculating the substructure area and thus determining the photon fluxes. Figures 3.13 and 3.14 show the respective spectra for substructures 3 and 4 in Figure 3.12 as an example for different substructure scales. In this process, each component in the flare map is analyzed as an independent event.

Figure 3.13 Spectrum of substructure # 3 in the flare of October 29, 2003, with fits to the thermal and non-thermal parts

For substructure 3, we determine the following parameters:

- Surface area = $3.38 \times 10^{17}$ cm$^2$ (c.f. total flare area is $4.82 \times 10^{18}$ cm$^2$)
- Total thermal energy flux above 3keV = $1.8 \times 10^{-11}$ keV cm$^{-2}$s$^{-1}$cm$^{-2}$
Total thermal photon flux above 3keV = $5.64 \times 10^{-12}$ photons cm$^{-2}s^{-1}cm^{-2}$

Total nonthermal photon flux above 20keV = $3.32 \times 10^{-16}$ photons cm$^{-2}s^{-1}cm^{-2}$

Figure 3.14  Spectrum of substructure # 4 in the flare of October 29, 2003, with fits to the thermal and non-thermal parts

For substructure 4, we determine the following parameters:

Surface area = $2.19 \times 10^{18}$ cm$^2$

Total thermal energy flux above 3keV = $6.4 \times 10^{-12}$ keV cm$^{-2}s^{-1}cm^{-2}$

Total thermal photon flux above 3keV = $2.02 \times 10^{-12}$ photons cm$^{-2}s^{-1}cm^{-2}$

Total nonthermal photon flux above 20keV = $6.7 \times 10^{-16}$ photons cm$^{-2}s^{-1}cm^{-2}$
We notice that there is no direct correlation between thermal and nonthermal fluxes in these two cases and also no direct correlation between area and total thermal energy which is only twice as big for the second case than the first although the area is greater by a factor of 7.

Figure 3.15 shows the different substructures identified for the X 4.8 flare of July 23, 2002. The image in (A) corresponds to the 30-32keV energy bin and UT 00:28:45 to 00:28:57 time interval. (B) shows a map of the different discernable substructures. Each one is then mapped as an independent event in (1), (2), (3), (4) and (5).

Figure 3.15  Reconstructed Pixon map (B) for the multiple substructures identified in the case of the flare of 07/23/2002 (A), together with automatically generated maps of the different independent substructures 1,2,3,4 and 5 (SolarSoft)
Figure 3.16 Spectrum of substructure # 4 in the flare of July 23, 2002, with fits to the thermal and non-thermal parts

For substructure 4, we determine the following parameters:

Surface area = $6.76 \times 10^{17}$ cm$^2$ (c.f. total flare area is $3.46 \times 10^{18}$ cm$^2$)

Total thermal energy flux above 3keV = $1.95 \times 10^{-11}$ keV cm$^{-2}$s$^{-1}$cm$^{-2}$

Total thermal photon flux above 3keV = $6.08 \times 10^{-12}$ photons cm$^{-2}$s$^{-1}$cm$^{-2}$

Total nonthermal photon flux above 20keV = $6.65 \times 10^{-16}$ photons cm$^{-2}$s$^{-1}$cm$^{-2}$
3.3.3 Spectral result: Nonthermal Photon Flux Saturation

Figure 3.17 Total thermal (diamonds) and nonthermal (asterisks) photon fluxes for the substructures of all flares of table 3.1 plotted against the total thermal energy

Figure 3.17 shows the total thermal and nonthermal photon fluxes for the 26 substructures listed in Table 3.2.

We notice that while the total thermal photon flux rises linearly on the log scale with the total thermal energy, the total non-thermal photon flux rises and then saturates around $9 \times 10^{-16}$ photons.cm$^{-2}.s^{-1}.cm^{-2}$, a number consistent with the saturation limit described in section 3.2.1. This limit is reached when the total thermal energy flux is around $8 \times 10^{-12}$ keV.cm$^{-2}.s^{-1}.cm^{-2}$. 
Figure 3.18 Total number of substructures observed at each nonthermal photon flux range

Figure 3.18 is a histogram of observed nonthermal sources. It shows that as the structures reach nonthermal photon flux saturation, their number gradually increases. This stops when the nonthermal photon flux reaches a maximum around $10^{-15}$ photons cm$^{-2}$s$^{-1}$cm$^{-2}$. No substructure detection lies above this limit. Since the flare range in this study covers an entire significant set from low M to the highest X flares, one can be safe to claim that this limit is real and not a selection artefact.

It is significant to note that the lowest nonthermal fluxes do not only correspond to structures within small flares, but that some of them are recorded in many substructures in large flares. On the other hand, a fewer number of high fluxes were also recorded in substructures within the small flares. This shows that within any
type of flare, a small structure can reach saturation while the surrounding flux is still low. This individual characteristic demonstrates that there is little similarity in the down-flowing electron fluxes responsible for these emissions when looking at different substructures within the same flare. However, the average nonthermal photon flux increases with increasing thermal energy flux in flares as can be seen in section 3.3.1 until it eventually reaches saturation. This shows that the classification of flares according to the total thermal energy flux does not give a completely clear picture of the physics behind the emission mechanism.

Indeed, the true physical identity of what is going on is only evident when we have well resolved images that explain the different substructures as independent events rather than a whole averaged emission.

3.3.4 Coulomb Collisions and Return Currents in Substructures

In the case of hard X-ray emission, an electron in the beam undergoes a high angle deflection collision with an ambient proton, giving off a photon of comparable energy to the initial electron energy. This process we know as Bremsstrahlung has been discussed in Section 1.3.

The energy loss rate adopted in (1.16) to analyze nonthermal emission is for the case of Coulomb collisions. This is the normal behavior far below photon flux saturation. However, there are limits for a propagating current to exist in a well defined beam geometry as we discussed in Section 1.4. As the current increases
and nears its maximum allowed value for beam stability, the return current in the ambient plasma also increases following (1.42). Gradually, the energy loss mechanism will change from a Coulomb collision to a return current dominated regime.

One can clearly argue that the stability limit for the beam current is a major, if not the principal cause of the saturation in nonthermal photon flux. To verify this, the substructures in Figure 3.17 for which the thermal energy flux is less than $10^{-12}$ keV.cm$^{-2}$.s$^{-1}$.cm$^{-2}$ are sampled, this covers the data range of ascending nonthermal photon fluxes below the saturation limit. Then, using (1.25), (1.26) and (1.29), the electron flux distribution can be inferred for these substructures assuming Coulomb collisions are dominant. This will directly imply the current in the beam. We can then inspect the variation of beam current with nonthermal photon flux to check for the validity of Coulomb collisional energy loss assumption.

Figure 3.19 shows the results for these substructures plotted against increasing nonthermal photon flux. Assuming Coulomb collisional energy losses dominate, the calculated beam current rises with nonthermal photon flux until it reaches an average saturation limit of about $6.5 \times 10^{12}$A.

As the electron flux flowing down into a given substructure increases, the corresponding beam current increases too. Those electrons are responsible for the production of the nonthermal emission measured in spectral images, and so it is a direct implication that the total nonthermal photon fluxes will increase subsequently. Si-
Figure 3.19  Beam currents (diamonds) for substructures inferred from the nonthermal flux spectra assuming Coulomb collisions dominate

multaneously, reverse currents are generated (van den Oord, 1990) to keep the total current constant. Assuming circular geometry, the maximum limiting current for a beam flowing into a substructure of area $A$ is found using (1.41) to be

$$I_{max} = \frac{2(\pi A)^{1/2} B_{amb}}{\mu_0}$$  \hspace{1cm} (3.1)

For a typical flare ambient chromospheric magnetic field of 1000G (varies from 200G to 1500G), the maximum allowed current can be calculated and compared to the actual beam current (Figure 3.20).
Figure 3.20  Beam currents for substructures inferred from the nonthermal flux spectra assuming Coulomb collisions dominate compared to maximum allowed currents

We notice that for a nonthermal photon flux below $10^{-17}$ photons.cm\(^{-2}\). s\(^{-1}\).cm\(^{-2}\), the beam currents are 1 to 3 orders of magnitude below their theoretical stability limits and therefore the assumption of a Coulomb collisional dominant energy loss mechanism is valid.

Above this limit, currents are close to and sometimes higher than the stability limit, which implies that the assumption of Coulomb collisions dominating the energy loss mechanism is not valid. This critical value for the nonthermal photon flux
corresponds in Figure 3.18 to a thermal energy flux of $2 \times 10^{-13}$keV.cm$^{-2}$. s$^{-1}$.cm$^{-2}$. Under this limit, both nonthermal and thermal photon fluxes are monotonically increasing. Therefore, this value can be adopted as a limit for dominating Coulomb collisional losses.

On the log scale of Figure 3.17, an exponential function approximation for non-thermal photon flux of the form $I_{nt} = I_0 e^{-E_r/\tau}$ is generated, where $I_0$ is the averaged logarithm of the saturation value for the nonthermal photon flux. We calculate $\tau$ to be around 0.7. We assume that this flux reaches steady state ($5\tau$) around a total thermal energy flux of $5 \times 10^{-11}$keV.cm$^{-2}$.s$^{-1}$.cm$^{-2}$. We adopt this value as a rough estimate of where return currents dominate the energy loss mechanism.

3.3.5 Substructures Area Dependence

The different substructure areas are read from the corresponding maps and plotted against the total thermal energy in Figure 3.21. We notice an increase of substructure surface area with energy. However, this is not a linear increase, and this confirms the results in Section 3.2.2 that flare magnitudes are not just dependent on flare areas.

In fact, while the surface area increases by a factor of 100 over the whole span of data points, the respective total thermal energy rises by six orders of magnitude. Also, for the data points in Figure 3.21, the linear correlation is not obvious, with a poor correlation factor of 0.138. Moreover, it is interesting to note that both high and low energies emanate from regions of small and large areas, which weakens the
Figure 3.21 Substructure areas plotted against total thermal energy for the flares of table 3.1

link between strength of emitted energy and area variation. This proves that higher energy flares are in fact not explained by a simple increase in flare area, which linearly increases the total energy for a slightly varying flux. They are most likely due to an increase in the photon flux, which together with a moderate variation in flare area, will lead to the increase in total released energy.
Chapter 4
Conclusion

This short chapter is intended to provide an overall conclusion to the results described in previous sections in order to give a more coherent overview of what was achieved, and indicate some of the many follow-ups and future work required beyond this research.

4.1 Results

Earlier hard X-ray analysis, with little or no spatially-resolved data, alluded to a potential beam current problem when trying to accelerate $10^{36}$ electrons.s$^{-1}$ across a typical flare area of $10^{18}$cm$^2$. Under this area assumption, the observed photon fluxes implied beam currents of the order of $10^{17}$A, far in excess of the current instability threshold for beam propagation, driven by the self-induced magnetic field (Alfvén, 1939; Lawson, 1957).

In this study, we have shown that while the total flare area is within an order of magnitude of $10^{18}$cm$^2$, it is comprised of several smaller hard X-ray emitting sources each signifying a separate current system. The unprecedented spatial and spectral resolution of RHESSI allows us to deal with each of these sources separately.

Initially, we represented the earlier 'whole flare' analysis, for a sample of 10 flares spanning a factor of 200 (M1 to X17) in the GOES 1-8Å peak flux. RHESSI satellite
data is used to generate sets of spectral images for each flare around the peak of hard X-ray emission, spanning the energy range 6-100keV.

Using advanced image reconstruction algorithms and specially developed data analysis techniques, photon counts and effective flare areas were computed and used to generate a hard X-ray spectrum for each flare. A fit to the isothermal and nonthermal branches of the spectrum were generated from which total thermal and nonthermal photon fluxes and total thermal energy were inferred.

We noticed that while total thermal photon flux above 3keV increased, the total nonthermal photon flux above 20keV stayed below a saturation limit, defined by Emslie (1980), of $10^{-15}$ photons cm$^{-2}$ s$^{-1}$ cm$^{-2}$. We also deduced that higher thermal energy flares are not due to larger flare areas since the increase in total energy does not correlate with an increase in area, but to higher photon fluxes.

Furthermore, for a more thorough investigation of this saturation limit, the unprecedented spatial resolution of RHESSI helped us develop an automated technique to divide flares into multiple independent substructures. Analyzing those individual substructures is a more realistic approach to check for the nonthermal photon flux saturation limit.

A spectrum is generated for every substructure, from which a similar analysis leads to a confirmation of nonthermal photon flux saturation. The saturation limit was found to be around $10^{-15}$ photons cm$^{-2}$ s$^{-1}$ cm$^{-2}$. Substructures start reaching this
limit when the thermal energy flux reaches the critical value of $10^{-12}$keV.cm$^{-2}$.s$^{-1}$.cm$^{-2}$.

Substructures below this thermal energy flux limit were sampled and studied and beam currents were inferred from respective nonthermal photon fluxes assuming coulomb collisions dominating the energy loss mechanism. We found that while the nonthermal photon flux increased but stayed below $10^{-17}$photons.cm$^{-2}$.s$^{-1}$.cm$^{-2}$, corresponding to a thermal energy flux of $2\times10^{-13}$keV.cm$^{-2}$.s$^{-1}$.cm$^{-2}$, the beam current was also increasing and was well below the stability limit described by Alfvén (1939). This confirms that energy losses are mostly dominated by Coulomb collisions in this domain.

Furthermore, from the substructure nonthermal photon flux distribution, we can note that above a thermal energy flux value of $5\times10^{-11}$keV.cm$^{-2}$.s$^{-1}$.cm$^{-2}$, return currents dominate the energy loss mechanism.

Between those limits, both return currents and Coulomb collisions are responsible for energy losses.

Areas and total thermal energy for substructures were also compared. This approved the previous results that large flares are not primarily due to larger areas, but to larger photon fluxes.
4.2 Future Work

4.2.1 Substructure Analysis

Our next step is to increase our flare database and therefore sample many more substructures in order to refine our photon fluxes results, thus giving a better insight on the energy loss dominant mechanisms and their limit of application. For this process, the time evolution of solar flares must be thoroughly inspected on both whole flare and substructure scales, since in this study, we have concentrated on times around the peak of hard X-ray emission from the flare as a whole. However, we will be looking at substructures as independent emission mechanisms and analyzing them around their respective peaks of hard X-ray emission.

4.2.2 Coulomb Collisions - Return Currents Transition

Our results show that there is a transition between Coulomb collisions and return currents dominated energy losses. Therefore, further analysis would require a detailed numerical approach to include the joint effects of both loss mechanisms for this transition region. The way to determine the thick target photon flux will require solving the following equation:

\[
I_{thick}(\varepsilon) = \frac{S}{4\pi R^2} \int_{E_0=\varepsilon}^{\infty} F(E_0) \int_{\varepsilon}^{\infty} \frac{\sigma_B(\varepsilon, E) dE}{E(\sigma_{E,\text{coll}}(E) + \sigma_{E,\text{ret}}(E))} dE_0,
\]

where we include the cross sections for the particle energy loss process for both Coulomb collisions, \(\sigma_{E,\text{coll}}(E)\), and return current \(\sigma_{E,\text{ret}}(E)\) cases in (1.15), knowing
that for large electron fluxes (Alexander and Metcalf, 2003)

\[
\frac{\frac{dE}{dt}}{\frac{dE}{dt}}_{ce} = \left( \frac{\pi}{128} \right)^{1/2} \left( \frac{n_b}{n} \right) \left( \frac{\nu_b}{\nu_e} \right) \left( \frac{E_c}{kT_e} \right) > 1
\] (4.2)

This, together with a solution to (4.1), will help us set the limits for Coulomb collisions, transition region, and return currents dominant energy loss mechanisms.

### 4.2.3 Substructure Distribution

Furthermore, the automatic source identification code developed here can be applied to the detailed study of substructure distribution in solar flares. In this study (Section 3.3.3), we have reported that some substructures with very high photon fluxes existed in small flares while large flares included multiple substructures with low photon fluxes. Inspecting the flaring phenomenon at the level of substructures will yield better results in generating the distribution of fiducial flare events.

In fact, whole flare data show that flare size distribution covers a range of several orders of magnitude, with small events occurring much more frequently than large ones, especially during the years near sunspot maximum. The distribution of flare frequency with size exhibited a power law form with spectral index $\delta=1.8$ (Dennis, 1985) and a high energy cut-off (Figure 4.1).

Such a distribution is insufficient to explain the heating of the solar atmosphere by flare-like processes. A spectral index greater than 2 at low energies is required to match the radiative output of the solar atmosphere. Identifying individual flares as
Figure 4.1  Distribution of flare frequency versus size of event (Dennis, 1985)

comprised of the sum of elementary events may shed some new light on this problem.

Analyzing solar flare emission not only helps understand flares and their related energy release and particle acceleration mechanisms, but also helps better understand other physical processes in the Sun, like energizing the solar Corona. Examining the unprecedented RHESSI spatial and spectral resolutions with the image analysis package we have developed is a good step in this direction.
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