Contributions of the solar ultraviolet irradiance to the total solar irradiance during large flares

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[1] The solar X-ray radiation varies more than other wavelengths during flares; thus solar X-ray irradiance measurements are relied upon for detecting flare events as well as used to study flare parameters. There is new information about the spectral and temporal variations of flares using solar irradiance measurements from NASA’s Solar Radiation and Climate Experiment (SORCE) and the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) missions. For one, the improved measurement precision for the total solar irradiance (TSI) measurements by the SORCE Total Irradiance Monitor (TIM) has enabled the first detection of flares in the TSI. These flare observations indicate a total flare energy that is about 105 times more than the X-ray measurements in the 0.1–0.8 nm range. In addition, solar spectral irradiance instruments aboard TIMED and SORCE have observed hundreds of flare events in the 0.1 nm to 190 nm range. These solar ultraviolet measurements show that the ultraviolet irradiance changes during flares account for 50% or more of the flare variations seen in the TSI, with most of the ultraviolet contribution coming from the ultraviolet shortward of 14 nm. The remaining part of the flare energy is assumed to come from the wavelengths longward of 190 nm, typically only needing to be about 100 ppm increase for the largest flares. Another result is that the flare variations in the TSI have a strong limb darkening effect, whereby the flares near the limb indicate variations in the TSI being almost entirely from the ultraviolet shortward of 14 nm.


1. Introduction

[2] Solar flares have long been a topic of discussion in solar physics and are also very important for space weather research and associated effects on satellite, aircraft, communications, and navigation operations. Because flares can emit a large amount of radiation in the X rays and over a broad wavelength range, the large flare events and associated influence on Earth’s upper atmosphere are an important aspect of Sun-Earth connection studies. While solar flares have been observed in the visible for more than 100 years [e.g., Carrington, 1859], the X-ray and ultraviolet solar emissions more clearly identify the flare events due to the flare irradiance variations being a factor of 10 or more for X-ray (λ < 10 nm) radiation and being an increase of 10% or more for most vacuum ultraviolet (VUV: λ < 200 nm) emissions. Consequently, the satellite measurements of the Sun at X-ray and VUV wavelengths have enabled more detailed studies of flares starting in the 1960s. As used throughout this paper, the VUV wavelength range is subdivided into the hard X-ray (λ < 0.1 nm), soft X-ray (XUV: 0.1–10 nm), extreme ultraviolet (EUV: 10–120 nm), and far ultraviolet (FUV: 120–200 nm) wavelength ranges.

[3] Flare time series are often decomposed into the impulsive phase and the subsequent gradual (slow) phase [e.g., Donnelly, 1976]. The gradual component normally peaks several minutes after the impulsive phase, and the initial rise during the gradual phase can usually be described as the time integral of the impulse component. This relation is well known as the Neupert flare effect [Neupert, 1968] that was derived from studying the impulse component seen in microwaves and the gradual component seen in soft X rays. The Neupert effect is typically explained by the thick-target flare model [e.g., Brown, 1971; Hudson, 1972], whereby the same energetic electrons that produced the Bremsstrahlung emissions seen in microwaves and hard X rays near the magnetic reconnection footprints in the transition region and upper chromosphere also heat the plasma that rises and emits the soft X rays at a later time. The interaction of these energetic electrons can also produce enough emissions in the visible to contribute to the detection of white-light flares [e.g., Hudson, 1972]. The local heating in the upper chromosphere and transition region also radiates down to the lower solar atmosphere where the photospheric warming can also produce radiance increases in the visible [e.g., Metcalf et al., 1990]. For example, there is usually the detection of white-light flares (WLF) in solar visible images during the times of the larger X-ray flares.
[e.g., Neidig, 1989; Metcalf et al., 2003], but the WLFs had not been detected in the TSI record until 2003 because they are very small energetically compared to the spatially and spectrally integrated emission from the Sun.

[4] The solar X-ray irradiance measurements are commonly used to identify and classify flare events. The X-ray measurements in the 0.05 nm to 0.8 nm range have been made continuously for almost half a century by the X-ray Sensor (XRS) aboard a series of Solar Radiation satellites (SOLRAD) and Geostationary Operational Environmental Satellites (GOES) [Kahler and Kreplin, 1991; Garcia, 1994]. The X-ray classification of flares are based on the GOES XRS measurement in the 0.1 nm to 0.8 nm range, also referred to as the XRS-B channel. The X-ray classification includes a letter for the magnitude of the peak irradiance followed by a number within that magnitude. The letters (magnitude) used in this classification are A (10^-8 W/m^2), B (10^-7 W/m^2), C (10^-6 W/m^2), M (10^-5 W/m^2), and X (10^-4 W/m^2). For example, a M3.2 flare means that the 0.1–0.8 nm irradiance had a peak value of 3.2 x 10^-5 W/m^2. During solar cycles 21 and 22 there were, on average, one M-class (modest) solar flare every 2 days and one X-class (extreme) flare per month as determined from a survey of flares [Garcia, 2000].

[5] The primary source of energy for flares is considered to be magnetic reconnection in the corona, and this concept has been supported with numerical simulations of magnetic flux tubes in the corona [e.g., Fan, 2005; DeVore and Antiochos, 2005]. Emslie et al. [2004] have examined the magnetic energy released during two solar events and also examined the partition of the released energy into coronal mass ejections (CMEs) and flares. Despite it being limited to two flares, their results indicate that the CME kinetic energy is about the same as the released magnetic energy and that the flare energy is about 0.1 of the magnetic energy. They derived the energy content of the thermal and non-thermal electrons from the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) X-ray images and spectra. These flare energy results suggest that the total flare energy scales by about a factor of 10 of the X-ray energy as measured by the GOES XRS-B channel (0.1–0.8 nm). The new (first) measurements of the flares in the TSI record by SORCE TIM indicate instead that a flare’s total energy scales by about a factor of 10 of the X-ray energy as measured by the GOES XRS-B channel (0.1–0.8 nm). The X17 flare measurements from SORCE are [2005b]. The Spectral Irradiance Monitor (SIM) measures the solar spectral irradiance from 200 nm to 3000 nm with a resolving power of 300 and a design goal accuracy of 300 ppm [Harder et al., 2005a, 2005b; Rottman et al., 2005]. The SOLSTICE experiment used in data processing, the TSI data are effectively smoothed over 400 s with a near-Gaussian filter of 58-s.

The SORCE instruments measure the total solar irradiance (TSI) and the spectral irradiance in the 0.1–27 nm and 115–2500 nm ranges. The TIMED SEE instrument measures the solar VUV spectral irradiance shortward of 194 nm.

[7] The TIMED SEE consists of two instruments to measure the solar VUV spectral irradiance [Woods et al., 2005a]. The EUV Grating Spectrograph (EGS) has a spectral range of 26 nm to 194 nm with 0.4 nm spectral resolution. The XUV Photometer System (XPS) measures the solar irradiance from 0.1 nm to 34 nm with each photometer filter having a bandpass of 7–10 nm. The accuracy of the SEE solar irradiance is about 15% longward of 30 nm and about 30% shortward of 30 nm. The TIMED spacecraft was launched in December 2001, and the SEE daily measurements of the solar VUV irradiance have been made since 22 January 2002. The SEE solar observations are limited to 3 min per orbit (3% duty cycle) and obtain full VUV coverage with a 10 s time cadence during its observations. Some of the flare measurements by TIMED SEE are given by Woods et al. [2003, 2004, 2005a] and Chamberlin [2005].

[8] The SORCE spacecraft consists of four different instruments to measure the solar spectral irradiance and the TSI [Rottman, 2005]. The TSI is measured by the Total Irradiance Monitor (TIM), which has a design goal accuracy of 100 ppm [Kopp and Lawrence, 2005; Kopp et al., 2005a, 2005b]. The Spectral Irradiance Monitor (SIM) measures the solar spectral irradiance from 200 nm to 3000 nm with a resolving power of 300 and a design goal accuracy of 300 ppm [Harder et al., 2005a, 2005b; Rottman et al., 2005]. The SORCE spacecraft was launched in January 2003, and its daily measurements of the solar irradiance began in March 2003. SORCE solar observations are acquired for about 70 min each orbit (~70% duty cycle). Both SOLSTICE and SIM normally take an orbit to obtain a full spectral scan, so their measurements are not optimized for flare observations. However, the SOLSTICE has a miniscan experiment for the H I Lyman-α (121.6 nm) and Mg II (280 nm) emissions during one orbit each day, and this experiment, which has a time cadence of ~1 min, was fortuitously running during the X17 flare on 28 October 2003. The SORCE XPS and TIM are well suited for flares with their observing time cadences of 300 s and 50 s, respectively. The X17 flare measurements from SORCE are given by Woods et al. [2004], and Woods and Rottman [2005] give an overview of other flare measurements by SORCE XPS.

[9] The XPS and TIM measurements and their associated uncertainties are described briefly in more detail as these measurements are primarily used for the following flare analysis. The TIM measures the TSI using a mechanical, bistable open/close shutter operating at a 50% duty cycle over a period of 100 s. With the phase sensitive detection analysis used in data processing, the TSI data are effectively smoothed over 400 s with a near-Gaussian filter of 58-s.

2. Solar Irradiance Measurements

[6] The solar irradiance measurements of recent large flares are from solar instruments aboard the Solar Radiation and Climate Experiment (SORCE) spacecraft and the Solar EUV Experiment (SEE) on the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) satellite.

The SORCE spacecraft consists of four different instruments to measure the solar spectral irradiance and the TSI [Rottman, 2005]. The TSI is measured by the Total Irradiance Monitor (TIM), which has a design goal accuracy of 100 ppm [Kopp and Lawrence, 2005; Kopp et al., 2005a, 2005b]. The Spectral Irradiance Monitor (SIM) measures the solar spectral irradiance from 200 nm to 3000 nm with a resolving power of 300 and a design goal accuracy of 300 ppm [Harder et al., 2005a, 2005b; Rottman et al., 2005]. The Solar Stellar Irradiance Comparison Experiment (SOLSTICE) aboard SORCE measures the solar ultraviolet irradiance from 115 nm to 320 nm with 0.1 nm spectral resolution and with an accuracy of 5% [McClintock et al., 2005a, 2005b]. The SORCE XPS [Woods et al., 2005b; Woods and Rottman, 2005] is essentially identical to the XPS that is part of the TIMED SEE.

[8] The SORCE spacecraft was launched in January 2003, and its daily measurements of the solar irradiance began in March 2003. SORCE solar observations are acquired for about 70 min each orbit (~70% duty cycle). Both SOLSTICE and SIM normally take an orbit to obtain a full spectral scan, so their measurements are not optimized for flare observations. However, the SOLSTICE has a miniscan experiment for the H I Lyman-α (121.6 nm) and Mg II (280 nm) emissions during one orbit each day, and this experiment, which has a time cadence of ~1 min, was fortuitously running during the X17 flare on 28 October 2003. The SORCE XPS and TIM are well suited for flares with their observing time cadences of 300 s and 50 s, respectively. The X17 flare measurements from SORCE are given by Woods et al. [2004], and Woods and Rottman [2005] give an overview of other flare measurements by SORCE XPS.

[10] The XPS and TIM measurements and their associated uncertainties are described briefly in more detail as these measurements are primarily used for the following flare analysis. The TIM measures the TSI using a mechanical, bistable open/close shutter operating at a 50% duty cycle over a period of 100 s. With the phase sensitive detection analysis used in data processing, the TSI data are effectively smoothed over 400 s with a near-Gaussian filter of 58-s.
standard deviation, and the resulting TSI values are reported at 50 s cadence. The phase sensitive analysis, along with a good thermal design, permits unprecedented precision of 2 ppm for the TSI measurements. This precision for the instrument noise was empirically determined on-orbit from servo system and thermal noise measurements with the instrument’s shutters closed. The details of the TIM design, calibrations, and data processing are given by Kopp and Lawrence [2005] and Kopp et al. [2005a]. The TIMED XPS and SORCE XPS include 12 Si photodiodes of which 8 have XUV/EUV filters. These photometers are arranged with a filter wheel mechanism such that three photometers are making simultaneous observations, and the filter wheel is stepped during solar observations such that all photometers make an observation with a time cadence of 5 min for the SORCE XPS (see Woods et al. [2005b] for more details). The TIMED XPS only makes a single solar observation for 3 min per TIMED orbit, so the SORCE XPS provides the best time coverage for flares. These XUV/EUV photometers have broad spectral bands of 7–10 nm, and the detailed spectral characteristics and conversion factors are given by Woods et al. [2005b]. The measurement precision for the XPS is less than 1% as determined from in-flight dark measurements. The accuracy of the XUV/EUV irradiance from XPS measurements is about 30% due to preflight calibration uncertainties and because of the interpretation of the broad spectral bands and multiple spectral bands for some of the photometers as related to the assumptions of the solar spectral distribution used in the data processing [Woods et al., 2005b].

3. Irradiance Variations of Large Flares

3.1. Ultraviolet Variations of Flares

[11] Irradiance variations for flares are most clearly detected at the shorter wavelengths. As already pointed out, the GOES XRS-B measurements in the 0.1–0.8 nm band are used to classify a flare over 5 orders of magnitude change in intensity. The broadband XUV/EUV measurements in the 0.1–14 nm range also show large increases by factors up to 150 during flares. Using a threshold of a factor of two for the ratio of the flare peak irradiance to the preflare irradiance, the SORCE XPS has observed over 1000 flares between March 2003 and October 2005, and the TIMED XPS, with its much shorter duty cycle of 3%, has observed over 200 flares since January 2002. Four of the flares observed by the SORCE XPS were large enough to have a detectable signal in the SORCE TIM. In the EUV range from 27 nm to 120 nm, the irradiance variation is lower but is as much as a factor of 2 during the gradual phase of the large X-class flares and is even more than a factor of 10 during the impulsive phase for a few transition region emissions [Woods et al., 2004, 2005a, 2005b]. In the FUV range from 120 nm to 200 nm, the spectral irradiance variations for flares decrease with a general trend of less variability toward the longer wavelengths, reaching a non-detectable level longward of 185 nm [Woods et al., 2003, 2004, 2005a; Brekke et al., 1996]. The chromospheric emissions at longer wavelengths, such as the Mg II 280 nm emission, also indicate flare variations of about 10% or less [Woods et al., 2004].

[12] Because the irradiance variations due to flares are relatively easy to detect throughout most of the VUV range, there is better understanding of the flare events from the solar VUV observations. For one, it is well known that the location of the flare event on the solar disk greatly affects the magnitude of the flare as observed by Earth-based satellites [e.g., Donnelly, 1976]. Throughout most of the spectrum, the flare events near the solar disk limb are suppressed due to the radiative transfer out of the solar atmosphere. For example, the EUV increase during the X28 flare on 4 November 2003 at the solar limb is about a factor of 1.5, whereas the EUV increase during the X17 flare on 28 October 2003 near disk center is about a factor of 2 [Woods et al., 2004]. The exception is in the XUV/EUV range where the emissions are more optically thin, so the XUV/EUV variations are much less sensitive to flare location on the solar disk. Another important aspect of characterizing flare events is how different wavelengths contribute during the impulsive phase and gradual (slow) phase. The hard X-rays and microwave emissions are often used to characterize the impulsive phase, and the soft X-rays are used to describe the gradual phase [e.g., Neupert, 1968; Kane and Donnelly, 1971]. At wavelengths longward of 14 nm, the solar irradiance generally displays both impulsive phase and gradual phase components, whereby most wavelengths tend to have a larger impulsive phase component from 60 nm to 155 nm [Chamberlin, 2005].

[13] With the improved knowledge of flare events and with the new simultaneous measurement of the solar spectral irradiance shortward of 194 nm by TIMED SEE, several empirical and semiempirical models of the solar VUV irradiance are being updated or created to include variations due to flares. We mention briefly here the new flare model developments by Rodgers et al. [2006] and Chamberlin [2005]. Rodgers et al. [2006] uses the differential emission measure technique to semiempirically fit the TIMED SEE XPS measurements during flares, and their modeling results indicate that the irradiance in the 0–2 nm range contributes the most to the flare variation in the XUV/EUV range. Chamberlin [2005] developed a new empirical model of the solar VUV irradiance in the 0–190 nm range using the TIMED SEE, SORCE XPS, and UARS SOLSTICE measurements. This model, called the Flare Irradiance Spectral Model (FISM), has five components: (1) solar cycle minimum irradiance, (2) solar cycle variation, (3) solar rotation variation, (4) flare gradual phase variation, and (5) flare impulsive phase variation. Examples of the FISM components are shown in Figure 1. Several daily proxies appropriate for the emissions from the chromosphere, transition region, and corona are used for estimating the solar cycle and solar rotation variations. The standard total uncertainty for the FISM daily components is less than 15% longward of 30 nm and is about 35% shortward of 30 nm due primarily to the accuracy of SEE and SORCE XPS measurements. The GOES X-ray 0.1–0.8 nm irradiance and its time derivative, both at 1-min cadence, are the flare proxies for the gradual and impulsive phase components. The standard total uncertainty for the FISM flare components is about twice as large as the FISM daily components. These uncertainties for the flare components are simply empirical results that might be underestimated because FISM is based on a limited number of large two-ribbon flares. The FISM estimates for the four large flares seen in the TSI are included in Table 1 and discussed in section 3.3.
Most studies and models of flares concern the physics of the flare events (e.g., magnetic reconnection) and changes in the solar intensity throughout a flare event, but the focus here is instead on the total energy of the flare as derived by integrating solar irradiance observations over the time period of the flare event. For the XUV/EUV range, this time integration is a simple numerical integration of the SORCE XPS data with 5-min cadence with the start and stop times defined by when the irradiance is above the preflare irradiance level. A linear background level is subtracted prior to the time integration. Figure 2 shows an example XUV/EUV irradiance time series for the X10 flare on 29 October 2003. This flare’s energy at 4–14 nm is about 60% more than the 0–4 nm flare energy, and the 0–27 nm flare energy is about 50 times more than the GOES 0.1–0.8 nm flare energy. The diamonds are the measurements, and the lines are log-interpolations between the measurements that are used for numerical integration of the flare energy. The dashed line is the background irradiance level subtracted before integrating for the flare energy.

Table 1. X-Ray and Ultraviolet Energy for Four Large Flares

<table>
<thead>
<tr>
<th>Observation Date and Peak Time, UT</th>
<th>GOES Class (Location)</th>
<th>GOES 0.1–0.8 nm Energy, ergs</th>
<th>XPS 0.1–27 nm Energy, ergs</th>
<th>FISM 0–190 nm Energy, ergs</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/28/03 1110</td>
<td>X17 (E08 S16)</td>
<td>3.7 x 10^{36}</td>
<td>1.3 x 10^{32}</td>
<td>2.6 x 10^{32}</td>
</tr>
<tr>
<td>10/29/03 2049</td>
<td>X10 (W02 S15)</td>
<td>1.9 x 10^{36}</td>
<td>9.1 x 10^{31}</td>
<td>1.2 x 10^{32}</td>
</tr>
<tr>
<td>11/04/03 1957</td>
<td>X28 (W83 S19)</td>
<td>5.3 x 10^{36}</td>
<td>2.2 x 10^{32}</td>
<td>1.8 x 10^{32}</td>
</tr>
<tr>
<td>9/7/05 1740</td>
<td>X17 (E77 S11)</td>
<td>4.7 x 10^{36}</td>
<td>2.0 x 10^{32}</td>
<td>3.0 x 10^{32}</td>
</tr>
</tbody>
</table>

aThe GOES 0.1–0.8 nm energy, XPS 0.1–27 nm energy, and FISM 0–190 nm energy are obtained over the same time period as the TSI integration for these flares. The total flare energy results are given in Table 2.
being 30% for both XPS [Woods et al., 2005b] and GOES XRS (R. Viereck, private communication, 2005). Partly because both spectral bands are in the XUV where the emissions are more optically thin and less sensitive to the location of the flare events on the solar disk, the comparison indicates a reasonable linear relationship. The slope for the fitted line is 45 indicating that the flare energy in the 0.1–27 nm range is 45 times greater than the flare energy derived from the GOES 0.1–0.8 nm measurement. However, a 2-parameter power law relationship as listed in equation (1) is a better fit for these data with K being 63 and N being 0.80.

\[ E_{XPS} = KE_{XSV}^N \]  

The XPS subscript is the 0.1–27 nm range as measured by SORCE XPS, and the SX subscript is the 0.1–0.8 nm range as measured by GOES XRS-B. If the data for just the four flares observed by TIM are fitted, then the resulting K parameter is 50 while maintaining the same N value of 0.80. This difference is well within the flare energy uncertainty of 30%. The XPS variation is discussed more in section 3.3 when comparing the flare variations in the TSI to the GOES and XPS flare measurements.

3.2. TSI Variations of Flares

[16] While white light flares have been observed in solar images for a long time [e.g., Carrington, 1859], there had not been a clear indication of a flare detection in the TSI record until SORCE TIM detected the X17 flare on 28 October 2003 [Woods et al., 2004]. In examining the TSI time series for other flares, it appears that the TSI variations for the larger X-class flares is only about 100 ppm, which is only slightly larger than the magnitude of disk-integrated background solar fluctuations observed continually. These solar fluctuations are likely a disk-integrated combination of p-mode oscillations [Woodard and Hudson, 1983] and convection noise [Harvey, 1985]. Consequently, only the very largest flares are detectable in the TSI record. For example, Hudson and Wilson [1983] were unable to detect flares in the ACRIM TSI time series but were able to place upper limits for the flare energy from this earlier study. So far during the SORCE mission, there are four flares that have been detected in the TSI time series as listed in Table 2. Figures 4 and 5 show the TSI variations of these TIM flare observations, sorted by position of the flare on the solar disk. All of the flares indicate a significant TSI component for both the impulsive phase and gradual phase, as indicated by the GOES flare components shown in Figures 4 and 5 and listed in Table 2. The two flares shown in Figure 4 are when the flare event was near the solar disk center, and these flares are most clearly identified. The limb flares shown in Figure 5 are comparable in magnitude to the normal daily solar fluctuations; thus the integration over time for these flares is more difficult in both selecting the start and stop times and in identifying the background level to subtract from the time series. Instead of doing a numerical integration on the TSI time series as done for the GOES and XPS time series with their small background levels, components that represent the impulsive phase and gradual phase of the flare are fitted to the TSI time series after estimating a linear trend for the TSI background level. As done for FISM [Chamberlin, 2005], the GOES X-ray time series represent the gradual phase component, and the derivative of the GOES time series represents the impulsive phase component.

[17] The selection of the TSI background level and accounting for the solar fluctuations are the largest sources of uncertainty of the total flare energy estimates. The background level is defined as the line between the average

![Figure 3. XUV and EUV flare energy comparison. The 194 M and X class flares observed during the SORCE mission are compared to the GOES 0.1–0.8 nm flare energy. The XPS 0.1–27 nm flare energy is, on average, 45 times greater than the GOES X-ray energy, but a power law relationship is best fit for these data as shown by the black, dashed line. The grey diamonds are the four flare events also observed in the TSI by SORCE TIM. The grey, dashed (lower) line shows the fit of just these data. See the text for the fit results.](image)

### Table 2. Total Flare Energy for Four Large Flares

<table>
<thead>
<tr>
<th>Observation Date</th>
<th>GOES Class</th>
<th>XPS Total Flare Energy for TSI, 10(^{-12}) ergs</th>
<th>TSI Fit IP Amplitude, %</th>
<th>Ratio (E_{TSI}/E_{TSI}^0)</th>
<th>Ratio (E_{XPS}/E_{XPS}^0)</th>
<th>Ratio (E_{SX}/E_{SX}^0)</th>
<th>Total Flare Energy Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/28/03</td>
<td>X17</td>
<td>6.0</td>
<td>50%</td>
<td>162</td>
<td>0.22</td>
<td>0.43</td>
<td>39%</td>
</tr>
<tr>
<td>10/29/03</td>
<td>X10</td>
<td>2.4</td>
<td>32%</td>
<td>126</td>
<td>0.38</td>
<td>0.50</td>
<td>86%</td>
</tr>
<tr>
<td>11/04/03</td>
<td>X28</td>
<td>2.6</td>
<td>17%</td>
<td>49</td>
<td>0.85</td>
<td>0.69</td>
<td>65%</td>
</tr>
<tr>
<td>9/7/05</td>
<td>X17</td>
<td>3.0</td>
<td>0%</td>
<td>64</td>
<td>0.67</td>
<td>1.00</td>
<td>71%</td>
</tr>
</tbody>
</table>

*The total flare energy is from a fit of the TSI time series using the impulsive phase and gradual phase components from the GOES X-ray data. The “TSI Fit IP Amplitude” column is the amplitude of the impulsive phase relative to the sum of the amplitudes of both phases. For example, a relative amplitude of 50% means the two flare components have equal amplitudes in fitting the TSI time series. The ratios are for the energy integrated over the flare event and for the spectral bands listed.
of the TSI two orbits before and after the flare. Thus the selected background level should represent the TSI trend through the middle of the fluctuations. Attempts to model the solar fluctuations in the TSI time series during the flare event were not successful. While one can see the 5 min oscillation in the TSI time series, the spectral power analysis of the TSI data indicates that the 5 min period is only about 10% (4 ppm) of the total fluctuations seen; consequently, the fluctuations need to be modeled using many different frequencies. However, these frequency components are not consistent from orbit to orbit, so the TSI fluctuation results from adjacent orbits are not directly applicable for the orbit that contains the flare event. So instead of modeling (removing) the solar fluctuations, the flare components from the GOES X-ray data are fitted to the TSI data that have the background subtracted but still contain the fluctuations. This approach does increase the uncertainty for the results that are proportional to the amount of the solar fluctuations relative to the flare increase. The total flare energy listed in Table 2 is the time integration of the flare components that are based on the GOES X-ray data. A direct, numerical integration of the TSI time series was also done for validation, and these results agree reasonably well, to about 30%, with the results using the GOES flare components. The results based on the fitting with the GOES flare components are the ones used for the ratios given in Table 2 and for discussing the total flare energy.

The uncertainties for the total flare energy from the TSI measurements have the largest contributions from the selection of the TSI background level and fitting the two flare components using the GOES X-ray measurement. The solar fluctuations play a major role in these error sources. The variations from the solar fluctuations are about ±30 ppm and thus are 20–30% of the TSI variations at the time of the flare peaks. The uncertainty for the total flare energy due to the solar fluctuations affecting the selection of the TSI background level is about 30% for the flare on 28 October 2003, but this uncertainty is about 60% for the other flares. The uncertainties for fitting the two flare components are estimated to be 20% to 40% as based on the variation of the different magnitudes of the impulsive and gradual phases for the different fits. The selection of the time period for the time integration contributes a small

Figure 4. TSI variation for the large flares on 28 October 2003 and 29 October 2003. Both of these flares were from the same active region near the solar disk center. The GOES X-ray time series (gradual phase) and its time derivative (impulsive phase) are used to fit the TSI time series with an additional linear background trend (red line). The combination of the flare components is shown as the green line, and the dashed green line is just the gradual phase component. The time period for the integration is indicated by the dotted-dashed lines. The XPS 0.1–27 nm data (blue line) after being added to the TSI background level are also shown.

Figure 5. TSI variation for the large flares on 4 November 2003 and 7 September 2005. These flares were from an active region near the solar limb. These plots have the same color coding as those shown in Figure 4.
uncertainty of about 2% based on selecting different start and stop times for the integrations. Combining these uncertainties, the total uncertainties for the total flare energy, as listed in Table 2, are about 40% for the flare on 28 October 2003 and about 70% for the other flares.

The source of energy for these large flares is considered to be magnetic reconnection, whereby protons and electrons are highly accelerated, both downward to produce the flare radiation and upward to create potentially solar energetic particles (SEPs) and coronal mass ejections (CMEs). For example, Metcalf et al. [2005] report that the NOAA active region 10486 had \( 5.7 \times 10^{33} \) ergs of magnetic free energy during the time of the X10 flare on 29 October 2003. The TIM result for this flare indicates total flare energy of about \( 2 \times 10^{32} \) ergs, which is more than an order of magnitude less than the magnetic free energy.

The comparison of the total flare energy from the TSI measurement to the GOES X-ray flare energy is limited to a small number of flares and is challenging because of the issues in integrating the TSI time series. The X17 flare on 28 October 2003 is the most accurate detection of a flare in the TSI time series. For the two flares near disk center, the total flare energy is a factor of about 140 times the GOES X-ray flare energy. The other two flares occurred near the limb, and the total flare energy to the GOES X-ray flare energy is a factor of about 50 for the limb flares. This lower factor for the limb flares is related to how the flare intensity depends on the location of the flare on the disk.

The TSI to X-ray ratio is expected to be lower for limb flares as compared to disk center flares because the solar X-ray emissions are optically thin with flat or slight limb-brightening center-to-limb variation (CLV) and ultraviolet wavelengths longward of 160 nm and visible emissions are limb-darkened. The ratios of the total flare energy to the GOES X-ray flare energy, \( R \), are fitted with a CLV function given in equation (2) and shown in Figure 6.

\[
R = R_C \cdot \left( k + 2 \cdot (1 - k) \cdot \left( \frac{\mu^2}{2} \right) \right)
\]

In this equation, \( R_C \) is the ratio at disk center, \( \mu \) is the cosine of the heliocentric angle, and \( k \) is the limb ratio relative to the center using the CLV equation from Brekke and Kjeldseth-Moe [1994]. The least-squares fitted values for these parameters are 149 for \( R_C \) and 0.11 for \( k \). The uncertainty for the \( R_C \) parameter is about 50% as it is dependent mostly on the disk center flares, and the uncertainty for the \( k \) parameter is about 70% as it is dependent mostly on the limb flares.

As preliminary validation for this CLV result, the XPS results for these four flares and some WLF results from Hudson et al. [2006] are included in Figure 6. Hudson et al. [2006] discusses several WLFs observed by the Transition Region and Coronal Explorer (TRACE) using its white-light filter. The ratio included in Figure 6 is their peak intensity in white-light to the peak irradiance from the GOES X-ray \((0.1-0.8 \text{ nm})\) measurement, and with this ratio normalized to the TSI/GOES ratio at disk center. While the WLF ratio is not the total flare energy, the WLF comparison shows a similar variation with heliocentric angle as the TSI ratio. The ratio of the XPS \(0.1-27 \text{ nm}\) flare energy to the GOES flare energy is also shown in Figure 6. The XPS ratio is essentially flat (constant) with heliocentric angle. Consequently, the XPS ratio is much lower than the TSI ratio for the disk center flares, and the XPS ratio is slightly lower than the TSI ratio for the limb flares. The WLF and XPS results suggest that the CLV function fit for the TSI ratio is a reasonable result.

It has been assumed in these discussions about the total flare energy that all of the radiation has uniform angular distribution. Thus, the irradiance integration result (in units of \( \text{J/m}^2 \text{ at Earth} \)) has been converted to units of ergs at the Sun by multiplying by \( 1.406 \times 10^{30} \left( \frac{\text{erg}}{\text{AU}^2} \right) \). While this assumption is more reasonable for the XUV and EUV emissions that are optically thin, the above CLV function provides a means to estimate this conversion factor for the TSI. The integration over a hemisphere of the CLV function (with \( k = 0.11 \) and without the \( R_C \) parameter) is \( 1.4 \cdot \pi \), and this result falls about midway between a uniform angular distribution \( (2 \cdot \pi) \) and the Lambertian (isotropic) distribution \( \pi \). Assuming the \( 2 \cdot \pi \) factor is still used for the GOES X-ray flare energy conversion and this new factor of 1.4 \( \cdot \pi \) is applied for the TSI energy conversion, then the improved parameters for the ratio of the total flare energy to the GOES X-ray energy are 105 for \( R_C \) and 0.11 for \( k \) for the CLV function. It is important to note that the CLV function is for the flare energy observed at Earth and is dependent on the heliospheric angle for the flare and that the total flare energy scales as a factor of 105 times the GOES X-ray flare energy and is independent of flare location. In other words, the CLV relationship is useful for Sun-Earth studies such as for space weather applications, and the scale factor of 105 times the GOES X-ray flare energy is useful for solar physics studies.

This new result for the total flare energy is significantly larger than previously expected. Hudson and Willson
Hudson/C2 Shimizu Emslie et al. [2004] are somewhat, Woods et al. ergs for the April and July 2002 flares, respectively.

However, the total flare energy, independent of the heliocentric angle or view angle, is estimated by scaling the GOES X-ray flare energy by a factor of 105, so the estimated total flare energy is $1.7 \times 10^{32}$ ergs for both flares. These results are a factor of 8.5 and 14 larger than the method using emission measure and the Chianti atomic database. These differences are possibly related to the limited wavelength range for the calculations using the Chianti atomic database and to the fact that the emission measure technique is not appropriate for the emissions at the longer UV wavelengths.

3.3. Contribution of VUV Variations to TSI Variations

Another aspect to consider is how the flare variations are distributed in wavelength. The XUV/EUV and TSI variations are measured with about 300 s and 50 s cadence by SORCE XPS and TIM, respectively. The temporal coverage at the other wavelengths is much less frequent, so there is limited information for studying the flare time series at most wavelengths. There are two techniques considered here to study the spectral variations of flares. One approach is to compare the flare energy from both the VUV and TSI time series by integrating over the same time period. This approach is only applicable if both time series have similar time cadence and are almost continuous (high duty cycle), thus the XPS and TIM measurements can be compared in this way with their ratio listed in Table 2. From this comparison, the XPS flare energy in the 0.1–27 nm range is about 30% of the total flare energy for the two flares near disk center. This result implies that about 70% of the flare energy is at wavelengths longward of 27 nm. For the flares near the limb, the XPS flare energy is 70% or more of the total flare energy. This increase of the XUV/EUV contribution is expected as the XUV/EUV emissions have flat or slight limb-brighten CLV and the visible wavelengths, which contribute the most to the TSI, are limb-darkened. Considering the relatively large uncertainty for the TSI flare results, it is possible that the total flare energy for the limb flares could be entirely from the XUV/EUV variation.

Another approach is comparison of the irradiance variation at certain times during the flare event, and this technique is useful for limited data sets, either in time cadence or duty cycle. Woods et al. [2004] report that the spectral irradiance variations relative to the TSI variation near the peak of the X17 flare on 28 October 2003 are 19% for the XPS (0.1–27 nm), 1.4% for the EUV (27–120 nm), and 2.3% for the FUV (120–194 nm). This result is based on SORCE measurements near the impulsive phase peak and on TIMED SEE measurements 9 min after the flare peak. Because these measurements are not at the same time, these variations from Woods et al. [2004] are somewhat misleading, and a new analysis is presented here with a more detailed time series of the variations for this X17 flare as shown in Figure 7. This figure includes the time series of the TSI measurement from SORCE TIM, the XPS 0.1–27 nm irradiance measurement from SORCE XPS, and the VUV 0–190 nm irradiance estimate from the Flare Irradiance Spectral Model (FISM) [Chamberlin, 2005]. The SORCE TIM and XPS measurements are reported with 50 s and 300 s cadences, respectively, both with observation gaps during the eclipsed portion of the orbit, and FISM estimates are at 1 min cadence without any gaps. The

![Figure 7. Time series of the UV irradiance and TSI for the X17 flare on 28 October 2003.](image_url)
average ratio of the XPS to the TSI variation during the early part of the gradual phase is 0.25, and the average ratio of the VUV to the TSI is 0.60. These ratios are for the estimated flare contribution after the TSI background (linear trend) is subtracted from each time series. It is interesting to note that most of the VUV radiation, which is longward of the XPS range, has a strong impulsive phase contribution and that the XPS range has a strong gradual phase contribution. The flare variation in the TSI indicates a stronger and earlier rise than the FISM estimates. All of the flares studied here indicate a similar trend as this X17 flare on 28 October 2003 that is shown in Figure 7. The technique of using the time derivative of the GOES X-ray time series to represent the impulsive phase contribution in FISM is possibly the primary reason why FISM estimates do not better represent the flare variations during the impulsive phase. However from the irradiance measurements alone, we cannot rule out the possibility that the chromospheric and photospheric emissions at wavelengths longward of 190 nm might contribute to these impulsive phase variations seen in the TSI.

[28] These results are based on a limited number of flares, so it is difficult to generalize the expectations on how the VUV variations might contribute to the TSI variations during flare events. There are many more flares observed by TIMED SEE with simultaneous spectral coverage from 0.1 nm to 194 nm. These SEE flare measurements do consistently have similar spectral variations if they are sorted into impulsive phase flares and gradual phase flares [Chamberlin, 2005]. These spectral variations are similar to those shown by Woods et al. [2004, 2005a] whereby the XPS irradiance has the largest variations shortward of 14 nm, the EUV irradiance has moderate variations between 14 nm and 140 nm, and the FUV irradiance has low variations to very low variations at wavelengths longward of 170 nm. Assuming this type of spectral variation for most flares, then about 50% of the TSI variation can be explained by the 0.1–194 nm variations for flares near disk center. The missing flare energy (~50%) would need to come from the ultraviolet longward of 200 nm, visible, and near infrared by a magnitude similar to the TSI variation during the flare, being about 100 ppm. This concept is consistent with the expectations for white-light flares observed in solar images, but now the magnitude for the spectral variations has some constraints with the recent TSI measurements of these large flares.

[29] For flares near the solar limb, the ultraviolet radiation contributes much more to the TSI variation as seen in both the XPS 0.1–27 nm measurements and FISM 0–190 nm estimates. For these limb flares, the XPS contribution is 70–90%, and the FISM estimates indicate an ultraviolet contribution of 70–100%. The X28 flare on 4 November 2003 is the flare closest to the limb, and the XPS (0.1–27 nm) variation appearing 20% larger than the FISM (0.1–190 nm) variation during this flare is an unrealistic result. The XPS measurements of this X28 flare have a 30 min data gap right after the flare peak as shown in Figure 5a, and the interpolation over this gap appears to be the source for larger uncertainty in deriving the integrated flare energy in the XPS 0.1–27 nm range. These limb flares do pose issues in obtaining the total flare energy; nonetheless, the XPS measurements do provide a lower limit for the flare results from the TSI measurements.

4. Summary

[30] The new results from the TSI measurements of four large X-class flares are that (1) the total flare energy is more than 10^{28} ergs, (2) this total flare energy is about 105 times the flare energy observed by GOES in the 0.1–0.8 nm range, (3) the flare energy in the VUV is about 50% of that in the TSI for flares near disk center, (4) the VUV variation dominates the TSI flare variation for limb flares, and (5) the remaining part of the TSI flare variation is apparently at wavelengths longward of 200 nm in the near ultraviolet, visible, and infrared ranges. As already stated, the flare spectral variations and associated total flare energy strongly depend on the flare location. The flares near solar disk center are more intense than the limb flares in TSI, and these limb center flares show a factor of about 105 for total flare energy as compared to the GOES X-ray (0.1–0.8 nm) flare energy. The values of 105 for Rc and 0.11 for k in the CLV function (equation (2)) are recommended for estimating the flare energy observed at Earth relative to the GOES X-ray (0.1–0.8 nm) flare energy, and this result assumes that factors of 2 \bullet \pi and 1.4 \bullet \pi are used for the energy conversion of the GOES X-ray irradiance and TSI, respectively. For estimating the total flare energy, independent of heliocentric angle, then we recommend that the GOES X-ray flare energy be multiplied by a factor of 105. These flare results support the thick-target flare concept whereby the flare event in the corona, presumably initiated by magnetic reconnection, accelerates particles that are absorbed in the transition region and upper chromosphere, which in turn respond by significantly increasing the emissions during the impulsive phase to further heat the chromosphere and photosphere [e.g., Brown, 1971; Hudson, 1972; Metcalf et al., 2003]. Further analysis of the WLFs from TRACE, as done by Hudson et al. [2006], is expected to provide additional useful information about the total flare energy. These TSI measurements of flares shed new light on the energy partition between SEPs, CMEs, and flares during solar storm events and have potential to advance both solar physics of flares and studies of flare effects on Earth’s environment.

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