CONTINUUM CONTRIBUTIONS TO THE SDO/AIA PASSBANDS DURING SOLAR FLARES

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ABSTRACT

Data from the Multiple EUV Grating Spectrograph component of the Extreme-ultraviolet Variability Experiment (EVE) on board the Solar Dynamics Observatory (SDO) were used to quantify the contribution of continuum emission to each of the extreme ultraviolet (EUV) channels of the Atmospheric Imaging Assembly (AIA), also on SDO, during an X-class solar flare that occurred on 2011 February 15. Both the pre-flare-subtracted EVE spectra and fits to the associated free–free continuum were convolved with the AIA response functions of the seven EUV passbands at 10 s cadence throughout the course of the flare. It was found that 10%–25% of the total emission in the 94 Å, 131 Å, 193 Å, and 335 Å passbands throughout the main phase of the flare was due to free–free emission. Reliable measurements could not be made for the 171 Å channel, while the continuum contribution to the 304 Å channel was negligible due to the presence of the strong He ii emission line. Up to 50% of the emission in the 211 Å channel was found to be due to free–free emission around the peak of the flare, while an additional 20% was due to the recombination continuum of He ii. The analysis was extended to a number of M- and X-class flares and it was found that the level of free–free emission contributing to both the 171 Å and 211 Å passbands increased with increasing GOES class. These results suggest that the amount of continuum emission that contributes to AIA observations during flares is more significant than stated in previous studies which used synthetic, rather than observed, spectra. These findings highlight the importance of spectroscopic observations carried out in conjunction with those from imaging instruments so that the data are interpreted correctly.

Key words: Sun: corona – Sun: flares – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

Since its launch in 2010 February, the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) has been producing high-resolution, full-disk images of the Sun in 10 wavelength bands with a 12 s cadence. This instrument has a similar spatial resolution to that of a former solar imager, the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999), but has an increased field of view, temporal resolution, and spectral coverage. Seven of the 10 passbands are tuned to observe emission in the extreme ultraviolet (EUV; 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å, and 335 Å) and each of these passbands contain emission lines formed at distinctly different temperatures, as well as potential continuum emission. Knowledge of which emission processes dominate the images under different conditions is crucial for interpreting the data correctly.

Analysis of the emission contributing to the 171 Å and 195 Å channels on TRACE during solar flares was previously carried out by Phillips et al. (2005) using the CHIANTI atomic database (Version 5; Dere et al. 1997). Typically, these channels were dominated by emission at quiescent coronal temperatures (1–2 MK). During flares, however, the 195 Å channel became sensitive to emission from the Fe xxiv line at 192.03 Å, which is formed at ~15 MK. Above these temperatures, continuum emission was found to dominate the 171 Å channel. In the 195 Å channel, the maximum contribution from continuum emission was estimated to be about 10% at a temperature of 4 MK. Feldman et al. (1999) and Warren & Reeves (2001) also showed that the continuum contribution to the 171 Å channel introduced further ambiguities when determining flare temperatures using filter ratio techniques.

Theoretical analysis of the composition of the SDO/AIA images has been conducted by O’Dwyer et al. (2010). The authors examined the contribution of both line and continuum (free–free) emission to each of the EUV channels for quiet Sun, coronal hole, active region, and flare plasmas by convolving synthetic spectra, obtained using the CHIANTI atomic database (Version 6.0.1; Dere et al. 2009) under an assumed differential emission measure (DEM), with the response function for each AIA channel (Boerner et al. 2012). In the case of flaring plasma, the DEM of Dere & Cook (1979) from the decay phase of an M2 flare was used. Coronal abundances from Feldman et al. (1992), ionization equilibrium, and an electron density of 1011 cm−3 were also assumed. Under these conditions the authors found that the continuum contribution to each channel was negligible (<6%), except in the case of the 171 Å and 211 Å channels where it was found be as high as 23% and 41%, respectively.

More recently, however, Milligan et al. (2012a) used spectral data from the EUV Variability Experiment (EVE; Woods et al., 2012), also on SDO, to show that continuum emission, both free-free (due to thermal bremsstrahlung) and free-bound (due to recombination), became significantly enhanced during an X-class solar flare. It was shown that the light curves of the free-free emission rose in concert with that of the GOES 1–8 Å lightcurve suggesting that the emission is predominantly coronal in nature, while the free-bound emission from H (Lyman continuum) and He i peaked around the time of hard X-ray (HXR) emission as observed by the Ramaty High-Energy Solar Spectroscopic Imager (Lin et al. 2002) indicating a
The flare (01:55:32 UT). The pre-flare irradiance was calculated by averaging over 90 s prior to the flare onset (from 01:00:12–01:01:42 UT) and was subtracted from the total irradiance to isolate the flux produced by the flare itself. This figure shows that the underlying free–free emission (represented by the solid blue curve) spans the entire MEGS-A spectral range, and that the enhancement due to the flare is greater at shorter wavelengths. The locations of the AIA passbands are also noted. The recombination continuum of He II (purple curve blueward of the recombination edge at 228 Å; vertical dashed purple line) is also visible and appears to straddle the 211 Å passband.

Measurements of the continuum emission during this flare were previously carried out by Milligan et al. (2012a) by fitting the line-free portions of the EVE MEGS-A spectrum (deduced from a synthetic flare spectrum from CHIANTI) with an exponential function. However, given that the EVE wavelength range is likely to contain emission lines that are not present in the CHIANTI database (cf. Brown et al. 2008) it is possible that a number of weak lines may have biased the previous fits to the continuum. Furthermore, this technique was found to produce erratic continuum time profiles for other events. So, rather than assuming that a limited number of spectral ranges were free from continuum. Furthermore, this technique was found to produce erratic continuum time profiles for other events. So, rather than assuming that a limited number of spectral ranges were free from continuum contributions, and its first and second derivatives of the EVE spectra (I(λ, t); bottom two panels of Figure 2) with respect to wavelength, such that

\[
\frac{dI(\lambda, t)}{d\lambda} \approx 0 \quad \text{and} \quad \frac{d^2I(\lambda, t)}{d\lambda^2} > 0, \quad \text{and} \quad \frac{dI(\lambda_i+1, t)}{d\lambda} > \frac{dI(\lambda_i-1, t)}{d\lambda},
\]

where \(i\) is the index of the wavelength bin at which the first two conditions were met.

These local minima (blue diamonds in Figure 2) were then fit with an exponential function of the form \(I(\lambda, t) = a \exp(b\lambda)\) (solid blue curve) similar to that of Milligan et al. (2012a). However, three wavelength ranges (light shaded areas in Figure 2) were omitted from the fitting process in order to
Figure 2. Example of how EVE spectra were fit in order to quantify the continuum emission. Top panel: pre-flare-subtracted EVE MEGS-A spectrum ($I(\lambda)$) from 60–350 Å near the SXR peak of the 2011 February 15 flare. Bottom two panels: first and second derivatives of the spectrum with respect to wavelength, respectively. The blue diamonds denote the location of the local minima, $I(\lambda_i)$, where $dI(\lambda)/d\lambda \approx 0$ and $d^2I(\lambda)/d\lambda^2 > 0$. These data points were fit with an exponential function with which to represent the free–free continuum (solid blue curve in top panel). Similarly, the purple asterisks denote the location of the local minima over the 210–228 Å range (having subtracted the fit to the free–free emission) with which to quantify the He ii continuum (purple curve). The gray shaded areas illustrate the portions of the spectra which were omitted during the fitting process (see text).

(A color version of this figure is available in the online journal.)

Prevent possible biases: 60 Å < $\lambda$ < 80 Å was omitted due to edge effects in the background-subtracted EVE data at these wavelengths; 100 Å < $\lambda$ < 125 Å was omitted to avoid the pseudo-continuum generated by the close proximity of the high-temperature Fe lines (Fe xix–Fe xxiii); and 160 Å < $\lambda$ < 230 Å was omitted to avoid any negative flux values around 171 Å due to possible coronal dimming (Woods et al. 2011), and the free-bound emission blueward of the He ii edge at 228 Å.

Having generated a fit to the free–free continuum, this was then subtracted from the data to allow the fitting of the free-bound continuum of He ii (assumed to extend from 200–228 Å) using a similar local minimum tracking procedure. The 200–210 Å range (dark shaded region in Figure 2) was omitted from the fitting process due to an elevated pseudo-continuum, while the local minima between 210–228 Å (purple asterisks in Figure 2) were fit with an exponential function. However, these fits were only carried out up until the end time of the flare as stipulated in the GOES event list,4 beyond which the continuum became too weak to measure reliably.

Both the pre-flare-subtracted EVE data and the fits to the underlying continua were convolved with the AIA response functions at each 10 s interval throughout the course of the flare.

4 The end time of a GOES event is defined as the time when the flux in the 1–8 Å channel decays to a point halfway between the maximum flux and the pre-flare background level.
to yield a measurement of the relative continuum contribution to each channel. The continuum was subtracted from the total irradiance in each channel to establish the relative contributions from the total line emission at each time interval as well.

The effective areas for each of the seven EUV channels on AIA were retrieved using the aia_get_response function (Version 4) available in SolarSoftWare IDL (Freeland & Handy 1998). The EVENORM keyword was applied to normalize the wavelength response functions to give a better agreement with full-disk EVE observations. Each channel has a fairly symmetric Gaussian response function centered on its primary wavelength (red curves in Figure 3).

However, the response function for the 335 Å channel also shows additional contributions from shorter wavelengths. Boerner et al. (2012) predicted a second-order peak around 184 Å due to mirror reflectivity, which is shown in Figure 3(g). The existence of crosstalk at 131 Å in this channel was also predicted. Each telescope on the AIA instrument carries two channels which are grouped to minimize crosstalk. However, the effects are non-negligible for the wavelength response function of the 335 Å channel which shares telescope 1 with the 131 Å filter. Focal-plane filters select the required channel for data acquisition, but the 335 Å focal-plane filter also receives some light from the highly reflective 131 Å channel. More recently, a significant “red leak” was discovered in the 335 Å channel during flares, as the response function at 335 Å channel during flares, as the response function at

Figure 3. Plots of the EVE spectra (black histograms) and fits to the free–free continuum (solid blue line) around each of the seven EUV passbands on AIA at the SXR peak of the 2011 February 15 flare. In panel (e), the fit to the He II continuum is also shown. The AIA effective areas are overplotted as the solid red curves. The convolved profiles are also overplotted: the black dotted lines for the total EVE spectra, the blue dashed lines for the free–free continuum, and the dot-dashed purple line for the He II continuum.

(A color version of this figure is available in the online journal.)
Figure 4. EVE MEGS-B spectrum, from 350–1050 Å, also taken at the peak of the 2011 February 15 flare (pre-flare-subtracted), plotted using the same y-axis scaling in Figure 3(g). Overlaid is the component of the 335 Å response function (red curve) that spans this wavelength range. The “red leak” can be seen as a hump between 500–800 Å. The recombination edges of He i and H Lyman are also plotted as the vertical dashed purple lines.

3. RESULTS

3.1. Spectral Convolution for the 2011 February 15 Flare

Figure 3 shows the pre-flare-subtracted spectra from EVE (black histogram) around the central wavelength range of each of the seven AIA channels at a time close to the peak in SXR emission of the 2011 February 15 flare. The black dotted lines show the EVE spectra having been convolved with the AIA effective areas and so shows the total predicted irradiance observed by each of the AIA passbands. The solid blue line shows the fit to the free–free continuum obtained using the method described in Section 2, while the blue dashed line shows this fit convolved with the AIA effective areas for each passband. The effective areas themselves are overplotted in red. In Figure 3(e), the fit to the He ii continuum around the 211 Å channel is overlaid in purple. The convolution of this fit with the response function is shown as a dot-dashed purple line.

At the peak of the flare, the 94 Å channel showed a strong line at 93.93 Å due to Fe xvii above the underlying free–free emission (Figure 3(a)), while the 131 Å channel appeared to be dominated by Fe xxi and Fe xxii at 128.75 Å and 132.91 Å, respectively, but also contained a considerable continuum component (Figure 3(b)). Results for the 171 Å channel were somewhat ambiguous for this event as the Fe xxi line at 171.07 Å that is believed to dominate this channel appeared to be very weak, or possibly even non-existent, as evidenced in Figure 3(c). As the 171 Å channel does not contain any high-temperature flare lines, it is likely that any pre-existing material at Fe xix temperatures will have been heated to higher ionization states at this stage of the flare. However, the absence of any Fe xix emission may also be due to coronal dimming at these temperatures as noted by Woods et al. (2011) in several events observed by EVE, although this often only becomes significant at later stages in the flare.

Emission in the 211 Å channel (Figure 3(d)) appeared to be mostly due to the Fe xxiv line at 192.03 Å with a weak contribution from Fe xii at 195.12 Å, as well as continuum emission. The 211 Å channel (Figure 3(e)) was found to comprise multiple lines formed over a range of temperatures:

- Fe xi (209.78 Å), Fe xii (209.62 Å), Fe xiv (211.32 Å), Fe xvii (204.67 Å), and Ca xvi (208.60 Å), all of which were relatively weak. As in the case of the 171 Å channel, this could also be due to the heating of these elements to higher ionization stages, or possible coronal dimming. Strong contributions from both free–free and free-bound (He ii) continuum emission were also present. The 304 Å channel is dominated by the self-blended He ii line at 303.78 Å (Figure 3(f)), which is the strongest line in the EVE spectrum, and the continuum was therefore negligible in this channel. Figure 3(g) shows that the 335 Å channel comprised a strong contribution from Fe xvi at 335.41 Å as well as contamination from the Fe xxi and Fe xxiii lines, as well as continuum emission from the 131 Å passband due to crosstalk as discussed in Section 2. However, there did not appear to be any significant contribution from the second-order peak at 184 Å as predicted.

3.2. Continuum Time Profiles for the 2011 February 15 Flare

Using the method described in Section 2, light curves of the total emission predicted for each AIA channel were compiled for the duration of the 2011 February 15 flare between 01:40–03:40 UT for each passband as shown in Figure 5 (solid black curves in the upper panels). Light curves of the corresponding line (red) and continuum (blue) emission are also plotted, as well as the He ii continuum (purple) in the case of the 211 Å channel (Figure 5(d)). To draw more discernible comparisons, the relative contribution from both line and continuum emission are shown in the lower panels of each plot. Each curve is also overlaid with a six-point (one minute) boxcar smoothed function from which the relative contributions at various stages during the flare were ascertained (Table 1 and vertical lines in Figure 5).

The 94 Å channel might have been expected to have shown the strongest contribution of continuum emission given that free–free emission increases at shorter wavelengths. From the relative contribution plots in Figure 5(a), it can be seen that the continuum is particularly significant at the flare onset (15%–20%) but gradually decreases to about 10% by the time the GOES flux reaches 10% of its maximum before eventually returning to zero. The continuum also makes a significant contribution to the 131 Å channel. Throughout the course of the flare, it makes up about 20%–30% of the total emission before decreasing during the late decay phase (Figure 5(b)).
Figure 5. Light curves of the predicted emission in each of the AIA channels (except 171 Å) during the 2011 February 15 flare. Upper panels: total emission in each passband (black), free–free continuum (blue), and line emission (red). In panel (d), the time profile of the free-bound emission from He ii is also shown (purple). Lower panels: relative contributions of free–free continuum (blue), line emission (red), and He ii continuum (purple, panel (d) only). The vertical dotted, dashed, dot-dashed, and triple-dot-dashed lines denote the times of the peak of the GOES derivative (a proxy for the HXR peak), the peak of the SXR emission, and points in the X-ray decay phase when the flux was 50% and 10% of the maximum, respectively.

(A color version of this figure is available in the online journal.)

Table 1
Relative Continuum Contributions to Each AIA Channel
During the 2011 February 15 Flare

| Passband | HXR Peak | SXR Peak | 50% of SXR Peak | 10% of SXR Peak |
|----------|----------|----------|-----------------|-----------------|
| 94 Å     | 0.19     | 0.19     | 0.13            | 0.11            |
| 131 Å    | 0.21     | 0.24     | 0.23            | 0.22            |
| 171 Å    | 0.08     | 0.09     | 0.13            | 0.15            |
| 193 Å    | 0.35     | 0.43     | 0.37            | 0.25            |
| 211 Å (free–free) | 0.21 | 0.19 | 0.14 | 0.25 |
| 304 Å (He ii) | 0.01 | 0.01 | 0.01 | 0.01 |
| 335 Å    | 0.16     | 0.16     | 0.11            | 0.09            |

continuum in the 193 Å channel increases from 0%–15% over the main phase of the flare before returning to zero (Figure 5(c)).

Free–free continuum emission was found to be comparable to line emission in the 211 Å channel, making up between 40%–50% of the total emission around the peak of the flare. In Figure 5(d), the ratios shown for this channel are quite noisy, perhaps due to the existence of several lines, each being more prevalent at different stages of the flare, as well as scatter due to the fits to the continuum. O’Dwyer et al. (2010) also predicted the 211 Å channel to have the greatest proportion of continuum emission, but their estimate of 41% was obtained using a DEM from the decay phase of an M2 flare. The findings presented here suggest that around 45% of the emission around the SXR peak of the flare was due to free–free emission, while 25% contributed to the 211 Å channel during the decay phase. Emission from the
3.3. Continuum Contributions as a Function of GOES Classification

The analysis performed on the 2011 February 15 X2.2 flare was repeated for 54 other flares of GOES class M2 or greater. Reliable measurements of the contribution of free–free continuum to all channels except 171 Å were made for 24 events. In the case of the 171 Å channel, the continuum level could only be measured in 18 flares. Figure 6 shows how the continuum contribution to each channel varies as a function of GOES class at the SXR peak of each event. For the 193 Å and 304 Å channels the continuum contribution does not change appreciably with respect to GOES class, with both channels exhibiting less than 10% continuum emission. The 94 Å, 131 Å, and 335 Å channels show a slight dependence on X-ray classification but still contained less than 20% continuum emission in all but the largest events. The 171 Å and 211 Å channels, however, both reveal a strong correlation between continuum contribution and peak X-ray flux. For the case of the 211 Å channel the continuum contribution increased from 20% for M2 flares up to ∼55% for the X6.9 flare of 2011 August 9. In one outlying event (an X1.9 flare that occurred on 2011 November 3), this increased to over 80%. The distribution for the 171 Å channel shows a similar slope but has a maximum contribution of 45% in the largest flares.

4. SUMMARY AND CONCLUSIONS

Detailed measurements of the amount of continuum emission (both free–free and free-bound) contributing to each of the EUV passbands on SDO/AIA throughout an X-class solar flare are presented. Background-subtracted EVE spectra, and the corresponding fits to the underlying continua, were convolved with the AIA response functions to determine the relative amount of line and continuum emission in each channel as a function of time throughout the flare. The findings are in broad agreement with those of O’Dwyer et al. (2010), who performed a similar analysis using synthetic flare spectra from CHIANTI. Both studies show that the 211 Å channel exhibits the largest contribution of free–free continuum emission during flaring conditions. The results presented show that this continuum can contribute between 40%–50% to the total emission in the 211 Å channel at the SXR peak of an X-class flare. It is also shown that the recombination continuum of Fe II, not considered in the work of O’Dwyer et al. (2010), also made up ∼20% of the 211 Å channel emission during the impulsive phase. While continuum emission in the He II 304 Å channel was found to be negligible for the duration of the flare, and measurements for the 171 Å channel were inconclusive, typically between 10%–25% of emission observed in the remaining EUV channels was found to be due to free–free bremsstrahlung for the 2011 February 15 flare.

This analysis was repeated for a number of flares between M2.0 and X6.9 and the level of continuum emission in both the 171 Å and 211 Å channels at the peak of each event was found to scale with respect to its GOES classification. This is due to the primary lines in each of these channels (Fe xix for Fe xvi line) becoming inherently weaker during flares, and therefore the relative intensity of the underlying continuum increased. The decrease in line intensity was most likely due to plasma at these temperatures becoming heated to higher ionizations states, although there is also a possibility that there was a depletion of material due to coronal dimming (Woods et al. 2011).

EVE observations also help remove, or at least constrain, some of the assumptions used in generating synthetic flare spectra. For example, Milligan et al. (2012b) identified three pairs of Fe xix lines within the EVE spectral range that can be used to measure electron densities, particularly in large events. They found densities on the order of $10^{12}$ cm$^{-3}$ for X-class flares, an order of magnitude larger than that assumed by O’Dwyer et al. (2010) in their study. Similarly, Warren et al. (2013) have developed techniques to generate DEM profiles throughout a flaring event, also using EVE data, which would mark a significant advancement over the currently assumed flare DEM from Dere & Cook (1979). Several authors have also attempted to generate flare DEMs directly from AIA data (e.g., Hannah & Kontar 2012; Battaglia & Kontar 2012; Fletcher et al. 2013), but the resulting profiles may be inaccurate due to the

![Figure 6. Plots of the continuum contribution to each of the AIA channels as a function of GOES class at the time of peak SXR emission in 24 events. The tick marks on the y-axis denote steps of 0.1 dex in the 1–8 Å flux. (A color version of this figure is available in the online journal.)](image)
underestimation or exclusion of the continuum emission in each of the filters. So while AIA often saturates during even moderate flaring events (e.g., Raftery et al. 2011), the findings presented here underscore the need for coordinated spectral and imaging data to correctly interpret the observations.

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