OBSERVATIONS OF THERMAL FLARE PLASMA WITH THE EUV VARIABILITY EXPERIMENT

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Received 2012 December 6; accepted 2013 April 2; published 2013 June 3

ABSTRACT

One of the defining characteristics of a solar flare is the impulsive formation of very high temperature plasma. The properties of the thermal emission are not well understood, however, and the analysis of solar flare observations is often predicated on the assumption that the flare plasma is isothermal. The EUV Variability Experiment (EVE) on the Solar Dynamics Observatory provides spectrally resolved observations of emission lines that span a wide range of temperatures (e.g., Fe\textsubscript{XV}–Fe\textsubscript{XXIV}) and allow for thermal flare plasma to be studied in detail. In this paper we describe a method for computing the differential emission measure distribution in a flare using EVE observations and apply it to several representative events. We find that in all phases of the flare the differential emission measure distribution is broad. Comparisons of EVE spectra with calculations based on parameters derived from the Geostationary Operational Environmental Satellites soft X-ray fluxes indicate that the isothermal approximation is generally a poor representation of the thermal structure of a flare.

Key word: Sun: corona

Online-only material: color figures

1. INTRODUCTION

It is widely believed that solar flares are powered by magnetic reconnection (e.g., Priest & Forbes 2002). How this energy is released over short timescales relative to magnetic diffusion is not well understood. Since a significant fraction of the energy released during a solar flare is ultimately radiated away, fully characterizing thermal emission and how it evolves with time is critical for providing strong observational constraints on theoretical models. During the past several decades, flare observations have generally focused on either broadband, soft X-ray measurements or high spectral resolution measurements of individual emission lines. Such observations have been unable to determine the full distribution of plasma temperatures in a flare, and there have been only a few calculations of flare differential emission measure (DEM) distributions that extend to temperatures of 5 MK and lower (e.g., McTiernan et al. 1999; Dere & Cook 1979).

The launch of the EVE Variability Experiment (EVE; Woods et al. 2012) on the Solar Dynamics Observatory (SDO) provides a new opportunity to study thermal flare plasma. EVE is a spectral irradiance monitoring instrument that observes the full Sun at wavelengths between approximately 65 and 1050 Å with 1 Å spectral resolution and a 10 s cadence. The spectral coverage of EVE allows for the observation of flare emission lines in the 90–150 Å wavelength range, which has not been systematically observed on the Sun for many decades (e.g., Kastner et al. 1974). Relatively recent stellar observations of this wavelength range do exist (e.g., Ayres et al. 2001; Maggio et al. 2004) and illustrate the utility of these observations. Emission lines at these wavelengths cover Fe\textsubscript{XIII} to Fe\textsubscript{XXIV} and, in combination with observations of other emission lines in the EUV such as Fe\textsubscript{XV} \( \lambda \) 284.16 and Fe\textsubscript{XXIV} \( \lambda \) 192.04, provide a complete description of thermal flare plasma at temperatures from 2 to 30 MK. Moreover, the Fe\textsubscript{XXI} lines in this wavelength range are sensitive to the electron density (Mason et al. 1979; Milligan et al. 2012b) and provide information on the emission-measure-weighted density in the flare.

In this paper we describe a method for calculating the DEM using EVE observations and illustrate the application of this method using several long-duration events associated with coronal mass ejections. We focus on two-ribbon, eruptive events because the magnetic geometry of the post-eruption arcade, a Y-type current sheet, appears to be consistent with the observations and provides perhaps the simplest environment in which to study magnetic reconnection in the solar atmosphere. Furthermore, two-ribbon flares provide an ideal way to test the hydrodynamics of loop evolution. The observations suggest that flare loops are heated impulsively, leading to the evaporation of material into the corona and subsequent cooling to lower temperatures. It remains to be seen, however, whether one-dimensional hydrodynamic simulations can accurately model the flow of mass and energy through the solar atmosphere in even this very simple case.

For the events we consider we find a relatively broad DEM during all phases of the flare. As expected, the highest temperature emission is observed during the rise phase and at the peak of the event. During the decay phase of the flare the magnitude of the emission measure decays exponentially but the peak temperature declines very slowly. We also find that the shape of the temperature distribution remains relatively constant as the flare decays over many hours, suggesting that plasma temperature is relatively insensitive to the magnitude of the energy released by the magnetic reconnection process.

For these observations, we also compute the isothermal temperature and emission measure from the ratio of the Geostationary Operational Environmental Satellites (GOES) soft X-ray fluxes and use these parameters to infer the expected EVE spectrum. These comparisons show that the DEM distribution reproduces the observations at EUV wavelengths much better than an isothermal model. Single temperature fits are often used...
2. OBSERVATIONS

EVE is actually a collection of instruments designed to measure the solar irradiance at many EUV wavelengths. In this work we will consider observations from the Multiple EUV Grating Spectrograph A (MEGS-A), which is a grazing incidence spectrograph that observes in the 50–370 Å wavelength range. MEGS-A has a spectral resolution of approximately 1 Å and an observing cadence of 10 s. For more detail, see Woods et al. (2012).

An example EVE spectrum from the peak of the X1.7 flare that occurred on 2012 January 27 between approximately 17 and 22 UT is shown in Figure 1. We will use this event to describe our analysis in detail and then consider other events more briefly. Figure 1 clearly shows the utility of the MEGS-A wavelength range for determining the properties of thermal flare plasma. Observations between 90 and 150 Å, where we find some of the most intense emission lines from Fe xviii–Fe xxiv, are a particularly rich source of diagnostics. Additionally, there are the strong Fe xxiv λλ 192.04 and 255.10 flare lines within the MEGS-A wavelength range. Observations of Fe xv λ 284.16 and Fe xvi λ 335.41 provide information on lower temperature plasma.

For this work, we also analyze observations from the soft X-ray monitors on the GOES, which provide spatially integrated fluxes in the 0.5–8 Å wavelength ranges at a 2 s cadence. These bandpasses have contributions from Fe xxv and Fe xxvi emission lines. These ions are formed at somewhat higher temperatures than the lines found in the MEGS-A wavelength range. Free–free continuum is also important at these wavelengths. Additional details on the GOES soft X-ray monitors can be found in Garcia (1994), White et al. (2005), and Aschwanden & Freeland (2012).

The GOES light curves for the 2012 January 27 X1.7 event are shown in Figure 2. We use the GOES light curves to identify various times of interest during the rise, peak, and decay of the flare. These six times are indicated on the light curves shown in Figure 2. For the analysis of both the GOES and EVE data background subtraction is necessary to isolate the contribution of the flare. For this we use a 60 s interval centered around the lowest observed flux in the GOES 0.5–4 Å channel during the 30 minutes preceding the peak of the flare. This time interval is also indicated in Figure 2.

Like GOES, EVE makes spatially unresolved observations. In contrast to GOES, the EUV irradiance is generally dominated by non-flare emission (see Figure 1). Also, at a spectral resolution of 1 Å, the vast majority of the flare lines in the EUV are blended with other lines formed at much cooler temperatures.

(A color version of this figure is available in the online journal.)
Figure 3. AIA 131 Å images from various times during the 2012 January 27 X1.7 flare and coronal mass ejection. All of the images shown here have the same logarithmic scaling. This AIA channel is sensitive to both high-temperature flare plasma from Fe \textsuperscript{xxi} \lambda 128.75 and lower temperature emission from Fe \textsuperscript{viii} emission lines. (A color version of this figure is available in the online journal.)

To further complicate the analysis, many of these lower temperature emission lines are unidentified and there are no atomic data for them (e.g., Testa et al. 2012). Given these constraints the best strategy is to remove the lower temperature emission by subtracting a pre-flare observation from the EVE measurements during the event. The primary risk in this approach is that the lower temperature emission will also evolve during the event. For example, for eruptive events dimming is often observed in emission lines formed around 1 MK (e.g., Gopalswamy & Hanaoka 1998), which would lead to an underestimate of flare emission.

To prepare the EVE observations for analysis, we performed some additional processing to the calibrated level2 data. We first computed time-averaged EVE spectra for each of the time intervals indicated in Figure 2. We use the observed standard deviation in the irradiance measurements (\(\sigma_I\)) to estimate the statistical uncertainty in each spectral bin, \(\sigma_I = \sigma_I / \sqrt{N}\), where \(N\) is the number of spectra in the average. We then subtracted the pre-flare, background spectrum from each of these spectra and propagate the errors in the usual way. The statistical uncertainties for the background subtracted flare irradiances are generally very small (approximately 1% at most wavelengths) and are likely to be dominated by systematic errors in the analysis, such as the assumption that the non-flare irradiance is constant during the event.

Both free–free and free–bound continuum emission has been observed during flares with EVE (Milligan et al. 2012a), but to simplify our analysis we have chosen to remove it. To accomplish this we determine the lowest intensity in each 10 Å wavelength bin and subtract this from the observed spectrum. An example background subtracted spectrum from the peak of the X1.7 flare is shown in Figure 1.

Finally, to provide context for these observations we have investigated the images from the Atmospheric Imaging Assembly (AIA) instrument on SDO (Lemen et al. 2012). AIA is a set of multi-layer telescopes capable of imaging the full Sun at high spatial resolution (0.6 pixels) and high cadence (typically 12 s). Images are available at 94, 131, 171, 193, 211, 304, and 335 Å. AIA images are also available at UV and visible wavelengths, but they are not used in this analysis. The AIA 131 Å includes contributions from Fe \textsuperscript{xxi} \lambda 128.75 and other high-temperature lines and is particularly useful for flare observations. It also includes contributions from lower temperature emission lines. Figure 3 shows several images from the event. An animation of these data clearly shows an eruption followed by the formation of a classical post-flare loop arcade.

3. FLARE DENSITY AND EMISSION MEASURE

In this section we will determine the density and temperature evolution for the 2012 January 27 event. We will consider both the isothermal emission measure model that can be derived from the GOES observations as well as the DEM model that can be derived from EVE. Calculations of plasma emissivities, which form the basis of the temperature analysis, require information
on the density, so we begin with electron densities that can be inferred from the Fe\text{xii} emission lines observed in the EVE spectra.

### 3.1. Electron Densities

Most emission lines formed at flare temperatures are largely insensitive to the density, and it is possible to compute the emission measure using any reasonable value. But, since observed intensity is very sensitive to the density, such measurements do provide an important constraint for hydrodynamic modeling. Anticipating this we consider the evolution of densities for this event.

As mentioned in the introduction, there are several emission lines in the 90–150 Å wavelength range from Fe\text{xii} that form density sensitive pairs (Mason et al. 1979). More recent theoretical calculations are available from the CHIANTI atomic physics database (e.g., Dere et al. 1997, 2009; Landi et al. 2012). The application of these ratios to the EVE data has been considered recently by Milligan et al. (2012b). Their analysis suggests that the 145.73/128.75 Å ratio is the most useful. This ratio has a larger dynamic range than the (142.14+142.28)/128.75 Å ratio and is not as blended as 121.21/128.75 Å. For very large events, all three ratios yield similar results. Following Milligan et al. (2012b), we use the peak intensity above the local continuum as a proxy for the total intensity.

As is shown in Figure 4, the 145.73/128.75 Å ratio is approximately 0.02 over most of the event, indicating an electron density of approximately $10^{11}$ cm$^{-3}$. As suggested by the spectrum shown in Figure 4, this result is sensitive to the selection of the continuum region for each line. We experimented with various combinations and found that the largest densities (approximately $10^{11.4}$ cm$^{-3}$) are obtained by ignoring the continuum entirely. The peak temperature of formation of Fe\text{xii} is 10$^7$ K, and we will assume a constant pressure of 10$^{18}$ K cm$^{-3}$, corresponding to a density $10^{11}$ cm$^{-3}$, for these calculations. We note that because of the weakness of the Fe\text{xii} $\lambda$145.73 lines, densities are only available near the peak of the event. The GOES light curves and the AIA images show flare emission extending to at least 2 UT on 2012 January 28. It is likely that the densities are lower during the decay and these measured values serve as an upper bound.

### 3.2. Isothermal Emission Measure

The GOES observations can be used to compute an isothermal temperature and emission measure as a function of time. This calculation is based on theoretical spectra determined from version 7 of the CHIANTI atomic database that have been convolved with the spectral responses of the two channels. Additional details on the temperatures and emission measures derived from the GOES observations are provided in White et al. (2005). To isolate the emission from the flare, pre-flare fluxes are subtracted from the observed light curves. The temperature and emission measure for this event are displayed in Figure 2. These calculations are performed using the IDL routine \textit{goes\_chianti\_tem} distributed in the Solar Software Library (Freeland & Handy 1998). As has been noted in previous analyses (e.g., Sterling et al. 1997), the highest temperatures are observed before the peak in the emission measure. Here we also see that the emission measure decays exponentially in time while the temperature is approximately constant during the decay of the event. A relatively constant temperature evolution has been noted in previous analysis (see, for example, Doschek et al. 1980). We will return to this point in the next section.

In converting from the temperature and volume emission measure derived from \textit{GOES} to the irradiance measured with EVE, it is useful to recall that the irradiance is simply the intensity, or radiance, multiplied by the solid angle:

$$ I(\lambda) = \frac{A}{R^2} \left[ \frac{1}{4\pi} \int \epsilon(\lambda, T_e, n_e) \xi(T_e) dT_e \right], $$

where $\epsilon(\lambda, T_e, n_e)$ is the emissivity of the line of interest, $A$ is the area of the feature, $R$ is the Earth–Sun distance, $A/R^2$ is the solid angle, and $\xi(T_e) = n_e^2 dv/dT$ is the line-of-sight DEM. Note that the spatially unresolved \textit{GOES} observations yield a volume emission measure $(\xi = \Lambda \xi(T_e))$ which incorporates the area factor into the line-of-sight emission measure. The isothermal \textit{GOES} model is equivalent to a $\delta$ function emission measure distribution:

$$ \xi_v(T_e) = EM_0 \delta(T_e - T_0). $$

To facilitate the rapid calculation of synthetic EVE spectra, we have computed a grid of emissivities as a function of wavelength, temperature, and density using the CHIANTI atomic database. We assume the CHIANTI ionization fractions and coronal abundances (Feldman et al. 1992). The spectral ranges we consider are completely dominated by Fe emission lines. We interpolate on this grid to produce a spectrum at a specified temperature and density. For this work we chose a spectral binning of 0.1 Å and convolve with a Gaussian smoothing function to account for the instrumental broadening. We find that an FWHM of 0.7 Å best reproduces the observed line widths in MEGS-A.

In Figure 5 we compare the EVE spectra inferred from the \textit{GOES} model with the actual observations at various times during the event. Note that no scaling factors have been applied to either the spectra inferred from \textit{GOES} or the actual EVE observations. The wavelength range between 90 and 150 Å is generally well matched by the \textit{GOES} model. The most significant discrepancy is for the Fe \textit{xviii} emission at 93.93 and 103.95 Å. Similarly, the wavelength range near 192 Å, which contains the Fe \textit{xxiv} $\lambda$192.04 line, is also well matched by the \textit{GOES} model. The wavelength range between 245 and 290 Å contains a mixture of high-temperature flare lines, such as Fe \textit{xxiv} $\lambda$255.10 and Fe \textit{xxvii} $\lambda$263.76, and lower temperature emission lines from Fe \textit{xxv} and Fe \textit{xxvii} (see, for example, Warren et al. 2008 and Del Zanna 2008 for a description of the high-temperature emission in this wavelength range). In this wavelength range, the \textit{GOES} model only reproduces the highest temperature emission. Finally, we also see that the isothermal \textit{GOES} model does not reproduce any of the observed Fe \textit{xvi} $\lambda$335.41 irradiance. The inability of the \textit{GOES} single temperature model to reproduce the observed EVE emission over a wide range of temperatures suggests that the flare is not isothermal.

### 3.3. Differential Emission Measure

To solve for the temperature distribution implied by the observed spectra, we assume that the volume DEM can be approximated as a sum of Gaussians in log space,

$$ \xi_v(T_e) = \sum_{k=1}^{N_T} \text{EM}_k \exp \left[ -\frac{(\log T_e - \log T_k)^2}{2\sigma_k^2} \right], $$

where the number ($N_T$), position ($\log T_k$), and width ($\sigma_k$) of the Gaussians are fixed for a given calculation and only the
Figure 4. EVE observations of the 85–150 Å wavelength range for the X1.7 flare that occurred on 2012 January 27. The top panel shows the spectra as a function of time and wavelength. The middle panel shows the spectrum at the peak of the event with many of the most intense emission lines identified. A pre-flare spectrum has been subtracted from the observed irradiance during the flare. The peak intensities above the local continuum estimate the total intensity of Fe \textsc{xxi} \( \lambda \lambda 128.75 \) and 145.72. The bottom panels show the evolution of these lines. During most of the event the line ratio is approximately 0.02, corresponding to a density of \( 10^{11} \) cm\(^{-3} \). This theoretical ratio was computed using the CHIANTI database.

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

To solve for \( \xi_v(T) \), we define a temperature domain of interest \([T_1, T_2]\) and select a value for \( N_v \). We assume that components are equally spaced and that the width of the component is related to the width of the temperature domain by

\[
\sigma_k = \sigma = \frac{\log T_2 - \log T_1}{2N_v}.
\]
Figure 5. Comparison of observed EVE flare spectra with spectra inferred from the GOES isothermal temperature and emission at various times during the 2012 January 27 event. The gray bands indicate the statistical uncertainty in the background subtracted flare spectra. The magnitude of the GOES temperature and emission measure is indicated for each time interval of interest.

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

We then select initial values for $EM_k$ and use the Levenberg–Marquardt least-squares minimization routine MPFIT to determine the values that produce the lowest value of $\chi^2$. In computing the differences between the spectrum computed using the emission measure model and the observed spectrum, we only consider the wavelength ranges shown in Figure 5 so that lines at other wavelengths, such as He II $\lambda 304$, do not affect the calculation.

In Figures 6 and 7, we show the EVE spectra inferred from the DEM inversion and the individual DEMs for several times during the event. These calculations were performed assuming $N_g = 10$. We have investigated how the goodness of fit depends on the assumed number of components and found that the $\chi^2$ declines only by a small amount for values of $N_g$ of approximately 8–12. We also varied the assumed instrumental FWHM and found that a value of 0.7 Å produces the lowest
\( \chi^2 \). Finally, we also confirmed that using different values for the assumed pressure has very little influence on the goodness of fit.

For all of the spectra considered here, the DEM model reproduces the observations more closely than the isothermal model does. The isothermal model produces \( \chi^2 \) values that are 5–10 times higher than the DEM model, although this may be due in part to absolute differences in calibration between EVE and GOES. The DEM model accounts for the cooler Fe\textsubscript{XV}, Fe\textsubscript{XVI}, and Fe\textsubscript{XVIII} emission lines in the observed spectra. The discrepancies between the computed and observed spectra for the higher temperature emission lines are also reduced. For the 19:39, 20:28, and 21:35 spectra, however, the DEM model appears to overestimate the observed emission near 192 Å. Since this discrepancy is actually smaller for the GOES isothermal spectra, it suggests a sharp drop in the DEM above a temperature of approximately 10\textsuperscript{7} K. Adding additional Gaussian components to the DEM, however, does not reduce
the intensity of the Fe xxiv $\lambda$192.04 line significantly. Since this region of the spectrum is dominated by emission lines formed near 1 MK, it seems likely that there actually is some Fe xxiv $\lambda$192.04 emission during this time; it is just difficult to observe in the pre-flare subtracted spectra, which may overestimate the intensities of the warm emission during this time. The absence of detectable emission from Ca xvii $\lambda$192.86, which is formed at about $\log T_e = 6.5$, is consistent with this interpretation. We also note that the discrepancy between the observed spectra and the DEM model spectra for the Fe xxiv $\lambda$255.10 line is generally small.

The selection of a limited number of intervals for considering the DEM allows us to make detailed comparisons between the modeled and observed spectra as well as with parameters inferred from the GOES observations. The EVE data, however, are continuously available at a cadence of 10 s, allowing the temperature evolution to be followed at high cadence over long periods of time. The isothermal temperature derived from GOES shown in Figure 2 suggests that analysis of high cadence data would be of interest. The isothermal model indicates a rapid increase in the temperature during the rise phase of the flare followed by a decline to a relatively constant temperature of approximately 10 MK during the decay. The DEMs shown in Figure 7 appear to be consistent with this behavior. The DEMs from 18:10 and 18:36 show considerable emission at temperatures above $\log T_e = 7.1$. At later times most of the emission lies at temperatures between $\log T_e = 6.5$ and 7.1.

The reasonable agreement between EVE and GOES illustrated in Figures 5 and 6 also suggests that we could combine these data. GOES is also sensitive to somewhat higher temperatures than EVE, and the combined data would provide a more complete description of the thermal distribution of the flare. To accomplish this we incorporated the GOES fluxes as an additional constraint on the calculation of the best-fit DEM parameters. We found that adding this constraint made the convergence much more sensitive to the initial conditions. To account for this, we select 25 random initial guesses for the DEM at each time step, iterate each one until convergence is reached, then select the solution with the lowest $\chi^2$.

In Figure 8 we show the result of calculating the DEM as a function of time for the 2012 January 27 event. Here we have divided the data into 240 s intervals. The DEM during the rise of the flare is dominated by very high temperature plasma. Near the peak of the flare, the DEM becomes very broad with strong emission at temperatures between $\log T_e = 6.4$ and 7.4. During the decay the highest temperature emission fades away as the DEM assumes an approximately constant shape. At the very end of the event, the DEM at the lowest temperatures also becomes small. It seems likely, however, that this is due to the difficulty of separating the flare from the background irradiance in Fe xv $\lambda$284.16 and Fe xvi $\lambda$335.41. As is seen in Figure 3, the AIA images from this time continue to show the formation of relatively weak post-flare loops at a wide range of temperatures.

Comparisons between the DEM and the isothermal GOES temperature show that the evolution of the GOES temperature is consistent with the evolution of the DEM. These comparisons also show that the GOES temperature is strongly weighted toward the highest temperatures in the flare.

We have preformed this time-dependent DEM calculation on four other long-duration events that were associated with coronal mass ejections observed in AIA. The DEMs for these events are shown in Figure 9 and are generally similar to those computed for the 2012 January 27 event. All of the events that we have studied show a broad distribution of temperatures throughout the entire evolution of the flare. During the rise phase and at the peak of the events, we find the highest temperatures
and a rapid evolution in the DEM. During the decay we find somewhat lower peak temperatures and an approximately constant shape for the DEM.

4. DISCUSSION

The combination of continuous observations, broad wavelength coverage, and relatively high spectral resolution of the EVE instrument on SDO provides a new opportunity to study the evolution of thermal flare plasma in detail. We have shown that these observations can be used to construct DEMs between approximately $\log T_e = 6.3$ and $7.8$. Flare-related emission at lower temperatures is clearly evident in the AIA images, but it is difficult to isolate this signal in the spatially integrated irradiance observations. The highest temperature emission lines observed by EVE are from Fe XXIV, which limits the reliability of the DEM at the highest temperature. EVE alone is unlikely to be able to detect low emission measure, “super hot” plasma ($\log T_e > 30$ MK; see, for example, Caspi & Lin 2010). Combining EVE flare observations with measurements of broadband, soft X-ray fluxes from GOES provides additional constraints on the DEM at the highest temperatures. We note that much stronger constraints on the DEM at high temperatures are provided by spectrally resolved soft and hard X-ray measurements from RHESSI (Lin et al. 2002). Work is underway to combine EVE and RHESSI data to explore the thermal and non-thermal emission in greater detail (A. Caspi et al., in preparation).

The uncertainties in these DEM calculations are difficult to assess. The statistical uncertainty in the EVE observations is very small. During the periods selected to compute the pre-flare background spectra, the variance in the EVE measurements suggests a statistical uncertainty of about 1%. As indicated in Figure 6, the precision in the EVE measurements led to relatively small statistical uncertainties even in the pre-flare subtracted irradiances. The uncertainties in EVE’s absolute calibration appear to be 25% or better (Woods et al. 2012). The variance in the observed GOES fluxes during quiet periods suggests statistical uncertainties of less than 1%. The absolute uncertainties in the GOES calibration are believed to be about 15% (Garcia 1994). To gauge the impact of statistical uncertainty on the analysis, we have performed some simple tests where we randomly perturb the observations and recompute the DEMs. Since we are fitting spectra, the addition of noise to each wavelength bin, even at relatively large levels, has little effect on the solution. Systematic variations, such as modifying all of the intensities at long wavelengths, would change the solution more dramatically.

The uncertainty in the DEM is likely to be dominated by the unknown uncertainties in the atomic parameters as well as in the inherent difficulty in inferring temperature distributions from the observations of intensity (e.g., Craig & Brown 1976; Testa et al. 2012). Discussions of the many potential systematic effects are also given in Kashyap & Drake (1998), Judge et al. (1997), and Lang et al. (1990). Kashyap & Drake (1998) considered the impact of some of these effects on DEM reconstruction and concluded that the general shape of the distribution, but not the fine structure, could be inferred in the presence of large errors. We note that many of these systematic effects, particularly those related to the atomic physics parameters, are unlikely to be well represented by random perturbations to the observed intensities. Errors in the ionization fractions, for example, should be addressed by perturbing the ionization and recombination rates and solving for new ionization equilibria. This would lead to systematic changes for each ionization stage. Similar arguments can be made for some of the other processes that contribute to the intensity of the observed emission lines. It is clear that considerable work remains to be done to fully understand our ability to make inferences about the temperature structure of the solar corona from the available observations.

Our view is that while these uncertainties are likely to influence the detailed structure of the inferred DEMs, the general properties of the DEM are likely to be robust. The DEMs inferred from the data are uniformly broad, and it is difficult to imagine how the observed spectra, which generally show flare emission from emission lines ranging from Fe XV to Fe XXIV, could be reproduced by a narrow temperature distribution.

EVE measurements of thermal flare plasma evolution provide important constraints on theories of energy release during a flare. These observations also provide useful tests on the hydrodynamics of loop evolution. For the events considered here, it is clear from both the broad temperature distributions and the AIA images showing emission over a wide range of temperatures that flares are not consistent with the evolution of a small number of loops. A more likely scenario is the continuous formation of loops that are initially heated to high temperature and then cool. This idea of heating and cooling occurring on a succession of independently heated loops has been incorporated into simple hydrodynamic flare models that can reproduce not only the evolution of the observed intensities (Hori et al. 1997, 1998; Reeves & Warren 2002; Warren 2006; Reeves et al. 2010) but also detailed properties of the line profile (Warren & Doschek 2005). Most of this work, however, has focused on the emission at the highest temperatures as well as on the evolution of the thermal plasma during the rise and peak of an event. It remains to be seen if these models can reproduce the distribution of temperatures observed by EVE over the full evolution of a flare.

As noted in the introduction, the evolution during the extended decay of a flare holds particular promise for probing
the fundamental process of magnetic reconnection. During this time, we see a relatively constant shape to the emission measure over many hours. The emission measure, however, is decaying exponentially, indicating that the temperature and the density are reacting very differently to changes in the heating rate. Simple hydrodynamic arguments by Warren & Antiochos (2004) have shown that the peak density of an impulsively heated loop scales as

$$n \sim \left( \frac{E}{A} \right)^{2/3} \frac{1}{L},$$

while the temperature at the time of the peak density scales as

$$T \sim \left( \frac{E}{A} \right)^{1/3},$$

where $E$ is the total energy input, $A$ is the cross-sectional area, and $L$ is the loop length. For the two-ribbon events considered here, we anticipate that the broad temperature distributions we measure will require that the flares be modeled as a succession of impulsively heated loops. Furthermore, we anticipate that over time the energy input into each loop will decline. These relationships suggest that the decline in input energy for each newly formed loop will lead to relatively large changes in the
magnitude of the emission measure over time while leaving the temperature structure relatively unchanged. It remains to be demonstrated, however, that simple hydrodynamic models can reproduce the EVE observations in detail.

The SDO mission and this research were supported by NASA. H.P.W. thanks Amir Caspi and Jim McTiernan for many interesting discussion on EVE flare observations.

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11