MEASUREMENTS OF ABSOLUTE ABUNDANCES IN SOLAR FLARES

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ABSTRACT

We present measurements of elemental abundances in solar flares with the EUV Variability Experiment (EVE) on the Solar Dynamics Observatory. EVE observes both high temperature Fe emission lines (Fe x–Fe xxiv) and continuum emission from thermal bremsstrahlung that is proportional to the abundance of H. By comparing the relative intensities of line and continuum emission it is possible to determine the enrichment of the flare plasma relative to the composition of the photosphere. This is the first ionization potential or FIP bias (f). Since thermal bremsstrahlung at EUV wavelengths is relatively insensitive to the electron temperature, it is important to account for the distribution of electron temperatures in the emitting plasma. We accomplish this by using the observed spectra to infer the differential emission measure distribution and FIP bias simultaneously. In each of the 21 flares that we analyze we find that the observed composition is close to photospheric. The mean FIP bias in our sample is \( f = 1.17 \pm 0.22 \). This analysis suggests that the bulk of the plasma evaporated during a flare comes from deep in the chromosphere, below the region where elemental fractionation occurs.

Key word: Sun: corona

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1. INTRODUCTION

Solar flares are characterized by the rapid formation of very high temperature and density plasma in the solar atmosphere. Flares are thought to result from the release of energy from magnetic reconnection occurring the hot, but relatively tenuous, corona (e.g., Priest & Forbes 2002). This energy is transported down to the cool, dense chromosphere where it leads to the heating and evaporation of plasma into the corona (e.g., Fisher 1987).

A similar process has been invoked as a solution to the more general problem of coronal heating. It has been conjectured that much lower energy magnetic reconnection events (nanoflares, e.g., Parker 1988) lead to the formation of the million degree plasma that fills the upper layers of the solar atmosphere. As in the case of large flares, evaporation plays a central role in supplying mass to the corona. Intriguingly, the process of bringing mass into the corona changes its relative composition. The abundance of elements with a low first ionization potential (FIP \( \lesssim 10 \text{ eV} \)), such as Fe, Si, and Mg, is often enriched in the corona relative to values measured in the photosphere (e.g., Feldman et al. 1992). The abundance of high-FIP elements, such as O, Ar, and Ne, appears to be unchanged. Thus measurements of plasma composition hold potential clues as to how mass and energy flow through the solar atmosphere.

In this Letter we present the first measurements of elemental abundances observed in solar flares with the EVE Variability Experiment (EVE; Woods et al. 2012) on the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). EVE observes a broad range of the solar EUV spectrum (60–1050 Å) at a spectral resolution of about 1 Å and a cadence of about 10 s. This spectral range includes strong emission lines from Fe viii to Fe xxiv that are formed over a very wide range of temperatures. This wavelength range also includes continuum emission from thermal bremsstrahlung (Milligan et al. 2012) whose intensity is directly related to the abundance of H. Thus the analysis of EVE spectra can yield measurements of the absolute abundance in flares. To fully account for temperature effects we compute the differential emission measure distribution using a method described in Warren et al. (2013). Here, however, we consider the line and continuum contribution to the observed spectra separately and allow for a variable enrichment relative to the composition of the photosphere. In each of the 21 events that we analyze we find that the composition is close to photospheric.

Past measurements of elemental abundances observed during flares are generally inconsistent with what we find here. These measurements have often found abundances that are coronal or intermediate between the coronal and photospheric values (Phillips & Dennis 2012; Phillips et al. 2010; Fludra & Schmelz 1999, 1995; Schmelz 1993; Schmelz & Fludra 1993; Sterling et al. 1993; Doschek et al. 1985). EVE observations are unique in that they cover both a wide range of temperatures and a wide range of wavelengths. As we will show, our modeled flare spectra largely account for both the wavelength dependence of the continuum as well as the magnitude of the line emission. We note, however, that some previous work considered emission lines that are not observed with EVE. Schmelz (1993), for example, investigated relative abundances using S and Ne emission lines at soft X-ray wavelengths. Our results apply almost exclusively to Fe—at the EUV wavelengths that we consider more than 95% of the flare emission is from Fe emission lines—and it may be that the composition during a large flare is more complicated than our analysis suggests or that there is still uncertainty in the photospheric abundances of the minor ions (e.g., Asplund et al. 2009).

Current models suggest that fractionation in the non-flaring corona occurs at the top of the chromosphere where the high-FIP elements are neutral and low-FIP elements are ionized (e.g., Laming 2004). The observation of nearly photospheric abundances in solar flares suggests that the bulk of the plasma evaporated during a flare comes from deep in the chromosphere. This has implications for how energy is transported from the reconnection region to the lower layers of the solar atmosphere.

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
The mean FIP bias for all of the measurements is 0.12 ± 0.13.  
A total of 640 spectra have been fit for the DEM model and for the exploratory work conducted here we have simply selected the 21 most intense flares observed between 2010 February and 2013 October. These large events provide ample counts and reduce the statistical uncertainties. A list of events is given in Table 1.

One difficulty with the analysis of EUV spectra at the spectral resolution of EVE is that many of the emission lines of interest are blended with other emission lines for which there is no reliable atomic data. This is particularly problematic for the wavelength range between 90 and 150 Å where there are many unknown emission lines that appear to be formed at temperatures near 1 MK (e.g., Testa et al. 2012; Warren et al. 2011). Given these constraints our 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 flare. For example, in eruptive events dimming is often observed in emission lines formed around 1 MK (e.g., Gopalswamy & Hanaoka 1998), which leads to a decrease in the irradiance. Alternatively, bright emission from cooling flare loops will cause the irradiance from million degree emission lines to increase.

To account for the evolution of the million degree corona during the flare we multiply the pre-flare spectrum by the ratio of the flare to the pre-flare irradiance, i.e., 

$$f = \frac{I_{\text{flare}}}{I_{\text{pre-flare}}}$$

where $$I_{\text{flare}}$$ and $$I_{\text{pre-flare}}$$ are the irradiance of the flare and pre-flare observed during the event.

In the next section we turn to computing a full DEM and the FIP bias simultaneously for all phases of the flares.

Table 1  
EVE Abundance Measurements

| Date       | Class | Isothermal | DEM |
|------------|-------|------------|-----|
| 2011 Aug 9 | X6.9  | 08:21:10   | 1.19 ± 0.13 |
| 2012 Mar 7 | X5.4  | 00:52:14   | 1.19 ± 0.13 |
| 2013 May 14| X3.2  | 01:31:07   | 1.19 ± 0.13 |
| 2013 May 13| X2.8  | 16:27:04   | 1.02 ± 0.32 |
| 2011 Feb 15| X2.2  | 02:13:21   | 1.00 ± 0.15 |
| 2011 Sep 6 | X2.1  | 22:35:42   | 1.20 ± 0.19 |
| 2011 Nov 3 | X1.9  | 20:34:20   | 1.01 ± 0.19 |
| 2012 Sep 4 | X1.9  | 09:55:24   | 1.09 ± 0.49 |
| 2012 Oct 23| X1.8  | 03:27:11   | 1.19 ± 0.10 |
| 2011 Sep 7 | X1.8  | 22:47:52   | 1.19 ± 0.24 |
| 2013 May 13| X1.7  | 02:39:30   | 1.13 ± 0.25 |
| 2012 Jan 27| X1.7  | 18:37:41   | 1.17 ± 0.13 |
| 2011 Mar 9 | X1.5  | 23:27:19   | 1.22 ± 0.11 |
| 2012 Jul 12| X1.4  | 17:21:12   | 1.23 ± 0.21 |
| 2011 Sep 22| X1.4  | 11:24:33   | 1.28 ± 0.30 |
| 2012 Mar 7 | X1.3  | 00:52:14   | 1.19 ± 0.13 |
| 2013 May 15| X1.2  | 01:51:32   | 1.14 ± 0.11 |
| 2012 Jul 6 | X1.1  | 23:13:14   | 1.10 ± 0.13 |
| 2012 Mar 5 | X1.1  | 04:23:29   | 1.16 ± 0.11 |
| 2011 Aug 4 | M9.3  | 05:59:07   | 1.21 ± 0.11 |
| 2011 Jul 30| M9.3  | 02:11:49   | 1.39 ± 0.14 |

Notes. 
- FIP bias calculations for the 21 largest flares observed with EVE. For the isothermal model only a single spectrum during a 120 s interval during the decay of the event is analyzed. The mean FIP bias is 0.12 ± 0.16. For the DEM model all of the spectra observed when the GOES flux is above M1 are considered. A total of 640 spectra have been fit for the DEM model and the mean FIP bias for all of the measurements is 1.17 ± 0.22.

In the next section we turn to computing a full DEM and the FIP bias simultaneously for all phases of the flares.

3. AN ISOTHERMAL MODEL

In our previous work on the distribution of temperatures in flares observed with EVE we subtracted the continuum and considered only the contribution of emission lines to the spectrum (Warren et al. 2013). This allowed the shape of the temperature distribution to be determined, but left some ambiguity as to the magnitude of the distribution. Because of the complexity of emission measure analysis we first consider a simplified isothermal model that we can use to estimate the composition of flare plasma. Our previous work has shown that the temperature distribution in a flare is generally broad and that an isothermal model often provides a poor representation of the observed spectrum. Still, our previous work also suggested that the spectrum between 90 and 150 Å was often reasonably well approximated by a single temperature model, particularly during the decay of an event. Thus we focus on the decay for this highly simplified approach. These calculations should only be considered a very rough estimate of the FIP bias and should not be considered a proper “result.”
is only weakly dependent on temperature and there is no unique solution. Instead we use emission line ratios to infer the isothermal temperature and the product of the FIP bias and the emission measure \( EM = \int n_e^2 ds \). Then by comparing the observed and modeled continuum emission we can infer the magnitude of the FIP bias. That is, we rewrite Equation (1) as

\[
I(\lambda) = \frac{A}{R^2} \left[ \epsilon_{\lambda}^L(\lambda, T_0) EM_0 + \epsilon_{\lambda}^C(\lambda, T_0) \frac{EM_0}{f} \right].
\]

To further simplify matters we derive the temperature and emission measure from the ratio of the Fe XXIII and Fe XXII features near 133 Å.

In Figure 2 we show the application of this simple analysis to a single spectrum from the 2013 May 15 X1.2 flare. The comparison of the observed intensity ratio to the theoretical ratio, which is computed from the CHIANTI atomic physics database (e.g., Dere et al. 1997, 2009; Landi et al. 2012), yields the temperature and emission measure. Using these parameters we synthesize the expected continuum emission. The FIP bias parameter is then determined from the ratio of the computed to observed continuum. Finally, we add the line and continuum emission together to calculate the expected EVE spectrum. As is shown in Figure 2 this procedure yields a reasonable fit to the line and continuum emission in the 60–150 Å wavelength range for a FIP bias close to 1.

The spectrum shown in Figure 2 was taken after the peak in the GOES flux when the temperatures are down somewhat from the peak (e.g., Sterling et al. 1997) and we might expect the isothermal approximation to be somewhat more useful. We have repeated the isothermal analysis on each of the 21 largest flares observed by EVE. For each event we pick the first spectrum taken after the temperature derived from the ratio of the GOES channels falls below 15 MK. Note that the GOES temperature plays no role in the analysis of the EVE observations other than to select the spectrum for analysis.

The result of this calculation for each event is summarized in Table 1. The mean of the measured FIP bias factors is \( f = 0.85 \pm 0.16 \), which is close to a photospheric composition. This approach provides an estimate of the composition using a very simple model.

4. A DEM MODEL

To account for the distribution of temperatures in the flare we must compute the differential emission measure or DEM. The DEM represents an empirical description of the solar atmosphere and is determined by inverting the ill-posed integral equation

\[
I(\lambda) = \frac{A}{R^2} \int \left( f \epsilon_L(\lambda, T_x) + \epsilon_C(\lambda, T_x) \right) \xi(T_x) dT_x,
\]

where, as before, \( \epsilon_L(\lambda, T_x) \) and \( \epsilon_C(\lambda, T_x) \) are the emissivities of the emission lines and continua computed with CHIANTI. The function \( \xi(T_x) = n_e^2 ds/dT \) is the line-of-sight DEM. Note that the spatially unresolved EVE observations yield a volume emission measure \( \xi_v = A \xi(T_x) \) which incorporates the area factor into the line-of-sight emission measure.
Figure 2. Isothermal model of the flare emission near 133 Å. (top left panel) The line and continuum intensities are determined by fitting two Gaussians and a constant background to the observed emission. The line intensities are used to determine an isothermal temperature and emission measure, which are then used to compute the irradiance at these wavelengths. The “FIP bias” is determined from the ratio of the observed to calculated continuum emission near 133 Å. For this example the computed FIP bias is 0.69.

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

Figure 3. Differential emission measure analysis of EVE and GOES flare observations. The top panel shows the best-fit DEM. Individual components of the DEM are indicated by the dotted lines. The middle panel shows the observed and modeled spectra. The dotted lines show the contribution of the lines and continua to the CHIANTI spectrum. The bottom panel shows the difference between the model and the observation. The best-fit FIP bias parameter for this observation is $f = 1.05$.

(A color version of this figure is available in the online journal.)
As in our previous work we represent the DEM as a sum of Gaussians in log space

$$\xi_V(T_e) = \sum_{k=1}^{N_v} EM_k \exp \left[ -\frac{\left(\log T_e - \log T_{ek}\right)^2}{2\sigma_k^2} \right].$$

(4)

where the number ($N_v$), position ($\log T_{ek}$), and width ($\sigma_k$) of the Gaussians is fixed for a given calculation and only the magnitude of each component is varied. We select random initial values for $EM_k$, initialize $f = 1$, and use the Levenberg–Marquardt least-squares minimization routine MPFIT (Markwardt 2009) to determine the values for the emission measure components and the FIP bias that minimize $\chi^2$. The entire spectrum is not used to compute the deviates, but only spectral regions that contain strong, optically thin flare emission lines. This includes 70–145 Å as well as regions around 192, 255, 284, and 336 Å. The GOES fluxes are used as additional constraints in computing the DEM. They influence the DEM the highest temperatures, but do not play a major role in determining the shape of the distribution. See Warren et al. (2013) for additional details on the calculation.

An example calculation is shown in Figure 3. The peak of the DEM is near 10 MK, as one would anticipate from the single temperature model, but the improved fit to the observed spectra clearly requires significant emission over a broad range of temperatures. The best-fit value for the FIP bias for this spectrum is $f = 1.05$, very close to photospheric.

As in our previous work we can calculate the best-fit DEM and FIP bias parameters for each spectrum in each of the 21 flares in our sample. As we stated earlier we have considered observations for all times when the GOES long wavelength flux is above M1 and averaged each spectra over 120 s intervals. This yields a total of 640 spectra for which we have performed calculations. Calculations for two representative events are illustrated in Figure 4, which show the DEM, GOES flux, and FIP bias as a function of time. Almost all of the computed FIP bias parameters are close to 1. Only 43 spectra, or about 6.7%, indicate a FIP bias above 1.5. Considering all of the measurements the mean FIP bias is $f = 1.17 \pm 0.22$.

We note two curious features of the time-dependant FIP bias calculations. There tends to be more scatter in the measurements during the impulsive phase of the event, perhaps because the temperature distributions are generally broader and the FIP bias is less well constrained during these times. We also notice secular trends in the FIP bias, such as is seen in the top panels of Figure 4, where the parameter increases over time. The leads to an enhancement of the variance in the measurements.

5. SUMMARY AND DISCUSSION

We have presented measurements of absolute abundances during solar flares observed with the EVE irradiance instrument on SDO. These measurements provide compelling evidence that the composition is close to photospheric at all times during a flare. Coronal plasma often shows an enrichment of low-FIP elements of about four (Feldman et al. 1992). The mean FIP bias for the 21 large flares considered here is $f = 1.17 \pm 0.22$.

These results do not agree with many previous measurements which have generally indicated an enrichment of a factor of
two or more during flares (Phillips & Dennis 2012; Phillips et al. 2010; Fludra & Schmelz 1999, 1995; Schmelz 1993; Schmelz & Fludra 1993; Sterling et al. 1993; Doschek et al. 1985). The results of Fludra & Schmelz (1999) are the closest to what we obtain here. Using an emission measure analysis of line and continuum observations at soft X-ray wavelengths they obtained an FIP bias of 1.4 for Fe, but larger factors for Ca and S. EVE has a broad temperature coverage, which includes emission lines from Fe xiv to Fe xxiv, continuous observing, and the sensitivity to observe continuum emission over a very wide wavelength range. The ability of the DEM model to reproduce the wavelength dependence of the continuum emission from 60 to 200 Å is the most compelling aspect of this analysis. The weakest aspect of this analysis is the DEM model at high temperatures, which is constrained largely by the observed GOES fluxes. Since these channels have a broad response the DEM at high temperatures is not fully constrained. We generally find that the DEM is peaked at around 10 MK so the behavior of the high temperature component has little effect on the determination of the FIP bias. The use of spectral data from the RHESSI hard X-ray instrument to observe “super hot” plasma (e.g., Caspi et al. 2014) would be ideal and efforts to combine EVE and RHESSI are underway (e.g., Ryan et al. 2014).

Our results suggest that the bulk of the flare is plasma evaporated from deep in the chromosphere, below the layer at which fractionation occurs, and the in situ heating of coronal plasma does not make a significant contribution to the observed emission. This result needs to be reconciled with simulations of both the FIP effect (e.g., Laming 2004) and chromospheric evaporation. These results also have implications for simulations of the heating and cooling of flare plasma (e.g., Warren & Doschek 2005).

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REFERENCES

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Caspi, A., Krucker, S., & Lin, R. P. 2014, ApJ, 781, 43
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, A&AS, 125, 149
Dere, K. P., Landi, E., Young, P. R., et al. 2009, A&A, 498, 915
Doschek, G. A., Feldman, U., & Seely, J. F. 1985, MNRAS, 217, 317
Feldman, U., Mandelbaum, P., Seely, J. F., Doschek, G. A., & Gursky, H. 1992, ApJS, 81, 387
Fisher, G. H. 1987, ApJ, 317, 502
Fludra, A., & Schmelz, J. T. 1995, ApJ, 447, 936
Fludra, A., & Schmelz, J. T. 1999, A&A, 348, 286
Gopalswamy, N., & Hanaoka, Y. 1998, ApJ, 498, L179
Grevesse, N., & Sauval, A. J. 1998, SSRV, 85, 161
Hock, R. A., Chamberlin, P. C., Woods, T. N., et al. 2012, SoPh, 275, 145
Laming, J. M. 2004, ApJ, 614, 1063
Landi, E., Del Zanna, G., Young, P. R., Dere, K. P., & Mason, H. E. 2012, ApJ, 744, 99
Markwardt, C. B. 2009, in ASP Conf. Ser. 411, Astronomical Data Analysis Software and Systems XVIII, ed. D. A. Bohlender, D. Durand, & P. Dowler (San Francisco, CA: ASP), 251
Milligan, R. O., Chamberlin, P. C., Hudson, H. S., et al. 2012, ApJL, 748, L14
Parker, E. N. 1988, ApJ, 330, 474
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, SoPh, 275, 3
Phillips, K. J. H., & Dennis, B. R. 2012, ApJ, 748, 52
Phillips, K. J. H., Sylwester, J., Sylwester, B., & Kuznetsov, V. D. 2010, ApJ, 711, 179
Priest, E. R., & Forbes, T. G. 2002, A&A, 386, 10
Ryan, D. F., O’Flannagain, A. M., Aschwanden, M. J., & Gallagher, P. T. 2014, SoPh, 31
Schmelz, J. T. 1993, ApJ, 408, 373
Schmelz, J. T., & Fludra, A. 1993, AdSpR, 13, 325
Sterling, A. C., Doschek, G. A., & Feldman, U. 1993, ApJ, 404, 394
Sterling, A. C., Hudson, H. S., Lemen, J. R., & Zarro, D. A. 1997, ApJS, 110, 115
Testa, P., Drake, J. J., & Landi, E. 2012, ApJ, 745, 111
Warren, H. P., Brooks, D. H., & Winebarger, A. R. 2011, ApJ, 734, 90
Warren, H. P., & Doschek, G. A. 2005, ApJL, 618, L157
Warren, H. P., Mariska, J. T., & Doschek, G. A. 2013, ApJ, 770, 116
Woods, T. N., Eparvier, F. G., Hock, R., et al. 2012, SoPh, 275, 115