

A SYSTEMATIC SURVEY OF HIGH-TEMPERATURE EMISSION IN SOLAR ACTIVE REGIONS

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ABSTRACT

The recent analysis of observations taken with the EUV Imaging Spectrometer and X-Ray Telescope instruments on *Hinode* suggests that well-constrained measurements of the temperature distribution in solar active regions can finally be made. Such measurements are critical for constraining theories of coronal heating. Past analysis, however, has suffered from limited sample sizes and large uncertainties at temperatures between 5 and 10 MK. Here we present a systematic study of the differential emission measure distribution in 15 active region cores. We focus on measurements in the “inter-moss” region, that is, the region between the loop footpoints, where the observations are easier to interpret. To reduce the uncertainties at the highest temperatures we present a new method for isolating the Fe XVIII emission in the AIA/*SDO* 94 Å channel. The resulting differential emission measure distributions confirm our previous analysis showing that the temperature distribution in an active region core is often strongly peaked near 4 MK. We characterize the properties of the emission distribution as a function of the total unsigned magnetic flux. We find that the amount of high-temperature emission in the active region core is correlated with the total unsigned magnetic flux, while the emission at lower temperatures, in contrast, is inversely related. These results provide compelling evidence that high-temperature active region emission is often close to equilibrium, although weaker active regions may be dominated by evolving million degree loops in the core.

Key word: Sun: corona

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The distribution of temperatures in the solar atmosphere holds many important clues as to how the solar corona is heated. Coronal loops observed at temperatures near 1 MK, for example, often have very narrow temperature distributions (Aschwanden & Nightingale 2005; Tripathi et al. 2009; Warren et al. 2008) and are evolving (e.g., Winebarger et al. 2003; Ugarte-Urra et al. 2009; Tripathi et al. 2010; Mulu-Moore et al. 2011), suggesting that these loops are far from equilibrium. Coronal emission at higher temperatures (~ 4 MK) appears to behave differently. There is some evidence that the high-temperature emission in the core of an active region is close to equilibrium (Winebarger et al. 2011; Warren et al. 2011), suggesting that heating events must occur at high frequency to prevent loops from cooling.

This difference in behavior between loops at different temperatures appears puzzling, but may be explained by recent work on wave models of coronal heating. Van Ballegoijen et al. (2011) and Asgari-Targhi & van Ballegoijen (2012) have studied the dissipation of Alfvén waves in the chromosphere and corona. The heating rate that they derive is highly localized at the loop footpoint and heating events occur at high frequency. This implies that short loops that are strongly heated will have high apex temperatures and, because heating events occur frequently, they will be close to equilibrium. For longer loops that are heated more weakly the apex temperature will be lower. For such loops it is possible that no equilibrium exists regardless of the frequency of heating events (e.g., Serio et al. 1981; Peter et al. 2012). This would give rise to evolving loops at lower temperatures.

The observational evidence for equilibrium loops at high temperatures, however, is limited. Winebarger et al. (2011) and Warren et al. (2011) presented the emission measure

(EM) analysis for small areas in two active regions. In their analysis they find EM distributions that are strongly peaked, suggesting that loops are not evolving through a broad range of temperatures. Because of the limited sample size, it is unclear how general these results are. Tripathi et al. (2011), for example, have found somewhat broader EM distributions for two other active regions. Viall & Klimchuk (2011) have analyzed the temporal evolution of the emission in yet another active region and find evidence for evolving loops, even in the core.

In this paper, we present a more systematic survey of active region core emission. It is well known that the amount of high-temperature emission scales with the total unsigned magnetic flux (e.g., Schrijver 1987) and we use this metric to parameterize the observed active regions. We have selected 15 observations that span a wide range of magnetic flux values (10^{21} – 10^{23} Mx). For each region we compute the differential EM (DEM) in the active region core using observations from the EUV Imaging Spectrometer (EIS) and the Atmospheric Imaging Assembly (AIA). We focus on intensities measured in the “inter-moss” region, that is, the region between the loop footpoints where we are measuring the properties near the loop apex. Measurements of the entire active region would potentially combine emission from both loop footpoints and cooling loops and would require full models of the active region to interpret.

To better constrain the DEM at high temperatures we present a new method for isolating the Fe XVIII emission in the AIA 94 Å channel. Observations of emission lines formed at very high temperatures are critical for constraining the EM distribution above 5 MK (Winebarger et al. 2012). The results of this method have been calibrated against spectroscopic observations of Fe XVIII 974.86 Å (Teriaca et al. 2012). We find that for regions with appreciable magnetic flux, the DEM in the active region core is strongly peaked near 4 MK, consistent with our

Table 1
A Survey of Solar Active Regions^a

Region	NOAA	Date	X_{cen}	Y_{cen}	A_M	Φ_M	I_{hot}	α	β	EIS File
1	1082	2010 Jun 19 01:57:44	-306.4	439.3	2.87(19)	4.08(21)	1.36(04)	2.2	6.1	eis_l1_20100619_014433
2	1158	2011 Feb 12 15:32:13	-248.4	-211.8	3.04(19)	4.22(21)	1.88(04)	2.7	6.8	eis_l1_20110212_143019
3	1082	2010 Jun 21 01:46:37	162.9	405.2	3.29(19)	4.72(21)	1.05(04)	2.0	7.8	eis_l1_20100621_011541
4	1259	2011 Jul 25 09:36:09	224.7	323.4	3.98(19)	5.68(21)	7.81(03)	2.0	7.7	eis_l1_20110725_090513
5	1150	2011 Jan 31 11:25:19	-470.9	-250.6	5.17(19)	7.50(21)	1.47(05)	2.2	8.7	eis_l1_20110131_102326
6	1147	2011 Jan 21 14:10:50	26.6	476.5	6.49(19)	1.02(22)	2.28(05)	3.6	8.3	eis_l1_20110121_133954
7	1243	2011 Jul 2 03:38:08	-299.0	216.6	6.79(19)	1.09(22)	6.18(04)	2.9	9.0	eis_l1_20110702_030712
8	1089	2010 Jul 23 15:03:07	-363.4	-453.6	6.96(19)	1.12(22)	1.84(05)	3.5	9.5	eis_l1_20100723_143210
9	1109	2010 Sep 29 23:51:36	361.5	261.5	7.19(19)	1.16(22)	1.50(05)	4.3	9.8	eis_l1_20100929_223226
10	1193	2011 Apr 19 13:32:20	36.3	363.5	7.94(19)	1.35(22)	2.50(05)	3.3	10.3	eis_l1_20110419_123027
11	1190	2011 Apr 11 12:00:42	-492.6	281.0	8.61(19)	1.37(22)	1.11(05)	3.0	8.5	eis_l1_20110411_105848
12	1271	2011 Aug 21 12:25:42	-50.8	150.8	9.59(19)	1.57(22)	1.47(05)	3.6	8.4	eis_l1_20110821_105251
13	1190	2011 Apr 15 01:17:19	218.1	304.4	1.04(20)	1.78(22)	5.22(05)	3.7, 3.3	9.8, 8.7	eis_l1_20110415_001526
14	1339	2011 Nov 8 19:14:27	88.1	258.4	1.41(20)	2.60(22)	6.08(05)	4.8	8.6	eis_l1_20111108_181234
15	1339	2011 Nov 10 11:33:19	406.0	266.8	1.48(20)	2.73(22)	9.75(05)	3.7	9.4	eis_l1_20111110_100028

Note. ^a X_{cen} and Y_{cen} are the NOAA active region coordinates differentially rotated to the mid-point of the EIS raster. A_M is the total area occupied by pixels between 50 and 500 G in cm^2 . Φ_M is the total unsigned magnetic flux in Mx. I_{hot} is the total AIA Fe XVIII intensity in the field of view in DN s^{-1} . The parameter α is the slope of the emission measure distribution between $\log T$ 6.0 and 6.6. The parameter β is the negative of the slope of the emission measure distribution between $\log T$ 6.6 and 7.0.

previous results. For regions with weaker magnetic fields the amount of high-temperature emission diminishes significantly and the DEM becomes broader, consistent with the analysis of Tripathi et al. (2011) and Viall & Klimchuk (2011).

The observation of strongly peaked EM distributions in active region cores is a challenge for the Parker nanoflare model of coronal heating (Parker 1988). The very small spatial scales expected for magnetic reconnection relative to the 1'' (725 km) resolution of current coronal instruments suggest that observed coronal loops should be composed of many unresolved threads that are various stages of heating and cooling. This implies that the observed temperature distributions should be broad (e.g., Cargill 1994; Klimchuk & Cargill 2001; Cargill & Klimchuk 2004). A survey of hydrodynamic simulations of coronal loops by Mulu-Moore et al. (2011) suggests that for nanoflare heating models the temperature distribution has a power-law index of about 2 or less ($\text{EM} \sim T^\alpha$). Our analysis, in contrast, shows that the temperature distribution in the core of an active region is often strongly peaked, with $\alpha \sim 3$ –4. Of course, while simple one-dimensional hydrodynamic models are a useful tool for simulating the response of the solar atmosphere to various heating scenarios, they are a step removed from the physics of coronal heating. Ultimately, we must compare observations such as those presented here with three-dimensional MHD simulations that fully account for radiation and thermal conduction. Such simulations are computationally difficult, but significant progress has been made recently (e.g., Dahlburg et al. 2012; Hansteen et al. 2010).

2. OBSERVATIONS

Our aim here is to investigate the temperature structure of solar active regions systematically. The observations of individual emission lines from the EIS instrument provide detailed temperature diagnostics and introduce a strong constraint on our analysis. EIS (Culhane et al. 2007; Korendyke et al. 2006) is a high spatial and spectral resolution imaging spectrometer. EIS observes two wavelength ranges, 171–212 Å and 245–291 Å, with a spectral resolution of about 22 mÅ and a spatial resolution of about 1'' pixel⁻¹. Solar images can be made by stepping

the slit over a region of the Sun and taking an exposure at each position.

Telemetry constraints generally limit the spatial and spectral coverage of an observation. These constraints necessitate the selection of a limited number of spectral windows in a raster and not all EIS observations include all of the potentially useful emission lines. We have designed several EIS observing sequences that contain all of the emission lines needed to compute EM distributions. Of particular importance is the observation of emission lines from Ca XIV to Ca XVII, which constrains the analysis at temperatures above 3 MK (Warren et al. 2008). These studies have been run frequently and we used summary images to manually review the available data and select a set of observations that appeared to span a wide range of solar conditions. Each EIS raster was processed in the usual way to remove the CCD pedestal and dark current, identify any defective pixels, and calibrate the data. Intensities were then determined for each emission line of interest at every spatial pixel using Gaussian fits to the line profiles.

For each observation we determined the NOAA coordinates for the active region of interest at the mid-point of the EIS raster. NOAA region numbers, times, and solar coordinates are given in Table 1. There are EIS observations taken during the interval considered by Viall & Klimchuk (2011), but they do not include several of the high-temperature Ca lines and are not optimal for EM analysis. For completeness we have included an EIS raster from this time. The observations analyzed by Tripathi et al. (2011) pre-date the launch of *Solar Dynamics Observatory* (SDO) and are not included here.

For each observation we obtained full-disk AIA images (Lemen et al. 2012) and full-disk Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) magnetograms from the Stanford JSOC data center. AIA is a set of multi-layer telescopes capable of imaging the 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. HMI also images the full Sun at high spatial resolution (0.5 pixels) and high cadence (typically 45 s). To simplify the data management we selected all of the data within 300 s of the raster mid-point (the dates and

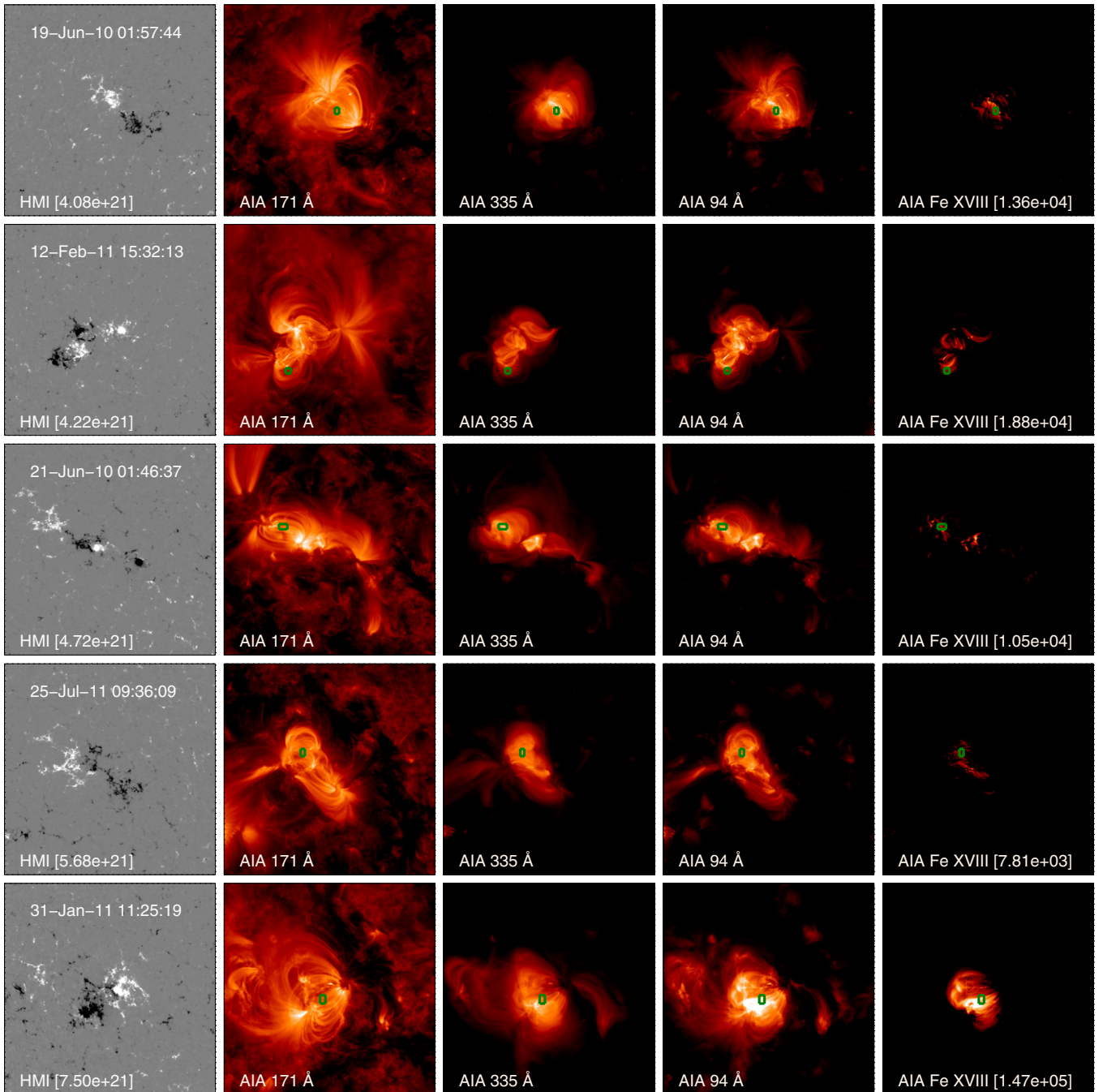


Figure 1. AIA and HMI observations of solar active regions. The regions are presented in order of increasing total unsigned magnetic flux. Every image at a particular wavelength is displayed with the same scaling. The green boxes represent the regions selected to compute the emission measure distribution. The numbers in brackets are the fluxes given in Table 1. Data for regions 1–5 are shown here.

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

times given in Table 1), processed the images with the standard `aia_prep` software to provide a common plate scale, and averaged the images at each wavelength together. For the AIA EUV images we divide each image by the exposure time. We then extracted a $400'' \times 400''$ region centered on the NOAA active region coordinates. For each magnetogram the line-of-sight magnetic field is corrected to the radial value by dividing by the cosine of the heliospheric angle. Representative images are shown in Figures 1–3. For each observation we co-aligned the EIS Fe XII 195.119 Å raster with the AIA 193 Å image.

For each HMI magnetogram we compute the total unsigned flux (Φ_M) for radial magnetic field strengths between 50 and 500 G. The lower bound excludes the quiet Sun and the upper bound excludes sunspots. These limits were used by Warren & Winebarger (2006) to study the relationship between the total unsigned flux and the total soft X-ray intensity. As in previous studies, they found a power-law relationship between the total intensity and the magnetic flux, $I_{\text{SXR}} \sim \Phi_M^b$, with $b \approx 1.6$. The values for the total unsigned magnetic flux we find here are similar to those from our earlier study, which used magnetogram data from the Michelson Doppler Imager (MDI) instrument on

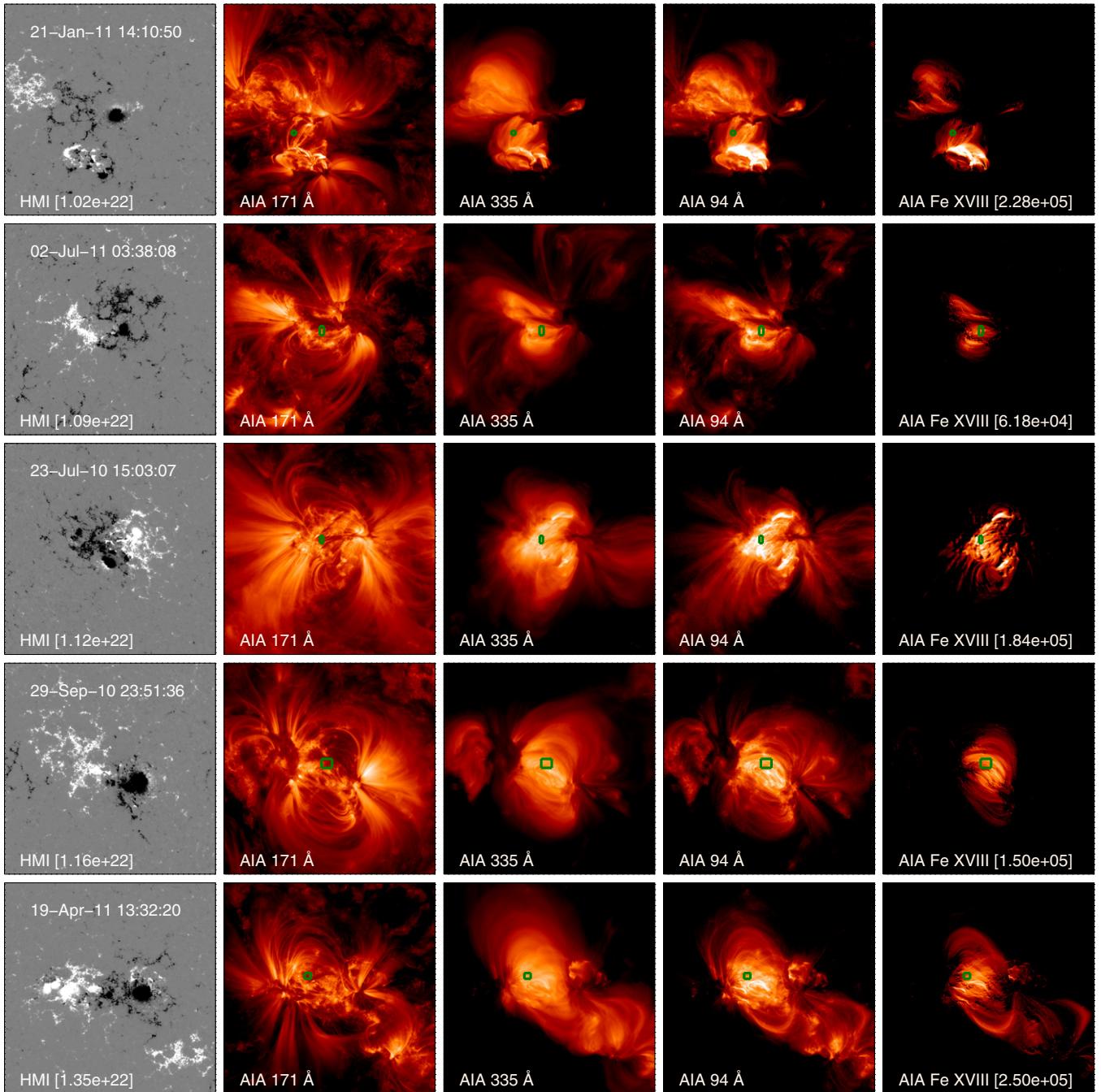


Figure 2. Same as Figure 1 but for regions 6–10 in Table 1.
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the *Solar and Heliospheric Observatory* (SOHO; Scherrer et al. 1995). Note that the absolute magnetic fluxes measured with HMI need to be reduced by a factor of 1.4 to agree with those measured with MDI (Liu et al. 2012).

The 94 Å channel on AIA contains the Fe XVIII 93.92 Å line, which is one of the most intense Fe XVIII transitions (e.g., Desai et al. 2005). Since this line is formed at a high temperature (7.1 MK) we expect that its integrated intensity will have a dependence on Φ_M similar to that of the soft X-ray emission. Unfortunately, as can be seen in Figures 1–3, this wavelength range also contains emission lines formed at lower temperatures. The atomic data for this wavelength range is incomplete (O’Dwyer et al. 2010; Testa & Reale 2012),

further complicating the quantitative use of this channel. As we describe in detail in the Appendix, it is possible to use a combination of AIA 171 Å and 193 Å images to estimate the amount of contaminating emission in the 94 Å channel empirically. Subtracting the estimated warm emission from the observed 94 Å image isolates the Fe XVIII 93.92 Å contribution. We have applied our algorithm to each active region observation of interest and the results are shown in the final columns of Figures 1–3. Comparisons with spectroscopic observations of Fe XVIII 974.86 Å are given in Teriaca et al. (2012).

For each AIA Fe XVIII image we have computed the total intensity in the active region above 2 DN s^{-1} , which we consider to be the noise level introduced by the subtraction method, and

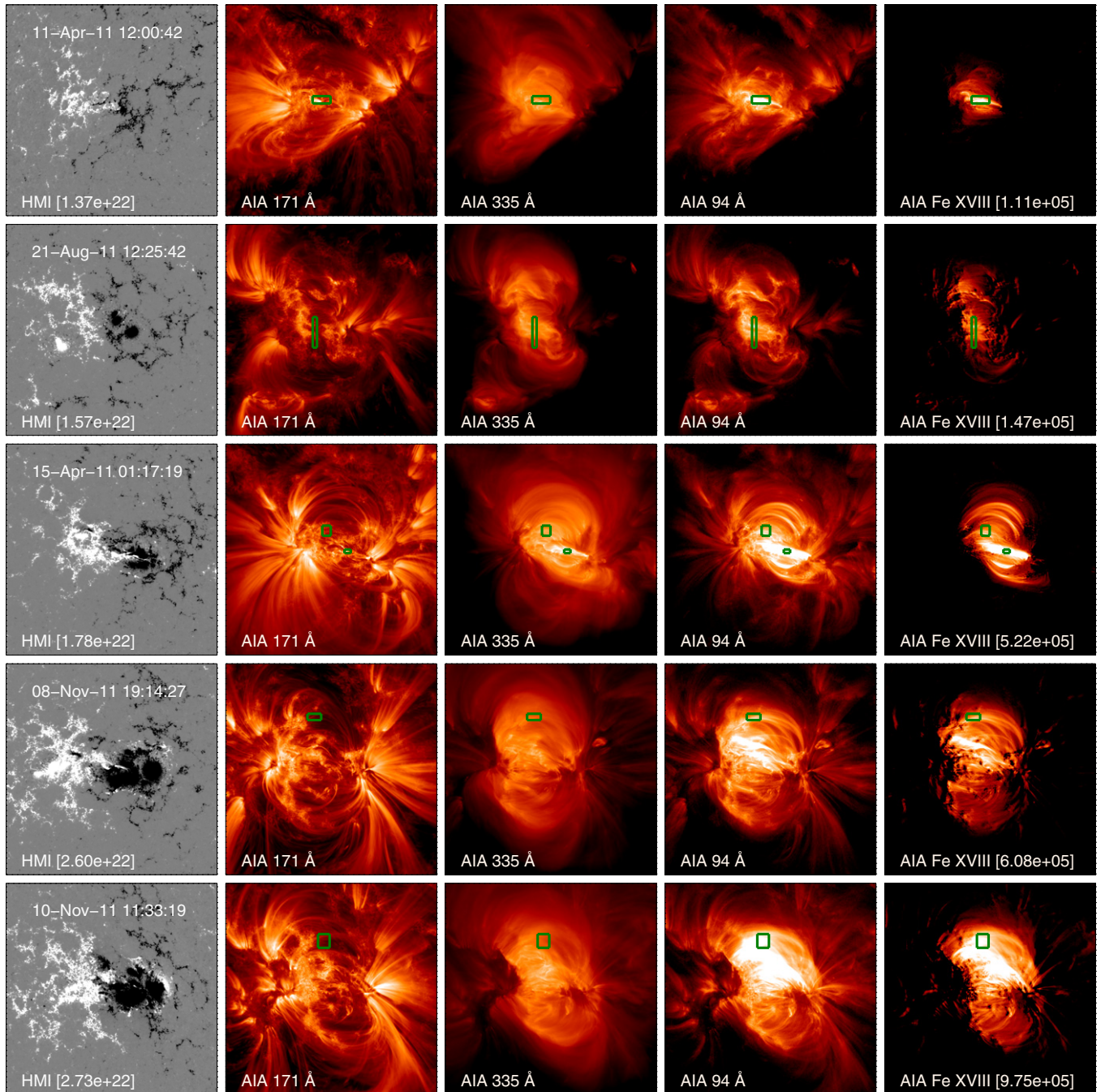


Figure 3. Same as Figure 2 but for regions 11–14 in Table 1.
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list these values in Table 1. In Figure 4, we show a plot of the total intensity as a function of the total unsigned magnetic flux. We also perform a power-law fit to the data and obtain a power-law index of 2.3, which is somewhat higher than our previous result using soft X-ray images. This exercise confirms that while our set of active region observations is not large, it does sample a wide range of solar conditions. The range of total Fe XVIII intensity varies by almost 2 orders of magnitude, from 10^4 to 10^6 DN s $^{-1}$.

The next step in this analysis is to manually select a small “inter-moss” region for each active region. These sub-regions were chosen if they were bright in AIA Fe XVIII but did not contain significant footpoint (moss) in AIA 171 Å. The term

moss refers to the footpoint emission of high-temperature loops which appears bright in emission lines formed near 1 MK (see Berger et al. 1999 and references therein). We also attempted to avoid 171 Å loop emission in the core of the active region, but for some observations this was not possible. These selections are indicated by the boxes displayed in Figures 1–3. Note that the inter-moss region considered here for the 2010 July 23 active region is slightly different from that analyzed in Warren et al. (2011). The highest AIA Fe XVIII intensities are seen in the 2011 April 15 active region as a bright “bar” of emission. For this active region we select two fields of view, one on the bright bar and the other where the intensities are weaker, but more similar to the intensities observed in the other active regions.

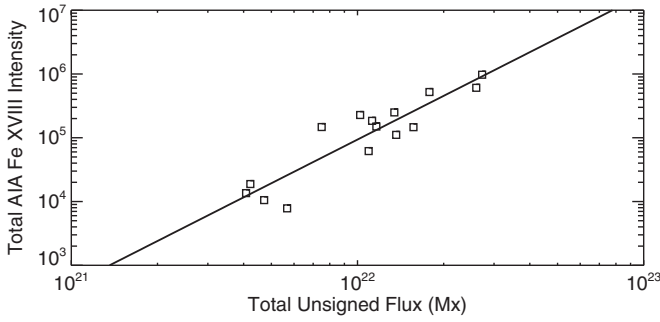


Figure 4. Total AIA Fe XVIII intensity (I_{hot} in Table 1) as a function of the total unsigned magnetic flux (Φ_M). The solid line is a power-law fit to the data. The total amount of high-temperature emission in an active region varies strongly with the total unsigned magnetic flux.

For each inter-moss region we extracted all of the relevant EIS data from each spectral window and averaged them together to create high signal-to-noise line profiles. In computing these averaged profiles, missing data are not included. We then fit the line profiles with single Gaussians. The Ca XVII 192.858 Å line is blended with Fe XI 192.813 Å and a complex of O V lines. We use the method outlined by Ko et al. (2009) to disentangle this blend. To ensure consistency between the fits to the Ca lines we use the widths measured for the Ca XIV 193.874 Å and Ca XV 200.972 Å lines to constrain the fits to the other Ca lines. The width of the Ca XVI 208.604 Å is set equal to that of Ca XV 200.972 Å. The width of Ca XVII 192.858 Å is limited to be within 0.05 mÅ of the width of Ca XIV 193.874 Å. Example rasters, line profiles, and fits are shown in Figure 5.

The final EIS line list for each active region is generally the same used in Warren et al. (2011), except that we now add intensities for Ar XIV 194.396 Å, a high first ionization potential (FIP) element that is useful for measuring the composition. As before, we also include S X 264.233 Å and S XIII 256.686 Å, but Ar is formed at a somewhat higher temperature and has a higher FIP. Del Zanna (2012) have considered the relative intensities of some of these high FIP lines in a diffuse off-limb active region spectrum and suggested potential problems with blends. Our intensities for these lines are approximately 50 larger and we are able to obtain consistent results for these lines. The Ca XIV–Ca XVI lines are not available for the 2010 June 19 active region, which is included here because it was studied by Viall & Klimchuk (2011). An example set of observed intensities is given in Table 2.

The intensity that we observe with EIS is related to line emissivity and the EM distribution by the usual expression

$$I_\lambda = \frac{1}{4\pi} \int \epsilon_\lambda(n_e, T_e) \xi(T_e) dT_e, \quad (1)$$

where $\epsilon_\lambda(n_e, T_e)$ is the emissivity computed with the CHIANTI atomic database version 7 assuming coronal abundances (Feldman et al. 1992) and the CHIANTI ionization fractions (Dere et al. 2009). The function $\xi(T_e) = n_e^2 ds/dT_e$ is the DEM distribution and the challenge we face is to infer this distribution from the observed intensities. It is also useful to consider the EM loci computed from

$$\xi_{\text{loci}}(T_e) = \frac{4\pi I_\lambda}{\epsilon_\lambda(n_e, T_e)}, \quad (2)$$

which indicates the temperature range where the various lines are sensitive. Note that to aid in the comparisons with the EM

Table 2
Differential Emission Measure Model^a

Line	I_{obs}	σ_I	I_{dem}	R
Si VII 275.368	66.85	14.76	60.84	1.10
Fe IX 188.497	71.23	15.74	70.38	1.01
Fe IX 197.862	39.80	8.79	42.71	0.93
Fe X 184.536	258.70	57.04	184.81	1.40
Fe XI 180.401	795.27	175.33	902.59	0.88
Fe XI 188.216	498.81	109.77	449.07	1.11
S X 264.233	55.27	12.22	55.45	1.00
Si X 258.375	213.53	47.05	272.39	0.78
Fe XII 192.394	357.50	78.67	354.19	1.01
Fe XII 195.119	1147.35	252.44	1104.23	1.04
Fe XIII 202.044	1076.80	236.95	597.49	1.80
Fe XIII 203.826	1839.12	404.73	1008.01	1.82
Fe XIV 264.787	653.64	143.84	727.20	0.90
Fe XIV 270.519	336.02	73.95	372.43	0.90
Fe XV 284.160	5931.55	1305.03	7302.59	0.81
S XIII 256.686	462.30	101.78	507.82	0.91
Fe XVI 262.984	630.81	138.82	604.16	1.04
Ar XIV 194.396	62.34	13.74	45.75	1.36
Ca XIV 193.874	182.64	40.21	138.98	1.31
Ca XV 200.972	127.92	28.21	89.28	1.43
Ca XVI 208.604	31.12	7.86	41.47	0.75
Ca XVII 192.858	41.75	9.35	36.62	1.14
AIA 94 Å	7.20	1.40	7.33	0.98

Note. ^a The observed intensities (I_{obs}) and statistical uncertainties (σ_I) are from region 7 in Table 1. Calculated intensities (I_{dem}) are from the MCMC emission measure inversion. The variable R is $I_{\text{obs}}/I_{\text{dem}}$. EIS intensities are in units of $\text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. AIA intensities are in units of DN s^{-1} .

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

loci we will always plot the DEM multiplied by the temperature bin,

$$\xi(T_e) dT_e, \quad (3)$$

and we refer to this as the EM distribution.

We also wish to use AIA Fe XVIII intensities derived from our subtraction method to further constrain the EM calculations. The hottest strong emission line observed with EIS during non-flaring conditions is Ca XVII 192.858 Å, which is formed at about 5 MK. As mentioned previously, this line is blended, which adds considerable uncertainty to the intensity. To utilize the subtracted AIA Fe XVIII intensities, we have computed a new response for this channel that only contains contributions from Fe XVIII and continuum. The response distributed with the official AIA software contains contributions from several of the known emission lines formed at lower temperatures.

To compute the DEM, we use the Monte Carlo Markov Chain (MCMC) EM algorithm (Kashyap & Drake 1998, 2000) distributed with the PINTofALE spectral analysis package. This algorithm has the advantage of not assuming a functional form for the DEM. The MCMC algorithm also provides for estimates of the error in the EM by calculating the EM using perturbed values for the intensities. The algorithm assumes that the uncertainties in the intensities are uncorrelated so that systematic errors in the calibration, which could depend on the wavelength, or in the atomic data, which could vary by ion, are not accounted for.

For each “inter-moss” field of view we have run the MCMC algorithm to compute the DEM. Additionally, 250 Monte Carlo runs have also been performed for each field of view. The resulting temperature distributions are shown in Figures 6–8.

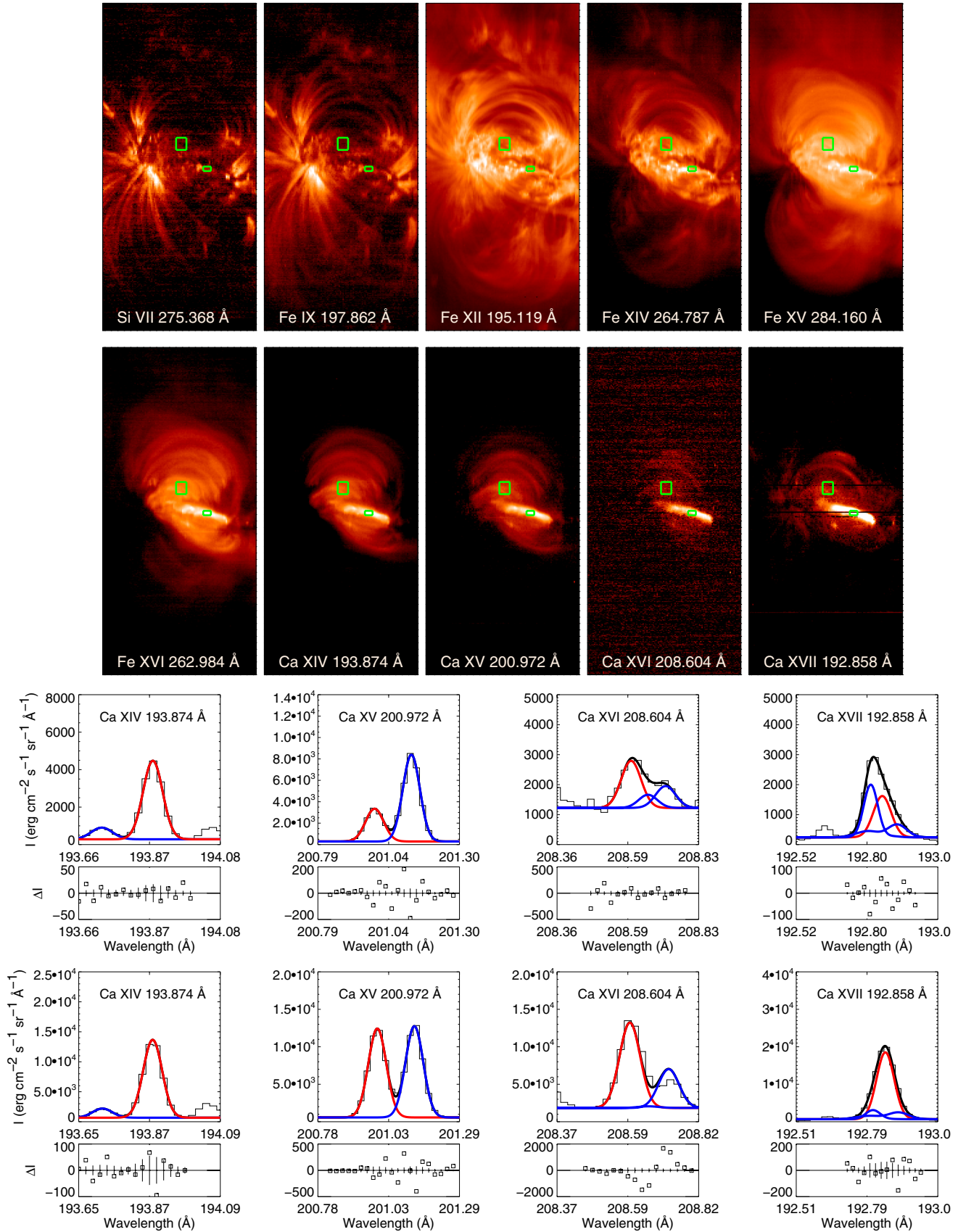


Figure 5. Example EIS active region observations. Selected rasters and line profiles are shown for the 2011 April 15 active region. The profiles from the intense “bar” of emission are displayed in the lower panels. The profiles from the larger box are displayed in the top panels. The red curves indicate the Ca lines of interest. The blue curves indicate emission lines formed at lower temperatures. Below each profile the difference between the fit and the observed line profile is displayed. The vertical line indicates the 1σ error for the intensity in the spectral bin.

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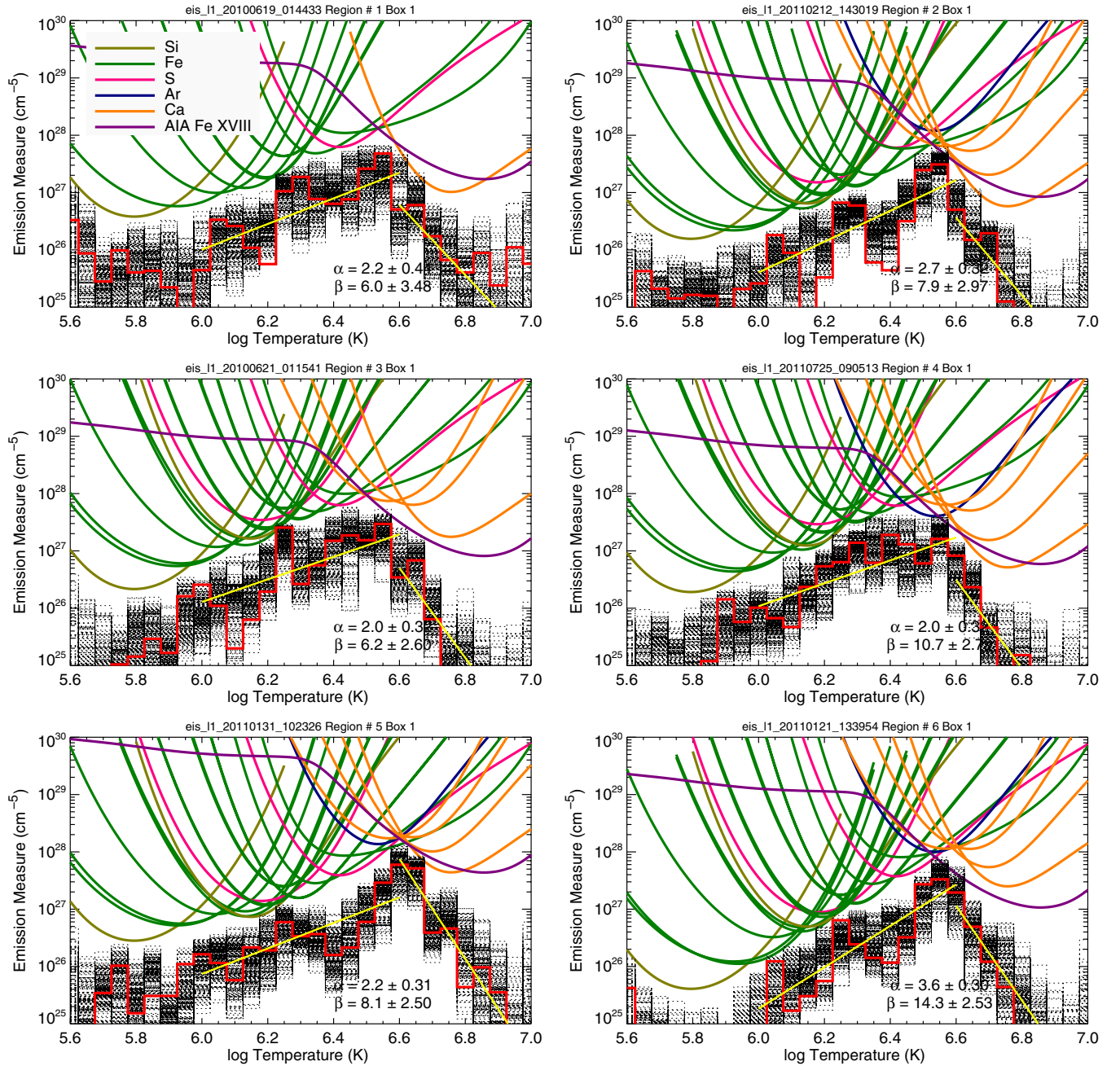


Figure 6. “Inter-moss” emission measure distribution for 15 active regions. The field of view used to derive the intensities is indicated in each panel in Figures 1–3. For each measurement the emission measure distribution derived from MCMC is shown (thick red line) as well as the results from 250 Monte Carlo runs (black lines). The emission measure locus curves are color coded by ion. The slope of the distribution from 6.0 to 6.6 and from 6.6 to 7.0 is indicated by the yellow lines. The power-law indexes are also indicated on each plot. Regions 1–6 are shown here. Both the observed and calculated intensities for each EM calculation are included in the machine readable table in the online version of the journal.

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

The agreement between the observed intensities and those computed from the EM is generally good, with most differences at the $\pm 25\%$ level. For some of the weakest active regions the intensities of the hot Ca lines become difficult to determine and the differences between the observed and computed intensities are as much as 50%. An example set of intensities computed from the EM is given in Table 2. Inspection of quiet regions suggests that the Ca lines are all weakly blended. Quiet-Sun intensities are typically about 5% of the intensity in the core of a very bright active region. For the weaker regions the impacts of the blends are more significant. We have not attempted to correct

for these blends and so the observed intensities represent upper bounds.

Inspection of the EM distributions indicates that many are strongly peaked near 4 MK ($\log T_e = 6.6$), similar to the result from our previous analysis (Winebarger et al. 2011; Warren et al. 2011). To quantify the steepness of the EM at cool temperatures, we fit a power law of the form $\text{EM} \sim T^\alpha$ to each distribution between $\log T = 6.0$ and 6.6 . We have used two methods to perform the fits. First, we take the median value of the EM in each temperature bin from each Monte Carlo simulation and fit the resulting distribution. We have also fit each distribution

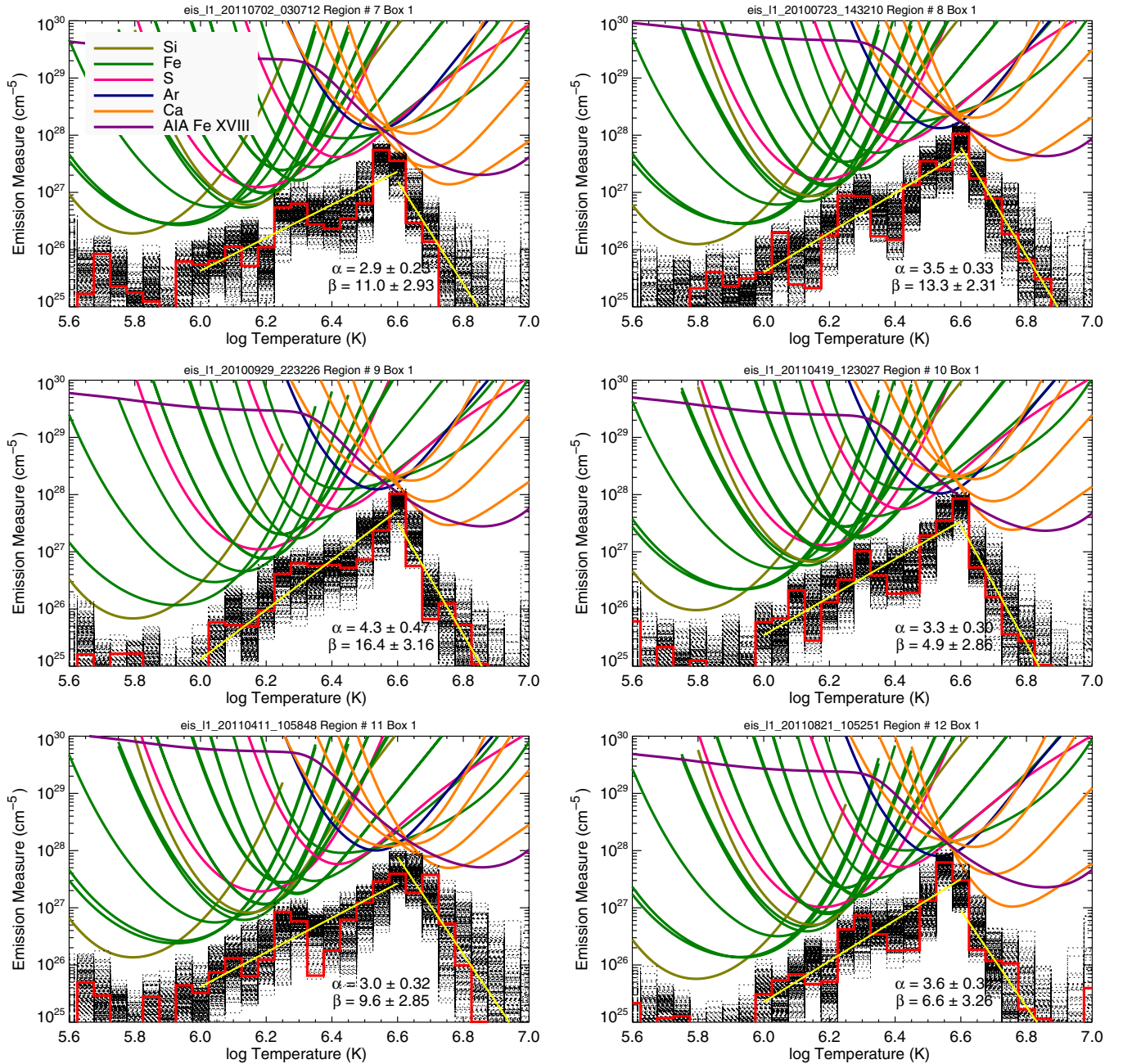


Figure 7. Same as Figure 6 but for regions 7–12.

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

individually. Both methods yield consistent results. The values for α are indicated on each plot as well as in Table 1. The uncertainties indicated in the plots are the 1σ standard deviations in the indexes determined from fitting each distribution and suggest uncertainties of 10%–20%. In this sample, 11 of the 16 EMs have $\alpha \geq 3$. However, we also measure five temperature distributions that are much shallower, with $\alpha \sim 2$, which is similar to the results from Tripathi et al. (2011). It is clear that these shallow EMs are much more common in the active regions with the weakest magnetic fields.

To summarize the behavior of these EM distributions at high temperatures, we fit a power law of the form $EM \sim T^{-\beta}$ to each distribution between $\log T = 6.6$ and 7.0. As before, we fit both the best-fit EM distribution and the result of each Monte

Carlo run. The resulting parameters are given in Table 1 and indicated on each plot. The slope above $\log T = 6.6$ shows a much stronger dependence on temperature with $\beta \sim 6$ –10. These slopes are also much more uncertain, with typical values of σ_β/β of about 35%.

Inspection of the EM distributions reveals an unexpected trend in the amount of 1 MK emission in the core of an active region. In regions 1–5, the EM near 1 MK is often between 10^{26} and 10^{27} cm⁻⁵. In the regions with the strongest magnetic fluxes (regions 10–15), the EM appears to be somewhat smaller, typically between 10^{25} and 10^{26} cm⁻⁵. To quantify this, we sum the EM between $\log T_e$ of 6.0 and 6.2 and plot it as a function of total unsigned magnetic flux. As is indicated in Figure 9, the EM at these lower temperatures is inversely proportional to the

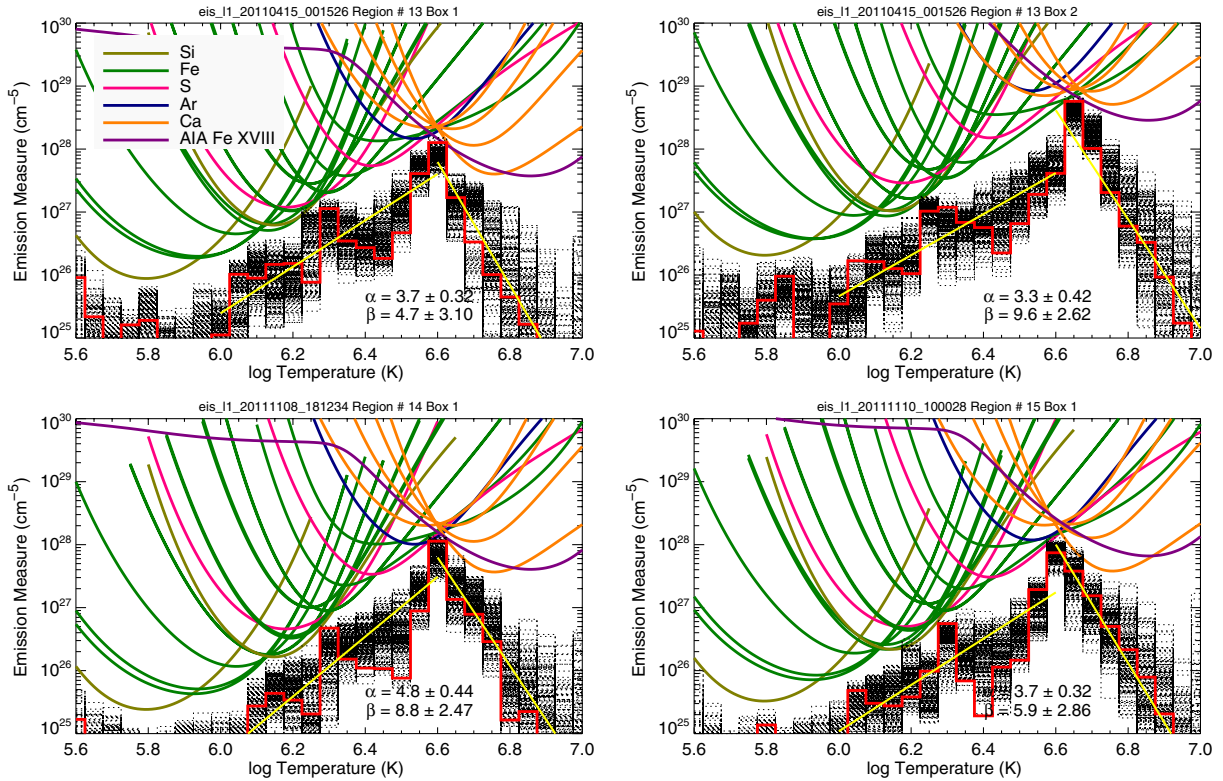


Figure 8. Same as Figure 6 but for regions 13–15. Two emission measure distributions are shown for region 13. (A color version of this figure is available in the online journal.)

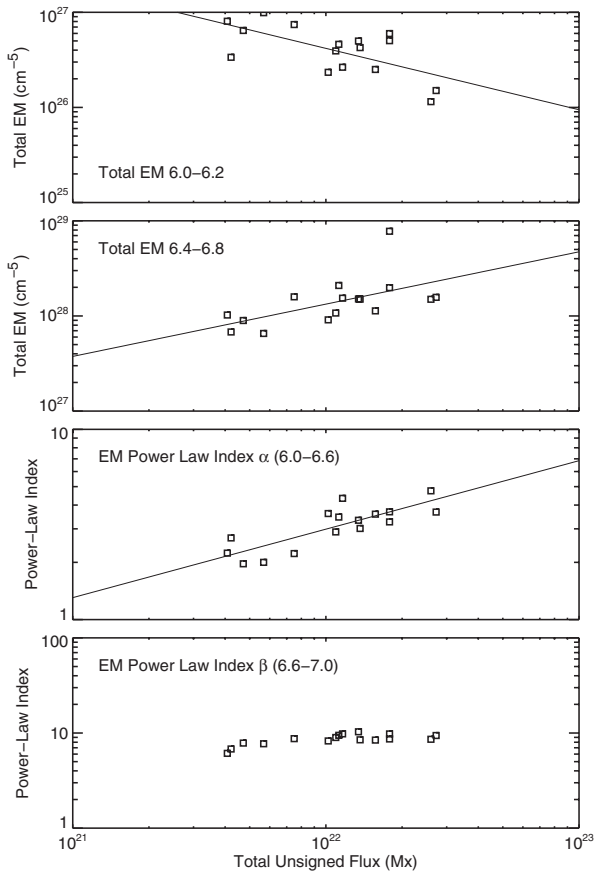


Figure 9. Total inter-moss emission measure at “warm” temperatures ($\log T_e = 6.0\text{--}6.2$) and hot temperatures ($\log T_e = 6.4\text{--}6.8$) as a function of the total unsigned magnetic flux. The bottom panel shows the power-law index (α) on the EM distribution between $\log T_e$ of 6.0 and 6.6.

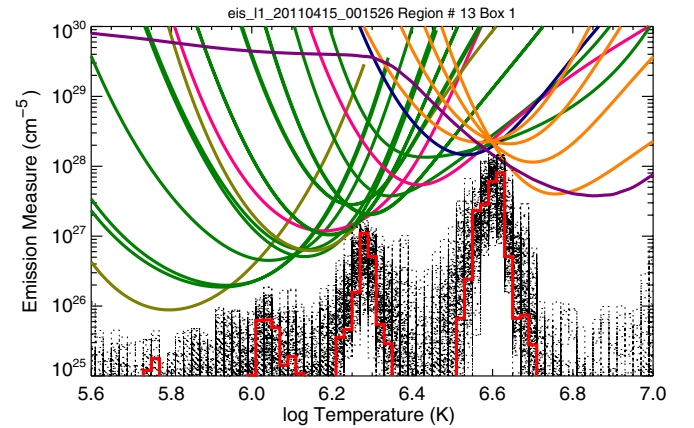


Figure 10. Alternative emission measure distribution derived for region 1 of the 2011 April 15. This DEM was computed using a much smaller bin size ($\Delta \log T_e = 0.02$) than those shown in Figures 6 and 7 ($\Delta \log T_e = 0.05$). (A color version of this figure is available in the online journal.)

field strength. This clearly is evident in Figures 1–3, which show relatively few loops in the inter-moss regions in the 171 Å for the largest values of magnetic flux.

The EM at the highest temperatures, as expected, increases with increasing total unsigned magnetic flux. This is also shown in Figure 9. It is important to recognize that this comparison between the properties of the inter-moss DEM and the total unsigned magnetic flux is not ideal since we are comparing an apex property of selected loops with the magnetic properties of the entire active region. As pointed out by Schrijver (1987), much of the increase in the total unsigned magnetic flux simply reflects an increase in the area of the active region. The mean field strength also rises with increasing active region area, but

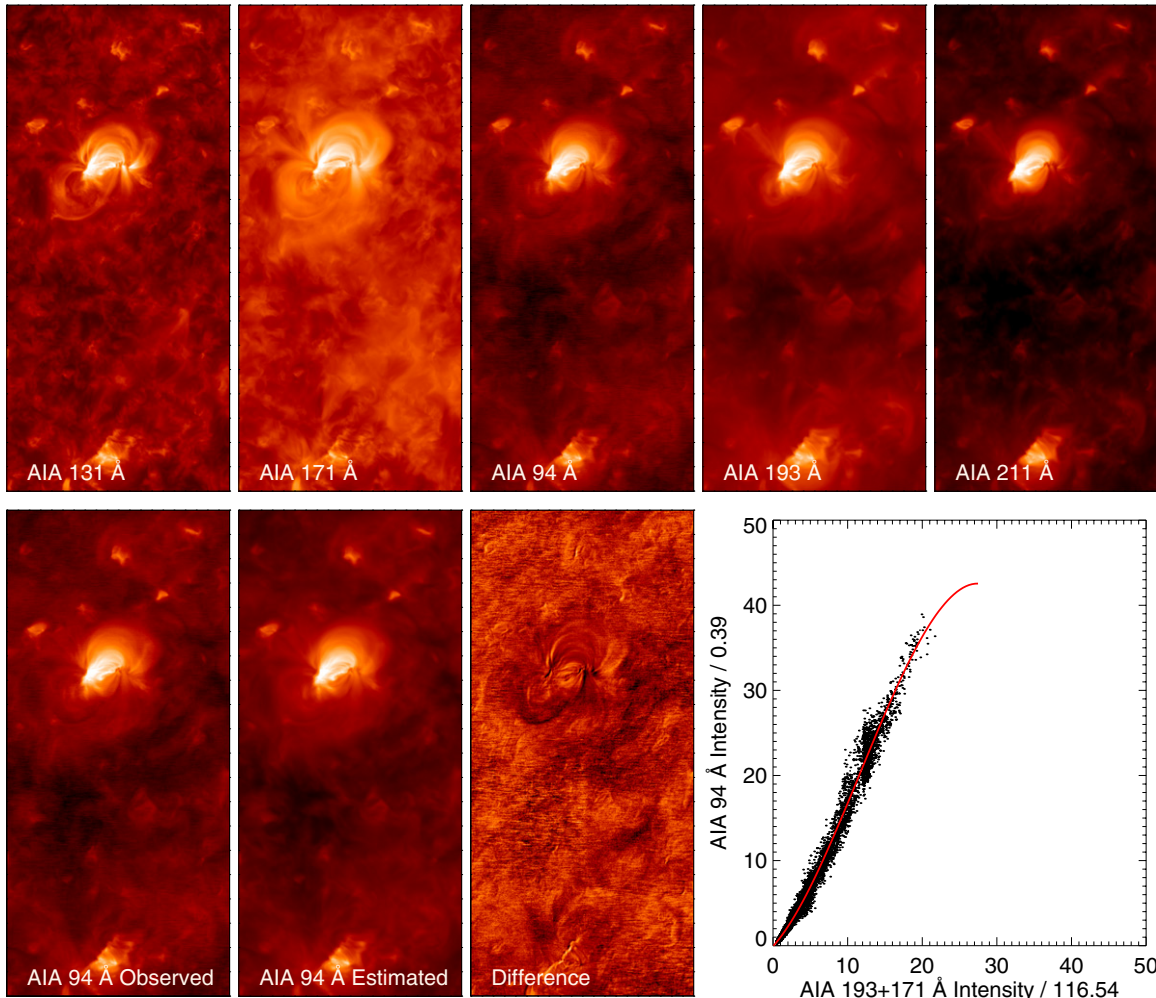


Figure 11. Time-averaged AIA images of a bright point and the quiet Sun. Each image is an average of 300 co-aligned exposures. These data were taken 2010 March 22 from 12 to 13 UT. The bottom panels show the observed AIA 94 Å image compared with the intensities inferred from 171 and 193 Å. The differences between these images are also shown. The far right panel shows a polynomial fit to the intensities.

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

weakly (also see Fludra & Ireland 2008). Ideally, we would compare the properties of the DEM with the magnetic properties at the loop footpoints, but this would depend on having accurate methods for extrapolating the photospheric field into the corona and such extrapolations have proven difficult to achieve (De Rosa et al. 2009). It seems likely that trends observed in Figure 9 would also be evident in a plot of EM as a function of footpoint field strength, but this has yet to be demonstrated.

3. DISCUSSION

We have presented the calculation of EM distributions for 15 active region observations spanning almost an order of magnitude in the total unsigned magnetic flux. This analysis suggests that the shape of the EM distribution depends on the magnetic properties of the active region. For regions with appreciable magnetic flux, the EM distribution is often strongly peaked at a temperature of about 4 MK. For lower levels of magnetic flux, however, we do observe shallower temperature distributions. This suggests a possible resolution of the varied results presented previously (Tripathi et al. 2011; Viall & Klimchuk 2011; Winebarger et al. 2011; Warren et al. 2011).

These results present a challenge to the Parker nanoflare model of coronal heating (Parker 1988), at least as it has

often been interpreted (Cargill 1994; Klimchuk & Cargill 2001; Cargill & Klimchuk 2004). As mentioned previously, hydrodynamic simulations suggest much flatter EM distributions than we observe in most of these active regions (Mulu-Moore et al. 2011). In the simulations, the steepest slopes ($2.0 \leq \alpha \leq 2.3$) are obtained for radiative losses based on coronal abundances. For all of the inter-moss regions that we considered, the intensities of the S and Ar emission lines computed from the DEM are consistent with what is observed, indicating that our assumption of coronal abundances is correct. It is possible, however, that some of the assumptions made in the hydrodynamic simulations, such as constant loop cross section or the highly simplified chromosphere, produce misleading results.

It seems likely that high-frequency heating that is concentrated at low heights in the solar atmosphere will be able to account for the active region properties that we present here. The wave heating model described in van Ballegoijen et al. (2011) and Asgari-Targhi & van Ballegoijen (2012) appears to be a viable candidate. Detailed numerical simulations, however, are required to establish this.

A number of previous studies have suggested that EM analysis is of little utility since the inversion of Equation (1) is ill-posed (e.g., Craig & Brown 1976; Judge et al. 1997). It is

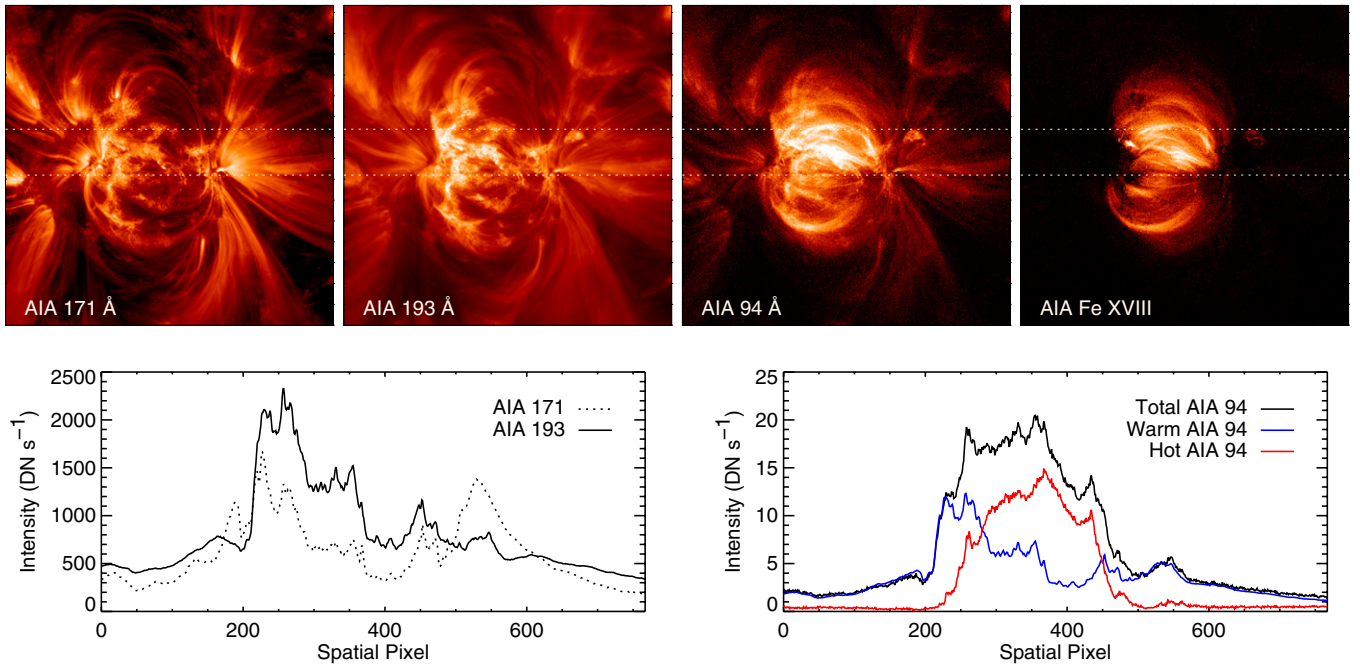


Figure 12. Example calculation of the Fe XVIII 93.92 Å intensity. The 171 Å and 193 Å images are combined and scaled to estimate the warm contribution to the 94 Å channel. The warm emission is then subtracted from the observed 94 Å channel image to yield an estimate of the Fe XVIII 93.92 Å intensity. The bottom panels show the intensity as a function of position across the image. The intensities are averaged along the region indicated by the dotted lines. These data are from 2011 November 8 near 16:34 UT.

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

clear, however, that the general properties of active region temperature structure can be determined from the available data. We can, for example, safely conclude that the EM near 4 MK is approximately 100 times larger than the EM near 1 MK in many of these active regions. This result is evident in all of the Monte Carlo runs and in many different active regions, so it is robust against perturbations in the observed intensities. The application of different inversion techniques to these data also yield similar results for the EM distribution (Hannah & Kontar 2012).

It is also clear, however, that the detailed structure of the EM distributions is much more difficult to determine with confidence. Small changes in the parameters used in the inversion can lead to different results (e.g., Landi et al. 2012). If we run the MCMC code with a smaller temperature binning, for example, we obtain distributions with much more structure. In the example shown in Figure 10, the general trend is preserved, but the EM distribution appears to break up into a series of nearly isothermal components (see Landi & Feldman 2008 for a similar result). Understanding the detailed structure of the EM distribution will require more detailed mathematical analysis. At present, however, developing models of the coronal heating process which make predictions comparable to the observations described here is likely to lead to the most rapid progress on this long-standing problem in solar physics.

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APPENDIX

AN EMPIRICAL CORRECTION TO THE AIA 94 CHANNEL

The AIA 94 Å channel is contaminated by “warm” emission formed at temperatures much less than the 7.0 MK temperature characteristic of Fe XVIII. To illustrate this, we have taken 1 hr of AIA observations (UT 2010 March 22 12–13) and computed time-averaged images from all of the available data. These data were chosen because they contained a large bright point in addition to the quiet Sun and show a relatively large range of intensities. The bright point, however, is unlikely to contain significant Fe XVIII, which would complicate the analysis. The averaging naturally leads to some smearing of the images but is necessary to improve the signal to noise. The averaged images for five wavelengths are shown in Figure 11.

Inspection of these images suggests that the warm emission is closest to 193 Å in morphology. Note the strong contrast between the bright point and the quiet Sun, for example. A detailed examination of the loops around the bright point indicates that there is also a contribution from cooler emission similar in temperature to 171 Å. See Testa & Reale (2012) for a discussion of stellar observations of this wavelength range. To estimate the intensities in the 94 Å channel, we consider a polynomial fit to a mixture of 171 Å and 193 Å images:

$$I_{94\text{warm}} = 0.39 \sum_{i=1}^4 a_i \left[\frac{f I_{171} + (1-f) I_{193}}{116.54} \right]^i, \quad (\text{A1})$$

where the scaling factors derived from the median intensities (116.54 and 0.39) have been introduced for convenience. We have determined that for $f = 0.31$ the estimated intensities are closest to what is observed. For this value of f , the coefficients to the polynomial fit are -7.31×10^{-2} , 9.75×10^{-1} , 9.90×10^{-2} ,

and -2.84×10^{-3} . Since there is very little data for very high intensities in these data, we limit the value of the composite 171/193 Å intensity to 30 in using the polynomial fit. The observed and estimated 94 Å intensities for these data are shown in Figure 11.

An example set of images is shown in Figure 12. These data were considered by Teriaca et al. (2012) and compared with spectroscopic observations of Fe XVIII 974.86 Å. Note that this procedure will not work during a flare since Fe XXIV 192.04 Å is likely to contribute to the 193 Å channel. This approach will also run into problems for very bright 1 MK emission, such as is found in the moss.

A similar method for isolating the Fe XVIII in the AIA 94 Å channel was considered by Reale et al. (2011). They used only 171 Å, however, which does not approximate the contaminating emission as well as a combination of 171 Å and 193 Å. An innovative technique for visualizing the relative contributions of active region emission at various temperatures, including the very high temperature Fe XVIII emission, has been presented by Testa et al. (2012).

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