

Nonequilibrium Ionization Effects on Solar EUV and X-Ray Imaging Observations

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Abstract

During transient events such as major solar eruptions, the plasma can be far from the equilibrium ionization state because of rapid heating or cooling. Nonequilibrium ionization (NEI) is important in rapidly evolving systems where the thermodynamical timescale is shorter than the ionization or recombination timescales. We investigate the effects of NEI on EUV and X-ray observations by the Atmospheric Imaging Assembly (AIA) on board the *Solar Dynamic Observatory* and X-ray Telescope (XRT) on board *Hinode*. Our model assumes that the plasma is initially in ionization equilibrium at low temperature, and it is heated rapidly by a shock or magnetic reconnection. We tabulate the responses of the AIA and XRT passbands as functions of temperature and a characteristic timescale, $n_e t$. We find that most of the ions reach equilibrium at $n_e t \leq 10^{12}$ cm⁻³ s. Comparing ratios of the responses between different passbands allows us to determine whether a combination of plasmas at temperatures in ionization equilibrium can account for a given AIA and XRT observation. It also expresses how far the observed plasma is from equilibrium ionization. We apply the ratios to a supra-arcade plasma sheet on 2012 January 27. We find that the closer the plasma is to the arcade, the closer it is to a single-temperature plasma in ionization equilibrium. We also utilize the set of responses to estimate the temperature and density for shocked plasma associated with a coronal mass ejection on 2010 June 13. The temperature and density ranges we obtain are in reasonable agreement with previous works.

Key words: plasmas – Sun: activity – Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: UV radiation – Sun: X-rays, gamma rays

1. Introduction

Study of the physical properties of erupting solar coronal plasma is needed to understand the mechanisms of solar eruptions. Recent high temporal and spatial resolution measurements make the detailed analysis of erupting solar coronal plasma possible. Most coronal analyses assume ionization equilibrium to determine the physical properties of the erupting plasma (Cheng et al. 2012; Hannah & Kontar 2013; Patsourakos et al. 2013; Tripathi et al. 2013; Hanneman & Reeves 2014; Lee et al. 2015, 2017; Reeves et al. 2017). In ionization equilibrium, the responses of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory and X-ray Telescope (XRT) on board Hinode are functions of temperature alone. However, if the thermodynamical timescale in a rapidly evolving system is shorter than the ionization and recombination timescale, then the plasma is out of equilibrium ionization (EI; e.g., Cox 1972; Shapiro & Moore 1977; Golub et al. 1989; Dudík et al. 2017). In that case, the instrument responses are functions of temperature and a characteristic timescale, $n_e t$, which are the parameters of the time-dependent ionization equation (e.g., Shen et al. 2015), where n_e and t are density and time, respectively.

A time-dependent ionization model (Shen et al. 2015) performs fast calculations by an eigenvalue method (Masai 1984; Hughes & Helfand 1985). The model precomputes the ionization and recombination rates, and those are saved into tables of eigenvectors and eigenvalues. Therefore, the model can calculate ion fractions easily for a large grid of temperature and $n_e t$. Models using the eigenvalue method have

been used for rapidly heated astrophysical plasma such as supernova remnants (Hughes & Helfand 1985; Kaastra & Jansen 1993), current sheets (Shen et al. 2013), and streamers (Shen et al. 2017). Smith & Hughes (2010) present the characteristic timescale, $n_e t$, to reach equilibrium for astrophysically abundant elements. This gives a rough idea of whether the plasma with a combination of n_e and t is in equilibrium. The importance of nonequilibrium ionization (NEI) effects in the solar atmosphere has been addressed in specific cases (see the references in Bradshaw & Raymond 2013; Dudík et al. 2017).

In this analysis, we investigate the effects of NEI on EUV and X-ray observations by AIA and XRT. For the investigation, first, we obtain the ion fractions for all the ions as a function of temperature and a characteristic timescale, $n_e t$, using a time-dependent ionization model (Shen et al. 2015). Second, we calculate the emissivities for all the lines of ions of abundant elements using CHIANTI 8.07 (Del Zanna et al. 2015), and then we find the temperature response for each ion by multiplying the emissivities by the effective area for each AIA and XRT passband. Lastly, the ion fractions are multiplied by the temperature response for each passband, which results in a 2D grid for each combination of temperature and the characteristic timescale. This set of passband responses is used for plasma that is rapidly ionized in a current sheet or a shock. We calculate the ratios between different passband responses to compare with the observations by AIA and XRT. We find that the ratio-ratio plots can be used to determine the departure of equilibrium as well as the constraints on temperature and density. As examples, we apply our results to a supra-arcade



Figure 1. Time and temperature grids.

plasma sheet (Hanneman & Reeves 2014) and the shocked plasma in a 2010 June 13 CME (Kozarev et al. 2011; Ma et al. 2011).

In Section 2, we describe the calculations to obtain the set of passband responses for plasma in nonequilibrium. In Section 3, we show the ratios between passbands in NEI and the application to a supra-arcade plasma sheet and a shock event. In Section 4, we present our conclusions.

2. Calculations

We find the temperature and characteristic responses of AIA and XRT using a time-dependent ionization model (Shen et al. 2015) and an atomic database CHIANTI 8.07 (Del Zanna et al. 2015) in *SolarSoft* (SSW). This allows us to analyze the observations by the AIA and XRT in NEI states.

2.1. Ion Fractions in NEI

We obtain the ion fractions for all the ions of the 16 most abundant elements, H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Cr, Fe, and Ni. Our model assumes that the plasma is in equilibrium at a low temperature in the initial state, and then it is rapidly heated in a short time. We calculate the ion fractions as a function of temperature and a characteristic timescale, $n_e t$, using a time-dependent ionization model (Shen et al. 2015), which uses an eigenvalue method. The model precomputes the ionization and recombination rates, and the rates are saved into tables containing the eigenvalues and eigenvectors for fast calculation. Using the precomputed tables, the ion fractions are calculated with the time-dependent ionization equation,

$$\frac{df_i}{dt} = n_e [C_{i-1}f_{i-1} - (C_i + R_i)f_i + R_{i+1}f_{i+1}], \qquad (1)$$

where f_i is ion fraction with charge state *i*, n_e is density, and *t* is time. C_i and R_i are ionization and recombination rate coefficients, which are taken from CHIANTI 8.07.

The equation gives the ion fractions with a characteristic timescale, $n_e t$. We use time steps that increase exponentially to $\sim 3 \times 10^4$ s (Figure 1(a)). We use a time step index of 1000, which increases exponentially with t = t + dt to apply a larger set of timescales, where dt is $e^{0.005 \times k}$ and k is a time grid.

Using a density, $1 \times 10^8 \text{ cm}^{-3}$, we calculate the ion fractions with the characteristic timescales from 1×10^8 to $3 \times 10^{12} \text{ cm}^{-3}$ s. The ionization and recombination rate

coefficients are only very slightly density dependent at coronal densities (Vernazza & Raymond 1979), and so the density dependence is ignored.

The rate coefficients are functions of temperature. We assume an initial temperature of 10^5 K, and the plasma is heated to 10^5-10^8 K at the first time step (Figure 1(b)). The initial temperature is not important after a very short time provided that the temperature jump in substantial. We use a temperature step index of 300, which is the temperatures with $10^{(5+(0.01)\times k)}$ K, where k is a temperature grid. We find the ion fractions as a function of element (Z), ion (z), temperature (T), and characteristic timescale, $f(Z, z, T, n_e t)$.

Figure 2 shows the change of ion fractions with n_et with different temperatures from 1 to 63 MK for Fe XII and Fe XXIV, which are the dominant lines in the AIA 193 Å passband (Lemen et al. 2012). The Fe XII fraction for the temperature of ~1.6 MK (purple) evolves into equilibrium in $n_et \leq 2 \times 10^{10} \text{ cm}^{-3}$ s while at higher temperatures, the fractions approach equilibrium earlier. The Fe XXIV fraction for the temperature of ~20 MK (green) evolves into equilibrium in $n_et = -8 \times 10^{11} \text{ cm}^{-3}$ s. This indicates that the plasmas with 1.6 MK and 20 MK take about $2 \times 10^2 \text{ s}$ and $8 \times 10^3 \text{ s}$ to reach the equilibrium, respectively, for a plasma density of 10^8 cm^{-3} .

2.2. Emissivities

We calculate the temperature responses for each element and ion so that they can be multiplied by the ion fractions, which are also functions of each element and ion. First, we calculate the line emissivities for each ion of elements using atomic data from CHIANTI 8.07 (Del Zanna et al. 2015), and then we find the temperature responses by multiplying the line emissivities for each ion by the effective area for each AIA and XRT passband. The temperature response is given by

$$\operatorname{Resp}(Z, z, T, \operatorname{band}) = \sum_{i=1}^{\operatorname{nlines}} \frac{\epsilon(i, T)}{10^9} A_{\operatorname{eff, band}}(\lambda(i)), \qquad (2)$$

where Resp(*Z*, *z*, *T*, band) [DN cm⁵ s⁻¹] is the temperature response for each element (*Z*), ion (*z*), temperature (*T*), and the passband (band) of the AIA and XRT. We calculate the emissivities for the temperature range from 10^5 to 10^8 K, which is the same range used in the calculation of ion fractions. We find the responses for the seven EUV passbands of AIA (94,



Figure 2. $n_e t$ vs. Fe XII and Fe XXIV fractions. Colored lines represent different temperatures. These ions dominate the AIA 193 Å passband except at very low T and $n_e t$.

131, 171, 193, 211, 304, and 335 Å) and all nine XRT passbands (Al_mesh, Al_poly, Al_med, Al_thick, Be_thin, Be med, Be thick, C poly, and Ti poly). The line emissivity, $\epsilon(i, T)$ [photon s⁻¹], is calculated at an arbitrary density, $n_e = 10^9 \text{ cm}^{-3}$, by the procedure (emiss_calc.pro) in CHIANTI 8.07. Then, the $\epsilon(i, T)$ is divided by the density. The choice of the density does not affect the calculation of the temperature responses because the density is an independent parameter for calculating the ion balance since we do not include photoexcitation and stimulated emission. We include the transitions by dielectronic recombination. The procedure calculates all the lines including the transitions where only theoretical energies are available for at least one of the two levels. Among these transitions, there are unrealistically high emissivities for a few lines at high temperatures in the CHIANTI database. We exclude the emissivities of 58 lines (81 transitions) at higher temperature than 63 MK. A_{eff} [cm² DN photon⁻¹] is the effective area for each passband (band) as a function of the wavelength (λ) for each transition line (i). The effective areas are calculated by procedures, aia get response.pro and make xrt wave resp. pro in SSW for AIA and XRT, respectively. The effective areas are calculated at a given specific date to consider the time-varying degradation of instruments (Narukage et al. 2011; Boerner et al. 2014). In this analysis, we calculate the responses on 2012 January 27 and also on 2010 June 13 for a shocked plasma in Section 3.2.

2.3. Temperature and Characteristic Timescale Responses

We find the temperature and characteristic timescale responses. This is the set of passband responses for plasma that is rapidly ionized in a current sheet or a shock. The ion fractions are multiplied by the temperature responses calculated in Section 2.2, which results in a 2D grid for each combination of temperature and the characteristic timescale. The responses are given by

$$R(T, n_e t, \text{band}) = \sum_{Z} \sum_{z} \text{Resp}(Z, z, T, \text{band}) AB(Z) f(Z, z, T, n_e t),$$
(3)

where $R(T, n_e t, \text{ band})$ is the temperature (K) and characteristic timescale response (cm⁻³ s), AB(Z) is abundance, and $f(Z, z, T, n_e t)$ is the ion fraction calculated using the time-dependent ionization model in Section 2.1. We use a coronal abundance (sun_coronal_1992_feldman_ext.abund) in CHIANTI (Feldman et al. 1992; Landi et al. 2002; Grevesse & Sauval 1998). Lastly, we add the continuum to the responses as below

$$R(T, n_e t, \text{band}) = R(T, n_e t, \text{band}) + \sum_{\lambda} \operatorname{cont}(T, \lambda) A_{\text{eff,band}}(\lambda),$$
(4)

where cont(T, λ) is the continuum calculated by procedures in CHIANTI 8.07, freefree.pro, freebound.pro, and two_photon. pro for Bremsstrahlung emission, free-bound emission, and, two-photon emission, respectively.

Finally, we find the temperature and characteristic timescale responses in units of DN cm⁵ s⁻¹ pix⁻¹ multiplying by $\Omega/4\pi$, where Ω is given by the pixel size, 0."6 and 1."0286 for AIA and XRT, respectively

As an example, we show the temperature and characteristic timescale responses for the AIA 193 Å in Figure 3. In the left panel, the temperature response approaches the responses in equilibrium (Lemen et al. 2012; Lee et al. 2017) with $n_e t \approx 10^{12} \,\mathrm{cm}^{-3}$ s. The red solid colors in the left panels of Figures 3 and 4 represent the responses in equilibrium. The responses with small $n_e t$ (e.g., black and purple colors) at higher temperature are due to the contribution of OV (Ciaravella et al. 2000; Bryans & Pesnell 2012; McCauley et al. 2013) and other low ionization species. In the right panel, a small bump at the larger $n_e t$ and higher temperature corresponds to the peak Fe XXIV fraction around $n_{et} \approx 1 \times$ $10^{11} \text{ cm}^{-3} \text{ s}$ in the right panel of Figure 2. The temperature response of the XRT Be_thin also shows that the response goes to the response in equilibrium (Golub et al. 2007; Lee et al. 2017) with around $n_e t \approx 10^{12} \,\mathrm{cm}^{-3} \,\mathrm{s}$ (left panel in Figure 4). The responses show that most of the ions are fully ionized at the highest temperature and large $n_e t$, and most of the high temperature emission is due to the Bremsstrahlung emission. In the right panel of Figure 4, the peak in Be_thin at $n_e t =$ 10^{10} - 10^{11} cm⁻³ s is from emission lines that are strong in equilibrium at $T = 3 \sim 20$ MK.



Figure 3. Temperature and characteristic timescale responses for AIA 193 Å. Colored lines represent characteristic timescales and temperatures in the left and right panels, respectively. Note the compressed logarithmic scale of the Y-axis.



Figure 4. Temperature and characteristic timescale responses for XRT Be_thin. Colored lines represent characteristic timescales and temperatures in the left and right panels, respectively.

3. Results and Discussion

We show the ratios between different passbands to make available a comparison with the AIA and XRT observations and discuss the departure from equilibrium as well as the constraints on temperature and density. As examples to compare our results with observations, we apply the model to a supra-arcade plasma sheet (Hanneman & Reeves 2014) and shocked plasma in the 2010 June 13 CME (Kozarev et al. 2011; Ma et al. 2011).

3.1. Passband Ratios in NEI

We examine the two-dimensional response ratios as a function of temperature and $n_e t$, which are calculated in Section 2.3, and examine whether they can be used to constrain temperature and density using the AIA and XRT observations. As an example, we show two passband ratios from AIA and XRT in Figure 5. We show a combination of 131 and 171 Å in the left panel of Figure 5. The ratio is a good indicator to determine the existence of hot plasma. The AIA ratio is almost

independent of $n_e t$ at low temperatures because similar low ionization species, OV, OVI, and FeVIII, dominate both bands. At temperatures above about 10^7 K, a strong dependence of the ratio on $n_e t$ is apparent due to the time needed to ionize into and out of the Fe XX and Fe XXI ions that are found near 10^7 K in equilibrium. A filter ratio between the XRT passbands has also been used to estimate the temperature of the observed plasma (e.g., Lee et al. 2015). We show a combination of Al_poly and Be_thin in the right panel of Figure 5. The XRT ratio is dominated by the Boltzmann factor, $e^{-hv/kT}$, so it is primarily dependent on T. Both plots of AIA and XRT show a banana shape with ratios of at about $-0.5 \sim 0.5$ (red and green) in the left panel and <0.8 (blue and purple) in the right panel at higher temperatures than $\sim \text{Log } T = 6.5$ in the AIA and XRT, respectively. The ratios are not different with various $n_e t$ values for most temperatures. Therefore, it is hard to constrain the temperature and density with these plots.

We try another method, a ratio-ratio plot. As examples of ratio-ratio plots, we show three ratio-ratio plots in Figure 6 for several temperatures and values of $n_e t$. The different symbols



Figure 5. 131 Å/171 Å and Al_poly/Be_thin in temperatures and characteristic timescales in the left and right panels, respectively. In the right panel, bigger ratios than 2.0 are represented by red colors below Log T = 6.0. The ratios are shown with contours.

and colors indicate the different temperatures and values of $n_e t$, respectively. The red solid curves are the ratio-ratio values corresponding to equilibrium. The red symbols indicate the corresponding equilibrium temperatures along the red curve. If any observed value lies on a straight line between points on the red curve, plasma with a combination of temperatures in equilibrium can match the observation. For example, the temperature at the location of "A" (black \times) in the black dashed line in the top panel of Figure 6 can be interpreted as a combination of 3.2 MK (red star) and 13 MK (filled red diamond) plasmas in equilibrium. In that case the contributions of 3.2 and 13 MK can be found with a relation of $a:b = (13 \text{ MK} - 3.2 \text{ MK}):(T_{\times} - 3.2 \text{ MK}), \text{ where } a \text{ and } b \text{ are}$ the distances along the black dashed line between two ratioratio points and T_{\times} is the temperature at the point \times . We find that the temperature is 6.2 MK with the relation. The temperature of "A" can also be estimated by the combination of temperatures of 4 MK (red triangle) and 20 MK (filled red square) on the black dotted line, In this case, the temperature is 18 MK. However, many other combinations of temperatures could produce the observed ratios. As another example, the temperature at the location of "A'" (black +) on the black dashed-dotted line could be an average temperature of 8.7 MK produced by a combination of 3.7 and 13 MK equilibrium plasmas. Otherwise, if the observed value does not lie on a line between points on the red curve (for example, the location of "B" in the top panel of Figure 6), it cannot be produced by any combination of equilibrium plasmas, and we can get a rough idea of the density and temperature in NEI. Therefore, the ratio-ratio plot allows us to estimate the temperature using the combination of temperatures in equilibrium and give a rough idea of how far the observed plasma is from EI in those cases. We show the region where the temperature can be estimated by some combination of temperatures in equilibrium in yellow in Figure 6.

3.2. Application to the Post-flare Arcade in 2012 January 27

Figure 7 shows the ratio images of a post-flare loop arcade associated with an X1.7 flare observed by AIA and XRT on 2012 January 27. We discuss whether the observed ratios are

consistent with ionization equilibrium by comparing them with the model ratios in Figure 6. Black dots in the right panels are the ratios of all pixels in the left ratio images. Gray bars are uncertainties in both ratios for each point calculated by using a formula in Lee et al. (2017), which tends to Gaussian for high count regimes and Poissonian for low count regimes (Gehrels 1986). We show the model ratios in Figure 6 with pastel blue colors to help compare the observations with the model. Rainbow colored crosses and purple stars in the right panels are the ratios of the pixels within the white box and the black box, respectively, in the left panels. Pastel orange and green colors are the ratios of the pixels within the pastel orange box near foot points of loops and the pastel green box on outer larger loops, respectively. The observed ratios near the foot points (pastel orange color) are close to the equilibrium temperatures between 2 MK (red cross) and 3.2 MK (red star). In the top right panel, the cloud of black dots above the red curve near [0.1, 0.5] requires a combination of equilibrium components with temperatures between 2 and 4 MK, and these ratio values cannot be explained by NEI because the NEI solutions all lie below the red curve (see Figure 6). The observed points from the pastel green box are located in this cloud of black dots, indicating that these loops are mutethermal and have temperatures between 2 and 4 MK. Yellow regions are the same as in Figure 6.

In this ratio–ratio plot with AIA only pairs, the swath of rainbow colored crosses agrees very well with the model ratios for 3.7-4 MK (diamond and triangle symbols) as the n_et values are varied. The rainbow colored crosses move from red to blue as their associated location moves further from the left-hand side of the white box. Thus the location of these values in the ratio–ratio plot is consistent with plasma at 3.7-4 MK that is closer to equilibrium the closer it is to the arcade. However, we note that we cannot rule out that the plasma in the white box is a result of a combination of plasma in equilibrium at different temperatures, since the rainbow colored crosses are within the red equilibrium curve.

In the middle right panel, the black dots with 193 Å/Al_med between 1 and 3 require one component in a narrow temperature range between 3.7 and 6.3 MK in equilibrium. The black dots with 193 Å/Al med >3 require a combination



Figure 6. Ratio–ratio with different temperatures (symbols) and characteristic timescale (colors) of 94 Å/171 Å vs. 94 Å/131 Å(top), 193 Å/Al_med vs. 211 Å/Al_med (middle), and 131 Å/Be_thin vs. 193 Å/Al_med (bottom). We show the temperature range from 2 MK to 20 MK in the top panel. Red solid curves with symbols represent the ratio–ratio in equilibrium. Please see the text for "A," "A'," "B," a, and b in the top panel. Yellow represents the region where the temperature can be estimated by some combination of temperatures in equilibrium.

of temperatures between 2 and 6 MK. These points are all located at the foot points of the flare loops (pastel orange color), so they probably correspond to pixels with more than one temperature along the line of sight. The black dots with 193 Å/Al_med <1 require a combination of two components

of 6.3 and 10 MK in equilibrium, but probably an isothermal 6 MK plasma is within the uncertainties, or else a hotter plasma (e.g., filled circle, diamond, and square) with moderate n_{et} (blue color in the middle panel of Figure 6). The rainbow colored crosses can be explained with a combination of 4 MK and 7 MK in equilibrium. The red and yellow crosses are hard to see here because these are underneath the green and blue crosses. This result indicates higher temperatures than those seen in the top panel. We note that combinations between 4 and 7 MK would not work to explain the rainbow colored crosses in the top right panel. The pastel orange (<3.7 MK) and green points (between 3.2 and 4 MK) also show higher temperatures than the temperatures (2 and 3.2 MK) in the top panel. One possibility for the discrepancy could be that the 131 and 171 Å filters are both sensitive to plasma at around 1 MK, which may be contaminating the points in the top ratio-ratio plot.

In the bottom right panel, the black dots with 193 Å/Al_med >3 can be explained with a single low temperature (e.g., 3.2 MK) in equilibrium. The black dots with 193 Å/Al_med <3 require a combination of temperatures in equilibrium, which are mostly inside the red curve. The red and yellow crosses are close to equilibrium, but the temperatures are between 6.3 and 8 MK. The ratios of green and blue crosses might come from the plasmas between 4 MK and 8 MK. These temperatures are higher than the ones in the top panel but similar to the temperatures in the middle panel.

Hanneman & Reeves (2014) have calculated a differential emission measure (DEM) for the supra-arcade region observed by AIA and XRT at the same time as in Figure 7 assuming EI. From the DEMs, they find that there are three temperature components of about 1 MK, 6-8 MK, and 30 MK for the flare arcade ("ARC" in Figure 20 in their paper). The low temperature plasma of 1 MK is possibly from background or foreground but not likely from the arcade. It is possible that this low temperature plasma affects the AIA only pair ratios, but has less of an effect on the other AIA and XRT pair ratios. We select a similar location with the arcade near [100, 150] (black box). The ratios are seen as purple stars in the ratio-ratio plots. The locations of "A" and "A" in Figure 6 correspond to the ratios of the purple stars for the observed points within the black box. We show the "A" and "A" also in Figure 7. The average temperature of these points could be 6.2 MK or 18 MK on the location "A" and 8.7 MK on the location "A" as estimated in Section 3.1. In the middle panel, the purple stars are in the head of a narrow long black cloud. This location in the ratio-ratio plot is consistent with hot plasma about 8 MK $(red \times)$ in EI or hotter plasma close to 20 MK (blue filled square in the bottom panel of Figure 6) with the moderate $n_e t$. In the bottom panel, the locations of the purple stars are consistent with about 8 MK (red \times) in EI or 20 MK (blue filled square) with moderate $n_e t$, although these are overlapped with much higher temperatures (blue filled up and down triangles), which can be rejected by comparing with the plot in the middle panel. The two hot temperature components in the middle and bottom panels are similar to each other. The lower temperature component in EI is similar to the results in Hanneman & Reeves (2014). However, the temperature of 20 MK for the hotter plasma is lower than the temperature of 30 MK calculated by assuming equilibrium in Hanneman & Reeves (2014). In this case, the hotter temperature of 18 MK estimated



Figure 7. Post-flare loop arcade at 20:45 UT on 2012 January 27. Ratio images of 94 Å/131 Å and 94 Å/171 Å (top), 193 Å/Al_med and 211 Å/Al_med (middle), and 131 Å/Be_thin and 193 Å/Al_med (bottom) and their ratio-ratio plots. Black dots on the ratio-ratio plots represent the ratios for pixels on the ratio images. The ratios of the pixels within the white box on the left panels are represented by rainbow colored crosses in the right panels. The color indicates the distance from the left side of the white box. The ratios of the pixels within the same colored boxes on the left panels are represented by purple stars in the right panels. Pastel blue and orange × represent the ratios within the pixels within the same colored boxes. On the ratio-ratio plots, the red curves and the red symbols are the same as in Figure 6. Gray bars represent uncertainties in both ratios for each point on the plot. Ratios with a value of 100 or greater involving the Al-med filter should probably not be believed. The lower left of the swarm of points in the 94 Å/171 Å vs. 94 Å/131 Å plot is more uncertain, because there are more low value 94 Å points there. Yellow regions are the same as in Figure 6.



Figure 8. Left: AIA observations showing the morphology of the shock wave (reversed color table). The figure is taken from Ma et al. (2011). Right: intensity flux tracking in the white box in the left. The dotted and dashed–dotted vertical lines represent the time when the shock and CME bubble arrived in the white box, respectively. See details in Ma et al. (2011). Solid vertical lines are the start and end times for the comparison with the characteristic responses. Black is the start time (\sim 05:39:15 UT) for 193, 211, and 335Å, blue is the end time (05:41:06 UT) for 193 Å, and red is the end time (\sim 05:42:15 UT) for 211 and 335Å.

from the AIA only pair is similar to the temperature of hotter plasma from the AIA and XRT pairs. The method of the ratio– ratio plot can give several temperatures from a ratio–ratio pair. Thus, we should consider several combinations of the ratio– ratio pairs, and find which solution might be reliable. It would be good to compare this method to many other events.

Using the example of an application to the post-flare arcade, we find indications in the data that the plasma closer to the arcade is closer to EI. However, we also find that most of the observed points may be described by using a combination of temperatures in equilibrium, so the presence of plasma out of equilibrium is difficult to establish definitively. In this example, the ratio-ratio plot with AIA only pairs gives lower temperatures than the temperatures in AIA and XRT pairs. It is possible that this discrepancy is because AIA is less sensitive to the hotter plasma while XRT is more sensitive to it. The ratio-ratio plot gives several different temperatures in EI or/ and NEI. It is possible since the observed coronal plasma is multithermal rather than isothermal, and also there is an effect of the background emission along the line of sight. Foreground or background contributions will tend to pull the ratios inside the regions where combinations of equilibrium plasmas can account for the ratios. It would be best to subtract the background emission for comparison with the ratio-ratio plots, but that can be difficult if the background varies. Therefore, we should examine carefully several ratio-ratio pairs together. We show the first application of our NEI models to the observations. In the future, a more detailed analysis is required with other observations.

In this analysis, we find that the temperatures estimated from ratio-ratio plots using a combination of the AIA and XRT passbands are higher than the temperatures estimated by using ratio-ratio plots that only use the AIA only passbands. One possibility is that the 131 and 171 Å are less sensitive to the higher temperatures, so the passband pairs tend to the lower temperatures. However, we cannot rule out the possibility of the calibration issue between the AIA and XRT instruments. If we adopt the factor of two multiplied to the calculated XRT responses for NEI (Testa et al. 2011; Cheung et al. 2015; Schmelz et al. 2015; Wright et al. 2017) then the model ratios tend toward the lower left in the ratio–ratio plots. In this case, the temperatures obtained with ratio–ratio plots using both the AIA and the XRT passbands are lower and therefore more similar to the temperatures obtained with ratio–ratio plots using AIA only. The effect of the cross-calibration between the two instruments will need further investigation.

It is hard to say exactly whether the observed ratios represent that the plasma is in EI or NEI. One possibility is that there are no observations that are certain to be in equilibrium. Bradshaw & Klimchuk (2011) show that small-scale, impulsive heating including a nonequilibrium ionization state predicts the observable quantities that are entirely consistent with what is actually observed.

3.3. Application to the Shocked Plasma in 2010 June 13

We apply our results to the CME-driven shock of 2010 June 13 studied by Kozarev et al. (2011) and Ma et al. (2011). We use the count rates in the AIA 193, 211, and 335 Å bands measured in the white box in Figure 8 by Ma et al. (2011). In this event, the ratio plots (Figure 5) and ratio–ratio plots (Figure 6) with the three passbands are hard to apply directly to distinguish the temperature and density, because each ratio corresponds to a banana-shaped region in the $T-n_et$ plane. For this reason, we match the observed intensity histories to the characteristic timescale responses and find the temperature, density, and line-of-sight depth (*dl*) ranges that satisfy the observations. The advantage of this method is that it incorporates the information in the time dependence of the shocked plasma.

The method assumes that the plasma is in EI before the shock, and then the plasma within the white box was shocked at earlier times as the shock passes beyond the box. We use the averaged intensities between $\sim 05:30:00$ UT and $\sim 05:39:00$ UT for each passband as the preshock background. As the shock bubble expands past the box, more and more of the background plasma is pushed out in front of the shock wave. The amount of gas in the white box is constant or slightly increased because of the shock compression. If the Fe IX ionization fraction stayed



Figure 9. Left: characteristic timescale response of 193 Å at 2.5 MK. Dotted line represents the starting $n_e t$ of the response for the comparison with the observation. Right: comparison of the observed intensity of 193 Å (dashed black line with a diamond symbol) and the model responses with different densities by different colors.

constant, the 171 Å band would brighten. Therefore, we model the light curve under the assumption that the FeIX is ionized away in the preshock gas, so that the fading in the 171 Å band tracks the reduction of the background. We then multiply the preshock backgrounds in the other bands by the ratio of the 171 Å band count rate to the preshock 171 Å band value. We indicate the start and end times of the observations used for the comparison with the characteristic responses in the right panel of Figure 8. We use the 193 Å observations from 05:39:18 UT to 05:41:06 UT. The 211 and 335 Å observations are used from 05:39:12 UT and 05:39:15 UT to 05:42:12 UT and 05:42:15 UT, respectively. This time range avoids the arrival (dashed-dotted line in Figure 8) of CME material within the box and only part of the box contains shocked plasma for a few exposure times of the observations. By dividing $n_e t$ by density, we have the characteristic responses as a function of time. Thus, we can compare the observations with the characteristic response in times once we give a specific density and a line-of-sight depth. We apply the grid of T from 2×10^6 K to 10^8 K, n_e from 10^7 cm⁻³ to 10^9 cm⁻³, and *dl* from 10^8 to 10^{11} cm. We then search for combinations of T, n_e , and dl that match the observed count rate curves.

The left panel of Figure 9 shows the characteristic response of the 193 Å band at 2.5 MK as an example. The second peak of the response near $n_e t \sim 5 \times 10^9 \text{ cm}^{-3}$ sec is the major contribution of Fe XII in the 193 Å passband as seen in Figure 2. At the very low $n_e t$, the peak may be from Fe IX, and it is not the major contribution to 193 Å band. We compare the responses starting at the minimum shown by the dotted vertical line in the left panel of Figure 9. The emission at the minimum is subtracted from the response, and the shock emission is set to zero at the initial time. That is reasonable because the emission by shock at 193 Å is mostly due to the Fe XII and the emission at the minimum is due mostly to low temperature lines. For the comparison with the observations in DNs, we multiply n_e^2 , dl, exposure time, and the number of pixels to the characteristic response. In the right panel of Figure 9, we show the observations in DNs (dashed black line with a diamond symbol) and the responses for different densities, indicated by different colors, at T = 2.5 MK and $dl = 6.3 \times 10^9$ cm as an example.

We compare the observed profile of each passband with the responses for all T, $n_e t$, and dl. Then, we find the allowed ranges of temperature, density, and line-of-sight depth where χ^2 is less than it is minimum value + 1.6. We use 1.6 rather than 1.0, because the rms deviations in the pre-CME background DN levels were about 1.6 times larger than expected from the count rate alone. The reduced χ^2 is given by

$$\chi^{2} = \frac{\sum_{t=1}^{n} \sqrt{(I_{\text{band}}(t) - f n_{e}^{2} dl R(T, n_{e}t, \text{ band}))^{2}} / I_{\text{obs,band}}(t)}{(n-1)},$$
(5)

where f is a constant, exposure time × the number of pixels within the box (40 × 32 pixels). The exposure times during the observations are 2.9 s for all four passbands. $I_{\text{band}}(t)$ is the observed DNs after the background subtraction. $I_{\text{obs,band}}(t)$ is the observed DNs. The number of observations, n, is 10, 16, and 16 for 193 Å, 211Å, and 335Å, respectively.

We show the profiles of observations and the predicted models in Figure 10 with the reduced χ^2 values. The dotted lines with a cross symbol are the best models. The reduced χ^2 value for 335 Å is smaller than others since the uncertainty of 335 Å is relatively much larger than the observations in the 193 Å and 211 Å bands.



Figure 10. Blue, red, and green solid lines represent the observed DN for 193 Å, 211 Å, and 335 Å, respectively. Dotted lines are the model responses with the best fitting in the constraints in Figure 11.

We show the constraints on *T*, n_e , and *dl* for each passband in Figure 11 and Table 1. There is no constraint that satisfies all three passband observations. However, there is a clear indication that temperatures of about 2.4–2.7 MK are preferred, while the widths of the peaks require a range of densities of at least 8×10^7 to 1.2×10^8 cm⁻³. The density and line-of-sight depth depend on each other, in the sense that the density tends to decrease with the increase of the line-of-sight depth to match the peak of the observations.

It is apparent that no single set of parameters fits all three bands. The probable reasons are (1) the parameters changing during the course of the observation—the shock sweeps up material from different heights as it moves through the corona; (2) the background subtraction method is not adequate; and (3) the shock is not a simple planar structure seen edge-on, but is curved. The increasing path length through the shocked gas as a function of time that results from the spherical shape of the shock will distort the evolution of the brightness curves, and we believe that this accounts for most of the discrepancy.

Kozarev et al. (2011) found temperatures ranging from about 2.0 to 6.8 MK in two regions behind the shock using DEM curves (their Figure 3), with most of the emission at the lower temperatures. Recent work has modified the response of the AIA 94 Å band (Del Zanna et al. 2015), which might remove the need for emission near 6.8 MK. Since Kozarev et al. (2011) implicitly assumed ionization equilibrium, their temperatures would tend to be too low. Ma et al. (2011) obtained a temperature of 2.8 MK. They only considered the ionization timescales to reach the ionization states Fe XII, Fe XIV, and Fe XVI that dominate the 193 Å, 211 Å, and 335 Å bands, respectively, and since they did not detect emission from in the 94 Å band, they found no emission near 6.8 MK. Ma et al. did not consider the fading of the 335 Å band, which requires a higher temperature to ionize Fe XVI to Fe XVII and above, but the fading is complicated by the geometrical effects mentioned above. Thus overall, the temperature ranges we obtain are in reasonable agreement with those of Kozarev et al. and Ma et al.



Figure 11. Constraints of temperature, density, and line-of-sight depth (a) Temperature vs. density; (b) temperature vs. line-of-sight depth; (c) density vs. line-of-sight depth.

 Table 1

 Constraints on Temperature, Density, and Line-of-sight Depth

Passband	Temperature (MK)	Density (cm ⁻³)	Line-of-sight Depth (cm)
193 Å 211 Å 335 Å	$2.4 \sim 3.2$ $2.4 \sim 2.7$ $2.0 \sim 4.7$	$\begin{array}{c} 4.6 \times 10^7 \sim 7.8 \times 10^7 \\ 1.1 \times 10^8 \sim 1.5 \times 10^8 \\ 6.5 \times 10^7 \sim 5.9 \times 10^7 \end{array}$	$\begin{array}{c} 4.0 \times 10^9 \sim 1.3 \times 10^{10} \\ 1.3 \times 10^9 \sim 2.6 \times 10^9 \\ 4.1 \times 10^8 \sim 2.1 \times 10^{10} \end{array}$

The density ranges shown in Figure 11 span an order of magnitude centered around $1.2 \times 10^8 \text{ cm}^{-3}$. This is in good agreement with the density of about 10^8 cm^{-3} obtained from the type II radio burst (Kozarev et al. 2011; Ma et al. 2011). Our estimates of the line-of-sight depth also span a large range, from below 10^9 to above 10^{10} cm. Based on the shock heights given by Kozarev et al. and Ma et al., the depth increased from zero when the shock entered the extraction box, to about 4×10^{10} cm at our last data point. Our estimates are probably low because of the spherical geometry of the shock and perhaps a small thickness of the shell of shocked material.

It is clear that a detailed model of the spherical shock is needed to fit the observations of this event in detail, but since our purpose in this paper is to present a general approach to the AIA response to time-dependent ionization, we defer that to a future paper. However, it is worthwhile to point out that the modest temperature we derive supports the estimate of Ma et al. (2011), and that temperature is well below that expected for a 600 km s^{-1} shock unless the electrons are much cooler than the protons (see Ghavamian et al. 2013) or else much of the shock energy goes into compressing the magnetic field (quasiperpendicular shock).

4. Conclusion

We find the set of passband responses of *SDO*/AIA and *Hinode*/XRT, which can be applied to the rapidly evolving systems such as a current sheet or a shock. We calculate the responses as a function of temperature and characteristic timescale for each passband using a time-dependent ionization model that performs fast calculations. The two-dimensional ratio plot against temperature and n_{et} , the ratio is almost independent of n_{et} , but dependent on temperature for both AIA and XRT. The ratio–ratio plots between a pair of passband responses allow us to determine temperature by a combination of temperatures in equilibrium and how far the observed plasma is from EI in specific cases. We also find that most of the ions reach equilibrium at $n_{et} \leq 10^{12} \text{ cm}^{-3}$ s. The responses used in this analysis can be found online.⁶

We apply our results to the post-flare arcade of 2012 January 27 and the CME-driven shock of 2010 June 13. We find that the temperatures of the flare arcade are similar in the previous work. However, the temperature of hotter plasma in NEI is lower than the temperature calculated by assuming EI. For the shock, we find that temperatures of about 2.4 to 2.7 MK are preferred, while the widths of the peaks require a range of densities of at least 8×10^7 to 1.2×10^8 cm⁻³. The temperature ranges we obtain are in reasonable agreement with previous works. However, a detailed model of the spherical shock is needed to fit the observations.

We apply our model to the post-flare arcade and the CMEdriven shocked plasma with two different methods. The method of ratio-ratio plots applied to the post-flare arcade can be used for most of the events if the observed DNs have a good signal to noise for each passband. However, the method of comparison the observed light curves to the responses in times applied to the shocked plasma can be used only for the event that happens for a short time, i.e., the observations show an increase and decrease in light curves, such as the shocked plasma in this analysis.

We prepare a robust tool to investigate the physical properties of the plasma in rapidly evolving systems. We expect that it could contribute to understanding more quantitatively the evolution of erupting solar events.

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