IMAGING AND SPECTROSCOPIC OBSERVATIONS OF A TRANSIENT CORONAL LOOP: EVIDENCE FOR THE NON-MAXWELLIAN $\kappa$-DISTRIBUTIONS

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The distance and nature of the stellar coronae with temperatures of up to several million Kelvin together with the proximity of the stars themselves make direct probing of these environments impossible at present. In the absence of in situ measurements, the emitted spectrum remains the only source of information about the physical conditions in these emitting media. Most of the coronal radiation is emitted in the X-ray, EUV, and ultraviolet parts of the electromagnetic spectrum, requiring space-borne observatories. This poses further problems with limited availability of the data, calibration and its stability.

In many instances, it is advantageous to combine imaging and spectroscopic observations (e.g., Schmelz et al. 2009; Warren et al. 2012; Del Zanna 2013a). Imaging observations employing narrow-band EUV filters, as those made by the Atmospheric Imaging Assembly (AIA, Boerner et al. 2012; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO, Pesnell et al. 2012), offer high spatial and temporal resolution. These are complemented with spectroscopic observations made in similar wavelength ranges, such as those performed by the EUV Imaging Spectrograph (EIS, Culhane et al. 2007) on board the Hinode spacecraft (Kosugi et al. 2007). Traditionally, the vast majority of both the imaging and spectroscopic data are analyzed and modeled under the assumption of a local equilibrium, that is, the Maxwellian distribution of particle energies. This is because calculation of the synthetic spectra requires integration of many individual ionization, recombination, excitation, and deexcitation cross sections over the (unknown) distribution function in order to obtain the rates of these processes and finally the corresponding emissivities at individual wavelengths. The assumption of a Maxwellian distribution affords easy calculation of the synthetic spectra, such as by using the CHIANTI atomic database and software (Dere et al. 1997; Landi et al. 2013).

However, this assumption is incorrect if there are correlations between the particles in the system. Such correlations can be induced by any long-range interactions in the system (Collier 2004; Leubner 2004; Livadiotis & McComas 2009, 2010, 2013), for example, particle acceleration due to magnetic reconnection (e.g., Petkaki & MacKinnon 2011; Zharkova et al. 2011; Burge et al. 2012, 2014; Cargill et al. 2012; Stanier et al. 2012; Gordovskyy et al. 2013, 2014), shocks, or wave–particle interactions (e.g., Vocks et al. 2008). In such cases, the particle distribution will depart from the Maxwellian one and will likely exhibit an enhanced high-energy tail. Furthermore, turbulence with the diffusion coefficient inversely proportional to particle velocity will also lead to the appearance of non-Maxwellian distributions with characteristic high-energy tails (e.g., Hasegawa et al. 1985; Laming & Leprès 2007; Bian et al. 2014). We note that the collision cross section scales with $E^{-2}$, where $E$ is the particle energy (Meyer-Vernet 2007). This leads to the behavior of the collision frequency as $E^{-3/2}$ that is, the high-energy tail is difficult to equilibrate. Therefore, the currently favored theories of nanoflare heating of the solar corona (Klimchuk 2006; Klimchuk et al. 2010; Tripathi et al. 2010; Viall &
Klimchuk 2011a, 2011b, 2013; Bradshaw et al. 2012; Winebarger 2012) should afford situations for departures from the Maxwellian distribution. Scudder & Karimabadi (2013) argue that the particle distribution in the solar and stellar coronae above 1.05\(R_\odot\) is strongly non-Maxwellian.

Observational clues that the solar corona could be non-Maxwellian come from the in situ detection of the non-Maxwellian \(\kappa\)-distributions in the solar wind (Collier et al. 1996; Maksimovic et al. 1997a, 1997b; Zouganelis et al. 2008; Le Chat et al. 2011). Spectroscopic evidence for the presence of \(\kappa\)-distributions in the transition region was found from active-region Si \(\text{m}\) spectra (Dziřičáková & Kulinová 2011). The \(\kappa\)-distributions are characterized by a high-energy power-law tail (Section 2), with the power-law index being given by the value of \(-\kappa + 1/2\). In the solar wind, the typically detected values are \(\kappa \gtrsim 2.5\), whereas the detection in the transition region yielded \(\kappa \approx 7\) from the active-region Si \(\text{m}\) spectrum. The presence of high-energy electrons in the transition region at the base of coronal loops has also recently been established by Testa et al. (2014) by analyzing the transition-region Si \(\text{iv}\) emission observed by the Interface Region Imaging Spectrograph (IRIS) instrument (De Pontieu et al. 2014).

Despite these detections in the solar wind and the transition region, no direct, unambiguous detection of the non-Maxwellian distribution in the coronal spectra have been made to date. Attempts at doing so were made, for example, by Feldman et al. (2007), Ralchenko et al. (2007), Dziřičáková & Kulinová (2010), Hannah et al. (2010), and Mackovjak et al. (2013). Feldman et al. (2007) assumed a bi-Maxwellian distribution, with the temperature of the second Maxwellian chosen to be 10 MK, and argued that no such second Maxwellian is necessary to explain the observed spectra of He-like lines. This analysis was, however, limited and did not include the effects of \(\kappa\)-distributions on the spectra. Ralchenko et al. (2007) showed that the quiet-Sun Si, Ca, and Ar spectra are consistent with a bi-Maxwellian distribution, where the second Maxwellian contains only a small fraction of particles, of the order of several percent. Its temperatures range from 2.3 MK (300 eV) to 7.7 MK (1000 eV), with the fraction of particles being at most 5–7% and 1% for these temperatures, respectively. No diagnostics of \(\kappa\) were performed. Hannah et al. (2010) used off-limb quiet-Sun observations performed by the RHESSI spacecraft (Lin et al. 2002) to constrain the emission measures corresponding to individual power-law and \(\kappa\)-distributions. However, the constraints obtained on the emission measures were rather large, even for small values of \(\kappa\). Dziřičáková & Kulinová (2010) and Mackovjak et al. (2013) studied the possibilities of diagnosing \(\kappa\) using lines observed by EIS. Despite having found several combinations of line ratios sensitive to \(\kappa\), mostly involving neighboring ionization stages, unambiguous detections were difficult due to atomic data uncertainties and possible multithermal effects along the line of sight that were not accounted for. Subsequently, Mackovjak et al. (2014) showed that the techniques to obtain the differential emission measures (DEMs) also work for the \(\kappa\)-distributions and studied the influence of \(\kappa\) on such analyses.

In this paper, we use the imaging and spectroscopic observations performed by SDO/AIA and Hinode/EIS in conjunction with the latest instrument calibration, atomic data sets, and DEM techniques to analyze a transient loop observed within an active region core. Spectral synthesis for the non-Maxwellian \(\kappa\)-distribution is briefly discussed in Section 2. An analysis of the AIA imaging observations is performed in Section 3. In Section 4, the ratios of spectral lines observed by EIS are analyzed to obtain the electron density and \(\kappa\) in the loop. The influence of the atomic data uncertainties on the diagnostics are discussed in Section 5. The results are summarized and discussed in Section 6.

2. SYNTHETIC SPECTRA FOR THE \(\kappa\)-DISTRIBUTIONS

2.1. The Non-Maxwellian \(\kappa\)-Distributions

The \(\kappa\)-distribution of electron energies (Figure 1) is defined as a two-parametric distribution with parameters \(T \in (0, +\infty)\) and \(\kappa \in (3/2, +\infty)\) (e.g., Owocci & Scudder 1983; Livadiotis & McComas 2009):

\[
f_\kappa(E)dE = A_\kappa \frac{2}{\sqrt{\pi}(k_B T)^{3/2}} \frac{E^{1/2}dE}{(1 + \frac{E}{(\kappa - 3/2)k_B T})^{\kappa + 1}},
\]

where \(A_\kappa = \Gamma(\kappa + 1)/(\Gamma(\kappa - 3/2))(\kappa - 3/2)^{3/2}\) is the normalization constant and \(k_B = 1.38 \times 10^{-16}\) erg s\(^{-1}\) is the Boltzmann constant. The Maxwellian distribution at a given \(T\) is recovered for \(\kappa \rightarrow \infty\). The maximum departure from the Maxwellian occurs for \(\kappa \rightarrow 3/2\).

The mean energy \(\langle E \rangle = 3k_B T/2\) of a \(\kappa\)-distribution does not depend on \(\kappa\). Because of this, \(T\) can be defined as the temperature. Meyer-Vernet et al. (1995) and Livadiotis & McComas (2009, 2010) showed that \(T\) indeed has the same physical meaning for the \(\kappa\)-distributions as the (kinetic) temperature for the Maxwellian distribution, and that it also corresponds to the definition of physical temperature in the framework of the generalized Tsallis statistical mechanics (Tsallis 1988, 2009). This permitted these authors to generalize from the zeroth law of thermodynamics for the \(\kappa\)-distributions, and it also permits, for example, the definition of electron kinetic pressure \(p = n_e k_B T\) in the usual manner.

It is straightforward to see from Equation (1) that, in the high-energy limit, the \(\kappa\)-distribution approaches a power law with the index of \(-\kappa + 1/2\). On the other hand, Livadiotis & McComas (2009) showed that, in the low-energy limit, the \(\kappa\)-distribution behaves as a Maxwellian with \(T_M = T(\kappa - 3/2)/(\kappa + 1)\) and scaled to an appropriate constant (see Dziřičáková

![Figure 1. \(\kappa\)-distributions with \(\kappa = 2, 3, 5, 10, 25\) and the Maxwellian distribution plotted for \(\log(T/K) = 6.0\). Colors and line styles denote the different values of \(\kappa\).](image-url)
et al. 2015). Therefore, the \( \kappa \)-distribution can be thought of as a Maxwellian core (at a lower temperature) with a power-law tail.

### 2.2. Line Intensities for the \( \kappa \)-Distributions

The emissivity \( \varepsilon_j \) of an optically thin spectral line arising due to a transition \( j \rightarrow i \), \( j > i \), in a \( k \)-times ionized ion of the element \( X \) is given by (e.g., Mason & Monsignori Fossi 1994; Phillips et al. 2008)

\[
\varepsilon_j = \frac{hc}{\lambda_j} A_j n(\lambda_j) n^{(X^j)}(\lambda_j) n^{(X^{k})} A_X n_e n_H
\]

\[
= A_X G_{X,j}(T, n_e, \kappa)n_e n_H, \tag{2}
\]

where \( h \approx 6.62 \times 10^{-27} \text{ erg s} \) is the Planck constant, \( c \approx 3 \times 10^{10} \text{ cm s}^{-1} \) represents the speed of light, \( \lambda_j \) is the wavelength of the resulting spectral line, \( A_j \) is the corresponding Einstein coefficient for spontaneous emission, \( n(\lambda_j) \) is the density of the ion \( +k \) with an electron in the excited upper level \( j \), \( n^{(X^j)}(\lambda_j) \) is the total density of ion \( +k \), \( n^{(X)}(\lambda_j) \equiv n_X \) is the total density of element \( X \) whose abundance is \( A_X \), \( n_H \) is the hydrogen density, and \( n_e \) is the electron density. The function \( G_{X,j}(T, n_e, \kappa) \) is the contribution function for the line \( \lambda_j \). The \( G_{X,j}(T, n_e, \kappa) \) is a function of \( \kappa \) due to the dependence of the individual collisional processes of ionization, recombination, excitation, and deexcitation on \( \kappa \) (e.g., Dzifčáková 1992, 2002, 2006a; Wannawichian et al. 2003; Dzifčáková & Mason 2008; Dzifčáková & Dudík 2013; Dudík et al. 2014a, 2014b; Dzifčáková et al. 2015).

The intensity \( I_j \) of the spectral line is then given by the integral of emissivity along a line of sight \( l \):

\[
I_j = \int_{\Delta t} A_X G_{X,j}(T, n_e, \kappa)n_e n_H dl, \tag{3}
\]

or

\[
I_j = \int_{\Delta t} A_X G_{X,j}(T, n_e, \kappa)\text{DEM}_e(T) dT, \tag{4}
\]

where the quantity \( \text{EM} = \int n_e n_H dl \) is the plasma emission measure, and \( \text{DEM}_e(T) = n_e n_H dl / dT \) is the DEM, generalized for the \( \kappa \)-distributions by Mackovjak et al. (2014).

The line intensities for \( \kappa \)-distributions are evaluated using the ionization equilibrium calculations for \( \kappa \)-distributions (Dzifčáková & Dudík 2013). The relative level population is obtained using the approximative method of Dzifčáková (2006b), Dzifčáková & Mason (2008), and Dzifčáková et al. (2015) based on atomic data corresponding to the CHIANTI database, version 7.1 (Dere et al. 1997; Landi et al. 2013). The accuracy of this method for allowed transitions is less than 10% (Dzifčáková & Mason 2008). For the Fe \( \kappa \)-Fe \( \kappa \), which are the ions used for the diagnostics in Section 4, the line intensities are obtained by direct integration of the collision strengths (Dudík et al. 2014b). The collision strengths for these calculations are state of the art and taken from Del Zanna (2010, 2011), Del Zanna & Storey (2012, 2013), and Del Zanna et al. (2012a, 2012b, 2014).

![Figure 2](image-url)

**Figure 2.** Ionization equilibrium for Fe \( \kappa \)-Fe \( \kappa \) for the \( \kappa \)-distributions, according to the calculations of Dzifčáková & Dudík (2013).

### 3. SDO/AIA OBSERVATIONS OF A TRANSIENT CORONAL LOOP: IMAGING

The AIA (Boerner et al. 2012; Lemen et al. 2012) on board NASA’s SDO (Pesnell et al. 2012) mission consists of four identical, normal-incidence, two-channel telescopes with a diameter of 20 cm. AIA provides multiple, near-simultaneous full-Sun images with high temporal (12 s) and spatial resolution (1'25, pixel size 0'6). AIA images of the Sun are taken in 10 filters, seven of which are centered on EUV wavelengths (94, 131, 171, 193, 211, 304, and 335 Å), and three on UV or visible wavelengths (1600, 1700, and 4500 Å). The EUV filters are centered on some of the strongest Fe lines in the solar EUV spectrum. However, other emission lines originating at different temperatures are present within each filter bandpass. This makes the temperature responses of the AIA EUV filters highly multithermal (e.g., O’Dwyer et al. 2010; Del Zanna et al. 2011b; Schmelz et al. 2013).

Compared to the Maxwellian distribution, the AIA responses for \( \kappa \)-distributions are even more multithermal (Dzifčáková et al. 2015, Figure 8 therein). This is mostly caused by the behavior of the ionization equilibrium (Dzifčáková & Dudík 2013), with the relative ion abundances of individual ions becoming wider and flatter with decreasing \( \kappa \) (see also Figure 2). The peaks of the individual filter responses can also be shifted toward higher \( T \), especially for low \( \kappa = 2–3 \) (Dzifčáková et al. 2012, 2015). Typically, an in-depth understanding of the AIA observations requires DEM analysis; see, for example, Hannah & Kontar (2012, 2013).

In the following, we report on the AIA observations of a transient coronal loop and its spatial and temporal relation to the solar microflaring activity. A DEM analysis of the AIA data is performed in Section 3.3, and its influence on spectroscopic diagnostics is studied in Section 4.3.

### 3.1. Relation of the Transient Loop to Microflaring Activity

The transient loop studied here was observed in the active region (hereafter, AR) NOAA 11704. This active region was a small bipolar AR, of Hale class \( \beta \)/\( \alpha \), characterized by two leading negative sunspots and dispersed plages of both polarities. On 2013 March 30, a compact B8.9-class microflare was observed within this AR, peaking at about 10:24 UT (Figure 3, top left). A weaker B4.8 microflare was observed to peak at 13:21 UT in a different AR NOAA 11708. Perhaps by
coincidence, during the same time, we observed a transient loop within AR 11704 in the same place as the previous B8.9 microflare (Figure 3).

Figure 3 and its animation show the location of the B8.9 microflare and the transient loop within AR 11704 in the AIA 171 Å channel. The 171 Å channel is chosen because it provides the best representation of the morphology of all features. The B8.9 flare was related to a failed eruption of a long intermediate filament. One end of the filament lies within AR 11704, with the filament extending farther away in the northeast direction (Figure 3). The activation of the filament starts at about 10:00 as a series of brightenings within the
filament and its immediate neighborhood, subsequently leading to apparently untwisting motions of bright threads. The filament does not erupt, however, perhaps due to the overlying field seen, for example, in the AIA 193 Å band.

The failed eruption is accompanied by the appearance of a flare arcade within AR 11704. The arcade first appears in the AIA 131 Å band (Figure 3, top right) and subsequently in cooler AIA channels. The arcade is still visible in 171 Å an hour later at 11:24 UT and subsequently fades. The fading of the arcade is accompanied by the appearance of falling blobs along the arcade in 304 Å (Figure 3’s animation) that are visible until about 12:30 UT. After this time, evolving loops are still observed in the same location. The evolution of these loops (Figure 3’s animation) resembles slipping reconnection (e.g., Aulanier et al. 2006, 2007, 2012), although this is ambiguous given the presence of many individual loops and other emitting structures. The loop emission at the loci of the flare arcade completely fades out of the AIA 171 Å channel at about 12:53 UT. However, at approximately 13:01 UT, a transient coronal loop starts brightening up once more (Section 3.2), preceded again by activity in the filament (Figure 3, bottom left). No restructuring of the large-scale magnetic configuration of the AR 11704 is noticeable during the period studied here (09:00–15:00 UT, Figure 3).

3.2. Multiwavelength Evolution of the Loop

We now focus on the evolution of the transient loop. The multiwavelength evolution of the EUV emission is shown in Figure 4 with a cadence of 20 minutes. The emission of the transient loop is observed in AIA 171 Å for nearly 2 hr (see the animation of Figure 3). The images in Figure 4 are chosen to include the time of 13:19 UT, during which the EIS spectrometer observes a part of the transient loop (Section 4).

Upon careful examination, we find spatial misalignments of unknown origin between various AIA bands, especially in the Solar Y direction. These misalignments are corrected for manually by matching the positions of the low-lying moss emission. In this correction, the AIA 171 and 193 Å bands are taken as the reference ones because no detectable misalignment between these two bands is found. The AIA 211 Å is corrected by shifting it by \( \Delta Y = -1.6 \text{ px} \) (1 px \( \equiv 0.06 \)) to match the 193 Å band, which has similar emission morphology. Subsequently, the 335 Å band is corrected by shifting it by \( \Delta Y = 2.13 \text{ px} \) to match the corrected 211 Å band, again due to similar emission morphology. The 131 Å band is shifted \( \Delta Y = 1.5 \text{ px} \) to match the 171 Å band. No correction is necessary for the 94 Å band. After these corrections, the location of the moss emission is the same throughout the AIA bands, and the spatial correspondence of loops observed in different bands is substantially improved as well. We also note that the AIA data shown in Figure 4 are corrected for solar differential rotation using the drot_map routine available within Solar Soft under Interactive Data Language (IDL).

Before the loop appears in AIA 171 Å, it is visible in AIA 335, 211, and 193 Å (Figure 4, top row). The transient loop belongs to the series of evolving loops already present at the same location (Figure 3’s animation). At about 13:01 UT (Figure 5), the loop is discernible as a brightening structure in all AIA EUV channels. In the vicinity of its right footpoint at \( X = 235", Y = 370" \), we observe heightened activity (see the animation of Figure 3), with the appearance of many bright, short, short-lived closed loops and jetting activity, likely indicating ongoing magnetic reconnection. The transient loop continues to brighten, and at 13:19 UT, corresponding to the time of the EIS observation, the loop is already a prominent emitting structure (Figure 4, second row). The temporal evolution of the loop emission is shown in Figure 5. The top panel of this figure shows background-subtracted light curves in a small black box of \( 4 \times 5 \) AIA pixels at the position of the loop. The background is represented by the green box of \( 4 \times 5 \) AIA pixels located to the right of the black box (Figure 4, second row). Its location is chosen so that its intensity is not contaminated by the jet emission (Figure 5).

The loop emission first peaks in the 335 Å filter at about 13:20 UT, followed by 211 and 193 Å at 13:26 UT, and subsequently by 94 Å at 13:27 UT, 171 Å at 13:29 UT, and 131 Å at 13:32 UT in that order. That is, the emission first peaks in Fe xvi and subsequently cools down to the Fe xvi observed in 131 Å. This is important because these results show that no hot flare-like emission is present. If it were, it would be detected as Fe xxi and Fe xvm emission in the AIA 131 and 94 Å bands (e.g., Del Zanna et al. 2011a; Petkaki et al. 2012) prior to the maximum of the 335 Å light curve. The 94 Å emission is observed to be very weak, of the order of several DN s\(^{-1}\) px\(^{-1}\), suggesting the absence of a strong, dense plasma emitting in Fe xvm. The 131 Å emission closely follows the 171 Å, showing that it is dominated by Fe xvi. This conclusion is confirmed using the time–distance plots constructed as a function of Solar X using a slit placed at Solar \( Y = 392" \), that is, through the centers of the black and green boxes (Figure 4, second row).

We note that the light curves show multiple peaks. This is most likely due to the multithermal nature of the AIA bands. In principle, a DEM analysis can help identify the contributions to individual peaks, if the distribution function (i.e., value of \( \kappa \)) is known. Because \( \kappa \) cannot be determined from AIA data alone (Section 3.3), we do not perform this analysis.

We also note that the loop evolution is accompanied by the presence of multiple jets originating near the loop’s right (western) footpoint (Figure 3’s animation). With increasing height, these jets diverge from the loop and thus do not contaminate the loop emission. In Figure 5, bottom, the jets appear as a series of fast-moving, short-lived brightenings near the position of the loop (black horizontal lines). The jetting activity starts at about 13:14 UT and extends beyond the lifetime of the transient loop. With increasing time, the loop evolves into a series of individual threads and subsequently fades away (Figures 4, 5, and the animation of Figure 3).

3.3. Multithermality of the Loop as a Function of \( \kappa \)

Because the loop is observed in all six AIA coronal EUV bands, it is expected to be multithermal. We used the regularized inversion method of Hannah & Kontar (2012, 2013) to obtain the DEMs as a function of \( \kappa \). The results are shown in Figures 6 and 7.

The DEM\(_\kappa \) reconstruction is performed for each pixel of the 1 minute averaged AIA data observed at 13:19 UT (Figure 4, second row). Before the DEM reconstruction, we remove the stray light from the AIA data using the method of Poduval et al. (2013). In the DEM reconstruction, a temperature interval of \( \log(T/K) = 5.5–7.4 \) (\( \Delta \log(T/K) = 0.1 \)) is used. The value of \( \kappa \) is assumed to be constant throughout the field of view. We note that such an assumption may not be justified because individual
Multiwavelength imaging observations of the loop evolution made by SDO/AIA. The time cadence shown is 20 minutes. AIA data are averaged over 1 minute intervals to increase the signal-to-noise ratio, especially in the 335 and 131 Å bands. The images are scaled logarithmically. The field of view shown corresponds to the box in Figure 3. Small black and green boxes in the second row denote the selected portion of the loop and background, respectively. The white box shows the field of view of a portion of the EIS raster shown in Figure 8.
emitting and indeed overlapping structures could in principle have different values of $\kappa$. However, in the absence of simultaneous stereoscopic and spectroscopic observations throughout the field of view, it is not possible to obtain the value of $\kappa$ for each emitting structure in each pixel at a given time; an assumption is therefore necessary. By adopting a single value of $\kappa$ for the entire field of view, we demonstrate the feasibility of the regularized inversion method to recover the non-Maxwellian DEMs from AIA observations using the corresponding responses for the $\kappa$-distributions (Dzifčáková et al. 2015), which (to our knowledge) has not been done before.

The background-subtracted DEMs averaged over the small box along the loop (Figure 4) are shown in red in Figure 6. DEMs corresponding to the black box are shown in black, while the background DEMs corresponding to the green box in Figure 4 are shown in green. The background-subtracted DEMs peak at $\log(T/K) = 6.2$ for the Maxwellian distribution and $\kappa = 5$. The peak of the DEM is shifted to higher $T$ for $\kappa = 2\text{–}3$, being at $\log(T/K) = 6.3$ and 6.4 for $\kappa = 3$ and 2, respectively. This behavior of the DEMs is mainly the result of the shifts in the ionization equilibrium to higher $T$; see Figure 2 and Mackovjak et al. (2014). The DEMs are multithermal, with a significant amount of emission originating at temperatures lower than the peak of the DEMs, down to about $\log(T/K) = 5.9\text{–}6.1$.

The pixel-by-pixel reconstructed $EM_\kappa(T)$ are shown in Figure 7 for the five temperature bins where the background-subtracted DEMs is the highest (Figure 6). Note that the width of the temperature bin is $\Delta \log(T/K) = 0.1$. We see that the loop is present in all of these temperature bins. At lower temperatures, it is relatively well defined, with the $EM_\kappa(T)$ becoming more fuzzy with increasing $T$ for all $\kappa$. This behavior comes from the emission morphology in the progressively hotter AIA bands.

The DEMs for the Maxwellian distribution and $\kappa = 5$ contain a spurious high-temperature peak at $\log(T/K) \geq 7.0$. This peak is about a factor of $\approx 30$ weaker than the main one and was reported for on-disk AIA observations also by Dudík et al. (2014c, Section 3 therein). This peak is also present in the background DEMs, which may suggest that it is an artifact of the method. The peak gets progressively suppressed with decreasing $\kappa$, until it is absent from the background-subtracted DEMs for $\kappa = 2$.

We note that, in principle, a combination of AIA filter ratios permits the diagnostics of $\kappa$, but only for isothermal or near-isothermal structures (Dudík et al. 2009; Dzifčáková et al. 2012). This is because such color–color diagrams are not monotonic, but contain complicated curves. Because the DEMs obtained are significantly multithermal for all $\kappa$ studied, it is not possible to use the combinations of AIA filter ratios to diagnose $\kappa$. Instead, the diagnostic of $\kappa$ has to be performed using ratios of individual spectral lines that produce monotonic ratio–ratio diagrams (see Section 4.3).

4. Hinode/EIS Observations during HOP 226

The Extreme-Ultraviolet Imaging Spectrometer (EIS, Culhane et al. 2007) on board the Hinode mission (Kosugi et al. 2007) provides EUV spectra of the Sun in the wavelength ranges 171–212 and 245–291 Å with a spectral resolution of about 22 mA and spatial resolution down to 1″, corresponding to the width of the slit chosen.

On 2013 March 30, EIS was observing a portion of AR 11704 as a part of the Hinode Operation Plan (HOP) 226. HOP 226 was originally designed for diagnostics of non-Maxwellian $\kappa$-distributions using weak O iv–O vi and S xi–S xii lines (see Mackovjak et al. 2013). Because these lines are weak, EIS was rastering an area within the AR core using a 2″ slit and long exposures (60 and 600 s). Each 60 and 600 s raster contained 10 exposures of the 2″ slit at contiguous positions in Solar X, covering 512″ in Solar Y (heliocentric coordinates). For context, as well as density diagnostics, the raster contained additional lines, notably several strong Fe xii–Fe xiii lines.

Upon examination of the data, we find that the 600 s rasters suffer badly from an accumulation of cosmic rays and that the weak O and S lines do not have sufficient intensities for diagnostics. However, the last 60 s raster, starting at 13:11 UT and progressively rastering in the west-to-east direction,
captures a portion of the coronal loop in its ninth exposure at 13:19 UT (position 9 in Figure 8), with the portion of the loop lying directly along the EIS slit. Some of the O and S lines proposed for diagnostics are again too weak in this 60 s exposure. Nevertheless, the strong Fe XII–Fe XIII lines (Table 1) are sufficient to perform diagnostics of the \( \kappa \)-distributions. It is these data that are analyzed here.

4.1. EIS Data Processing and Calibration

We first performed a coalignment of the raster with the AIA data. To do this, we use the Fe xii 195.119 Å self-blend (hereafter, “195.119 Å sbl”) and the AIA 193 Å data uncorrected for solar differential rotation but with stray light removed (Poduval et al. 2013). These AIA data are used to build an AIA 193 Å pseudoraster image by extracting the EIS field of view during each exposure within the raster, averaging individual AIA 193 Å frames within the duration of each raster exposure, and convolving with the EIS point-spread function, which is assumed to be a Gaussian with FWHM of 2" in both the X and Y directions (Del Zanna et al. 2011b, Appendix A therein). By comparing this AIA 193 Å pseudoraster image with the EIS 195.119 Å sbl, we found shifts in the EIS positioning of \( \Delta X = 13'' \) and \( \Delta Y = -9.5'' \) with respect to AIA. Furthermore, the EIS slit is found to be rotated by +1° with respect to the Solar Y. Note that because the EIS raster has only 10 exposures in Solar X, the EIS raster image cannot be rotated. Rather, the AIA data have to be rotated by −1° before constructing the AIA 193 Å pseudoraster image. Because of the relative rotation between the two instruments, as well as for simplicity, the positions of the individual EIS pixels will be given in pixel units x and y rather than Solar X and Y.

The EIS data were calibrated using the standard \texttt{eis\_prep. pro} routine available within the SolarSoft platform running under the IDL. During the calibration, the latest in-flight radiometric calibration of Del Zanna (2013a) was used. The calibrated data contain intensities in physical units (erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) Å\(^{-1}\)) and the 1σ errors on the observed intensities at each spatial and wavelength pixel. The intensities and uncertainties are stored in separate files, with the error file also containing flags for missing pixels (dusty, hot, warm pixels and pixels affected by cosmic rays). We note that usually these missing pixels are interpolated during the calibration procedure. However, the number of missing pixels in the raster is relatively high, up to 30%. This brings up concerns about uncertainties in the fitting of the observed intensities at each single spatial pixel (Young 2010).

In this work, the pixels flagged as missing were interpolated only for purposes of visualizing the raster field of view containing the loop (Figure 8, right). The missing pixels were excluded from any further analysis because they cannot always be interpolated with accuracy due to their high number. Instead, we rely on intensities obtained by averaging along a selected loop segment observed in position 9 of the EIS slit. The intensity averaging is done over \( y \) at each wavelength pixel using exclusively pixels not flagged as missing. The same is done at position 5 of the EIS slit, which we chose to represent the background. We selected two loop segments over which the averaging is performed. The first one consists of pixels \( y = 288 \) to 317, denoted simply as “loop (288:317),” and representing the average loop spectrum. The second one is much shorter, consisting of pixels \( y = 300–309 \), denoted as “loop (300:309),” and representing a much shorter segment of the loop.

We chose to average over longer rather than shorter loop segments in order to minimize the errors from photon noise. We also note that the effective EIS resolution in \( y \) is only about 3"–4" because of the instrument point-spread function.

Subsequently, the average spectrum of the background at position 5 is subtracted from the average loop spectrum. The resulting background-subtracted loop spectrum is fitted with
Gaussian line profiles and locally linear continua, taking into account known blends and self-blends (e.g., Del Zanna 2010, 2011, 2012; Dudík et al. 2014b). The intensities obtained are listed in Table 1. The uncertainties on these intensities are obtained by error propagation of the uncertainties of the photon noise and dark-current subtraction that are the output of the eis_prep.pro. These uncertainties are then added in quadrature with the uncertainty of the EIS radiometric calibration. We consider two values of the radiometric calibration uncertainty, 10% and 20%. The 20% uncertainty is the uncertainty of the ground calibration (Culhane et al. 2007), and Wang et al. (2011) argues that the in-flight uncertainty is smaller, about 10%. The final uncertainties on the line intensities are denoted $\sigma_{10\%}$ and $\sigma_{20\%}$, respectively, and are also listed in Table 1.

We note that we employed the revised radiometric calibration of Del Zanna (2013a) rather than the ground calibration (Culhane et al. 2007) or the calibration of Warren et al. (2014). Del Zanna (2013a) showed that significant departures from the EIS ground calibration occurred over time, especially with the lines in the long-wavelength channel of EIS being underestimated by about a factor of two for observations after 2010. Line ratios were used to obtain a calibration corrected for the decrease in sensitivity. Warren et al. (2014) obtained similar results, comparing the EIS radiances from the whole Sun with the SDO/EVE irradiances together with the quiet-Sun DEM modeling. However, the EVE calibration can be an additional source of uncertainty. Furthermore, the quiet-Sun DEM modeling used by Warren et al. (2014) can in itself be sensitive to $\kappa$ (Mackovjak et al. 2014), which could entangle the calibration to diagnostics and overcomplicate the problem. The Del Zanna (2013a) calibration is sufficient for our purposes because the diagnostics of electron density (Section 4.2) as well as the diagnostics of $\kappa$ (Section 4.3) rely only on line ratios (Dzifčáková & Kulínová 2010; Mackovjak et al. 2013; Dudík et al. 2014b) and thus do not require absolute calibration.

We also note that the decrease in sensitivity of the long-wavelength channel of EIS by about a factor of two is clearly significant for our diagnostic purposes. This is because the

![Figure 7. Emission measure $EM_k(T)$ at different temperatures $T$ as a function of $\kappa$. The values of $\kappa$ and $\log(T/K)$ are indicated at each frame.](image)
diagnostics of $\kappa$ in Section 4.3 involve lines from both the short-wavelength and long-wavelength EIS channels. We note that the Del Zanna (2013a) calibration applies only to observations up to 2012 September, so we have assumed that no further degradation has occurred since. If the long-wavelength channel sensitivity further degraded significantly, the radiiances of the long-wavelength channel would be underestimated, and the ratios shown in Figures 10–12 would decrease.

4.2. Density Diagnostics

Diagnostics of electron density are a necessary prerequisite to diagnostics of $\kappa$ (Section 4.3). The Fe lines observed by EIS (Table 1) contain several combinations of lines sensitive to electron density (e.g., Watanabe et al. 2009; Young et al. 2009; Del Zanna 2010, 2011; Del Zanna et al. 2012b; Dudík et al. 2014b). The density-sensitive line ratios are listed in Table 2, where the diagnosed densities are also listed.

The diagnostics of density are performed using the method developed first by Dzíčkáková & Kulinová (2010). The theoretical line ratios were calculated by Dudík et al. (2014b) using the latest available atomic data (see also Section 2.2). This density diagnostics method employs ratios of lines arising in the same ion. The sensitivity of these ratios to $n_e$ cannot be significantly influenced by their sensitivity to $T$ and $\kappa$, otherwise the density diagnostics would be precluded. Typically, it was found that density-sensitive ratios commonly used for the Maxwellian distribution can be used under the assumption of $\kappa$-distributions in the same manner, albeit the resulting densities can be up to 0.1 dex lower for $\kappa = 2$ (red color in Figure 9). This uncertainty due to the unknown value of $\kappa$ is however comparable to or smaller than the uncertainty due to the dependence of individual ratios on $T$ (Dzíčkáková & Kulinová 2010; Mackovjak et al. 2013; Dudík et al. 2014a, 2014b). The overall uncertainty due to the a priori unknown values of $T$ and $\kappa$ can be in some instances as large as 0.4 dex in log($n_e$/cm$^{-3}$) (e.g., Figure 9).

In principle, calibration uncertainties compound the uncertainty of the diagnosed density. However, the EIS density-sensitive lines belonging to the same ion typically have similar wavelengths and are all observed within the same EIS channel. It is unlikely that the corresponding line ratios are severely affected by calibration uncertainties. Therefore, we chose to ignore the calibration uncertainties when diagnosing the electron density. Nevertheless, for illustration, the values of individual ratios derived from the background-subtracted observations (Section 4.1) are plotted in Figure 9 with their uncertainties.

The densities diagnosed using the Fe xi and Fe xiii ratios are consistent within their respective errors (Figure 9, Table 2). However, the densities diagnosed using Fe xiii are higher by about 0.5 dex compared to those diagnosed using Fe xi. That is, given the densities diagnosed using Fe xi and Fe xii, the calibrated intensities of the Fe xii 186.887 Å self-blend seem to be too high compared to the intensities of the Fe xii 195.119 Å self-blend by about 20–30%. The reason for this discrepancy is unknown. Del Zanna et al. (2012b) showed that the new atomic model for Fe xii provides significantly lower densities than the previous model, by about 0.4 dex. The previous model consistently provided values much higher than those obtained from Fe xi to Fe xiii (see, e.g., Young et al. 2009). The densities obtained for the background-subtracted ratios from Fe xii are much reduced using the new atomic data of Del Zanna et al. (2012b), but still higher by about 0.5 dex than those obtained here from Fe xi to Fe xiii. The discrepancy is lower when background subtraction is ignored. The reason is unclear despite the fact that we use here the same atomic data and calibration as Del Zanna et al. (2012b) and Del Zanna (2013a).

Nevertheless, the intensity of the 186.887 Å line is somewhat suspect because the shape of the EIS effective area curve in the Del Zanna (2013a) calibration differs from that of the ground calibration (see Figure 8, top, therein) or from that of Warren et al. (2014, Figure 7 therein). The differences are of the order of several tens of percent, which is comparable to the 20% calibration uncertainty. We note that changing the Fe xii 186.887 Å self-blend /195.119 Å self-blend ratio by about 20% would bring the diagnosed densities into consistency with the Fe xi and Fe xiii ones (Figure 9). Furthermore, if the 20% calibration uncertainties are taken into account, the observed Fe xii ratio still yields densities consistent with the other ratios because the lower violet line in Figure 9 yields densities of log($n_e$/cm$^{-3}$) = 9.2–9.4.

Additionally, because of the strong overlap of the Fe xi–Fe xiii relative ion abundances (Figure 2) at temperatures corresponding to the peaks of the background-subtracted DEMs for all $\kappa$ (Figure 6), it is unlikely that the diagnosed loop is a multidensity one. If it were, the Fe xiii density-sensitive ratios, which have stronger density sensitivity at log($n_e$/cm$^{-3}$) = 9.5, should be biased toward higher densities more than the Fe xi ratio, whose increase with $n_e$ is weaker.

For these reasons, we adopt the densities diagnosed using Fe xi and Fe xiii for further analysis. For the average loop spectrum, the diagnosed value is log($n_e$/cm$^{-3}$) = 9.0–9.5, and for the loop spectrum averaged through pixels $y = 300$–309 we obtain the value of log($n_e$/cm$^{-3}$) = 8.8–9.6. We note that these values are conservative because they are chosen to contain all...
of the densities diagnosed using Fe xi and Fe xiii together with their respective errors (Table 2).

4.3. Diagnostics of T and \( \kappa \)

4.3.1. Ratio–Ratio Diagrams

Having obtained constraints on the electron density, we can next diagnose \( \kappa \). A principal constraint is that the diagnostics of \( \kappa \) have to be performed using lines that are also sensitive to temperature. This comes from the nature of the task, as both the excitation and the ionization and recombination rates are a function of both \( T \) and \( \kappa \). Typically, line ratios sensitive to \( \kappa \) involve lines populated by different parts of the distribution (Dzifčaková et al. 2006a) (lines with different behavior of the excitation cross section with \( E \)), or lines with different excitation thresholds \( \Delta E_{\mu} \) (lines formed at different wavelengths), or both. Such line ratios will always be sensitive to temperature as well. Line ratios sensitive to \( \kappa \) are then combined with the line ratios involving lines from neighboring ions that are strongly sensitive to \( T \) but also sensitive to \( \kappa \).

Furthermore, if the relative level population depends on density, \( \kappa \)-sensitive line ratios belonging to the same ion typically have smaller sensitivity to \( \kappa \) than to \( n_e \), although exceptions occur (Dzifčaková et al. 2006a; Dzifčaková & Kulínová 2010; Mackovjak et al. 2013; Dudík et al. 2014b). The diagnosed electron density is then used to constrain the diagnostics using the ratio–ratio diagrams (Dzifčaková & Kulínová 2010; Mackovjak et al. 2013).

This is the approach we chose here. From the lines listed in Table 1, Fe xi is the only ion offering strongly temperature-sensitive line ratios. There are four temperature-sensitive ratios of Fe xi lines, each involving a line from the EIS short-wavelength channel (182.167, or 188.216 Å) and a line from the EIS long-wavelength channel (257.554 Å sbl or 257.772 Å sbl, see Table 1). These Fe xi line ratios are combined with ratios involving a Fe xi line. Both of the self-blends at 186.887 and 195.119 Å are used. This is because of the possible calibration problems involving the 186.887 Å sbl (Section 4.2). The various combinations are shown in Figures 10–12. The observed line ratios together with their uncertainties are shown as large crosses, where the azure and violet error bars are calculated using the \( \sigma_{10\%} \) and \( \sigma_{20\%} \) uncertainties of the individual lines involved, respectively (see Table 1). The calibration uncertainty is included because various ratios involve lines observed in both EIS channels.

The ratio–ratio diagrams involving the 257.554 Å sbl (Figure 10) show strong sensitivity to \( T \) and sensitivity to \( \kappa \) that is of the order of \( \approx 20\% \). However, the large calibration uncertainties together with the uncertainty in the diagnosed \( \log(n_e/\text{cm}^{-3}) \) prevent positive diagnostics using some of these diagrams for both loop segments. This is because the \( \sigma_{20\%} \) error bar intersects all curves for different \( \kappa \) for at least one of the diagnosed limits on \( \log(n_e/\text{cm}^{-3}) \). The situation is worse for the loop (300:309), where the observed ratios are closer and intersect more curves for different \( \kappa \) on the ratio–ratio diagrams (Figure 10, left) than in the case of the average loop spectrum (loop (288:317), Figure 10, right). For the average loop spectrum, we can diagnose \( \kappa \lesssim 5 \) using the ratios involving Fe xi 188.216 Å/(Fe xi 257.554 Å sbl). This is because for all ratios in Figure 10, right, the red and orange ratio–ratio curves corresponding to \( \kappa = 2 \) and 3 intersect all of the violet error bars, while others do not. Nevertheless, the green ratio–ratio curve (\( \kappa = 5 \)) is in close vicinity to the error bar in the top right panel.

The situation is much better when using ratio–ratio diagrams involving the Fe xi 257.772 Å self-blend (Figure 11). Compared to the spread of the curves for individual \( \kappa \) and \( \log(n_e/\text{cm}^{-3}) \), the uncertainty of the observed ratios is smaller, and the observed ratios are located farther away from the curves. This permits diagnostics of \( \kappa \lesssim 3 \), a strongly non-Maxwellian distribution. We note that this result is the same whether the Fe xii 186.887 Å self-blend or the 195.119 Å self-blend is used.

To confirm this diagnostic, in Figure 12 we substitute the Fe xii 257.772 Å sbl by other Fe xii lines in the Fe xii/Fe xi ratio. Again, \( \kappa \lesssim 3 \) is found independently of the combination of lines used (Figure 12), with the majority of the ratio–ratio diagrams indicating \( \kappa \lesssim 2 \).

We note that the results of the diagnostics of \( \kappa \) are not dependent on which of the two Fe xii lines is used. Both the Fe xii 186.887 and 195.119 Å self-blends yield similar results in terms of \( \kappa \) (Figures 10–12). This allows us to establish confidence in using the Fe xii lines to diagnose \( \kappa \) despite the possible calibration problems mentioned in Section 4.2.

Finally, we point out that the loop evolution as observed by AIA (Section 3.2) is unlikely to strongly affect the diagnostics of \( \kappa \). This is because the AIA 193 Å intensities (dominated by Fe xii; Del Zanna 2013b) do not change by more than 1–2% during the EIS observations at 13:19 UT (Figure 5, top).
Figure 9. Diagnostics of density using Fe xi, Fe xii, and Fe xiii ratios. The black color corresponds to the Maxwellian distribution; red stands for $\kappa = 2$. Different line styles correspond to different $T$ for each distribution (see Dudík et al. 2014b, Figures 5–7 therein): full lines stand for the temperature corresponding to the peak of the ion abundance, dashed and dot-dashed lines for the temperatures at which the relative ion abundance is 1% of its maximum. The observed value of the ratio is plotted as the full cyan line. Uncertainties including calibration uncertainties are plotted for illustration.
Figure 10. Diagnostics of $\kappa$ involving the Fe xi 257.554 Å self-blend. Different colors correspond to different $\kappa$, and line styles denote electron density. Diamonds and asterisks denote the predicted ratios based on the DEM analysis.
Figure 11. Diagnostics of $\kappa$ involving the Fe xi 257.772 Å self-blend. Different colors correspond to different $\kappa$, and line styles denote electron density. Diamonds and asterisks denote the predicted ratios based on the DEM analysis.
Figure 12. Diagnostics of $\kappa$ involving the Fe x 257.72 Å self-blend and Fe x ii / Fe x i ratios using lines only from the EIS short-wavelength channel. Different colors correspond to different $\kappa$, and line styles denote electron density. Diamonds and asterisks denote the predicted ratios based on the DEM analysis.
4.3.2. Influence of the DEM on Diagnostics of \( \kappa \)

Originally, the ratio–ratio diagrams were developed for simultaneous diagnostics of \( T \) and \( \kappa \) based on the assumption that the observed structure is isothermal (Dziřičáková & Kulinová 2010; Mackovjak et al. 2013). The results presented for the transient loop in Section 3.3, however, suggest that the loop is multithermal, independent of the value of \( \kappa \). Therefore, we investigated the influence of DEM on the diagnostics of \( \kappa \).

Unfortunately, the EIS raster obtained during HOP 226 does not contain enough strong lines for determining and constraining the DEM, especially throughout the entire \( \log(T/kK) \) = 5.5–7.0 range. Therefore, we use the AIA data to perform the DEM diagnostics and note that Del Zanna (2013b) showed that the AIA observations can be used to predict the EIS radiances to within the calibration uncertainties of both instruments. Although these authors preferentially used a DEM reconstruction technique different from the Hannah & Kontar (2012) one that is used here (Section 3.3), the Hannah & Kontar (2012) technique was also tested by Del Zanna (2013b) and a reasonable agreement was found.

First, we produce an AIA pseudoraster for each AIA band similar to that shown in Figure 8, left. Subsequently, the DEM is derived using the technique of Hannah & Kontar (2012, 2013), similar to that in Section 3.3, for each pixel of these AIA pseudorasters. We perform the averaging of the DEMs the same way as for the EIS raster (i.e., over pixels at position 9 corresponding to the loop, \( y = 288–317 \) and 300–309), subtract the background at position 5, and then use these background-subtracted DEMs to predict the intensities of individual EIS Fe xi–Fe xiii lines.

The predicted ratios of individual lines are shown as a function of \( \kappa \) on each of the ratio–ratio diagrams in Figures 10–12. Diamonds are used for the diagnosed lower limits on \( \log(n_e/cm^{-3}) \) (Section 4.2), with asterisks for the upper limits. Generally, the predicted ratios for each \( \kappa \) are located close to the corresponding curves, indicating that these curves can still be used to indicate the value of \( \kappa \) in the observed plasma even if this plasma is multithermal. Furthermore, we find that with decreasing \( \kappa \), the predicted ratios converge on the observed values in all cases, indicating that the plasma is strongly non-Maxwellian with \( \kappa \lesssim 2 \). This is true even for the cases when the isothermal ratio–ratio diagrams cannot be used to constrain the value of \( \kappa \), such as the Fe xi 188.216 Å/(Fe xi 257.554 Å sbl)–(Fe xii 186.887 Å sbl)/(Fe xii 257.554 Å sbl) in Figure 10, middle row, or the similar combination with Fe xii 195.119 Å sbl in Figure 10, bottom row.

5. ATOMIC DATA UNCERTAINTIES

The atomic data sets for astrophysical spectroscopy are always incomplete because they contain only a finite number of energy levels and the corresponding transitions. Therefore, we investigated the influence of the atomic data uncertainties on the analysis presented here. To do that, we repeated the analysis presented in Section 4 using the older atomic data that are available in the CHIANTI, version 7.1 (Dere et al. 1997; Landi et al. 2013). The calculations for the Maxwellian distribution were performed using CHIANTI v7.1, and the corresponding calculations for the \( \kappa \)-distributions were performed using the KAPPA package (Dziřičáková et al. 2015).

The density diagnostics performed in Section 4.2 using Fe xi and Fe xiii ratios remain valid because these density-sensitive ratios do not change appreciably (see Figures 5 and 7 in Dudík et al. 2014b), even if the individual line intensities change by up to \( \approx 20\% \). Therefore, the conservative densities adopted (Table 2) are kept.

Examples of the diagnostics of \( \kappa \), including the effect of DEM using the older atomic data, are presented in Figure 13, which shows ratios involving the Fe xi 257.772 Å self-blend. These diagrams correspond to those shown in Figure 11 for the newest atomic data. From Figure 13 we see that the diagnostics of \( \kappa \lesssim 2 \) remain valid even if the older atomic data are used.

We note that the newest atomic data of Del Zanna (2010, 2011), Del Zanna et al. (2012b), and Del Zanna & Storey (2013) used in Sections 2–4 represent a significant improvement over the previous ones, especially in the case of Fe xiii, where differences of up to 60% in intensities of key lines were found (Del Zanna et al. 2012b), including the 195.119 Å self-blend. We find similar increases for all \( \kappa \). The Fe xi line intensities are found to be increased for all \( \kappa \) by about 10–20%, although the details depend on \( \kappa \) and the particular line. These increases in line intensities are due to the increased contribution from resonances as well as cascading from \( n = 4 \) level (Del Zanna et al. 2012a, 2012b; Del Zanna & Storey 2013) and cause the change in the theoretical ratio–ratio diagrams (compare Figures 11 with 13).

Finally, we note that the newest atomic data used in Sections 2–4 do not include contributions from \( n \geq 5 \) levels. For Fe xi, the contributions of cascading from \( n \geq 5 \) to Fe xi line intensities are about 10–20% (Del Zanna & Storey 2013). For the transitions from the \( 3s^2 3p^2 \) 3d configuration in Fe xiii (i.e., the 186.887 and 195.119 Å lines), the missing contributions from cascading is smaller, of the order of only 5% (Del Zanna et al. 2012b). Including these contributions would move the diagnostic diagrams (Figures 10–12) down in the direction. Therefore, more complete atomic data are unlikely to change the results of the diagnostics of \( \kappa \).
Figure 13. Same as Figure 11, but with atomic data corresponding to CHIANTI 7.1 and the KAPPA package.
6. SUMMARY

We reported on imaging and spectroscopic observations of a transient coronal loop observed within the core of AR 11704 on 2013 March 30. The loop reappeared in the same location as the already faded flare arcade of the B8.9-class microflare peaking about 3 hr earlier. The transient loop persisted for nearly 2 hr, during which it evolved into a series of individual threads. By examining the AIA data, we found no signatures of hot, flare-like emission being associated with the loop. These results were confirmed using the DEM reconstruction by the regularized inversion method of Hannah & Kontar (2012, 2013), showing the relative absence of hot plasma, except for a spurious peak that is also present in the background. This method was employed in conjunction with the AIA responses emission calculated for the $\kappa$-distributions by Dzifčáková et al. (2015). We found that the loop is multithermal for all $\kappa$ considered, with the DEMs peaking at $\log(T/K) = 6.3$ for the Maxwellian distribution and at 6.5 for $\kappa = 2$. The spurious high-temperature peak becomes less prominent with decreasing $\kappa$, and it disappears for $\kappa = 2$.

We analyzed the spectroscopic data obtained by Hinode/EIS in order to perform diagnostics of density and $\kappa$. Several density-sensitive ratios of Fe XI, Fe XII, and Fe XIII were used in conjunction with the latest EIS calibration and the latest available atomic data. We find consistency between the densities diagnosed from the background-subtracted Fe XI and Fe XII intensities and the Fe XIII intensities yielding higher densities. However, the density diagnostics using Fe XIII may still be consistent with the Fe XI and Fe XII ones if the EIS calibration uncertainty is taken into account. Using Fe XI and Fe XII yields a conservative estimate of electron density of the order of $\log(n_e/cm^3) = 8.8-9.6$ for a loop segment 10″ long, and $\log(n_e/cm^3) = 9.0-9.5$ for the average spectrum of the loop along position 9 of the EIS slit.

This diagnosed electron density is then used to constrain the diagnostic of $\kappa$. To do that, we use the temperature-sensitive ratios involving Fe XI lines from both EIS detectors in combination with the ratios involving Fe XII and Fe XIII lines. We found that ratios involving the Fe XI 257.554 Å blend can preclude a successful diagnostic because the calibration uncertainty is larger than the spread of the curves for individual $\kappa$. However, all ratios involving the Fe XI 257.772 Å blend together with other Fe XI and Fe XII lines consistently yield $\kappa \lesssim 2$, an extremely non-Maxwellian situation.

We next studied the influence of the plasma multithermality on the diagnostics of $\kappa$. Because the EIS data are insufficient to obtain the DEMs, we obtained the DEMs from the AIA data. These DEMs were used to predict the EIS line intensities as a function of $\kappa$. We found that, with decreasing $\kappa$, all ratios of the predicted Fe line intensities converge on the observed values. These results confirm the diagnosed value of $\kappa = 2$ and provide a first quantitative description of the non-Maxwellian distribution of electron energies in a coronal loop.

We note that the transient loop studied here is not a typical coronal loop. This is due to its rather low temperature compared to typical active region cores, the ongoing magnetic reconnection as evidenced by the brightenings and jetting activity near its right footpoint, as well as its appearance in the same spatial location as the previous B8.9-class microflare. Nevertheless, the results presented here demonstrate the viability of the methods for diagnostics of $\kappa$. Such methods should be applied in the future in the analysis of typical, well-defined coronal loops to search for possible signatures of impulsive heating.

Finally, we note that the 20% calibration uncertainty, typical of the EUV spectroscopic instrumentation, can represent a severe limitation on the diagnostics of non-Maxwellian distribution. Such a large calibration uncertainty contributes to the possible misinterpretation of the observations because it is always possible to obtain some temperatures and DEMs if a diagnostic of $\kappa$ is not performed. Decreasing the calibration uncertainty to about 10% would significantly contribute to enabling the diagnostics of non-Maxwellian distributions from EUV spectra.

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