Benchmarking atomic data for the CHIANTI atomic database: coronal lines observed by Hinode EIS

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ABSTRACT

The coronal lines that are observable in the Hinode EUV Imaging Spectrometer (EIS) wavelengths are assessed with new atomic data that have recently become available for a range of important ions. EIS spectral lines are identified based on their spatial variation across different solar regions, their wavelengths, and their intensities. Two off-limb observations are presented, one above an active region, and one in the quiet Sun. The spectra are relatively free of low-temperature lines. Accurate wavelengths and intensities are provided. The observed and predicted line intensities generally agree excellently, once blending is taken into account. The main diagnostics available for measuring the electron density of the solar corona using EIS are highlighted with the use of the emissivity ratio technique. Densities obtained from different ions agree excellently. Most of the previous identifications are confirmed. A considerable number of weaker lines still await identification, however. The approximate formation temperature of the main unidentified lines is provided to aid the identification process. The EIS radiometric calibration appears to be in need of revision. A new quiet-Sun argon/iron relative abundance of 0.16, in line with Galactic measurements, is found. The abundances of sulphur and argon in the “background” unresolved active region emission are found to be lower by a factor of about two at 1.5 MK, and even lower at 3 MK.

Key words. atomic data – line: identification – Sun: corona – Sun: abundances – techniques: spectroscopic

1. Introduction

This paper is one in a series where atomic data and line identifications are benchmarked against experimental data (Del Zanna et al. 2004, Paper I). A substantial effort was devoted (within the Iron Project (IP) and the UK APAP network) in the past few years to calculate new atomic data for coronal ions and extreme-ultraviolet (EUV) wavelengths, which are important for many solar missions, in particular for the Hinode EUV Imaging Spectrometer (EIS, see Culhane et al. 2007), which covers two wavelength bands (SW: 166–212 Å; LW: 245–291 Å). New atomic data for Fe VII (Witthoeft & Badnell 2008), Fe VIII (Del Zanna 2009b), Fe IX (Storey et al. 2002), Fe X (Del Zanna et al. 2004), Fe XI (Del Zanna et al. 2010), Fe XII (Storey et al. 2005), Fe XIII (Storey & Zeppen 2010), Fe XIV (Liang et al. 2010), and Si X (Liang et al. 2009) have been produced. These data represent a significant improvement over previous ones. The data for Fe IX, Fe X, and Fe XII are already available within the CHIANTI database (Dere et al. 1997), and those for Fe VIII, Fe XI, Fe XIII, Fe XIV, and Si X have been included into CHIANTI v.7 (Landi et al. 2011).

These ions are emitting most of the lines in the Hinode/EIS wavelengths. The instrument was radiometrically calibrated on the ground (Lang et al. 2006) with an accuracy of about 20%, hence it is well-suited for benchmarking atomic data. The benchmark for Fe VII, Fe IX (Del Zanna 2009a), Fe VIII (Del Zanna 2009b), Fe XI (Del Zanna 2010), Fe XIII (Del Zanna 2011) has recently been made also using Hinode/EIS spectra. However, the benchmark of Fe X (Del Zanna et al. 2004) and Fe XII (Del Zanna & Mason 2005) was made with limited experimental data, and many identifications were tentative.

The main aim of this paper is to reassess all previous identifications for the main coronal ions, and suggest which lines are best for diagnostic purposes for use with EIS. The work presented here is a follow-up of the preliminary discussion of the main lines in the EIS spectra given in Young et al. (2007) and is part of the assessment that is routinely made to ensure that the CHIANTI database has the best atomic data.

Brown et al. (2008) provided an extensive list of lines observed with Hinode/EIS, but line identifications were not substantiated with a quantitative analysis. Even at the high spectral resolution of EIS, most lines are blended, and blending strongly depends on the source region. The EUV range is very crowded, and the best way forward is to study clean spectra of different sources. The main hot flare lines have been identified in Del Zanna (2008) and Del Zanna & Ishikawa (2009). An almost pure EIS spectrum containing only transition-region lines was presented by Del Zanna (2009a). It allowed a detailed benchmark of low-temperature transition-region (TR) emission from a range of cool ions, including Fe VII, Fe VIII and Fe IX. A similar work was independently carried out by Landi & Young (2009), although the EIS spectrum did contain a mixture of cold and warm (1 MK) emission.

This paper focuses on the coronal lines. To limit contamination from cool lines, off-limb spectra have been carefully selected for this study. This has been done because in on-disk observations of active regions a large number of lines that become visible only at high electron densities appear, and the line identification becomes even more complex. This discussion is left to a separate paper.

The identification and the atomic data for Hinode EIS are of particular relevance for many EUV imagers such as SOHO/EIT

and the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA), because many of their bands cover the same spectral region (O'Dwyer et al. 2010; Del Zanna et al. 2011). Indeed, the interpretation of imaging data relies on the accuracy of the underlying atomic data. Section 2 outlines the benchmark method. Sections 3 and 4 present off-limb active region and quiet-Sun observations. Section 5 presents a combined summary of the benchmark, while Sect. 6 discusses the relative abundances. Section 7 draws the conclusions.

2. Benchmark method

All identifications of the strongest lines were checked with laboratory and solar spectra. Line intensities, whenever available, were compared to confirm identifications and assess the possible presence of blending. For the line identification, we made use of the “emissivity ratio” technique, which divides the observed intensity of a line by its emissivity:

$$F_{ji} = \frac{I_{\text{ob}} N_e C}{N_j(N_e, T_e) A_{ji}} \quad (1)$$

calculated at a fixed electron temperature T_e (or density N_e) and plotted as a function of the density N_e (or temperature T_e). I_{ob} is the observed intensity in the line. The scaling constant C is chosen so that the curves are close to unity. The same constant is chosen for each plot. If theoretical and observed intensities agree, all F_{ji} curves should either overlap or cross, if the plasma is nearly isodensity and isothermal. This allows one to assess at once, in one single plot, how good observed vs. theoretical intensities are for a group of lines (see Del Zanna et al. 2004 for details).

In the emissivity ratio plots below, the observed wavelength λ_{ob} (Å) and the indices of the transition(s) contributing to the line are shown. The observed intensity is also shown. Whenever a line is blended with a known line, this is indicated, and the observed intensity decreased by a factor shown in the plot. For example, 95% of the line at 256.94 Å in the active region observation is caused by the 1–14 transition in Fe XI, and 5% by the 2–15 transition in Fe XII. This is indicated in the plots as λ_{ob} 256.94 Å (1–14) 0.95 $\times$ I_{ob} = 28.6 (Fe XI), and λ_{ob} 256.94 Å (2–15) 0.05 $\times$ I_{ob} = 1.5 (Fe XII), given that the total observed intensity is 30.1. When a line is a known self-blend of transitions from the same ion, this is indicated as “sbl”.

For many lines, the observed intensities are higher than the predicted ones. In these cases, the possible presence of a blend with an unidentified line is listed as “(bl u)”, and sometimes the observed intensity is decreased by a factor displayed in the plots to have its emissivity ratio agree with those of the other lines. This provides an indication for the degree to which the observed line appears to be blended. When other effects such as instrument calibration problems could be present, a question mark is shown. New identifications are shown as “N”, and tentative new ones as “TN”.

Any emission measure modelling is specifically avoided for the benchmark because of the various problems associated with it (Del Zanna et al. 2002). The emissivity ratio method was carried out for all the ions, and the main blending contribution of the various transitions to each observed line was established.

3. Active region off-limb, 2007 August 19

Here we consider a long-exposure (90 s) full-spectral observation of an active region at the limb on 2007 August 19. Long

Fig. 1. Monochromatic images (negative, integrated counts) of some of the strongest lines observed by EIS on 2007 Aug. 19 and formed over a range of temperatures. The box represents the area chosen to obtain a sample spectrum. The coordinates are solar X and solar Y, in arcseconds from disk centre.

exposures are needed to increase the signal-to-noise, but have the drawback of increasing the incidence of cosmic rays. The data had to be processed with custom-written software by visually inspecting each exposure for cosmic ray hits. A complex data processing, which included various geometrical corrections and a wavelength calibration procedure was applied to the data as described in detail in Del Zanna (2009b). More than 200 lines were fitted with Gaussian profiles using the *cfit* package (Haugan 1997), and their “morphology” (the aspect of the line radiance) was examined in detail, one by one. Figure 1 shows the resulting monochromatic images for a selection of lines, and the off-limb area chosen to obtain an averaged spectrum, displayed in Fig. 2. This off-limb region is in the unresolved “background” corona outside the core of the active region (which is in the lower part of the field-of-view). This diffuse emission was first described using lower-resolution SOHO/CDS observations by Del Zanna & Mason (2003) as being pervasive and multi-thermal.

The spectrum was wavelength-calibrated using a selection of coronal lines, assuming that there are no Doppler-shifts in the lines, a common and reasonable assumption. The rest wavelengths for EUV coronal ions found in the literature and all databases (e.g. NIST) mostly originate from Behring et al. (1976), who provided a whole-Sun spectrum in the 160–770 Å range with excellent resolution (0.06 Å). The maximum difference between reference and observed lines was 5 m Å for both EIS channels, and in many cases the EIS wavelengths are actually more accurate than the Behring et al. (1976) ones.

Fig. 2. Hinode EIS off-limb active region spectra recorded on 2007 Aug. 19 (abscissa: wavelengths in Å; ordinate: averaged counts per pixel). The locations of the estimated EIS CCD bias are shown as dashed lines. The locations of all the spectral lines fitted in the spectrum are also shown.

Table 1 provides the list of the strongest lines present in this spectrum, with their measured wavelengths λ_0 and intensities. Notice that both the intensities in terms of total counts in the lines are given, as well as the calibrated ones. This was done to highlight the fact that many intrinsically weak spectral lines that fall near the peak sensitivity of the channels do indeed have high count rates, so are very well observed. Many wavelengths are within a few mÅ from the literature values, also shown in Table 1. This agreement is remarkable. The table also clearly indicates that a considerable number of rest wavelengths need to be revised.

Figure 3 shows the EM loci curves (see Del Zanna et al. 2002 for an explanation of the method), indicating a multi-thermal plasma, as expected (Del Zanna & Mason 2003). Strong decays to the ground states have been selected for iron (Fe VIII 185.2, Fe X 184.5, Fe XII 192.4, Fe XIII 202.0, Fe XIV 264.8, Fe XV 284.2, Fe XVI 263 Å) sulfur (S X 264.2, S XI 281.4, S XII 288.4, S XIII 256.7 Å), argon (Ar XI 188.8 and Ar XIV 194 Å) and calcium (Ca XIV 193.9 and Ca XV 201 Å). The curves are displayed with the Asplund et al. (2009) photospheric abundances, with the exception of sulphur, decreased by a factor of 1.7. Nearby off-limb areas show very similar EM loci curves.

4. Quiet Sun off-limb, 2007 March 11

Here we consider a long-exposure (90 s) observation on 2007 March 11 of the quiet Sun at the limb, the same as used for the Fe XI benchmark (Del Zanna 2010), although the data were re-processed here with visual inspection for cosmic ray hits. Figure 4 shows the monochromatic images for a selection of

Fig. 3. EM loci curves for the 2007 Aug. 19 off-limb active region spectrum and a selection of iron (solid lines), sulfur (dashed), argon (dot dash), and calcium (dash triple dots) ions. The Asplund et al. (2009) photospheric abundances were adopted (with the exception of sulphur, decreased by a factor of 1.7).

lines to show how they are different for each ion stage. This fact was taken into account for the assessment.

An averaged spectrum was obtained over eight exposures from an off-limb area shown in Fig. 4. This area is farther off-limb compared to the one selected in Del Zanna (2010),

Table 1. List of emission lines from the 2007 Aug. 19 off-limb active region spectrum.

λ_o	DN	Int	F	ID	λ_r
171.077	19.8	265.0	77	Fe ix	171.072
174.535	77.0	172.7	72	Fe x	174.534
175.266	11.4	20.2	77	Fe x	175.263
175.488	6.4	10.3	77	u	
176.751	5.0	4.7	77	? Ni xv	176.74
176.987	10.6	9.0	77	u (bl oc Fe vii)	176.950
177.241	126.8	95.0	72	Fe x	177.242
178.068	21.0	11.1	76	Fe xi	178.056
179.247	11.0	3.6	76	u (? S ix)	
179.755	24.2	6.7	76	Fe xi	179.760
180.403	1006.4	221.2	71	Fe xi (bl Fe x)	180.400
180.591	47.5	9.8	76	Fe xi	180.595
180.738	16.8	3.3	76	S x	180.733
180.864	12.1	2.3	76	u	
181.136	70.3	12.0	76	Fe xi (bl oc u TR)	181.131
182.072	15.8	1.9	76	u (bl oc Fe vii)	182.100
182.169	286.7	34.3	65	Fe xi	182.167
182.301	49.5	5.7	76	Fe x (bl u)	182.308
182.507	19.8	2.1	76	u (? Co xiii)	
182.819	14.3	1.4	76	u	
182.946	14.0	1.3	76	u	
183.181	20.3	1.8	79	u	
183.464	23.0	1.8	79	Ca xiv (bl u, Ar xiv)	183.460
183.603	20.2	1.6	79	u	
183.834	36.8	2.6	79	u (bl oc Fe vii)	183.820
183.957	42.5	2.9	79	O vi	183.937
184.112	59.5	3.9	79	O vi (bl Ni VIII?)	184.117
184.409	87.3	5.2	79	u X (bl Fe xi)	
184.538	825.7	47.9	68	Fe x	184.543
184.670	41.4	2.3	79	u X	
184.798	92.3	5.0	79	Fe xi (bl)	184.793
184.952	30.1	1.6	79	? Ni x	184.937
185.225	275.3	13.4	89	Fe viii (bl Ni xvi)	
185.423	32.5	1.5	79	? Mn viii	185.460
185.551	33.7	1.5	79	u (bl oc Fe vii)	
185.678	67.3	2.9	79	u	
185.791	32.2	1.4	79	u (bl Ni xv ?)	
185.981	42.1	1.7	79	u	
186.109	39.1	1.5	79	u	
186.246	87.8	3.4	79	Fe xii (bl u)	186.248
186.614	225.2	8.0	89	Fe viii (bl Ca xiv)	186.61
186.877	1688.7	56.7	85	Fe xii (sbl, bl S xi)	186.880
186.988	208.5	6.8	65	Fe xii (bl Ni xi)	187.000
187.083	62.3	2.0	79	? Mg x (bl Ar xi?)	
187.202	50.1	1.6	79	? Mg x (bl Fe viii)	187.18
187.434	64.8	1.9	79	Fe xi	187.450
187.592	58.3	1.7	79	u	
187.700	42.9	1.2	79	u	
187.835	77.3	2.2	79	u	
187.961	117.9	3.2	79	u VIII-IX (bl Ar xiv)	
188.217	4860.7	127.3	70	Fe xi (bl oc)	188.216
188.300	3048.1	78.7	65	Fe xi (bl u)	188.299
188.361	339.8	8.6	79	u XI	
188.490	490.6	12.3	75	Fe ix	
188.589	80.7	2.0	70	u VIII (Ni viii?)	
188.670	361.6	8.8	75	S xi (bl Fe xii)	188.667
188.805	221.4	5.3	79	Ar xi	188.82
189.009	188.0	4.3	79	Fe xi	189.020
189.119	338.1	7.7	79	Fe xi (bl u)	189.123
189.260	65.3	1.5	79	u	
189.405	81.9	1.8	79	u (bl oc Fe vii 189.450)	
189.584	59.5	1.3	79	Ar xi (bl u)	189.57
189.724	266.9	5.6	79	Fe xi (bl u)	189.733
189.931	277.7	5.6	69	Fe ix	
190.040	1144.1	22.9	79	Fe x (bl Fe xii)	TN
190.308	110.9	2.1	79	u XII	
190.382	372.8	7.1	79	Fe xi (bl u)	190.390
190.535	39.1	0.7	79	? Mg x	190.56
190.708	57.7	1.1	79	u	
190.872	109.7	2.0	79	? Na x	190.874
191.042	266.3	4.7	79	Fe xii (bl Ar xi)	191.050
191.257	733.2	12.7	79	S xi (bl Fe ix)	191.27
191.407	98.7	1.7	79	u (bl Ar xiv)	
191.622	72.4	1.2	79	? Mn ix	
191.713	41.4	0.7	65	u	
191.817	178.1	2.9	79	Fe xii (bl)	TN
192.017	316.1	5.1	79	Fe xi (bl oc many)	192.01
192.104	23.2	0.4	69	u X	
192.171	245.5	3.9	79	Fe xii	TN
192.297	146.3	2.3	66	u X	
192.394	6068.7	94.1	70	Fe xii	192.390

Table 1. continued.

λ_o	DN	Int	F	ID	λ_r
192.624	305.7	4.6	79	Fe xi (bl Ni x ?)	192.630
192.811	2266.0	34.0	70	Fe xi (bl Ca xvii ?)	192.813
192.880	87.0	1.3	79	O v	192.910
193.218	93.6	1.4	79	u	
193.347	132.4	1.9	79	u VII-VIII	
193.509	14407.5	205.5	71	Fe xii	193.509
193.710	508.2	7.2	79	Fe x (bl u)	193.715
193.879	186.7	2.6	79	Ca xiv	193.866
193.963	14.7	0.2	65	Fe viii	193.968
194.070	147.0	2.0	79	Ar xi	194.09
194.308	196.8	2.7	79	u IX-X (?Mn x)	
194.431	93.7	1.3	79	Ar xiv	194.390
194.642	217.5	2.9	79	Fe viii	194.660
194.817	170.7	2.3	79	u	
195.118	23503.1	312.1	70	Fe xii (sbl)	195.119
195.240	371.1	4.9	79	u XI-XII (bl Ni xvi)	
195.388	328.6	4.3	79	u X	
195.510	144.3	1.9	79	? Ni xv	195.540
195.731	105.0	1.4	79	u	
195.961	119.5	1.6	79	Fe viii	195.972
196.098	71.2	0.9	79	u (bl Fe vii 196.046)	
196.261	63.3	0.8	79	u (bl Fe vii)	
196.405	69.8	0.9	79	u	
196.520	703.6	9.4	68	Fe xiii	196.525
196.645	1261.1	17.0	74	Fe xii (bl oc Fe viii)	196.640
196.816	139.0	1.9	79	u (bl S x 196.814)	
196.915	142.1	1.9	65	u	
197.019	291.9	4.0	79	u XIV	
197.354	66.9	0.9	70	u (bl Fe viii)	
197.429	840.3	11.9	71	Fe xiii (bl Ni x?)	197.433
197.567	89.3	1.3	79	? Ni x	
197.857	491.7	7.3	79	Fe ix	
198.040	108.7	1.7	79	u	
198.289	53.7	0.8	79	u (bl Ni xvi)	
198.424	195.8	3.2	74	u XI (bl Ni xi)	
198.552	773.7	12.8	78	S viii (bl Fe xi)	198.550
198.756	89.6	1.6	79	u	
198.948	93.1	1.7	79	u	
199.239	207.4	4.0	79	u	
199.338	36.1	0.7	79	u	
199.598	92.5	1.9	79	u	
199.824	113.0	2.6	79	u XI (bl oc Ni xvii)	
200.018	1178.6	28.0	78	Fe xiii	200.021
200.161	56.1	1.4	79	u	
200.354	120.6	3.2	79	u XI-XII	
200.471	44.3	1.2	79	u	
200.689	149.3	4.4	79	u X-XII	
200.798	55.7	1.7	79	u	
201.000	67.9	2.2	79	Ca xv	200.980
201.123	2473.7	86.4	77	Fe xiii	201.121
201.494	187.2	7.5	65	u	
201.557	354.3	14.6	79	Fe xiii (bl)	
201.743	282.4	12.6	79	Fe xi (bl Ar xiii?)	201.734
201.939	84.1	3.9	79	u	
202.047	6915.7	349.5	70	Fe xiii	202.044
202.426	356.0	20.9	79	Fe xi (bl u)	202.420
202.606	122.7	7.8	79	S viii (bl Fe xi)	202.608
202.711	219.5	14.4	68	Fe xi (bl Fe xiii)	202.710
202.885	22.9	1.6	79	u (?Mn x)	
203.169	223.3	17.4	79	Fe xiii (bl Fe xii)	203.173
203.729	359.3	33.5	79	Fe xii (bl Fe xiii)	203.728
203.825	1211.4	116.4	80	Fe xiii (sbl)	203.826
204.258	140.1	15.2	70	Fe xiii	204.263
204.352	26.5	3.0	79	u IX-XII	
204.734	28.4	3.4	79	u VIII (bl oc Fe viii)	204.700
204.939	196.8	25.2	70	Fe xiii	204.942
205.018	16.4	2.2	79	? Cr viii	
205.921	29.4	4.6	77	Fe xiii	
206.172	39.7	6.5	65	Fe xi (bl u)	
206.258	50.5	8.4	65	Fe xi (bl u)	
206.366	54.3	9.2	74	Fe xii (bl u)	206.371
207.449	41.6	8.5	65	Fe x (bl u)	207.449
207.751	18.3	3.9	79	Fe xi (bl u)	
207.944	53.6	12.0	66	u XI (bl Ni xi ?)	
208.318	22.0	5.3	65	Fe xii (bl Ca xv, u)	208.318
208.664	10.6	2.7	71	u (bl Fe xiii, Ca xvi?)	
208.694	12.8	3.3	79	Fe xiii (not Ca xv)	TN
209.032	8.1	2.2	65	u	
209.115	25.8	7.2	65	Fe xii (bl u)	
209.622	54.9	16.9	65	Fe xiii	209.617
209.771	13.2	4.1	70	Fe xi (bl u)	
209.921	173.1	56.2	67	Fe xiii	209.919

Table 1. continued.

λ_o	DN	Int	F	ID	λ_r
211.203	16.0	6.5	79	u	
211.321	584.6	242.3	66	Fe xiv (bl)	211.316
211.407	22.3	9.4	79	u XII (bl Ni xi)	
245.894	17.5	3.7	78	TN Fe xii	
246.208	174.6	35.8	74	Fe xiii (bl oc Si vi)	246.208
246.372	14.9	3.0	78	u	
246.899	24.7	4.8	78	S xi	246.895
247.005	11.0	2.1	78	TN Fe xii	
247.156	27.7	5.3	78	S xi (bl Fe xii, u)	247.159
247.266	17.7	3.4	78	u	
247.404	26.0	4.9	78	u	
247.753	8.4	1.5	78	Fe xiv	247.760
248.502	30.0	5.3	78	u (bl oc O v)	
249.185	73.2	12.6	77	Ni xvii (bl Si vi)	249.177
249.384	81.4	13.8	78	TN Fe xii (sbl)	249.388
250.678	24.4	3.7	78	u	
251.071	85.7	12.5	78	Fe xvi	251.074
251.584	13.1	1.8	78	u	251.580
251.868	40.2	5.4	77	Fe xii (bl u)	
251.953	491.0	65.5	77	Fe xiii	251.953
252.198	136.5	17.8	78	Fe xiv	252.197
253.792	116.1	13.2	79	Si x	253.795
253.950	13.8	1.6	79	Fe viii (bl S x)	
254.506	10.1	1.1	79	u (bl oc Fe xvii 254.530)	
254.598	71.1	7.6	67	Fe xi	254.6
254.681	18.1	1.9	79	u	
254.841	22.8	2.4	148	u (bl oc Fe xvii 254.870)	
255.082	11.0	1.1	79	S x (bl u, Fe viii, oc Fe xxiv)	
255.436	15.6	1.6	79	u	
255.755	17.9	1.8	79	u	
256.282	194.7	18.4	80	He ii (bl)	256.320
256.391	700.4	65.7	108	Si x (bl many)	256.400
256.683	359.4	33.1	79	S xiii	256.686
256.926	332.1	30.1	79	Fe xi (bl Fe xii)	256.925
257.151	126.3	11.2	79	S x	257.150
257.264	614.2	54.4	69	Fe x	257.262
257.394	351.1	31.0	79	Fe xiv	257.300
257.548	205.1	17.8	79	Fe xi (sbl)	257.547
257.771	112.2	9.6	79	Fe xi (bl u)	257.772
257.913	39.6	3.4	79	u	
258.083	42.1	3.5	79	? Si ix (bl u)	258.082
258.375	804.8	66.3	79	Si x	258.372
259.492	344.2	26.5	93	S x (bl Fe xii)	259.494
259.747	10.7	0.8	79	Si ix (bl u, oc Fe xvii)	259.765
259.973	89.8	6.7	79	Fe xii (bl u)	
260.314	25.7	1.9	79	u	
261.059	539.4	37.8	84	Si x	261.056
261.428	15.6	1.1	79	u	
261.741	138.8	9.4	79	Fe xiii	261.730
262.702	8.2	0.5	79	? Mn xv (bl oc Fe xvii)	262.7
262.984	358.6	22.6	78	Fe xvi (bl Fe xiii)	262.984
263.436	15.8	1.0	79	u	
263.661	16.2	1.0	79	u	
263.803	9.8	0.6	79	u (bl oc Fe xiii)	263.765
264.234	481.0	28.5	79	S x (bl oc u)	264.233
264.649	22.4	1.3	79	u	
264.787	1595.3	92.1	76	Fe xiv (bl Fe xi)	264.787
265.002	47.6	2.7	79	Fe xvi	265.000
265.746	28.7	1.6	79	u	
266.082	42.0	2.3	79	u	
266.199	10.3	0.6	79	u	
266.370	10.3	0.6	79	u (bl oc Fe xvii)	266.410
266.539	13.7	0.7	79	u	
266.602	58.3	3.1	79	u	
266.757	43.9	2.3	79	u	
267.464	14.0	0.7	79	? Ni xiii	267.468
267.806	29.8	1.5	119	? Ni xi	
269.174	11.0	0.6	79	? Mn xv	269.19
269.489	15.4	0.8	79	u	
269.870	37.6	1.9	79	u	
270.428	39.1	2.0	79	? Mg vi	270.391
270.520	1063.0	53.4	72	Fe xiv	270.524
270.599	38.0	1.9	79	u	
270.788	20.9	1.0	79	Fe xiv (bl u)	270.80
271.777	24.6	1.3	79	u	
271.990	689.7	35.3	86	Si x (bl u)	271.992
272.105	15.9	0.8	77	u	
272.182	37.6	1.9	74	Fe xiii	
272.538	28.2	1.5	79	u (bl Fe xii)	
272.657	37.9	2.0	79	Si vii	272.660
272.884	17.1	0.9	79	u	
273.031	14.7	0.8	79	u (bl Fe xiv)	

Table 1. continued.

λ_o	DN	Int	F	ID	λ_r
273.169	18.5	1.0	79	u	
273.552	20.0	1.1	79	Fe xiv	N
274.203	2516.2	139.9	81	Fe xiv (bl Si vii)	274.203
275.364	93.7	5.6	79	Si vii	275.370
275.694	19.5	1.2	79	Si vii (bl u)	275.690
276.143	15.4	1.0	79	Mg vii	276.145
276.459	9.9	0.6	79	u	
276.852	62.1	4.1	79	Si viii bl Si vii	276.839
277.040	154.5	10.4	117	Si viii (bl Mg vii)	277.000
277.260	393.9	27.1	87	Si x	277.265
278.154	11.1	0.8	79	Si x (bl u)	
278.400	80.1	6.1	118	Mg vii (bl Si vii)	278.395
278.706	11.5	0.9	79	? Ni xi	
279.479	12.3	1.1	79	u	
280.144	17.7	1.6	125	Al ix (bl u oc Fe xvii)	280.160
281.411	109.1	11.5	77	S xi	281.401
282.418	20.5	2.4	77	Al ix	282.422
282.990	14.3	1.8	77	u	
283.468	26.7	3.6	77	Fe xu (bl u)	
283.779	11.2	1.5	77	u	
283.943	21.7	3.0	77	u (bl Fe xvii)	283.930
284.044	76.6	10.9	72	Al ix (bl u oc Fe xvii)	284.042
284.159	3999.0	576.6	81	Fe xv (bl)	284.160
284.618	13.7	2.1	77	u	
285.594	31.2	5.3	77	S xi	285.587
285.832	47.3	8.2	94	S xi	285.822
286.376	9.8	1.8	77	Al ix	286.380
287.872	6.7	1.5	77	Fe xiv	287.870
288.158	11.9	2.7	77	Ni xvi	288.160
288.407	58.7	13.7	84	S xii	288.400
288.548	9.9	2.3	76	Fe xiii	288.54
289.152	26.3	6.7	77	Fe xiv	289.148
290.703	22.0	6.8	90	Si ix (bl oc Fe vii)	290.687
291.010	23.6	7.5	65	Fe xii	291.010

Notes. λ_o (Å) is the measured wavelength. DN is the number of total counts in the line, while Int is the calibrated intensity (phot cm⁻² s⁻¹ arcsec⁻²). F is the full-width-half-maximum in mÅ (wide lines are clearly blended) while the column ID provides the identification (bl: blended; sbl: self-blend; u: unidentified; bl oc: blended in other plasma conditions). In a few cases, the class of a line is given (i.e.: u VII is a line with a morphology similar to Fe VII), as well as the rest wavelength (λ_r , Å) from the literature. “N” indicates a new identification proposed here, while “T N” a tentative new one.

hence the contribution of cooler TR lines is more reduced. The averaged EIS spectrum is shown in Fig. A.1. Table A.1 provides the list of the strongest lines present in this spectrum.

Figure 5 shows the EM loci curves, which indicate a nearly isothermal plasma around $\log T[K] = 6.15$. Strong decays to the ground states were selected for iron (Fe viii 185.2, Fe x 184.5, Fe xii 192.4, Fe xiii 202.0, Fe xiv 264.8, Fe xv 284.2, Fe xvi 263 Å) sulfur (S x 264.2, S xi 281.4, S xii 288.4, S xiii 256.7 Å) and argon (Ar xi 188.8 Å). The curves are displayed with the [Asplund et al. \(2009\)](#) photospheric abundances, with the exception of argon, increased by a factor of two.

A few exposures were averaged to obtain a series of good spectra along the slit, crossing the solar limb. Figure A.2 shows the intensities in a few selected lines as they vary across the solar limb, to illustrate the approximate formation temperature of some of the unidentified lines. This is a rough estimate, considering that even lines from the same ion do have different profiles because of the varying density and temperature across the limb.

5. Discussion

A summary of the main findings based on the analysis of both off-limb observations now follows. The atomic data are either mentioned or are from CHIANTI v.6 ([Dere et al. 2009](#)). The in-

Fig. 4. Monochromatic images (negative, integrated counts) of some of the strongest lines observed by EIS on 2007 March 11 and formed over a range of temperatures. The box represents the area chosen to obtain a sample spectrum, shown in Fig. A.1. The coordinates are solar X and solar Y, in arcseconds from disk centre.

Fig. 5. EM loci curves of the 2007 March 11 off-limb region for Ar xi (dot dash), and a selection of iron (solid lines), and sulfur (dashed) ions, using the Asplund et al. (2009) photospheric abundances, with the exception of argon, increased by a factor of two.

indices and spectroscopic notation for each transition can be found in the cited papers or directly within the CHIANTI database.

5.1. Cooler lines

The atomic data and identifications for Fe VII have been presented in Withoef & Badnell (2008) and Del Zanna (2009a), although some contradicting line identifications were presented at the same time by Young & Landi (2009). Given this uncertainty, the Withoef & Badnell (2008) atomic data are not included in CHIANTI v.7. The atomic data and identifications for Fe VIII

Fig. 6. Emissivity ratio curves relative to the main Fe x EUV transitions observed by Hinode EIS on 2007 Aug. 19.

have been discussed in Del Zanna (2009b) and have been included in CHIANTI v.7. There is hardly any Fe VII residual emission in the off-limb spectra and the Fe VIII lines are weak.

The CHIANTI atomic data for Fe IX are from Storey et al. (2002). Young (2009) identified four new lines. The three main decays from the $3s^2 3p^4 3d^2$. $^3G_{4,5,3}$ were confirmed by Del Zanna (2009a). The fourth line was identified by Young (2009) with the main decay from the $3s^2 3p^5 4p$ configuration (13-140), observed at 197.862 Å. Del Zanna (2009a) provided a different tentative identification for the 13-140 transition, as the 194.784 Å line. This identification appears to be incorrect, given that in the off-limb spectra the observed line is too weak. There are no other observed levels from the $3s^2 3p^5 4p$ configuration, so it is not easy to identify any lines originating from this configuration.

There are consistent discrepancies between the strongest 171.0 Å resonance line and the other strong Fe IX lines in the sense that the 171.0 Å has an observed intensity too high compared to the predicted one. This could be caused by a problem in the EIS calibration at the very edge of the EIS responsivity in the SW channel. More analysis is in progress.

Finally, the cooler emission that is residually present in the spectra and caused by Si VI, Si VII, Si VIII, Mg V, Mg VI, Mg VII, O VI, and O V is discussed in Del Zanna (2009a).

5.2. Fe x

The electron scattering calculations adopted within CHIANTI for this ion are from Del Zanna et al. (2004). The identifications are also from the benchmark work described in that paper, where most lines were identified. Many weaker transitions were only tentatively identified, however, given the paucity of high-resolution solar spectra available at the time. All identifications of lines in the Hinode/EIS wavelengths proposed by Del Zanna et al. (2004) are now confirmed.

The emissivity ratio curves relative to the Fe x EUV transitions observed by Hinode EIS are shown in Fig. 6. The curves indicate very good agreement between theory and experiment, with the exception of the 257.26 Å self-blend (identified in Del Zanna et al. 2004), which has a temperature sensitivity and also a slight density dependence above $\log N_e [\text{cm}^{-3}] = 9$.

Fig. 7. Emissivity ratio curves relative to the main Fe XI EUV transitions observed by Hinode EIS on 2007 Aug. 19.

Fig. 8. Emissivity ratio curves relative to the main Fe XII EUV transitions observed by Hinode EIS on 2007 Aug. 19.

5.3. Fe XI

This ion has been the most complex of all coronal ions. Final agreement between observation and theory has been achieved after a few years of work along the S-like sequence. The R-matrix scattering calculation performed as part of the Iron Project is described in [Del Zanna et al. \(2010\)](#). The new calculation, obtained with an optimal target, finally allowed the identifications of most transitions. The details are given in [Del Zanna \(2010\)](#), and the data have been made available within CHIANTI v.7. Fe XI lines represent a good fraction of all the coronal lines in the Hinode/EIS spectra, so solving the problems for this ion was necessary for this work. Figure 7 gives one example of emissivity ratio curves for this ion, confirming the results presented in [Del Zanna \(2010\)](#). There are some interesting temperature diagnostics for this ion, discussed in [Del Zanna \(2010\)](#). There is an ample range of line ratios that can be used to measure the electron density, as Fig. 7 shows.

5.4. Fe XII

CHIANTI adopted for Fe XII ($n = 3$ configurations) the [Storey et al. \(2005\)](#) R-matrix electron collisional data and the new identifications of [Del Zanna & Mason \(2005\)](#). For the first time, good agreement between theory and observations for the

strongest lines was found, and most lines were identified. As in the Fe X case, many weaker transitions were only tentatively identified.

Almost all of the proposed identifications for the Hinode/EIS wavelengths are now confirmed (see Fig. 8). A few new tentative identifications are proposed here. [Del Zanna & Mason \(2005\)](#) gave a tentative suggestion for the identification of the 6–84 line, as a self-blend with the 5–40, observed at 191.05 Å. The 6–84 is the strongest decay from the $3s 3p^3 3d$ configuration, from the $^4D_{7/2}$. In the present spectra the 191.05 Å line is well observed, and it is true that the predicted intensity of the 5–40 transition is not sufficient to explain the observed intensity, but this line cannot be a self-blend with the 6–84 line because it is too weak. The energy difference between observed and theoretical values for the other configurations suggests a wavelength around 188 Å. There are a few possibilities, in particular that the line is blended with the strong Fe XI 188.2, 188.3 Å lines, but a few other decays from the 4D should be observable with the present deep exposures.

A search over many possibilities has resulted in one reasonable option, namely that the 6–84 is blended with the Fe X 190.04 Å line. The residual intensity is about right. The difference between observed and theoretical energies is about -17500 cm^{-1} . The decay from the $^4D_{5/2}$ level (87) to level 7 is the

Fig. 9. Emissivity ratio curves relative to the main Fe XIII EUV transitions observed by Hinode EIS on 2007 Aug. 19.

second strongest line from this configuration, and there is a line at the predicted wavelength ($192.17 \text{ \AA}$, from the ^4D theoretical splittings) and intensity, although it would be blended with a cooler line on-disk. The 6–87 (weaker) line would be blended at $188.68 \text{ \AA}$. The weak decays from the $^4\text{D}_{3/2}$ (level 88) to levels 8, 7 should be observable, and would be at 193.41 and $191.82 \text{ \AA}$ respectively. The former would be blended, while the latter has the proper wavelength and about the correct intensity.

The best density diagnostic is the ratio of the two self-blends at 186.88 and $195.12 \text{ \AA}$, both of which were identified as such for the first time by [Del Zanna & Mason \(2005\)](#). At high densities, the $196.65 \text{ \AA}$ is the best choice, although this line is blended in on-disk observations.

5.5. Fe XIII

The most accurate collisional data for this ion have recently been published by [Storey & Zeippen \(2010\)](#), as part of the Iron Project. These data have been benchmarked by [Del Zanna \(2011\)](#), where a number of new identifications have been suggested. These data have been made available within CHIANTI v 7. Figure 9 shows the emissivity ratio curves relative to the main Fe XIII EUV transitions observed by Hinode EIS on 2007 Aug. 19. The Fe XIII lines discussed here are not significantly temperature-dependent, i.e. similar emissivity ratios are obtained for different temperatures. The observed intensities of the 246.2 and $251.95 \text{ \AA}$ are too low by a factor of 1.5 because of an EIS calibration problem (see [Del Zanna 2011](#) and below).

[Del Zanna \(2011\)](#) suggested two possible identifications for a new strong self-blend (7–60, 8–60): either this self-blend is blending the Fe XI $202.42 \text{ \AA}$ or the important self-blend at $203.82 \text{ \AA}$. Evidence that supports both choices has been found, with the quiet-Sun off-limb measurements favouring the first option, and the active region ones favoring the latter, which is adopted here. In either case, the 4–26 $196.52 \text{ \AA}$ line appears to be blended in both off-limb spectra. The latter choice lets the emissivity ratio of the $203.82 \text{ \AA}$ blend agree very well with those of the 202.04 , 209.62 , 209.92 , $261.74 \text{ \AA}$ lines, providing densities of $\log N_e = 8.5$ and 8.35 for the active region and quiet Sun, both measurements being very close to those obtained from Si X, but slightly lower than Fe XII. The slightly higher emissivity ratio

curves for the Fe XIII 200.02 , 204.26 , $203.16 \text{ \AA}$ lines could mean that these (weaker) lines are blended. Laboratory measurements for this ion are necessary to clarify the various blends.

5.6. Fe XIV

Significant discrepancies between observed and predicted intensities of the very strong Fe XIV EUV coronal lines existed until the calculation of [Storey et al. \(2000\)](#). [Liang et al. \(2010\)](#), as part of the UK APAP network, have performed a much more extensive R-matrix calculation that has been made available within CHIANTI v.7 and is adopted here.

Figure 10 shows the emissivity ratio curves for the off-limb active region spectrum, where the Fe XIV lines are very strong. There are obvious discrepancies between observed and predicted intensities, in particular when branching ratios are considered, as also noticed in [Liang et al. \(2010\)](#). The $211.3 \text{ \AA}$ is at the edge of the SW channel, and therefore it makes sense that the radiometric calibration at the edge is not correct. Notice that the very nearby Fe XIII lines do agree well, so the problem seems to be just at the edge. There appears to be another calibration problem for lines around $250 \text{ \AA}$, as also found looking at the Fe XIII lines. The comparison improves if the intensities of the lines around $250 \text{ \AA}$ is increased by 20%.

[Malinovsky & Heroux \(1973\)](#) published an excellent rocket EUV spectrum, radiometrically calibrated with an accuracy of 10–20% for lines close in wavelength. Figure 11 shows the emissivity ratio curves from their data, with the Si VII contribution removed from the $274.20 \text{ \AA}$ line. The agreement is impressive, within a relative 10% for all strong lines, and confirms the Hinode/EIS calibration problem around $250 \text{ \AA}$.

Several very weak transitions are tentatively identified as Fe XIV. The benchmark work on Fe XI ([Del Zanna 2010](#)) has suggested the presence of a new Fe XI line blending the strong Fe XIV $264.79 \text{ \AA}$ line. Indeed, in the quiet Sun off-limb spectrum the Fe XIV lines are very weak, but the Fe XI are not, and excellent agreement between observed and predicted intensities for both Fe XIV and Fe XI is obtained considering that Fe XI contributes a significant 20% to the blend. The width of the $264.79 \text{ \AA}$ line is indeed broader than the widths of the other Fe XIV lines. The exact wavelength of the Fe XI line is difficult to assess. Laboratory

Fig. 10. Emissivity ratio curves relative to the Fe XIV EUV transitions observed by Hinode EIS on 2007 Aug. 19.

Fig. 12. Emissivity ratio curves relative to the Si X EUV transitions observed by Hinode EIS on 2007 Aug. 19.

Fig. 11. Emissivity ratio curves relative to the Fe XIV EUV transitions observed by Malinovsky & Heroux (1973).

measurements are needed. The presence of the Fe XI line could affect Doppler measurements of the 264.79 Å line. The best density diagnostic for this ion is the ratio of the 264.79 and 274.20 Å lines, although both lines are blended.

5.7. Fe XVI and Fe XVII

For Fe XVI the atomic data are from Sampson et al. (1990). There are only three lines at the EIS wavelengths, the strongest of which is the 262.98 Å line. Observed and predicted intensities agree well, but again the branching ratio between the 251.06 and the 265 Å lines indicates that the 251.06 Å is too weak by 20%, again confirming the Hinode/EIS calibration problem.

It is interesting to notice that the EM loci plots (see Fig. 3) indicate that the Fe XVI emission measure is much lower than what it should be, unless the S/Fe abundance changes with temperature. This is difficult to establish, given that Fe XVI is one of the “anomalous ions” discussed in a series of papers (see the review in Del Zanna et al. 2002). See the discussion on the calcium lines below.

For Fe XVII the scattering data calculated as part of the UK APAP network by Liang & Badnell (2010), together with the identifications of the EUV lines described in Del Zanna & Ishikawa (2009), have been made available within the CHIANTI database v.7 and were used for the present study.

There is no clear evidence of any measurable Fe XVII emission in the active region spectrum. This is a significant result because it puts constraints on active-region heating models. Various weak coronal lines are present at the same wavelengths as the Fe XVII lines, as already described in Del Zanna & Ishikawa (2009).

5.8. Ca ions

The Ca XIV lines are difficult to assess because two out of the three strongest lines are significantly blended. The 183.46 Å line is a known blend with at least Ar XIV. The 186.61 Å line is a known blend with at least a strong Fe VIII transition. The only line possibly not blended is the strongest, at 193.87 Å. However, the estimate of the Fe VIII contribution from the 186.61 Å line suggests that the 193.87 Å is blended as well.

Several Ca XV transitions should be observable with Hinode/EIS, at 200.97, 208.72, 181.90, 176.93, 208.32 Å. However, it appears that all lines, with perhaps the exception of the strongest one at 200.97 Å, contribute very little (less than 20%) to the observed intensities.

5.9. Si ions

There are a few weak Si IX transitions in the EIS wavelengths. The strongest, predicted at 290.69 Å and observed at 290.70 Å is possibly the only un-blended line from this ion. The others, at 258.08, 259.76, 261.43 Å are all blended according to the present atomic data.

Liang et al. (2009), as part of the UK APAP network, has produced an extensive R-matrix calculation for Si X, finding significant differences with previous calculations. This ion is potentially very important for Hinode/EIS because it provides some of the best density diagnostics, which turn out to be slightly modified when the new atomic data, now made available through CHIANTI v.7, are used. The new atomic data for Si X provide

Fig. 13. Emissivity ratio curves relative to the Al IX EUV transitions observed by Hinode EIS on 2007 Mar. 11.

an impressive agreement between predicted and observed intensities, as Fig. 12 shows. The best density diagnostics are the 258.37 and 261.06 lines, because they are strong, unblended and nearby.

5.10. Al IX

The strongest of the Al IX lines at 284.02 Å is particularly important because it is in the blue-wing of the Fe XV 284.16 Å resonance line. The Al IX is a strong line, and work on the Fe XV line profile should take it into account. In active region conditions, the Al IX line is blended in the blue-wing of the Fe XV and is difficult to measure. The quiet Sun off-limb spectrum is better suited to study the Al IX lines. The emissivity ratio curves for that observation are shown in Fig. 13. Excellent agreement for the 282.42 and 284.02 Å is found, providing a density in line with what was found from the other ions. The very weak 280.14, which would blend an Fe XVII self-blend first identified in Del Zanna & Ishikawa (2009), appears to be even more blended in these quiet Sun conditions. The strong Al IX 284.02 Å line is also blended in solar flares with an Fe XVII line identified for the first time in Del Zanna & Ishikawa (2009).

5.11. Mg X

Brown et al. (2008) suggested the presence of a few Mg X lines in the EIS spectra. In the off-limb observations analysed here, there is no clear evidence of any significant Mg X emission. If the very weak 190.56 Å line is entirely caused by Mg X, then the other 187.07 and 187.18 Å lines are significantly blended.

5.12. Ni ions

It is probable that a few Ni X are present in the EIS spectra. Regarding Ni XI, Brown et al. (2008) lists a few possible Ni XI lines in the EIS spectra, and Landi & Young (2009) identified a few transitions, despite noting some unexplained inconsistencies, which could be caused by problems with the atomic data for this ion. The present observations indicate that most Ni XI lines are blended, but the benchmark is complicated by the presence of some unidentified transitions. At first sight, the strongest Ni XI is the 1–4 transition, with a NIST wavelength of

Fig. 14. Emissivity ratio curves relative to the S X EUV transitions observed by Hinode EIS on 2007 Aug. 19.

207.93 Å. There is indeed an observed line in the EIS spectra at 207.94 Å. Assuming that this line is caused entirely by Ni XI would predict that other Ni XI transitions (1–10: 186.98 Å; 1–7: 198.38 Å; 1–3: 211.43 Å) are blending some observed lines. However, there are two still unidentified lines (4–16 and 5–16) that should be well observable in the EIS LW channel, around 270 and 280 Å. There are no observed lines with the required strength, so the only option appears to be that they would blend the Si X 271.99 Å and the S XI 281.41 Å. The Si X is indeed a wide line and could be blended, but the current atomic data for S XI do not indicate that the 281.41 Å is blended. Therefore, with the current atomic data for Ni XI and S XI, the only explanation is that all the Ni XI are blended. A more in-depth benchmark of Ni X and Ni XI lines is left to a future paper.

In the case of Ni XII, Ni XIII and Ni XIV it appears that most lines, if present, are blended. For Ni XV the only line that might be observed is the strongest one at 176.74 Å. For Ni XVI the only line which might not be blended is the very weak 198.31 Å transition. Three other lines (194.02, 195.27, 185.23 Å) provide significant contributions to blended lines, the main one being the 185.23 Å one (80% of the observed line caused by Ni XVI, the rest by Fe VIII). The 195.27 Å forms a branching ratio with the 185.23 Å one, and could be used in principle to remove the Ni XVI contamination from the Fe VIII in on-disk active region observations, but the presence of a further unidentified coronal line complicates the matter.

5.13. S ions

The comparison between predicted and observed intensities for S X is satisfactory once all the blends are taken into account, as Fig. 14 shows. The strongest and unblended line is the 1–6 264.23 Å line. The 3–12 180.73 Å line can be used to measure the electron density. The values obtained agree well with those from ions formed at similar temperatures.

The strongest and unblended line for S XI is the 1–8 281.40 Å line. It can be used to obtain the electron density in combination with the 2–7 285.82 Å or with the 3–12 246.89 Å line, as Fig. 15 shows. The densities obtained are close to those obtained from ions formed at similar temperatures. Many lines for this

Fig. 15. Emmissivity ratio curves relative to the S XI EUV transitions observed by Hinode EIS on 2007 Aug. 19.

Fig. 16. Emmissivity ratio curves relative to the Ar XI EUV transitions observed by Hinode EIS on 2007 Aug. 19.

ion are blended. The most notable one is the 1–14 because it blends the most important density diagnostic for Hinode/EIS, the Fe XII 186.88 Å. There have been reports that densities obtained from this line are too high, which could be explained by the presence of blends. For both off-limb cases, the S XI contribution to the Fe XII 186.88 Å line is very low (3% or less), so any additional significant blending could only come from some lines that become bright at high-densities.

There is only one line from S XII, observed at 288.41 Å, so it is difficult to assess if any blending is present. The same is true for the strong S XIII 256.7 Å line, although the emission measures for both these lines (cf. Fig. 3) suggest that there is no blending.

5.14. Ar ions

Brown et al. (2008) suggested the presence of a few weak Ar XI lines in the EIS spectra. Figure 16 shows that in the off-limb active region spectra the only lines that are possibly not blended are the strongest one, at 188.806 Å, and the weaker 194.1 Å line

(within 20%). These lines are intrinsically weak, but are well observed by Hinode/EIS, given the fact that they are located not far from the peak sensitivity of the multi-layer coatings for the SW channel.

Ar XIV has a typical formation temperature of $\log T[\text{K}] = 6.55$, and a few lines are observable with EIS in active region spectra. Unfortunately, the analysis has shown that all lines seem to be significantly blended, with the exception of the 194.40 Å line. These Ar XI and Ar XIV lines are potentially very important for studying the relative argon abundance in active regions.

6. Relative abundances

The EM loci curves offer the possibility to estimate the abundances of a few elements relative to iron. The active region EM loci curves (Fig. 3) suggest that either the strongest Ca XIV and Ca XV lines are blended or that the calcium abundance is too low. Alternatively, the strongest lines are not blended, the calcium abundance is correct, the emission measure for Fe XVI is also correct, but then both the sulphur and argon abundances are much lower in higher-temperature regions. This second option is favoured here.

If this result is confirmed, it could explain some of the large discrepancies found in the literature by assuming that abundances vary at different heights. For example, observations in the X-rays, associated with hot ($\log T[\text{K}] = 6.5\text{--}7.0$) plasmas often suggest lower “coronal” abundances when compared to observations at lower heights (transition-region temperatures) in the EUV/UV (see, e.g. Veck & Parkinson 1981), which often produce measurements close to photospheric values. A detailed discussion of these questions is deferred to a future paper.

Interestingly, the sequence of sulphur ions (S X, S XI, S XII, S XIII) presents the opportunity to measure the sulphur abundance relative to iron quite accurately. The Asplund et al. (2009) recommended photospheric abundance S/Fe ratio is 0.42. The present quiet Sun off-limb spectrum confirms this value. Gloeckler & Geiss (2007) used Ulysses measurements of solar-wind particles emanating from coronal holes and found a similar S/Fe ratio (0.52).

A range of values are found in solar flares. One of the most recent and direct line/continuum analyses of RESIK X-ray spectra (Chifor et al. 2007) produced an S/Fe ratio of 0.25, much lower than photospheric. Monsignori Fossi et al. (1994) used a SERTS 1989 rocket spectrum over an active region (on-disk) to obtain the same value, a S/Fe ratio of 0.25. The present is possibly the first measurement of the sulphur abundance in the diffuse AR emission, suggesting the same S/Fe ratio of 0.25, i.e. a first ionization potential (FIP) bias of 1.7.

A similar result was found by Feldman et al. (1998) from off-limb SOHO / SUMER observations of a quiescent streamer. Mohan et al. (2000) used off-limb SOHO / SUMER observations above an active region to find a FIP bias of 2–3 in the S/Si abundance. Brooks & Warren (2011) used Hinode/EIS observations to find a FIP bias of about 3 in the S/Si abundance in the “coronal outflow” regions, where blueshifts in coronal lines are observed.

The active region spectrum indicates an Ar/Fe relative abundance of 0.08, while the quiet Sun one indicates a value of 0.16. Other nearby regions within the two off-limb observations have been analysed, and the results are the same.

These are the first measurements obtained using Ar XI. There is no measurement of the photospheric abundance of argon, and there is ample literature on the large discrepancies between all previous solar measurements and those obtained from stars

or nebulae in the solar neighbourhood. Most solar measurements have produced an abundance about a factor of two lower. For some details see, e.g. the recent Lanz et al. (2008) study. Asplund et al. (2009) used some solar measurements to recommend an Ar/Fe relative abundance of 0.08. Lanz et al. (2008) recommended instead a higher photospheric value, between 0.11 and 0.17. There are plenty of solar flare measurements based on the he-like X-ray argon lines, but they all provide low argon abundances (e.g. an Ar/Fe abundance of 0.05, Chifor et al. 2007). There are indications, however, that the argon abundance increases when low-activity X-ray spectra are examined. For example, Sylwester et al. (2010) found Ar/Fe values of 0.09. Monsignori Fossi et al. (1994) measured an Ar/Fe abundance of 0.04, from the SERTS 1989 active region rocket spectrum. Doschek & Bhatia (1990) used an Ar XI forbidden line to measure an Ar/Fe abundance of 0.031 from Skylab S082-B slit spectrograph exposures taken off-limb above an active region.

Argon is a high-FIP element, hence it is expected to show a variation in its abundance depending on the region of the solar atmosphere considered. It is expected that its abundance in active regions should be lower than in the quiet Sun. Indeed, there are measurements far off-limb of very weak argon lines observed by SOHO/UVCS that suggest sub-photospheric argon abundances above active regions (Raymond et al. 1997), although most other elements were also found to have sub-photospheric abundances.

The present EIS measurements do indicate that the argon abundance decreases, as does the sulphur one, by a factor of about two from the quiet Sun to active region diffuse emission. The present quiet-Sun measurement remarkably agrees with the value recommended by Lanz et al. (2008), hence if confirmed would end the 40-year long puzzle of the solar photospheric argon abundance.

It is obviously possible that all argon lines are blended with unidentified coronal lines in the Hinode/EIS spectra. If that was the case, the quiet-Sun argon abundance would decrease. However, any blending would still be present in the off-limb active region spectrum, where the argon abundance is already a factor of two lower and is close to the RESIK measurement of Sylwester et al. (2010). A detailed discussion of these questions is deferred to a future paper.

7. Conclusions

Spatially-resolved high-resolution EUV solar spectroscopy is very valuable for line identification purposes. After very careful data analysis, Hinode EIS spectra can provide very accurate wavelengths (down to a few mÅ) and line intensities. The overall benchmark of the most recent atomic data using off-limb coronal spectra is very satisfactory, at last. All the strongest lines in the spectra have now finally been identified, and agree well (within a relative 20% or better) in terms of expected and observed line intensities when blending is taken into account. Indeed, the majority of spectral lines are blended. Only blending with coronal lines was taken into account here. Some wavelengths have been revised.

A large number of transitions still await firm identifications, however, the results presented here clearly indicate the approximate formation temperature of the unidentified lines, which will aid the identification process. Work is in progress to improve some of the atomic models for a range of ions, but new laboratory measurements are essential to confirm the many tentative identifications provided here.

A few important temperature diagnostics for Hinode/EIS were discussed in Del Zanna (2009a,b and 2010) and have not

been repeated here. The various calibration problems for the Hinode/EIS instrument, highlighted here, will need to be properly assessed before these new temperature diagnostics can be used reliably. The main density diagnostics for Hinode/EIS have now been assessed. Very good agreement from different ions is found, which supports the accuracy of the new atomic data.

The results of the emission measure analysis are new and potentially important, if confirmed. A quiet-Sun argon abundance in line with Galactic measurements is found. Argon and sulphur show the well-known FIP bias, i.e. their abundances (relative to iron) are much reduced (by a factor of about two) in active region diffuse emission when compared to the quiet Sun. The emission measures at high temperatures ($\log T[\text{K}] = 6.4\text{--}6.7$) suggest that the argon and sulphur FIP bias might increase even more with temperature. These questions will be discussed in a forthcoming paper.

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References

- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, 47, 481
- Behring, W. E., Cohen, L., Doschek, G. A., & Feldman, U. 1976, *ApJ*, 203, 521
- Brooks, D. H., & Warren, H. P. 2011, *ApJ*, 727, L13
- Brown, C. M., Feldman, U., Seely, J. F., Korendyke, C. M., & Hara, H. 2008, *ApJS*, 176, 511
- Chifor, C., Del Zanna, G., Mason, H. E., et al. 2007, *A&A*, 462, 323
- Culhane, J. L., Harra, L. K., James, A. M., et al. 2007, *Sol. Phys.*, 60
- Del Zanna, G. 2008, *A&A*, 481, L69
- Del Zanna, G. 2009a, *A&A*, 508, 501
- Del Zanna, G. 2009b, *A&A*, 508, 513
- Del Zanna, G. 2010, *A&A*, 514, A41
- Del Zanna, G. 2011, *A&A*, 533, A12
- Del Zanna, G., & Ishikawa, Y. 2009, *A&A*, 508, 1517
- Del Zanna, G., & Mason, H. E. 2003, *A&A*, 406, 1089
- Del Zanna, G., & Mason, H. E. 2005, *A&A*, 433, 731
- Del Zanna, G., Landini, M., & Mason, H. E. 2002, *A&A*, 385, 968
- Del Zanna, G., Berrington, K. A., & Mason, H. E. 2004, *A&A*, 422, 731
- Del Zanna, G., Storey, P. J., & Mason, H. E. 2010, *A&A*, 514, A40
- Del Zanna, G., O'Dwyer, B., & Mason, H. E. 2011, *A&A*, 535, A46
- Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, *A&AS*, 125, 149
- Dere, K. P., Landi, E., Young, P. R., et al. 2009, *A&A*, 498, 915
- Doschek, G. A., & Bhatia, A. K. 1990, *ApJ*, 358, 338
- Feldman, U., Schüthle, U., Widing, K. G., & Laming, J. M. 1998, *ApJ*, 505, 999
- Gloeckler, G., & Geiss, J. 2007, *Space Sci. Rev.*, 130, 139
- Haugan, S. V. H. 1997, CDS software note, 47
- Landi, E., & Young, P. R. 2009, *ApJ*, 706, 1
- Landi, E., Del Zanna, G., Young, P. R., Dere, K. P., & Mason, H. E. 2011, *ApJ*, accepted
- Lang, J., Kent, B. J., Paustian, W., et al. 2006, *Appl. Opt.*, 45, 8689
- Lanz, T., Cunha, K., Holtzman, J., & Hubeny, I. 2008, *ApJ*, 678, 1342
- Liang, G. Y., & Badnell, N. R. 2010, *A&A*, 518, A64
- Liang, G. Y., Whiteford, A. D., & Badnell, N. R. 2009, *A&A*, 499, 943
- Liang, G. Y., Badnell, N. R., Crespo López-Urrutia, J. R., et al. 2010, *ApJS*, 190, 322
- Malinovsky, L., & Heroux, M. 1973, *ApJ*, 181, 1009
- Mohan, A., Landi, E., & Dwivedi, B. N. 2000, *A&A*, 364, 835
- Monsignori Fossi, B. C., Landini, M., Thomas, R. J., & Neupert, W. M. 1994, *Adv. Space Res.*, 14, 163
- O'Dwyer, B., Del Zanna, G., Mason, H. E., Weber, M. A., & Tripathi, D. 2010, *A&A*, 521, A21
- Raymond, J. C., Kohl, J. L., Noci, G., et al. 1997, *Sol. Phys.*, 175, 645

- Sampson, D. H., Zhang, H. L., & Fontes, C. J. 1990, Atomic Data and Nuclear Data Tables, 44, 209
- Storey, P. J., & Zeippen, C. J. 2010, A&A, 511, A78
- Storey, P. J., Mason, H. E., & Young, P. R. 2000, A&AS, 141, 285
- Storey, P. J., Zeippen, C. J., & Le Dourneuf, M. 2002, A&A, 394, 753
- Storey, P. J., Del Zanna, G., Mason, H. E., & Zeippen, C. 2005, A&A, 433, 717
- Sylwester, B., Sylwester, J., & Phillips, K. J. H. 2010, A&A, 514, A82
- Veck, N. J., & Parkinson, J. H. 1981, MNRAS, 197, 41
- Witthoeft, M. C., & Badnell, N. R. 2008, A&A, 481, 543
- Young, P. R. 2009, ApJ, 691, L77
- Young, P. R., Del Zanna, G., Mason, H. E., et al. 2007, PASJ, 59, 857

Table A.1. List of emission lines from the 2007 March 11 off-limb quiet-Sun spectrum.

λ_o	DN	Int	F	ID	λ_r
171.074	10.5	140.7	68	Fe ix	171.072
174.535	53.3	119.7	69	Fe x	174.534
177.241	87.8	65.8	69	Fe x (bl Fe VII)	177.242
178.065	12.3	6.5	75	Fe xi	178.056
179.756	6.9	1.9	65	Fe xi	179.760
180.403	608.1	133.6	73	Fe xi (bl Fe X, u TR)	180.400
180.594	24.2	5.0	77	Fe xi	180.595
180.750	7.4	1.4	77	S x	180.730
181.135	32.5	5.5	66	Fe xi (bl oc u TR)	181.131
182.168	177.9	21.3	69	Fe xi	182.167
182.303	26.9	3.1	77	Fe x (bl u TR)	182.308
183.944	18.8	1.3	77	O vi	183.937
184.119	29.8	1.9	77	O vi (bl Ni VIII?)	184.117
184.413	33.2	2.0	77	u X (bl Fe xi)	184.420
184.538	579.7	33.6	70	Fe x (bl u ?)	184.543
184.689	17.4	1.0	77	u X	
184.800	36.5	2.0	66	Fe xi (bl)	184.793
185.210	61.1	3.0	85	Fe viii (bl oc Ni XVI)	185.216
185.457	9.1	0.4	77	? Mn viii	185.460
185.564	10.0	0.5	71	u (bl oc Fe vii)	
185.619	9.5	0.4	65	u	
185.711	17.4	0.7	77	u	
186.000	12.5	0.5	77	u	
186.117	14.3	0.6	77	u	
186.249	27.5	1.1	77	Fe xii	186.248
186.609	70.4	2.5	85	Fe viii (bl oc Ca xiv)	186.605
186.876	610.4	20.5	87	Fe xii (sbl, bl S xi)	186.880
186.989	92.1	3.0	65	Fe xii (bl u)	187.000
187.101	29.9	1.0	77	? Mg x (bl Ar xi?)	
187.208	21.9	0.7	77	? Mg x (bl Fe viii)	187.240
187.437	26.6	0.8	77	Fe xi	187.450
187.579	20.8	0.6	77	u	
187.681	20.5	0.6	77	u	
187.847	25.8	0.7	65	u	
187.951	55.9	1.5	77	u VIII-IX (bl oc Ar xiv)	
188.216	3111.1	81.5	73	Fe xi (bl oc Fe VII)	188.216
188.299	1919.1	49.6	65	Fe xi	188.299
188.367	192.9	4.9	77	u	
188.490	247.3	6.2	73	Fe ix (bl Mn IX ?)	188.490
188.579	28.8	0.7	69	u VIII (Ni viii?)	188.570
188.667	131.3	3.2	77	S xi (bl Fe IX)	188.667
188.805	96.4	2.3	77	Ar xi	188.82
189.007	96.2	2.2	77	Fe xi	189.020
189.121	193.6	4.4	77	Fe xi (bl u)	189.123
189.254	29.2	0.7	77	u	189.240
189.407	33.3	0.7	77	u (bl oc Fe vii 189.450)	
189.585	30.6	0.6	77	Ar xi (bl u)	189.57
189.724	156.6	3.3	77	Fe xi	189.733
189.929	154.7	3.1	73	Fe ix	189.940
190.038	728.4	14.6	77	Fe x (bl Fe xi)	190.038
190.320	77.0	1.5	77	u XII	
190.386	185.6	3.5	69	Fe xi (bl u)	190.390
190.508	19.1	0.4	77	u	
190.703	25.6	0.5	77	u	
190.877	61.6	1.1	77	? Na x	
191.043	115.8	2.0	77	Fe xii (bl Ar xi)	191.050
191.255	260.5	4.5	77	Fe ix (bl S xi)	191.210
191.406	44.8	0.8	77	u (bl oc Ar xiv)	
191.583	37.3	0.6	79	u	
191.710	34.7	0.6	79	u	
191.845	54.5	0.9	79	u	
192.019	192.6	3.1	79	Fe xi (bl oc many)	192.020
192.095	36.1	0.6	65	u X	
192.181	139.7	2.2	79	Fe xii	TN
192.291	67.2	1.0	65	u X	
192.394	2865.0	44.4	73	Fe xii	192.390
192.622	167.1	2.5	79	Fe xi (bl Ni x ?)	192.630
192.811	1439.5	21.6	72	Fe xi (bl u, oc Ca xvii, O v)	192.813
192.880	62.0	0.9	79	O v (bl ?)	192.910
193.204	48.5	0.7	79	u	
193.347	70.8	1.0	79	u VII-VIII	
193.508	6636.0	94.6	74	Fe xii	193.509
193.706	292.7	4.1	79	Fe x (bl u)	193.715
193.837	42.5	0.6	77	Ca xiv (bl u)	193.866
193.951	31.0	0.4	79	u (bl oc Fe viii)	193.968
194.073	61.6	0.8	79	Ar xi	194.09
194.315	116.6	1.6	79	u IX-X	
194.447	35.3	0.5	79	u (bl oc Ar xiv)	
194.637	90.9	1.2	79	Fe viii	194.660
194.817	80.1	1.1	79	u	
195.117	10257.5	136.2	74	Fe xii (sbl)	195.119

Table A.1. continued.

λ_o	DN	Int	F	ID	λ_r
195.239	165.9	2.2	79	u XI-XII (bl Ni xvi)	
195.388	191.7	2.5	79	u X	195.390
195.509	66.5	0.9	79	u	
195.724	49.8	0.7	79	u	
195.952	42.8	0.6	79	Fe viii	195.972
196.097	35.5	0.5	79	? Fe vii	196.046
196.263	31.1	0.4	79	? Fe vii (sbl)	196.210
196.391	33.4	0.4	79	u	
196.519	170.3	2.3	74	Fe xiii	196.525
196.644	490.6	6.6	78	Fe xii (bl u, oc Fe viii)	196.640
196.814	69.1	0.9	79	u	
196.912	65.2	0.9	75	u	
197.021	72.1	1.0	79	u XIV	
197.347	38.3	0.5	79	u (bl Fe viii, Fe vii)	197.362
197.427	242.1	3.4	79	Fe xiii (bl Ni x?)	197.433
197.598	36.9	0.5	79	? Ni x	
197.856	267.7	4.0	79	Fe ix	197.850
198.054	37.7	0.6	79	u	198.050
198.287	29.8	0.5	79	u	
198.424	106.6	1.7	75	u XI (bl Ni xi)	
198.550	492.8	8.2	79	S viii (bl Fe xi)	198.550
198.750	48.1	0.8	79	u	
198.951	44.7	0.8	79	u	
199.237	51.3	1.0	79	u	
199.336	19.9	0.4	79	u	
199.600	52.1	1.1	79	u	
199.816	56.0	1.3	79	u XI (bl oc Ni xviii)	
200.009	302.8	7.2	89	Fe xiii	200.021
200.169	27.2	0.7	79	u	
200.341	49.2	1.3	79	u XI-XII	
200.441	23.8	0.6	79	u	
200.684	83.7	2.5	79	u X-XII	
200.798	28.5	0.9	79	u	
200.998	26.8	0.9	79	Ca xv (bl)	200.980
201.117	796.8	27.8	85	Fe xiii (bl)	201.121
201.498	86.3	3.5	79	u	
201.573	103.1	4.2	79	Fe xiii (bl)	
201.738	156.5	7.0	79	Fe xi (bl oc u)	201.734
201.918	29.5	1.4	79	u (bl oc Fe vii)	201.860
202.046	2043.1	103.3	74	Fe xiii	202.044
202.425	221.1	13.0	79	Fe xi (bl u)	202.420
202.603	78.5	5.0	79	S viii (bl Fe xi)	202.608
202.710	141.0	9.3	74	Fe xi (bl Fe xiii)	202.710
202.892	17.0	1.2	79	u	
203.166	53.1	4.1	79	Fe xiii (bl Fe xii)	203.165
203.722	131.5	12.3	78	Fe xii (bl Fe xiii)	203.728
203.822	243.1	23.4	88	Fe xiii (sbl)	203.826
204.254	39.0	4.2	79	Fe xiii	204.263
204.351	17.7	2.0	79	u IX-XII	
204.730	12.8	1.5	79	u VIII (bl oc Fe viii)	204.700
204.937	57.3	7.3	79	Fe xiii	204.942
206.173	31.8	5.2	79	Fe xi (bl u)	206.170
206.259	32.1	5.3	65	Fe xi (bl u)	206.250
206.365	29.6	5.0	79	Fe xii (bl u)	206.371
207.449	35.6	7.3	77	Fe x (bl u)	207.449
207.747	13.6	2.9	79	Fe xi (bl u)	207.712
207.946	34.7	7.8	79	u XI (bl Ni xi ?)	
208.310	12.8	3.1	79	Fe xii (bl Ca xv, u)	208.318
209.108	15.7	4.4	79	Fe xii (bl u)	
209.620	16.0	4.9	73	Fe xiii (bl u)	209.617
209.766	15.3	4.8	79	Fe xi (bl u)	
209.920	51.3	16.7	77	Fe xiii (bl oc u TR)	209.919
211.320	80.6	33.4	73	Fe xiv (bl)	211.316
211.442	12.3	5.2	79	u XII (bl Ni xi)	
246.211	50.2	10.3	76	Fe xiii (bl oc Si vi)	246.208
246.913	10.4	2.0	77	u	
247.168	12.1	2.3	75	u (bl S xi Fe xii)	247.147
247.405	16.8	3.2	76	u	
248.502	14.7	2.6	77	u (bl oc O v)	248.490
249.383	35.9	6.1	77	Fe xii (bl u)	249.388
251.872	20.0	2.7	75	Fe xii (bl u)	
251.952	143.7	19.2	79	Fe xiii	251.953
252.199	19.2	2.5	79	Fe xiv	252.197
253.793	72.1	8.2	83	Si x	253.795
254.598	54.6	5.8	72	Fe xi	
256.280	96.4	9.1	80	He ii (bl)	256.320
256.384	435.3	40.8	109	Si x (bl)	256.400
256.659	10.2	0.9	79	S xiii	256.686
256.926	233.5	21.1	79	Fe xi (bl Fe xii)	256.925
257.150	87.8	7.8	79	S x	257.150
257.264	463.9	41.1	73	Fe x	257.262
257.393	55.0	4.9	79	Fe xiv	257.300

Table A.1. continued.

λ_o	DN	Int	F	ID	λ_r
257.550	141.8	12.3	79	Fe xi (sbl)	257.547
257.771	72.2	6.2	79	Fe xi (bl u)	257.772
257.913	27.1	2.3	79	u	
258.084	30.9	2.6	79	? Si ix	258.082
258.376	535.8	44.1	84	Si x	258.372
259.496	228.6	17.6	88	S x (bl Fe xii)	259.494
259.975	40.9	3.1	76	Fe xii (bl u)	
261.059	375.4	26.3	84	Si x	261.056
261.432	10.0	0.7	79	u	
261.741	40.6	2.7	79	Fe xiii	261.730
262.975	5.7	0.4	79	Fe xvi (bl Fe xiii)	262.984
263.452	6.9	0.4	79	u	
264.235	386.9	22.9	85	S x (bl oc u)	264.233
264.785	296.5	17.1	80	Fe xiv (bl Fe xi)	264.787
264.912	6.5	0.4	79	Fe xvi	265.000
265.796	7.2	0.4	79	u	
266.085	23.7	1.3	79	u	
266.568	22.4	1.2	70	u	
266.619	28.7	1.5	70	u	
266.755	28.8	1.5	79	u	
267.801	18.8	1.0	119	? Ni xi	
269.490	12.4	0.6	79	u	
269.871	11.3	0.6	79	u	
270.426	10.8	0.5	79	? Mg vi	270.391
270.519	128.2	6.4	68	Fe xiv (bl oc)	270.524
270.600	11.6	0.6	79	u	
271.782	14.3	0.7	79	u	
271.991	475.0	24.3	88	Si x	271.992
272.156	19.1	1.0	79	u	
272.546	15.7	0.8	79	u (bl Fe xii)	
272.659	13.7	0.7	79	Si vii	272.660
272.885	12.2	0.6	79	u	
273.170	9.7	0.5	79	u	
274.203	349.1	19.4	84	Fe xiv (bl Si vii)	274.203
275.367	32.8	2.0	79	Si vii	275.35
275.695	9.9	0.6	79	Si vii (bl u)	275.690
276.056	6.5	0.4	79	u	
276.467	8.6	0.6	79	u	
276.855	27.0	1.8	79	Si vii bl Si vii	276.839
277.049	74.9	5.0	115	Si viii (bl Mg vii)	277.000
277.262	273.0	18.8	88	Si x	277.265
278.156	6.8	0.5	79	Si x (bl u)	278.180
278.411	27.8	2.1	149	Mg vii (bl Si vii)	278.395
278.648	6.3	0.5	79	? Ni xi	
279.479	6.5	0.6	79	u	279.480
280.129	12.0	1.1	148	Al ix (bl u oc Fe xviii)	280.160
281.414	46.5	4.9	79	S xi	281.401
282.422	14.7	1.7	79	Al ix	282.422
282.980	9.5	1.2	79	u	282.980
283.465	12.0	1.6	79	Fe xii (bl u)	
284.029	27.1	3.9	79	Al ix (bl oc Fe xviii)	284.042
284.161	168.6	24.3	84	Fe xv (bl)	284.160
284.614	6.0	0.9	79	u	284.700
285.602	13.8	2.3	79	S xi	285.600
285.833	17.6	3.1	96	S xi	285.828
286.379	5.1	0.9	79	Al ix	286.380
288.409	6.9	1.6	98	S xii	288.400
289.146	5.1	1.3	79	Fe xiv	289.148
290.710	17.3	5.3	83	Si ix (bl oc Fe vii)	290.687
291.018	10.3	3.3	65	Fe xii	291.010

Notes. λ_o (Å) is the measured wavelength. DN is the number of total counts in the line, while Int is the calibrated intensity (phot cm⁻² s⁻¹ arcsec⁻²). F is the full-width-half-maximum in mÅ, while the column ID provides the identification (bl: blended; sbl: self-blend; u: unidentified; bl oc: blended in other plasma conditions). In a few cases, the class of a line is given (i.e.: u VII is a line with a morphology similar to Fe VII), as well as the rest wavelength (λ_r , Å) from the literature. “N” indicates a new identification proposed here, while “T N” a tentative new one.

Fig. A.1. Hinode EIS spectrum (units are averaged counts per pixel) of the quiet-Sun off-limb region observed on 2007 March 11 (see Fig. 4).

Fig. A.2. Intensities (ordinate) in a selection of Hinode/EIS lines as they vary across the solar limb (abscissa: in arcseconds along the N-S direction from disk centre, see Fig. 4). The top row shows strong well-known lines for reference, the rest are unidentified.

Fig. A.3. Emissivity ratio curves relative to the main Fe x EUV transitions observed by Hinode EIS on 2007 Mar. 11. I_{ob} : observed intensity; bl: blend; sbl: self-blend; N: new identification proposed here.

Fig. A.4. Emissivity ratio curves relative to the main Fe xi EUV transitions observed by Hinode EIS on 2007 Mar. 11.

Fig. A.5. Emissivity ratio curves relative to the main Fe xii EUV transitions observed by Hinode EIS on 2007 Mar. 11.

Fig A.6. Emissivity ratio curves relative to the main Fe XIII EUV transitions observed by Hinode EIS on 2007 Mar. 11.

Fig A.7. Emissivity ratio curves relative to the Fe XIV and Si X EUV transitions observed by Hinode EIS on 2007 Mar. 11.