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Emission lines of iron in the 150–250 Å region on National Spherical Torus Experiment

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Abstract

We measured iron emission from the National Spherical Tokamak Experiment. We focused our attention on several band pass regions of the *Solar Dynamics Observatory*'s Atmospheric Imaging Assembly. We found that all significant iron emission in the 171, 193 and 211 Å band pass regions are accounted for by the CHIANTI atomic database, although some strong emission lines of carbon are present that may complicate interpretation of solar data if not taken into account.

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(Some figures may appear in colour only in the online journal)

1. Introduction

The Atmospheric Imaging Assembly (hereafter referred to as AIA) of the *Solar Dynamics Observatory* has six extreme ultraviolet (EUV) channels to measure highly ionized iron emission with high spatial and temporal resolution. The goal of this assembly is to construct narrow-band temperature maps of the solar corona over a temperature range of 1–20 MK. Success in this endeavor depends on accurate differential emission measure models, so comprehensive knowledge of the emission lines occurring in each wavelength band is essential. Any missing or incorrectly modeled emission will result in inaccurate temperature maps.

Recently, attention has been paid to deficiencies in the emission models in the regions covered by the AIA 94 and 131 Å bandpass channels [1–4], with missing flux due to iron lines that were not included in the atomic models, even though these lines had been known for nearly a decade [5]. Other elements, such as magnesium and neon, may also contribute to missing flux in these regions [4]. While the problems with the atomic models in the 94 and 131 Å band passes have been apparent for some time, e.g. [6], the region around the 171 and 193 Å band passes were thought to have been known much more completely [4]. Indeed, a recent survey of iron lines in the 170–285 Å region produced by collisional excitation in the Livermore electron beam ion trap [7] found that essentially all lines were well reproduced by CHIANTI (v7.0 [8, 9]). The only exceptions were about a dozen weak features that were not reproduced by CHIANTI. In this paper we extend our EUV measurements of iron to the National Spherical Torus Experiment (NSTX), including emission at temperatures and densities higher than those found in electron beam ion traps that may be relevant to ionizing plasmas such as solar flares.

2. Methods

We obtained time-resolved spectra on NSTX using the long-wavelength EUV spectrometer (LoWEUS; [10]) instrument. LoWEUS is a flat-field grating spectrometer with variable line spacing and a mean 1200 ℓ mm^{-1}. The spectral resolution is ∼0.3 Å, resulting in a resolving power $\lambda/\Delta\lambda \sim 500$–800 in the 150–250 Å region we examined.

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New faster CCD cameras have achieved a time resolution of ∼13 ms [11], enabling examination of impurity evolution over the duration of the shot, as well as better correlation of emission with plasma conditions as measured by multi-point Thomson scattering (e.g. figure 1 in [11]).

3. Results

We present data from shot 141111, taken on 16 September 2010. Iron and, to a lesser extent, nickel are present as impurities in some shots due to sputtering of stainless steel components in the tokamak vessel. M-shell iron emission, when present, occurs during the beginning of the shot, typically in the first 10–100 ms, when the electron temperature of the plasma is ∼100–300 eV. Shot 141111 unexpectedly included a second iron emission period ∼170–225 ms into the shot, when T_e was 500–700 eV, which provides an opportunity to examine iron emission at higher temperatures and densities that may be relevant to ionizing plasmas such as solar flares.

In figure 1, we show the AIA response function (obtained from [12]) overlaid with three time frames from shot 141111. Strong lines are noted; lines labeled simply by charge state are of iron. Lines of C V and C VI (from the wall tiles) and from Li II (from lithium injection) are used as calibration. Figure 1(a) shows emission from ∼40 ms into the shot, when the electron temperature T_e was ∼170 eV and the density N_e was $\sim 8\times10^{12}$ cm^{-3}. Figure 1(b) shows emission from ∼80 ms into the shot, when T_e was ∼250 eV and $N_e \sim 1\times10^{13}$ cm^{-3}. Figure 1(c) shows emission from ∼200 ms into the shot, when T_e was ∼750 eV and $N_e \sim 4\times10^{13}$ cm^{-3}.

4. Discussion

All significant iron emission observed by LoWEUS on NSTX, ranging from Fe VIII through Fe XV, could be identified with the CHIANTI atomic database. Figure 1(a) shows a typical M-shell iron spectrum at low temperature, comparable to the quiet Sun spectrum, where the dominant emission is from Fe IX in the 171 Å band pass. In figure 1(b), as expected, emission from higher charge states of iron have become prominent, as the ionization balance evolves with increasing temperature. As expected, the 193 Å band pass is dominated by Fe XII emission. The iron M-shell emission typically ceases to be visible after 100 ms into the discharge, when $T_e > 500$ eV. The lack of iron M-shell emission after this time can be attributed to the fact that the observable ionization balance favors L-shell and K-shell iron ions, and to a dearth of new iron influx from the vessel wall. Although most lines that fall within the band pass regions for AIA are iron, we note that a few lines of nickel are present (in figure 1(b) only) within the 171 Å band pass. Resumption of iron M-shell emission in figure 1(c) is attributed to an influx of cold iron from the plasma edge, probably from plasma striking the wall or an in-vessel hardware component. Emission in the 211 Å band pass is dominated by Fe XIV.

A few new strong lines (marked by asterisks), not present in CHIANTI, appear in figure 1(c). These we tentatively attribute to C V and C VI emission (table 1). These lines are found in either the NIST (v4; [13]) or Kelly [14] databases, but their absence from CHIANTI may result in their being

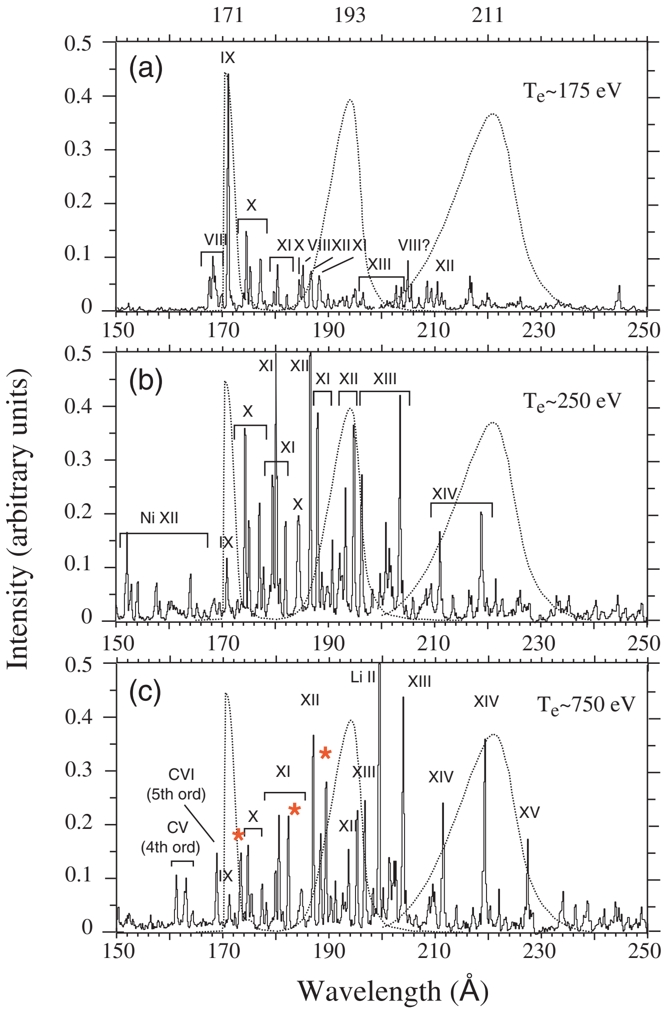

Figure 1. Overlay of the AIA instrument response function (dotted lines) with spectra taken by LoWEUS (solid lines) at three time frames with increasing electron temperature and density of shot 141111 on NSTX. Strongest lines are identified by charge state. (a) T_e ∼175 eV, ∼40 ms into the shot. (b) $T_e \sim 250$ eV, ∼80 ms into the shot. Ni XII is noted, while other features are of iron. (c) $T_e \sim 750$ eV, ∼200 ms into the shot. Strong non-iron lines that may interfere with analyses of AIA spectra are indicated by asterisks.

overlooked by the solar community, which relies heavily on CHIANTI. Seven 3d → 2p, 3s → 2p and 3p → 2s transitions of hydrogenic C VI between 182.1 and 182.3 Å are likely to either comprise the feature at 182.29 Å (much stronger in figure 1(c) than in figure 1(b) or to be blended with the Fe XI line at that position. The Kelly database lists a further line from a 4p → 2s transition of helium like C V at 173.28 Å, which may account for the feature observed at 173.26 Å. In addition, NIST lists a 4s → 2p transition of C V we believe may account for the feature at 189 Å. However, the accompanying 3p → 2s transition at 227 Å appears to blend with Fe XV (see figure 1(c), but the 3d → 2p transition that should be strongly visible at 248 Å is either missing or very weak (see figure 1(c), which complicates the identification of the feature at 189 Å as C V. We speculate that the strength of these features may be indicative of non-equilibrium processes, in particular of charge exchange with neutral hydrogen, which affects the population of the $n = 4$ levels in carbon. Neutral deuterium was injected into the plasma when these lines

Table 1. Carbon emission lines in the 171, 193 and 211 Å AIA band pass regions.

Ion	Wavelength (Å)	Lower level	Upper level
C V	173.281	$1s2s^3\ P_1$	$1s4p^3\ P_1$
C VI	182.088	$2p^2\ P_{1/2}$	$3d^2\ D_{3/2}$
C VI	182.097	$2p^2\ P_{1/2}$	$3d^2\ D_{3/2}$
C VI	182.132	$2p^2\ P_{1/2}$	$3d^2\ D_{1/2}$
C VI	182.144	$2p^2\ P_{1/2}$	$3d^2\ D_{1/2}$
C VI	182.230	$2p^2\ P_{3/2}$	$3d^2\ D_{5/2}$
C VI	182.246	$2p^2\ P_{3/2}$	$3d^2\ D_{3/2}$
C VI	182.290	$2p^2\ P_{3/2}$	$3d^2\ D_{1/2}$
C V	189.255	$1s2p^3\ P_1$	$1s4s^3\ S_1$
C V	189.260	$1s2p^3\ P_0$	$1s4s^3\ S_1$
C V	189.304	$1s2p^3\ P_2$	$1s4s^3\ S_1$
C V	227.190	$1s2s^3\ S_1$	$1s3p^3\ P_2$
C V	227.202	$1s2s^3\ S_1$	$1s3p^3\ P_0$
C V	227.203	$1s2s^3\ S_1$	$1s3p^3\ P_1$
C V	248.660	$1s2p^3\ P_1$	$1s3d^3\ D_2$
C V	248.660	$1s2p^3\ P_1$	$1s3d^3\ D_1$
C V	248.672	$1s2p^3\ P_0$	$1s3d^3\ D_1$
C V	248.740	$1s2p^3\ P_2$	$1s3d^3\ D_3$
C V	248.748	$1s2p^3\ P_2$	$1s3d^3\ D_1$
C V	248.748	$1s2p^3\ P_2$	$1s3d^3\ D_2$

were seen in the form of very energetic beams for core plasma heating. These lines persist even when iron is no longer seen. Without better knowledge of the origin of these lines and their formation processes, it will be impossible to include them in models of the AIA temperature-dependent response functions. However, it is important to be aware of their existence, particularly as some blend with known Fe XI and Fe XV lines and may therefore lead to incorrect flux determinations.

5. Summary

We studied iron emission on the NSTX tokamak, taking advantage of an unusual shot in which M-shell iron emission was present at two separate periods. We found that all significant iron emission we observed was accounted for in the CHIANTI atomic database, but a few strong lines not found in CHIANTI appeared at the higher temperature period, some of which blend with iron and which could therefore affect the interpretation of AIA spectra.

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