Laboratory study supporting the interpretation of Solar Dynamics Observatory data

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Abstract. High-resolution extreme ultraviolet spectra of ions in an electron beam ion trap are investigated as a laboratory complement of the moderate-resolution observation bands of the AIA experiment on board the Solar Dynamics Observatory (SDO) spacecraft. The latter observations depend on dominant iron lines of various charge states which in combination yield temperature information on the solar plasma. Our measurements suggest additions to the spectral models that are used in the SDO data interpretation. In the process, we also note a fair number of inconsistencies among the wavelength reference data bases.

1. Introduction
The Solar Dynamics Observatory (SDO) spacecraft \cite{1} aims to study the highly variable Extreme Ultraviolet (EUV) emission of the solar corona (which fluctuates by several orders of magnitude), combining high spatial resolution observations at a high exposure frequency with determinations of the actual plasma temperature in the range from 1 MK to 20 MK. The Atmospheric Imaging Assembly (AIA) experiment \cite{2} on board the SDO spacecraft observes in seven, mostly iron-dominated, EUV channels (centered at wavelengths 94, 131, 171, 193, 211, 304, 355 Å) with moderate wavelength selection by multilayer reflective optics. Supported by extensive modeling \cite{3, 4}, the observations also yield the temperature in the solar coronal field of view. The seven AIA data channels have spectral band passes from 1 Å to about 20 Å wide. In parallel, a grating spectrograph of the Extreme ultraviolet Variability Experiment (EVE) \cite{5} monitors the EUV spectrum with a band width of 1 Å.

The solar spectrum reflects the chemical composition of the Sun with elements at their natural abundances and charge state distributions depending on the local temperature. In the laboratory, the spectra of elements can be studied individually, and the charge state balance in a plasma can be adjusted. Hence it is possible to recognize the origin of spectral lines, possibly resolve spectral blends that originate from different elements, and check spectral models for consistency.

Among terrestrial experiments, an electron beam ion trap (EBIT) offers the laboratory environment that is closest to the solar corona. Various elements of coronal interest (He, C, N, O, F, Ne, Mg, Si, S, Ar, Ca, Fe, Ni) are introduced into EBIT and ionized and excited by an energetic electron beam. The EUV spectra in the vicinity of the SDO/AIA observation channels are studied with spectrographs of resolving powers 1100 to 3000. We thus check the
Completeness of the spectral data that are used in the collisional-radiative modeling necessary for the interpretation of the SDO/AIA raw data, but with deliberate control over the elements introduced as well as the charge state distribution, and at a much higher spectral resolution than is available on board of the SDO spacecraft.

We mainly compare our observations with the NIST on-line data base [6] and with the CHIANTI data base (v. 7.1) [7]; the latter compiles wavelength data mostly from solar observations and models the relative line intensities. We note quite a number of inconsistencies among the wavelength reference data tables. Overall, the CHIANTI wavelengths are better compatible with our observations of the three (out of six) AIA iron channels covered so far. However, in our work in progress [8, 9, 10] we also find a number of spectral lines that may have been under-appreciated in the spectral models.

2. Experiment
The experiment was performed at the EBIT-I electron beam ion trap [11] at the Lawrence Livermore National Laboratory. The device has been optimized for spectroscopic studies of highly charged ions [12], including the study of spectra needed for diagnosing high energy density plasmas [13]. We employ flat-field EUV spectrographs with cryogenically cooled CCD detectors [14, 15] that exceed the resolving power of the grating spectrograph on board SDO by one to two orders of magnitude, in spectral slices 15 to 20 Å wide and thus exceeding the widths of the AIA detection bands. For each injected gas (CO$_2$, N$_2$, SF$_6$, Ne, Ar, ironpentacarbonyl, nickelocene, and so on) spectra were recorded at several electron beam energies from 200 to 1000 eV. This procedure enabled a rough estimate of the charge state range of emitting ions. All spectra contained emission from low charge states, because neutral gas was bled into the trap continually.

![Figure 1. EBIT spectrum of Ne in the vicinity of the SDO/AIA 211 Å band. Only three of the Ne lines are known from the literature (NIST on-line data base and CHIANTI). The newly found and as yet unidentified Ne lines carry question marks.](image)
Figure 2. Sum of EBIT spectra of Fe recorded at various electron beam energies in the vicinity of the SDO/AIA 211 Å band. While most of the stronger Fe lines are identified, the lines marked with an asterisk are not listed in the CHIANTI data base.

3. Wavelength calibration

Calibration lines are needed within the field-of-view of each spectrograph setting. Our wavelength calibrations are based on sequential observations of several elements (C, N, O, F, Ne, Mg, Si, S, Ar, Ca, Fe, Ni), the combination of individual data sets yielding an average calibration curve. Fortunately, lines of oxygen, which is an indigenous background material in EBIT-I, appear in many of the spectra we measure.

Reliable reference lines are often scarce; from historic measurements of light elements, one would expect the best reference data from ions such as those of O, F, or Ne (see [16]). However, even the spectra of the lighter ions are incompletely known, as we see for the case of Ne. Near 94 Å (one of the AIA channels), neon has lines of various charge states, and some of these lines also appear in second diffraction order and then appear near 196 Å, useful for calibrating the spectra in the vicinity of the 193 Å AIA channel [10]. Ne lines are not only wanted for the present laboratory astrophysics work, but they are important also for the calibration in our measurements on Li- and Be-like ions of specific isotopes of rare earth elements (such as \(^{141}_{59}\)Pr [17]).

Most of the neon lines listed in the neighbourhood of the seven SDO/AIA bands belong to charge states 2+ to 8+, and none of them are known with high accuracy. Actually, some 90 Ne lines are expected from the NIST and CHIANTI tables in the neighbourhood of the seven AIA bands, but only about 60 of these are seen in our EBIT spectra. Of the predictions, about 40 lines appear in only one of the two tables and not in the other. Some 60 Ne lines are seen in our EBIT spectra that have no equivalent in the tables. In the special example of the 211 Å SDO/AIA band, three known Ne IV lines are seen in the EBIT spectrum as well as 26 unidentified Ne lines [9] (Fig. 1). The Ne wavelength listings of the two tables perfectly agree in some cases and differ by up to 80 mÅ in others. Consequently most of our line positions are limited in precision by statistics and in accuracy by the calibration problem, combining to 10 to 20 mÅ in most cases.
4. Discussion
The complexity of the spectra causes identification problems. The charge states of elements Fe and Ni that are of particular interest feature an open $n=3$ valence shell, with a multitude of lines. Around 200 Å, Fe has many more than just one line per 1 Å interval (see the sample spectrum in Fig. 2). In order to identify known lines, the wavelength calibration has to be much better established than 0.1 Å. Correspondingly, calculations of wavelengths that are not better than 100 mÅ may be easy to obtain, but are largely useless in practice. In the present study, parts of the Fe spectrum are so crowded with spectral lines that other elements would be difficult to recognize, unless their relative abundance exceeds the natural one. Fe is the element with the ninth highest natural abundance. Most elements beyond H, He, C, N, O, Ne, Mg, and Si are clearly less abundant and thus their spectra are correspondingly less bright in the Sun, and their lines are progressively difficult to discern in the presence of line-rich Fe.

The present example of Ne reveals many previously unknown lines of Ne in the vicinity of the SDO/AIA 211 Å band. Although Ne is more abundant than Fe in the Sun, the Ne lines in this band are likely hidden in the solar spectra by the dense line forest of Fe. However, now knowing that Ne has these lines that are not yet listed in models such as CHIANTI points out the necessity for refining the model, so that the pedestal under the Fe lines can be treated more correctly in the interpretation of the SDO observations.

Our investigation reveals a number of cases in which the modeling of the solar signal of the seven AIA data channels should benefit from the inclusion of additional spectral lines that we identify. Hence the reliability of the interpretation of the SDO data for establishing a temperature scale can be expected to improve.

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