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Tokamak Spectroscopy for X-ray Astronomy

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Abstract. This paper presents the measured x-ray and XUV spectra of three astrophysically abundant elements (Fe, Ca and Ne) from three different tokamak plasmas. In every case, each spectrum touches on an issue of atomic physics that is important for simulation codes to be used in the analysis of high spectral resolution data from current and future x-ray telescopes. The utility of the tokamak as a laboratory test bed for astrophysical data is demonstrated. Simple models generated with the HULLAC suite of codes demonstrate how the atomic physics issues studied can affect the interpretation of astrophysical data.

1. Introduction

We are at the beginning of a new age of x-ray astronomy. With the launch of the Chandra X-ray Observatory (CXO) and the X-ray Multi-Mirror Mission (XMM) astrophysicists will be able to study the x-ray universe with unprecedented spectral resolution. Ongoing solar missions such as SOHO and TRACE rely on precise spectroscopy to probe conditions and dynamics in the solar chromosphere. In every case, the study of well resolved high energy emission spectra relies on ionization equilibrium calculations (Arnaud and Raymond 1992), and in the case of collisional plasmas, emission line tabulations (Bickhouse, Raymond, and Smith 1995). There are many issues known to plague existing codes for simulating x-ray emission from astrophysical sources, such as incomplete sets of lines for different ions (Beiersdorfer et al. 1999). and inaccurate atomic data. In order to exploit fully the abundance of x-ray data that will soon be arriving, ionization equilibrium models and emission models need to be well tested and made robust. The solution is to be found in laboratory experiments. Recent programs of observations of astrophysically abundant elements at electron beam ion traps (Bbrown et al. 1998) and tokamaks (Wargelin et al. 1998) are shedding light on the issues of completeness and accuracy in x-ray emission models.

The tokamak is a toroidally symmetric vessel for containing a hot, low density thermonuclear plasma (up to several keV and $10^{12} - 10^{14}\,\mathrm{cm}^{-3}$, respectively). The working gas in the vessel is usually a mixture of hydrogen isotopes or helium. The hot plasma is confined by magnetic fields. The principal magnetic field (of the order of tens of kG) is a toroidal field created by external field coils. However, in order to obtain equilibrium and stability it is necessary to have a poloidal magnetic field. In tokamaks this field is produced by currents in the plasma itself. The resulting net magnetic field spirals around the torus. The tokamak can provide an excellent source of emission from astrophysically abundant elements in high temperature plasmas; metallic impurities can be introduced into the plasma mechanically or injected by laser ablation from glass slides, gasses can be puffed through fueling valves on the vessel. The current profile which provides heating and confinement can be well controlled, so the shape and temperature of the plasma can be set by the users' needs. The temperature and density conditions in the plasma are known by independent diagnostics. Electron temperatures are measured by monitoring

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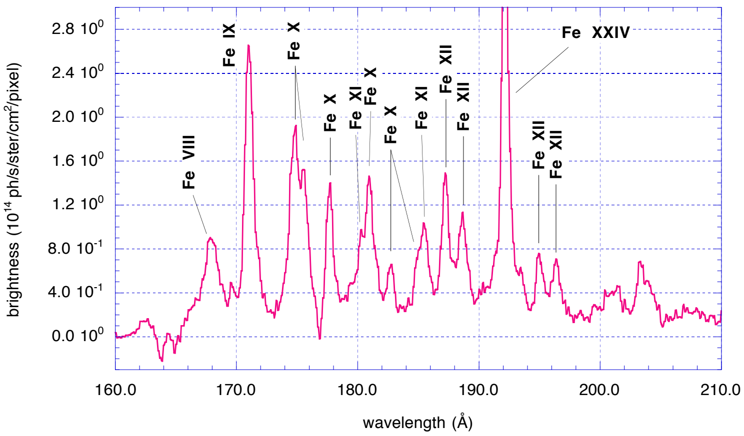

Figure 1. Fe spectrum measured following injection into the Frascati Tokamak Upgrade.

electron cyclotron emission, or by Thomson scattering of laser light. Electron densities are know by interferometry or reflectometry. The fact that the temperature and density conditions are known independently of spectroscopy means that spectroscopic models can be rigorously tested by observations. In what follows, we will discuss high spectral resolution observations of x-ray and soft x-ray emission following the controlled introduction of an impurity into a tokamak plasma (May et al. 2000). These observations are made with x-ray crystal spectrometers (Rice and Marmar 1990; Bartiromo et al. 1995) and a grazing incidence grating spectrometer (Stratton et al. 1984).

Throughout this paper, we will compare our observed tokamak spectra to collisional-radiative (CR) simulations. Our application of CR modeling techniques to tokamak spectra have been discussed elsewhere (Fournier et al. 1996). In brief, we use the HULLAC package of atomic structure codes to generate the data required to calculate CR emissivities for x-ray and XUV transitions. HULLAC provides fully relativistic calculations of energy levels and radiative transition rates as well as semi-relativistic calculations of autoionization rates (Klapisch et al. 1977); it also calculates semi-relativistic collisional excitation rates in the distorted wave approximation (DWA) (Bar-Shalom et al. 1988). These data are used to find the quasi-steady state level populations (and thus line emissivities) for one or more ions of a given element. In what follows, we compare observations of x-ray, soft x-ray and XUV emission from three different astrophysically abundant elements made following injection into tokamak plasmas to CR simulations.

2. M-shell Iron Spectra

Ionization balance models such as that of Arnaud and Raymond (1992) are essential to creating simulations of x-ray and XUV emission from astrophysical objects. As the spectral resolution and collecting area of x-ray telescopes dramatically increases, the interpretation of individual emission lines will strongly test ionization balance models. It is essential that such models be tested under controlled laboratory conditions. Figure 1 shows the spectrum of iron following an injection into the Frascati Tokamak Upgrade (Associazione EURATOM - ENEA, Frascati, Italy). By ramping down the plasma current profile during the later phase of the discharge, we can create a unique plasma configuration that is characterized by a broad, single temperature shelf in the outer part of the plasma. By injecting our samples into this 'ramp-down' state, we can study emission from a single temperature plasma.

The spectrum in Figure 1 shows emission from several M-shell iron ions, K-like FeVIII to P-like FeXII. The strong resonance line of L-shell Li-like FeXXIV is also seen (this is because our spectrometer's line of sight intersects a hotter part of the plasma closer to the core). The temperature profile measured with Thomson scattering as well as charge state distribution measurements indicate that the iron ions are emitting from a 10 cm wide, 80 eV plasma. A simulation using HULLAC CR models and the ionization equilibrium calculations of Arnaud and Raymond (1992) is shown in Figure 2 for T_e = 84 eV and N_e=

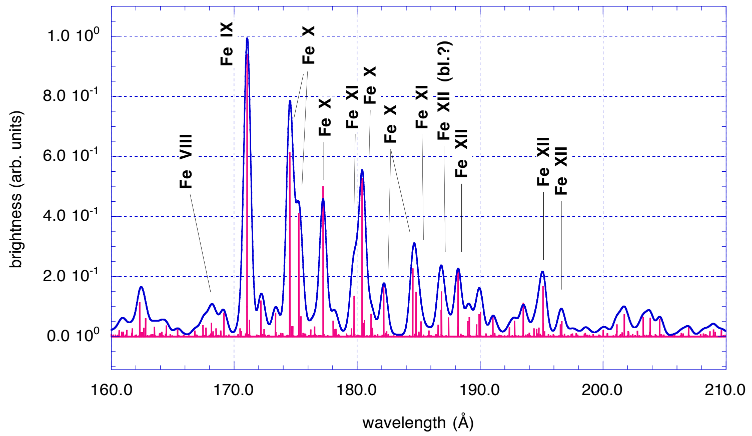

Figure 2. Synthetic Fe spectrum including charge states FeVIII to Fe XIII at T_e = 84 eV and N_e = 6×10^{13} cm^{-3}.

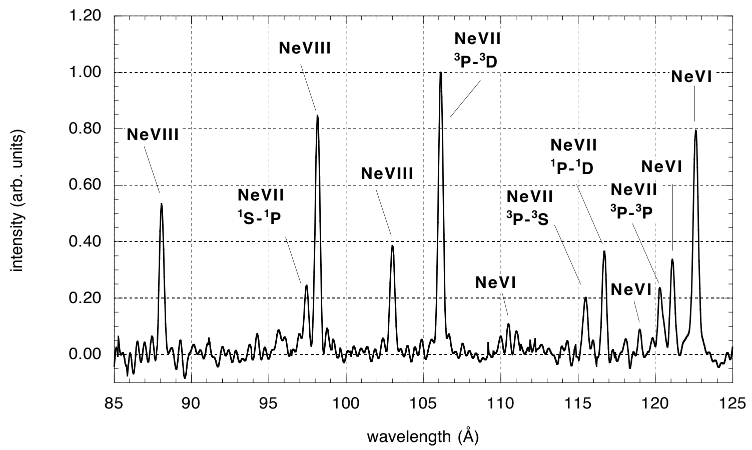

Figure 3. Neon spectrum measured in the Tore Supra Tokamak. The labeled features are Δn=1 (n=2–n=3) transitions.

6×10^{13} cm^{-3}. Simulations going from 68 to 108 eV (log(T_e K)=5.9 to 6.1) are found to be extremely temperature sensitive due to the rapidly changing charge state distribution. By performing a spline fit to the curves of Arnaud and Raymond, we find the best match to the experimental spectrum at 84 eV, in good agreement with the Thomson scattering data. Figure 2 has two synthetic spectra at 84 eV, one in which each line has been given a fwhm of 0.65Å (comparable to the experimental resolution) and one in which each line is given a fwhm of 1 mÅ. The simulation is similar to the data, the correct relative heights of FeIX (171Å) and FeX (174.5, 175.3 and 177.2Å) are recovered (the feature at 174.5Å in the simulation is more blended than are the two FeX lines in Figure 1). The FeX and FeXI lines at 177.2 and 180.4Å, respectively are also in the correct ratio. The FeXII resonant line at 195.1Å is in agreement with Figure 1; however, the lines around 188Å may be blended with the FeXVIII resonance line in second order.

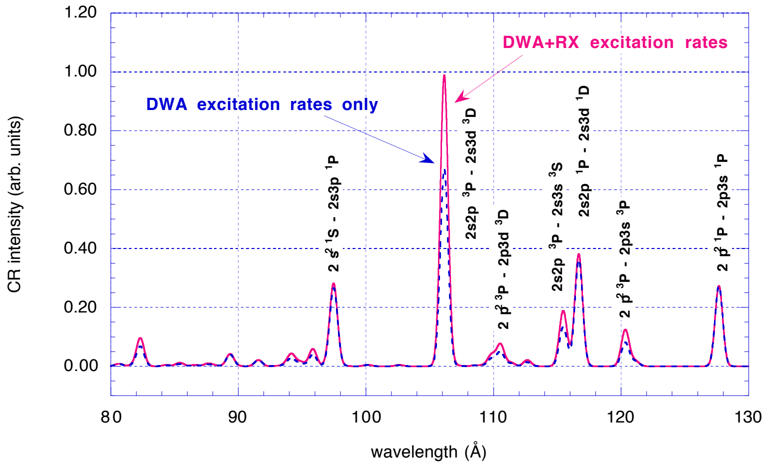

Figure 4. NeVII spectrum computed with and without resonant enhancement of the $2s^2 - 2s2p\ ^{3,1}P$ excitations.

3. L-shell Neon Spectra

The soft x-ray emission from highly charged L-shell neon ions has been observed in the Tore Supra Tokamak (Association Euratom - CEA sur la Fusion, Cadarache, France) (Mattioli et al. 1999). These emission lines fall within the range covered by the low-energy transmission grating spectrometer onboard the CXO. A typical neon spectrum following the injection of the gas is shown in Figure 3; lines from Li-like NeVIII, Be-like NeVII and B-like NeVI have been labeled. Simulations for these ions' spectra were run with the HULLAC suite of codes. There are two independent tests of the simulations in these data. First, the simulation for the features from a single charge state is tested against the spectrum of that ion; this tests the quality of the atomic data used in the simulation. Second, the combined spectra of the different ions must match the observed data; this tests the ionization equilibrium models used for the simulation (as was done above for M-shell iron).

In the present work, the simulation for NeVII is used to test collisional excitation rates. The calculation that used DWA collisional excitation rates failed to match the observed line intensities. The discrepancies were systematic, the relative strengths of transitions between singlet levels were consistent with the data, but the relative strengths of all transitions between triplet levels were underestimated. The spectrum of NeVII has been studied in tokamak discharges before (Finkenthal et al. 1987; Hunag et al. 1998). The measured NeVII relative line intensities in this work show excellent agreement with those measured in (Huang et al. 1998). The transitions between singlet levels are fed (primarily) by excitations from the ground level $2s^2\ ^1$S or the excited $2s2p\ ^1$P level, the transitions between triplet levels are fed by excitations from the $2s2p\ ^3$P levels. The authors in (Finkenthal et al. 1987) conclude that in order to get the populations in the $2\ell 2\ell'$ levels correct, R-matrix collision strengths must be used. Comparing HULLAC's DWA Δn=0 excitation rates between the ground level and the $2s2p\ ^{3,1}$P levels with sophisticated R-matrix calculations (Ramsbottom et al. 1995), we find that the $2s^2 - 2s2p\ ^1$P excitation rate agrees to better than 10%, while the $2s^2 - 2s2p\ ^3$P DWA excitation rates are underestimated by as much as 60%. By substituting the R-matrix rate coefficients for the $2s^2 - 2s2p\ ^3$P excitations, the population in the $2s2p\ ^3$P levels is enhanced by $\approx$ 50%, the increased population is then collisionally transferred to the upper levels of the triplet-triplet transitions in Figure 3. Two simulations for the spectrum of NeVII are shown in Figure 4. The dashed line is the simulation done using only the DWA collisional excitation rates. The solid line in Figure 4 is the NeVII spectrum calculated including resonant enhancement (RX) of the $2s^2 - 2s2p$ excitations. The overall agreement between the data in Figure 3 and the simulation with RX is excellent. This level of agreement is better than that found between the simulations and observations in Huang et al. (1998). This is most likely due to the larger atomic models used in the

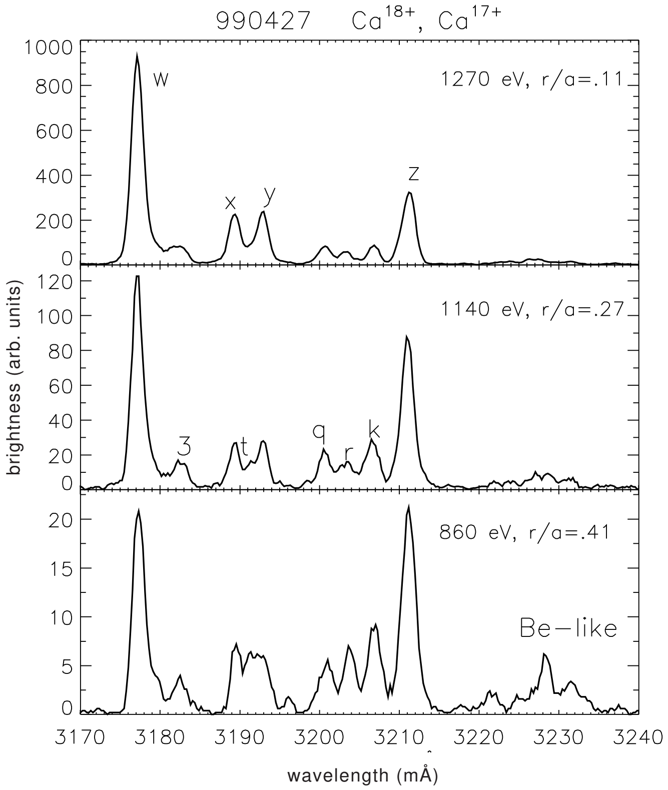

Figure 5. Calcium x-ray spectra measured from three different lines of sight in the Alcator C-Mod tokamak.

present work, which include DWA calculations of the full spectrum of collisional transitions between all $2\ell 3\ell'$ levels.

4. K-shell Calcium Spectra

Figure 5 shows the K-shell x-ray spectrum from calcium injected in the Alcator C-Mod Tokamak (Plasma Science Fusion Center, Massachusetts Institute of Technology). High resolution observations of the K-shell spectra of calcium and iron are important for diagnosing conditions in solar flares (Kato et al. 1998). The figure shows the calcium spectrum from three different lines of sight in the plasma which correspond to three different peak electron temperatures.

The effect on the spectrum of moving out in radius in the plasma (moving to cooler temperatures) is significant. First, the absolute level of the signal drops because the excitation rates for all transitions are falling as the temperature is reduced. Further, the ratio of the He-like resonant line 'w' to the He-like $1s^2\ ^1\mathrm{S}$ – $1s2s\ ^3\mathrm{S}$ 'z' line changes as the spectrum evolves from a collisionally excited ionizing spectrum to one that is recombination dominated. Finally, the emission from inner shell excited Be-like lines is visible in the spectrum observed from the coolest part of the x-ray emitting plasma.

Simple calculations show that a small population of hot electrons in addition to the Maxwellian bulk electron distribution can strongly affect diagnostic ratios. An example of our calculations is shown in Figure 6. For this simulation, we have assumed a bulk electron distribution with a temperature of 1.4 keV and a density of 1.0×10^{13} cm^{-3} and a population of 20 keV electrons 3% of the bulk. The two simulations have been normalized to the 'w' line. We observe that the presence of the hot electrons enhances the resonance 'w' line, the intercombination 'x' and 'y' and the forbidden 'z' lines differently.

This is due to the different weights of the direct and exchange terms in the collisional excitation rates of these lines. The radial direct and exchange parts of the excitation cross sections have different high energy asymptotes. This different energy dependence results in the 'w' line being more enhanced by the 20 keV electrons than are the 'x', 'y' and 'z' lines.

5. Conclusions

We have presented observations of M-shell Fe XUV spectra, soft x-ray L-shell Ne spectra and K-shell Ca x-ray spectra. In each case, the observed element was injected into a hot, well diagnosed tokamak plasma. In the case of the Fe emission, ionization equilibrium calculations have been benchmarked. In the case of the Ne emission, a case is shown where DWA collision rates needed resonant enhancement. In the case of the Ca emission, the evolution of the K-shell spectrum was seen going from the case of an ionizing to a recombining plasma. Also, the effect on the K-shell models of a small population of hot electrons was demonstrated. This work was performed under the auspices of the U.S. Department of Energy at the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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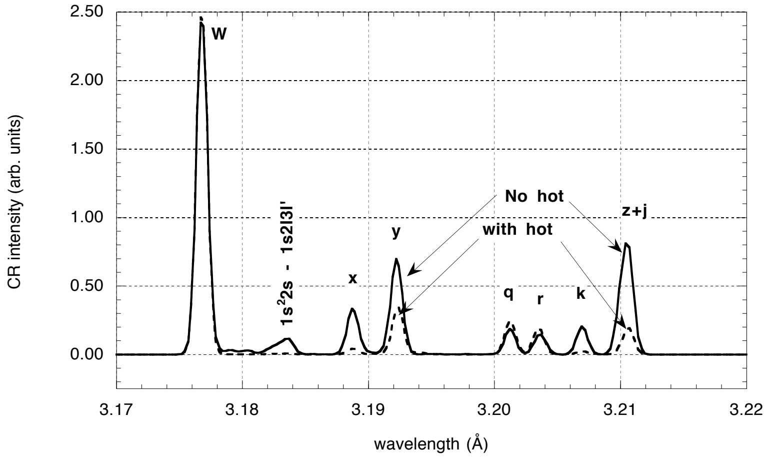

Figure 6. Calcium x-ray spectra with and without a small fraction of hot electrons added to a bulk Maxwellian distribution. The two spectra have been normalized to the intensity of the 'w' line.

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