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Abstract

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The grating instruments on board Chandra and XMM-Newton now allow measurements of electron densities. These rely on the ratios of fluxes in emission lines, where one line depends on both collisional and radiative decay rates. The electron density is required to constrain the physical extent of the emitting region, and large samples of measurements are of interest in the context of trends in coronal activity. Here we discuss the important He I-like ions and the differences in densities that result when different current data bases are used.

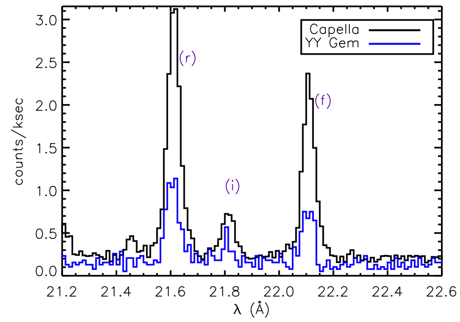

Figure 1: Chandra LETGS measurements of the O VII He-like triplets for Capella and for YY Gem (blue), scaled to the distance of Capella. The spectra show different behaviour in the ratio of the lines marked with (i) and (f).

Densities in X-ray Spectra

Measurements of plasma densities are possible now

X-ray instruments with low spectral resolution cannot measure densities. Their spectra for different densities do not differ from each other. High-resolution X-ray grating spectra can identify high and low densities and plasma densities can be constrained (Fig. 2).

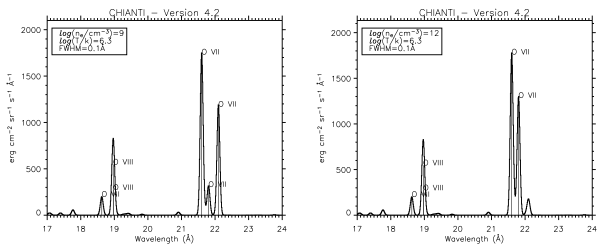

Figure 2: Simulations of spectra with low densities (left) and high densities.

The He-like ions provide a valuable method of measuring the electron density (n_e), in principle over a wide range of electron temperatures (T_e). The method depends on the competition between collisions between the 1s2s ^{3}S and 1s2p ^{3}P levels and the radiative decay in the forbidden line (1s2s ^{3}S – 1s^2 ^{1}S). The ratio of the flux in the forbidden line to that in the intersystem (+magnetic quadrupole) line, then becomes sensitive to n_e, and can be parameterized as

$$\frac{f}{i} = \frac{R_0}{1 + n_e/N_c}, \qquad (1)$$

where R_0 is the ratio in the low density limit and N_c is the critical density. Both R_0 and N_c contain atomic data relating to collisional and radiative rates. Fig. 2 shows simulated spectra for O VII at densities of $10^9\,\mathrm{cm}^{-3}$ and $10^{12}\,\mathrm{cm}^{-3}$, between which the ratio depends on n_e. The densities obtained will always be averages over all plasma present.

Density measurements with He-like triplets

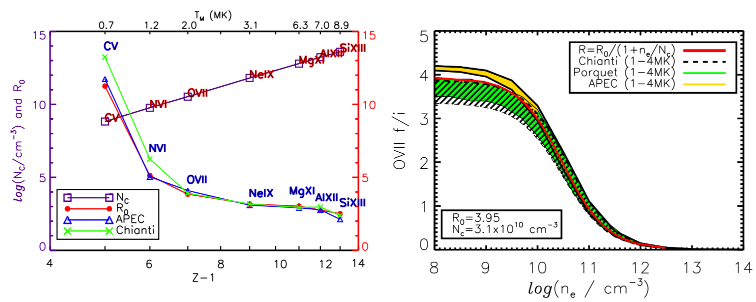

Figure 3: He-like f/i ratios: Comparison of the parameters in Eq. 1, R_0 (comparison of different data bases) and N_c (Blumenthal et al. 1972, ApJ, 172, 205; in purple). In the right hand panel density-dependent f/i line flux ratios are shown for O VII.

The Chandra LETGS measurements of Capella and the flaring M dwarf binary YY Gem (Fig. 1) show clear differences in f/i ratios, which indicate different densities in the two different coronae.
The atomic rates have different dependences on Z - 1, where Z is the nuclear charge, but should depend smoothly on Z - 1, for the ions of interest. Fig. 3 (left) shows the parameters R_0 and N_c as a function of Z - 1. This brings out the differences between the data in the data bases CHIANTI and APEC and data used by Blumenthal et al. (1972). Values of R_0 are compared and marked by different colors; values of N_c are from Blumenthal et al. (1972) and $\log N_c$ depends linearly on Z-1. This plot suggests that the data in R_0 for C V and N VI in CHIANTI need to be re-examined, and that those for Si XIII warrant closer examination.
The right hand panel of Fig. 3 shows the resulting variation of the ratio f/i for O VII, indicating the importance of accurate atomic data when observed ratios are close to the low density limit. Those He-like triplets formed at high temperatures probe only high densities (above $10^{12}\,\mathrm{cm}^{-3}$), while low-temperature ions measure only lower densities ($\sim 10^{10} - 10^{11}\,\mathrm{cm}^{-3}$); this leaves two cases unexplored: low densities in hot plasma and high densities in cool plasma.

Use of densities – Results –

What can we learn from density measurements?

In stellar coronae the density measurements provide important links between physical and geometrical properties. This is expressed in the definition of Emission Measure EM:

$$\mathrm{EM} = {n_e}^2 * V \qquad (2)$$

where n_e is the electron density and V is the emitting volume.
Densities n_e are also needed to explore the optical depths of the lines:

$$\tau = 1.2\ 10^{-14} \left(\frac{n_i}{n_{el}}\right) A_z \left(\frac{n_H}{n_e}\right) \lambda\, f \sqrt{\frac{M}{T}} n_e \ell \qquad (3)$$

where n_i/n_{el} is the fractional ionization, A_z is the elemental abundance, $n_H/n_e = 0.85$ is the ratio of hydrogen to electron density, f is the oscillator strength, M is the atomic number, λ is the wavelength (Å), T is the temperature (K), and ℓ is the path length (cm).

Results

A survey of density measurements was carried out by Ness et al. (2004; A&A 427, 667). Densities were measured from the He-like triplets (O VII and Ne IX) probing densities at temperatures $2\,10^6$ K and at $4\,10^6$ K. Measurements from higher-Z ions (Mg XI and Si XIII) result only in low-density limits $< 10^{12.5}\,\mathrm{cm}^{-3}$ (Fig.4). The observed range of f/i ratios shows that real differences in n_e do occur between different coronae.

Conclusion

Accurate atomic data are essential in order to use these and other diagnostics of n_e, thus exploiting the excellent new spectra being obtained. Values of n_e can then be used to constrain physical models of the atmosphere.

Application of derived quantities

Quantities derived from the densities are emitting volumes V and optical depths τ (Eqs. 2 and 3). In addition, various models of the emitting geometry or loop scaling-laws can be applied with measured densities. The derived quantities can be used to

- find out whether an average corona with lines formed over a pressure-squared isothermal scale-height is plausible
- apply loop models and scaling laws to determine loop lengths and hence volume filling factors.
- derive path lengths ℓ from estimates of τ.

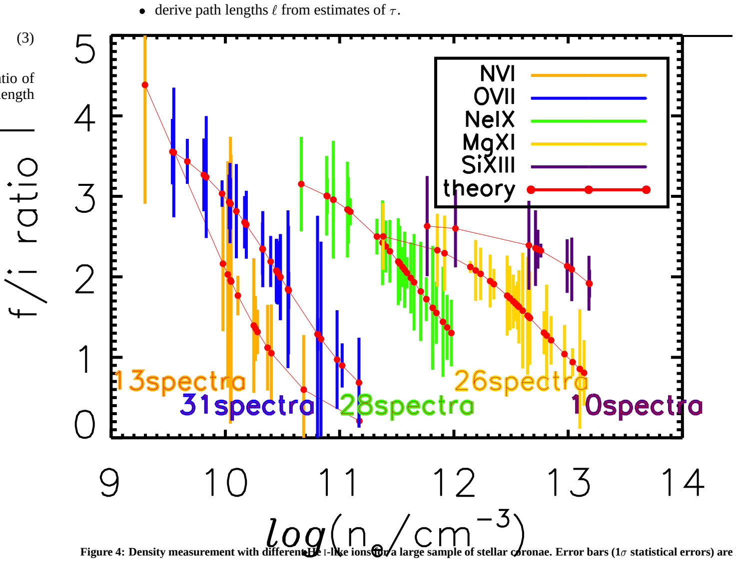

Figure 4: Density measurement with different He I-like ions for a large sample of stellar coronae. Error bars (1σ statistical errors) are large due to faint intercombination lines in case of large f/i ratios. Mg XI and Si XIII cannot constrain densities below $10^{12.5}$.

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