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A New Temperature Determination Using the Fe XVII Emission of Capella

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Abstract. Typically, the most reliable way to spectroscopically determine the electron temperature is to measure the strength of dielectronic recombination (DR) satellite lines relative to the associated resonance line, I_{DR}/I_r, as this ratio varies steeply with temperature and does not require assumptions associated with the calculations of ionization equilibria. We have applied this method to the Fe XVII lines, which are very bright in the spectrum of Capella observed with high resolution with *Chandra's* High Energy Transmission Grating Spectrometer. In particular, we have determined the intensity of the dielectronic satellite lines next to the Fe XVII $2p - 3d$ resonance line, commonly denoted $3C$. The atomic data needed to do this are supplied by the Flexible Atomic Code. The temperature, T_{DR}, we have derived from this method is somewhat lower than T_{DEM}, derived from the differential emission measure for Fe XVII. We show that the precision of this method is very high, and we discuss the its limitations.

1. Introduction

A determination of the differential emission measure (DEM) is a prerequisite for describing the temperature structure of stellar coronae and thus for understanding such properties as stellar activity, energy balance, and luminosity, and for constraining stellar models in general. Determinations of the DEM rely on fitting the observed spectral emission with output from spectral modeling calculations and are highly sensitive to the accuracy of underlying calculations of the ionization equilibrium as a function of temperature. Unfortunately, calculations of the ionization equilibrium of a given element are not yet as reliable as one would like them to be – any updates in ionization or recombination rates appear to result in major changes in the predicted charge state fractions at a given temperature (Bryans et al. 2006, 2009). Ionization equilibrium calculations are thus typically the dominant underlying source of error in temperature determinations.

A recent analysis of the X-ray, EUV, and FUV emission of Fe XVIII and Fe XIX found that the observed X-ray flux greatly exceeded that of the predictions (Desai et al. 2005). This may be another manifestation of errors in ionization equilibrium calculations, which may wrongly place a given charge fraction at too low a temperature and thus in a region where the X-ray flux (but not the EUV and FUV emission) will be underpredicted (Brickhouse, private communication). Measurements of coronal temperatures that do not invoke assumptions associated with the calculations of ionization equilibria are, therefore, highly desirable but generally have either not been applicable to *Chandra* grating spectrometer observations or were fraught with even higher uncertainty – an example is given by the fitting of the bremsstrahlung continuum underlying the EUV spectrum of α Cen recorded with the short wavelength band instrument on the *Extreme Ultraviolet Explorer*, which resulted in an unphysical peak well above 10^8 MK in the DEM (Mewe et al. 1995).

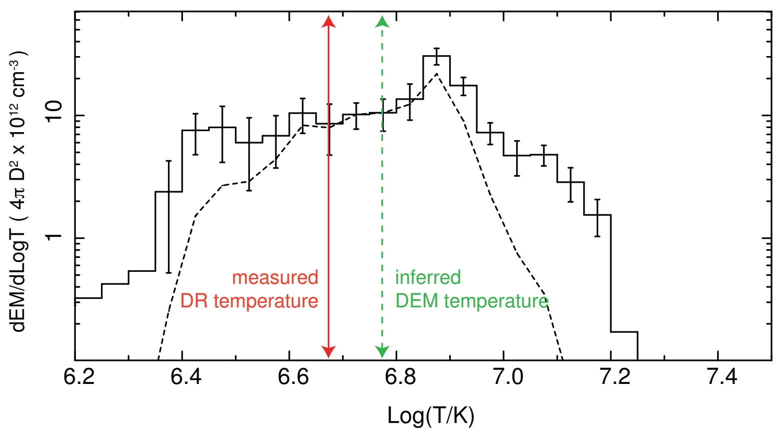

Figure 1. DEM of Capella determined by Gu (2009) from 596 ksec observations with the HETGS on *Chandra*. The Fe XVII emissivity-weighted DEM is shown as a dashed trace. The dashed vertical arrows indicate the electron temperature inferred from the emissivity-weighted Fe XVII DEM. The solid vertical arrows indicate the electron temperature inferred from the fit of the dielectronic satellite lines.

In Fig. 1 we show the DEM for Capella. It was derived from a joint analysis of the plus and minus orders of both HEG and MEG spectra from *Chandra*. This analysis relied on an augmented APEC spectral data base, as described by Gu (2009). The DEM peaks near 7.94 MK, or 685 eV (Gu et al. 2006; Gu 2009). The Capella spectrum in the 10 to 18 Å region is dominated by line emission from various charge states of iron, and among those much of the emission is from Fe XVII. The DEM weighted by the Fe XVII emission is indicated in Fig. 1 by the dashed trace. This trace characterizes the temperature of the plasma regions that are the source of the Fe XVII emission. It is somewhat narrower than the DEM of Capella overall, as the Fe^{16+} ion does not exist at the very high or the very low temperatures. Charge balance calculations predict that the fractional abundance of the Fe^{16+} ion peaks at a temperature around 4.0 MK. By comparison, spectral codes predict that the Fe XVII emission peaks in ionization equilibrium at somewhat higher temperatures. In fact, for Capella the emissivity weighted temperature is T_{DEM} = 5.85 MK, or 504 eV Gu (2009).

Given the uncertainties associated with the calculation of the charge state fractions, it is very important to find an independent way to determine the temperature of the coronal regions that are the source of the Fe XVII emission. Here we show that a temperature determination can be accomplished using a very different approach. In particular, we employ the dielectronic recombination (DR) satellite lines to the strongest Fe XVII line to infer the average temperature experienced by the Fe^{16+} ion. As we show, measurements of the strength of the DR satellite lines relative to the associated resonance line, I_{DR}/I_r, represents, in principle, a very reliable way to spectroscopically determine the electron temperature of a high temperature plasma.

2. Dielectronic Satellite Lines

Dielectronic satellites are produced by the resonant electron capture by the parent ion at discrete energies below the threshold for electron-impact excitation of a given electric-dipole allowed resonance line. The captured electrons, thus, sample discrete values of the Maxwell-Boltzmann electron distribution. By contrast, the resonance line can be excited by any electron with energy above the treshold.

The DR method of determining the plasma temperature makes use of the fact that I_{DR}/I_r has a simple functional dependence on the temperature T:

$$\frac{I_{DR}}{I_r} = const. \times \frac{E_r}{T} e^{(E_r - E_s)/kT} \tag{1}$$

Here, E_r is the X-ray energy of the resonance line, and E_s is the autoionization energy of the valence electrons associated with a given DR satellite line. The value of the constant incorporates the radiative transition rates of the resonance and dielectronic satellite lines. The method is nice not only because of its simplicity but also because no assumptions about charge state fractions need to be made: Both I_r and I_{DR} are directly proportional to the abundance of the parent ion; that dependence drops out in the ratio.

For heliumlike ions, such as Mg XI, S XV, Ca XIX, and Fe XXV, the DR method has been successfully used in solar observations (Gabriel 1972; Dubau & Volonté 1980), and the method has been tested and verified extensively in the laboratory (Bitter et al. 1979, 2003). This method works best for high-Z heliumlike ions, especially for Fe XXV, in which the dielectronic satellites are strong. For low-Z ions, such as O VII, the DR satellites are basically absent.

2.1. Satellites to Neonlike Ions

The DR method can, in principle, be applied to neonlike ions. However, simple considerations have shown that DR satellite lines are considerably weaker than those found in heliumlike ions, even in the spectra of high-Z neonlike ions (Beiersdorfer 1988). However, given sufficient spectral resolution, a low-noise background, and enough flux in the spectrum, the DR lines can be observed. In laboratory measurements, it was already shown that the prerequisite DR satellite lines exist for some but not for all Fe XVII lines. In particular, these measurements have shown that DR lines exist only for the $3d \rightarrow 2p$ transitions in Fe XVII, i.e., lines $3C$ and $3D$, but not for the $3s \rightarrow 2p$ transitions, i.e., lines $3F$, $3G$, and $M2$ (Beiersdorfer et al. 2000; Beiersdorfer 2003). This means it may be possible to detect the DR lines associated with the resonance lines $3C$ or $3D$ in order to make a temperature determination based on the I_{DR}/I_r ratio provided a high signal-to-noise ratio is attained in the observations.

3. HETGS Spectrum of Capella

Capella has been extensively observed with *Chandra's* grating spectrometers, and its Fe XVII spectral emission is the most promising candidate for applying the DR method. Because of the weakness of the DR lines associated with neonlike resonance lines, long exposure times are needed. HETGS observations of Capella meet these criteria, as numerous HETGS observations can be added up. Figure 2 shows the co-added plus and minus orders of 596 ksec HETG spectra of Capella. A fit with the augmented APEC model provides excellent agreement with the observed spectrum. The fit, however, is poor on the long-wavelength side of line 3*C*. Here, the observations provide excess flux, which is not accounted for by the model. MEG spectra show a similar behavior, albeit with reduced resolution. This excess is likely due to the DR satellites.

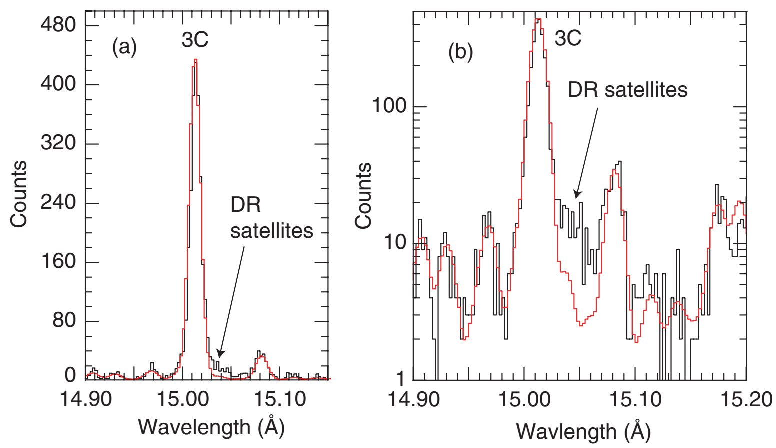

Figure 2. Co-added (596 ksec) HEG spectra of Capella: (a) plus order, linear scale; (b) minus order, logarithmic scale. The observations are overlaid with a best fit model (red line) based on an augmented APEC data base. Excess flux due to possible DR satellite lines is indicated.

4. Analysis

In order to apply the DR method for determing the temperature, we need to know the predicted strength of the dielectronic satellite lines relative to line 3*C* as a function of temperature. For this we calculated the radiative and autoionization rates needed for determining the DR satellite intensities, the collisional excitation rates for 3*C*, and the associated transition energies using the Flexible Atomic Code (Gu 2008).

In Fig. 3 we show the calculated spectral emission from the DR satellite lines. The satellite lines to 3*C* with energy $h\nu$, are produced by the following process:

$$1s^2 2s^2 2p^6 + e \rightarrow 1s^2 2s^2 2p^5 3\ell n\ell' \rightarrow 1s^2 2s^2 2p^6 n\ell' + h\nu \tag{2}$$

The perturbing influence of the spectator electron $n\ell'$ on the transition energy $h\nu$ diminishes with the increasing value of n so that $h\nu$ converges to the energy of the resonance line. As a result, the DR emission from high-n satellites blends with line 3*C* and thus cannot be observed. However, the emission produced from the $3\ell 4\ell'$ and $3\ell 5\ell'$ intermediate states, falls on the long-wavelength side of this line and can, in principle, be resolved by the HETGS.

An overlay of the normalized calculated satellite emission onto the Capella spectrum near line 3*C* is shown in Fig. 4. The match of the calculated emission with the observational data is very poor, as seen in subfigure (a). The reason is that the wavelengths of the calculated satellites are not of spectroscopic accuracy. We, therefore,

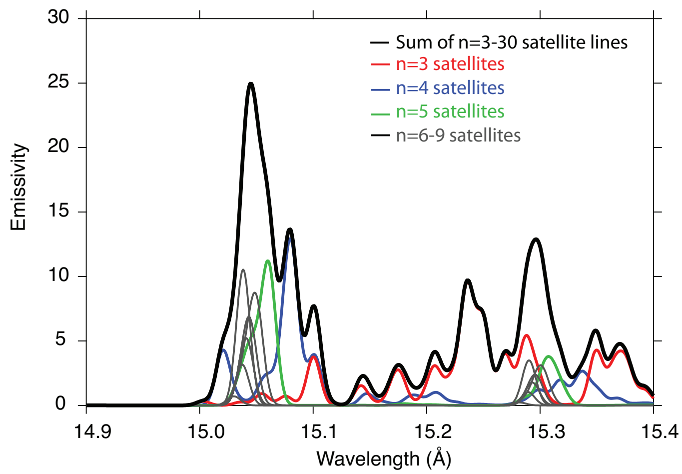

Figure 3. Calculated dielectronic recombination satellite emission in the vicinity of the Fe XVII lines 3*C* and 3*D*.

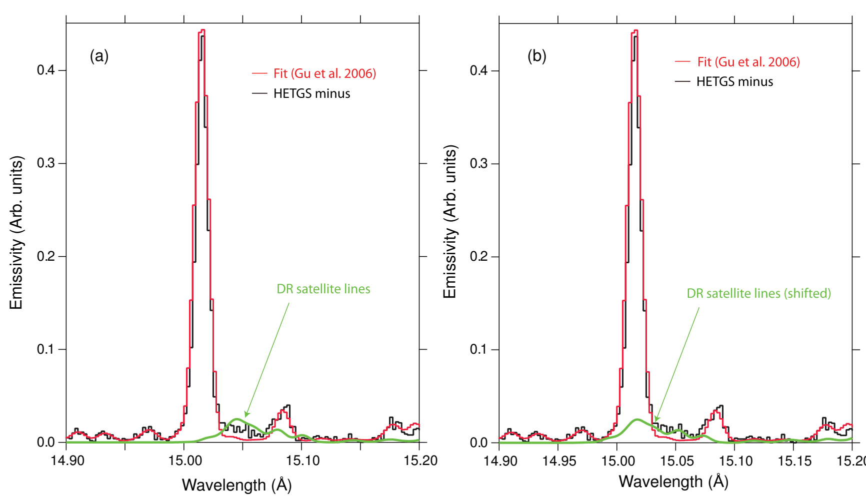

Figure 4. Comparison of the calculated dielectronic recombination satellite emission in the vicinity of the Fe XVII line 3*C* with the observed Capella emission: (a) *ab initio* wavelengths, (b) shifted wavelengths, as described in the text.

shifted the entire satellite spectrum by the amount needed to make the wavelengths of the high-n satellites match that of line 3*C*. The result is shown in subfigure (b).

By adjusting the intensity of the (shifted) DR satellite spectrum a good match to the Capella spectrum is achieved, as shown in detail in Fig. 5. While most DR satellite lines either blend with line 3*C* (those with $n \geq 5$) or with other L-shell iron lines (those with $n = 3$), the bulk of the $n = 4$ satellites are fairly isolated on the long-wavelength side of 3*C* (cf. Fig. 3) and form the bulk of the previously unfitted flux in that region.

The fit thus yields a good value of the intensity of the $n = 4$ satellites, and we find a ratio $I_{n=4}/I_{3C} = 0.045$. The error in this ratio is about 10%.

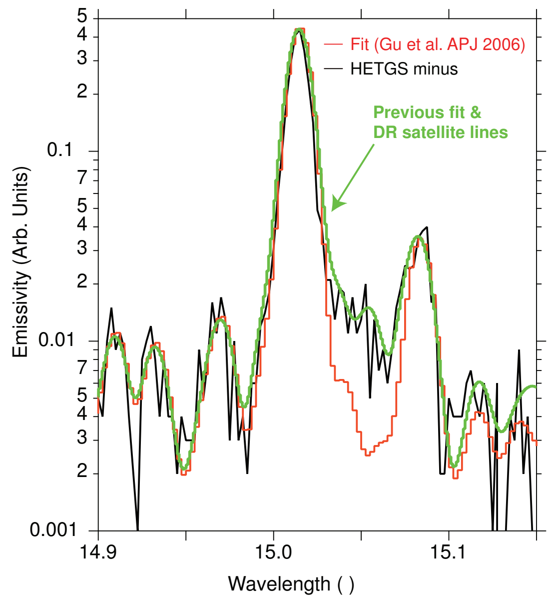

Figure 5. Fit of the HETGS (minus order) Capella Fe XVII emission.

In Fig. 6 we show the predicted functional dependence of $I_{n=4}/I_{3C}$ on the electron temperature. The ratio $I_{n=4}/I_{3C} = 0.045$ we inferred from our fit of the Capella observation corresponds to a temperature of $T_{DR} = 407 \pm 25$ eV, or $\log(T_{DR}) = 6.67 \pm 0.026$ K.

As mentioned in the Introduction, the emissivity weighted temperature is 504 eV or $\log(T_{DEM}) = 6.77$ MK (Gu 2009). This value is 0.1 dex higher than the value we infer from the dielectronic satellite intensity (cf. Fig. 1).

5. Discussion

Although we can determine the relative intensity of the $n = 4$ DR satellites to only 10%, we can use this ratio to infer a highly precise value of the electron temperature of $\log(T_{DR}) = 6.67 \pm 0.026$ K. This illustrates the high precision associated with the DR method of determining the electron temperature.

The accuracy of the temperature inferred by the DR method is reduced by several factors. One of these we have already mentioned, i.e., the fact that the location of the DR satellite lines is not well known from calculations. The constant shift applied to all DR lines is far from optimal, as it is likely that the error in the calculated wavelength varies from line to line. Measurements are clearly needed to determine the line positions.

The calculated line intensities should also be confirmed by measurement. Past measurements of DR satellite intensity have confirmed calculation to within 10 to 20%

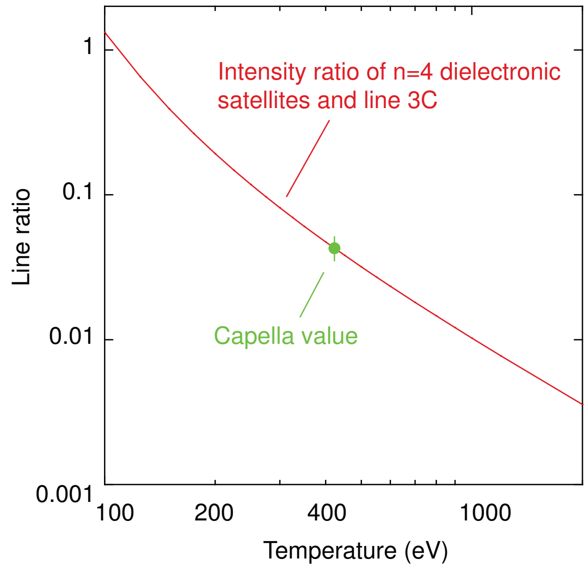

Figure 6. Predicted intensity ratio of the $n = 4$ DR satellites and line $3C$. The value inferred from fitting the Capella spectrum is indicated.

(Beiersdorfer et al. 1992; Savin et al. 2002). A 10% change in the satellite intensity, however, will not change the temperature by more than 0.03 dex.

The calculated intensity of line $3C$ is known to be fraught with uncertainty, as discussed in numerous studies (Beiersdorfer et al. 2004; Brown 2008). Electron-impact excitation cross section measurements (Brown et al. 2006) indicate that the calculated intensities of $3C$ are probably overestimated by 20%. If so, this would mean that the measured $I_{n=4}/I_{3C}$ ratio of 0.045 corresponds to a temperature much closer to that inferred from the DEM analysis. Again, experimental investigations are needed to address this issue.

Despite the uncertainty in the theoretical calculations used to infer T_{DR} the method we have used here to determine the temperature experienced by the Fe^{16+} ions in Capella is a very promising method for making temperature determinations. It complements the few existing methods, which all themselves have their own uncertainties due to the underlying calculated atomic data.

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References

Beiersdorfer, P. 1988, Ph.D. thesis, Princeton University
— 2003, ARA&A, 41, 343
Beiersdorfer, P., Bitter, M., von Goeler, S., & Hill, K. W. 2004, ApJ, 610, 616
Beiersdorfer, P., Brown, G. V., Drake, J. J., Gu, M.-F., Kahn, S. M., Lepson, J. K., Liedahl, D. A., Mauche, C. W., Savin, D. W., Utter, S. B., & Wargelin, B. J. 2000, Revista Mexicana Astronomía y Astrofísica, 9, 123

Beiersdorfer, P., Schneider, M. B., Bitter, M., & von Goeler, S. 1992, Rev. Sci. Instrum., 63, 5029
Bitter, M., Gu, M. F., Vainshtein, L. A., Beiersdorfer, P., Bertschinger, G., Marchuk, O., Bell, R., LeBlanc, B., Hill, K. W., Johnson, D., & Roquemore, L. 2003, Phys. Rev. Lett., 91, 265001
Bitter, M., Hill, K. W., Sauthoff, N. R., Efthimion, P. C., Merservey, E., Roney, W., von Goeler, S., Horton, R., Goldman, M., & Stodiek, W. 1979, Phys. Rev. Lett., 43, 129
Brown, G. V. 2008, Can. J. Phys., 86, 199
Brown, G. V., Beiersdorfer, P., Chen, H., Scofield, J. H., Boyce, K. R., Kelley, R. L., Kilbourne, C. A., Porter, F. S., Gu, M. F., Kahn, S. M., & Szymkowiak, A. E. 2006, Phys. Rev. Lett., 96, 253201
Bryans, P., Badnell, N. R., Gorczyca, T. W., Laming, J. M., Mitthumsiri, W., & Savin, D. W. 2006, ApJS, 167, 343
Bryans, P., Landi, E., & Savin, D. W. 2009, ApJ, 691, 1540
Desai, P., Brickhouse, N. S., Drake, J. J., Dupree, A. K., Edgar, R. J., Hoogerwerf, R., Kashyap, V., Wargelin, B. J., Smith, R. K., Huenemoerder, D. P., & Liedahl, D. A. 2005, ApJL, 625, L59
Dubau, J., & Volonté, S. 1980, Rep. Prog. Phys., 43, 199
Gabriel, A. H. 1972, MNRAS, 160, 99
Gu, M. F. 2008, Can. J. Phys., 86, 675
— 2009, ArXiv e-prints, 0905.0519
Gu, M.-F., Gupta, R., Peterson, J. R., Sako, M., & Kahn, S. M. 2006, ApJ, 649, 979
Mewe, R., Kaastra, J. S., Schrijver, C. J., van den Oord, G. H. J., & Alkemade, F. J. M. 1995, A&A, 296, 477
Savin, D. W., Behar, E., Kahn, S. M., Gwinner, G., Saghiri, A. A., Schmitt, M., Grieser, M., Repnow, R., Schwalm, D., Wolf, A., Bartsch, T., Müller, A., Schippers, S., Badnell, N. R., Chen, M. H., & Gorczyca, T. W. 2002, ApJS, 138, S337