Modeling the Ne IX Triplet Spectral Region of Capella with the *Chandra* and *XMM-Newton* Gratings

Jan-Uwe Ness[a], Nancy S. Brickhouse[b], Jeremy J. Drake[b], and David P. Huenemoerder[c]

[a]Hamburger Sternwarte, Gojenbergsweg 112, D-21029 Hamburg, Germany

[b]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

[c]MIT Center for Space Research, 70 Vassar Street, Cambridge, MA 02139

The grating instruments on board *Chandra* and *XMM-Newton* cover a variety of chances and limitations. While the LETGS offers the largest wavelength range with high sensitivity the MEG and the HEG have a much higher spectral resolution. A very popular method to analyze the grating spectra is the He-like triplets because they are density sensitive and a large temperature range is covered with different ions ranging from C V (~ 1 MK) up to Si XIII (~ 15 MK). However, only the LETGS wavelength range covers all these triplets simultaneously, while with the MEG the C V and the N VI triplets are not measurable and the HEG can only measure Si XIII, Mg XI, and Ne IX. The Ne IX triplet can be measured with all instrument, but with different success. The triplet line are in principle resolved by all grating, but severe blending with Fe XIX line can hamper the analysis in the hotter plasmas, e.g., active stars or flares. In those cases highest spectral resolution is highly desirable, and the LETGS is not sufficient to resolve all blending lines.

The most popular X-ray calibration target is Capella and it has been observed with all gratings with significant exposure times. We gathered together all available data of the HEG and MEG (155 ksec), the LETGS (219 ksec) for comparative analysis of the Ne IX triplet. 18 emission lines can be identified in the region around 13.5 Å with the HEG. Good agreement of these lines with predictions from a theoretical model constructed from the APEC line database using an emission measure distribution derived from Fe IX to Fe XXIV lines can be seen. These 18 emission lines cannot be identified in the LETGS spectrum, but we show that these spectra are consistent with the wavelengths and fluxes measured with the HEG.

1. Introduction

Our work focuses on the analysis of grating spectra. The gratings measuring on the new instruments are two transmission gratings on board *Chandra* and a reflection grating on board *XMM-Newton*. These are the High Energy Transmission Grating HETGS (consisting of a High Energy Grating (HEG) and a Medium Energy Grating (MEG) indicating peak sensitivities at different energies), the Low Energy Transmission Grating (LETGS), and the Reflection Grating Spectrometer (RGS). The LETGS covers the largest wavelength range (1-175 Å) with FWHM$\sim$ 0.06 Å, the RGS is most sensitive at higher energies (1-40 Å; FWHM$\sim$ 0.05 Å), and the HETGS gratings measure at the highest energies with the highest resolution (HEG 1-20 Å; FWHM$\sim$ 0.01 Å, MEG 1-30 Å; FWHM$\sim$ 0.015 Å). In Fig. 1 we show the effective areas for the different gratings for the wavelength range relevant for measuring Ne IX. It can be seen that the RGS has the best effective areas. However, the resolution in first dispersion order is the worst, but in second order it is comparable with the LETGS with still larger effective areas. Although the resolution of the HEG is the best it's effective area is by far the smallest such that significant exposure times are necessary. The best instrument for the Ne IX triplet is the MEG with high effective area and resolution, however, other possibly interesting wavelength ranges are not accessible with the MEG but with, e.g., the LETGS.

The Ne IX triplet is one of the He-like triplets that can be used for probing average plasma densities over all regions forming Ne IX. A recent application of the He-like triplets for measuring coronal densities using *Chandra* data is made by, e.g., [10]. The wavelength ranges provided by the gratings cover the C V triplet (only LETGS), N VI (LETGS and RGS), O VII (LETGS, RGS, and MEG), Ne IX, Mg XI, and Si XIII (all gratings). These triplets are formed at different tem-

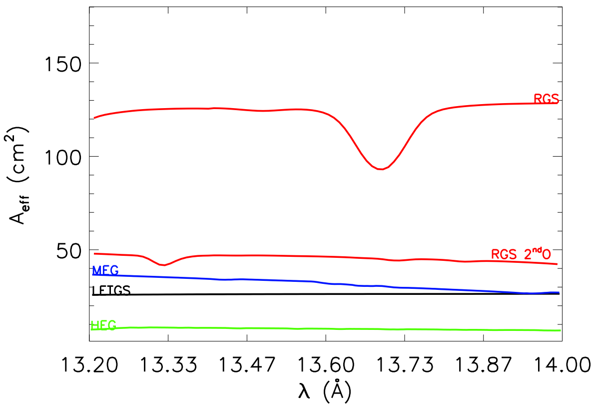

Figure 1. Effective areas in the wavelength range 13.2 to 14 Å for the different gratings.

peratures (C V at 1 MK up to Si XIII at 14 MK) and are sensitive in different density ranges (C V around 10^9 cm^{-3} up to Si XIII around 10^{14} cm^{-3}). Ne IX is formed at 4 MK and is density sensitive at moderate densities around 10^{10} cm^{-3}. With these settings the Ne IX triplet fills the gap between the low-pressure plasma measured with O VII and the high pressure plasma measured with Mg XI.

For the Sun the Ne IX triplet was used to measure densities during quiescence (low density limits) and during flares (higher densities expected). From the flare measurements suspicion occurred that the triplet is blended by hotter lines from Fe (e.g., [6,3]). From databases like APED ([14]) it can be seen that Fe XIX contributes most of this blending and analysing the details of the blending is the main objective of this paper.

The corona of the binary system Capella (G1III+G8 at a distance of 13 pc) is the brightest stellar X-ray source and has been used by all X-ray missions as a calibration target. The first detection of X-rays was reported by [2]. Further measurements revealed Capella to be a relatively steady X-ray source with no signatures of flares. The best coronal spectra of Capella were obtained with the *Einstein* Observatory FPCS and OGS ([15,7]), the *EXOSAT* transmission grating ([8], [5]), and EUVE ([4,13]). The *Chandra* grating spectra of Capella were analyzed by, e.g., [1,11,9], but none of these works include a detailed analysis of Ne IX.

2. Measurements

In the spectrum of Capella taken with the High Energy Grating (HEG) on board *Chandra* (Fig. 2a) 18 emission lines are identified in the range 13.6 - 13.85 Å. The triplet lines of Ne IX are severely blended mostly by Fe XIX. All these emission lines can also be identified in the (simultaneous) MEG measurement (Fig. 2b), but not in the LETGS and RGS spectra (Fig. 2c,d). The over-plotted spectrum in Fig. 2b-d is the HEG spectrum, scaled to the respective line widths and exposure times and a minimal line shift is allowed in order to decrease χ^2. The continuum is the HEG best-fit continuum, scaled to the different exposure times and effective areas. It can be seen that all four spectra are consistent with each other, such that understanding the HEG spectrum automatically means understanding the MEG, LETGS, and RGS spectra.

3. Interpretation

The measured HEG spectrum is compared with a prodiction from the Astrophysical Plasma Emission Code APEC ([14]) Version 1.2.[1]. We measured Fe line fluxes from ionization stages XV to XXIV in order to construct a consistent emission measure distribution (Fig. 3a). From Fig. 3b it can be seen that the prediction is quite good ($\chi^2 \sim 5$). Discrepancies are mainly due to incorrect placement of some lines around 13.7 Å and a too small flux predicted for the line at 13.78 Å which is possibly a Ni line such that an assumed under-abundance of Ni could fix that. The predicted fluxes for Ne are made under the assumption of low densities, and iterating the three Ne IX lines independently allows to test this assumption. It can be seen that the f-line and the i-line are both enhanced by the same factor 1.5, such that the assumption of low densities is obviously true. However, Ne seems to be overabundant, since all Ne lines are scaled higher in the best fit. The scaling of the resonance line is much weaker than that for f and i resulting in a higher G ratio indicating a peak at lower temperature which is not modeled with the emission measure distribution.

[1] Available at http://cxc.harvard.edu/atomdb

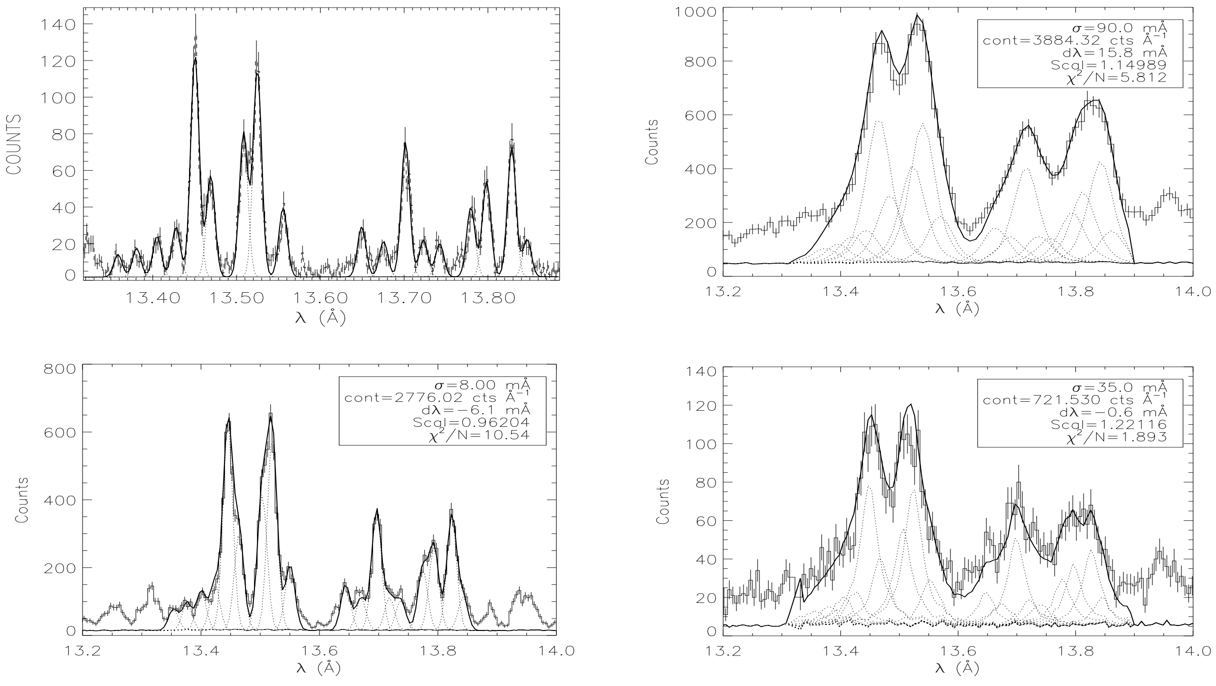

Figure 2. Wavelength range 13.2 – 14 Å of the Capella spectrum measured with the HEG (a; upper left), MEG (b; lower left), LETGS (c; upper right), and RGS (d; lower right). The HEG spectrum, scaled to the individual instrumentation, is over-plotted in (b)-(d).

4. Conclusions

From the analysis of four grating spectra with different spectral resolutions we found all spectra to be consistent with each other. Concentrating on the HEG spectrum therefore allows to draw conclusions on the other spectra, namely MEG, LEGS, and RGS. Modeling the HEG spectrum using a constructed emission measure distribution gives satisfactory results, such that the application of the APEC database is advisable for the lower-resolution spectra. However, small discrepancies are encountered, mainly arising from assumptions about the abundances, which can in principle be fixed.

From the direct measurement of the Ne IX lines we find a value for the density for Capella of $\log(n_e) = 11.61 \pm 0.1$ from an f/i ratio of 2.1 ± 0.3. From the APED model, however, we find an Fe XIX line at 13.554 Å which is not resolved even with the HEG. Believing the predicted flux for this line the low density limit can not be excluded. An interesting finding is that the measured G-ratio is not consistent with the emission measure distribution demanding more emission measure at lower temperatures than is found by the Fe lines (the low temperature part of our emission measure distribution is based on EUVE measurements). A possible explanation is that the Ne lines predominantly are emitted by the G1 star while the Fe lines used to construct the emission measure distribution are stronger from the G8 giant.

As to the LETGS and RGS data, we proved that the HEG data are consistent with data obtained for Capella with the other instruments, i.e., all understanding of the HEG spectrum implies that the LETGS and RGS spectra are consistent with these findings. From the Capella spectra we were not able to independently come out with the same results for the LETGS and RGS spectra as for the HEG spectrum. The construction of an emission measure distribution is more complicated because not all Fe lines are well enough resolved or strong enough to be detected above the background. A different approach is suggested by, e.g., [12], where the emission measure distribution is constructed by use of tem-

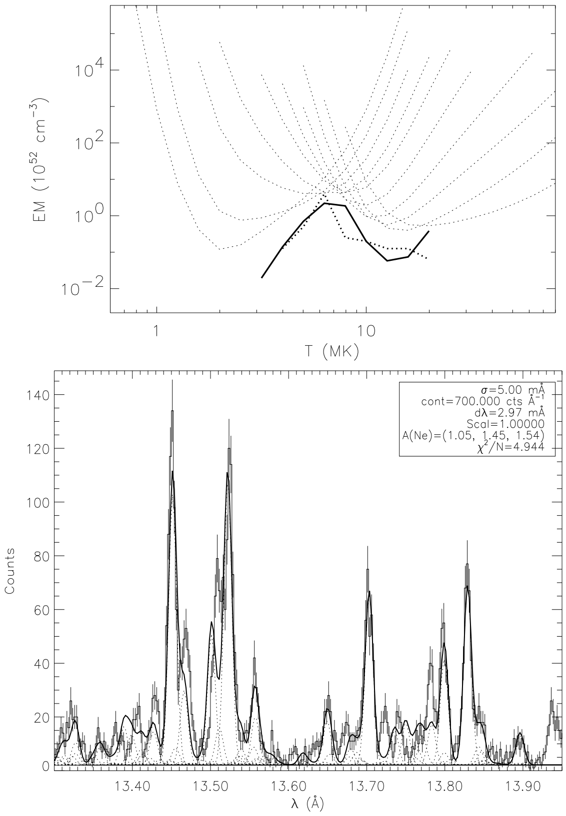

Figure 3. The emission measure distribution consistent with Fe lines in ionization stages XV to XXIV (a; upper panel) is used for predicting an HEG spectrum from the APEC database (b)

perature sensitive line ratios (e.g., Ly_α/He_α of six ions) for the LETGS. The DEM distribution is modeled by an approximation with Chebyshev polynomials on the one hand and with the help of a Gaussian distribution of magnetic loops on the other hand. Estimating the fluxes of the contaminating lines by scaling from an isolated Fe XIX line could be an approach that is independent of the emission measure distribution (when assuming the Fe XIX lines being formed all at the same temperature). Unfortunately the contamination by Fe XIX does not represent all blending of the i-line, because an Fe XXI line at 13.507 is also blending the intercombination line. Scaling this line is even more difficult, because no sufficiently isolated Fe XXI line detectable by the LETGS and RGS can be found. In addition the uncertainties in the data bases are too large for reliable line ratios for predictions of certain blending lines.

REFERENCES

1. Ayres, T. R., Brown, A., Osten, R. A., *et al.* 2001, ApJ, 549, 554
2. Catura, R.C., Acton, L.W., & Johnson, H.M. 1975, ApJL, 196, L47
3. Doyle, J.G. & Keenan, F.P. 1986, A&A, 157, 116
4. Dupree, A.K., Brickhouse, N.S., Doschek, G.A., *et al.* 1993, ApJL, 418, L41
5. Lemen, J.R., Mewe, R., Schrijver, C. J., *et al.* 1989, ApJ, 341, 474
6. McKenzie, D.L. 1985, ApJ, 296, 294
7. Mewe, R., Gronenschild, E.H.B.M., Westergaard, N.J., *et al.* 1982, ApJ, 260, 233
8. Mewe, R., Schrijver, C.J., Lemen, J.R., *et al.* 1986, Advances in Space Research, 6, 133
9. Ness, J.-U., Mewe, R., Schmitt, J.H.M.M., *et al.* 2001, A&A, 367, 282
10. Ness, J.-U., Schmitt, J.H.M.M., Burwitz, V., *et al.* 2002, A&A, 394, 911
11. Phillips, K. J. H., Mathioudakis, M., Huenemoerder, D. P., *et al.* 2001, MNRAS, 325, 1500
12. Schmitt, J.H.M.M. & Ness, J.-U. 2002, submitted to A&A
13. Schrijver, C.J., van den Oord, G.H.J., Mewe, R., *et al.* 1995, A&A, 302, 438
14. Smith, R.K., Brickhouse, N.S., Liedahl, D.A., & Raymond, J.C. 2001, ApJL, 556, L91
15. Vedder, P.W. & Canizares, C.R. 1983, ApJ, 270, 666

ACKNOWLEDGEMENTS

J.-U.N. acknowledges financial support from Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) under 50OR98010.
J.J. D. and N.S. B. were supported by NASA contract NAS8-39083 to SAO for the CXC and D.P. H. was supported by NASA through Smithsonian Astrophysical Observatory (SAO) contract SVI-61010 to the CXC.