Status of Line identifications in the Chandra LETG Spectrum of Procyon

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Abstract. We report on our ongoing efforts to produce a relatively complete set of X-ray emission lines present in the Low Energy Transmission Grating (LETG) spectra of Procyon. In addition to using recently reprocessed HRC-S/LETG spectra of Procyon, we use LETG spectra of Capella, along with recent Electron Bean Ion Trap (EBIT) laboratory data and new Flexible Atomic Code (FAC) calculations to identify the wealth of weaker lines present in the spectrum. Experimental measurements at the EBIT-I and EBIT-II facilities at Livermore of astrophysically abundant elements (Fe VII-Fe X, Lepson et al. 2002, Ar IX- Ar XVI, Lepson et al 2003, S VII- S XIV, Lepson et al 2004) and new FAC calculations of Mg and Ne (Gu, 2008 in press) provide an opportunity to identify many of the previously unassigned lines in Procyon (Raassen et al, 2002).

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MOTIVATION

Accurate line identification is paramount for the analysis of any high-resolution spectrum. Line lists relevant to spectra taken with the High Energy Transmission Grating (HETG) on Chandra in the 8-20 Å region are well-established thanks in part to dedicated laboratory studies. In contrast, the spectral models and line lists corresponding to the spectral emission recorded on the LETGS, i.e., the soft X-ray and extreme ultraviolet region between 25-170 Å is incomplete and not well understood. Given the multitude of possible spectral lines, including lines in second, third and higher orders, and their general weakness, it is not surprising that many lines observed with the LETGS in this region have either not been identified or their identity is uncertain. As a result, it is difficult to obtain reliable emission measure distributions for L-shell ions in this region, and that in turn makes it impossible to use these L-shell and M-shell lines as plasma diagnostics.

Accurate modeling of the X-ray solar emission has also been limited due to the deficiencies in the atomic data in the 50-150 Å regions. This region of the spectrum contains numerous weak blended lines of Fe and other astrophysical abundant elements like Si, S, Mg, and Ne, which may significantly contribute to raising the continuum.

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This lack of accurate and complete data has prompted us to embark on a comprehensive effort to produce a systematic identification of emission lines observed in the LETGS spectra of the coronae of cool stars, starting first with Procyon.
The Procyon data used in the analysis were observed using the LETG aboard Chandra and obtained from the Chandra Public data archive. The two observations (ObsID's 1461 and 63) have been reprocessed using CIAO version 4.0.1. The two observations were summed and the plus and minus orders were co-added and binned by a factor of 2 to get better signal to noise. Wavelength corrections were applied to the data and effective area files and response matrix files were generated using Sherpa threads. Higher orders were accounted for in the continuum and line fitting.
A targeted effort was also being made to measure the relevant emission of astrophysically abundant elements in this wavelength band in the laboratory at the Livermore. Spectroscopic measurements of atomic data have been taken on the Lawrence Livermore electron beam ion traps, EBIT-I and EBIT-II. These are particularly well suited for such investigations because they can be operated at the low voltages (100-1000 eV) necessary to produce the charge states investigated and measurements can be carried out at densities relevant to stellar coronae (Lepson et al, 2005a). Definitive line lists for many of the relevant ions including Fe VII-X, S VII-XIV and Ar IX-XVI have been established and analysis of many others including Si V-XII, Mg VI-X, and Fe XI-XVI are under way.
Additional line lists using the Flexible Atomic Code (FAC) (Gu, M. F. 2004), CHIANTI (Dere et al, 1997, Landi et al 2006) and Astrophysical Plasma Emission Database (APED) (Smith et al 2001) were used in identifying weaker, previously unknown lines. Wavelengths calculated using FAC are obtained by combining the configuration interaction and many body perturbation theory methods.

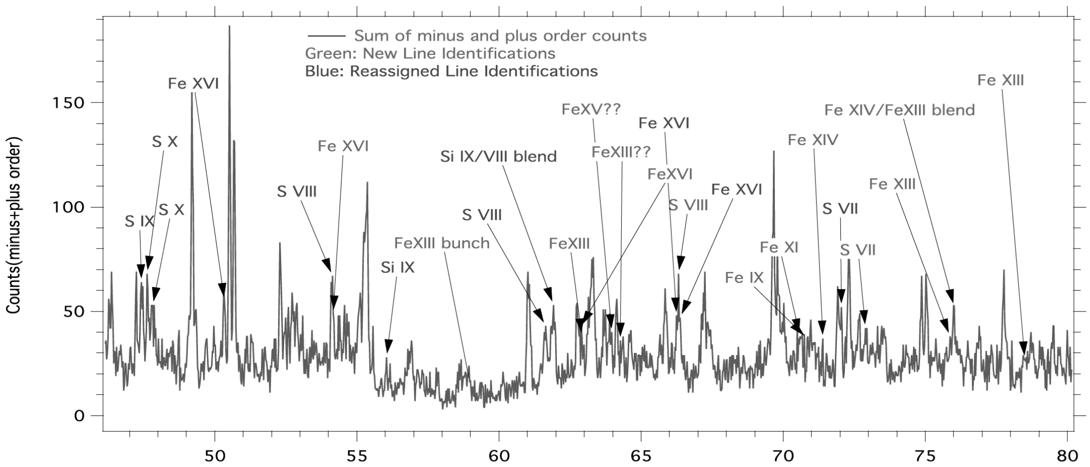

FIGURE 1: Co-added LETG spectra of Procyon (in red) between 48 -80 Å with previously unidentified lines (green) and reassigned lines (blue). We have reassigned some of the lines previously identified by Raasen, et al (2002). Two observations of Procyon were summed and the plus and minus orders were co-added and binned by 2 to get better signal to noise. Several new tentative identifications of Fe IX-XIV have been made for the first time and many lines have been reassigned to other ions. Laboratory measurements were carried out at densities relevant to stellar coronae and at voltages necessary to produce the L and M shell spectra of these astrophysically abundant elements. Note that some of these identifications are preliminary, as the laboratory data are not published yet.

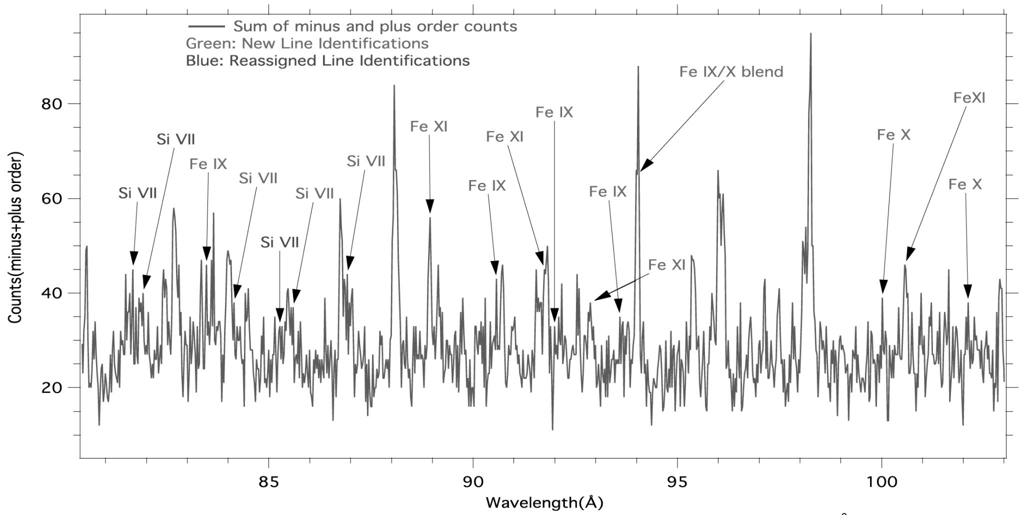

FIGURE 2: Same as above except that the spectrum shown is between 80-102 Å. For this part of the spectrum the Fe IX-XI line assignments are new.

DISCUSSION AND CONCLUSIONS

Figures 1 and 2 show the co-added LETG Procyon spectra (red) between 45-102 Å with previously unidentified lines (green) and reassigned line identifications (blue). We have employed a systematic approach for identifying lines. Once one line of a give ion has been identified, we locate others from the same ion based on based on laboratory wavelengths and intensities and test candidate features against such criteria as reasonableness of the relative line intensity and possibility of blending with lines from other ions. We also compared these lines with the observed spectra of Capella and Alpha Cen to get a better handle on the wavelength calibration of the LETG spectrum. We note that from the wealth of possible lines, there is no real mechanism to discern which of the lines are relevant to the astrophysical spectrum at hand. As theoretical wavelength calculations are accurate only up to a few percent, even with a fairly good spectral model we need accurate laboratory measurements to assign the right transitions and flux to the correct emission lines and then benchmark the spectral models with observed spectra. For example we note that in the 48- 80 Å band there are many S and Si lines that we believe were previously misidentified. For example, detailed laboratory measurements and new wavelength calculations suggest that the line at 73.03 Å that was previously identified as a Mg IX line is probably a S VII 3 -> 2 line. Similarly the line at 72.89 Å which did not have an identification, may correspond to the SVII 3->2 magnetic quadrupole transition line. These lines were first identified in the laboratory (Lepson, 2005b).

In the 80 -102 Å range we note that there are several possible newly identified Si VII lines that had been predicted by calculations and have now also been measured in the laboratory (Lepson et al, in prep). Similarly there are a multitude of weak Fe VIII and Fe IX lines that have been measured in the laboratory and predicted by the FAC calculation that we believe can be identified in the Procyon spectrum.

The next stage in this systematic line identification process is to generate an Emission Measure Distribution (EMD) using strong emission lines and some of these newly

identified lines and to then compare the predicted spectra with the observed spectra to confirm that the identifications are indeed correct. We are now in the process of generating an EMD model based on these new line measurements. We then plan to publish a systematic line list of the emission lines observed in the LETG spectra of Procyon. We are hopeful that we will be able to similarly analyze the spectra of other cool stars such as Capella, which will significantly contribute to our understanding of coronal emission in part of the X-ray spectra.
Incorporation of these critically evaluated data into spectral codes and databases will be paramount for the accurate analysis of high-resolution X-ray spectra.

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REFERENCES

1. Gu, M. F. 2008, Can. J. Phys. 86, 191
2. Gu M. F. 2004, 14th APS Topical Conference on Atomic Processes in Plasmas, AIP Proceedings, vol 730
3. Landi E., Del Zanna G., Young P. R, Dere, K.P., Mason, H. E. & Landini, M. 2006, ApJ (Suppl.)162, 261
4. Lepson, J. K. Beiersdorfer, P., 2005a , Phys Scripta TRO,62
5. Lepson, J. K. Beiersdorfer, P., Behar, E., & Kahn, S.H 2003, ApJ 590, 604
6. Lepson, J. K. Beiersdorfer, P., Brown, G. V. Liedahl, D. A. Utter, S. B. Brickhouse, N. S., Dupree, A. K. Kaastra, J.S., Mewe, R., & Kahn, S.M. 2002, ApJ 578, 648
7. Lepson, J. K. Beiersdorfer, P., Behar, E., & Kahn, S.M. 2005a, ApJ 625, 1045
8. Lepson, J.K., Beiersdorfer, P., Behar, E., & Kahn, S.M. 2005b, NIMB 235, 131
9. Lepson, J.K., Beiersdorfer, P., Bitter, M.., & Kahn, S.M. 2008, Can. J. Phys. 86, 175
10. Lepson, J.K., Beiersdorfer, (in prep)
11. Liang, G. Y. and Zhao, G. 2008, Mon. Not R. Astron. Soc., 384, 489
12. Raasen, A.J.J, Mewe, R., Audard, M., Gudel, M.,Kaastra, J. S. van der Meer, R.L.J., Foley, C.R., and Ness, J.U. 2002, A&A, 389, 238
13. Smith, R.K., Brickhouse, N. S. Liedahl, D.A., and Raymond, J.C., 2001, ApJ, 556, L91