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Chandra and the Emission Line Project

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Abstract. Calibration data obtained for the Chandra High Energy Transmission Grating and the Low Energy Transmission Grating Spectrometers are allowing us to test plasma spectral models against bright coronal sources with a range of electron temperatures. The three Emission Line Project targets — Capella, Procyon, and HR 1099 — are bright, well-studied X-ray and EUV emitters. The goals of the Emission Line Project are to determine and verify accurate and robust diagnostics; to identify and prioritize problems in fundamental spectroscopy; and to accelerate the improvement of the atomic database needed for modeling.

1. Introduction

The Emission Line Project (ELP) is a collaborative effort, organized by the Chandra X-ray Observatory Center, to improve the plasma spectral models used to analyze and fit X-ray spectral observations. During the first phase of the Emission Line Project we are analyzing the high quality spectra of three stellar coronal targets that are being obtained for the purposes of calibrating the Chandra transmission gratings. For select ELP observations by Chandra, overlapping measurements have been obtained by the Extreme Ultraviolet Explorer (EUVE), the HST Space Telescope Imaging Spectrograph, Beppo-SAX, and the NSF's Very Large Array radio telescope. Broadening the wavelength coverage provides additional important tests for the atomic models.

Stellar coronal spectra are rich in emission lines from high ionization states of cosmically abundant elements. The line source calibration targets — Procyon, Capella, and HR 1099 — were specially chosen because they exhibit emission corresponding to a wide range of plasma temperatures, dominated by $T_e \sim 2\times10^6$, 6×10^6, and 2×10^7 K, respectively (Figure 1). The three sources emit over a continuous range of temperatures, such that most elements and ionization states accessible to the Chandra gratings will be exhibited in these spectra. Current spectral models of collisionally ionized plasmas will be tested against the observations to assess the problem areas and to help set priorities for fundamental theoretical and experimental spectroscopy.

2. Assumptions of Collisional Plasma Emission Models

Given the electron temperature T_e, electron density N_e, and elemental abundances, models of collisionally ionized plasma calculate the power radiated from continuum and line emission processes. A number of assumptions are generally made, particularly that the plasma is optically thin and non-relativistic. Continuum emission from bremsstrahlung, radiative recombination, and 2-photon processes are included. Collisional impact cross sections are integrated over Maxwellian velocity distributions, and it is assumed that the radiation is not affected by electric and magnetic fields. Photoionization and photoexcitation are generally not included.

Often the emission is assumed to be time-independent; however, non-equilibrium ionization models may be constructed using a physical model. For emission lines which may be populated by recombination cascades, it is important to take the ionization balance into account, and thus one must link the ionization and level population calculations. Another common assumption of the "coronal approximation" is that the electron density is low. In that case the population of energy levels is dominated by transitions from the ground state. Generally today, the level populations are calculated using a rate matrix to account for

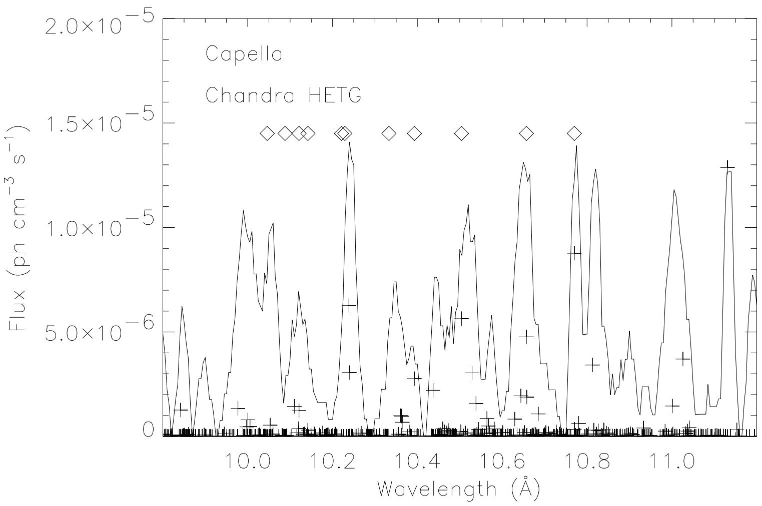

Figure 1. Emission measure distributions for Procyon (Drake, Laming, & Widing 1995), Capella (Dupree et al. 1993; Brickhouse 1996), and HR 1099 (Griffiths & Jordan 1998) compared with that of the quiescent Sun (Raymond & Doyle 1981). Procyon is shown as the solid line, Capella is dash-dotted, HR 1099 is dashed, and the Sun is dotted. The spectral resolution of the EUVE spectrometers allows the measurement of isolated emission lines which have been used to construct the stellar emission measure distributions. ASCA spectra set limits on the highest temperatures in the plasma.

all transitions, such that density effects on the level populations can be properly treated (up to densities $\sim 10^{14}$ cm^{-3}). Density effects on the ionization balance are still treated crudely, when treated at all.

The physical assumptions of ionization equilibrium and negligible optical depth appear to be good to a first order approximation. Since the coronal emission is weighted by N_e^2 for collisionally excited lines, the observed spectrum (time-averaged over several hours to several days) is naturally biased toward plasma with the shortest equilibration times. The good agreement among lines emitted from the same ionization state with the theoretical predictions, and particularly for branching ratios, can place tight constraints on the optical depths involved. To observe the breakdown of these assumptions, if applicable, will require high spectral resolution, such as provided by the XMM Reflection Grating Spectrometer (RGS) and Chandra Low Energy Transmission Gratings (LETG) and High Energy Transmission Gratings (HETG).

It is interesting to note that most of the simplifying assumptions break down somewhere in the solar corona! Measured particle distributions in the solar wind are non-Maxwellian (Olgivie & Scudder 1978), the strongest X-ray line in the quiescent corona, Fe XVII λ15.013, appears optically thick in active region loops (Schmelz et al. 1997), and the He II λ303.8 is influenced by recombination following photoionization of He II by the EUV corona (Athay 1988). Nevertheless, the assumptions work well to first order for most emission, thus allowing us to proceed.

In the absence of a significant radiation field, the line intensity I_{line} is the product of the population of the upper level N_k and the atomic transition probability A_{kj} from level k to j.

$$I_{line} = N_k A_{kj} \tag{1}$$

For a two-level atom collisions excite the level and thus I_{line} is proportional to the collisional excitation rate C_{jk} from the lower level j.

$$I_{line} = N_j N_e C_{jk} \tag{2}$$

More generally, the level populations are calculated, such that

$$I_{line} = \frac{1}{4\pi R^2} \varepsilon_{At} EM \tag{3}$$

where ε_{At} is the atomic emissivity, and EM is the emission measure

$$EM(\Delta T_e) = \int_{V(\Delta T_e)} N_e N_H dV \tag{4}$$

In principle, if the plasma is isothermal and isochoric, line ratio diagnostics provide the cleanest measurements of the physical conditions of the emitting region. In practice the astrophysical plasma is neither, and one must construct multi-component models. A high quality X-ray spectrum (defined as having sufficient bandpass, spectral resolution, signal-to-noise, and calibration) provides a wealth of information to infer the distribution of temperature and possibly density. Emission measure distributions are typically constructed by an inversion of Equation 3, such that a good fit is provided to the spectrum, either globally or to specified emission lines.

The temperatures, densities, emission measures, and abundances derived from such methods are subject to numerous uncertainties beyond the statistical errors associated with the observations, including instrument calibration, line blending, the atomic data, and the simplifying assumptions themselves. The ASCA spectrum of Capella could not be fit by the standard models, and eventually required the examination of all of these issues. The biggest improvement in the fit came with the addition of emission lines from $n > 5$ for Fe XVII to XIX, which had not previously been calculated (Brickhouse et al. 2000; D. A. Liedahl & N. S. Brickhouse 2000, in preparation).

3. Stellar Coronae as Tests of Models

Questions raised over the past several years about the validity of results from moderately resolved spectra from ASCA and EUVE, such as the elemental abundances of elliptical galaxies (Arimoto et al. 1997) and of stellar coronae (Jordan et al. 1998) have led many of us to the conclusion that the models need to be tested and validated; however, given the number of assumptions upon which the spectral models are based, and our limited understanding of stellar coronae, how can we be so confident that the ELP data will provide useful benchmarks?

Before answering that question it is important to emphasize that astrophysical spectra are no substitute for laboratory atomic physics experiments and well calibrated spectroscopic measurements under controlled conditions, and we fully support efforts such as the ones reported in this proceedings; however, the numbers of atomic rates for potentially important emission lines far exceed any conceivable laboratory resources. Moreover, the wide range of temperatures and densities observed in stellar coronae include conditions which are difficult to replicate under laboratory conditions. Thus, high quality astrophysical spectra provide a complementary data set for assessing the quality of the spectral models.

The answer, then, to the question of how useful the ELP data are as benchmarks, is twofold. (1) We begin with the underlying premise that we understand the emission processes in these sources reasonably well. These sources have been well observed with ASCA and EUVE, such that we do not expect gross departures from equilibrium. Since the emission from the strong collisionally excited lines is naturally weighted toward N_e^2, thermalization and equilibration are most likely to apply for the emission lines that we are most able to observe. Furthermore, EUV branching ratios place tight constraints on the optical depth effects for Capella (Brickhouse, Raymond, & Smith 1995). (2) The breakdown of the classical assumptions would have observable consequences. The Chandra observations (and other coordinated measurements) provide spectra of such high quality that consistency checks are built in. The broad bandpass provides multiple diagnostic lines, such that issues resulting from line blends can be identified. Multiple ionization states of different elements provide a cross-check on the ionization balance models, which underlie the derived shape of the emission measure distributions. While a few lines may have optical depths of order unity, these will easily be identified by line ratio measurements.

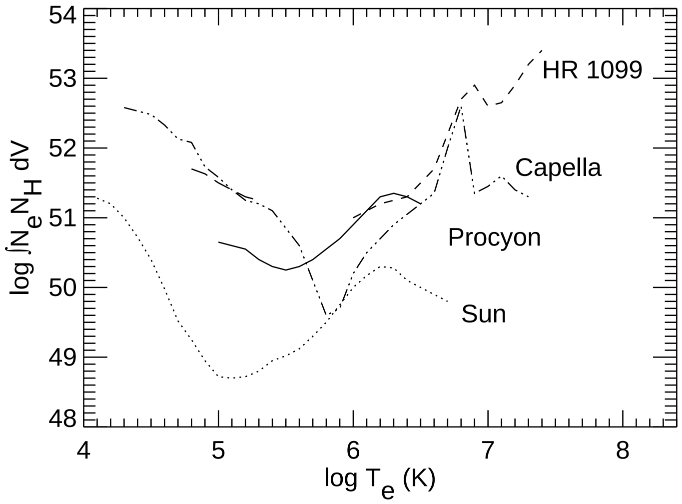

Figure 2. Region of the observed Chandra HETG spectrum of Capella compared with model emission lines, showing the "missing lines." The smoothed spectrum shown is the Observation Identification 1099, Medium Energy Grating spectrum, minus first order. Plus symbols mark the observed lines calculated using an APEC model (Smith et al. 1999) scaled to the strongest line shown, while diamonds mark the wavelengths of measured Fe XVII lines (Brown et al. 1998) from energy levels with principal quantum numbers $n > 5$. Such lines were estimated to account for nearly 30% of the flux in the waveband between 10 and 11 Å in the ASCA spectrum of Capella (Brickhouse et al. 2000).

4. Preliminary Emission Line Project Data Analysis

The first light papers for the LETG (Brinkman et al. 2000) and for the HETG (C. Canizares et al., in preparation) support the argument above that these data are useful for testing the plasma spectral emission models. Since the instrument calibration and data reduction and processing are still at an early stage, the results reported here are preliminary, and are intended to give an understanding of how the data can be used. We present two examples:

- *Optical depth.* Fe XVII λ15.014 is the strongest emission line in the X-ray spectrum of Capella. By comparing its ratio with the optically thin Fe XVII λ15.265 one can test the optical depth of λ15.014, and thus place constraints on the degree of resonance scattering in the atmosphere. The Capella line ratio appears to be consistent with the assumption of negligible net optical depth (Brinkman et al. 2000; C. Canizares et al., in preparation). While the theoretical predictions tend to be somewhat higher than the laboratory measurements (see Brown et al. 1998), and the jury is still somewhat out on the best data, the Capella measurements provide additional support for the idea that we can neglect optical depth effects in our analysis of these spectra.

- *The identification of spectral regions with "missing lines."* Figure 2 shows a small section of the Capella spectrum, which had presented modeling difficulties (Brickhouse et al. 2000) for the ASCA analysis. We can clearly identify lines of Fe XVII based on the work of Brown et al. (1998), which are not yet included in the plasma spectral models.

Other tests are planned once the data are felt to be reliable. Collisional ionization equilibrium can be tested by comparing $\Delta n = 0$ transitions in the EUV to $\Delta n = 1$ transitions in the X-ray, exploiting the broad bandpass of the LETG. For example, the ratio of the Fe XVIII λ93.92 intensity to the Fe XVIII λ14.22 intensity is temperature-sensitive due primarily to the Boltzmann factor in the collision rate. By comparing the line ratio temperature to the temperature derived from the ratios among adjacent ions, one tests the local temperature relative to the degree of ionization. Of course, the underlying collision strengths and the ionization balance models themselves are also in need of testing for these lines. Ultimately the comparison among several lines from the same ion will help to validate the collision strengths, while comparing lines from different elements will be useful in testing the ionization balance.

5. Conclusions

Our understanding of the coronal spectrum is sufficiently mature that the Emission Line Project will help to identify and solve problems with the plasma spectral emission models. Problems with the models affect both high spectral resolution data, for which the primary analysis will involve the measurement of specific diagnostic lines, and low to moderate resolution data, for which global spectral models are needed. This project has widespread implications for other types of astrophysical sources, including, galaxies, supernova remnants, clusters of galaxies, and stellar coronae.

The Chandra calibration data for Procyon, Capella, and HR 1099 have now been obtained, with many of the data sets available through the Chandra public archives. Preliminary results support the usefulness of these data for testing models. Meanwhile, calibration and processing improvements continue. The ELP website (http://asc.harvard.edu/elp/ELP.html) gives information on the distribution, collection, and organization of data as well as links to useful software and plasma models. We are in the process of producing an emission line catalog consisting of measured wavelengths, fluxes, line widths, and identifications.

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