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# CORONAL PHYSICS AND THE CHANDRA EMISSION LINE PROJECT

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RESUMEN

Con el lanzamiento del observatorio de rayos-X Chandra se ha iniciado la espectroscopía de alta resolución en rayos-X de las fuentes cósmicas. Observaciones profundas de tres fuentes estelares con emisión coronal – Capela, Proción y HR 1099 – están dando no sólo datos de calibración invaluables sino también medios de comparación para los modelos de emisión de plasmas. Estos modelos, que han sido cuestionados por los problemas para entender los datos de baja y moderada resolución de ASCA y en el EUVE, son necesarios para interpretar los datos de coronas estelares, galaxias y cúmulos de galaxias, remanentes de supernova y otras fuentes. El Proyecto de Líneas de Emisión es una colaboración para mejorar los modelos y su primera fase es la comparación de los modelos con los espectros observados de Capela, Proción y HR 1099. Las metas de la comparación son (1) determinar y verificar la precisión y fortaleza de los diagnósticos y (2) identificar y priorizar los elementos de la espectroscopía que requieran más trabajo tanto teórico como de laboratorio. Uno de los puntos críticos de esta labor es entender hasta que punto se pueden aplicar las hipótesis simplificadoras comunmente usadas (equilibrio coronal, baja opacidad). Discutimos, en este contexto, los avances más recientes en el entendimiento de las coronas estelares.

ABSTRACT

With the launch of the Chandra X-ray Observatory, high resolution X-ray spectroscopy of cosmic sources has begun. Early, deep observations of three stellar coronal sources — Capella, Procyon, and HR 1099 —are providing not only invaluable calibration data, but also benchmarks for plasma spectral models. These models are needed to interpret data from stellar coronae, galaxies and clusters of galaxies, supernova remnants and other astrophysical sources. They have been called into question in recent years as problems with understanding low resolution ASCA and moderate resolution EUVE data have arisen. The Emission Line Project is a collaborative effort to improve the models, with Phase 1 being the comparison of models with observed spectra of Capella, Procyon, and HR 1099. Goals of these comparisons are (1) to determine and verify accurate and robust diagnostics and (2) to identify and prioritize issues in fundamental spectroscopy which will require further theoretical and/or laboratory work. A critical issue in exploiting the coronal data for these purposes is to understand the extent to which common simplifying assumptions (coronal equilibrium, negligible optical depth) apply. We will discuss recent advances in our understanding of stellar coronae in this context.

*Key Words:* **ATOMIC DATA — ATOMIC PROCESSES — STARS: CORONAE — STARS: INDIVIDUAL (CAPELLA, HR 1099, PROCYON) — STARS: LATE-TYPE**

## 1. INTRODUCTION

The challenge of this paper is to argue convincingly along two seemingly contradictory lines: (1) that we understand stellar coronae so well that when our models fail to fit specific features in the spectrum, we should dedicate limited resources in atomic physics and spectroscopy toward re-examining the models; and (2) that we understand stellar coronae so poorly that high resolution X-ray studies of their properties will lead to rich and exciting new plasma astrophysics. The way out of this apparent contradiction lies in the nature of the modeling assumptions and of the research questions being addressed.

Under standard assumptions for a hot, optically thin, collisionally dominated plasma, the models predict the high temperature spectrum in equilibrium, given a set of values for density, temperature, and elemental abundances. Comparison with appropriate observations allows, in principle, the determination of these *physical parameters* which in turn can be considered in relation to other fundamental parameters of the system (e.g. rotation, stellar type); however, to gain a better understanding of the *physical processes* (e. g. coronal heating mechanisms, stellar dynamo, the development of magnetic structures) requires more detailed information.

To first order, the dominant temperature of the plasma is known from the ionization state through the strong line emission and/or from the broadband shape of the spectrum as determined by the bremsstrahlung continuum. Thus a great deal of progress has been made in understanding collisionally ionized plasmas using low spectral resolution instruments. For example, in stellar coronae the correlation between X-ray luminosity and temperature has been established. To make further progress requires that weaker features in the spectrum be used in the analysis, and that the physical parameters be determined under a variety of conditions (good sample of stars with different properties, including weak X-ray emitters, eclipses, flares and quiescence). Unfortunately, spectral analysis of stellar coronae and other collisionally ionized sources at moderate resolution over the past several years has led to questionable results, such as the elemental abundances of elliptical galaxies (Arimoto et al. 1997) and of stellar coronae (Jordan et al. 1998). Of primary concern is the use of plasma spectral models with inadequate atomic data.

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. The first phase of the Emission Line Project is to use the high quality spectra of three stellar coronal targets (Procyon, Capella, and HR 1099) 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 important tests for the atomic models.

The line source calibration targets were specially chosen because they exhibit emission corresponding to a wide range of plasma temperatures from $10^6$ to $3 \times 10^7$ K. The stellar spectra are rich in emission lines from high ionization states of cosmically abundant elements. 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 CODES

Given the electron temperature $T_e$, electron density $N_e$, and elemental abundances, collisionally ionized plasma models 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 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 will require higher 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 $\lambda$15.013, appears optically thick in active region loops (Schmelz et al. 1997), and the He II $\lambda$303.8 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 $\varepsilon_{At}$ 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 (Fig. 1) 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 CORONAL PHYSICS

Spectral studies of stellar coronae benefit tremendously from solar EUV and X-ray studies. The synergism of the so-called "solar-stellar connection" derives from the rich, detailed phenomenology of the solar corona and the wide parameter space available from studying a variety of systems with different physical parameters, levels of magnetic activity, or mass-loss rates.

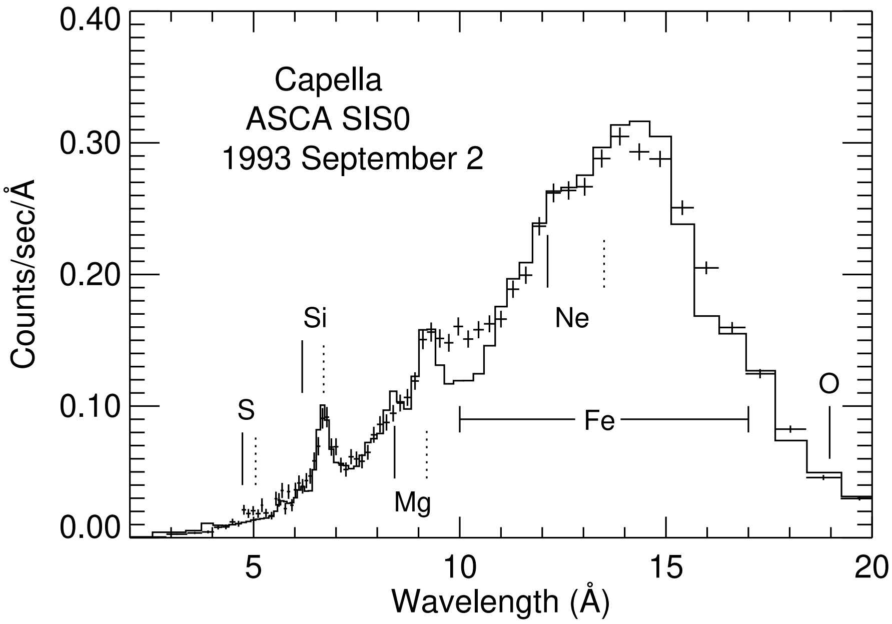


Figure 1. ASCA spectrum of Capella, showing a fitting problem around 1.2 keV. This problem was identified as due to lines missing in the plasma spectral models (Brickhouse et al. 2000).

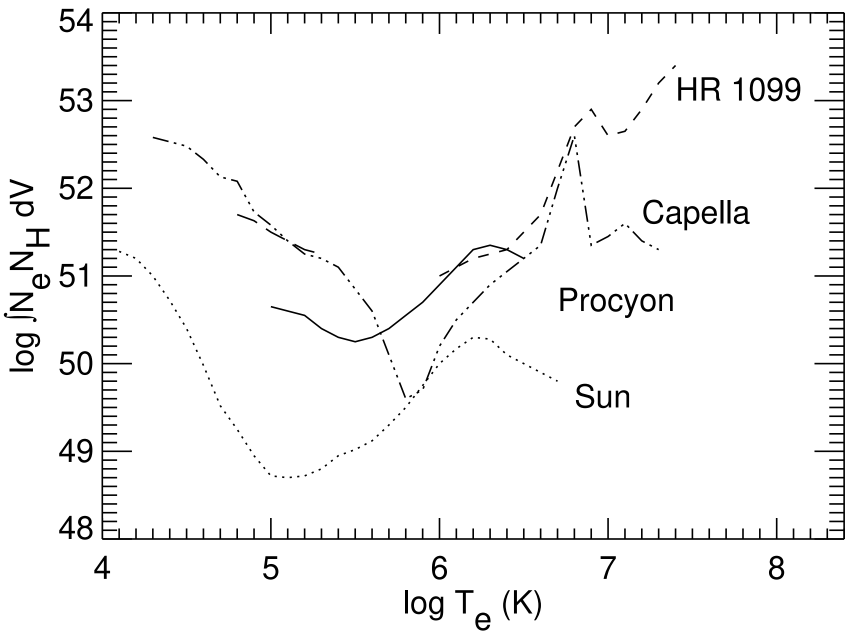


Figure 2. Emission Measure Distributions for Procyon, Capella, and HR 1099 compared with that of the Sun. Procyon is shown as the solid line, Capella is dash-dotted, HR 1099 is dashed, and the Sun is dotted. References are given in the text.

While many past missions have contributed to our general knowledge of the physical conditions, the instruments have primarily had low to moderate spectral resolution (Beppo-SAX, ASCA, ROSAT PSPC, XTE, Einstein IPC, Einstein SSS). A few missions with higher spectral resolution (Einstein FPCS, Einstein OGS, EXOSAT, EUVE) have been limited in the numbers of observations obtained or in the instrument sensitivity.

Since the launches of EUVE in 1992 and ASCA in 1993, studies of active cool stars have begun to show that coronal structure and abundance patterns are not always solar-like. The hotter coronae, known from earlier work, may not be scaled-up versions of the solar corona. The new results suggest questions for further work, much of which is beginning with Chandra grating observations.

### 3.1. *Emission Measure Distribution*

The spectral resolution of the EUVE spectrometers allows the measurement of isolated emission lines which can be used to construct the emission measure distribution. In conjunction with limits set by ASCA on the highest temperatures, the full coronal temperature range is accessible. Figure 2 compares the emission measure distributions derived from EUVE for Procyon (Drake, Laming, & Widing 1995), Capella (Dupree et al. 1993; Brickhouse 1996), and HR 1099 (Griffiths & Jordan 1998) to that of the quiescent solar corona (Raymond & Doyle 1981).

While the Procyon emission measure distribution appears similar in shape to that of the Sun with higher luminosity, Capella and HR 1099 are qualitatively different, in addition to being more luminous. Capella, in particular, shows a remarkably narrow feature at $6 \times 10^6$ K. Brickhouse, Raymond, & Smith (1995) have shown that the ionization balance models around Ne-like Fe are so uncertain as to dominate the uncertainties in deriving the shape of the emission measure distribution for Capella. Nevertheless, the feature cannot be made to disappear. Consistency checks on the shapes of the emission measure distribution using other sets of emission lines as well as increased accuracy in the ionization balance models are needed.

The physical implications of such a feature are not clear. Quasi-static magnetic loop models, assuming confined plasma in energy balance, can achieve steeply increasing emission measure by allowing the loop cross sections to expand. Models of Capella seem unrealistic, however, requiring large expansion factors. Not only are expanding magnetic loops not observed in the solar corona, but they would also seem to be rather unstable given the rapid rotation of the stars.

### 3.2. *Electron Density*

EUVE line intensity ratios also provide measurements of the electron density. For Procyon $N_e = 5 \times 10^9$ cm$^{-3}$ at $T_e \sim 2 \times 10^6$ K, similar in pressure to that of solar active regions (Schmitt, Haisch, & Drake 1994). The densities derived for Capella and HR 1099 may be as high as $\sim 10^{12}$ cm$^{-3}$ (Dupree et al. 1993; Brickhouse 1996; Griffiths & Jordan 1998); however, there are inconsistent results from different line ratios, and the signals of the density-sensitive lines are relatively weak. Other systems, notably the contact binary 44$\iota$ Boo, show better evidence for high density, as shown in Figure 3 (Brickhouse & Dupree 1998). Thus it seems that at least some stellar coronae may have magnetic pressures four to five orders of magnitude higher than those in the solar corona. Magnetic field strengths of hundreds of gauss are required, again far exceeding the values in the solar corona.

Emission measures and densities together can tightly constrain the sizes of applicable model loops. Further evidence for small loops has recently been produced the eclipse of a flare on Algol (Schmitt & Favata 1999). Confirmation of electron densities using X-ray and EUV diagnostics from Chandra and XMM will soon confirm (or not) the EUVE results.

### 3.3. *Abundances*

Coronal abundances feature in every interpretation of EUV and X-ray observations of late-type stellar coronae to some extent because observed emission line fluxes are proportional to the parent element abundance. The assumed coronal composition is an essential ingredient in determining emission measures, radiative cooling and hence for investigating the coronal energy balance and sources of coronal heating. An outstanding problem in solar physics is that the coronal composition differs from that of the underlying photosphere—elements

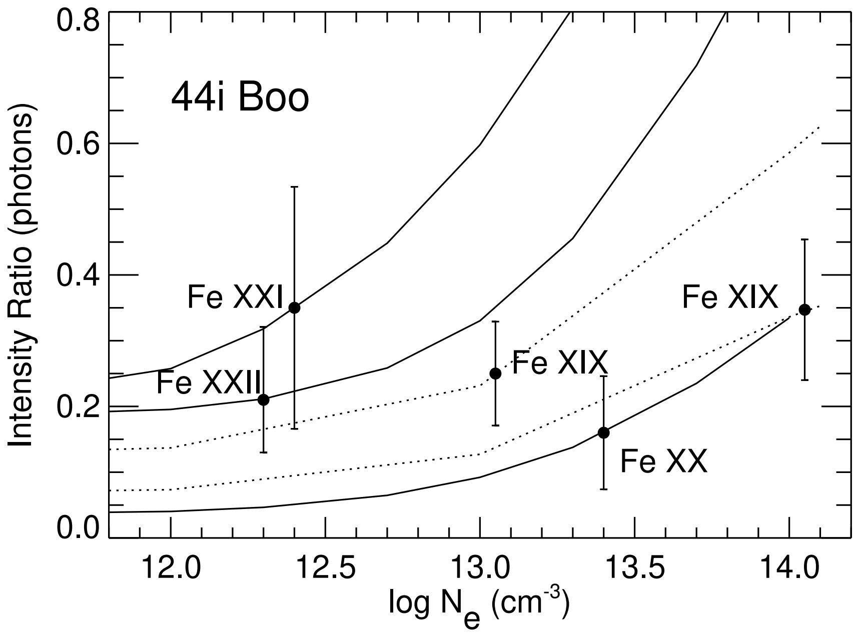


Figure 3. $N_e$ derived from line ratio diagnostics. The atomic models for Fe XX, XXI, and XXII (*solid curves*) are taken from Brickhouse, Raymond & Smith (1995). The line ratio models for Fe XIX (*dotted*) are from D. A. Liedahl (1996, private communication). The line ratios shown are: Fe XIX $\lambda$ 91.02/($\lambda$ 101.55 + $\lambda$ 109.97 + $\lambda$ 111.70) (upper); Fe XIX $\lambda$ 91.02/($\lambda$ 108.37 + $\lambda$ 120.00) (lower); Fe XX $\lambda$ 110.63/($\lambda$ 121.83 + $\lambda$ 118.66); Fe XXI $\lambda$ 102.22/$\lambda$ 128.73; and, Fe XXII $\lambda$ 114.41/$\lambda$ 117.17. The observed line ratios are plotted on the theoretical curves with 1$\sigma$ error bars representing the combined observational errors.

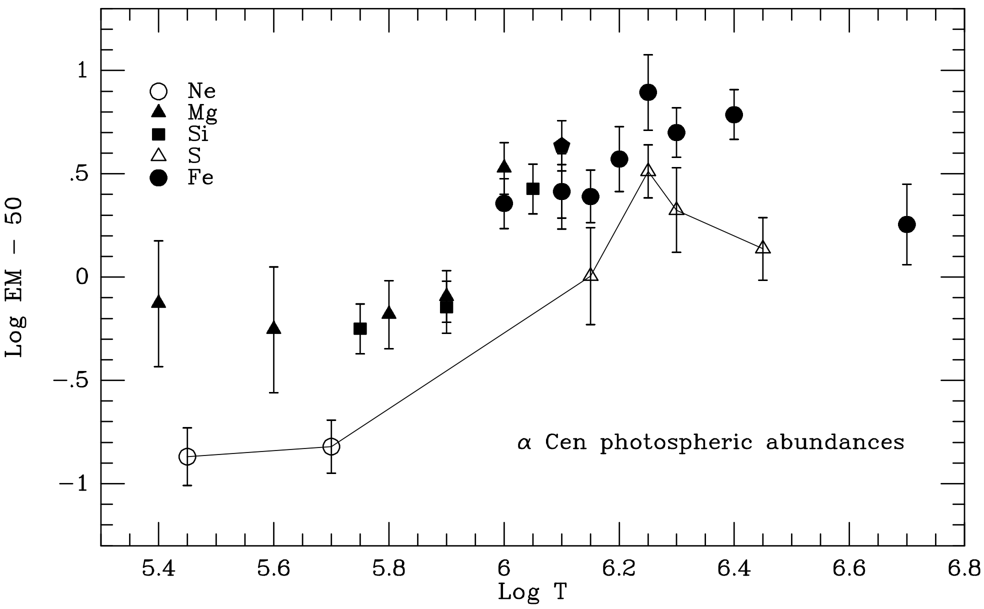


Figure 4. The emission measures as a function of temperature derived using $\alpha$ Cen photospheric abundances from individual ions observed in the *EUVE* spectra of $\alpha$ Cen. Low first ionization potential (FIP) elements are indicated by solid symbols; high FIP elements are indicated by open symbols. The emission measures for the low FIP elements lie clearly above those for high FIP elements by a factor of 2 or so. This indicates that the assumed photospheric abundances are inappropriate for the coronae of $\alpha$ Cen AB, and that the low FIP elements are relatively enhanced (Drake et al. 1997). A similar "FIP Effect" is observed in the solar corona.

with first ionization potentials (FIPs) $\leq 10$ eV are *overabundant by average factors of 3-4* in the corona (Meyer 1985). Recent studies of stellar coronal compositions with *EUVE*, *ASCA* and *SAX* have also yielded mysterious results: some are similar to the solar FIP effect, others suggest coronal compositions merely reflect photospheric abundances, and yet others appear to suggest strong metal *depletions* relative to the photosphere (e.g. Drake 1996), as shown in Figure 4.

The abundance anomalies are tracers of as yet unidentified physical processes by which material rises into the corona and which act on the coronal gas to either accelerate it into a stellar wind or bring some of it back to the photosphere. These anomalies could provide an unique new diagnostic for probing the physics of stellar outer atmospheres, stellar mass loss and the formation of winds.

## 4. ARE WE STUCK IN THE SOLAR PARADIGM?

One of the most exciting developments in the study of stellar activity over the past decade has been the coming of age of Doppler imaging of the photospheres of rapidly rotating systems. Measurements of HR 1099 spanning more than a decade show an exciting new phenomenon, namely the existence of long-lived polar active regions, in addition to more transient regions near the equator (Donati et al. 1992; Vogt et al. 1999). The existence of these active regions is counter-intuitive, since the polar regions of the Sun appear as "coronal holes" and are the source of open magnetic field lines along which flows the highly stable, fast solar wind. The Doppler imaging studies, along with helioseismology, are beginning a paradigm shift in stellar dynamo theory.

Dupree (1996) has suggested that features in the emission measure distribution, such as the narrow enhancement in Capella, high electron density, and small scale are the coronal extensions of the high latitude active regions found with Doppler imaging. For the eclipsing system 44$\iota$ Boo, EUVE light curves covering 19 orbital periods do not track the transition region light curves, but instead show modulation indicative of an active region on one star (Brickhouse & Dupree 1998). In conjunction with the high density signatures shown in Figure 3, the evidence for small-scale polar emitting regions is tantalizing.

By widening the scope of investigation from the Sun to a large range of stellar parameters, stellar observations will provide clues to the processes responsible for the abundance anomalies on the Sun. Any astrophysical situations in which neutral and ionized species co-exist in the presence of electric or magnetic fields and strong temperature gradients could be subject to FIP-like and diffusive elemental separation effects.

## 5. THE EMISSION LINE PROJECT

Clearly, our understanding of these coronal phenomena depends critically on atomic data. 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 these efforts; 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, is that 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.

Furthermore, these systems have been well observed with ASCA and EUVE, such that we do not expect gross departures from equilibrium. EUV branching ratios place tight constraints on the optical depth effects for Capella. While a few lines may have optical depths of order unity, these will easily be identified by line ratio measurements.

## 6. 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. At the same time, critical diagnostics for more than a few stellar systems will enrich our sample of coronal phenomenon.

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