ON X-RAY OPTICAL DEPTH IN THE CORONAE OF ACTIVE STARS

PAOLA TESTA,1 JEREMY J. DRAKE,2 GIOVANNI PERES,3 AND DAVID P. HUENEMOERDER1

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ABSTRACT

We have investigated the optical thickness of the coronal plasma through the analysis of high-resolution X-ray spectra of a large sample of active stars observed with the High Energy Transmission Grating Spectrometer on Chandra. In particular, we probed for the presence of significant resonant scattering in the strong Lyman series lines arising from hydrogen-like oxygen and neon ions. The active RS CVn-type binaries II Peg and IM Peg and the single M dwarf EV Lac show significant optical depth. For these active coronae, the Lyα/Lyβ ratios are significantly depleted as compared with theoretical predictions and with the same ratios observed in similar active stars. Interpreting these decrements in terms of resonance scattering of line photons out of the line of sight, we are able to derive an estimate for the typical size of coronal structures, and from these we also derive estimates of coronal filling factors. For all three sources we find that both the photon path length as a fraction of the stellar radius and the implied surface filling factors are very small and amount to a few percent at most. The measured Lyα/Lyβ ratios are in good agreement with APED theoretical predictions, thus indicating negligible optical depth, for the other sources in our sample. We discuss the implications for coronal structuring and heating flux requirements. For the stellar sample as a whole, the data suggest increasing quenching of Lyα relative to Lyβ as a function of both Lx/Lbol and the density-sensitive Mg xi forbidden-to-intercombination line ratio, as might generally be expected.

Subject headings: radiative transfer — stars: coronae — stars: late-type — X-rays: stars

Online material: color figures

1. INTRODUCTION

A fundamental issue in the physics of stellar outer atmospheres concerns the relationship between magnetic activity on stars with a wide range of physical parameters and solar magnetic activity. How directly and how far does the solar analogy apply to other stars, and do any of the underlying physical processes differ? The X-ray luminosities of late-type stars can span several decades (e.g., Vaiana et al. 1981), and these hot coronae are found on such a wide range of spectral types that the extrapolation of the now well-studied solar corona to the extremes of stellar activity is by no means obvious and could be inappropriate. Indeed, “scaled-up Sun” scenarios, in which a stellar surface is covered with bright solar-like active regions, only realize X-ray luminosities 100 times that of the typical active Sun (e.g., Drake et al. 2000). The most active stars, with X-ray luminosities of up to 10,000 times the solar X-ray luminosity, must have coronae that are structured differently in some way.

Since coronal structures can be imaged presently only on the Sun, the structuring of other stellar coronae is generally investigated through the application of techniques such as the study of light curves during flares (e.g., Schmitt & Favata 1999; Favata et al. 2000a; Maggio et al. 2000; Reale et al. 2004; Testa et al. 2007), rotational modulation (e.g., Brickhouse et al. 2001; Marino et al. 2003; Huenemoerder et al. 2006), and study of density properties together with information on emission measure (e.g., Testa et al. 2004a, hereafter TDP04; Ness et al. 2004). Most of these analyses indicate that the emitting plasma is rather compact (scale height ≤0.5R*) and localized at high latitude (see, e.g., Schmitt & Favata 1999; Brickhouse et al. 2001; Testa et al. 2004b, hereafter Paper I; TDP04); however, the presence of extended coronal plasma has also been claimed on some stars based on UV and X-ray Doppler studies (e.g., Chung et al. 2004; Redfield et al. 2003).

The search for signs of quenching in strong lines through resonance scattering represents a further technique that offers a potentially powerful diagnostic of the sizes of X-ray–emitting regions; the escape probability of a photon emitted by a resonance line in a low-density homogeneous plasma is in fact dependent on the line-of-sight path length through the plasma region. Significant scattering optical depth can be combined with density measurements to obtain an estimate of photon path length within the emitting plasma.

Several existing studies have explored optical depths of both solar and stellar coronal emission lines. Studies of solar X-ray spectra have aimed at probing the optical depth in the strong (gf = 2.66) 2p33dP1−2p6 1S0 resonance line of Fe xvii at 15.01 Å as compared to nearby weaker Fe xvii lines, although with controversial results concerning whether optical depth effects were seen or not (Phillips et al. 1996, 1997; Schmelz et al. 1997; Saba et al. 1999). In particular, Saba et al. (1999) review recent observational findings on the opacity inferred from the study of the bright iron resonance line at 15.01 Å and on the center-to-limb behavior. Among other issues, Saba et al. (1999) address the discrepancy they find in the derived direction and magnitude of the center-to-limb trend (also in agreement with Schmelz et al. 1997), as compared to the findings of Phillips et al. (1996), who find that the effect of resonant scattering is decreasing from the disk center toward the solar limb, a trend irreconcilable and totally opposite to that found by Saba et al. (1999) and Schmelz et al. (1997). Brickhouse & Schmelz (2006) have recently reanalyzed solar X-ray spectra and suggest that previously ignored blends might explain the departure of measured ratios from theoretical calculations.
Resonant scattering in stellar coronae has been investigated by Phillips et al. (2001) and Ness et al. (2003) through the analysis of the same transition observed at high resolution ($\lambda / \Delta \lambda$ up to $\sim 1000$) by Chandra and XMM-Newton. Both stellar studies of Fe xvii transitions fail to find evidence for significant deviation from the optically thin regime, and in particular the large survey of stellar spectra analyzed by Ness et al. (2003) shows that no firm results can be obtained from Fe lines. One exception is the suggestion of resonance scattering in Fe xvii $\lambda 15.01$ on the basis of the observed variability of line ratios seen during a flare on AB Dor by Matranga et al. (2005). We note that Phillips et al. (2001) attempted to derive constraints on emitting region size based on their upper limit to optical depth in the corona of Capella, although, as we discuss in this paper ($\S$ 6), such upper limits cannot be reliably used in this fashion because scattering into the line of sight renders optical depth measurements themselves only lower limits to the true scattering depth.

In Paper I we presented results obtained using a different approach to the study of coronal optical depth, through the analysis of Ne and O Lyman lines. There is thus still some doubt to respond to coronal abundances typically found in RS CVn systems (see text). Because of the typically higher Ne abundance and lower Fe abundance found in the coronae of RS CVn systems, the expected resonant scattering effects are greater for O viii and Ne x Ly$\alpha$ than for Fe xvii.

We discuss in $\S$ 2 the advantages of the Lyman series analysis with respect to the “standard” approach using Fe xvii lines. The observations are briefly described in $\S$ 3. Our technique of line flux measurement and spectral analysis are described in $\S$ 4. The results are presented in $\S$ 5. We combine the results of this study with our earlier density estimates and discuss these in the context of coronal structure on active stars in $\S$ 6; we draw our conclusions in $\S$ 7.

2. RESONANT SCATTERING IN Ne AND O LYMAN SERIES LINES

The Fe xvii soft X-ray complex at $\sim 15$ $\AA$ has been a primary tool to probe coronal optical depth because of the large oscillator strength of the $2p^6 \ ^1S_0 - 2p^5 3d \ ^1P_1$ $\lambda 15.01$ resonance line and its consequent prominence in solar spectra. However, Doron & Behar (2002) and Gu (2003b) have recently shown that the indirect processes of radiative recombination, dielectronic recombination, and resonance excitation involving the neighboring charge states are important for understanding the relative strengths of Fe xvii–xz lines. There is thus still some considerable difficulty in reconciling theoretical and observed line strength ratios. Recently, Brickhouse & Schmelz (2006) have found good agreement of solar observed ratios with new theoretical calculations (Chen & Pradhan 2005) and suggest that center-to-limb observed trends (Phillips et al. 1996; Schmelz et al. 1997; Saba et al. 1999) are due to chance rather than to optical depth effects.

An additional problem in using Fe xvii lines as diagnostics of optical depth is that this element has been found to be depleted in the coronae of active stars by factors of up to 10 (e.g., Drake et al. 2001; Huenemoerder et al. 2001; Drake 2003; Audard et al. 2003) as compared with a solar or local cosmic composition. The ratio of the line-center optical depths, $\tau_i / \tau_j$, of two lines $i$ and $j$ is given by

$$\tau_i = \frac{f_i \phi_i A_i \sqrt{m_i}}{f_j \phi_j A_j \sqrt{m_j}},$$

where $f$ is the oscillator strength, $\lambda$ is the wavelength, $\phi$ is the fractional population of the ion in question, $A$ is the element abundance, and $m$ is the ion mass. The line optical depth is directly proportional to abundance, and in the case of stellar coronae, where only the very strongest spectral lines might be expected to undergo any significant resonance scattering, any abundance depletions also reduce the sensitivity of lines as optical depth indicators. For coronal abundances typically found in RS CVn systems (see, e.g., reviews by Drake 2003; Audard et al. 2003), we expect resonant lines from the more abundant ions like oxygen and neon to be more sensitive to resonant scattering processes than the resonant Fe xvii line. This is illustrated in Figure 1, where we show the relative optical depths for the O viii and Ne x Ly$\alpha$ lines and the Fe xvii resonance line at $\sim 15.01$ $\AA$ for both a representative solar chemical composition (Grevesse & Sauval 1998) and a chemical composition typically found for active stars. For the latter, we assumed Ne and Fe abundances 0.3 dex higher and 0.5 dex lower, respectively, than the corresponding solar values; we note that in several active coronae abundance anomalies even more pronounced have been found (e.g., Brinkman et al. 2001; Huenemoerder et al. 2001).

As discussed in Paper I, the effect of resonance scattering of Ly$\alpha$ and Ly$\beta$ photons can be diagnosed by comparison of the measured Ly$\alpha$/Ly$\beta$ ratio with respect to the theoretical ratio. In principle, both $n = 2 \rightarrow 1$ Ly$\alpha$ and $n = 3 \rightarrow 1$ Ly$\beta$ lines can be affected by resonant scattering: when a large optical depth is reached in Ly$\alpha$, an enhanced population of the $n = 2$ level can lead to a potentially confusing enhancement in Ly$\beta$ (and Bal$\alpha$) through collisional excitation of the $n = 2 \rightarrow 3$ transition. However,
in the limit of fairly small scattering optical depth that we expect to characterize stellar coronae, Ly\(\beta\) essentially remains optically thin and should make a reliable comparison with which to diagnose optical depth in Ly\(\alpha\).

3. OBSERVATIONS

\textit{Chandra} High Energy Transmission Grating Spectrometer (HETGS; for a description of the instrumentation see Canizares et al. 2000, 2005) observations of 22 cool stars covering a wide-range activity level were analyzed. The stellar parameters and particulars of the observations were discussed in detail in a companion paper that addressed the coronal densities of active stars (TDP04). To the sample analyzed in TDP04 we added a set of observations of IM Peg obtained subsequent to the first three segments analyzed in Paper I and TDP04; the parameters of these additional observations are listed in Table 1.

The HETG spectra and the corresponding X-ray light curves for the observations can be found in TDP04; we also discuss there the variability observed for some of the stars. The source sample covers very different stellar characteristics, providing a wide view of X-ray-emitting stellar coronae; e.g., the X-ray luminosities (in the HETGS bandpasses; see TDP04) span more than 5 orders of magnitude, from the relatively weak emission of Proxima Centauri, with a few times \(10^{26}\) ergs s\(^{-1}\), up to the very high luminosity (\(\sim 6 \times 10^{31}\) ergs s\(^{-1}\)) of the giant HD 223460.

4. ANALYSIS

The data used here were obtained from the \textit{Chandra} Data Archive\(^{4}\) and have been reprocessed using standard CIAO version 3.2.1 tools and analysis threads. Effective areas were calculated using standard CIAO procedures, which include an appropriate observation-specific correction for the time-dependent ACIS contamination layer. Positive and negative spectral orders were summed, keeping HEG and MEG spectra separate. For sources observed in several different segments, we combined the different observations and analyzed the co-added spectra. For IM Peg, as noted above, a number of observations are available with which to probe optical depth properties at different times and orbital phases; IM Peg is discussed in more detail in § 5.1.

Spectra were analyzed with the PINTofALE\(^{5}\) IDL\(^{6}\) software (Kashyap & Drake 2000) using the technique of spectral fitting described in TDP04. We measured the spectral line intensities of the Ne x Ly\(\alpha\) (2\(p\)\(^2\)P\(_{3/2,1/2}\)→\(1s\)\(^2\)S\(_{1/2}\)) and Ly\(\beta\) (3\(p\)\(^2\)P\(_{3/2,1/2}\)→\(-1s\)\(^2\)S\(_{1/2}\)) transitions from both HEG and MEG spectra, as well as the O vii lines from MEG spectra alone (since the latter lie outside the HEG wavelength range).

In order to take into account the mild dependence of the Ly\(\alpha\)/Ly\(\beta\) ratio on plasma temperature, we also measured the intensities of the Ne x and O vii resonance lines, \(r (1s^2p\;^1P_{1}→1s^2\;^1S_{0})\), providing us with an estimate of a representative temperature through the Ly\(\alpha\)/r ratio. There are two potential problems with this approach. First, while resonant scattering is relevant, both Ly\(\alpha\) and r transitions can be depleted, and in such a case the Ly\(\alpha\)/r ratio might deviate from its expected theoretical behavior. Secondly, the coronae in which these X-ray lines are formed are expected to be characterized by continuous ranges of temperatures, rather than by a single, isothermal plasma. However, both of these concerns prove unproblematic. Figure 2 illustrates the theoretical temperature dependence of the Ly\(\alpha\)/r ratio and of the Ly\(\beta\)/Ly\(\alpha\) ratio for Ne lines (O lines show analogous behavior). The Ly\(\alpha\)/r is much more temperature-sensitive than Ly\(\beta\)/Ly\(\alpha\), and the relatively small deviations from the optically thin case that might be expected in stellar coronae can only incur small errors in temperature that will have a negligible impact on the predicted Ly\(\beta\)/Ly\(\alpha\) ratio.

The accurate temperature determination from the Ly\(\alpha\)/r ratio strictly holds only for isothermal plasma, whereas stellar coronae are characterized by a thermal distribution of the plasma, so that this diagnostic would give us a temperature weighted by the emission measure distribution (DEM). By computing line ratios for nonisothermal plasma models and interpreting as if isothermal, we can estimate the errors incurred by an isothermal assumption. We considered two different sets of DEMs: those derived from actual observations of some of the stars in our sample, and simple DEM models in which the emission measure is proportional to \(T^{3/2}\) (as expected for simple hydrostatic loop models; Rosner et al. 1978, hereafter RTV78), or proportional to \(T^{5/2}\) (as observed in some stars such as 31 Com [Scelsi et al. 2004] and reproduced by some hydrodynamic loop models [Testa et al. 2005]). For these models we used peak temperatures varying from \(10^6\) to \(10^7\) K. Observed DEMs were culled from the literature for the following sources: AB Dor (Sanz-Forcada et al. 2003b), HD 223460 (Testa et al. 2007), 31 Com, \(\beta\) Cet, \(\mu\) Vel (García-Alvarez et al. 2006), EV Vul, TZ CrB, \(\xi\) UMa (Sanz-Forcada et al. 2003a), 44 Boo (Brickhouse & Dupree 1998), UX Ari (Sanz-Forcada et al. 2002), II Peg (Huenemoerder et al. 2001), \(\delta\) And (Sanz-Forcada et al. 2002), AR Lac (Huenemoerder et al. 2003), and HR 1099 (Drake et al. 2001).

\begin{table}[h]
\centering
\caption{Parameters of the HETG Observations of IM Peg}
\begin{tabular}{lllll}
\hline
ObsID & Start Date and Time & \(t_{\text{exp}}\) & \(L_{\text{X}}^a\) & \(L_{\text{X}}^b\) \\
\hline
2527 & 2002 Jul 01, 15:39:08 & 24.6 & 2.95 \times 10^{31} & 3.04 \times 10^{31} \\
2528 & 2002 Jul 08, 02:07:29 & 24.8 & 2.37 \times 10^{31} & 2.55 \times 10^{31} \\
2529 & 2002 Jul 13, 06:27:34 & 24.8 & 2.03 \times 10^{31} & 2.19 \times 10^{31} \\
2530 & 2002 Jul 18, 21:13:58 & 23.9 & 1.96 \times 10^{31} & 2.15 \times 10^{31} \\
2531 & 2002 Jul 25, 11:30:11 & 23.9 & 1.99 \times 10^{31} & 2.20 \times 10^{31} \\
2532 & 2002 Jul 31, 20:45:59 & 22.5 & 3.00 \times 10^{31} & 3.23 \times 10^{31} \\
2533 & 2002 Aug 08, 00:50:22 & 23.7 & 2.57 \times 10^{31} & 2.79 \times 10^{31} \\
2534 & 2002 Aug 15, 14:28:06 & 23.9 & 2.35 \times 10^{31} & 2.50 \times 10^{31} \\
\hline
\end{tabular}
\end{table}

\footnotesize
\(^a\) Relative to the HEG range: 1.5–15 Å.

\(^b\) Relative to the MEG range: 2–24 Å.
Given the line ratio computed for each DEM model, we inverted the isothermal relation to obtain $T(\text{Ly}α/\gamma)$. Using that $T$, we then obtained the theoretical isothermal $\text{Ly}α/\gamma$ ratio ($\text{Ly}α/\gamma$ [DEM]) and compared it to the synthetic ratio ($\text{Ly}α/\gamma$ [DEM]). We find that the isothermal assumption is a good predictor of the ratio for both theoretical DEMs and representative stellar models: Figure 3 shows that the isothermal and DEM ratios are in very good agreement, with differences between the two generally amounting to a few percent. We conclude that the $\text{Ly}α/\gamma$ temperatures are quite adequate to assess the appropriate expected $\text{Ly}α/\gamma$ ratio, even if the real plasma temperature distributions of the coronae in our study are far from isothermality.

### 4.1. Deblending of Ne x Lyα and O viii Lyβ

Ne x Lyα and O viii Lyβ lines are affected by blending of iron lines unresolved at the HETGS resolution level. Specifically, significant blending is expected for O viii Lyβ by an Fe xviii line ($2s^22p^6(^3P)3s^2P_{2,22}−2s^22p^5^2P_{3,3}$, $\lambda = 16.004$ Å) and, to a lesser extent, for the Ne x Lyα line by a nearby Fe xviii transition ($2s^22p^6(^5P)4d^1P_{1,2}−2s^22p^5^1S_0$, $\lambda = 12.124$ Å).

O viii Lyβ.—In order to estimate the often significant contribution of Fe xviii to the O viii Lyβ spectral feature, we used the same method described in Paper I, which was also subsequently adopted by Ness & Schmitt (2005) in an analysis of spectra of the classical T Tauri star TW Hya. We estimated the intensity of the Fe xviii $\lambda 16.004$ line by scaling the observed intensity of the slightly stronger neighboring unblended Fe xviii $\lambda 16.071$ ($2s^22p^5(^3P)3s^4P_{3,2}−2s^22p^5^2P_{3,2}$) transition. Gu (2003b) has recently pointed out the similar behavior of Fe L-shell lines originating from 3s and 3p upper levels in respect to the indirect excitation processes of radiative recombination, dielectronic recombination, and resonance excitation. The $\lambda 16.004$ and $\lambda 16.071$ transitions originate from similar 3s upper levels, and their ratio should therefore not deviate greatly from current theoretical predictions. The APED (ver. 1.3.1) database (Smith et al. 2001) lists their theoretical ratio as 0.76 at the temperature of the Fe xviii population peak ($\sim 6.8$ MK), with a decrease of only a few percent up to 10 MK or so; this range covers the expected formation temperatures of Fe xviii in our target stars.

We investigated this scaling factor empirically by examining the departure of the resulting deblended Lyα/γ ratios from the theoretical value as a function of the ratio of the observed Fe xviii $\lambda 16.071$ to Lyβ line strengths. If the deblending scaling factor is correct, there should be no residual slope in the resulting data points; a positive slope would instead indicate an
overcorrection for the blend and a negative slope an undercorrection. We found that a slope of zero was obtained for a scaling factor of ~0.70, in good agreement with the APED value within expected uncertainties. This is illustrated in Figure 4.

Ne x Lyα.—In analogy with the procedure used for the O vii Lyβ, we searched for isolated and strong Fe xxiv lines to estimate the amount of blending from Fe xxv λ 12.124 Å in the Ne x Lyα line. A potentially good candidate would be the nearby Fe xxiv λ12.266 line \([2s^22p^6(2p)^4d_1-2s^22p^6(2p)^6S_0]\), which has a similar intensity and behavior as a function of temperature; however, this transition is rather weak in most of the observed spectra and can be affected itself by blending with a close Fe xxiv transition (λ 12.284) barely resolved by HETG.

We therefore chose to use a larger set of Fe xxv lines including stronger transitions. The intensity of the Fe xxv line blending with the Ne x Lyα is estimated by scaling the observed intensity of other Fe xxv lines (λ12.266, 15.014, 15.261, 16.780, 17.051, 17.096) by the ratio expected from Landi & Gu (2006; see also Gu 2003a; Landi et al. 2006), assuming \(T = 6.8\). These calculations include indirect processes involving the neighboring charge states and are quite successful at reproducing the relative intensity of these Fe xxv lines. Previous calculations (including those adopted in APED ver. 1.3.1) fail here, with, e.g., the ratio of the λ15 line to the λ17 lines being overestimated by about a factor of 2. The detailed comparison of the observed Fe xxv line ratios with the predictions of different theoretical calculations is addressed in a forthcoming paper.

The measured line fluxes after application of deblending corrections, together with the statistical errors, are listed in Table 2.

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5. RESULTS

The observed Lyα/Lyβ ratios and the temperature derived from the Lyα/r ratios are listed in Table 3 and illustrated in Figure 5. Measurements obtained from the MEG spectra generally result in smaller statistical errors due to the higher signal-to-noise ratio (S/N); however, we find a general agreement of HEG and MEG results. The main differences of the present work with respect to the analysis of Paper I, where results were presented for four sources (II Peg, IM Peg, HR 1099, and AR Lac), are that the line fluxes have been remeasured in the reprocessed data, Ne x Lyα fluxes have been corrected for blending, and the deblending procedure for O viii Lyβ has been slightly refined (see previous section). Also, IM Peg fluxes listed here refer to the total (~192 ks) HETGS spectrum, including ObsIDs 2530–2534 not yet publicly available when we carried out the analysis presented in Paper I (where we used the first three 25 ks pointings; see §5.1 for a detailed discussion).

The observed Ne x Lyα/Lyβ ratios follow closely the APED theoretical predictions as a function of temperature. The values for the O vii ratios (Fig. 5, right panel) show slightly more

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### Table 2

| Source       | Lyα λ12.132 | Lyβ λ10.239 | r λ13.447 |
|--------------|-------------|-------------|-----------|
|              | HEG         | MEG         | HEG       | MEG       | MEG       |
| AU Mic       | 374 ± 50    | 356 ± 15    | 51 ± 10   | 44 ± 4    | 208 ± 15  |
| Pro Cen      | 69 ± 20     | 6.5 ± 2.9   | 47 ± 9    |           |
| EV Lac       | 278 ± 22    | 262 ± 10    | 30 ± 6    | 32 ± 3    | 209 ± 8   |
| AB Dor       | 668 ± 50    | 682 ± 24    | 96 ± 16   | 86 ± 9    | 332 ± 27  |
| TW Hya       | 97 ± 9      | 95 ± 8      | 12 ± 8    | 96 ± 2.8  | 155 ± 14  |
| HD 233460    | 158 ± 20    | 137 ± 11    | 22 ± 6    | 16.0 ± 2.7| 20 ± 7    |
| HD 111812    | 58 ± 5      |             | 7.9 ± 1.6 | 14 ± 3    |
| β Cet        | 419 ± 24    | 408 ± 10    | 53 ± 10   | 48 ± 4    | 146 ± 10  |
| HD 45348     | 54 ± 4      |             | 4.7 ± 2.3 | 35 ± 7    |
| μ Vel        | 173 ± 21    | 159 ± 15    | 16 ± 13   | 18 ± 7    | 95 ± 7    |
| Algo         | 898 ± 50    | 832 ± 40    | 136 ± 23  | 120 ± 8   | 196 ± 20  |
| ER Vul       | 218 ± 22    | 201 ± 12    | 26 ± 8    | 24.3 ± 2.8| 74 ± 7    |
| 44 Boo       | 572 ± 60    | 537 ± 24    | 75 ± 11   | 68 ± 8    | 254 ± 20  |
| TZ CrB       | 1126 ± 30   | 1043 ± 24   | 145 ± 14  | 127 ± 6   | 516 ± 20  |
| UX Ari       | 730 ± 40    | 767 ± 20    | 126 ± 17  | 107 ± 8   | 245 ± 18  |
| ξ Uma        | 419 ± 27    | 394 ± 13    | 42 ± 8    | 47 ± 4    | 309 ± 16  |
| II Peg       | 1300 ± 70   | 1200 ± 30   | 183 ± 24  | 191 ± 10  | 356 ± 20  |
| λ And        | 557 ± 30    | 556 ± 14    | 80 ± 11   | 84 ± 5    | 189 ± 14  |
| TY Pyx       | 341 ± 29    | 312 ± 6     | 46 ± 12   | 40 ± 5    | 142 ± 15  |
| AR Lac       | 648 ± 40    | 621 ± 17    | 104 ± 15  | 94 ± 6    | 182 ± 20  |
| HR 1099      | 1960 ± 40   | 1730 ± 18   | 255 ± 14  | 230 ± 7   | 566 ± 18  |
| IM Peg       | 408 ± 25    | 383 ± 10    | 62 ± 7    | 60 ± 3    | 79 ± 8    |

|            | Lyα λ18.967 | Lyβ λ16.006 | r λ21.602 |
|            | HEG         | MEG         | MEG       | MEG       | MEG       |
|            |             |             |           |           |           |
| Fe         |             |             |           |           |           |
| Fe xxvi* λ12.124 |             |             |           |           |           |
| Fe xxv     |             |             |           |           |           |

* Ne Lyα fluxes after the deblending with the Fe xxv line at 12.124 Å.
* O Lyβ fluxes after the deblending with the Fe xxv line at 16.004 Å.
* Fe xxv line (at 12.124 Å) flux estimated by scaling the measured fluxes of the other Fe xxv lines.
scatter, with some departures below theory and some $1-2\sigma$ excursions above. We note that an enhancement of the $\text{Ly} \alpha/\text{Ly} \beta$ ratio is possible for the particular geometry in which an emitting region is optically thick in some directions but is optically thin in the line of sight of the observer (see also the radiative transfer study of Kerr et al. 2004). Such a situation is disfavored by the isotropic nature of the scattering process in which any line enhancements through scattering are diluted, roughly speaking, by the ratio of solid angles of optically thin to optically thick lines of sight. In the case of loop geometries, such a ratio is much larger than unity. We therefore interpret these small upward $1-2\sigma$ excursions as normal statistical fluctuations.

In the case of the Ne x lines, the MEG $\text{Ly} \alpha/\text{Ly} \beta$ ratio for II Peg is $\sim 3\sigma$ lower than the expected value; the ratio derived from HEG is consistent with the MEG measurement but does not depart significantly from theory. The only sources showing $\text{O viii Ly} \alpha/\text{Ly} \beta$ significantly ($>3\sigma$) lower than the theoretical ratio are II Peg and EV Lac. We note that the low $\text{Ly} \alpha/\text{Ly} \beta$ ratios for IM Peg discussed in Paper I were found in the spectra obtained in the first three pointings, while here we analyze the whole set of observations; in § 5.1 we discuss the variability observed in $\text{Ly} \alpha/\text{Ly} \beta$ ratios for IM Peg.

One other interesting case is the T Tauri star, TW Hya, that shows very high density, $n_e \gtrsim 10^{12}$ cm$^{-3}$, at the temperature...
of O vii lines (e.g., Kastner et al. 2002). In this case, the high densities are generally believed to arise from an accretion shock, rather than coronal loops; significant scattering effects could in principle provide interesting constraints on the dimensions of the shock region. Unfortunately, for this source the relatively low S/N results in large error bars in the Lyα/Lyβ ratios that do not provide any useful constraints (as was also noted in the analysis of Fe xvii lines by Ness & Schmitt 2005).

5.1. IM Peg

The different Chandra HETG observations of the RS CVn system IM Peg provide an opportunity for studying the optical depth and its possible variation with time. This system has been analyzed in great detail at optical wavelengths by Berdyugina et al. (1999, 2000). These works depict a scenario with stellar spots concentrated mainly close to the polar regions, similar to those found for many other active systems (e.g., Schuessler et al. 1996; Hatzes et al. 1996; Vogt et al. 1999; Hussain et al. 2002; Berdyugina et al. 1998).

Chandra observed IM Peg eight times over ~2 orbital periods (see Table 1). The X-ray light curve obtained from this sequence is illustrated in Figure 6 and shows significant modulation that is possibly related to the orbital and rotational period (these being essentially the same; $P_{\text{rot}} = 24.39$ days, $P_{\text{orb}} = 24.65$ days; Strassmeier et al. 1993). In Paper I we analyzed the first three 25 ks HETGS observations of IM Peg, publicly available at that time, and we found remarkably small photon path lengths based on optical depth effects. The compact emission regions implied might be associated with active regions revealed by optical Doppler imaging studies. Any significant net line photon loss to resonant scattering out of the line of sight would be expected to be sensitive to the orientations of the emitting structures. Modulation of the Lyα/Lyβ ratio with time could provide important new structure and morphology diagnostics. Such regions might also be expected to change on relatively short timescales as a result of flaring activity and consequent realignment of their defining magnetic fields.

Here we present an analysis of the complete data set, exploring possible temporal variability of the optical depth of the coronal plasma. Unfortunately, the single IM Peg exposures provided counts sufficient for reliable intensity measurement only for the strongest lines in the spectrum, such as Ne x Lyα. In order to probe secular change in the Lyα/Lyβ ratio, we therefore measured lines from spectra co-added from contiguous sets of two or three observations that sample different phases of the stellar period: ObsIDs 2527 and 2528; 2529, 2530, and 2531; and 2532, 2533, and 2534. The spectra in the Ne x and O Lyα/Lyβ regions for these three portions of the observation are shown in Figures 7 and 8. The measured Lyα/Lyβ ratios are listed in Table 4.

The Lyα/Lyβ ratios, while statistically all consistent with one another, are suggestive of different conditions in the different portions of the observation. Both Ne and O Lyα/Lyβ ratios in HEG and MEG spectra are lower than the corresponding APED theoretical value in the first segment, as already discussed in Paper I and noted earlier. The rest of the observation is characterized by Lyα/Lyβ values compatible with theory. The measured ratios are illustrated as a function of the hardness ratio $[\text{HR} = (H - S)/(H + S)]$, where $H$ is the flux integrated in the 2–9 Å wavelength band and $S$ is the flux integrated in the 9–25 Å band] in the different segments of the observation in Figure 9.
There is no obvious correlation of Lyα/Lyβ with spectral hardness that might suggest, e.g., that the former changes as a result of plasma temperature changes. These results show that it might be worthwhile to explore, when the data quality allows it, temporal variability of optical depth properties in stellar coronae, expected to some extent on the basis of their dependence on the line of sight and coronal geometry other than on the physical conditions of the emitting plasma.

5.2. Path Length Estimates

The data presenting more reliable evidence for optical thickness are the spectra of IM Peg from the first two observations, where Lyα of both oxygen and neon appears to be depleted with respect to the corresponding Lyβ transition (deviation of ~1.8 and ~3 σ, respectively), and the spectrum of II Peg characterized by an O vii Lyα/Lyβ ratio ~5 σ lower than the theoretical value. As pointed out in Paper I, the discrepancies between observed and theoretical Lyα/Lyβ line strength ratios in IM Peg and II Peg cannot be explained by photoelectric absorption along the line of sight on the basis of their measured H column densities (Mewe et al. 1997; Mitrou et al. 1997). It is worth discussing whether these transitions, and in particular their ratios, might be affected by nonequilibrium conditions that are possibly relevant for these active stars undergoing frequent flaring activity. Nonequilibrium effects might be responsible for changes in the O vii G ratio [(f + i)/r] observed for EV Lac between quiescent and flare phases (Mitra-Kraev 2006). It is well known that the G ratio is sensitive to deviations from coronal equilibrium because recombination processes contribute significantly to f and i but are almost negligible for r (e.g., Pradhan 1985). Even though recombination processes have nonnegligible effects on Lyα and Lyβ (10%–15%), they contribute to a very similar extent to the two transitions, and therefore their ratio is not expected to change significantly under mildly nonequilibrium conditions. Furthermore, we note that for the typical conditions of the coronal plasma in these active stars the expected timescales of these effects are only of the order of hundreds of seconds (e.g., Golub et al. 1989), i.e., very short with respect to our integration times of several tens of kiloseconds. We therefore interpreted the discrepant ratios in terms of a relative depletion of the Lyα line flux due to resonance scattering processes.

Another source apparently showing significant effects of resonant scattering is EV Lac, whose O vii Lyα/Lyβ ratio is more than 3 σ lower than the corresponding theoretical value. This result is supported to some extent by the findings of Ness et al. (2003): in their survey of coronal optical depth properties based on the analysis of Fe xvi transitions, EV Lac is the only source deviating significantly from the typical values found for all other coronae. However, Ness et al. (2003) did not consider this result robust due to discrepancies between HEG and MEG measurements.

For the stars with Lyα/Lyβ departing from the theoretical values we can derive an estimate of the photon path length using the Kaastra & Mewe (1995) approximation to the escape probability formalism of Kastner & Kastner (1990) as described in § 3.1 of Paper I. The observed Lyα/Lyβ can be expressed in terms of the line-center optical depths τk, f-values f k, and photon path length ℓ as

\[
\frac{(h_{\text{Lyα}}/h_{\text{Lyβ}})_{\text{obs}}}{(h_{\text{Lyα}}/h_{\text{Lyβ}})_{\text{th}}} = \frac{1}{3} \left[ \frac{2}{1 + 0.43C(\ell) f^\alpha_k} + \frac{1}{1 + 0.43C(\ell) f^\alpha_k/2} \right] \times [1 + 0.43C(\ell) f^\beta_k],
\]

(2)

where C(\ell)f^k = τk and the line-center optical depth is given by

\[
\tau = 1.16 \times 10^{-14} \frac{n_i}{n_e} A_Z n_{\text{H}} \frac{n_e}{\sqrt{\frac{M}{T} n_e \ell}},
\]

(3)

![Fig. 8.—O vii Lyα/Lyβ spectral region of MEG spectra of IM Peg for the three chosen time segments of the observation, in the same format of the plots in Fig. 7. The shift in wavelength of second and third spectra is of +0.06 Å with respect to the preceding spectrum. A clear trend in the Lyα/Lyβ line ratio is present. [See the electronic edition of the Journal for a color version of this figure.]

![Fig. 9.—Lyα/Lyβ ratios measured from IM Peg spectra for the three time segments selected for the analysis (2528+2528, 2529+2530+2531, and 2532+2533+2534; top), together with the hardness ratio, HR (bottom). In the top panel the horizontal lines represent the APED values expected for the Lyα/Lyβ ratio of O (dashed line) for a temperature of 5 MK and of Ne (dotted line) for a temperature of 9 MK. For better readability Lyα/Lyβ ratios of Ne x from HEG and of O vii are shifted with respect to MEG Ne x Lyα/Lyβ ratios by +0.05 and +0.1, respectively, on the phase axis.]

### Table 4

| O vii | Lyα/Lyβ Photon Ratios with 1 σ Errors |
|-------|--------------------------------------|
| Ne x  | HEG       | MEG       | MEG       |
|-------|-----------|-----------|-----------|
| 2527+2528 | 5.3 ± 0.8 | 5.5 ± 0.5 | 5.1 ± 1.2 |
| 2529+2530+2531 | 6.9 ± 1.7 | 6.5 ± 0.6 | 7.5 ± 3.0 |
| 2532+2533+2534 | 6.2 ± 1.2 | 7.1 ± 0.6 | 7.0 ± 2.1 |
where \( n_i/n_e \) is the ion fraction (from Mazzotta et al. 1998), \( A_Z \) is the element abundance, \( n_i/n_e \sim 0.85 \), \( f \) is the oscillator strength, \( M \) is the atomic weight, \( T \) is the temperature, and \( n_e \) is the electron density. The Ly\( \alpha \) and Ly\( \beta \) \( f \)-values are \( f^{\text{Ly} \alpha} = 0.2776 \) and \( f^{\text{Ly} \beta} = 0.05274 \) (e.g., Morton 2003).

We use the electron densities, \( n_e \), derived from the diagnostics of the He-like triplets (TDP04). The coronal abundances assumed for II Peg and IM Peg are discussed in Paper I; for EV Lac we assume \( O/H = 8.40 \), as derived by Favata et al. (2000b) expressed on the usual spectroscopic logarithmic scale in which \( X/H = \log[n(X)/n(H)] + 12 \), where \( n(X) \) is the number density of element \( X \).

In Table 5 we list the values obtained for the path length estimates, \( \ell_r \), and for comparison, we list the stellar radii and loop lengths expected for a standard hydrostatic loop model (e.g., RTV78) corresponding to the observed temperatures and densities.

| Source      | Lines | \( \ell_r \) (cm) | \( L_{RTV} \) (cm) | \( \ell_r/R \) | \( f^c \) | \( E_3^d \) (ergs cm\(^{-2} \) s\(^{-1} \)) |
|-------------|-------|-----------------|-------------------|--------------|--------|-------------------|
| IM Peg      | O vii | \( 1.5 \times 10^{10} \) | \( 2.2 \times 10^8 \) | 0.017 | \( \sim 0.006 \) | \( \sim 7.2 \times 10^7 \) |
|             | Ne x (HEG) | \( 2.1 \times 10^8 \) | \( 2.8 \times 10^7 \) | 0.00024 | \( \sim 0.0003 \) | \( \sim 5.2 \times 10^7 \) |
|             | Ne x (MEG) | \( 1.7 \times 10^8 \) | \( 2.8 \times 10^7 \) | 0.00019 | \( \sim 0.0004 \) | \( \sim 5.3 \times 10^7 \) |
| II Peg      | O vii | \( 9.5 \times 10^8 \) | \( 1 \times 10^7 \) | 0.04 | \( \sim 0.021 \) | \( \sim 1.2 \times 10^9 \) |
| EV Lac      | O vii | \( 1.6 \times 10^8 \) | \( 2.6 \times 10^7 \) | 0.058 | \( \sim 0.016 \) | \( \sim 1.9 \times 10^8 \) |

*\( L_{RTV} \) is derived in TDP04. The surface filling factors, \( \psi \), combined with electron densities, \( n_e \), derived in TDP04. The surface filling factors, \( f^c \), are then given by \( f^c = A/A_e = (V/\ell_r)/A_e \). The derived filling factors, listed in Table 5, are very small, and especially so for the hotter plasma.

6. DISCUSSION

This work presents a detailed and extensive study of the O vii and Ne x Ly\( \alpha \)/Ly\( \beta \) ratios in a sample of active stars, paying careful attention to the presence of blends and to the validity of theoretical line ratio predictions. Our analysis shows that optical depth effects are generally negligible in the disk-integrated X-ray spectra emitted by coronae over a wide range of activity, in line with previous studies based on Fe xvii lines (e.g., Ness et al. 2003; Audard et al. 2004). We argued in § 2 that the coronal abundance patterns exhibited by most active stars render the Ne and O Lyman lines more sensitive diagnostics of optical depth than the Fe lines, and in this regard our study extends the results of previous surveys.

However, our study has also yielded a convincing indication of line-of-sight photon loss through resonant scattering in the spectra of three stars, IM Peg, II Peg, and EV Lac. The detection of significant X-ray optical depth is particularly interesting because it provides us with insights into the characteristic dimensions of the emitting coronal structures.

Before proceeding, we note here that a simple escape probability analysis does not include the scattering source term itself, and so photons scattered into the line of sight that could enhance the observed line strength are not included. For instance, in the case of a spherically symmetric corona in which the line optical depth were significant, scattering into and out of the line of sight would be balanced and line strengths not affected (see, e.g., Wood & Raymond 2000). Strictly, then, the photon path, \( \ell \), entering into the equations in § 5.2 should be interpreted as a lower limit to the true photon path length. This is potentially important. Phillips et al. (2001), for example, used the lack of appreciable depletion of the Fe xvii resonant line at \( \sim 15.01 \) Å to deduce an upper limit of 3000 km for size of emitting regions in the corona of Capella; however, such a measurement in reality only provides an upper limit to the lower limit, therefore not providing a constraint. Indeed, the lack of evidence for line quenching through scattering in most of our sample stars does not imply that scattering is not a significant source term, but merely that the scattering geometry is such that there is no net loss or gain of photons in the line of sight.

Instead, a positive detection of resonance scattering has interesting implications and points to a nonuniform “aspect ratio” of the dominant coronal emitting regions: for any net line depletion to occur, an emitting structure must generally be more elongated along the line of sight than in the perpendicular direction. In the context of a corona comprising plasma contained by magnetic loops, there are different ways in which this can be interpreted: (1) scattering loss results from the structure and viewing angle of the loops themselves; (2) scattering loss arises because of a particular conglomeration of loops viewed at a particular angle. Each case leads to fundamentally different interpretations of observed scattering. In the former case, a loop with random orientation must generally be viewed from the top, in which direction the photon path length through the plasma is largest. Photon loss through resonance scattering then implies that loops are preferentially placed on the stellar surface facing the observer (a perfect alignment of loops seen edge-on on the stellar limb could produce a similar effect, although such a chance alignment is unlikely). In the latter case, the coronal structures or active regions must be placed preferentially on the stellar limb.

6.1. Scattering within Individual Loops

With the proviso that a scattering-derived path length is a lower limit to the true emitting region size, we note that the photon path lengths implied by the analysis of line ratios (§ 5.2) observed in II Peg, IM Peg, and EV Lac and listed in Table 5 are all much smaller than the corresponding stellar radii, but they are also about an order of magnitude larger than expected from RTV78 loops.

Under the assumption that scattering within individual loops arises when they are viewed from the top, we can interpret the path length estimates, \( \ell_r \), in terms of the coronal scale height. With knowledge of the total emitting volume we can also derive an estimate of the surface filling factors. Emitting volumes can be estimated using the emission measures implied by the different lines, \( V = EM/n_e^2 \), combined with electron densities, \( n_e \), derived in TDP04. The surface filling factors, \( f_3 \), are then given by \( f_3 = A/A_e = (V/\ell_r)/A_e \). The derived filling factors, listed in Table 5, are very small, and especially so for the hotter plasma.
They are also an order of magnitude smaller than those previously derived in TDP04 based on RTV78 loops, a direct consequence of the optical depth scale height being commensurately larger than those suggested by simple quasi-static loop models.

The small filling factors we find here have interesting implications for the surface heating flux requirements. A very rough estimate of the heating required to sustain the observed physical conditions of the plasma can be obtained from the RTV78 scaling laws. While our estimated loop lengths are significantly longer than suggested by RTV78 models, these relations should still suffice for the purposes of estimation. The volumetric heating per unit time, \( E \), is given by \( E \sim 10^7 p^{7/6} L^{-5/6} \), where \( p \) is the plasma pressure and \( L \) is the loop length. By assuming \( L = \ell_r \), we find for the surface flux values of order of \( 10^8 \) ergs cm\(^{-2}\) s\(^{-1}\) for O vii lines and several times \( 10^{10} \) ergs cm\(^{-2}\) s\(^{-1}\) implied by the Ne x lines in IM Peg (Table 5). These compare with typical surface heating rates for the cores of solar active regions of a few times \( 10^7 \) ergs cm\(^{-2}\) s\(^{-1}\) (e.g., Withbroe & Noyes 1977).

In the comparison of \( \ell_r \), with \( L_{RTV} \) we assumed to some extent that \( \ell_r \) is a reasonable estimate for the coronal scale height (i.e., for the loop length). However, an alternative interpretation is possible in which the actual coronal loops are larger and \( \ell_r \) represents only an estimate of the length of the part of the loop containing plasma at the characteristic temperature of the quenched lines. In such a scenario, the values found for \( \ell_r \) can suggest the presence of cooler loops with maximum temperature around 3 MK, similar to solar loops, coexistent with loops with much higher maximum temperature (\( \geq 10 \) MK). In these hotter loops, the plasma emitting the Ne x lines (\( T \geq 6-7 \) MK) would be confined in the lower portion of the loop, which is characterized by higher density. In order to estimate the region of the loop occupied by the plasma emitting the observed line, \( \Delta l \), we can use the equations for the conductive flux,

\[
F_c = k_c T^{5/2} (dT/dl) \sim k_c T^{5/2} (\Delta T/\Delta l),
\]

and from RTV78 relations for a radiative power loss function \( P(T) \),

\[
F_c/\Delta l \sim n_e^2 P(T).
\]

Assuming that \( T \) is the temperature of maximum formation of the line \( k_c T_{max} \), and \( \Delta T \) is the width in temperature of the line emissivity curve (~0.3 dex), we can solve the equations for \( \Delta l \):

\[
\Delta l \sim \begin{cases} 
5 \times 10^8 \text{ cm}, & \text{O vii}, \\
2 \times 10^7 \text{ cm}, & \text{Ne x}.
\end{cases}
\]

The resulting values of \( \Delta l \) are rather close to \( L_{RTV} \) (see Table 5), obtained assuming \( T_{max} \) as maximum temperature of the loop, and are still much smaller than \( \ell_r \). We can conclude, then, that the values derived for the path length do not seem to agree with the hypothesis of standard uniformly heated quasi-static loop models.

### 6.2. Scattering within Active Regions

The maximum path length, \( l_{max} \), through a spherically symmetric corona of height \( h \) on a star with radius \( R_* \) and surface filling factor \( f_s \) (assuming that this filling factor does not vary significantly with height) is

\[
l_{max} = 2 f_s \sqrt{h^2 + 2hR_*}.
\]

Considering typical parameters found for stellar coronae, we can estimate from the above equation whether or not we expect significant photon scattering in stellar coronae, regardless of whether we see a net photon loss. From equation (3) we can estimate the optical depth at the limb for Ne and O Lyα lines. Assuming the temperature of maximum formation of the line, i.e., about 6 and 3 MK for Ne and O Lyα respectively, and typical density of about \( 10^{10} \) and \( 10^{11} \text{ cm}^{-3} \), respectively (see, e.g., TDP04; Ness et al. 2004), we derive \( \tau(\text{Ne}) \sim 5.2 \times 10^{-10} l_{max} \) and \( \tau(\text{O}) \sim 3.6 \times 10^{-10} l_{max} \).

The height derived for coronal structures with different techniques (see § 1 for references) is \( \lesssim R_*/2 \); on the Sun a typical coronal height is closer to \( R_*/10 \). Assuming \( h = R_*/10 \) and \( R_* = R_\odot \), we obtain \( l_{max} \sim f_s (0.9 R_\odot) \sim 6 \times 10^{10} \text{ cm} \).

Under these assumptions, the values of the optical depth at the limb, for a spherically symmetric corona, are therefore \( \tau(\text{Ne}) \sim 30 f_s \) and \( \tau(\text{O}) \sim 20 f_s \) (or \( \tau(\text{Ne}) \sim 80 f_s \) and \( \tau(\text{O}) \sim 55 f_s \)

![Fig. 10.—Ratios of measured to theoretical O vii Lyα/Lyβ ratios vs. \( L_x/L_{bol} \) (top) and vs. the Mg xi forbidden-to-intercombination line ratio (from TDP04; bottom), which is a diagnostic of plasma density (low f/i ratios correspond to high density.)](image-url)
if we assume \( h = R_e / 2 \) and \( R_e = R_s \). For the typical filling factors lower than a few percent (e.g., TDP04) we obtain optical depth \( \tau \lesssim 1 \) for both Ne and O.

6.3. Correlation of Scattering with Stellar and Coronal Parameters

While only three of the members of our stellar sample present a significant case for resonance scattering, it is possible that trends of the departure from the theoretical \( \text{Ly_\alpha}/\text{Ly_\beta} \) ratio with fundamental stellar parameters can be found. We have examined the departures of observed from theoretical \( \text{Ly_\alpha}/\text{Ly_\beta} \) ratios as a function of X-ray surface flux, surface flux in the \( \text{Ly_\alpha} \) line, \( L_X/L_{\text{bol}} \), filling factors, and plasma density. These comparisons are suggestive of correlations between quenching of \( \text{Ly_\alpha} \) photons and both \( L_X/L_{\text{bol}} \) and the density-sensitive ratio of strengths of the forbidden and intercombination lines, \( f/\ell \), of Mg \( \text{x} \).

These correlations are illustrated in Figure 10, where we show the measured-to-theoretical ratios of O viii \( \text{Ly_\alpha}/\text{Ly_\beta} \) of our sample as a function of \( L_X/L_{\text{bol}} \) (top panel) and Mg \( \text{x} \) \( f/\ell \) (bottom panel). Error-weighted linear fits to the data in these figures yield slopes of \(-0.11 \pm 0.04 \) and \( 0.25 \pm 0.06 \), respectively. The sources presenting evidence of optical depth effects are the stars characterized by the highest activity level (\( L_X/L_{\text{bol}} \)) and the highest plasma densities (i.e., lowest \( f/\ell \)) in our sample. Such correlations are what are expected based on equation (3).

Optical depth is proportional to the product of electron density and typical path length within an emitting region, \( n_e \ell \). For a given fixed volume emission measure, \( n_e^2 \ell \sim n_e^2 \ell^3 \), the optical depth varies as \( n_e^3 \ell^{1/2} \) and so increases with increasing plasma density. In the case of \( L_X/L_{\text{bol}} \), an increase in \( L_X \) can arise through either \( \ell \) or \( n_e \), such that any increase in \( L_X \) might typically be expected to lead to greater scattering optical depth. While only a small handful of our measurements present truly significant detections of resonance scattering, the evidence for trends of increasing \( \tau \) with \( L_X/L_{\text{bol}} \) and Mg \( \text{x} \) \( f/\ell \) as is expected adds confidence to the interpretation of the \( \text{Ly_\alpha}/\text{Ly_\beta} \) ratios in these terms.

7. CONCLUSIONS

We have investigated the optical thickness of stellar coronae through the analysis of \( \text{Ly_\alpha} \) and \( \text{Ly_\beta} \) lines of hydrogen-like oxygen and neon ions in \textit{Chandra} HETG spectra of a large sample of active stars. Our study indicates that most stellar coronae are characterized by negligible visible signs of optical depth, in agreement with the results of previous studies based on \( \text{Fe Xvii} \) lines. This indicates either that coronae are in general optically thin, or that for cases in which optical depths reach of order unity or higher the geometry does not strongly favor lines of sight showing net \( \text{Ly_\alpha} \) photon loss.

We do find evidence of significant optical depth in the O viii Lyman lines of the RS CVn binary II Peg and of the single M dwarf EV Lac; the RS CVn binary IM Peg also shows depletion of both Ne and O \( \text{Ly_\alpha}/\text{Ly_\beta} \) ratios as compared with theoretical predictions, and our analysis indicates that it is a transient effect present only in part of the observations. The detection of significant optical depth allows us to derive an estimate for the photon path length and therefore for the typical height of the corona. The size of coronal structures derived for all three sources is of the order of a few percent of the stellar radius at most, implying very small coronal filling factors and high surface heating fluxes. We searched for correlation with basic stellar parameters and coronal properties and find that the sources presenting evidence of significant optical depth are at the high end of activity level, with \( L_X/L_{\text{bol}} \) at the saturation limit and high densities in their hot plasma, as revealed by the Mg \( \text{x} \) He-like triplet lines.

For the stellar sample as a whole, we also find evidence of increasing quenching of \( \text{Ly_\alpha} \) relative to \( \text{Ly_\beta} \) as a function of both \( L_X/L_{\text{bol}} \) and the density-sensitive Mg \( \text{x} \) forbidden-to-intercombination line ratio. Such a trend is expected in the scenario in which optical depths are significant but generally small: viewing geometry rarely favors large net photon enhancements, but for favorable lines of sight photon depletion is expected to increase with both increasing \( L_X \) and increasing plasma density.

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