SPECTRAL INDICATIONS OF DENSITY VARIABILITY IN THE CORONA OF AD LEONIS

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\textbf{ABSTRACT}

Direct comparison of high-resolution X-ray spectra of the active dMe star AD Leo, observed three times with \textit{Chandra}, shows variability of key density-sensitive lines, possibly due to flaring activity. In particular, a significant long-duration enhancement of the coronal density is indicated by the Ne IX and Si XIII He-like triplets, and possibly also by density-sensitive Fe XXI line ratios.

\textit{Subject headings:} stars: individual (AD Leo) --- stars: activity --- stars: coronae --- stars: late-type --- X-rays: stars

1. INTRODUCTION

The plasma density is a crucial parameter for understanding the structure of stellar coronae. Rather than being uniformly distributed on large spatial scales, as occurs in the photosphere, the coronal plasma is trapped by surface magnetic fields within scale lengths typically much smaller than the stellar radius, and is likely to be very inhomogeneous in density. The patchy appearance of the solar corona in X-rays is mainly a density effect; since the radiative emission of an optically thin plasma excited by collisional excitation is proportional to the square density, the observed irradiance traces preferentially high-density “compact” regions, confined by small-scale magnetic fields. The plasma density is also expected to vary in time owing to the dynamics of these fields and of the plasma itself; in particular, the coronal density is expected to increase \textit{locally} as a consequence of impulsive heating events (flares) which trigger an upward motion of denser plasma from deeper atmospheric layers (“chromospheric evaporation”).

The measurement of plasma densities in stellar coronae is a relatively recent practice in X-ray spectroscopy; Chandra and XMM-Newton high-resolution gratings provide us with a number of density-sensitive emission lines, which are now routinely employed to this purpose. However, density estimates and their interpretation are more difficult and challenging than expected, for several reasons; first, even in relatively strong X-ray sources the relevant emission lines may be difficult to measure owing to low ion abundances, severe blends with other spectral features, or insufficient instrumental sensitivity in the relevant wavelength ranges; secondly, different spectral diagnostics probe coronal regions at different temperatures, and they often yield density estimates which are difficult to reconcile; finally, the lack of spatial resolution in observations of stellar coronae allows us to obtain only “effective” densities, averaged over all the coronal structures in the visible hemisphere and weighted by the plasma irradiance, so that any interpretation becomes model dependent.

For the above reasons, it is currently easier to look for variations with time in the plasma density in a given coronal source, rather than comparing absolute values derived from snapshots of different stars. In this respect, energetic events like stellar flares are natural experiments to examine, and they have been the subject of several investigations in recent years; nonetheless, convincing evidence of density variations are scanty in the literature, with notable exceptions such as the flare recently observed in the nearby dMe star Proxima Centauri (Güdel et al. 2002).

In this paper we present the first evidence of significant long-term density variations in the corona of AD Leo, another well-known dMe flare star observed several times with the \textit{Chandra} X-ray Observatory (Weisskopf et al. 2003). The strength of the present evidence comes from the direct comparison of high-resolution X-ray spectra taken at different times, with little need of data adjustments or problematic atomic models. On the other hand, the interpretation of the results is unclear, but gives some new hints on issues under debate in stellar X-ray spectroscopy and coronal physics.

2. TARGET AND OBSERVATIONS

AD Leo is one of the X-ray brightest single dMe stars currently known, having quite a stable quiescent X-ray luminosity, \(L_x = 3\times10^{28}\) erg s\(^{-1}\) (0.5–4.5 keV band) over a 17 yr period, as determined by Favata et al. (2003). On the other hand, it is also a quite variable X-ray source on short time scales, owing to its characteristic coronal magnetic activity (see e.g. Audard et al. 2000).

AD Leo was observed twice with the \textit{Chandra} Low-Energy Transmission Grating Spectrometer (LETGS) in January and October 2000, as part of the GTO program, and once again in June 2002 with the High-Energy Transmission Grating Spectrometers (HETGS). A detailed analysis of the October 2000 observation was presented by Maggio et al. (2004), including a reconstruction of the plasma emission measure distribution (EMD) with temperature, and evaluation of the plasma densities at various temperatures by means of the He-like triplets and Fe XXI lines. Here we will focus on the comparison of this observation with the previous one, since they have about the same exposure time (48 ks and 46 ks, respectively), and we will also briefly discuss results based on the shorter Jan 2000 observation (10 ks).

The data were retrieved from the \textit{Chandra} archive and reprocessed with the \textit{Chandra} Interactive Analysis of Observations (CIAO V3.1) software. We used the tool FULLGARF to calculate effective detector areas. From each observation we have extracted either the LETGS spectrum (6–140 Å), or both the first-order Medium-Energy Grating (MEG, 1–25 Å) and High-Energy Grating (HEG, 1–18 Å) spectra, simultaneously provided by the HETGS; photons from the two dispersion di-
reactions were coadded to maximize the S/N ratio. We also extracted the spectra in consecutive time bins in order to create the light curves, as described in the following section.

3. ANALYSIS AND RESULTS

3.1. X-ray light curve

Figure 1 shows the X-ray light curves obtained from the three Chandra observations: dispersed spectra were extracted from successive time intervals of equal duration, and total X-ray fluxes were computed in the common wavelength range 7–25 Å, after background subtraction and correction for the instrumental effective area.

No strong isolated flare is visible during these observations, but the Jan and Oct 2000 light curves both show an initial emission level higher than the quiescent one (flux \( \sim 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \)) by a factor \( \lesssim 2 \), followed by a clear decline; this behavior resembles the decay phase of a flare, but we note that in the Oct 2000 light curve the decline is much slower than the expected exponential rate. The latter observation was recently studied by van den Besselaar et al. (2003), who performed a separate analysis of the first 12 ks segment and concluded that the high-temperature tail of EMD was enhanced with respect to the following time segment; on the other hand, Maggio et al. (2004) argue that a rotational modulation effect cannot be completely excluded because the duration of the October 2000 observation is a sizable fraction (\( \sim 20\% \)) of the photometric rotational period \( (P_{\text{rot}} = 2.7 \text{ d}) \), Spiewak & Hawley 1986).

3.2. Analysis and Comparison of Spectra

We have focused our attention on the spectral ranges including the Si XIII, Mg XI, Ne IX, and O VII He-like triplets, and on selected density-sensitive Fe XXI lines. Note that the first three triplets are visible in all LETGS and HETGS spectra, while the O VII triplet can be observed only with the LETGS and the HETGS/MEG. With regard to the Fe XXI lines, we have considered both \( 2s^22p3d \) transitions to the \( 2s^22p^6 \) ground state which fall at wavelengths in the range 12.28–12.53 Å, and transitions from \( 2s2p^3 \) states which are visible at wavelengths 102.2–145.7 Å only in LETGS spectra (Ness et al. 2004, for more details).

![Fig. 1 — AD Leo X-ray light curves (net observed flux in the 7–25 Å wavelength range) derived from the Chandra observations reported in the legend. The fluxes were computed by integrating the dispersed spectra extracted in equal time bins, within each observation.](image)

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>( \log N_e^\beta )</th>
<th>Counts</th>
<th>( A_{\text{eff}} )</th>
<th>ISM</th>
<th>( \lambda/128.73 )</th>
<th>( \log N_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>97.88</td>
<td>12.0</td>
<td>&lt; 10</td>
<td>7.08</td>
<td>0.91</td>
<td>&lt; 0.13</td>
<td>&lt; 12.3</td>
</tr>
<tr>
<td>102.22</td>
<td>12.0</td>
<td>18±8</td>
<td>6.71</td>
<td>0.90</td>
<td>0.19±0.10</td>
<td>&lt; 12.3</td>
</tr>
<tr>
<td>117.51</td>
<td>13.5</td>
<td>&lt; 8</td>
<td>6.17</td>
<td>0.85</td>
<td>&lt; 0.13</td>
<td>&lt; 11</td>
</tr>
<tr>
<td>121.21</td>
<td>12.4</td>
<td>22±9</td>
<td>5.57</td>
<td>0.84</td>
<td>0.30±0.15</td>
<td>12.0–12.9</td>
</tr>
<tr>
<td>128.73</td>
<td>12.7</td>
<td>46±11</td>
<td>3.67</td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>142.16</td>
<td>12.7</td>
<td>&lt; 15</td>
<td>3.87</td>
<td>0.76</td>
<td>&lt; 0.43</td>
<td>&lt; 13.0</td>
</tr>
<tr>
<td>145.65</td>
<td>12.5</td>
<td>15±9</td>
<td>3.69</td>
<td>0.75</td>
<td>0.35±0.23</td>
<td>12.0–13.1</td>
</tr>
</tbody>
</table>

Note: Col 1: theoretical wavelength. Col 2: critical density, and arrow indicating the emissivity trend for increasing \( N_e \). Col 3: observed counts or upper limits. Col 4: LETGS effective area. Col 5: ISM absorption factor, assuming \( N_H = 3 \times 10^{20} \text{cm}^{-2} \) (Cully et al. 1997). Col 6: photon flux ratio. Col 7: estimated electron density.

For the comparison of LETGS and HETGS spectra (Fig. 2) we proceeded as follows. First, we have fitted the relevant lines in the MEG and HEG spectra using the program CORA (Ness & Wichmann 2002), the smooth representation of each spectral region obtained with the above line fitting was converted to energy fluxes by use of the effective areas and exposure times, and finally rebinned to the resolution of the LETGS spectra; this procedure allows the proper overlay of the LETGS and HETGS data for ease of direct comparison.

Note that the line fitting is performed with a maximum likelihood method applied to the total source+background spectrum. In each spectral region the strongest lines are fitted with normalized Moffat profiles (Lorentzians with an exponent \( \beta = 2.4 \)), representing the instrumental line spread function. The instrumental background is not subtracted from the total measured spectrum, but is instead added to the model spectrum consisting of the sum of all emission components. The line counts are obtained as normalization factors of the line profiles.

Figure 2 shows the HETGS vs. LETGS (October 2000) comparison for the Si XIII and Ne IX triplets; the original HETGS/MEG spectrum in the region of Ne IX is also shown. What is immediately evident is the excess emission at the position of the Si XIII and Ne IX intercombination lines (6.69 Å and 13.55 Å, respectively) in the LETGS spectrum with respect to the HETGS case. No such enhancement is visible in the O VII (21.6, 21.8, 22.1 Å) and Mg XI (9.17, 9.23, 9.31 Å) triplets (not shown); note that the latter is affected by low signal to noise ratio because of the relatively low Mg abundance in the corona of AD Leo (Maggio et al. 2004).

We have verified that the above enhancements are still visible, although somewhat reduced, also in the last 32 ks of the October 2000 observations, i.e. where the X-ray emission is again at its quiescent level. Some enhancement is also visible in the Ne IX intercombination line of the January 2000 LETGS spectrum, although the shorter exposure time makes the signal to noise ratio too low for any robust indication.

We have also carefully re-examined the long-wavelength (\( \lambda > 100 \text{Å} \)) region of the LETGS spectrum, for evidence of density-sensitive Fe XXI lines; in particular, we have searched the lines listed in Table I and measured total counts or upper limits, as appropriate. We confirm the detection of the strong 128.7 Å line (Fig. 2), and also of weaker spectral features at \( \lambda \) 102.2, 121.2, and 145.65 Å, already tentatively identified by...
Density variations in the corona of AD Leo

Unfortunately, all the latter three features are characterized by quite a low S/N ratio (2–3σ), and there are residual uncertainties in the wavelength calibration of the LETGS that suggest caution in their identification; they fall at the nominal position of density-sensitive Fe XXI lines, and we will treat them as such in the following. The densities (or upper limits) implied by these diagnostics were estimated from the predicted line ratios (Fig. 3), according to APED (Plasma Emission Database V1.3, Smith et al. 2001); all the observed ratios, properly corrected for the instrument effective area and ISM absorption factor, consistently indicate a density \( N_e \) in the range \( 10^{12.0} \ldots 10^{12.2} \) cm\(^{-3} \), within statistical uncertainties, with the exception of the 117.51/128.73 ratio. Note that the non-detection of the 117.51 Å line is puzzling, because this line is predicted to be relatively strong and very weakly dependent on the electron density, hence we suspect that its theoretical emissivity is overestimated.

It is more difficult to measure the Fe XXI line fluxes at short wavelengths because the spectral region 12.2–12.6 Å is especially crowded with hundreds of relatively faint iron lines, mostly from Fe XIX–XXII. In particular, we have searched for the density-sensitive lines at 12.284 Å, and 12.327 Å. The former has the highest emissivity at densities below \( N_e \approx 10^{12.7} \) cm\(^{-3} \) and it is clearly present in all X-ray spectra we have analyzed, while the second line is expected to become enhanced only in the high-density regime, above \( N_e \approx 10^{12.4} \) cm\(^{-3} \), and it is not convincingly detected in any of the spectra.

**Fig. 2.** — Upper panels: LETG Si XIII and Ne IX triplets compared with scaled HETGS line fitting models. Lower left: LETG spectral region including Fe XXI lines at 121.2 Å and 128.7 Å. Lower right: Ne IX triplet in the MEG spectrum of AD Leo, with 18 best-fit line components.

**Fig. 3.** — Fe XXI predicted density-sensitive Fe XXI line ratios, for the temperature range \( 10^6 \ldots 10^7.2 \) K (lower and upper borders). The shaded areas indicate the density ranges consistent with the data; the vertical lines are placed at the high-density limits.

**DISCUSSION AND CONCLUSIONS**

The measurement of coronal plasma densities by means of X-ray spectral diagnostics is a difficult task (see §1). For example, the Ne IX triplet is heavily blended with Fe XIX lines, and to a lesser extent with Fe XX–XXI lines. A detailed analysis of this spectral region in *Chandra* and XMM-Newton spectra of Capella [Ness et al. 2003] showed that APED is sufficiently accurate and complete that all significant observed...
In any case, the interpretation of widely used spectral diagnostics, such as the He-like triplets or Fe XXI density-sensitive lines, is complicated by the likely existence of density inhomogeneities in the coronal plasma, besides obvious uncertainties in the atomic physics and in our ability to resolve all the relevant spectral components with the available data. In fact, as already pointed out by Güdel (2004), the observed line ratios may not describe “local densities” but rather the steepness of the density distribution with temperature. In this respect, predictions of the coronal X-ray spectra, taking into account physically realistic distributions of the magnetic structures, would be the next step in achieving progress in stellar coronal physics and X-ray spectroscopy.

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