A Lot of Observations of the Coronae of AR Lac

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\textbf{Abstract.} We report on X-ray and EUV observations of AR Lac. Our compiled set of observations from the CXO, EUVE, and RXTE provide the most comprehensive high quality data yet obtained on the time-variability of the X-ray emission of AR Lac. The light curves show significant stochastic flare-like variability that would, in general, render invalid 3-D reconstructions of coronal structure based on sparse or single-orbit coverage. Based on modeling of the observed eclipses, we find that the coronae are extended to $\sim R_\ast$.

1. Observations

X-ray observations of the eclipsing RS CVn system AR Lac were obtained at four different epochs in years 1999 and 2000 with the \textit{Chandra} X-ray Observatory (CXO) High Resolution Camera imaging and spectroscopic detectors (HRC-I, HRC-S) as part of the calibration of the point spread functions of these instruments, and at two different epochs in years 1996 and 1997 with the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA). Extreme ultraviolet (EUV) observations were obtained in 1997 and 2000 by the Extreme Ultraviolet Explorer (EUVE) Deep Survey Photometer. The system parameters of AR Lac are outlined in Table 1. Examples of the \textit{Chandra}/HRC-I and EUVE/DS observations are shown in Fig. 1.

2. Results

The sensitivity of \textit{Chandra}, combined with its high elliptical orbit and continuous 80 hour duty cycle, has provided what are arguably the best quality data yet obtained on the time-variability of the X-ray emission of AR Lac. During one primary eclipse, the HRC-I count rate was observed at approximately 60\% of its value outside of eclipse and during periods of relative quiescence. A similar minimum is seen during one primary eclipse observed by EUVE (Fig. 1, right panel 3). However, other primary eclipses observed by EUVE are not well defined owing to intrinsic source variability. Little evidence for secondary eclipses is present in the data, reminiscent of earlier X-ray and EUV observations (Christian et al. 1996).

The unambiguous eclipses observed with \textit{Chandra} allow us to estimate the extent of the quiescent coronae of $\sim R_\ast$. Modeling the coronae as spherically
Table 1. System Parameters

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<th>Primary</th>
<th>Secondary</th>
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<td>K0 IV</td>
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<tr>
<td>Separation\textsuperscript{a}</td>
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<tr>
<td>Distance\textsuperscript{b}</td>
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<td>Dec (2000.0)</td>
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<tr>
<td>Ephemeris\textsuperscript{c}</td>
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\textsuperscript{a}Chambliss 1976
\textsuperscript{b}Perryman et al. 1997
\textsuperscript{c}Marino et al. 1998 (primary eclipsed at phase = 0)

symmetric atmospheres with intensity decaying exponentially with height above the photosphere, we find that the emission scale heights are $H_{\text{primary}} \approx 1.6$ $R_\odot$, $H_{\text{secondary}} \approx 2.1$ $R_\odot$, and the ratio of intensities is $L_{\text{secondary}}/L_{\text{primary}} \approx 0.2$. The quoted values are the best-fit parameters determined by computing the eclipse models over a grid. Hence, we rule out compact coronae where all emission is confined to $\ll R_*$. Interestingly, the emission scale-heights correspond to thermal scale-heights with log $T \sim 7.2 - 7.6$, which is not too dissimilar to peak temperatures found in detailed EUVE spectral analyses (ex. Griffiths & Jordan 1998). A phase-folded plot of the definitive set of Chandra/HRC-I observations together with the best-fit model light curve is shown in Fig. 2. A similar plot of the EUVE/DS observations, which provide good light curve coverage with several eclipses of depths and widths comparable to those seen with Chandra/HRC-I, is shown in Fig. 3.

The primary eclipse observed by RXTE/PCA (Fig. 4) corresponds to an apparent dip in the count rate which is significantly deeper than that seen with Chandra/HRC-I, and noticeably offset in phase, occurring after by $\sim 0.05$ phase (though flare-like activity precludes definitive analysis). The deeper dip relative to the eclipses seen by Chandra and EUVE would suggest that the hotter emitting regions to which RXTE is sensitive are more compact than the regions dominating the Chandra and EUVE count rates. Indeed, model eclipse light curves for RXTE/PCA observations suggest $H_{\text{primary}} \approx 0.9$ $R_\odot$.

Several moderate flares, in which count rates are observed to increase by factors of 2-3 above quiescence, together with numerous smaller flare-like brightenings, are observed in Chandra, RXTE, and EUVE data. Flare radiative decay times are $\tau \approx 7$ ksec, from which we derive $n_e \sim 7 \times 10^{10}$, for log $T = 7.4$; this value would be a lower limit in the presence of continual post-impulsive heating, and an upper limit in the limit of negligible post-flare heating but significant energy loss by thermal conduction. Enhanced emission was often observed at phase 0.6–0.8 over all epochs in this study (1996–2000).
Figure 1. *Chandra*/HRC-I (left column) and EUVE/DS (right) observations. Data are binned by 100 and 500 seconds, respectively.
Figure 2. Phase-folded Chandra/HRC-I observations with best-fit light curve model over-plotted (grey curve). Data are binned every 100 seconds.

Figure 3. Phase-folded EUVE/DS observations with best-fit light curve model derived from Chandra/HRC-I observations over-plotted (grey curve). Data are binned every 500 seconds.

We note that, in general, 3-D reconstructions of the spatial distribution of coronal emission based on light curves with sparser sampling are likely to be invalid because of the assumption that observed modulations are caused
Figure 4. Phase-folded RXTE/PCA observations with best-fit light-curve model derived from Chandra/HRC-I observations over plotted (grey curve). “Better fitting” model to RXTE/PCA data (black curve) requires emission region to be more compact than Chandra/HRC-I observations indicate. Top/bottom plots show the eclipse, middle plot shows “goodness” of background subtraction. Data are binned by 0.005 phase.

by rotation and eclipses. Instead, the modulations appear to be dominated by stochastic variability and are often non-repeating.

Finally, we have compared the observed Chandra, RXTE, and EUVE count rates for periods of relative quiescence to earlier EUVE, EINSTEIN, EXOSAT and ROSAT count rates outside of discernible flares (Christian et al. 1996). The observed “quiescent” count rates are: 5.5 count s$^{-1}$ (Chandra/HRC-I), 0.3 count s$^{-1}$ (EUVE/DS), 4.0 count s$^{-1}$ (RXTE/PCA). Modeling the coronal emission in PIMMS as an optically thin, collision-dominated plasma with $T \sim 10^7$, these count rates correspond to an X-ray flux $f_x \approx 4 - 7 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. Therefore, the level of “quiescent” coronal emission at short wavelengths is essentially constant and has varied by less than a factor of two since the first c.1980 EINSTEIN observations of Walter, Gibson, & Basri (1983).
Acknowledgments. This work was supported by Chandra X-ray Center NASA contract NAS8-39073.

References

Marino, G., Catalano, S., Frasca, A., & Mavilli, E. 1998, IBVS, 4599