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I. INTRODUCTION

Traditionally stellar sizes and shapes have been determined by analyzing the optical light curves of eclipsing binaries. Now it is possible to extend our knowledge to structures above the photosphere by making similar observations at X-ray, UV, and radio wavelengths. We report the first such observations, together with their geometrical and physical interpretation, which allow us to determine coronal and chromospheric properties of the stars in the RS CVn binary AR Lac. In this paper we discuss the properties of the system, Einstein observations which provide a reasonably good X-ray light curve, IUE data which enable us to tie the inferred coronal features to the surfaces, and radio observations which allow us to separate geometric and intrinsic variations by acting as a flare monitor. We also discuss the construction of simple coronal model which, when applied to the X-ray light curve, yields the sizes and shapes of the coronae in this system. In another paper (Paper II: Walter, Gibson, and Basri, 1982), the geometrical properties of the coronae are discussed and used to determine the physical conditions within.

II. PROPERTIES OF AR LAC

AR Lac is ideally suited for a study of this type. It is the nearest (40 pc; Chambliss, 1976) eclipsing RS CVn binary. It exhibits the full range of phenomena usually attributed to the class (Hall, 1976) including bright X-ray emission ($L_x \sim 10^{31}$ ergs s⁻¹; Walter *et al.*, 1980) and strong radio flaring (Gibson and Hjellming, 1974). It has a short period, $P = 1.98$ days, and nearly central eclipses ($i = 87^\circ$) which allow for geometrically simple models of coronal structures.

The primary star is of spectral type G2IV, with a radius of $1.55R_\odot$ and mass $1.35 M_\odot$, while the secondary is of spectral type KOIV, with a radius $2.81 R_\odot$ and mass $1.35 M_\odot$ (Chambliss, 1976). The semi-major axis of the system is $9.1 R_\odot$. We have adopted the ephemeris of Hall (1980)

$$JD (\phi=0) = 2439376.4973 + 1.9831956E$$

in computing our models.

III. THE X-RAY LIGHT CURVE

The X-ray observations of AR Lac began at phase 0.023 on 1980 June 13 and ended two days later at phase 0.027, giving a short overlap during primary eclipse. The total time on target was 29414 sec or 17% of the orbital period. Data were taken during egress from primary eclipse, ingress into secondary eclipse, and at both quadratures. We show these data in Figure 1 together with Einstein MPC (2–10keV) data and the times of complementary IUE and radio (Feldman, 1980) observations.

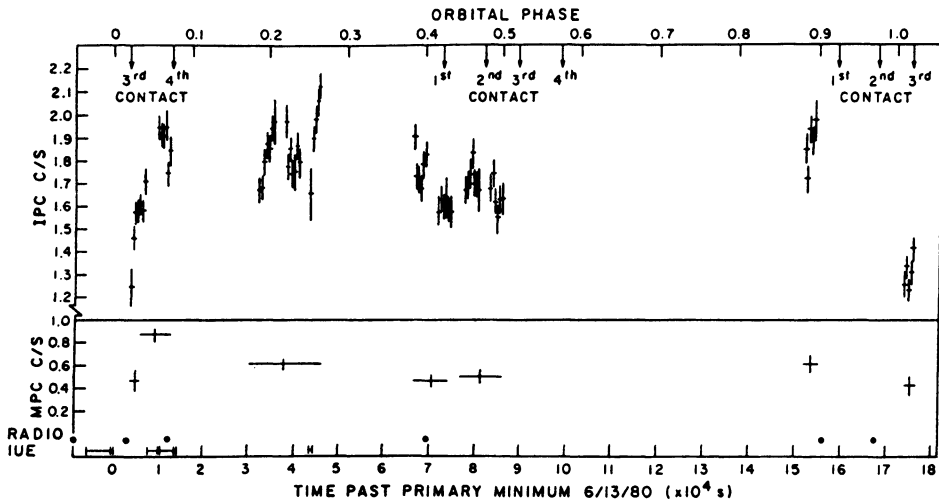


Figure 1. X-ray light curve for AR Lac. 1st and 4th contacts are points of external tangency, 2nd and 3rd contacts are points of internal tangency for the primary (G-star behind) and secondary eclipses.

There are several remarkable features in these data:

a) The out-of-eclipse observations around phases 0.2 and 0.9 show significant variations. We note this aspect of the light curve first to emphasize that although these variations complicate efforts to interpret the light curve geometrically they cannot be unexpected since bright coronae probably result from highly dynamic processes. Nevertheless, both quadratures have the same average count rate, 1.86 cts s^{-1} . We assume this represents the mean level of the system for subsequent analyses and refer eclipse levels to this value.

b) Primary eclipse appears to be total, with both observations prior to third contact giving a level of 1.26 cts s^{-1} . Thus, the G-star contributes 30% of the system's X-ray flux. Egress from primary eclipse in X-rays begins immediately after third contact (see Figure 2a)

suggesting the coronal height is small ($h_G \sim 0.02R_G$). However, these data are complicated by either a flare or the uncovering of an X-ray bright active region as shown by the factor of two increase on the MPC count rate 5500 sec past primary eclipse.

c) Secondary eclipse appears to be shallow and very wide. The deepest part of the eclipse occurs near first contact where the count rate is down 14% from the quadrature values. The length of the eclipse allows one to infer the extent of the K-star's corona in the equatorial plane to be $\sim 1R_K$. The coronal height and the observed depth of the eclipse through ingress combine to constrain the size of the K-star's corona to $\lesssim 30^\circ$ latitude.

IV. THE ULTRAVIOLET AND RADIO DATA

Six ultraviolet spectra were taken with the IUE satellite on 1980 June 13. They show the usual range of emission lines from the chromospheres and transition regions though at somewhat lower surface fluxes than other RS CVn systems. The most significant results come from the two high-dispersion long-wavelength (LWR-HI) Mg II h and k spectra which separate the two stars in velocity and were taken at phases 0.05 (when the G-star is about half uncovered) and 0.26 (at quadrature). The blue-shifted (G-star) line strengths increased by only one-third from the former to the latter exposure suggesting that the inner-leading quadrant of the G-star is three times more active than the outer-leading quadrant.

The red-shifted (K-star) line strengths, on the other hand, increased by a factor of 2.6 over the same interval. Examination of a low-resolution long-wavelength (LWR-LO) spectrum taken at phase 0.082 indicates the increased emission seen at quadrature has begun to appear. This indicates there is a bright plage region on the inner-trailing edge of the K-star at about stellar longitude 300° . It is interesting to speculate that this increased activity is related to the "flare" seen in X-rays which begins at phase 0.032. If a flaring loop were uncovered by stellar rotation, then X-rays from the top of the loop would be observable "over-the-limb" before the UV-emission from the base. The phase delay in the appearance of the UV-emission relative to the appearance of the X-ray emission could be used to estimate the height of the loop -- in this case $0.01 R_K \lesssim R_L \lesssim 0.05 R_K$.

AR Lac was not detected in radio observations by Paul Feldman (1980) using the 45-m telescope at Algonquin Radio Observatory at 2.8 cm. The individual upper limits (3σ) for each of the six 15-minute integrations (see Figure 1) was 15 mJy. Thus, the source was radio quiet even during the presumed flare during egress from primary eclipse.

V. SYNTHETIC X-RAY LIGHT CURVES

We have attempted to fit the IPC data using simple models based on the morphology of the solar corona and general characteristics of the

RS CVn binaries. Thus, our model coronae are equatorially symmetric, though they may be latitudinally confined. They are optically thin, but rather than modelling them as a sum of discrete emission regions, as is appropriate for the sun, we assume the emission arises in shells since the high X-ray luminosity suggests there should be a very large number of loops (Walter *et al.*, 1980) on each star. To mimic the "photometric wave" in X-rays we incorporate the option of a sinusoidal coronal wave. Based on these data and studies by Swank and White (1980) we assume that the G-star has a single-temperature corona at 8×10^6 K, while the K-star has a two-component corona with the inner one also of 8×10^6 K and an outer one at a temperature of 3×10^7 K.

Our model fits to the egress from primary eclipse and the ingress into secondary eclipse are shown in Figures 2 and 3. Egress from primary eclipse begins almost at third contact (implying the coronal depth of the G-star is small and increases rapidly until about 8000 seconds past mid-eclipse, the time of the probable flare (see Figure 2b). The increase appears too rapid to be modelled by a symmetric corona (dashed line) and is modelled more satisfactorily by a sinusoidal corona (solid line) in which the leading hemisphere of the star is brighter. This is consistent with the UV results. The high points around 10^4 sec after mid-eclipse may be due to the uncovering of progressively cooler flaring material as the K-star rotates.

Ingress into secondary eclipse is much more difficult to fit, though three aspects of the K-star's hot coronal component seem irrefutable: the corona is highly extended ($1.5 R_K < R_{hot} < 2.0 R_K$), is latitudinally confined ($lat_{hot} < 30^\circ$), and is also asymmetric in that its more luminous side is above the leading hemisphere. This asymmetric extended component is shown as the dashed line in Figure 3b. Taking the inner component to the asymmetric in the opposite sense (see dotted line in Figure 3b) seems to provide a better fit to ingress into secondary eclipse (see solid line in Figure 3a) but lacking data from egress from this eclipse we feel this conclusion is much less justified.

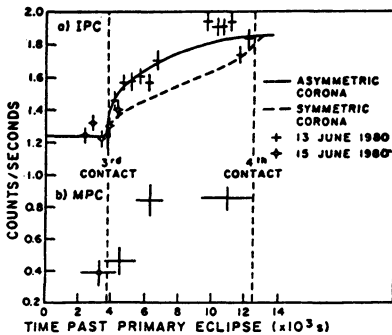


Figure 2. AR Lac's X-ray egress from primary eclipse. Though complicated by a flare, the data still require the G-star to have a brighter leading hemisphere.

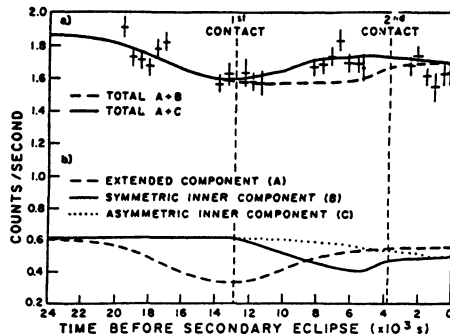


Figure 3. AR Lac's ingress into secondary eclipse. The model requires the hot outer component of the K-star's corona to be highly extended, latitudinally confined, and brighter on the leading edge.

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DISCUSSION

ROSNER: Do you recall at what phase(s) Swank and White measured the SSS (Solid State Spectrometer) spectra of AR Lac?

GIBSON: Yes. They observed at both primary and secondary minimum, but probably recorded a flare during the primary. Therefore, we used the secondary in setting the amount of flux at each temperature.

VILHU: Is there a photometric wave present in the optical light curve? If so, can that be explained by dark spots situated at the *same* place where your coronal belts are (at the particular time of your observations)?

GIBSON: Yes. The brighter hemisphere in X-ray emission corresponds to the longitude of the spots on the G star.