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AM HERCULIS: SIMULTANEOUS X-RAY, OPTICAL, AND NEAR-IR COVERAGE

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ABSTRACT

A 6 hour X-ray pointing at AM Her using the *HEAO 1* satellite is correlated with simultaneous broad-band *V* and *I* photometry and visual circular polarimetry. The absence of correlations on either a flickering or an orbital time scale implies distinct regions for the visual and X-ray emission. Significant changes in the light curves are observed from one binary cycle to the next.

Subject headings: polarization — stars: binaries — stars: individual — X-rays: binaries

I. INTRODUCTION

Since the first suggestion that the optically variable star AM Her was the visual counterpart of the X-ray source 3U 1809 + 50 (Berg and Duthie 1977), observations covering wavelengths from the X-ray through the infrared have revealed many interesting and puzzling aspects of this object. A 3.1 hour orbital period for the system has been established with polarization measurements (Tapia 1977; Michalsky, Stokes, and Stokes 1977; Stockman and Sargent 1979), and observations of periodic minima in X-rays (Hearn and Richardson 1977; Swank *et al.* 1977; Bunner 1978; Tuohy *et al.* 1978), ultraviolet (Raymond *et al.* 1979), optical (Szkody and Brownlee 1977; Priedhorsky and Krzeminski 1978), and infrared (Jameson *et al.* 1978; Priedhorsky *et al.* 1978). The shape and depth of the minima are observed to vary from cycle to cycle. The system also has long-term high ($V \sim 12.5$) and low ($V \sim 15$) states. Rapid light variations (flickering) on time scales of minutes or less occur at all wavelengths.

Proposed models for AM Her involve an M4–5 main-sequence star (Young and Schneider 1979) transferring matter to a highly magnetic white dwarf ($B = 10^7$–10^8 gauss). Most of the optical and ultraviolet light from the system is thought to be cyclotron emission from an accretion funnel at one or both of the poles of the white dwarf. The orbital variations in the X-ray and optical light are tied to the effects of self-absorption in an accretion column(s) and eclipse by the white dwarf of parts of the column(s) (Stockman *et al.* 1977; Chanmugam and Wagner 1977; Priedhorsky and Krzeminski 1978; Kruszewski 1978). The most detailed physical theory of accreting magnetic degenerate dwarfs has been developed by Lamb and Masters (1979). Recent observations in the ultraviolet, however, challenge this model unless substantial modifications to the theory are made (Raymond *et al.* 1979).

To investigate the interrelationship of the different spectral components and thus better constrain models for the geometry and physics of the emission region, simultaneous X-ray, visual, near-IR, and circular polarization observations of AM Her were obtained. While similar studies in *V* and *R* (Bailey, Mason, and Parkes 1977), circular polarization and *V* (Stockman and Sargent 1979), and *U*, *V* and λ4686 (Szkody and Margon 1980) have been made, this is the first simultaneous X-ray and optical observation published.

II. THE OBSERVATIONS

The *HEAO 1* X-ray satellite was pointed at AM Her on 1978 April 18 UT for almost two binary orbits, with coordinated ground-based observations for most of this time. AM Her was in a high state ($V \sim 12.5$–13) during these measurements.

Visual observations were conducted at the Mount Palomar 1.5 m telescope (F.A.C. and I.R.T.) with an S-20 phototube and *V* filter. Five second integrations were used (but delay times at the printer gave 5.39 s bins). Corrections for extinction were accomplished through repeated observations of AM Her W ($V = 12.20$; Priedhorsky and Krzeminski 1978).

I-band observations with a time resolution of 15 s were made at the Steward Observatory 1.5 m telescope (W.W.) with a Varian-159A detector. Magnitudes were obtained by comparison with the star 80″N of AM Her ($V = 13.10$, $I = 12.21$). The magnitudes were converted to intensity for an easier comparison with the visual and X-ray data.

The circular polarization data also were obtained at Steward Observatory (H.S.S., J.R.P.A.) with the 91 cm telescope in unfiltered light (bandpass about 3200–8600 Å for the C31034A photomultiplier used). Three 2 s integrations were averaged together to create 6 s bins with an average polarization error of less than 1%. Thin clouds at the beginning of the night caused sky changes of about 20% which affected the absolute value of the circular polarization by about 5%.

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The X-ray data presented here span only the energy range 0.1–0.5 keV. (A detailed treatment of the soft X-ray data alone is given by Tuohy *et al.* (1980). The simultaneous hard X-ray data have been briefly summarized by Swank 1979). For this paper the soft X-ray data, which were taken with a 1.28 s sample length, have been grouped into 5.12 s bins.

III. RESULTS

The available soft X-ray, *V*-band, *I*-band, and polarization data over a five and one-half hour interval are shown in Figure 1. The phasing was computed using the following convention:

$$\phi_0 = 2{,}443{,}014.71266 + 0.12892774E$$
$$\phi_m = 2{,}443{,}014.765 \quad + 0.12892774E\ .$$

The T_0 for the optical phase ϕ_0 is taken from Szkody and Brownlee 1977, while the T_0 for the polarization phase ϕ_m is taken from Tapia 1977. The refined orbital period is from Young and Schneider 1979.

a) *A Comparison of the Orbital Variations*

The two binary cycles of AM Her shown in Figure 1 have the gross characteristics previously reported by other authors, i.e., deep *V* and *I* primary minima and a shallower *V* secondary minimum, a soft X-ray minimum not in phase with the *V* and *I* primary minima, and a polarization "standstill" during the optical primary minimum. There are, however, interesting properties peculiar to these two cycles.

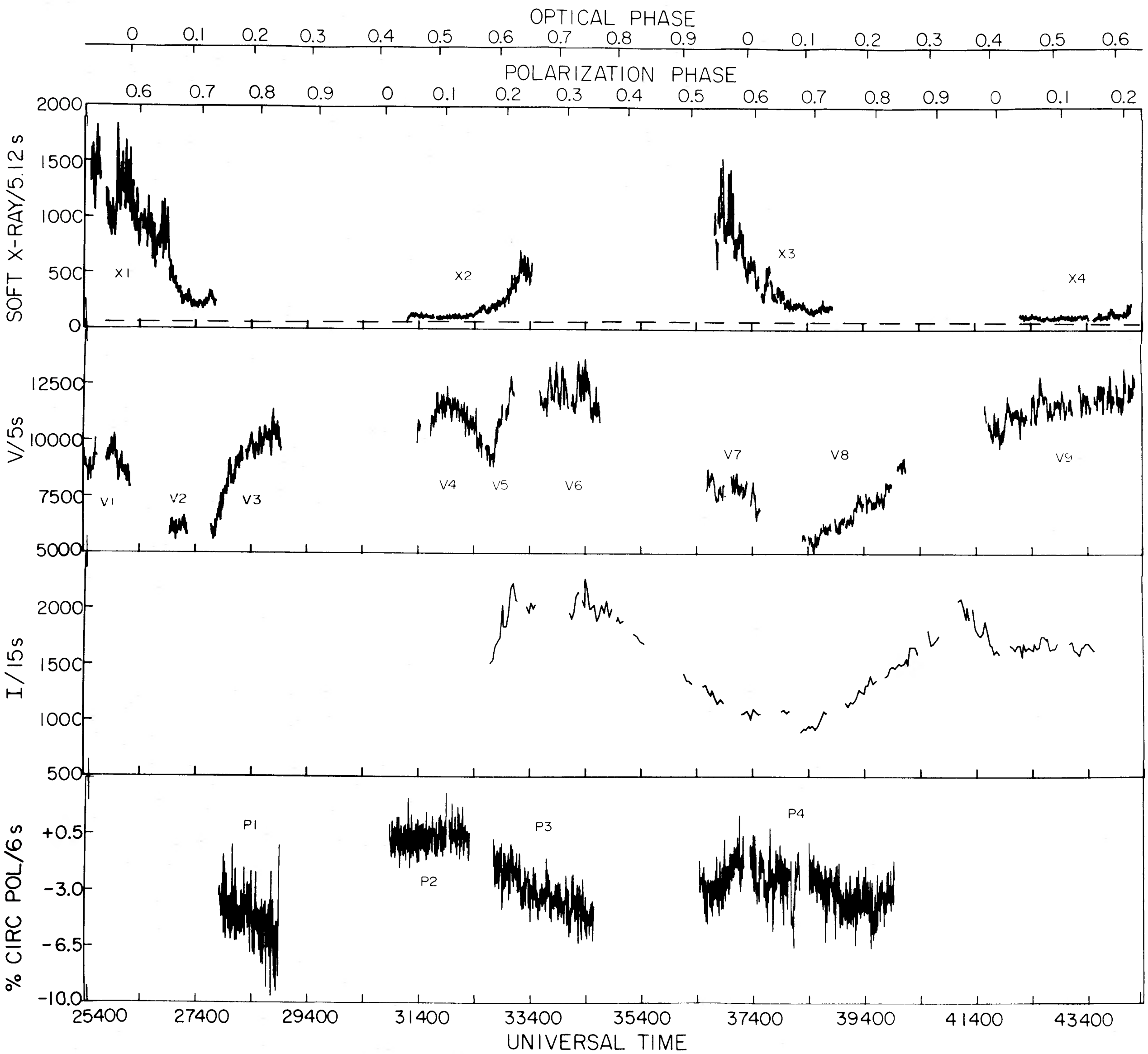

FIG. 1.—The light curves of AM Her on 1978 April 18 UT: (a) X-ray (0.1–0.5 keV); (b) *V*-band; (c) *I*-band; and (d) % circular polarization. The dashed line in (a) denotes the X-ray background level. The errors for the circular polarization data (see text) are much larger than for the approximately statistical errors of the X-ray, *V*, and *I* data.

TABLE 1

SUMMARY OF V AND X-RAY AUTOCORRELATIONS

Section	Mean	$\sqrt{\text{Variance}}$	$1/e$ (s)	Start (UT s)	End (UT s)	Correction Factor
V1	9075	335	17	25410	26239	1.09
V3	8935	361	17	27689	29005	1.07
V4	11110	322	10	31625	32550	1.12
V6	12074	614	24	33579	34832	1.03
V7	7757	263	19	36592	37549	1.13
V8	6617	248	40	39905	40160	1.12
V9	11707	399	21	41641	44321	1.08
X1	957	187	17	25827	27050	1.03
X2	138	17	43	31725	32785	2.01
X3	790	165	12	36763	37536	1.03
X4	124	18	33	42211	44212	1.62

The center of the V and I minima occur ~ 0.1 in phase *later* than the primary minima most often observed by previous experimenters (see, for example, the composite optical light curves of Priedhorsky and Krzeminski 1978 and Priedhorsky *et al.* 1978). A shallow V secondary minimum is not centered on the X-ray minimum (cf. Priedhorsky and Krzeminski 1978); the V secondary minimum is only detected during the first orbital cycle. Although uncommon, both the primary minimum delay and the transience of the secondary minimum have been observed previously (e.g., Bailey, Mason, and Parkes 1977). The I secondary minimum also differs from that observed before. In the second orbital cycle there is a slight decrease (0.2 mag) in the I intensity beginning at $\phi_m = 0.0$ and remaining at a constant level for at least 0.2 in phase. Unlike previous observations this minimum was not coincident with a V secondary minimum.

As apparent in both cycles in Figure 1, the "downward step" in the soft X-ray light curve observed by Tuohy *et al.* (1978) between phase, $\phi_m = 0.8$ and 1.0 begins at a much earlier phase: $\phi_m \approx 0.7$ in the first orbital cycle, and $\phi_m \approx 0.6$ in the second cycle. This step takes place during the (displaced) optical minimum.

b) *A Search for Flickering Correlations*

To investigate the nature of the short time-scale variability and any correlation between the different regions of the spectrum, autocorrelation functions were computed for each section of data and cross-correlations were made for overlapping data in the X-ray, visual, and polarization bands. In Figure 1 each large section of data used for the correlation analysis is numbered. Within the sections the actual intervals of time that were used for the autocorrelations are listed in Table 1. These intervals were selected to avoid large data gaps and to provide overlap, where possible, between the various wavelength bands. When short gaps occurred, linear interpolations between the existing data points were used to fill the gaps (such as occur in V1, V7, etc.). The I-band data were not taken with a constant time interval between measurements and so were not appropriate for autocorrelation analysis.

Each section of data was fit with a third-order polynomial, and residuals with respect to this fit were used to calculate the autocorrelation functions as follows:

$$A(\tau) = \frac{\sum_{i=1}^{N-\tau} R_i R_{i+\tau}}{\sum_{i=1}^{N-\tau} R_i R_i} ,$$

where τ is the time lag, the R's are the residuals, and N is the number of data points. A correction was made for noise by multiplying all lags other than the zero lag by the factor: variance/(variance-mean), according to the prescription of Weisskopf, Kahn, and Sutherland (1975). The variance =

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} R_i^{\,2} .$$

No correction has been made to the V-band data for seeing noise since the aperture used was large enough to include 99% of the light of the star.

The results of the autocorrelation are given in Table 1 for the V-band and X-ray data, and in Table 2 for the polarization data. The section numbers refer to designations denoted in Figure 1. Four of the V autocorrelations that match the X-ray sections are shown in Figure 2. Each section has a different shape—some show evidence of a

TABLE 2

SUMMARY OF POLARIZATION AUTOCORRELATION

Section	Mean pol. (%)	Variance	Ave. pol. error (%)	$1/e$ (s)	Start (UT s)	End (UT s)	Correction Factor
P1	−4.72	2.13	1.66	12	27822	28902	4.5
P2	0.17	0.59	0.66	...	30882	31896	...
P3	−3.15	0.83	0.56	14	32753	34547	3.1
P4a	−2.32	0.83	0.65	...	36443	37241	4.6

1980ApJ...241.1070S

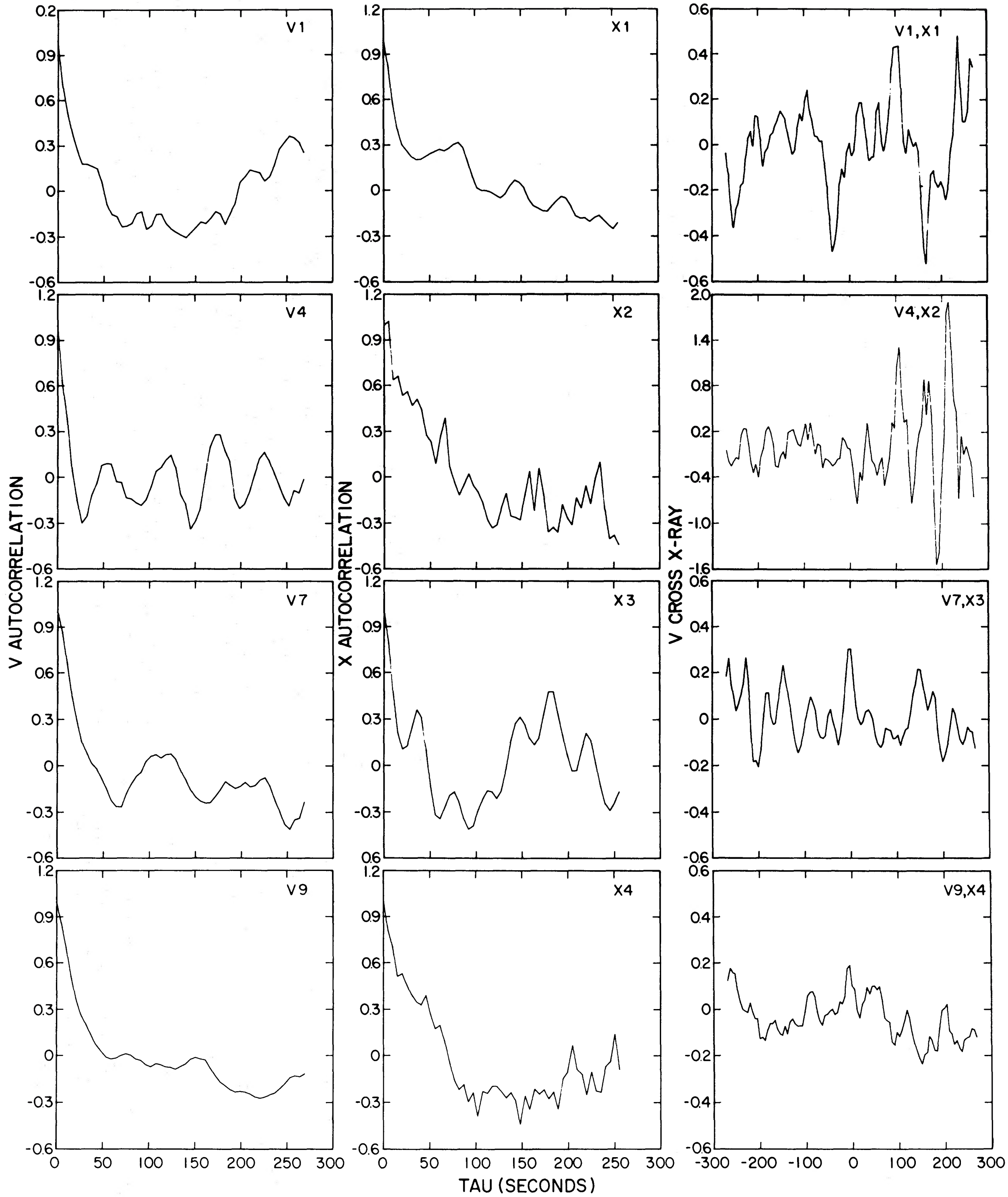

FIG. 2.—Autocorrelations and cross-correlations for the segments of the V and X-ray data that overlap. The numbers correspond to the sections shown in Fig. 1.

"ringing" (V4, V7), while others are fairly smooth (V9). Sections V3, V6, and V8, which are not shown, are also fairly smooth.

The upper limits to the exponential decay times for all sections of the data range from 10 to 43 s. Sections X2 and X4 have large correction factors associated with them (see Table 1) because most of the data in these sections are of very low signal strength; thus the time lags derived for these sections have much larger upper limits. The correction factors for the polarization data are also very large because the magnitude of the polarization error is approximately the same as the variance; hence there are large uncertainties associated with these decay times also.

Evidence of quasi-periodic behavior is seen in V4 ($P \sim 55$ s) and X3 ($P \sim 35$ s). This type of behavior has been noticed in U and V light (Szkody and Margon 1980), but on longer time scales (~ 80 s). What is most interesting is that when the periodicity or ringing is present in the V, it is not present in the X-ray and vice versa. See, for example, Figure 3, which is an expanded plot showing the quasi-periodicity in X3 and the lack of a similar periodicity in the simultaneous V7.

To further investigate a correlation of the visual and X-ray data, cross-correlations were computed. As a first step, the X-ray data (1.28 s integrations) were rebinned so that the integrations were in phase with the V-band data (5.39 s timing). Then third-order polynomials were fitted to each overlapping data set and the residuals cross-correlated according to:

$$C(\tau) = \frac{1}{N-\tau}\frac{1}{\sqrt{(\sigma_x{}^2 - \bar{x})}}\frac{1}{\sqrt{(\sigma_v{}^2 - \bar{v})}}\sum_{i=1}^{N-\tau} V_i X_{i+\tau}\,,$$

and

$$C(-\tau) = \frac{1}{N-\tau}\frac{1}{\sqrt{(\sigma_x{}^2 - \bar{x})}}\frac{1}{\sqrt{(\sigma_v{}^2 - \bar{v})}}\sum_{i=\tau}^{N} V_i X_{i-\tau}\,,$$

where $\sigma_x{}^2$ and $\sigma_v{}^2$ are the variances, and $\bar{x}$ and $\bar{v}$ are the mean values of the X-ray and visual data, respectively.

The results are shown in Figure 2. Essentially there is no strong correlation (≥ 0.2) between the X-ray and visual light (the large variations present at long lags in V4, X2 are probably due to deviations from the polynomial fit to the last portion of X2). Admittedly, greater overlap between the X-ray and V would have been desirable to test the correlation more thoroughly. As can be seen in Figure 1, when the X-ray emission is strong and evidences large flickering (X1 and X3), the V data are patchy (V1 and V7). A cross-correlation of X3 with the first polarization section in P4 also shows no significant correlation, although, as noted previously, the polarization data have large errors associated with them.

IV. DISCUSSION

It is fruitful to place the observations reported here in the context of previous work. Since its discovery as an X-ray source in 1976, AM Her has been in its high state except for two short excursions to the low state in 1976 May 1976 and 1977 February. During this time, extensive optical intensity and polarization measurements have been published for the high state, but only minimal intensity coverage with no polarization data are available for the low state (see references in Chiapetti, Tanzi, and Treves 1980 review). Four soft X-ray observations exist: one during the low state in 1976 May (Hearn and Richardson 1977) and the other three during the high state in 1976 November (Hearn 1979, private communication), 1977 September/October (Tuohy *et al.* 1978) and 1978 March/April (Tuohy *et al.* 1980). Only one other set of I-band measurements are published (Priedhorsky *et al.* 1978); these also were made during the high state.

In the optical region, changes from the high to low state are characterized by an overall decrease in brightness by

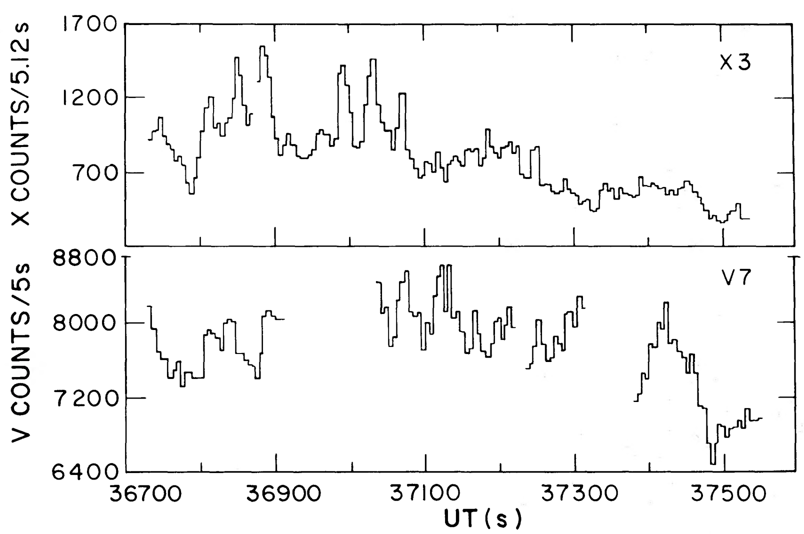

FIG. 3.—An expansion of the X-ray and V light curves corresponding to sections X3 and V7 in Fig. 1. The plot clearly shows a quasi-periodic ~ 35 s component in X3 that is absent in V7.

about 3 mag with an increase in the depth of the secondary minimum relative to the primary minimum (Priedhorsky *et al.* 1978; Szkody 1978). However, the soft X-ray light curves from the low in 1976 (Hearn and Richardson 1977) and the high in 1977 September/October (Tuohy *et al.* 1978) look approximately the same: the highest intensity occurs at $\phi_m \sim 0.4$–0.8 with a decrease in flux by about a factor of 2 beginning at $\phi_m \sim 0.8$–1.0 and lasting ~ 0.15 in phase. Thus, there does not appear to be a correlation between the gross features of the X-ray light curve and the visual state of the system.

On the other hand, there are various changes evident when comparing different observations made during the high state. Long-term variations in the amplitude of the polarization as a function of wavelength have been observed (Stokes and Michalsky 1979, private communication); intensity changes by several tenths of magnitudes are apparent in the light curves; and changes in the width and shape of primary minimum have been reported (Szkody 1978). However, it is not known whether these changes are random or are cyclic on a time scale other than the orbital period.

The X-ray observations during the high state also show differences. During the five days of *SAS3* soft X-ray data taken in 1976 November (Hearn 1979, private communication), when the overall X-ray intensity was twice as high as the low state observation in 1976 May, the composite light curve exhibited three humps of approximately equal extent and brightness with three minima occurring at $\phi_m = 0.2$, 0.5, and 0.9. One of the humps occurred during the phase of the previous 1976 May minimum, while one of the minima ($\phi_m \sim 0.5$) occurred during the 1976 May phase of greatest X-ray intensity. These X-ray data are the strongest evidence yet for the existence of a second X-ray pole. Conceivably, changes in the mass accretion rate onto the white dwarf could switch a predominantly one-pole accretor into a two-pole accretor, or precession of the poles might influence long-term changes in the X-ray emission. The relationship of the X-ray to optical light during this observation is not clear. During the period of the X-ray observations, the secondary visual minima were absent (Priedhorsky and Krzeminski 1978), while the primary minimum and rest of the light curve were relatively "normal." But on the basis of Figure 1, it is apparent that the secondary minimum can change from one cycle to the next, so that the exact correlation with the peculiar X-ray curve is not known.

The X-ray observation discussed in this paper has been analyzed in detail along with another *HEAO 1* pointing in 1978 March by Tuohy *et al.* (1980). These data are the first in which continuous soft X-ray light curves were obtained, and they show that significant changes in soft X-rays can also occur from orbital cycle to cycle. While the light curves are basically similar to the 1976 May and 1977 September/October observations, the better time resolution shows very large amplitude flickering and considerable changes in the area around $\phi_m \sim 0.6$–0.0 which cannot be directly correlated with any large-scale changes in the optical light curve at these times.

The only obvious correlation that appears out of all the data is that the primary X-ray and optical minima always appear considerably out of phase. The data taken to date, however, are insufficient to determine whether large-scale changes in the optical, IR, and polarization light curves are correlated with gross changes in the X-ray light curve (e.g., the presence or absence of secondary minima or the phase of the downward X-ray step). Whether or not there is a pattern to these changes can only be determined with much longer continuous simultaneous observations. The usual procedure of folding data with the 3.1 binary period may even be hiding important features that occur periodically on time scales less than an orbital period.

On a much shorter time scale, the X-ray, V-light, and polarization data discussed here evidence similar e-folding autocorrelation times, that is, $\langle\tau\rangle \sim 10$–$20$ s. This decay time is similar to the autocorrelation times found in a different observation of V, U, and $\lambda 4686$ (Szkody and Margon 1980) and from an analysis of circular polarization and V data derived by Stockman and Sargent (1979). It is also the time scale found in the related class of cataclysmic variable stars during their high states (cf. Cordova 1979).

Unlike the previous optical correlation studies mentioned above (see also Bailey, Mason, and Parkes 1977), the analysis of the soft X-ray and V data presented here show no evidence for a correlation $\gtrsim 20\%$. Thus there is not the simple relation between the X-ray flux and optical flux that might be expected in accretion (cyclotron) models or X-ray heating models. If the optical and soft X-rays come from different regions in the same accretion column, the optical light is not reprocessed X-rays unless either the X-ray or optical variations are due to opacity (i.e., electron scattering) effects. Alternatively, it may be that the visual and X-ray are produced in two different columns, each characterized by a different magnetic field strength (e.g., see Kruszewski 1978; King and Lasota 1979). Complicated geometries may also be envisioned wherein the optical emission region is illuminated by different X-rays (perhaps beamed) than the X-rays seen by the observer.

The observations reported here do not solve the problem of where the soft X-rays or the optical light originate. These measurements do, however, demonstrate the value of doing simultaneous observations and the need to do them over a continuous and long time base. Since AM Her exhibits such extreme variability it is necessary, for a better understanding of the relationship between the various line and continuum emission regions, to make *simultaneous* measurements at wavelengths ranging from the X-ray to the infrared.

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