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POINTED SOFT X-RAY OBSERVATIONS OF AM HERCULIS FROM *HEAO 1*

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ABSTRACT

We present the most extensive soft X-ray (0.1–1.5 keV) observations of AM Herculis reported to date. The data, acquired during two pointed observations by *HEAO 1* in 1978, collectively span four binary cycles and reveal considerable detail in the 3.09 hour light curve. Rapid X-ray flickering is evident throughout the bright section of the light curve ($\phi \approx 0.0$–0.8) and is characterized by an average *e*-folding autocorrelation time of ~ 10 s. No persistent X-ray pulsations are present, although quasi-periodic behavior with periods of ~ 20–60 s is occasionally observed. Analysis of the spectral data indicates $\sim 30\%$ variability; on occasion the X-ray spectrum becomes softer as the source intensity decreases, but this apparent correlation is not always present. We assess our current understanding of AM Her as an accreting magnetic white dwarf and relate various models to the present *HEAO 1* data. Possible explanations for the spectral variability and short time scale behavior of AM Her are considered.

Subject headings: stars: individual — stars: magnetic — stars: white dwarfs — X-rays: binaries

I. INTRODUCTION

In a previous paper (Tuohy *et al.* 1978*b*, hereafter Paper I), we reported the results of *HEAO 1* soft X-ray scanning observations of AM Herculis during 1977. These observations yielded an average light curve for the 3.09 hour period of AM Her which showed considerable scatter in the source intensity as a function of phase, as well as evidence for a small residual flux during X-ray minimum. We also measured the soft X-ray spectrum in the range 0.1–3 keV and detected a low energy turnover due to absorption at ~ 0.2 keV. However, owing to the scanning nature of the observations, it was neither possible to obtain a continuous measurement of the light curve, nor to investigate the temporal behavior of the flux and spectrum on short time scales. These aspects are emphasized in the present paper, which presents the results of two pointed observations of AM Her during 1978. A preliminary account of the observations has been given previously (Tuohy *et al.* 1978*a*).

II. EXPERIMENT AND OBSERVATIONS

The two Low Energy Detectors (LEDs) of the *HEAO 1* A-2 experiment[1] are described in detail by Rothschild *et al.* (1979). Both detectors are propane-filled proportional counters with one micron polypropylene windows and are sensitive to X-rays between 0.1 and 3 keV. LED 1 is used for pointed observations; this detector has a total effective area of 380 cm^2 which is shared by two coaligned fields of view measuring $1.^\circ5 \times 3^\circ$ and $2.^\circ8 \times 3^\circ$ FWHM. LED 2 is offset by 6° from the axis of LED 1 and acts as a low energy background monitor during spacecraft pointings.

AM Herculis was observed during two 6-hour intervals at the following times: 1978 March 28, 1407–2000 UT; and 1978 April 18, 0603–1217 UT. Both pointings spanned nearly two binary cycles of the source, with periodic gaps in the coverage due to Earth occultation. These gaps occurred at the same source phase in the two consecutive cycles (since the satellite orbital period is half the AM Her binary period). The second pointing, therefore, was scheduled to fill in the gaps which occurred during the first pointing. A total of six additional smaller gaps in the second cycle of the first pointing resulted from a sequence of "ping-pong" maneuvers which alternately moved the field of view of LED 1 to AM Her and to a background region. The spacecraft displacement angle was chosen to be exactly 6°, so that AM Her was in the field of view of LED 2 while background data were being accumulated by LED 1. However, LED 2 was operated at

[1] The A-2 experiment on *HEAO 1* is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL, and UCB.

a lower high-voltage setting than LED 1, thereby giving it a reduced sensitivity to low energy X-rays.

During the two pointings at AM Her, LED 1 was configured to give scaler readouts at 20 ms and 1.28 s intervals, together with a 32 channel measurement of the pulse height spectrum every 10.24 s. Owing to a commanding problem, however, no pulse height data were acquired from the March pointing.

III. LIGHT CURVE

The binary phase of AM Her during each pointing has been calculated using the same ephemeris as Paper I in order to facilitate comparison of the two sets of data; i.e., a period of $0^{d}.128927$ (Priedhorsky and Krzeminski 1978) and an epoch for phase zero of JD $2,443,014^{d}.7647$ corresponding to the center of the linear polarization event observed by Tapia (1977). The refined period of $0^{d}.12892774 \pm 0^{d}.00000012$ derived by Young and Schneider (1979) implies that, at the time of our April observation, an event which occurred at phase 0.0 according to the ephemeris used here, occurred at phase 0.0973 according to the refined ephemeris. The light curves determined from both pointings are shown as sections of two consecutive binary cycles in Figure 1. Corrections have been applied to the data to remove the background and to allow for small variations in the spacecraft aspect. The data are binned at 40.96 s intervals and represent the combined count rates from both fields of view of LED 1 between 0.17 and 0.5 keV. The two sections of data labeled HV + 2 in the second cycle of Figure 1*b* correspond to time intervals when the high voltage to LED 1 was increased two steps above the normal setting. This

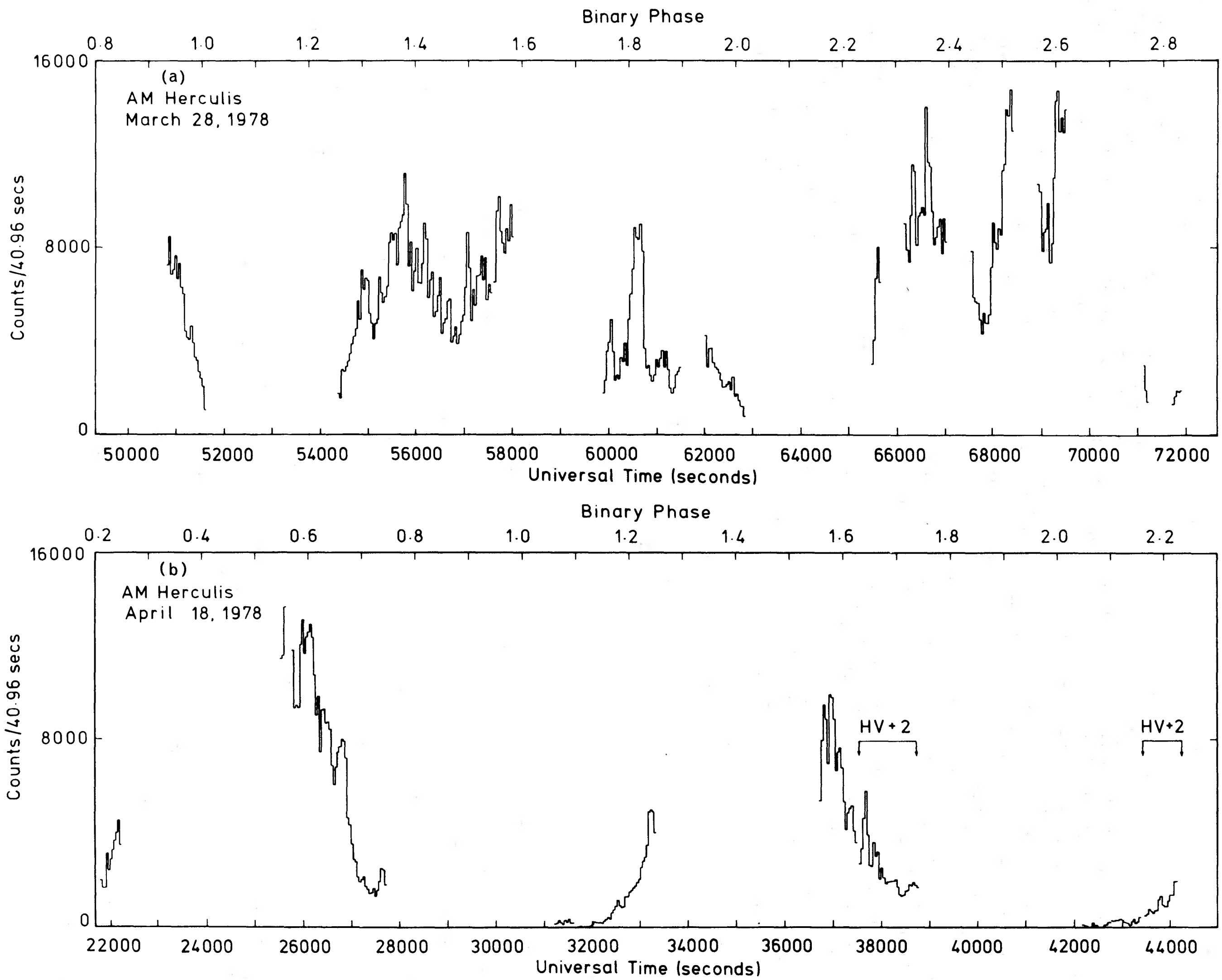

FIG. 1.—Soft X-ray light curves of AM Her obtained on 1978 March 28 (*a*) and April 18 (*b*) accumulated in 40.96 s intervals. Sections labeled HV + 2 correspond to times when the high voltage to LED 1 was increased above the normal setting (see text). Phase is calculated from an epoch of JD 2,443,014.7647 using a period of $0^{d}.128927$.

increase reduced the low energy threshold from 0.17 to 0.13 keV, but did not appreciably affect the total count rate from AM Her, owing to the turnover in the X-ray spectrum (see § V).

The key features apparent in Figure 1 can be summarized as follows:

1. The soft X-ray light curve of AM Her exhibits variability on a variety of time scales ranging from seconds up to at least an hour. Similar behavior is found in the optical light curve of the star (e.g., Berg and Duthie 1977; Olson 1977; Bailey, Mason, and Parkes 1977; Bailey *et al.* 1978; Szkody 1978; Stockman and Sargent 1979). The short time scale X-ray variability is investigated further in § IV. The range of count rates in Figure 1 is the same as that found for our average light curve in Paper I (when allowance is made for the different combinations of fields of view). The peak count rate observed (14500 counts/40.96 s^{-1}) corresponds to a photon flux of 2.14 photons cm^{-2} s^{-1}, or an energy flux of 7.6×10^{-10} ergs cm^{-2} s^{-1} between 0.1 and 0.5 keV. These conversions are based on the spectral data given in Paper I and § V.

2. Onset of the soft X-ray minimum (nominally $\phi = 0.0$–0.15; see Paper I) was monitored during the March observation and takes place in a phase interval $\Delta\phi \lesssim 0.1$. The rise following minimum was observed in April and occurs in a similar phase interval. These intervals are consistent with those inferred from our earlier light curve (Paper I). The residual flux detected previously during X-ray minimum appears to be present again (for at least part of the time), but we are unable to add any new information owing to the difficulty of establishing the background precisely during pointed observations.

3. Following the first minimum observed in March (Fig. 1*a*), the mean source intensity is relatively high until $\phi \sim 1.6$ but is substantially lower after $\phi \sim 1.75$, prior to X-ray minimum. During the subsequent cycle, the flux measured at $\phi \sim 2.8$ is again low compared to that measured before $\phi \sim 2.6$. In April, the phase interval between $\phi \sim 0.75$ and the onset of the minimum at $\phi \sim 1.0$ is not covered, but the soft X-ray flux does show a marked reduction between phase 0.6 and phase 0.7 in both the cycles monitored. This behavior is consistent with the "step" in the mean light curve reported previously (Hearn and Richardson 1977; Paper I). However, at times the source intensity is high in the phase interval 0.8–1.0, as shown by the flux at the beginning ($\phi = 0.92$) and near the middle ($\phi \sim 1.8$) of the March observation. Thus, the present data show that the scatter in the light curve reported in Paper I is due at least in part to variations in its shape and not simply to variations in the amplitude of a light curve of constant shape.

4. A broad ($\Delta\phi \sim 0.15$) dip is observed centered at $\phi \sim 0.47$ in the two consecutive cycles observed in March. This feature occurs near, but not coincident with, the primary optical minimum (e.g., Szkody and Brownlee 1977; Crampton and Cowley 1977; Bailey *et al.* 1978; Priedhorsky and Krzeminski 1978; Szkody 1978). Phases near $\phi = 0.47$ were not covered by the *HEAO 1* observations in April.

5. Near phase 1.8 in Figure 1*a*, the source intensity increases rapidly ($\Delta t \sim 1$ minute) by a factor of 3 and falls equally rapidly to the previous level about 6 minutes later. This steep increase in the flux is not repeated at the same phase ($\phi \sim 2.8$) in the following cycle (Fig. 1*a*, and LED 2 "ping-pong" data), indicating that the event was transient in nature and not a stable feature of the light curve.

The second measurement of the AM Her light curve (Fig. 1*b*) was accompanied by simultaneous optical photometry and polarimetry. These results and their relationship to the X-ray data are discussed by Szkody *et al.* (1980). The optical *V* band data show that AM Her was in an optical high state during the 1978 X-ray observations.

IV. X-RAY VARIABILITY

Inspection of the data plotted in Figure 1 on a finer time scale reveals the presence of rapid variability in the X-ray flux from AM Her. As an example, the data between phase 1.30 and 1.54 in Figure 1*a* are shown expanded into 5.12 s bins in Figure 2*a*. Pronounced flickering is evident on a time scale of 5–20 s, superposed on longer time scale variability. This behavior is typical of that seen throughout the bright section of the light curve. Even faster variability is occasionally evident in the 1.28 s data (not shown) when the average source intensity is high; there are a few cases in which the flux changes significantly between adjacent 1.28 s bins.

a) *Fourier Analysis*

The X-ray variability of AM Her has been investigated using different data analysis techniques applied to the 1.28 s and 20 ms data. Initially, segments of the data with a typical length of 30 minutes were Fourier transformed to search for regular periodic behavior. The procedure used was identical to that described by Brault and White (1971). Low frequency trends in the data were first removed by polynomial subtraction, followed by apodization of the data stream with a cosine bell function applied to each end.

The resulting power spectra computed over the phase interval 0.2–1.0 are generally similar. The spectrum shown in Figure 2*b*, which was computed from the data plotted in Figure 2*a*, is typical and illustrates the excess power below 0.05 Hz produced by flickering and flaring of the source. The feature labeled 28.2 s is due to a train of quasi-periodic pulses which can be discerned in a section of the raw data. Quasi-periodic oscillations at other periods occur elsewhere in the data and are discussed further below.

All the power spectra obtained have been searched for evidence of excess power at a coherent period. No persistent periodic pulsations are present. From our analysis we can set an upper limit of 0.5% on the semiamplitude of any sinusoidal X-ray pulsations with periods in the range 40 ms (the Nyquist limit) to 10 s.

Above 10 s, the power due to aperiodic variability becomes appreciable, so that the upper limit increases to 2% at 20 s, and 20% at 400 s. These results are in agreement with the absence of regular pulsations at optical wavelengths (Stockman and Sargent 1979).

b) *Autocorrelation Analysis*

The aperiodic flickering in AM Her can also be studied by an autocorrelation analysis; therefore, autocorrelation functions (ACFs) have been computed for all sections of the 1.28 s data. The analysis followed conventional procedures (e.g., Bailey, Mason, and Parkes 1977) and included a correction for the effect of counting noise in the first autocorrelation term (see, e.g., Weisskopf, Kahn, and Sutherland 1975). Prior to computing the ACFs, low frequency components with time scales greater than ~1000 s were removed from the data by subtracting a polynomial of appropriate degree. This filtering was found to be very important for adequately resolving the short and long time scale variability present in the data stream.

The results of this autocorrelation analysis are presented in Figure 3 as 12 separate plots (6 for each pointing) covering essentially the entire binary cycle of AM Her. During the bright portion of the light curve, each ACF is typified by an initial decay followed by oscillations whose time scale and amplitude are different for each set of data. The initial decay has an *e*-folding time that ranges between 7 and 12 s, with an average value of 9 s. There is no evidence that either the shape or time scale of the autocorrelation functions are significantly correlated with phase in the interval $\phi = 0.2$–1.0. However, it is evident from the raw data that the flickering amplitude is greatest in the interval $\phi = 0.3$–0.6 and decreases substantially after $\phi = 0.7$. The flickering disappears entirely during X-ray minimum as evidence by the ACF for section A6 in Figure 3, which is consistent with that expected for white noise. Thus, the residual flux believed to be present during X-ray minimum is steady on a time scale < 100 s.

The long-term oscillations in the autocorrelation functions are symptomatic of the quasi-periodic behavior

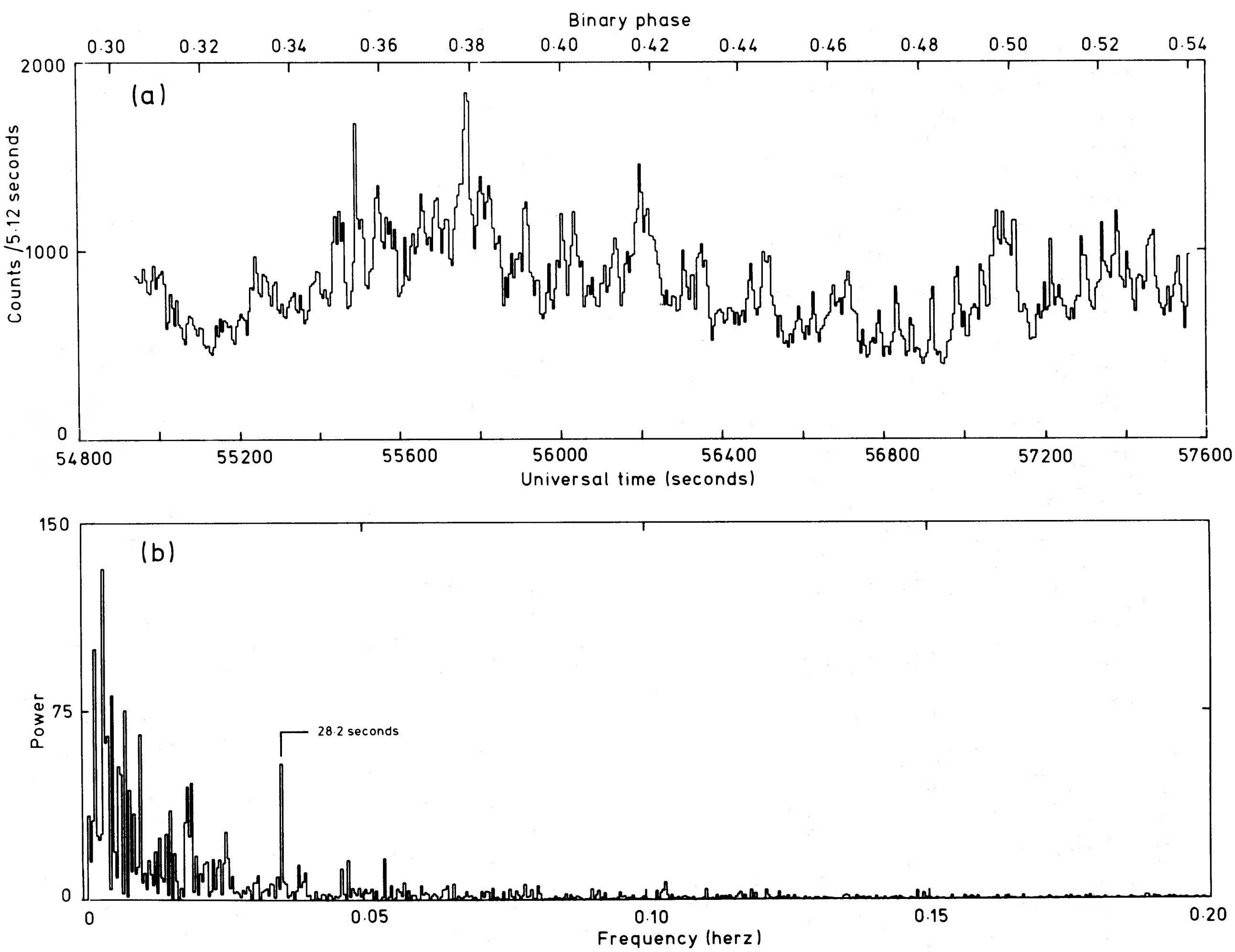

FIG. 2.—(*a*) Example of the rapid soft X-ray flickering from AM Her on a time scale of 5–20 s, taken from the March observation. Data are plotted in 5.12 s intervals. (*b*) Power spectrum of the data plotted in (*a*). The peak at 28.2 s is due to the presence of a train of quasi-periodic pulses at this period.

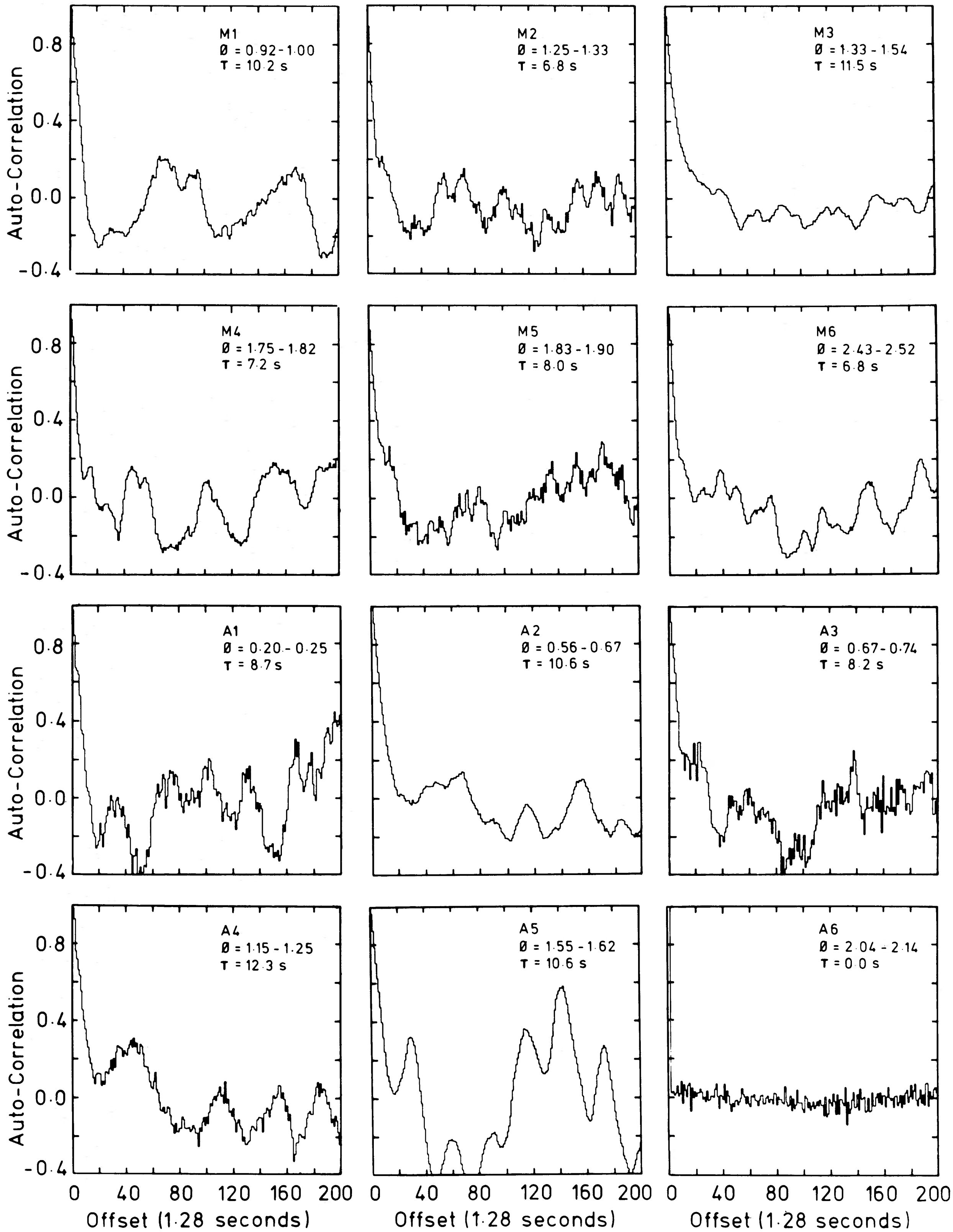

FIG. 3.—Autocorrelation functions for the March (M) and April (A) observations of AM Her for the phase intervals shown (refer to Fig. 1). The *e*-folding times are also indicated.

noted earlier. There is no single characteristic time scale for the fluctuations evident in Figure 3, and peaks in the autocorrelation functions typically occur at intervals of 20–60 s. The most dramatic example of this phenomenon is labeled A5 in Figure 3, where strong modulation with a period of 37 s is present (as confirmed by a sharp spike at this period in the corresponding power spectrum). The background subtracted data for the A5 interval ($\phi = 0.55$–0.62) are reproduced in Figure 4*a*. The pulse train persists for ~ 8 cycles with large changes in pulse amplitude and is superposed on longer time scale variability ($\Delta t \sim 100$–200 s).

An autocorrelation analysis has also been performed on several representative sections of the 20 ms data to search for the presence of very fast fluctuations. The ACFs covered an offset range of 0–4 s, and in all cases provided no evidence for variability faster than that discussed above. We therefore conclude that the X-ray variability of AM Her is confined to time scales in excess of 1 s or less than 20 ms.

V. X-RAY SPECTRUM

The X-ray spectrum of AM Her is best defined by the HV + 2 data acquired between phase 1.62 and 1.74, as shown in Figure 1*b*. The reduced threshold of 0.13 keV available in this mode permits the low energy turnover in the spectrum at ~ 0.2 keV to be clearly detected. A calibration of the absolute energy response of LED 1 occurred soon after acquisition of this section of data (while AM Her was occulted by the Earth). Removal of the diffuse background from the HV + 2 spectral data was accomplished by a field of view subtraction technique based on the two different solid angles subtended by LED 1. Although reliable, this procedure results in a net loss of statistical precision owing to the subtraction, rather than the addition, of data.

The background-corrected data were fitted with both blackbody and thermal bremsstrahlung models, as in Paper I. Both models gave good fits ($\chi^2 = 14.3$ for 14 degrees of freedom). The derived spectrum and the 90% confidence chi-squared contours for the two models are displayed in Figure 5. The chi-squared inset also includes the contours obtained from our 1977 spectrum (Paper I). The spectral parameters are not as well constrained in the 1978 measurement. Nevertheless, it is evident that the two independent spectral measurements are not consistent at the 90% confidence level. The reduced precision of the 1978 measurement is due in part to a slightly lower gain setting than in 1977, and in part because the source intensity was low at the time the 1978 HV + 2 data were acquired. The average X-ray intensity during the 1977 measurement was $\sim 9 \times 10^{-10}$ ergs cm^{-2} s^{-1} (0.1–0.5 keV), compared with $\sim 1.2 \times 10^{-10}$ ergs cm^{-2} s^{-1} during the present measurement.

Further evidence for variability in the AM Her spectrum is provided by spectral data acquired simultan-

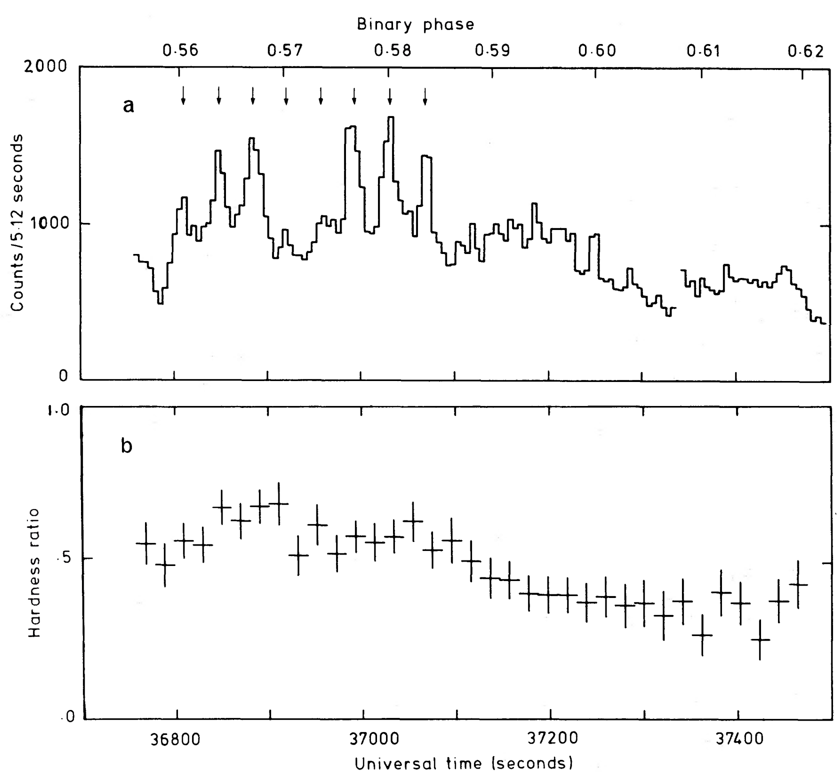

FIG. 4.—(*a*) Example of quasi-periodic behavior in AM Her. The positions of 8 peaks separated by a spacing of 37 s are indicated. The data correspond to Section A5 of Fig. 3. (*b*) Hardness ratios for the data in (*a*) computed from the ratio of the (0.23–0.49) to (0.17–0.23) keV count rates.

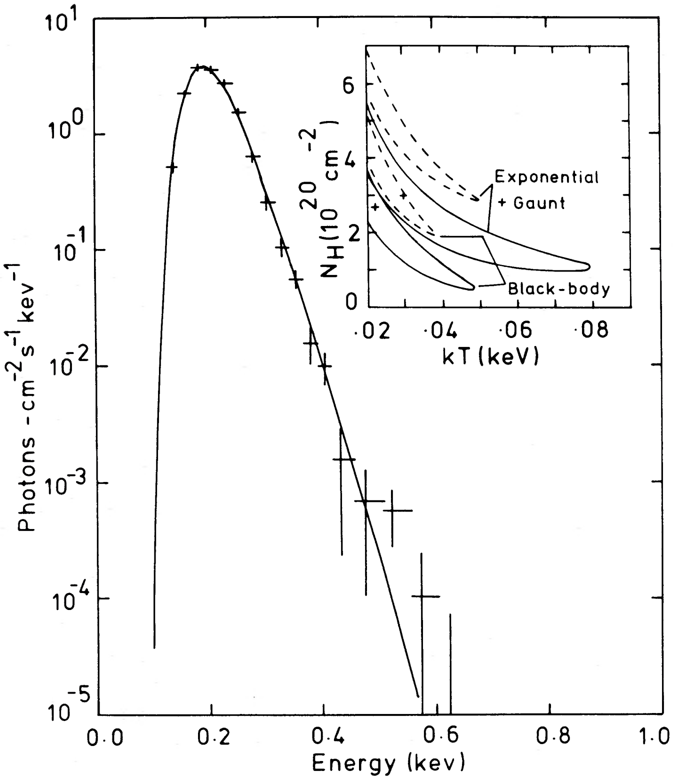

FIG. 5.—Soft X-ray spectrum of AM Her measured between $\phi = 1.62$ and 1.74 in Fig. 1*b*. The inset shows the 90% confidence chi-squared contours for both blackbody and exponential spectra (the dashed lines indicate the contours derived from an earlier 1977 spectrum; see Paper I). The 1978 best-fit values for kT and N_H, which are highly correlated, are marked by crosses.

eously with the data plotted in Figure 4*a*. The lower plot (Fig. 4*b*) shows the corresponding hardness ratio values derived from the ratio of the 0.23–0.49 keV to 0.17–0.23 keV count rates. A significant decrease in the hardness ratio is evident and follows a similar decrease in the average source intensity. These data were acquired at the normal high voltage setting and are of insufficient energy resolution to determine whether the decrease in the hardness ratio is caused by a reduction in the temperature or the low energy absorption, or both. If we alternately hold each parameter fixed at the best value for the blackbody fit, the observed decrease in the hardness ratio is equivalent to a temperature decrease of 28% or a decrease in the column density of 38%. It is apparent, however, that a reduction in the absorption at low energies should result in an increase, rather than the observed decrease in flux. Absorption could account for a reduction in both hardness ratio and flux only if it increased preferentially in the 0.23–0.49 keV band (e.g., due to scattering).

The sense of the short-term spectral variability in Figure 4 is the same as that of the long-term variation between the 1977 and 1978 spectra; the spectrum is softer when the source intensity is lower. Hardness ratio values for all other sections of data from the second pointing have been examined to determine whether this correlation always exists. Weaker correlation of the same kind does occur elsewhere, but is not always present. For example, there is no detectable change in the source spectrum over the phase interval of the previous cycle corresponding to that shown in Figure 4, although the source intensity was also highly variable then (see Fig. 1*b*). Thus, there does not appear to be a consistent correlation of the spectrum with either intensity or binary phase.

No flux was detected above 0.5 keV in our detectors. During the April observation, the upper bound of the pulse height analyzer for LED 1 was set at 1.5 keV. We have computed a limit to the 0.5–1.5 keV flux averaged over the whole observation by comparing the counts obtained with the two fields of view of LED 1, which subtend different solid angles on the sky. In this way, we obtain $F_{0.5-1.5} < 0.007$ photons cm^{-2} s^{-1} at the 99% confidence level, assuming a *flat* spectrum.

VI. DISCUSSION

Many of the properties of AM Her can be explained in terms of accretion onto a magnetic degenerate dwarf that rotates synchronously with its 3.09 hour orbital period about a binary companion (Chanmugam and Wagner 1977; Stockman *et al.* 1977; Priedhorsky and Krzeminski 1978; Kruszewski 1978; King and Lasota 1979; Lamb and Masters 1979). Models in which the rotation of the degenerate dwarf is not synchronous with the binary period have also been proposed (Fabian *et al.* 1977). However, the failure to detect the hypothesized rotation frequency of the star ($\sim$ 1 minute) at any wavelength (including now soft X-rays), and particularly in the circularly polarized light (Stockman and Sargent 1979), argues strongly against such models.

a) *Source Geometry*

Evidence concerning the location of the emission regions is provided by a comparison of the observed soft X-ray, hard X-ray, and optical fluxes. The great similarity of the hard (Swank *et al.* 1977) and soft (Paper I) X-ray light curves indicates that the radiation in both energy bands is produced in the same region. Table 1 summarizes the results of all the soft X-ray flux measurements to date, together with the *V* band flux densities observed at about the same time. The data of 1975 October, 1976 May, 1977 September-October, and 1978 March-April are consistent with similar behavior of the soft X-ray and optical fluxes, but in 1976 November the soft X-ray flux was low when the *V* band flux density was high. At the time of the latter observation, both the deep soft X-ray minimum (Hearn 1977; see also Szkody *et al.* 1980) and the *V* and *R* band secondary minima (Priedhorsky and Krzeminski 1978) were absent.

In the synchronously rotating model proposed by Priedhorksy and Krzeminski (1978), essentially all of the observed radiation is produced at one of the magnetic poles of the degenerate dwarf which receives the bulk of the accretion flow. They attribute the primary optical minimum to occultation of the optical emission region by the body of the white dwarf, while the X-ray minimum and the secondary optical minimum that occur approximately half a cycle later are due to obscuration by the accretion column. Several qualitative arguments can be made against this picture. First, the soft X-ray minimum, when present, is stable and well defined in phase. Moreover, the absence of detectable spectral variation during onset and recovery (Paper I) indicates that the soft X-ray minimum is not due to increased absorption. This suggests that the X-rays are occulted by the degenerate dwarf itself rather than by the accretion column, which might be expected to present a variable opacity along the line of sight and to absorb soft X-rays. Second, optical data taken simultaneously with our April *HEAO 1* data (Szkody *et al.* 1980) show that the secondary optical minimum was not then in phase with the X-ray minimum, while the primary optical minimum occurred about a tenth of a cycle later than had been observed by previous authors. Finally, as discussed below, there are theoretical reasons for believing that the soft X-ray emission comes from very near the surface of the degenerate dwarf and, hence, that it is very likely to be occulted by that star.

An alternative geometry is that put forward by Lamb (1976 and private communication). In this picture usually the accreting matter flows predominantly toward one of the magnetic poles which produces most of the X-ray and optical emission, but occasionally the flow toward the two poles is approximately equal. The X-ray minimum is attributed to self-occultation by the degenerate dwarf, and the primary optical minimum, to obscuration by the accretion flow. The disappearance of the deep soft X-ray and *R* and *V* band secondary minima in 1976 November (Table 1) is interpreted as due to more nearly equal accretion flows onto both poles, rather than to a decrease in the obscuration by the accretion column, as in the model of Priedhorsky and Krzeminski (1978). In this geometry, the broad dip in the soft X-ray flux sometimes observed near phase 0.47 (see Fig. 1*a*) might be due to obscuration by the accretion flow. The fact that the *V* band secondary minimum was observed to be offset from the soft X-ray minimum in 1978 April (Szkody *et al.* 1980) may force consideration of additional sources of *V* band flux or obscuring matter within this framework.

Still another picture has been proposed by Kruszewski (1978; see also King and Lasota 1979). In this model, both

TABLE 1

SOFT X-RAY AND OPTICAL OBSERVATIONS OF AM HERCULIS

Date	Energy Band (keV)	Flux[a] (10^{-11} ergs cm^{-2} s^{-1})	*V* Band Flux Density (mJy)	Deep X-Ray Minimum?
1975 Oct 11–12	0.15–0.28[b]	39[b]	35[c]	Yes[b]
1976 May 21–22	0.1 –0.3[d]	3.3[d]	4.6[e]	Yes[d]
1976 Nov 7–11	0.1 –0.3[f]	$\sim$7[f]	20[g]	No[f]
1977 Sep 22–Oct 12	0.15–0.5[h]	50[h]	24[i]	Yes[h]
1978 Mar 28–Apr 18	0.17–0.5[j]	76[j]	24–38[k]	Yes[j]

[a] Fluxes are averaged over all binary phases, except that of 1978, which is the peak flux observed.
[b] Bunner 1978.
[c] Berg and Duthie 1977.
[d] Hearn and Richardson 1977.
[e] Berg, private communication.
[f] Hearn 1977 and private communication.
[g] Priedhorsky and Krzeminski 1978.
[h] Tuohy *et al.* 1978*b*.
[i] Tapia, private communication.
[j] This work.
[k] Szkody *et al.* 1980.

poles of the degenerate dwarf emit radiation but unequally and at different wavelengths because of differences in the magnetic field strength and accretion rate. The stronger pole ($B \sim 10^8$ gauss) emits the polarized red flux observed, while the weak pole dominates in the X-ray and ultraviolet bands and in the far-infrared. The primary optical minimum and the X-ray minimum are interpreted as due to occultation of the strong pole and the weak pole, respectively, by the degenerate dwarf. The requirement that one pole dominate the soft X-ray emission but produce little optical flux while the other pole dominates the optical emission but produces little X-ray flux may pose a difficulty for this model, when the peak of the cyclotron spectrum is determined self-consistently and an allowance is made for the large soft X-ray luminosity (see below).

b) *Source Spectrum*

The spectrum of an accreting magnetic degenerate dwarf has been calculated by Fabian, Pringle, and Rees (1976), Lamb and collaborators (Kylafis *et al.* 1978, 1980; Lamb and Masters 1979), and King and Lasota (1979, 1980). In general, the emission is expected to have four components: (1) a blackbody-limited cyclotron component produced by the hot emission region; (2) a hard X-ray bremsstrahlung component also produced by the hot emission region; (3) a hard UV or soft X-ray thermal component produced by cyclotron and bremsstrahlung photons that are absorbed by the stellar surface and reemitted; and (4) secondary radiation from infalling matter above the shock or, possibly, from the stellar surface around the emission region. In the work of Fabian, Pringle, and Rees, components (3) and (4) were omitted. King and Lasota estimated the sizes of components (1)–(4) but treated ω^*, the frequency below which the cyclotron emission is self-absorbed, as a free parameter. In reality, ω^* is determined by the other parameters of the model, so a free choice will usually not be self-consistent. These authors also made a particular choice for f, the fraction of the stellar surface over which accreting matter falls, and for its dependence on the mass accretion rate $\dot{M}$ and the surface magnetic field B. The most detailed physical theory is that developed by Lamb and Masters, who first considered components (1)–(4) and used their numerical computations of high-harmonic cyclotron emission to determine ω^* self-consistently.

In Paper I we interpreted the soft X-ray flux observed between 0.1 and 0.5 keV as the high-energy tail of component (3), modified by interstellar absorption. Assuming that this component has a blackbody spectrum, as predicted by Lamb and Masters, it had a temperature $T_{bb} \lesssim 40$ eV and a total luminosity $L_{bb} \gtrsim 8 \times 10^{33}$ ergs s^{-1} at 100 pc at the time of the 1977 observation. The 2–60 keV flux measured at the same time corresponds to a luminosity of 3×10^{32} ergs s^{-1} at 100 pc. The 0.13–0.5 keV flux observed in 1978 and reported here is similar to that observed in 1977 but allows a slightly higher value of T_{bb}, ~ 45–50 eV, and hence a somewhat smaller value of L_{bb}. Assuming that the Rayleigh-Jeans tail of component (3) extends into the visual, the requirement that the V band flux density caused by it not exceed the V band flux density observed in 1977 September (~ 24 mJy; Tapia, private communication) implies $T_{bb} \gtrsim 20$ eV and $L_{bb} \lesssim 10^{36}$ ergs s^{-1} at 100 pc. The blackbody interpretation of the observed soft X-ray flux indicates an emitting area of 3×10^{15} cm^2 at 100 pc, if $T_{bb} = 40$ eV, or 3×10^{17} cm^2, if $T_{bb} = 25$ eV. For a degenerate dwarf of radius $R = 5.3 \times 10^8$ cm, appropriate to a mass $M = 1.0\, M_\odot$, these areas correspond to fractions $f = 9 \times 10^{-4}$ and 9×10^{-2}, respectively, of the stellar surface, and ratios L_{bb}/f of 9×10^{36} ergs s^{-1} and 1.4×10^{36} ergs s^{-1}.

For $B \sim 2 \times 10^8$ gauss, the value suggested by Tapia (1977) on the basis of the observed V band polarization, $M \gtrsim 1.0\, M_\odot$, and $L/f \lesssim 10^{36}$ ergs s^{-1}, the model of Lamb and Masters (1979) predicts $L_{bb} \approx L_{cyc} + L_{brems}$, where L_{cyc} and L_{brems} denote the luminosities in components (1) and (2). Then, since the X-ray observations imply $L_{bb} \gg L_{brems}$, one has $L_{cyc} \approx L_{bb}$ and an intense flux of UV cyclotron emission is expected (see Paper I). Recent *IUE* observations by Raymond *et al.* (1979) and Tanzi *et al.* (1980) show that AM Her is a strong UV source, but that the difference in the continuum flux density between maximum and minimum light at 1400 Å is ~ 10 mJy, 25 times smaller than predicted, if $T_{bb} = 40$ eV, or 1600 times smaller, if $T_{bb} = 25$ eV, assuming an electron temperature $T_e = 18$ keV.

Lamb (1979 and private communication; see also Raymond *et al.* 1979) has outlined various ways that the discrepancy between the observed spectrum and that predicted by theory might be resolved. First, consider component (1). If $B \approx 2 \times 10^7$ gauss rather than 2×10^8 gauss, and $L/f \gtrsim 10^{37}$ ergs s^{-1}, AM Her lies in the bremsstrahlung-dominated regime rather than in the cyclotron-dominated regime, L_{cyc} is reduced relative to L_{brems}, and component (1) peaks in the optical or near-infrared. The UV flux contributed by component (1) is then negligible. That the surface magnetic field in AM Her could be as small as $\sim 2 \times 10^7$ gauss is indicated by comparison with VV Pup, which shows high polarization in the optical but has spectral features which have been interpreted as indicating a magnetic field of $\sim 3 \times 10^7$ gauss (see Lamb 1979). The UV flux contributed by component (1) would also be reduced if the mass of the degenerate dwarf is ~ 0.6–$0.8\, M_\odot$, rather than $\sim 1.0\, M_\odot$.

Next, consider component (3). The observed UV flux density is consistent with a Rayleigh-Jeans spectrum ($f_\nu \propto \nu^2$) and is equal to that in the Rayleigh-Jeans tail of component (3), if the temperature T_{bb} of that component is ≈ 30 eV (Raymond *et al.* 1979), or greater, if $T_{bb} > 30$ eV (~ 18 times greater, if $T_{bb} = 40$ eV). Thus, there appear to be two possibilities: (a) the soft X-ray and UV fluxes are parts of a single blackbody spectrum which must then have a temperature ≈ 30 eV; or (b) the temperature of component (3) is greater than 30 eV and there is some additional source of UV emission.

In case (a), $L_{bb} \gg L_{cyc} + L_{brems}$, and there is an apparent luminosity balance problem. King and Lasota (1979) sought to avoid this problem by interpreting the soft X-ray flux as due to thermal bremsstrahlung from a hot gas rather than blackbody emission, but the *IUE* data provide clear evidence against this interpretation. D. Q. Lamb (private communication) has pointed out two other ways that this might occur. First, if $L/f \gg 10^{36}$ ergs s^{-1}, many of the photons produced by bremsstrahlung are scattered backward toward the stellar surface and are absorbed there, increasing L_{bb} with respect to L_{brems}; at the same time, the hard X-ray spectrum is degraded by Comptonization, which may account for the fact that the hard X-ray spectrum is poorly described by thin bremsstrahlung models (see Kylafis *et al.* 1980). Alternatively, if the accreting matter undergoes steady nuclear burning, L_{bb} is greatly increased (Weast *et al.* 1979; Fabbiano *et al.* 1980). Thermal conduction of energy from the hot emission region to the stellar surface (King and Lasota 1980) does not appear to be a workable solution (Imamura *et al.* 1979).

In case (b), the observed UV flux must be from component (4) or some other mechanism. If the temperature of component (3) is as large as 40–45 eV, then the luminosity in this component is $\sim 4\text{–}8 \times 10^{33}$ ergs s^{-1} at 100 pc (see Paper I), or $\sim$ 2–4 times the sum of the IR, *V*, UV, and hard X-ray luminosities. This might be consistent with $L_{bb} \approx L_{cyc} + L_{brems}$, to within the geometrical and other uncertainties in the theoretical models.

Finally, we note that the correlation between hardness and intensity that is sometimes present in the *HEAO 1* soft X-ray data (spectrum softens with decreasing intensity) is what is expected from component (3) if L/f decreases, either because L decreases or because f increases, or both. However, the fact that the intensity sometimes varies without any detectable change in the spectrum suggests that other mechanisms (such as scattering by intervening ionized material) also contribute to the variability of the soft X-ray flux.

c) Short-Term Variability

One of the properties of AM Her revealed for the first time by our pointed observations with *HEAO 1* is the existence of a well-defined flickering component in the soft X-ray band with a correlation time of the order of 10 s. The optical flux from AM Her also shows rapid flickering. Table 2 compares the correlation times in the optical reported by various authors with our soft X-ray results.

Care should be taken in comparing the various optical measurements of the correlation time with each other, and with our soft X-ray measurement, because of the different sampling rates and filtering techniques used by different workers. In addition, the effects of variations in seeing on the optical data have not always been assessed. Nevertheless, the data suggest that, on average, the soft X-ray correlation time is shorter than that in the optical (at least in the broad-band data). This may indicate that the optical emission comes from a more extended region than the soft X-rays. Further, Szkody *et al.* (1980) have shown that the soft X-ray and optical variability is uncorrelated, in contrast to the high correlation found between the fluxes in various optical energy bands (Bailey, Mason, and Parkes 1977; Szkody and Margon 1980). This lack of correlation suggests that the flickering is not simply due to fluctuations in the accretion rate, if the visual emission is optically thin, or in the surface area of the emission, since these would lead to correlations or anticorrelations, respectively, in the soft X-ray and visual fluxes. Fluctuations in the accretion rate could produce flickering in the soft X-ray flux from the hot emission region without significant flickering in the visual flux from the same region, if the latter is blackbody limited and the surface area of the region remains constant. A lack of correlation would also be expected if the soft X-ray and optical emission are produced at different magnetic poles of the degenerate dwarf star, if secondary emission contributes substantially to the optical flux, or if variable obscuration by intervening material is important.

We have also found a number of instances when there are quasi-periodic trains of pulses, with quasi-periods of the order of tens of seconds. We believe that these are not chance alignments of randomly occurring pulses. For instance, we calculate that, under the most favorable conditions of shot rate and assuming that the centroid of a pulse can only be determined with an accuracy comparable to the pulse width, the *a priori* probability of

TABLE 2

OPTICAL AND X-RAY FLICKERING TIME SCALES FOR AM HERCULIS

Date	Energy Band	*e*-Folding Time range	*e*-Folding Time mean	Reference
1976 Sep	*V*, *R*	30–200 s	90 s	Bailey *et al.* 1977
1977 May	*V*	30–60 s	...	Bailey *et al.* 1978
1977 Jun	*U*, *V*	...	20 s	Szkody and Margon 1980
1977 Jun	4686 Å	...	11 s	...
1977 Jul	3200–8600 Å flux	...	~60 s	Stockman and Sargent 1979
1977 Jul	Circular polarization	...	~28 s	...
1977 Nov	Unfiltered light	...	23 s	Kornilov and Moskalenko 1979
1978 Apr	*V*	10–40 s	~20 s	Szkody *et al.* 1980
1978 Mar and Apr	0.17–0.5 keV	7–12 s	9 s	This work

obtaining the sequence of six (strong) pulses shown in Figure 4*a* within eight cycles is 10^{-4}.

One form that the quasi-periodic variability could take is short sequences of periodic pulses (lasting only a few cycles) that occur randomly in time. Numerical simulations carried out by Kahn and Mason (unpublished) show that the autocorrelation function (ACF) of artifical data sets generated in this manner has an overall decay with superposed oscillations having the time scale of the underlying period of the pulse trains. The ACF is thus very similar to some of the autocorrelation functions determined for AM Her. Furthermore, if the pulse trains are positive definite (i.e., they always add to the flux), they can interfere constructively or destructively to produce overall long-term variations in the data similar to those seen in Figures 2*a* and 4*a*. In this interpretation of the variability of AM Her, the $\sim$ 100–200 s time scale fluctuations of the source are a consequence of the $\sim$ 20–60 s pulsations and are not a separate phenomenon.

Possible explanations for the origin of the quasi-periodic X-ray variations include: (a) emission by material orbiting at the inner edge of an accretion disk near the surface of the degenerate dwarf; (b) variations in the accretion flow from the inner edge of a disk; and (c) oscillations of the magnetic flux tubes conveying matter from the magnetospheric boundary to the surface of the degenerate dwarf. In each case, the time scale of the variability is set by the distance from the degenerate dwarf. One can calculate an approximate upper bound on the radius at which the magnetic field of the star channels the accretion flow (and hence on the inner radius of any accretion disk) from the fact that field-aligned flow must be sub-Alfvénic in order to be stable, and the fact that matter accreting onto the star falls almost freely along field lines until it is very close to the stellar surface (see Elsner and Lamb 1977, § III*d*). This approach can be applied to AM Her as follows.

The condition that the flow be sub-Alfvénic is $\rho v_p^2 < B_p^2/4\pi$, where v_p and B_p are the poloidal components of the bulk flow velocity and the magnetospheric field, respectively. For matter falling freely along the field, $\rho v_p/B_p =$ const. while $v_p \approx v_{\rm ff} = (2GM/r)^{1/2}$, where r is the radius from the center of the degenerate dwarf. The mass accretion rate $\dot{M}$ is related to the accretion luminosity L, and the stellar mass M and radius R by $\dot{M} = RL/GM$. Using these relations and assuming that the poloidal magnetic field is approximately dipolar (i.e., $B_p \approx B_s(R/r)^3$ in terms of the surface field B_s), one can trace the flow upstream from the stellar surface.

For this type of flow, channeling by the magnetic field cannot occur outside the radius

$$r_{\rm max} = 1.46 \times 10^9 (f/10^{-2})^{2/5} (M/M_\odot)^{1/5} R_8^{8/5} B_7^{4/5} L_{34}^{-2/5} \text{ cm}$$

at which the extrapolated flow becomes super-Alfvénic. Here f is the fraction of the stellar surface on which the matter falls, R_8 is R in units of 10^8 cm, B_7 is B_s in units of 10^7 gauss, and L_{34} is L in units of 10^{34} ergs s^{-1}. Assuming $M = 1.0 \; M_\odot$, $R_8 = 5.3$, and $B_7 = 2$, one finds $r_{\rm max} = 1.7 \times 10^{10}$ cm $= 32R$, if $L_{34} = 1.7$ and $f_{-2} = 9 \times 10^{-4}$ (case 1), or 3.2×10^{11} cm $= 610R$, if $L_{34} = 26$ and $f_{-2} = 9 \times 10^{-2}$ (case 2). These two cases are just those suggested by the V band, UV, and soft X-ray observations discussed above (case 1 corresponds to $T_{\rm bb} = 40$ eV, and case 2 to $T_{\rm bb} = 25$ eV). If case 1 applies, $r_{\rm max}$ is significantly less than the probable binary separation $a \sim 8 \times 10^{10}$ cm (Priedhorsky and Krzeminski 1978), implying that the accretion flow cannot be channeled all the way from the vicinity of the companion star to the surface of the degenerate dwarf. If, on the other hand, case 2 applies, then $r_{\rm max}$ greatly exceeds a, and completely channeled flow is at least possible.

Consider now possibilities (a)–(c) for the origin of the quasi-periods in the light of these estimates. Possibility (a), emission from the inner edge of a disk, has been proposed as an explanation for the quasi-periodic pulse trains observed in the dwarf nova SS Cyg (Cordova *et al.* 1980). For a 1.0 $M_\odot$ degenerate dwarf, the orbital period would be 35 s at 3R. However, the pulse trains of AM Her persist for shorter times (or, alternatively, wander more in phase) than those of SS Cyg and also U Gem (Cordova *et al.* 1981). Moreover, as noted above, the magnetic field of the degenerate dwarf in AM Her may be strong enough to channel the accretion flow directly from the companion star to the dwarf's surface (case 2), or at least to disrupt the accretion disk at a radius greater than 3R (case 1). Hence, it is not clear whether the quasi-periodic variability of AM Her arises in the same way as in the dwarf novae. Possibility (b), variations in the flow from the inner edge of the disk, is a different mechanism but would have a similar characteristic time scale, namely the dynamical time scale, $(\frac{2}{3})(r/v_{\rm ff})$, at the inner edge. This would be 35 s at 18R.

A possible source of quasi-periods unique to strongly magnetic stars such as the dwarf in AM Her is oscillation of the magnetic flux tubes along which matter flows to the stellar surface, possibility (c). Such oscillations, particularly if they occur at the point where the flow becomes channeled by the magnetic field, can cause quasi-periodic variations in the accretion rate or flow pattern. The natural period for such oscillations, $P_{\rm osc}(r)$, is the time scale $r/v_{\rm A}$ for an Alfvén wave to cross the magnetosphere. For the flow pattern discussed above, $P_{\rm osc}(r) = 2 \times 10^{-3} r_8^{11/4} L_{34}^{1/2} (f/10^{-2})^{-1/2} (M/M_\odot)^{-3/4} R_8^{-2} B_7^{-1}$ s, where r_8 is r in units of 10^8 cm. In case 1 above, the appropriate estimate is $P_{\rm osc}(r_{\rm max}) = 21$ s, indicating that the observed quasi-periods may arise in this way. On the other hand, if the flow is channeled from the vicinity of the companion star, the oscillation period where channeling occurs is $P_{\rm osc}(a) = 6 \times 10^4$ s, much longer than the 20–60 s pulsation period observed.

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