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X-RAY OBSERVATIONS OF AM HERCULIS IN ITS LOW STATE

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ABSTRACT

AM Her was observed with the *Einstein* Imaging Proportional Counter during the low state of 1980 August. The light curve shows an eclipse at $\phi_m = 0.0$ similar to the one observed in the customary high state. The spectral distribution of the X-ray photons does not show any soft component. The IPC flux suggests that the intensity of the hard component in the low state is about one-tenth of the intensity of the hard component during the high state, similar to the variation in the optical magnitude. The comparison of the present data with a previous *SAS 3* X-ray observation of AM Her in the low state suggests that the soft component is different in similar accretion regimes. The possibility that this component originates from reprocessing of the hard flux becomes then more unlikely.

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

I. INTRODUCTION

AM Her is an eclipsing binary ($P = 3.1$ hr) consisting of a magnetized white dwarf ($B \sim 10^7$ gauss; Latham, Liebert, and Steiner 1981) and a red dwarf. Although extensively observed at wavelengths ranging from the IR to the X-ray (see review of Chiappetti, Tanzi, and Treves 1980), it is still an unsolved system. In particular, this star shows an UV and soft X-ray component that, if interpreted as due to a single blackbody (Fabbiano *et al.* 1981 and references therein), is greatly more luminous than the hard X-ray emission, in disagreement with models of emission purely from gravitational accretion, both with and without magnetic fields (Lamb and Masters 1979; Kylafis and Lamb 1979). AM Her undergoes optical low states at intervals of a few years and with duration of typically 2–3 months. The low state of the summer 1980 was a unique opportunity for observing AM Her not only in the optical but both in the UV with *IUE* (Szkody, Raymond, and Capps 1982) and in X-rays with *Einstein*. We report here the results of the *Einstein* observations.

II. OBSERVATIONS AND RESULTS

AM Her was observed during the optical low state with the Imaging Proportional Counter (IPC) on board the *Einstein Observatory* (Giacconi *et al.* 1979). The satellite was pointed at the star from 234.19 UT to 234.26 UT 1980. The magnitude of AM Her at that time was $m_v \sim 14.5$ (AAVSO, private communication). Because of Earth occultation, AM Her was in the field of view of the IPC for a total of 2022 s.

a) *Light Curve*

Figure 1*a* shows the IPC light curve of AM Her. The counts are from a 50 pixel ($= 6\rlap{.}'7$) radius circle centered on the position of AM Her. To maximize the signal-to-noise ratio, we used the counts from PHA (pulse-height analyzer) channels 2–10 (~ 0.2–3.0 keV) because the statistical significance of the signal is very marginal in the first and in the last five PHA channels (see Fig. 2). To check for possible instrumental effects that could simulate variability, we obtained a background "light curve" from a 70 pixel radius circle not including the source. No variability in the background was observed. As is evident from the figure, the IPC observed the source in two distinct time intervals. The first begins during an eclipse, while the second one is during the ON time. There is a suggestion of variability on time scales of ~ 10 minutes, similar to that observed in X-rays during the high state (Fabbiano *et al.* 1981). We are limited by the poor statistics in searching for variability on shorter time scales.

b) *X-Ray Spectrum*

To derive the X-ray spectral parameters of AM Her in the low state, we performed spectral fits of the data from PHA channels 2–10 to three different models: a power-law spectrum, an exponential thermal spectrum with Gaunt factor, and a blackbody spectrum.

In order to perform a meaningful spectral fit to the IPC data, a reasonable knowledge of the instrumental gain at the time of the observation is needed. We measured the instrumental gain from on-flight calibra-

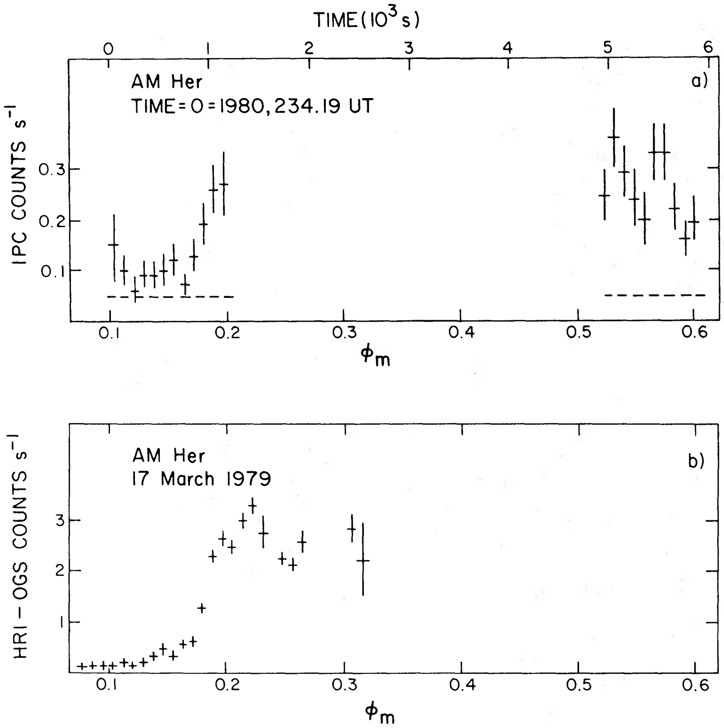

FIG. 1.—(a) The IPC light curve of AM Her during the 1980 August low state. The background level is indicated by the dashed line. (b) A portion of the high-state light curve (High Resolution Imager/Objective Grating Spectrometer) from Fabbiano *et al.* (1981), plotted at the same ϕ_m as Fig. 1a. The data are binned in 100 s bins for easy comparison with the light curve in Fig. 1a.

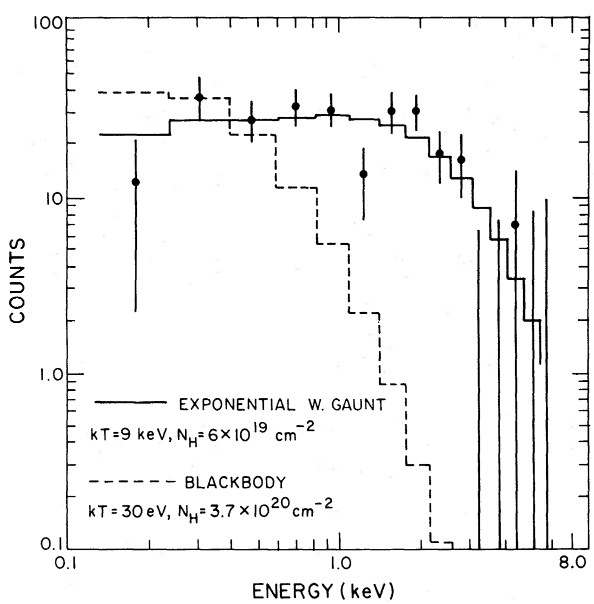

FIG. 2.—Spectral distribution of the AM Her photons in the IPC. The data are plotted for the nominal instrument gain. The solid line represents a fit to a 9 keV bremsstrahlung spectrum; the dashed line, to a 30 eV blackbody.

tions taken close in time to the observation. Using these calibration data, the peak PHA channel of the IPC instrumental response to the aluminum calibration line was calculated. Since the gain can vary both in time and with the position on the IPC plane, we did spectral fits for a range of $\pm 13\%$ in gain. We obtain reasonable fits for both bremsstrahlung with $kT > 2$ keV and power-law spectra with photon number index $\alpha_{ph} \approx -0.7$ to -2.5, respectively. The data can also be fitted with a blackbody spectrum, having kT in the range ~ 200–500 eV. We can exclude a blackbody spectrum with kT in the range ~ 20–40 eV, as is found for the strong soft component present in AM Her in the high state (Tuohy *et al.* 1978). The data and the fit to a 9 keV bremsstrahlung are shown in Figure 2. In this figure, the spectrum corresponding to a $kT = 30$ eV blackbody ($N_H = 3.7 \times 10^{20}$ cm^{-2}, in the range of the absorption column of Tuohy *et al.* 1978) is also plotted. The χ^2 for the fit to the blackbody spectrum is 81.7 for 7 degrees of freedom.

c) *X-Ray Flux and Luminosity*

The average value of the 0.5–4.0 keV X-ray flux of AM Her (background subtracted) for the entire length of the observation is $f_x \sim (3.4 \pm 0.8) \times 10^{-12}$

ergs cm^{-2} s^{-1}. The error quoted is given by the statistical error plus an additional systematic 20% error due to the uncertainty on the spectral parameters. The flux during eclipse is $(1.4 \pm 0.3) \times 10^{-12}$ ergs cm^{-2} s^{-1}, while the flux at phase 0.5–0.7 is $(4.8 \pm 1.0) \times 10^{-12}$ ergs cm^{-2} s^{-1}. Assuming a distance of 100 pc, the corresponding luminosities are L_x (eclipse) $\sim 1.7 \times 10^{30}$ ergs s^{-1}, L_x (ON) $\sim 5.8 \times 10^{30}$ ergs s^{-1}.

III. DISCUSSION

a) Low State of 1980 August versus High State

The X-ray spectrum of AM Her in high state shows two components: a strong soft component, whose nature is still controversial (see Fabbiano *et al.* 1981), and a hard component, which is interpreted as originating from a standing shock in the matter accreting onto the magnetic pole of a white dwarf (Lamb and Masters 1979; Kylafis and Lamb 1979). The flat spectral distribution of the photons in the *Einstein* observations during the 1980 August low state suggests that we are looking at the shock-heated gas in the accretion column. The 0.5–4.0 keV X-ray luminosity of AM Her (both in and out of eclipse) in our observations is one order of magnitude less than the corresponding luminosity of the hard component during the high state (Fabbiano *et al.* 1981). The variation in L_x is of the same order as the change in the optical luminosity of the visible and blue components (Szkody, Raymond, and Capps 1982). This suggests that the accretion rate during the low state is about one-tenth of the accretion rate during the high state.

Our light curve (Fig. 1*a*) shows that AM Her undergoes eclipses during low state in the ~ 0.2–3.0 keV energy range. The presence of X-ray eclipses at minimum in a softer energy range (0.1–0.4 keV) was reported by Hearn and Richardson (1977). By comparing the data of Hearn and Richardson with those of Tuohy *et al.* (1978), Hutchings, Crampton, and Cowley (1981) concluded that the X-ray eclipse occurs at magnetic phase $\phi_m = 0.0$ during both optical high and low states. Since AM Her was observed with the *Einstein* satellite also in a high state (Fig. 1*b*), we can make a direct comparison between the two light curves in the same energy range. We notice that the eclipse occurs at $\phi_m =$ 0.0 in both optical states. Given both statistical uncertainties and the flickering of the source, the eclipse duration is consistent with its being the same in the two optical regimes.

The occurrence of eclipse always at $\phi_m = 0.0$ confirms that only one pole of the white dwarf is responsible for the X-ray emission. Although the energy range of the high- and low-state light curves (Figs. 1*a* and 1*b*) is approximately the same, the low-state light curve is the light curve of the hard component (see above discussion), while the high-state light curve is dominated by the soft component (Fabbiano *et al.* 1981). Therefore, our observations relative to the eclipse duration are obviously in agreement with the model of Chanmugam and Wagner (1978), who suggested that the X-ray eclipses are due to the body of the white dwarf blocking off the X-ray–emitting region, but they are not relevant for a discussion of the model of obscuration by the accretion column (Priedhorsky and Krzeminski 1978).

b) Low State of 1980 August versus Low State of 1976 May

AM Her was observed by *SAS 3* during the 1976 minimum (Hearn, Richardson, and Clark 1976; Hearn and Richardson 1977). The results of the *SAS 3* observations are summarized in Table 1 together with the *Einstein* results. While the *SAS 3* upper limit for the harder energy band is consistent with our observation, it does not seem possible to reconcile the *SAS 3* soft detection with the IPC observations. We first explored the possibility that the discrepancy might be ascribable to instrumental differences. We folded blackbody spectra through the IPC instrumental response within the gain range of our observation, and we found that a blackbody of $kT > 10$ eV with a flux like the one detected by *SAS 3* in the 0.1–0.4 keV band should be easily detectable with more than 500 IPC counts in a 1000 s observation (the part of the observation not in eclipse). Blackbody spectra with $kT < 10$ eV can be ruled out because the total luminosity (normalized to the observed flux) would be physically unrealistic (see below).

Since the discrepancy between the soft X-ray behavior of AM Her during the 1976 and 1980 low states is a real one, we explored it further to see what could be

TABLE 1

X-RAY OBSERVATIONS OF AM HERCULIS DURING LOW STATE

Satellite	m_v	f_x(0.1–0.4 keV) (ergs cm^{-2} s^{-1})	f_x(> 0.4 keV) (ergs cm^{-2} s^{-1})
SAS 3 (1976 May)[a]	14.8	1.1×10^{-10}	$< 4.5 \times 10^{-11}$ (3 σ)
Einstein (1980 August) ...	14.5	$\leq 6.0 \times 10^{-13}$	4.8×10^{-12}

[a] Hearn and Richardson 1977.

inferred from it in terms of the emission models for this system. In the framework of the reprocessing models (Lamb and Masters 1979; Kylafis and Lamb 1979), the optical dimming of the system is due to a reduced mass outflow from the red companion, and one would expect that the luminosities of both the hard and soft X-ray components should vary together. We already know (see above discussion) that the optical magnitude and the hard X-ray luminosity vary by the same amount, as might be expected in the accretion flow picture. AM Her was at the time of the *SAS 3* observation as faint optically as at the time of our observation (or even fainter, see Table 1). We can then assume that its hard X-ray luminosity was comparable with the one derived from the *Einstein* measurements. Therefore, we would expect that the total luminosities of the *SAS 3* and *Einstein* soft components should be comparable, although we have no constraints on the temperatures of such components.

In Figure 3*a* we plot the ratio of L_{BB}, the luminosity obtained by fitting the data (*SAS 3, IUE*, and *Einstein*) to a blackbody spectrum of given temperature and assuming a distance $D \sim 100$ pc for the system, and L_{WD}, the blackbody luminosity of a white dwarf of radius $R_{WD} \sim 5 \times 10^8$ cm and the same temperature, versus the blackbody temperature. The *IUE* curve was

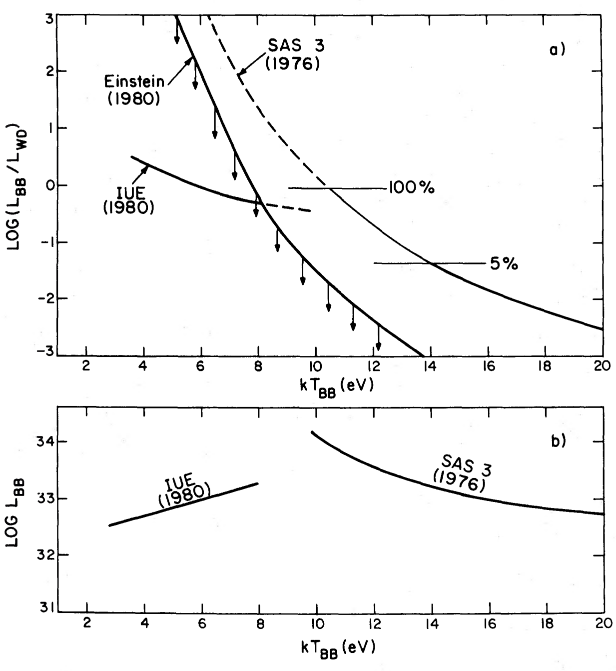

FIG. 3.—(*a*) Log L_{BB}/L_{WD} (see text) is plotted versus kT_{BB}. The three curves are derived as described in the text. The dashed part of the *SAS 3* curve is the portion that is not allowed because of the constraint that the emitting area cannot be larger than the projected area of the white dwarf. (*b*) The logs of the allowed blackbody luminosities for the *IUE* and the *SAS 3* observations are plotted as a function of the blackbody temperature.

derived from the UV spectra of Szkody, Raymond, and Capps (1982), taken at various times during the 1980 low state. The *Einstein* upper-limit curve was derived by calculating the best fit to the X-ray data for each given temperature assuming an equivalent hydrogen absorption column $N_H = 1 \times 10^{19}$ cm^{-2}. The *SAS 3* curve was derived using the same N_H; a larger N_H would result in an upward shift of both curves. As is evident from the figure, the *IUE* and *Einstein* data constrain the soft component of the summer 1980 low state to have $kT_{BB} \leq 8$ eV. More significant independent evidence of this comes from the UV data alone: the depth of the Lyα absorption feature suggests an upper limit $kT_{BB} < 8$ eV on the temperature of the UV-emitting region. A slightly larger upper limit (<10 eV) can be inferred from the He II λ1640 line ratio between *IUE* spectra taken during optical high and low states (Szkody, Raymond, and Capps 1982). The constraint that $L_{BB} < L_{WD}$ constrains the *SAS 3* soft component to have $kT_{BB} > 10.4$ eV.

The *IUE* data suggest that (in the blackbody approximation) the emitting area is more than 50% of the projected area of the white dwarf. If, as in the reprocessing framework, $L_{BB}(SAS\ 3) \sim L_{BB}(IUE) \sim 10^{33}$ ergs s^{-1} (see Fig. 3*b*), then $kT_{BB}(SAS\ 3) \gtrsim 14$ eV, which implies (see Fig. 3*a*) that the emitting area is only $\lesssim 5\%$ of the white dwarf area. This is in clear discrepancy with the *IUE* results. Moreover, a $L_{BB} \sim 10^{33}$ ergs s^{-1} would be ~ 100 times larger than the hard X-ray luminosity during the 1980 *Einstein* observations, again in contrast to the reprocessing models that predict about equal soft and hard components.

In the above, we have assumed that a blackbody adequately describes the emission from the white dwarf surface. In fact (S. Kahn, private communication), this is not true if the white dwarf atmosphere is helium-poor and metal-poor (Shipman 1979). In this case, the opacity, and thus the temperature, at monochromatic depth unity varies as a function of the wavelength, resulting in departure from the blackbody spectrum. The biggest effect would be for a pure hydrogen atmosphere and an emitting region of $kT \sim 4$ eV, where L_{BB} could be reduced by a factor of up to ~ 1000 (Wesemael 1980). We must then consider the *IUE* curves (both that in Fig. 3*a* and that in Fig. 3*b*) upper limits to L_{BB}, especially at the lower kT_{BB}'s. This could reduce the emitting area of the *IUE* component to match the *SAS 3* emitting area, but it would also give $L_{BB}(IUE) \ll L_{BB}(SAS\ 3)$, contrary to the predictions of the reprocessing models. Using a large radius for the white dwarf $R_{WD} \sim 10^9$ cm or a larger N_H would not result in matching the *SAS 3* with the *IUE* and *Einstein* data. We also explored the effects of variability in N_H. A larger N_H during the 1980 August observation than during the 1976 May observation might result in making the *Einstein* upper limits compatible with the *SAS 3* detection, but the *IUE* data would still not match. Moreover, the presence of a hot ($kT_{BB} > 10$ eV) blackbody would affect the *IUE* spectrum (line depths and ratios), even if a cloud in the line of sight made it invisible in the soft X-rays.

IV. CONCLUSIONS

The *Einstein* observations of AM Her in low state confirm that the same magnetic pole of the white dwarf is active during both high and low states. They also show that the hard X-ray luminosity of AM Her varies by the same amount as the optical magnitude, in agreement with the accretion flow picture. A surprising result is given by the comparison of the *Einstein* and *IUE* data (Szkody, Raymond, and Capps 1982) obtained during the summer 1980 low state with the *SAS 3* data (Hearn and Richardson 1977) obtained during the 1976 May low state. It appears that the UV–soft X-ray component behaves differently in the two cases. This leads us to the following conclusions:

1. If the *SAS 3* and *IUE* components have the same origin, then their integrated luminosities are different, suggesting that they are not due to reprocessing of the hard X-ray photons. If this soft component is due to nuclear burning (Fabbiano *et al.* 1981) or to some other mechanism not strictly connected with the accretion flow, it is, however, conceivable that it could be present for some time after accretion flow has decreased.

2. The *SAS 3* and *IUE* components might have different origins. While leaving intact the above reasoning on the nature of the EUV–soft X-ray component, this would indicate the presence in the AM Her system of an additional UV component that would be visible only in the low states and that would originate from the whole white dwarf surface or from a substantial fraction of it.

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