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NEW EVIDENCE ON THE NATURE OF THE SOFT X-RAY SOURCE IN AM HERCULIS FROM *HEAO 1*

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ABSTRACT

We report the results of scanning observations of AM Herculis from *HEAO 1* during the period 1977 September 22–October 12. The soft X-ray light curve constructed from our observations shows considerable scatter in intensity, together with clear evidence for a residual flux during X-ray minimum. At X-ray maximum, the flux in the energy range 0.15–0.5 keV is typically 8×10^{-10} ergs cm^{-2} s^{-1}. The spectrum of AM Her is characterized by a sharp turnover at 0.2 keV, and is well described by a blackbody model with absorption. There is no appreciable change in the spectrum with binary phase. The present observations, when combined with theoretical models, imply that the soft X-rays are produced by the heated surface of the degenerate dwarf component, and that the surface has a temperature $\sim 4 \times 10^5$ K and a luminosity ~30 times that observed at optical or hard X-ray wavelengths. We predict that AM Her is a spectacular UV source, with an intrinsic UV luminosity comparable to that in soft X-rays.

Subject headings: X-rays: binaries — X-rays: sources

I. INTRODUCTION

AM Herculis has been extensively studied in recent years and has been found to have a variety of interesting properties. A 3.1 hour flux modulation is present over a wide wavelength band extending from soft X-ray energies (~0.2 keV) to the infrared region (e.g., Hearn and Richardson 1977; Swank *et al.* 1977; Cowley and Crampton 1977; Priedhorsky *et al.* 1978). Optical polarization data (Tapia 1977) and emission-line spectra (Priedhorsky 1977; Greenstein *et al.* 1977) also show the 3.1 hour periodicity. At X-ray energies, AM Her is characterized by a very soft component below 0.5 keV and a hard component which extends to at least 60 keV (Swank *et al.* 1977; Bunner 1978). It is believed to be a binary system containing a strongly magnetic ($B \sim 10^8$ gauss), relatively massive ($M \sim 1$–$1.4\ M_\odot$) white dwarf rotating in synchronism with the orbital motion of the system and accreting matter from a low-mass ($M \sim 0.35$–$0.4\ M_\odot$) companion (see, e.g., Chanmugam and Wagner 1977; Stockman *et al.* 1977; Priedhorsky and Krzeminski 1978).

In this *Letter* we report new evidence on the nature of the soft X-ray source in AM Her obtained from *HEAO 1*. Our results include the first detection of a low-energy turnover in the spectrum and the first information on the behavior of the spectrum as a function of binary phase. We conclude that AM Her is predominantly a UV and soft X-ray source, with a total luminosity ~30 times larger than assumed previously.

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II. OBSERVATIONS AND RESULTS

The *HEAO* A-2 instrument[1] is described in detail by Rothschild *et al.* (1978). Briefly, the data reported here were obtained by LED 1, which is sensitive to X-rays in the interval 0.1–3 keV and has two coaligned fields of view measuring $1^\circ\!.5$ and $2^\circ\!.8$ FWHM in the scan direction. The angular response of the detector perpendicular to the scan path is 3° FWHM for each field of view. Owing to its high ecliptic latitude, AM Herculis was within 3° of the *HEAO* scan plane for an extended period of ~20 days between 1977 September 22 and October 12. Approximately 40 source transits occurred each day, but only an average of 4 scans per day were usable due to Earth occultations and various LED operating constraints.

Light curve.—A light curve of AM Her was produced in the following manner. Each source sighting (duration ~20 s) was fitted with the detector angular response and the resulting flux was then corrected for source aspect. Only data acquired when the source was within $2^\circ\!.2$ of the scan plane were accepted in order to avoid large aspect correction factors. The corrected source intensities were then folded with a period of 0.128927 days, using the epoch JD $2{,}443{,}014^{d}\!.7647$ for phase zero. This epoch corresponds to the center of the linear polarization event observed by Tapia (1977), while the period is that derived from circular polarization and optical observations during 1976 and 1977 (Priedhorsky and Krzeminski 1978); there is at present no evidence

[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.

for period change or for any difference between the photometric and polarimetric periods.

Figure 1*a* shows the light curve obtained for the 1°5 field of view of LED 1 in the band 0.18–0.5 keV. The light curve has a broad maximum lasting from phase 0.4 to 0.8, followed by a downward step in the average flux by a factor ~2. At the onset and termination of X-ray minimum, the flux changes by a factor ~5 in a phase interval $\Delta\phi \sim 0.1$. Although our light curve is consistent with the averaged light curve presented by Hearn and Richardson (1977), our data clearly demonstrate that the X-ray flux is highly variable throughout the phase interval 0.2–0.8. Furthermore, we have detected a significant residual flux during X-ray minimum ($\phi = 0.00$–0.15). The presence of this residual flux imposes an important new constraint on geometrical models of the X-ray minimum.

Temporal behavior of the flux.—The observed scatter in the X-ray light curve indicates changes in the source intensity by a factor of 2–3 in less than a few hours. This scatter is consistent with variation in either the amplitude or the shape of the mean light curve. We have examined the temporal behavior of the flux on shorter time scales, using data acquired when the detector was operated in an 80 ms integration mode. This analysis revealed no evidence for periodic variability or quasi-periodic short time scale behavior. From the strongest scans, we can set a 3 σ upper limit to the pulse fraction of ~15% for periods in the range 0.2–2 s.

Temporal behavior of the spectrum.—In order to study the X-ray spectrum as a function of binary phase, we have computed a hardness ratio, defined as the ratio of the (0.30–0.60) to (0.18–0.30) keV count rates, for each sighting. Figure 1*b* shows the results of folding the hardness ratio values with the 3.1 hour period. Note that *there is no appreciable change in the spectrum even during recovery from X-ray minimum*, contrary to what would be expected if the minimum were due to increased absorption. However, the fluctuations in the hardness ratio are larger than expected from statistics (reduced $\chi^2 \sim 2$), suggesting the possibility of small variations in the source spectrum.

Soft X-ray spectrum.—In order to obtain the best possible measurement of the AM Her spectrum, the high voltage to LED 1 was briefly increased during a single ground station pass, thus decreasing the low energy electronic threshold to 0.11 keV. At this time the source was at phase 0.39. The resulting data were fitted in turn with a blackbody and an exponential spectrum with an energy-dependent Gaunt factor (Karzas and Latter 1961; Kellogg, Baldwin, and Koch 1975), allowing for absorption in the interstellar medium (Brown and Gould 1970). Figure 2 shows the best-fit blackbody spectrum corrected for the detector response, together with the 90% confidence contours (Lampton, Margon, and Bowyer 1976) for both spectral types. Either model provides an acceptable fit (note that the best-fit values of kT and N_H are highly correlated).

These results show for the first time that there is a definite turnover in the observed spectrum at ~0.2 keV. From the chi-squared contours, we can set lower limits to the column density of 1.7×10^{20} (blackbody) and 2.8×10^{20} H atoms cm^{-2} (exponential) at the 90% confidence level. From Figure 2 we can also set 90% confidence upper limits to the source temperature of 4.5 ×

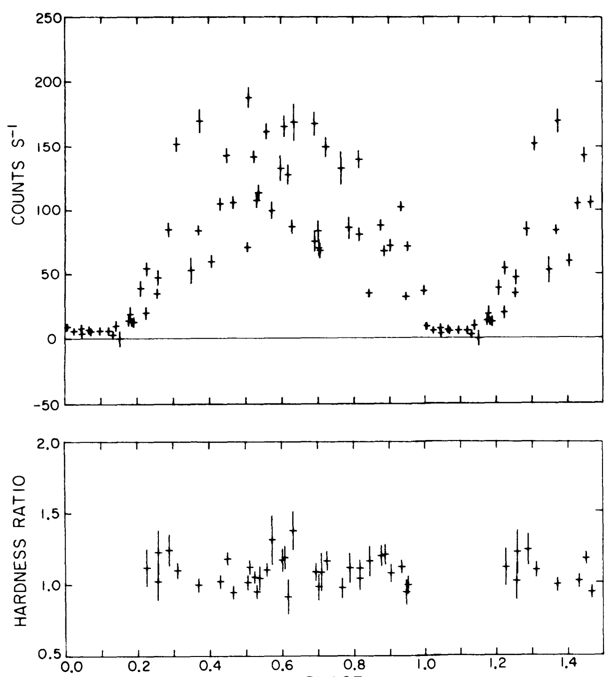

FIG. 1.—(*a*) Light curve of AM Her in the energy range 0.18–0.5 keV. The data are plotted for 1.5 cycles of the 0.128927 day period. (*b*) Hardness ratio (see text) of AM Her as a function of source phase. Error bars are ± 1σ.

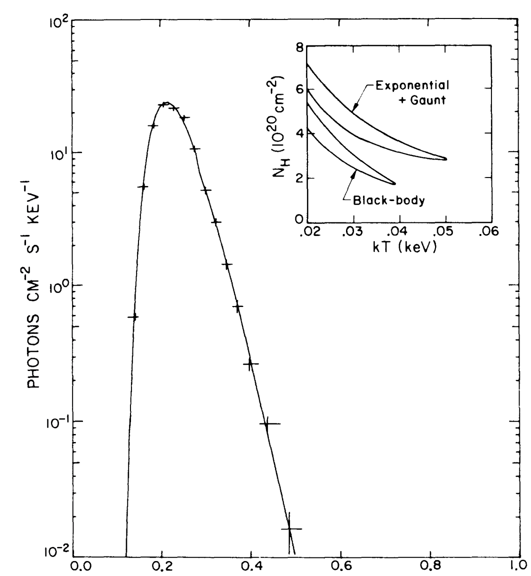

FIG. 2.—Inferred incident spectrum of AM Her for a blackbody model with $kT = 0.025$ keV and $N_H = 3.75 \times 10^{20}$ H atoms cm^{-2}. The inset shows the 90% confidence contours for blackbody and exponential models. The total flux corresponding to this spectrum is given in Table 1.

10^5 K and 5.8×10^5 K for blackbody and exponential spectra, respectively.

The flux observed in the energy range 0.15–0.5 keV was typically 8×10^{-10} ergs cm^{-2} s^{-1} at the maximum of the X-ray light curve ($0.5 \lesssim \phi \lesssim 0.8$), while the mean flux over all phases was 5.0×10^{-10} ergs cm^{-2} s^{-1}. This flux is the highest yet observed from AM Her and corresponds to a time when the source was in an optical high state (Tapia 1978). No flux was detected in the energy range 0.6–3 keV; summing the data from all the scans between phase 0.4 and 0.8 yielded an upper limit on the flux at 1 keV of 7.7×10^{-3} photons cm^{-2} s^{-1} keV^{-1} at the 99% confidence level. This upper limit is consistent with the flux reported by Bunner (1978) in this spectral region.

III. DISCUSSION AND CONCLUSIONS

The qualitative features of X-ray production by accretion onto a magnetic white dwarf have been discussed by Fabian, Pringle, and Rees (1976) and Masters *et al.* (1977), and a quantitative theory has been developed by Masters (1978) and Lamb and Masters (1978). One of the principal conclusions of Lamb and Masters is that the spectrum of the radiation from the plasma at the surface of such a star consists of three components: a high-temperature ($T \sim 10^8$–10^9 K) component produced by electron-ion bremsstrahlung in the hot postshock plasma, a much lower-temperature ($T \sim 10^5$–10^6 K) blackbody component produced by the heated surface of the white dwarf, and a still softer component produced by optically thick electron cyclotron emission in the postshock region. Lamb and Masters (1978) find that typically $L_{\rm bb} \approx L_{\rm cyc} + L_{\rm brems}$, where $L_{\rm bb}$, $L_{\rm cyc}$, and $L_{\rm brems}$ denote the luminosities in the blackbody, cyclotron, and bremsstrahlung components.

If we interpret the observed soft X-rays as the tail of the blackbody component, the temperature, spectral flux, and total luminosity associated with this component can have the values listed in Table 1 and be consistent with the observations reported here. The soft X-ray data allow $T_{\rm bb} < 16$ eV (see Fig. 2), but do not determine the source parameters accurately for such low temperatures. For comparison, the medium- and high-energy detectors of the *HEAO 1* A-2 experiment measured a 2–60 keV flux corresponding to a mean luminosity 3×10^{32} $(D/100\ {\rm pc})^2$ ergs s^{-1} at the same time that the present soft X-ray observations were made (Swank 1978). The blackbody interpretation of the soft X-rays therefore implies that the total luminosity of the system is completely dominated by soft X-ray and UV emission (the high inferred luminosity of the blackbody component requires a comparable UV luminosity due to cyclotron emission). The existence of such a copious soft X-ray and UV flux would help to explain the strong line emission observed in the optical (Priedhorsky 1977; Cowley and Crampton 1977; Stockman *et al.* 1977; Greenstein *et al.* 1977).

TABLE 1

BLACKBODY PARAMETERS CONSISTENT WITH THE OBSERVED SPECTRUM OF AM HERCULIS

$T_{\rm bb}$(eV)	$N_{\rm H}$(10^{20}cm^{-2})	B_1 (ergs cm^{-2} s^{-1} keV^{-1})*	$L_{\rm bb}$ (ergs s^{-1})†
40......	1.70	4.2×10^{-4}	8.4×10^{33}
35......	2.15	1.2×10^{-3}	1.4×10^{34}
30......	2.75	5.1×10^{-3}	3.2×10^{34}
25......	3.75	4.2×10^{-2}	1.3×10^{35}
20......	5.00	8.0×10^{-1}	1.0×10^{36}
16......	6.50	3.2×10	1.6×10^{37}

* The spectral flux $f_\nu^{\rm bb}$ is given by B_1 $(E/1\ {\rm keV})^3$ $[\exp(E/kT_{\rm bb}) - 1]^{-1}$.

† Blackbody luminosity for a distance of 100 pc.

Assuming that the blackbody interpretation is correct, the flux observed at optical wavelengths can be used to bound $T_{\rm bb}$ from below. The strongest constraint is imposed by the requirement that the V-band *cyclotron* flux not exceed the observed V-band flux. For the model developed by Lamb and Masters (1978) applied to AM Her, the cyclotron component has a luminosity comparable to that of the blackbody component but shows a Rayleigh-Jeans spectrum with a brightness temperature $\sim T_e$, the electron temperature in the postshock region. Equating the cyclotron luminosity and the blackbody luminosity inferred from the present observations, the spectral flux due to cyclotron emission below $\sim$10 eV is $\sim 10^{-26}$ $(\nu/2\ {\rm eV})^2$ $(T_e/10\ {\rm keV})$ $(B_1/10^{-4})$ ergs cm^{-2} s^{-1} Hz^{-1}, where B_1 is given in Table 1. This spectral flux is just consistent with the observed V-band flux if $T_{\rm bb} \sim 40$ eV and $T_e \lesssim 30$ keV, implying a soft X-ray luminosity $\sim 8 \times 10^{33}$ ergs s^{-1} at 100 pc.

The minimum column density 1.7×10^{20} cm^{-2} inferred from our observations appears to be consistent with the 21 cm data of Heiles (1975) for a scale height of 100 pc and a distance of $\sim$100 pc to AM Her. We note that Priedhorsky *et al.* (1978) estimate a distance $\sim$130 pc on the basis of the observed 1.6 μm flux and their hypothesis that the companion star is of class M2 V. The widely varying column densities derived from observations in different spectral regions ($\sim 2 \times 10^{20}$ cm^{-2}, this work; $\sim 10^{21}$ cm^{-2} from 0.5–10 keV data, Bunner 1978; $\sim 3 \times 10^{22}$ cm^{-2} from 2–60 keV data, Swank *et al.* 1977) as well as the poor fits provided by simple models of the 2–60 keV spectrum (Swank *et al.* 1977) suggest that the emission region is to some extent inhomogeneous and that the higher inferred column densities are artifacts of the attempt to characterize a complex spectrum by a simple model.

In conclusion, our results indicate (1) that the intense soft X-ray flux from AM Her is produced by a portion of the surface of the white-dwarf component which is heated to a temperature $\sim$40 eV by radiation from accreting plasma; (2) that AM Her has a soft X-ray luminosity $\sim 10^{34}$ $(D/100\ {\rm pc})^2$ ergs s^{-1}, roughly 30 times that in hard X-rays; and (3) that the soft X-ray flux is absorbed by intervening cold plasma with a column density comparable to the interstellar column density for a source at the distance of AM Her.

Finally, we predict that AM Her is a spectacular UV source with a UV luminosity $\sim 10^{34}$ $(D/100\ {\rm pc})^2$ ergs s^{-1}, giving it a total luminosity $\sim$30 times that previously assumed (Swank *et al.* 1977; Stockman *et al.* 1977; and Chanmugam and Wagner 1977).

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REFERENCES

Brown, R. L., and Gould R. J. 1970, *Phys. Rev. D.*, **1**, 2252.
Bunner, A. N. 1978, *Ap. J.*, **220**, 261.
Chanmugam, G., and Wagner, R. L. 1977, *Ap. J.* (*Letters*), **213**, L13.
Cowley, A. P., and Crampton, D. 1977, *Ap. J.* (*Letters*), **212**, L121.
Fabian, A. C., Pringle, J. E., and Rees, M. J. 1976, *M.N.R.A.S.*, **175**, 43.
Greenstein, J. L., Sargent, W. L. W., Boroson, T. A., and Boksenberg, A. 1977, *Ap. J.* (*Letters*), **218**, L121.
Hearn, D. R., and Richardson, J. A. 1977, *Ap. J.* (*Letters*), **213**, L115.
Heiles, C. 1975, *Astr. Ap. Suppl.*, **20**, 37.
Karzas, W., and Latter, R. 1961, *Ap. J. Suppl.*, No. 55, **6**, 167.
Kellogg, E., Baldwin, J. R., and Koch, D. 1975, *Ap. J.*, **199**, 299.
Lamb, D. Q., and Masters, A. R. 1978, in preparation.
Lampton, M., Margon, B., and Bowyer, S. 1976, *Ap. J.*, **208**, 177.
Masters, A. R. 1978, Ph.D. thesis, University of Illinois, Urbana-Champaign.
Masters, A. R., Pringle, J. E., Fabian, A. C., and Rees, M. J. 1977, *M.N.R.A.S.*, **178**, 501.
Priedhorsky, W. C. 1977, *Ap. J.* (*Letters*), **212**, L117.
Priedhorsky, W. C., and Krzeminski, W. 1978, *Ap. J.* **219**, 597.
Priedhorsky, W. C., Matthews, K., Neugebauer, G., Werner, M., and Krzeminski, W. 1978, *Ap. J.*, **226**, in press.
Rothschild, R., *et al.* 1978, in preparation.
Stockman, H. S., Schmidt, G. D., Angel, J. R. P., Liebert, J., Tapia, S., and Beaver, E. A. 1977, *Ap. J.*, **217**, 815.
Swank, J. 1978, talk presented at the 151st AAS Meeting, Austin, TX.
Swank, J., Lampton, M., Boldt, E., Holt, S., and Serlemitos, P. 1977, *Ap. J.* (*Letters*), **216**, L71.
Tapia, S. 1977, *Ap. J.* (*Letters*), **212**, L125.
———. 1978, private communication.

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