THE ASTROPHYSICAL JOURNAL, 230:L95–L98, 1979 June 1

ULTRAVIOLET OBSERVATIONS OF AM HERCULIS WITH *IUE*

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Received 1979 January 9; accepted 1979 March 2

ABSTRACT

Ultraviolet observations of the binary X-ray source AM Herculis from the *IUE* satellite show strong emission lines of ions from O I to N V, probably originating in photoionized gas, and a continuum which is partially eclipsed in phase with the X-ray eclipse. The emission lines have broad ($\sim$600 km s^{-1}) and sharp ($\sim$80 km s^{-1}) components at different velocities, as has been seen in optical lines. The continuum is interpreted as two components, a blackbody ($kT_{\rm BB}$ = 25–30 eV) which accounts for the X-ray emission below 0.5 keV and the eclipsed part of the UV continuum, and a component which is never eclipsed, whose spectrum is roughly $F_\nu \propto \nu^{-1}$. Strong ultraviolet emission due to optically thick cyclotron emission, which has been predicted theoretically, is not observed. This presents a severe difficulty for the theory of accretion onto the magnetic pole of a white dwarf.

Subject headings: stars: white dwarfs — ultraviolet: spectra — X-rays: sources

I. INTRODUCTION

AM Herculis is believed to be a white dwarf in close orbit with an M dwarf. The optical light curve shows a 3.1 hour period (Szkody and Brownlee 1977; Cowley and Crampton 1977), which is also seen in soft X-rays (Hearn, Richardson, and Clark 1976; Bunner 1978; Tuohy *et al.* 1978) and hard X-rays (Swank *et al.* 1977), in emission-line velocities (Priedhorsky 1977; Greenstein *et al.* 1977), and in linear and circular polarization (Tapia 1977; Stockman and Sargent 1978). The circular polarization implies a magnetic field $\sim 2 \times 10^8$ gauss. The two components of the X-ray spectrum have temperatures of $\sim$20 keV and $\sim$30 eV. Current models (Priedhorsky and Krzeminski 1978; Chanmugam and Wagner 1978; Lamb and Masters 1979) feature a hot spot at a magnetic pole of the white dwarf which rotates out of sight periodically. In the models of Masters *et al.* (1977), Lamb and Masters (1979; see also Masters 1978), and King and Lasota (1979), gas accreting onto the magnetic pole is shocked to a temperature $kT_e \sim 20$ keV, and produces the hard component of the X-ray spectrum by bremsstrahlung. This gas should also produce optically thick cyclotron emission, which will have a Rayleigh-Jeans spectral shape and kT = 20 keV brightness temperature longward of a very sharp cutoff at $\sim$600–1200 Å. This model also predicts that the bremsstrahlung and cyclotron radiation will heat the surface of the white dwarf at the pole to $kT_{\rm BB} \sim 30$ eV, thereby accounting for the soft component of the X-ray emission.

We observed AM Herculis with the *IUE* satellite in 1978 May and July. The instrument is an echelle spectrometer with long (2000–3400 Å) and short (1150–2000 Å) wavelength ranges and high and low dispersion modes ($\sim$0.1 and $\sim$6 Å, respectively). Further details of the instrumentation are given in Boggess *et al.* (1978).

We obtained long- and short-wavelength spectra at both low and high dispersion. Estimates of the brightness based on the fine error sensor counting rate indicate that AM Herculis was in its "high" state, $m_v \sim 13$, throughout the observing period. We adopt the magnetic phase convention (Tapia 1977) and the period of Stockman and Sargent (1978).

* Guest Investigator with the *IUE* satellite, which is sponsored and operated by NASA, by the SRC, and by ESA.

II. RESULTS

a) The Continuum

Figure 1 shows two short-wavelength low dispersion spectra taken at relative phases 0.11 and 0.66. These 45 minute exposures illustrate the differences in shape and intensity of the UV continuum between X-ray eclipse (ϕ = 0.11) and X-ray maximum. The strong emission lines are saturated in these exposures. Figure 2 gives light curves of the continuum flux (100 Å averages excluding reseau marks and emission lines), centered at 1400 Å and 1900 Å, together with the 0.15–0.5 keV light curve of Tuohy *et al.* (1978). It is apparent that the UV and X-ray eclipses coincide and that the eclipse is deeper at 1400 Å than at 1900 Å. In three long-wavelength exposures (ϕ = 0.53, 0.92, 0.03) the continuum fluxes at 2500 Å are the same to within the repeatability of the *IUE* flux measurements, $\sim$10%. Toward the long- and short-wavelengths ends of the long-wavelength spectrum ($\sim$2000 and $\sim$3200 Å) the flux appears to be constant with phase, but the uncertainty is larger.

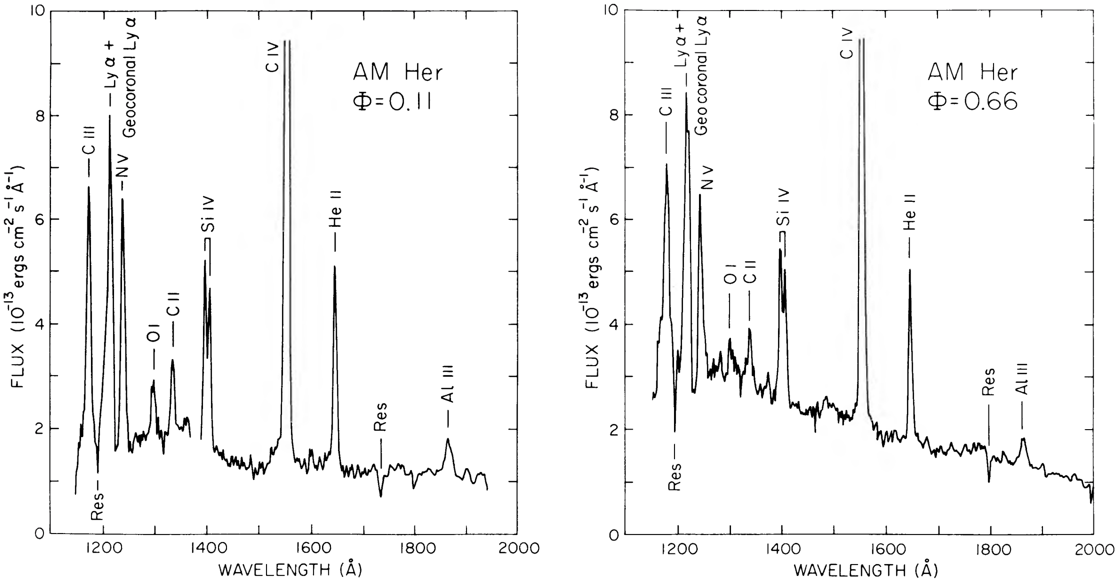

FIG. 1.—Short-wavelength, low dispersion spectra of AM Her at phases 0.11 and 0.66, near the center of the X-ray eclipse and the X-ray maximum, respectively. Note the difference in continuum level and slope. The strong emission lines are saturated.

The model of Lamb and Masters (1979) predicts strong UV emission from the X-ray–emitting gas. The X-ray eclipse is very nearly total, so any UV radiation from the same emitting region will be effectively totally eclipsed as well. On the other hand, the continuum flux in the 2000–3000 Å range and in the optical U-band is relatively constant. Thus the UV continuum may be divided into two components, one which is absent between $\phi \sim 0.95$ and $\phi \sim 0.2$ and is associated with the X-ray–emitting region and one which is never eclipsed. The latter is the continuum of Figure 1*a* and the former is given by the difference between Figures 1*b* and 1*a*.

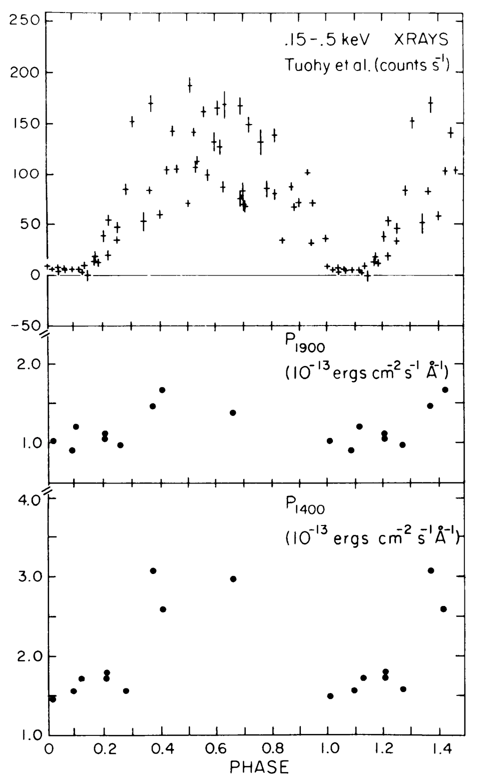

FIG. 2.—Continuum light curves at 1400 Å and 1900 Å together with the soft X-ray light curve of Tuohy *et al.* (1978).

The component associated with the X-rays has a spectrum consistent with $F_\nu \propto \nu^2$, the Rayleigh-Jeans spectrum. A least-squares fit $F_\nu \propto \nu^\alpha$ for the range 1250 Å $\leq \lambda \leq$ 1750 Å, the region which can be accurately extracted from our observation, gives $\alpha = 2.1$. The uncertainties are difficult to quantify, but we believe that $1.5 < \alpha < 3.0$ is the range permitted by the observations. [We have neglected reddening. On the basis of the 2200 Å bump, $E(B - V) \lesssim 0.05$.] Tuohy *et al.* (1978) find that the soft component of the X-rays can be fitted by blackbody emission with 16 eV $\leq T_{\rm BB} \leq$ 40 eV. From their Table 1, a blackbody of $T_{\rm BB} = 28$ eV fits both the soft X-rays and the eclipsed component of the UV continuum. The source is variable, and the UV and X-ray observations were not simultaneous, but since both sets of measurements were made during the "high" state, the X-ray flux at the time of our observations was probably within a factor of 2 of that given by Tuohy *et al.* This translates into a narrow range of blackbody temperatures 25 eV $\leq T_{\rm BB} \leq$ 30 eV, and the luminosity is $L_{\rm BB} \sim 10^{35}\ D_{100}{}^2$, where D_{100} is the distance in units of 100 pc. These temperatures also agree with the soft X-ray flux given by Bunner (1978).

The X-ray measurements cannot discriminate between blackbody or bremsstrahlung spectra for the soft component because of the additional free parameter of absorbing hydrogen column density. King and Lasota

(1979) seek to avoid difficulties in total energetics (discussed below) by suggesting that the soft X-rays are produced by bremsstrahlung from 3×10^5 K gas with an emission measure $n_e^2 V \sim 10^{57} D_{100}^2$ cm^{-3}. This would produce an F_ν = constant component in our spectral range with about twice as much flux at 1500 Å as the observed "blackbody" component. Thus the UV observations provide clear evidence that the soft X-rays are blackbody in origin.

Such blackbody emission is predicted by the models of Lamb and Masters (1979). In these models the magnetic pole of the white dwarf is heated by radiation from the $T_e \sim 20$ keV gas to a temperature of ~30 eV. These models also predict optically thick cyclotron emission from the $T_e = 20$ keV electrons in the $\sim 2 \times 10^8$ gauss magnetic field at wavelengths above ~1200 Å which should have a Rayleigh-Jeans spectrum longward of the cutoff wavelength and whose intensity should be $T_e/T_{\rm BB} \approx 600$ times the blackbody intensity. The smallest value for predicted cyclotron emission consistent with the soft X-ray fluxes of Tuohy *et al.* (1978) and Bunner (1978) and with $T_e = 18$ keV (Staubert *et al.* 1978) is 20 times the observed value at 1500 Å. The electron temperature may be higher than 18 keV (Kylafis *et al.* 1979), but this only makes the discrepancy worse. From the long-wavelength spectra, the eclipsed fraction of the continuum flux is less than 2×10^{-14} ergs cm^{-2} s^{-1} Å^{-1} in the range 2500–3000 Å, also a factor of 20 below the smallest flux expected from optically thick cyclotron emission. Thus if the hot gas responsible for the hard X-rays is located at the magnetic pole, the sharp cutoff predicted by Lamb and Masters (1979) must occur at a wavelength above 3000 Å. The apparent lack of a secondary eclipse in the *U*-band and weak eclipse in the B band indicate that the cutoff is ~4500 Å.

The Lamb and Masters model predicts a cutoff energy $E^* = 10$–20 eV (600–1200 Å) for the observed bremsstrahlung and blackbody temperatures. Still worse, the energy radiated by the blackbody comes from heating of the white-dwarf surface by bremsstrahlung and cyclotron emission, implying $L_{\rm BB} \sim L_{\rm brems} + L_{\rm cyc}$. The bremsstrahlung luminosity is an order of magnitude below $L_{\rm BB}$, and the lack of cyclotron emission in the UV, taken with the observed optical fluxes gives $L_{\rm cyc} \lesssim 0.1 \times L_{\rm BB}$.

The flat, uneclipsed portion of the UV continuum is similar to the continuum of the binary X-ray source HZ Her (Dupree *et al.* 1978), which we observed with the same instrument. This constant component of the continuum may be produced by the X-ray heated face of the secondary (see Milgrom and Salpeter 1975). Depending on the position of the hot spot, the secondary will absorb up to 3% of the XUV and X-ray radiation (Priedhorsky and Krzeminski 1978). With the range of blackbody temperatures determined above and the luminosities given by Tuohy *et al.* (1978), this fraction is adequate to account for the luminosity of the flat continuum. It is also possible that this radiation is produced by an accretion disk or accretion column. This component is roughly described by $F_\nu \propto \nu^{-1}$, in agreement with the slope of the optical continuum given by Stockman *et al.* (1977).

b) Emission Lines

The emission lines in the range 1150 Å $\leq \lambda \leq$ 3200 Å are listed in Table 1 along with the range of observed fluxes. The line intensities vary by factors of 2 or 3 while ratios of line intensities stay fairly constant. There is no obvious correlation with orbital phase. Our sample is small, and the strong lines are saturated in some spectra, while the weak ones cannot be measured in others. The search for phase dependence is further complicated by an apparent increase in the line intensities between May and July, so additional observations will be needed to investigate the line emission as a function of phase.

Three high dispersion spectra were obtained, two with the short-wavelength camera and one with the long. All were underexposed. The profile of He II λ1640 from a 30 minute exposure centered at $\phi = 0.86$ shows a narrow component ~80 km^{-1} wide at $v_s \sim +70$ km s^{-1} and a broad component ~600 km s^{-1} wide centered at ~−300 km s^{-1}. These agree with the He II λ4686 profile at this phase from Greenstein *et al.* (1977), although the λ1640 profile is very noisy. The fine structure and multiplet splitting of the sharp component of the λ1640 transition are partially resolved. The total flux of the broad component is about twice that of the narrow component.

Sharp components of Si IV λλ1393, 1402 and C IV λλ1548, 1551 are present in this spectrum, again at $v_s \sim 70$ km s^{-1}. The broad components of the C IV lines are generally similar to that of λ1640, but complicated by overlap and noise. The instrumental sensitivity is relatively low at 1400 Å, and broad components of the Si IV lines cannot be identified above the noise.

The Al III λ1864 line also appears to be present with a profile like that of He II λ1640. Each of the identifiable broad components has a dip at its center which suggests emission from a ring or disk. There is no indication that C IV shows higher velocities than the optical lines of the lower ionization stages reported by Greenstein *et al.*

TABLE 1

AM HERCULIS ULTRAVIOLET EMISSION LINES

Ion	Wavelength (Å)	Flux (10^{-13} ergs cm^{-2} s^{-1})
C III	1176	15–40
Si III	1206	~30*
Lα	1216	0–10*
N V	1240	27–57
O I†	1304	6–15
C II	1335	8–22
Si IV	1393, 1402	29–70
C IV	1550	180–330
He II	1640	32–84
Al III ?	1860	6–25
Si III ?	1892	~2
Mg II	2798	6–12
O III	3123, 3133	≲12

* Badly blended with geocoronal Lα.
† In some spectra this is blended with Si III λ1298.

Density estimates can be made from the ratios of emission-line intensities, but this is complicated because of the presence of the separate components of the emission lines. The upper limit to the flux in C III λ1909 is $\sim 5 \times 10^{-14}$ ergs cm^{-2} s^{-1}. If the gas which produces the C III λ1176 emission is collisionally ionized, then $T \approx 5 \times 10^4$ K, and the excitation rates of Dufton *et al.* (1978) imply $n_e > 3 \times 10^{11}$ cm^{-3} in whichever gas (sharp or broad component) dominates the λ1176 emission. If the gas is photoionized, $T =$ 1–2 $\times 10^4$ K and $n_e > 10^{13}$ cm^{-3}. These densities are not surprising in view of estimates $10^{12} \lesssim n_e \lesssim 3 \times 10^{14}$ cm^{-3} based on the Balmer lines (Stockman *et al.* 1977).

The relative intensities of the lines of C IV, N V, and He II are in good agreement with the model of optically thick gas photoionized by hard X-rays (Hatchett, Buff, and McCray 1976) or by a soft blackbody (Flower 1968). For the blackbody parameters given above, an assumed distance $\gtrsim 100$ pc and $n_e < 3 \times 10^{14}$ cm^{-3}, photoionization indeed dominates over collisional ionization within the orbital separation 7–9 $\times 10^{10}$ cm (e.g., Chanmugam and Wagner 1978). Therefore the expected temperature of the emitting gas is $\sim 10^4$ K, and the required emission measure is $\sim 10^{57}$ $(D/100 \text{ pc})^2$ cm^{-3}, where D is the distance to the star. This is consistent with a scale size of a few times 10^{10} cm, a thickness of $\sim 10^8$ cm, and the upper end of the density range $10^{12} \leq n_e \leq 3 \times 10^{14}$ cm^{-3} given by Stockman *et al.* (1977).

Further high dispersion spectra will be needed for more detailed analysis of the emission lines. Those we obtained were very underexposed, but the exposure time cannot be greatly increased without losing the phase dependence of the profiles, so summing of several exposures will be required.

III. CONCLUSIONS

The UV continuum of AM Her consists of a blackbody ($kT_{\rm BB}$ = 25–30 eV) component, which also produces the 0.15–0.5 keV X-ray spectrum, and a flat uneclipsed component produced by the X-ray heated secondary or by the accreting gas. The optically thick cyclotron emission predicted by Lamb and Masters (1979) is absent, which presents a major difficulty for the theory. D. Lamb (private communication) lists three possible ways to reconcile the theory of accretion onto the magnetic pole of the white dwarf with the observations: modification of the hard X-ray and optical emission by Compton scattering in the column of accreting gas; a magnetic field well below the 10^8 gauss usually quoted; and steady nuclear burning of the accreting matter. The second possibility also requires Compton degradation of the hard X-rays; the third possibility is an unstable situation.

Very strong emission in lines of ions ranging from O I through N V is probably produced in photoionized gas, and broad and sharp components of the lines at different velocities imply two distinct emitting regions.

We gratefully acknowledge the assistance of the *IUE* Observatory staff in the acquisition and reduction of these data, and we thank D. Lamb for helpful comments. This work has been supported by the National Aeronautics and Space Administration under grant NSG 5229 to Harvard University and contract NAS 5-24332 to the Smithsonian Astrophysical Observatory.

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