COORDINATED IUE, EINSTEIN AND OPTICAL OBSERVATIONS OF ACCRETING DEGENERATE DWARFS*

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ABSTRACT

Three binary systems believed to be composed of a white dwarf and a late type star, AM Her, SS Cyg and U Gem, were observed simultaneously in the UV X-ray and optical wavelengths. AM Her was in its customary high state at the time of the observations, while SS Cyg and U Gem were in a low state. In all three cases, a significant UV black body component with $\underline{KT} \lesssim 10$ eV was found. The flux in this component is in excess of the amount predicted by current scenarios of gravitational energy release.

We compare our observations of these objects with the data available in the literature, and we suggest an alternative scenario that would explain their general behavior.

INTRODUCTION

AM Her, U Gem, and SS Cyg are believed to be binary systems consisting of a late type star and of a more massive white dwarf. Optically they can be found in either a high emission state ($m_V \cong 12$, 8.1, 8.8 for AM Her, SS Cyg and U Gem respectively) or a low emission state ($m_V \cong 15$, 21.1, 14.4). SS Cyg and U Gem are optically quite similar, undergoing quasi-periodical outbursts lasting a few days. AM Her instead is found typically in the high emission state. These systems have all been detected in the X-rays. The mechanism of X-ray emission is generally believed to be radial accretion on the white dwarf. The three systems chosen for this study represent different kinds of accreting white dwarfs. AM Her has an intense magnetic field ($B \sim 10^8$G) (ref. 1) and because of this, it is believed to have no accretion disk and to be powered by an accreting column at the magnetic pole of the white dwarf. Optical spectroscopy shows that both SS Cyg and U Gem are associated with accretion disks. The X-ray behavior of SS Cyg has lead to an estimate of a magnetic field $B \sim 10^6$G associated with the white dwarf (ref. 2) No estimate of B has so far been produced for U Gem. The fact that

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the hard X-ray luminosity of U Gem is at least one order of magnitude smaller than that of SS Cyg suggests different magnetic field intensities and/or accretion rates in the two systems. The comparative study of these three accreting degenerate dwarfs should then give us information that can put interesting constraints on the theory for different values of the parameters of the systems.

In this paper, we report the results of coordinated observations in the optical/UV/X-rays of AM Her, U Gem and SS Cyg, and we compare our findings with the existing theoretical predictions. The simultaneity or quasi-simultaneity of our observations in the different energy bands allows us a straightforward, unambiguous comparison with the theory. For a more detailed discussion, see ref. 3.

OBSERVATIONS

A description of the X-ray instruments on board the Einstein Observatory may be found in ref. 4; for a description of the International Ultraviolet Explorer, see ref. 5.

AM HER

AM Her was observed with the 500 lines/mm Objective Grating Spectrometer in front of the High Resolution Imager (HRI) onboard the Einstein Observatory on March 17, 1979. The OGS allows us to obtain spectral information, which otherwise are not provided by the HRI. The soft X-ray spectrum of AM Her obtained from the OGS observations does not show any line contribution (Seward 1979, private communication). It is consistent with a black body radiation with KT ~ 30-40 eV (Heise 1980, private communication). The X-ray properties are summarized in Table I.

The short-wavelength spectra are spaced fairly uniformly over two orbital cycles. They confirm the suggestion of Raymond et al. (1979a) (ref. 6) that the UV continuum is the sum of two power law components. The $F_\nu \propto \nu^{-1}$ component is always present while the $F_\nu \propto \nu^2$ component disappears in phase with the X-ray eclipse. The UV continuum may be separated into the two components as shown by Raymond et al. (1979b) (ref. 7). The $F_\nu \propto \nu^2$ component may be interpreted as the Rayleigh-Jeans tail of the $\sim$ 30 eV black body which produces the soft X-ray emission.

U GEM

U Gem was observed on April 29, 1979 for 1,170s with the Imaging Proportional Counter (IPC) onboard the Einstein Observatory. This observation occurred 20 minutes after $\sim$ 8 hours of observation with the IUE satellite, during which six spectra of the source were taken. Each one of the IUE spectra was exposed from 40 to 60 minutes. U Gem was reported by the AAVSO to be in an optical low state at about m_v = 14.2 at the time of the X-ray and ultraviolet observations.

From a comparison of the hardness ratios of U Gem and SS Cyg, we find that the X-ray spectrum of U Gem at minimum appears to be softer than that of SS Cyg (KT ~ 20 keV). We define the hardness ratio as the ratio of the counts in the ($\gtrsim$ 1-4) keV band to those in the (< 1 keV) band. The IPC hardness ratio of U Gem is <.4 while that of SS Cyg is ∿ 1.7. The hardness ratio of SS Cyg has been calculated using unpublished IPC data taken in 1978 December, during an optical low state.

The (.5 - 4 keV) luminosity of U Gem is $1.3 \pm .2 \times 10^{30}$ erg s^{-1} for a distance of 76 pc (ref. 8). The X-ray observations show clear presence of variability. The X-ray intensity appears to decrease during the length of the observation; a feature involving a decrease of the intensity in a smaller time scale is also present. A χ^2 test shows that the data are definably incompatible with the hypothesis of constant intensity for time scales greater than 2 minutes.

The average of five short-wavelength IUE spectra is shown in Figure 4. In contrast to AM Her and SS Cyg (see below) the spectrum exhibits only absorption lines on a strong continuous background. There are no emission lines (the Lyα feature is very likely only geocoronal) while absorption lines of OI, CII, SiIV, CIV and HeII are present. A broad Lyα absorption line with a width $\Delta\lambda \sim 70$Å is also present.

Fig. 7 shows the composite spectrum of U Gem. A strong UV component can be seen with $f_{uv} \gtrsim 200\ (f_{opt} + f_x)$, assuming a UV temperature $\gtrsim$ 10 eV. For the distance found by Wade (1979) (ref. 8) the UV emitting area is between 3% and 15% of the canonical white dwarf projected surface. These facts, together with the facts that no strong and hard X-ray and no UV emission lines are seen, indicate that the UV component comes from the inner region of the disk (boundary layer) or from the accreting belt.

SS CYG

SS Cyg was observed simultaneously with the Einstein Observatory and the IUE satellite on May 17, 1979. The X-ray observation was done with the HRI/OGS (1000 lines/mm grating) in the focal plane of the telescope and lasted 9.9 hr. The total observing time, because of Earth occultation and other data gaps is 3.4 hr; of these about 2 hr are simultaneous with the observations in the ultraviolet. The IUE observations cover a total time of about 6 hr within the X-ray observing time. A total of nine low-dispersion long-wavelength spectra were taken, four of which are simultaneous to X-ray observations. SS Cyg was monitored by the AAVSO and appeared to be in an optical low state at the time of the Einstein and IUE observations, at a magnitude between 11.3 and 12.0. Szkody (1979, private communication) observed the source photometrically simultaneously with the Einstein and IUE observations.

The X-ray, UV and optical observations are summarized in Tables I and II. The MPC data are consistent with an exponential spectrum with kT = 10-30 keV and no significant low energy cut-off. The 2-6 keV intensity of SS Cyg is $(4.4 - 5.8) \times 10^{-11}$ erg cm^{-2} s^{-1}.

The average IUE spectrum of SS Cyg is shown in Figure 2. The emission lines are the same as the ones observed in AM Her, but the line/continuum ratios appear to be smaller. The main difference with the AM Her UV spectrum is in the presence of a broad Lyα absorption line. We measure a width for this line of $\Delta\lambda = (45 \pm 5)$Å.

The composite spectrum of SS Cyg during the May 17 observation is plotted in Figure 6. Here again, as in the case of AM Her, the UV data can be interpreted in terms of two components: a $\nu^{-1.3}$ power law that extends through the optical points and a ν^2 component that is predominant at the short wavelengths and could be representative of the Rayleigh-Jeans end of a black body spectrum.

The similarity between the AM Her and SS Cyg UV spectra suggests that SS Cyg, like AM Her, has magnetic funneling. This is consistent also with the hard X-ray emission at minimum. In maximum, however, the picture (fig. 3) is more like U Gem, which, we suppose, has an accreting disk. This difference can be explained by the higher accretion rate at maximum, when the Alfvèn radius is of the order of the star radius.

DISCUSSION

Despite previous work that indicates that AM Her, U Gem and SS Cyg have substantially different accretion patterns, they possess one outstanding similarity. All of these cataclysmic variables have an UV short wavelength component of their continuum spectrum which follows a $\sim \nu^2$ power law. This component had already been noticed in the spectrum of AM Her (ref. 6); our new observations show that it is also present in SS Cyg and in U Gem in quiescence. As discussed by Raymond et al. (1979a)(ref. 6), if this feature represents the Rayleigh-Jeans end of a black body with temperatures of the order of 20-30 eV (see also ref. 9), the UV and soft X-ray luminosity of AM Her would be far greater than its hard X-ray luminosity. As is apparent from our data (Figure 5, 6 and 7 and Table 2), the same is true in the case of SS Cyg and U Gem. This property disagrees with models of emission purely from gravitational accretion, both with and without magnetic fields (ref. 10, 11). A possible resolution of this problem is the action of nuclear burning. Kippenhahn and Thomas (1978) (ref. 12) have shown that it is possible to have localized burning in dwarf novae. They also suggested that the different geometry could alter the condition for unstable burning which plays a crucial role in current nova theories (ref. 13, 14). Moreover, the possibility of stable slow burning involving the p-p reaction instead of CNO burning is currently being investigated (Starrfield 1980, private communication). The results so far are very encouraging although detailed dynamical calculations applied to the particular dwarf novae configuration have not yet been performed. The action of nuclear burning on the X-ray flux in a radially symmetric accreting white dwarf has been investigated by Katz (1977) (ref. 15) and more recently by Weast et al. (1979) (ref. 16).

Our findings can be resumed as follows:

1) We have discovered the presence of a strong excess UV radiation in SS Cyg and U Gem. For U Gem we show that this radiation, for the most likely parameters for the system (ref. 8), is likely to originate from the boundary layer of the accretion disk. The luminosity of the UV component is 200 times larger than the combined optical and X-ray emissions. This is inconsistent with the traditional picture of gravitational accretion. We suggest that such a large UV flux might originate from nuclear burning (refs. 12, 16) (Sparks 1980, private communication) at the surface of the white dwarf in the vicinity of the disk boundary layer. A possible black body component of the UV flux similar to the one in U Gem is seen also in AM Her (confirming previous observations by Raymond et al. 1979a)(ref. 6) and in SS Cyg. Although the UV excess in these two systems is not as high as the one seen in U Gem, it is not possible to explain it in terms of the current theoretical framework (refs. 10, 17). In both cases the UV emitting area is of the same order of the X-ray emitting area, and in AM Her, in particular, the black body UV flux is eclipsed in phase with the X-ray flux. We suggest that nuclear burning of the accreted material might also happen in SS Cyg and AM Her and be responsible for the excess.

2) If nuclear burning is responsible for the UV black body excess, we find that AM Her, SS Cyg, and U Gem can be explained within a scenario of accretion in different magnetic regimes. A strong magnetic field ($\sim 10^8$G) in AM Her would be responsible for polar radial accretion, as suggested by many authors (see review of Chiappetti et al. 1980, ref. 18 and references therein). A re-examination of the data collected on SS Cyg both at maximum and at minimum, together with our new observations, shows the presence of a magnetic field $\sim 10^5 - 10^6$G, as suggested by Ricketts et al. (1979)(ref. 2). SS Cyg at minimum looks remarkably similar to AM Her, consistent with a picture of polar magnetic accretion. But the magnetic field is not so intense as to inhibit completely the formation of a disk, as shown by the observations of Walker and Chincarini (1968) (ref. 19). The increased accretion at maximum causes the magnetosphere to move closer to the white dwarf with the consequent building up of a disk. In U Gem instead, the magnetic field is so low as to make polar accretion impossible even at a minimum, as shown by the lack of emission lines in the UV.

TABLE 1
X-RAY OBSERVATIONS

	Start and Stop Times 1979 (UT)	Instrument	Energy Band (keV)	Flux (erg $cm^{-2}s^{-1}$)	D (pc)	L_x(erg s^{-1})
AM Her	$76^d\ 23^h\ 23^m\ 2^s$	HRI/OGS (500)	.1 - 4.5	$3.2 \times 10^{-10} \pm 15\%$ (ON time)	100	3.6×10^{32}
				$1.0 \times 10^{-11} \pm 15\%$ (eclipse)		
	$77^d\ 1^h\ 43^m\ 40^s$	MPC	2 - 6	$(6.6 \pm .2) \times 10^{-11}$ (ON time)		
				* (eclipse)		
U Gem	$119^d\ 1^h\ 34^m\ 16^s$	IPC	.5 - 4.5	$(2.0 \pm .2) \times 10^{-12}$	76 (2)	1.3×10^{30}
	$2^h\ 20^m\ 41^s$	MPC	2 - 6	$<2.5 \times 10^{-11}$ (3σ)		$<1.6 \times 10^{31}$ (3σ)
SS Cyg	$137^d\ 7^h\ 19^m\ 53^s$	HRI/OGS (1000)	.4 - 2	$3.5 \times 10^{-11} \pm 20\%$	120 (1)	5.7×10^{31}
	$17^h\ 14^m\ 29^s$	MPC		$(4.4 - 5.8) \times 10^{-11}$		8.3×10^{31}

*no eclipse data are available for MPC spectral analysis
(1) Kiplinger 1979 (ref. 20).
(2) Wade 1979 (ref. 8).

TABLE 2

	L_{opt} [a]	L_{BB} [a]	L_{HX} [a]	T_{BB}(eV)	T_{HX}(keV)
AM Her	6×10^{32}	$\sim 2.3 \times 10^{34}$	7.5×10^{31}	~ 28	> 30
SS Cyg	$\sim 1 \times 10^{33}$	$\geq 3.0 \times 10^{33}$	2.1×10^{32}	10-12	10-30
U Gem	$\sim 9 \times 10^{30}$	$\geq 2.3 \times 10^{33}$	1.3×10^{30}	≥ 10	

[a] In units of ergs s^{-1}; distance determinations are discussed in the text. The L_{HX} refer to the total hard X-ray emission.

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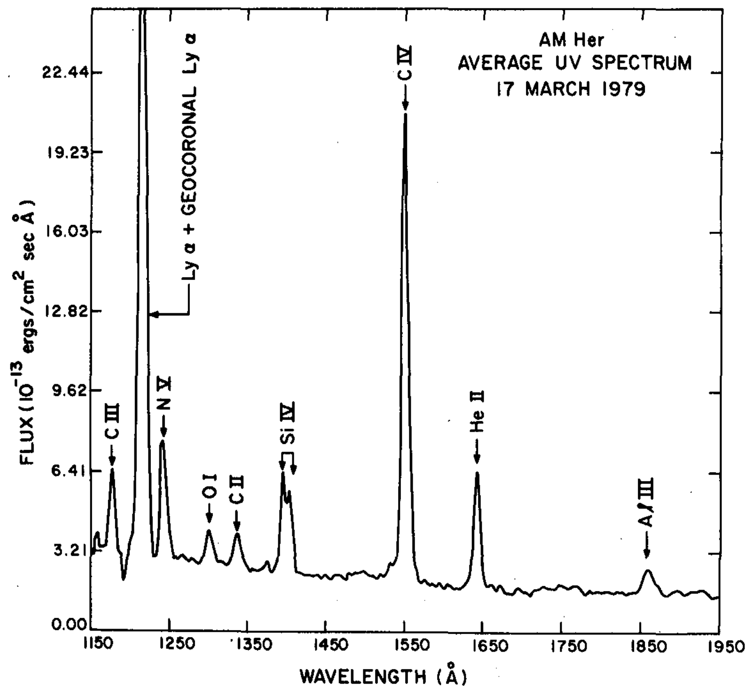

Figure 1. Average short wavelength UV spectrum of AM Her during the 1979 March 17 observations.

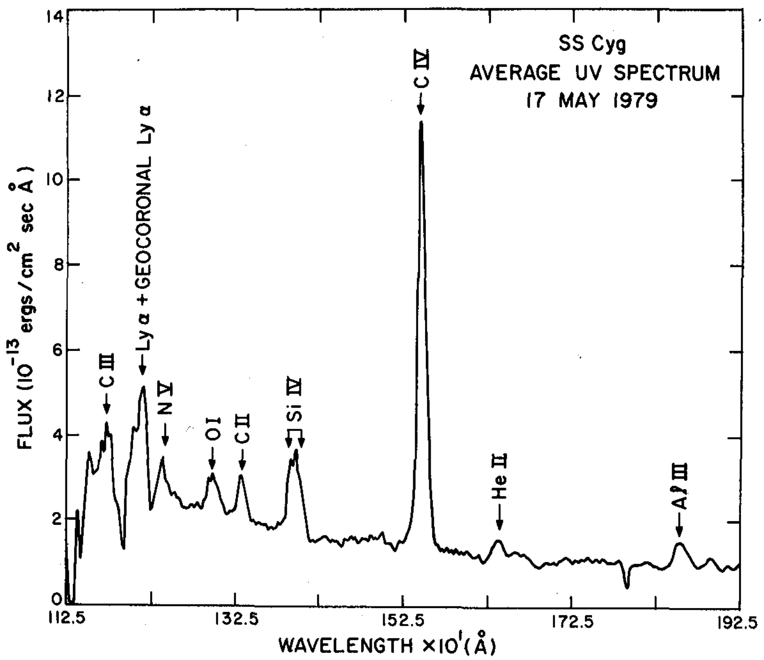

Figure 2. Average short wavelength UV spectrum of SS Cyg during the 1979 May 17 observations. SS Cyg was in quiescence at the time of the observations. Notice the similarity with the UV spectrum of AM Her (Fig. 1).

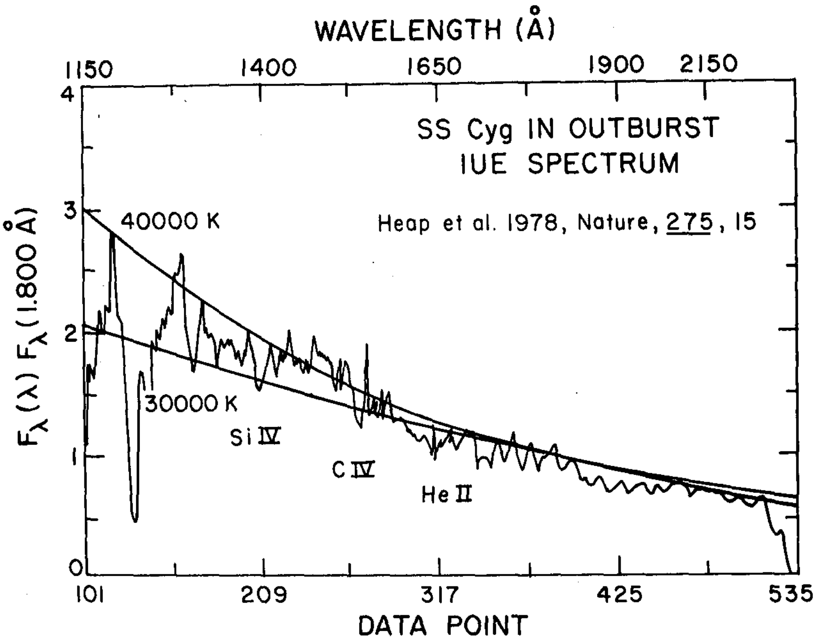

Figure 3. UV spectrum of SS Cyg in outburst.

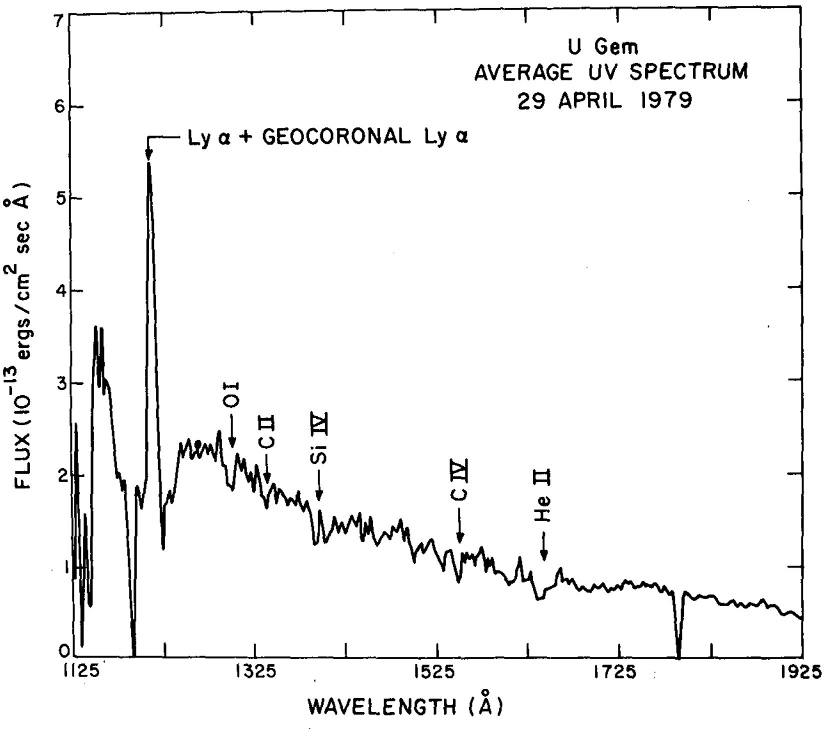

Figure 4. Average short wavelength UV spectrum of U Gem during the 1979 April 29 observations.

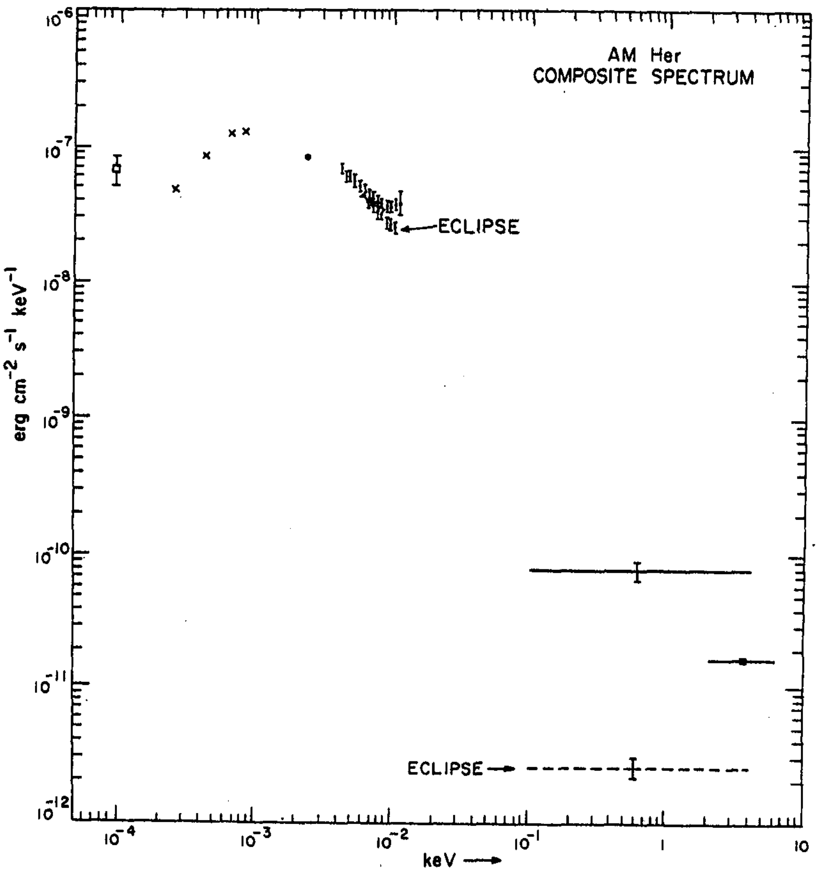

Figure 5. Composite spectrum of AM Her in high state. The optical, UV and X-ray points were obtained during the 1979 March 17 simultaneous observations. The optical point (dot) has been given to us by the AAVSO. The infrared points are the measurements of Merrill (crosses) and Rieke (square) as reported by Swank et al. (1977) (ref. 21).

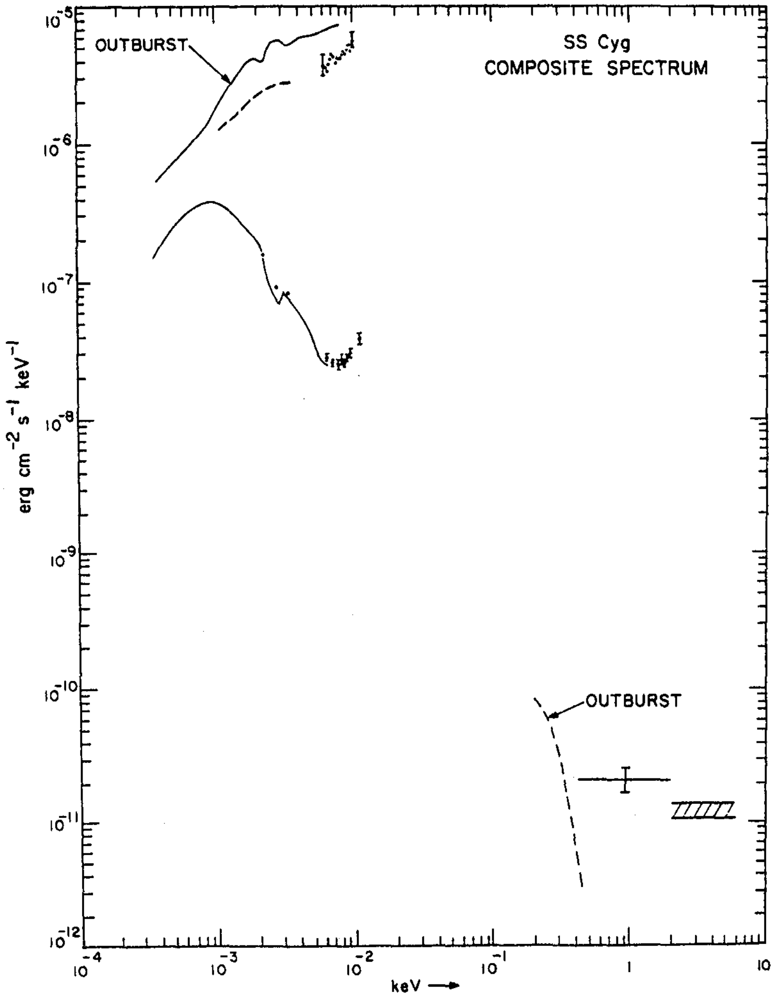

Figure 6. Composite spectrum of SS Cyg both in quiescence and in outburst. The U, B, V points (dots) in the spectrum in quiescence are the photometric measurements of Szkody (1980, private communication) simultaneous to the IUE (dots with error bars) and Einstein (lines) measurements of the 1979 May 17. The lower energy X-ray measurement is the HRI/OGS observation; the higher energy measurement represents the MPC data. The double line represents the range of variability of SS Cyg during the MPC observations. The continuous line that covers the IR through optical range is from the spectrophotometric measurements of Kiplinger (1979) (ref. 20). In the spectrum during outburst, the continuous line is again from Kiplinger (1979) (ref. 20) and the dotted line underneath it represents the Szkody (1976) (ref. 22) photometric measurements. Both these lines have been normalized to the UV data (Head et al. 1978) (ref. 23) during which the visual magnitude of the source was 9.5, one magnitude fainter than at maximum. The X-ray data are from Cordova et al. (1980) (ref. 24).

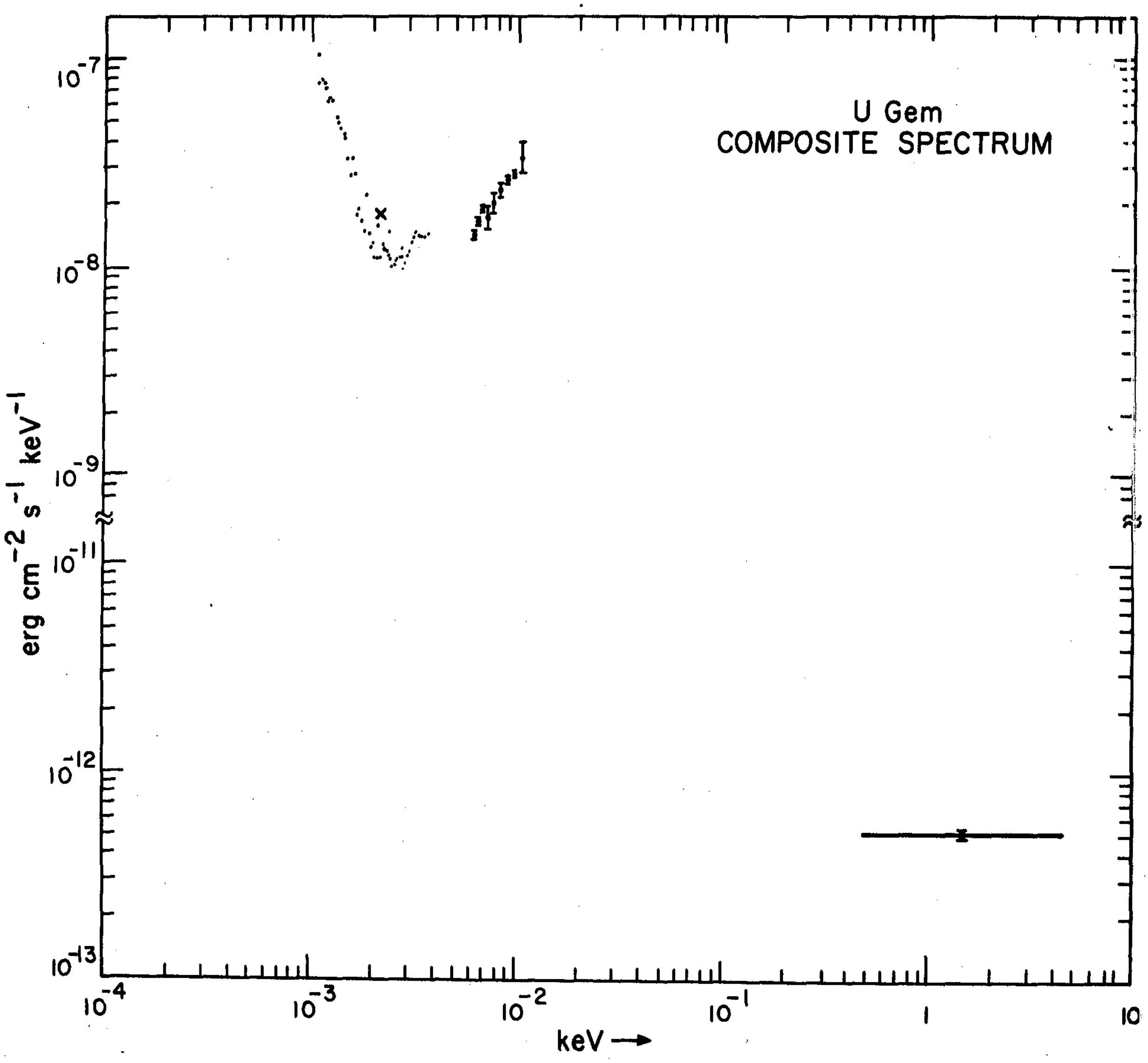

Figure 7. Composite spectrum of U Gem at minimum. The UV and X-ray points are relative to the quasi-simultaneous observations of 1979 April 29. The cross indicates the visual flux of U Gem at the time of the IUE and Einstein observations, as reported by the AAVSO. The dots cover the IR and optical observations of Wade et al. (1979)(ref. 8).