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EXTREME-ULTRAVIOLET OBSERVATIONS OF DWARF NOVAE FROM *APOLLO-SOYUZ*

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ABSTRACT

We report observations of four dwarf novae in the 50–150 Å region, using the extreme-ultraviolet telescope aboard the *Apollo-Soyuz* Test Project. SS Cygni was observed during optical outburst on 3 consecutive days of peak light. Z Chamaeleontis and VW Hydri were optically quiescent during the observations, and AE Aquarii was faint but highly variable. On the first 2 of 3 days, SS Cyg is positively detected in the 50–150 Å band, with a flux of 9×10^{-11} ergs $\mathrm{cm^{-2}\,s^{-1}}$ incident at Earth; this is a factor of 6 less intense than the soft X-ray flux observed during a 1973 outburst by Rappaport *et al.* On the third day of the observations, the extreme-ultraviolet flux dropped by a factor of almost 40, while the optical magnitude remained roughly constant. Simultaneous visible photometry is used to show that at least two and possibly more emission regions may be needed to explain the SS Cyg outbursts. As the intensity of the soft X-ray flux at visible light maximum is now known to vary by more than two orders of magnitude, the connection between the visible and X-ray outbursts is obviously complex. None of the remaining objects were detected, and flux upper limits are provided for these observations.

Subject headings: stars: dwarf novae — stars: U Geminorum — ultraviolet: general — X-rays: sources

The similarity of the dwarf nova systems to some X-ray binary stars has led many investigators (e.g., Saslaw 1968; Warner 1972; Kraft 1973; Pringle 1977) to suggest that dwarf novae may be detectable soft X-ray sources. During a sounding rocket flight in 1973, Rappaport *et al.* (1974) detected a poorly located but statistically significant soft X-ray source (44–80 Å) in Cygnus, and suggested an identification with SS Cygni, the brightest known dwarf nova, which was undergoing an optical outburst at the time. Subsequently there has been tentative verification of a soft X-ray flux from SS Cyg by Hearn, Richardson, and Li (1976) and Heise *et al.* (1975). Heise *et al.* (1978) have recently provided full details of the *ANS* observations of SS Cyg in quiescence. To our knowledge there are no further published reports of X-ray observations of SS Cyg in outburst. In this paper we report the detection of 55–150 Å extreme-ultraviolet (EUV) flux from SS Cyg during an optical outburst at an intensity level considerably below that of Rappaport *et al.* (1974). We also provide upper limits on fluxes from three additional related objects, Z Cha, VW Hyi, and AE Aqr. Multicolor optical photometry of SS Cyg and AE Aqr was obtained simultaneous with the EUV observations.

The EUV data were acquired in 1975 July during the *Apollo-Soyuz* Test Project, by using pointed grazing incidence optics and a channel-electron multiplier as a photon detector. Crude wavelength discrimination is provided by thin film filters, which divide the 55–1500 Å region into five bands. A more detailed description of the instrumentation and observing technique is given by Margon and Bowyer (1975), Lampton *et al.* (1976), and Haisch *et al.* (1977). A journal of observations for the four stars under discussion appears in Table 1. Although in general observations for each of these objects are available from the *Apollo-Soyuz* experiment in the 170–620 Å and 500–780 Å bands, in addition to the tabulated 55–150 Å count rates, we do not discuss these here as there were no positive flux detections, and the uncertain but large corrections for interstellar photoelectric opacity render the upper limits relatively uninteresting. Likewise, we have omitted our limits near 1500 Å as more sensitive data are available elsewhere (Wu 1976).

The most interesting data are on SS Cyg, which at the time of our EUV observations was fortuitously undergoing an optical outburst, as verified from both our own photometry, to be described below, and the published observations of Mattei (1976) and Lyutyi (1976). Observations of this source from *Apollo-Soyuz* of a few minutes' duration, in general preceded and followed by approximately equal-length background integrations performed 3° away, were obtained on three separate occasions, each separated by ~1 day. The individual source and background data accumulations in the 55–150 Å band are displayed in Figure 1. It is clear from these data that the source is detected

TABLE 1

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Object	Date (UT 1975 Jul.)	Duration on Source (s)	Background Subtracted Count Rate (s^{-1})	Flux (mJy, 50–150 Å)
SS Cyg..........	21.027	135	1.52 ± 0.61	0.25 ± 0.07
SS Cyg..........	21.700	103	1.49 ± 0.66	
SS Cyg..........	22.690	372	0.25 ± 0.36	< 0.22*
AE Aqr.........	20.534	156	< 4.6	< 0.76
VW Hyi.........	22.889	77	< 15	< 2.5
Z Cha...........	22.887	41	< 14	< 2.3

* Stronger limit available from Davidsen *et al.* 1977, as described in text.

above background on the first 2 days, but has decreased in intensity on the third day. On the first two observations, the combined excess of signal above background is 3.7 σ, including allowances for uncertainty in both source and background fluxes; the derived background-subtracted count rate is 1.51 ± 0.41 counts s^{-1}. The observed excess count rate from SS Cyg corresponds to a flux at Earth of 0.25 ± 0.07 mJy, or 2.5×10^{-27} ergs cm^{-2} s^{-1} Hz^{-1} in the 55–150 Å band. This may be compared to the value of $\sim 1.6 \times 10^{-26}$ ergs cm^{-2} s^{-1} Hz^{-1} in the 44–80 Å region observed 2 years earlier by Rappaport *et al.* (1974); this is a flux of $\sim$1.5 mJy, also applicable to a period of optical outburst. Assuming that we are observing the same object, as seems very likely, there can be little question that the soft X-ray and EUV flux is variable even for outbursts of about the same visible magnitude, as is the case here; a flux of the intensity reported by Rappaport *et al.* (1974) would have caused a signal at least 40 σ above background in our instrument.

On our third and final observation of SS Cyg, the observed excess count rate above background is 0.25 ± 0.36 counts s^{-1}. As the formal probability is only $\sim$0.02 that this decrease in intensity is due to a statistical fluctuation, and SS Cyg is known to vary in visible flux by a factor of 30 from outburst to quiescence, we conclude that we have quite probably observed intrinsic EUV flux variability. This conclusion is strengthened by the observations described by Davidsen *et al.* (1977), which were obtained from a soft X-ray proportional counter also onboard *Apollo-Soyuz*, coaligned with and operating simultaneously with our experiment during the third observation of SS Cyg. We estimate from their published data that an upper limit to the 44–100 Å flux of SS Cyg at this time is 6.6 μJy, i.e., a decrease in flux by a factor of almost 40 on a time scale of 1 day. Unfortunately, soft X-ray data from this instrument were not obtained during our first two observations.

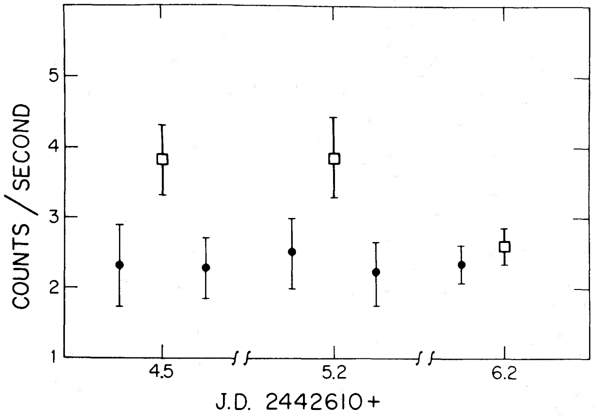

FIG. 1.—Count rates in the 50–150 Å band during three observations of SS Cygni from *Apollo-Soyuz*. *Squares*, data obtained pointed at the source; *circles*, background data obtained 3° off the source. One sigma statistical uncertainties are shown.

Photometry of this outburst of SS Cyg in the visible and near-infrared spectral regions is available from several sources. Photoelectric photometry using the Lick Observatory 61 cm reflector and *UBV* filters was kindly provided to us by Mr. R. P. S. Stone. These data span the period 1975 July 19.4–23.4 UT, yielding at least one magnitude and color each night. On July 21, we also obtained photoelectric data in the *U*, *B*, *V*, *r*, and *R*2 filters, using the 76 cm reflector of the Manastash Ridge Observatory. Lyutyi (1976) has published useful *UBV* data which also span the period of the *Apollo-Soyuz* observations. The extensive visual observations of SS Cyg made by the AAVSO during this period are summarized by Mattei (1976). Where overlap is available, all of these data are in agreement to within their expected precisions. These data indicate that the visible outburst began on 1975 July 18, and continued near maximum light ($V \sim 8.7$) throughout the *Apollo-Soyuz* observations. In particular, the very sharp drop in EUV/soft X-ray flux which we observe midway through the outburst is definitely not accompanied by an analogous visible event; if anything, the visible light output of the system increases slightly (from $V = 8.9$ to $V = 8.6$) on the third day of our observations. The duration of the optical outburst, $\sim$8 days, is not atypical of the occasional longer SS Cyg outbursts (see Mattei 1976).

The above data make it clear that during outburst SS Cyg exhibits an extremely large range of soft X-ray luminosities while remaining at about the same visible light level. The highest and lowest outburst X-ray luminosities quoted above differ by more than 200. Thus the connection between the optical and soft X-ray outbursts is not a simple one, and theories which

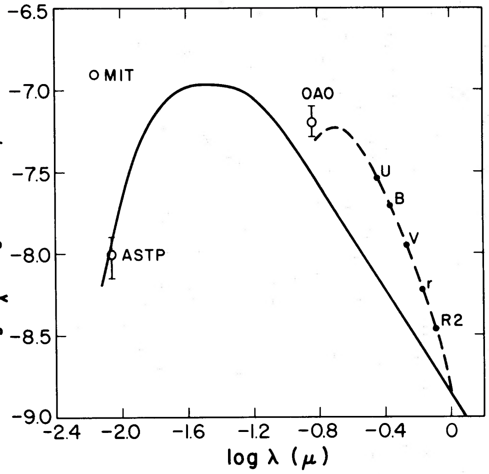

FIG. 2.—Observations of SS Cygni during outburst. *Open circles*, spacecraft data (MIT: Rappaport *et al.* 1974; ASTP: present work; OAO: Holm and Gallagher 1974 from observation denoted "rising to maximum"). *Closed circles*, photometry from Manastash Ridge Observatory; *solid line*, predicted flux (under assumptions described in the text) for a free-free emitter with $T = 2.5 \times 10^5$ K, $R \sim 4 \times 10^8$ cm; *broken line*, predicted flux for a blackbody with $T = 15{,}000$ K, $R \sim 1.4 \times 10^{10}$ cm.

ascribe these outbursts to accretion events (e.g., Bath *et al.* 1974; Osaki 1974) will have to cope with this rather surprising result. This behavior is also in contrast to that exhibited by SS Cyg in the far-ultraviolet, to wavelengths as short as 1400 Å, where the visible and UV brightness is thought to co-vary (Holm and Gallagher 1974). However, the SS Aur observations of Wu (1976) suggest an anticorrelation of visible and UV flux through an outburst.

We have examined the available outburst data on SS Cyg at all wavelengths in an attempt to synthesize a coherent model of the system. These data are summarized in Figure 2. The visible and near-infrared data in the figure are derived from the Manastash Ridge observations, reduced and standardized as described previously (Szkody 1976). A basic problem with model-fitting to these data has already been pointed out by Szkody (1974; 1977): visible and infrared observations at maximum light are difficult to reconcile with a single-component emitting region. The addition of our observed EUV flux exacerbates this problem. For example, for $T > 10^5$ K, a blackbody flux distribution which fits the EUV point supplies insufficient visual flux; for $T \lesssim 10^5$ K, although crudely consistent fluxes may be derived, the spectral shape in the visual region is not correct.

Similar difficulties are encountered when attributing the EUV and visible fluxes to separate optically, thick regions. If we assume a distance of 30–50 pc (Strand 1948; Wallerstein 1963; but see also Warner 1976), a $T \gtrsim 90{,}000$ K component of radius $\leq 2 \times 10^9$ cm will reproduce the observed EUV flux, and fall off rapidly enough into the visual to allow a second, cooler component to dominate there. If the EUV emission region is from the inner disk rather than the hot spot (Pringle 1977), then a lower bound on this size is given by the radius of the white dwarf, $\sim 7 \times 10^8$ cm, implying $T < 140{,}000$ K. A cooler blackbody component of $T = 15{,}000$ K will then fit the visual data; however, infrared fluxes of SS Cyg at maximum light (Szkody 1974, 1977) will lie above this distribution, as will *OAO 2* far-ultraviolet data of Holm and Gallagher (1974). Hypothesizing that these latter data vary from outburst to outburst would, of course, ease this problem.

A single free-free emission region has also been compared with the data of Figure 2. As the visible fluxes approximate a blackbody, such a region must become optically thick for $\lambda \gtrsim 3600$ Å. The best possibility seems a model of $T \sim 2 \times 10^5$ K; the requirement that $\tau \sim 1$ at 3600 Å implies $n_e \sim 6 \times 10^{14}$ cm^{-3}. More detailed calculations, including the effects of electron scattering opacity, will be required to derive the precise spectral shape in the visible.

Finally, a hybrid model which invokes a $T \sim 15{,}000$ K blackbody to account for the visible spectrum, and a hot, free-free emitter for the X-ray and IR flux may be feasible. An emitter at $T \sim 2.5 \times 10^5$ K which becomes optically thick near 1.25 μm would have $R \sim 3.5 \times 10^8$ cm and $n_e \sim 4 \times 10^{14}$ cm^{-3}; such a component may explain both the EUV and infrared fluxes, as shown in Figure 2, without substantially perturbing the visible flux distribution.

Details of the *Apollo-Soyuz* observations of AE Aqr, VW Hyi, and Z Cha are also summarized in Table 1. The limits on the latter two objects are weak, as the data were acquired in regions of high particle background. Each of these objects has interesting properties which might lead one to suspect detectable X-ray emission. AE Aqr is an irregular nova-like variable but is usually classed with U Gem (see Glasby 1970) and is one of the closest such systems. VW Hyi is the brightest southern hemisphere dwarf nova, and may well be the weak EUV source discussed by Henry *et al.* (1976). Z Cha is one of the better optically observed dwarf novae, and accretion models for this object have been discussed at some length by Bath *et al.* (1974).

The Lick Observatory photometry discussed above showed AE Aqr to have $V = 11.42$, $(B - V) = 0.80$, $(U - B) = -0.06$ at a time 2 hours prior to our observation from *Apollo-Soyuz*. Monitoring of the object for several days on either side of the EUV observations showed rapid excursions in V of up to 0.5 mag, typical for this very active object, even in the quiescent state. Information on the photometric behavior of VW Hyi and Z Cha was kindly provided by Mr. F. M. Bateson: both objects were also in their quiescent state. The most recent outbursts of VW Hyi were 15.3 and 12.5 days before and after the EUV data; for Z Cha, outbursts occurred 49.6 and 23.8 days before and after.

The limits in Table 1 for EUV flux from AE Aqr, Z Cha, and VW Hyi are far above the positive flux detections of 4×10^{-12} ergs cm^{-2} s^{-1} (44–80 Å) reported by Heise *et al.* (1978) for SS Cyg in quiescence. Thus the question of whether all dwarf novae have detectable quiescent soft X-ray/EUV emission must await further observation.

We are indebted to Mr. F. M. Bateson and the observers of the Variable Star Section of the Royal Astronomical Society of New Zealand, and especially to Ms. J. Mattei and the American Association of Variable Star Observers for providing the many observations that greatly aided the planning, execution, and analysis of the *Apollo-Soyuz* observations. We thank Drs. R. Stern and R. T. Giuli for their aid throughout the project, and Mr. R. P. S. Stone for obtaining the Lick photometry. This work was primarily supported by NASA grants NAS9-13807 and NGR 05-003-450. B. M. acknowledges the support of the UCLA Academic Senate Committee on Research.

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