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ASCA OBSERVATIONS OF SS CYGNI DURING AN ANOMALOUS OUTBURST

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ABSTRACT

SS Cygni was observed by the *ASCA* satellite on 1993 May 27, the first catalysmic variable studied by *ASCA*. The observations were conducted while the system was in an outburst of the "anomalous" variety. The SIS spectrum cannot be explained by two-temperature Raymond-Smith coronal plasma models as invoked in previous studies with lower spectral resolution. Significantly better agreement is found for models with plasma emission at $kT = 0.8$, 3.5 keV and thermal bremsstrahlung at $kT = 18$ keV. The GIS data are consistent with the SIS data, showing evidence for Fe line emission but showing no evidence of pulsation over times ranging from seconds to minutes.

These observations seem at variance with standard theory in two regards: we simultaneously see hard X-rays and optically thin soft X-rays while the system is in outburst, and we see a nonsmooth emission measure distribution. We speculate on possible scenarios which might resolve these differences.

Subject headings: accretion, accretion disks — novae, cataclysmic variables — X-rays: stars

1. INTRODUCTION

SS Cygni is by far the brightest of the dwarf novae and has been a frequent target for optical, UV, and X-ray observations (cf. Giovanelli & Martinez-Pais 1991). In this system material is being accreted by a white dwarf from a low-mass main-sequence star ($M \lesssim 1\ M_{\odot}$). The resulting accretion disk apparently switches between states of high and low luminosity, where the high-luminosity state is called the "outburst". Ordinarily the transition from low to high occurs rapidly (within 2 days), while the optical magnitude increases from ~12 to ~8.

Once the system reaches the high-luminosity state, it can remain in that state for some time (roughly 10 days), or it can immediately commence a slow decline. In the first case, the outburst is called "long"; the second, "short." In both cases the fallback to the low state takes about 10 days (Howarth 1978). Some rare outbursts have a slower rise, more comparable to the fall time, taking typically 10 days to reach maximum light. These outbursts are called "anomalous."

Recognizing the significance of SS Cyg as a prototype, and an excellent case study in the accretion process, the *ASCA* PV team selected it for a 1 day dedicated observing program on 1993 May 27. To maximize the utility of these data, simultaneous observations were conducted using *IUE* for ultraviolet spectroscopy; McDonald, Alfred, and Kiso Observatories for broadband optical photometry; and the Penn State Black Moshannon Observatory for optical spectroscopy. In this *Letter* we report on the preliminary results of the X-ray data analysis alone. In a later paper we will combine the simultaneous data to better understand the system.

2. OBSERVATIONS AND ANALYSIS

The *ASCA* satellite commenced observations of SS Cyg at 20:47 UT on 1993 May 26 and continued until 19:05 UT on May 27. Useful data were collected for 40,388 s during that time from the GIS. The data from the SIS only include "Faint" mode data to ensure the best spectral results and reduce the effects of light leakage, leaving about 27,872 s of data.

Through coordination arranged by Craig Robinson (Penn State) and Janet Mattei (AAVSO) the American Association of Variable Star Observers placed special attention on monitoring the optical brightness of SS Cyg in the week before and after the *ASCA* observations. Owing to their light curve we identified that at the time of *ASCA* observation, SS Cyg was still in a state of "anomalous" outburst, near the end of the period of maximum light (Mattei 1993). Over the day of *ASCA* observation, the optical light dropped from m_V of 8.6 (the plateau peak brightness) to about 9.3. The quiescent m_V is about 12.0.

Data were collected by four co-aligned detectors and telescope (XRT) systems. One pair, consisting of a CCD camera and XRT unit each, called the SIS (Ricker et al. 1994), offers the higher spectral resolution. The other pair, consisting of a gas scintillation proportional counter and XRT unit, offers higher quantum efficiency and simpler X-ray timing determination (Makishima et al. 1994).

2.1. *SIS Analysis*

The SIS cameras were operated in "2-CCD" mode, in which only two of the four CCD chips in each camera were read out.

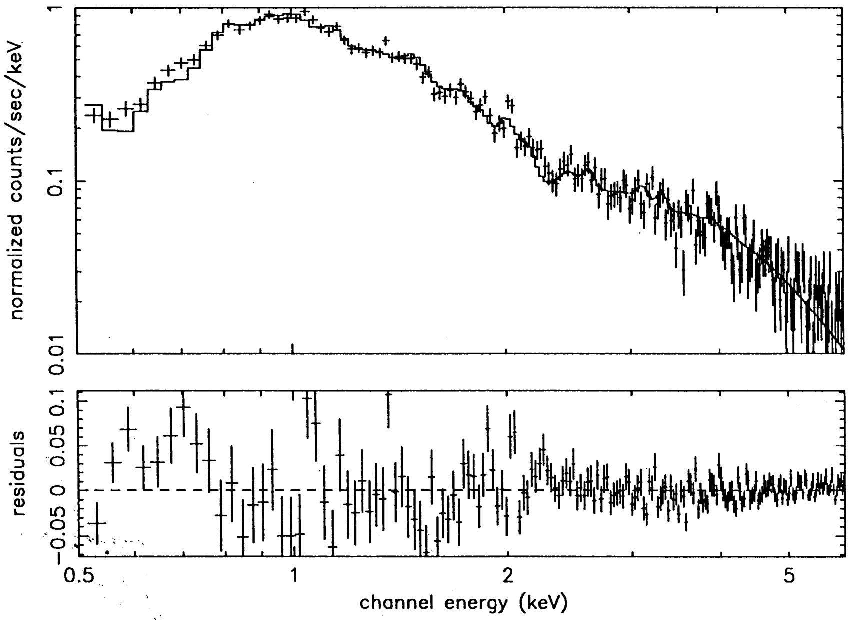

FIG. 1.—SIS0 spectrum of SS Cyg. The upper panel shows the observed data with uncertainties as crosses. The best two-temperature Raymond-Smith coronal model with thermal bremsstrahlung is shown as a histogram. The lower panel shows the residuals between data and model.

Telemetry limitations forced a division of time between "Bright" and "Faint" mode on-board X-ray event processing. Data collected in "Bright" mode had a higher background and are excluded from this analysis. We have also excluded times when the background rises due to a "light leak" in the SIS, near bright Earth lines of sight. The SIS contains an additional background resulting from "hot" and "flickering" pixels. We have ejected events from such pixels via the "CLEANSIS" software tool.

The spectrum resulting is shown in Figure 1. Models were fitted to these data by standard techniques of nonlinear regression using both χ^2 fits with data binned to avoid low count bins, and by maximum likelihood fitting based on the "C" statistic (Cash 1979), using the XSPEC spectra fitting package for both.

No smooth continuum models (power-law, blackbody, or thermal bremsstrahlung) could adequately describe the observed spectrum. The residuals to such fits are clearly systematic and are suggestive of an X-ray line radiation contribution. The best results for a traditional two-temperature plasma were $kT = 0.8$, 6 keV, similar to the results of Córdova & Mason (1983), but the χ^2 of this fit is 453 for 262 degrees of freedom.

Significant improvement results if a thermal bremsstrahlung component similar to that reported by Yoshida, Inoue, & Osaki (1992) is included. The χ^2 of this fit drops to 373 for 262 degrees of freedom. The best-fit model, consisting of two Raymond-Smith plasmas and a 13.6 keV bremsstrahlung, is plotted in Figure 1, and the parameters are listed in Table 1. Some additional χ^2 improvement is possible below 1 keV by adding a third, very low temperature ($kT \sim 0.5$ keV), but given the relatively immature state of the instrument calibration, we prefer not to add such a component.

The reason traditional two-component models fail is because the data are indicative of line emission, but with a much weaker line-to-continuum ratio than found in the coronal models alone. The addition of the smooth bremsstrahlung (as would approximate a very high temperature plasma) leads to the improved fits. Moreover, the lines characteristic of a 3.5 keV plasma agree far better than a 6 keV plasma.

We are reluctant to argue that the empirical agreement between models resulting from delta-function distribution implies the actual existence of isothermal plasmas in SS Cyg. Note that *ROSAT* observations (Belloni et al. 1991; Vrtilek et al. 1994) give evidence that CV X-ray spectra are neither optically thin thermal emission nor pure bremsstrahlung.

TABLE 1

PARAMETERS OF SPECTRAL FITS

	SIS		GIS	
PARAMETER	Value	Uncertainty	Value	Uncertainty
High Temperature (kT_1) (keV)	3.5	±0.5	3.4	±0.3
Flux (T_1) 0.7–10 keV (ergs cm^{-2} s^{-1})	1.8×10^{-11}	...	1.0×10^{-11}	...
Low Temperature (kT_2) (keV)	0.80	±0.015	0.69	±0.03
Flux (T_2) 0.7–10 keV (ergs cm^{-2} s^{-1})	4.9×10^{-12}	...	6.0×10^{-12}	...
Bremsstrahlung (kT_3) (keV)	23	±14	19	±9
Flux (T_3) 0.7–10 keV (ergs cm^2 s^{-1})	2.3×10^{-11}	...	1.4×10^{-11}	...
$N_{\rm H}$	0	$\pm 1.6 \times 10^{20}$	5.5×10^{21}	$\pm 0.4 \times 10^{21}$

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However, the lack of intermediate-temperature plasma lines would seem to indicate that the emission measure distribution with temperature is not monotonic, and little material can be found near $kT \sim 6$ keV, although substantial amounts are found near $kT \sim 18$ keV and $kT \sim 3$ keV and below.

It is also possible that the relative weakening of the lines with respect to the continuum might be due to the effect of a photoionizing radiation field altering the ionization state of the plasma from that assumed in the collisional ionization balance used in the Raymond-Smith models. The magnitude of this effect depends upon the geometry and the strength of the photoionizing flux, as shown by Raymond & Mauche (1991). If such a model is correct, then the absence of 6 keV lines may indicate an ion state deficit and not necessarily a discontinuity in the electron temperature distribution.

This observation illustrates quite nicely the value of the SIS energy resolution. While the broadband flux distribution can be adequately explained on the basis of two temperatures, the X-ray line emission (invisible to lower resolution proportional counters such as the GIS and previous instruments) demands a significantly different model.

2.2. *GIS Analysis*

The GIS detector is relatively immune to many of the background considerations needed for SIS analysis. Unfortunately, these data were collected a few days prior to the initiation of on-board spread discrimination processsing and rise time discrimination. Raw GIS image lacking discrimination exhibit a bright ring of diffuse emission which is largely made up of non–X-ray events. Fortunately, SS Cyg was positioned near the center of the detector where this effect was small. We have excluded events farther than $15''$ off axis and excluded all data when the background rate rose significantly.

X-ray spectra were extracted from the GIS images in the same way as described for the SIS. Figure 2 shows the data plotted with a three-temperature model similar to that used with the SIS. The Fe line is better measured in the GIS due to the greater quantum efficiency of the GIS at high energy. The observed Fe line (centroid at 6.70 ± 0.02 keV with 735 eV equivalent width) agrees with the *Ginga* observations of SS Cyg (Yoshida et al. 1992).

Oscillations have been frequently seen in the soft component of SS Cyg (Jones & Watson 1992). We have performed Fourier transforms of the photon arrival times and a periodogram analysis searching for any X-ray periodicities on time scales from 1 s to 20 minutes. We find no evidence for variations on these timescales in this data set.

3. CONCLUSIONS

The first *ASCA* observations of SS Cyg, taken during an anomalous outburst, have revealed that the previous characterization of the spectrum as a two-temperature plasma is incomplete. A far better characterization results from invoking a hard bremsstrahlung spectrum ($kT \sim 18$ keV), with a soft coronal spectrum ($kT \sim 3.5$ keV). We take this as evidence that the emission measure distribution has a minimum near 6 keV, with substantial emission from regions both hotter and cooler. The GIS data clearly detect Fe K-line emission (6.7 keV) and show no sign of significant pulsation or quasi-periodic oscillation.

These results are somewhat surprising. We are seeing both hard and soft X-rays during an outburst. Jones & Watson (1992) have previously reported hard X-rays, but they imply a strong anticorrelation with soft X-ray emission (see their Fig. 15). At least at this late phase in the outburst, soft and hard X-ray emission can coexist.

The nonsmooth emission distribution seems to contradict simple accretion disk models. The optically thin boundary layer models of Narayan & Popham (1993) seem to naturally produce the bimodal distributions required, but the models to date do not supply enough intermediate-temperature plasma

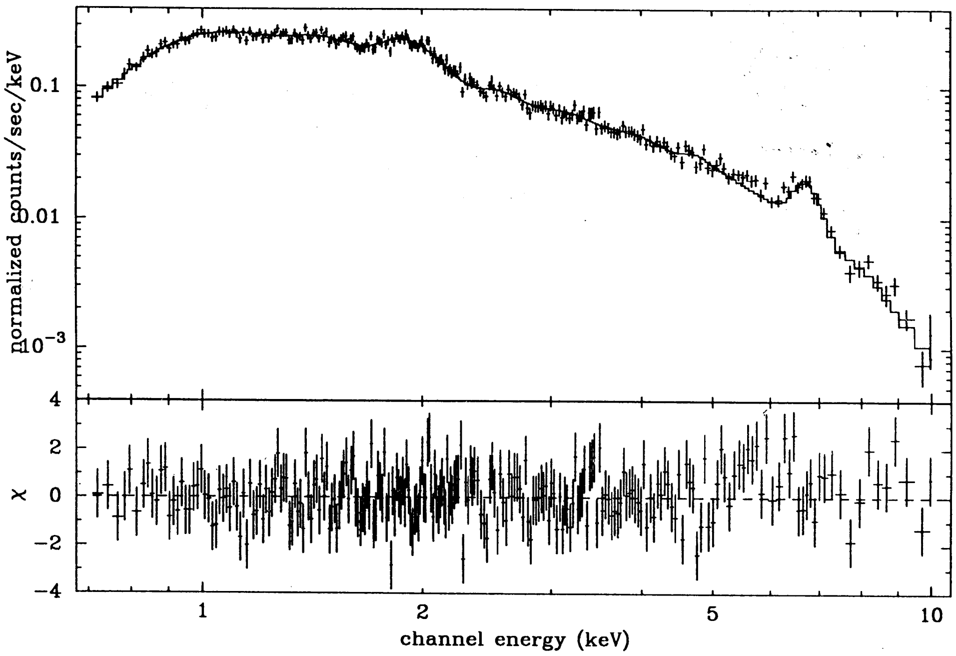

FIG. 2.—GIS2 + 3 spectrum of SS Cyg. The best-fit model spectrum is compared to the data in the same way as Fig. 1.

to explain the kT_2 component we see. Perhaps an accretion disk corona (Mineshige & Wood 1990) is required to supply this component. Further observations of SS Cyg in both quiescence and other outburst states will be required to unravel the true emission structure in the system.

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