

## The Quasi-Coherent Oscillations of SS Cygni

Christopher W. Mauche

*Lawrence Livermore National Laboratory,  
L-41, P.O. Box 808, Livermore, CA 94550*

**Abstract.** Properties of the quasi-coherent oscillations in the extreme ultraviolet flux of the dwarf nova SS Cygni are described.

### 1. Introduction

Rapid periodic oscillations are observed in the optical and soft X-ray flux of high accretion rate cataclysmic variables (CVs; nova-like variables and dwarf novae in outburst) (Patterson 1981; Warner 1995a; 1995b). These so-called “dwarf nova oscillations” (DNOs) have high coherence ( $Q \approx 10^4$ – $10^6$ ), periods of  $\approx 10$ – $30$  s, and amplitudes of  $\approx 10$ – $30\%$  in soft X-rays and  $\lesssim 0.5\%$  in the optical. DNOs have never been detected in dwarf novae in quiescence, despite extensive searches; they appear on the rising branch of the dwarf nova outburst, typically persist through maximum, and disappear on the declining branch of the outburst. The period of the oscillation also correlates with outburst state, decreasing on the rising branch and increasing on the declining branch.

The dwarf nova SS Cygni routinely exhibits DNOs during outburst. Optical oscillations have been detected at various times with periods ranging from 7.3 s to 10.9 s (Patterson, Robinson, & Kiplinger 1978; Horne & Gomer 1980; Hildebrand, Spillar, & Stiening 1981; Patterson 1981). At soft X-ray energies, oscillations have been detected in *HEAO 1* LED 1 data at periods of  $\approx 9$  s and 11 s (Córdova et al. 1980; 1984) and in *EXOSAT* LE data at periods between 7.4 s and 10.4 s (Jones & Watson 1992). Here, we describe the properties of the oscillations in the extreme ultraviolet (EUV) flux detected with the *Extreme Ultraviolet Explorer (EUVE)* Deep Survey (DS) photometer and Short Wavelength (SW) spectrometer during target-of-opportunity observations of SS Cyg in outburst in 1993 August and 1994 June/July. For additional details, see Mauche, Raymond, & Mattei (1995) and Mauche (1996).

### 2. Relation between Period and Mass-Accretion Rate

Oscillations in the EUV flux were detected by calculating power spectra of DS count rate light curves with 1 s time resolution. The period of the oscillation as a function of time and of the log of the 75–120 Å SW count rate is shown in Figure 1. These figures demonstrate that the period  $P$  of the oscillation anticorrelates with the SW count rate  $I_{\text{EUV}}$ , but an even stronger statement can be made. Because the EUV spectrum evolves homologously with time (Mauche, Raymond, & Mattei 1995), its bolometric correction is constant, and hence

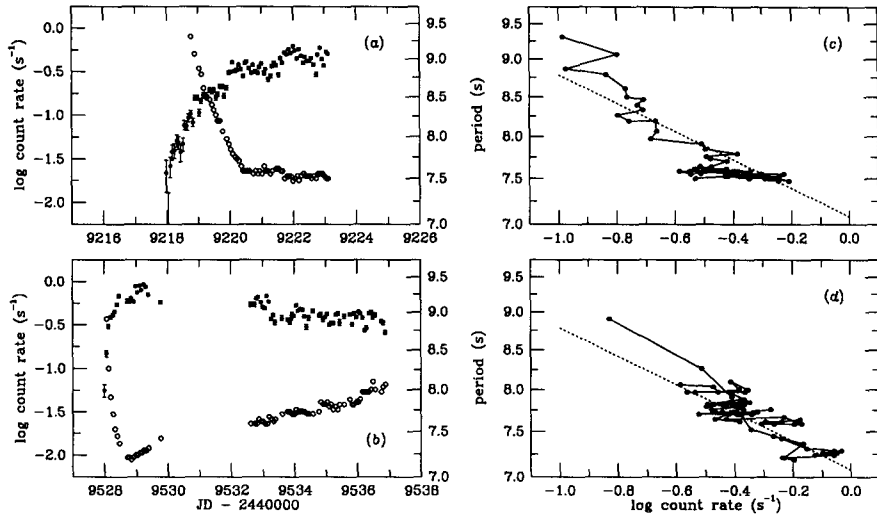


Figure 1. SW count rate (*filled circles with error bars*) and period (*open circles*) as a function of time for the (a) 1993 and (b) 1994 outbursts of SS Cyg. Period as a function of the SW count rate for the (c) 1993 and (d) 1994 outbursts.

we conclude that the period anticorrelates with the EUV/soft X-ray luminosity, and, by inference, with the mass-accretion rate  $\dot{M}$  onto the white dwarf: an unweighted fit to the combined data gives  $P = 7.08 I_{\text{EUV}}^{-0.094} \text{ s} \propto \dot{M}^{-0.094}$ . In contrast, the period of the QPOs of the transient Be-neutron star binary A0535+262 scale like  $P \propto \dot{M}^{-0.46}$  (Finger, Wilson, & Harmon 1996), in good agreement with the theory of disk accretion onto a magnetized star:  $P \propto \dot{M}^{-3/7}$  (Ghosh & Lamb 1991). For such a model to apply to SS Cyg, the field must be an effective high-order multipole ( $l \approx 7$ ) with a strength at the surface of the white dwarf of 0.1–1 MG (Mauche 1996).

### 3. Mean Power Spectra and Waveforms

Unlike the QPOs of A0535+262 and other neutron star binaries, the oscillations of SS Cyg are quite coherent. The slowest change of period with time occurred during the plateau of the 1993 outburst, when the coherence  $Q \equiv |\Delta P / \Delta t|^{-1} = (0.083 \text{ s} / 2.70 \text{ d})^{-1} = 3 \times 10^6$ ; the fastest change of period with time occurred during the rise of the 1994 outburst, when  $Q = (1.7 \text{ s} / 0.78 \text{ d})^{-1} = 4 \times 10^4$ ; on orbit-to-orbit timescales,  $Q \gtrsim (0.03 \text{ s} / 30 \text{ min})^{-1} = 6 \times 10^4$ . The coherence of the oscillation can be seen in the mean power spectra shown in Figures 2(a,b) constructed by adding the power spectra of the individual satellite orbits after scaling by the local oscillation period. In addition, these spectra demonstrate that the mean waveforms are sinusoids to high degree: very little power is observed in the first harmonic, and no power is observed in the second or subharmonics. Indeed, the additional power in the second harmonic of the power spectrum of the 1994

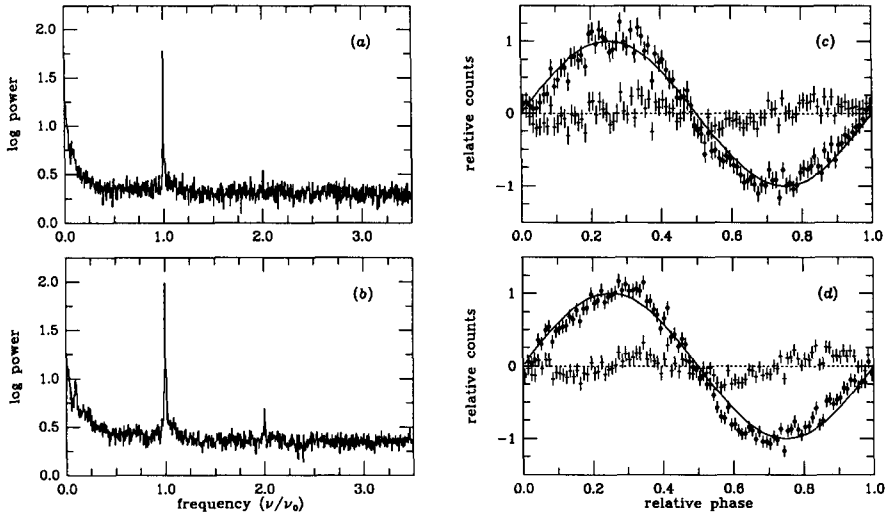


Figure 2. Mean power spectra of the (a) 1993 and (b) 1994 outbursts of SS Cyg. Mean waveforms (*filled circles*) and residuals relative to the fitted sinusoid (*crosses*) for the (c) 1993 and (d) 1994 outbursts.

outburst is due to the interval near the peak of the outburst ( $P < 7.5$  s); during the plateau phase of that outburst (JD  $> 2449532$ ), the power spectrum is actually cleaner than the power spectrum of the 1993 outburst. The peak power in the first harmonic relative to the fundamental is 2.5% for the 1993 outburst, 2.7% for the 1994 outburst, 9.0% for the peak of the 1994 outburst, and 1.8% for the plateau of the 1994 outburst. The mean waveforms of the 1993 and 1994 outbursts are shown in Figures 2(c,d). These figures demonstrate that the mean waveforms are surprisingly stable, and can be fit well by a function of the form  $A + B \sin 2\pi\phi - C \cos 4\pi\phi$ . For the 1993 outburst,  $B/A = 17.1\%$  and  $C/B = 12.3\%$ ; for the 1994 outburst,  $B/A = 16.5\%$  and  $C/B = 14.1\%$ ; for the peak of the 1994 outburst,  $B/A = 11.4\%$  and  $C/B = 27.9\%$ ; for the plateau of the 1994 outburst,  $B/A = 19.1\%$  and  $C/B = 11.0\%$ . Evidently, during the peak of the 1994 outburst, the amplitude of the oscillation is reduced and the waveform is distorted, with more flux coming out in the first harmonic.

#### 4. Spin Period of the White Dwarf?

Careful examination of the power spectrum of the 1994 outburst reveals a narrow peak at  $\nu/\nu_0 \approx 0.09$  which is also present in the direct mean power spectrum at  $\nu = 0.012 \pm 0.002$  Hz (FWZI). This feature is present above the noise in some orbits and not in others, and its period is relatively but not strictly constant. Because this feature is so far displaced from the fundamental, and because it persists in power spectra derived from light curves with 10 s bins, it is unlikely that this oscillation is an artifact of the dwarf nova oscillation. Perhaps it is the spin frequency of the white dwarf. If so, the corotation radius  $r_{co} \equiv$

$[GM_*/(2\pi\nu_*)^2]^{1/3} \approx 3 \times 10^9 \text{ cm} \sim 8 \text{ white dwarf radii}$ . In contrast, if the magnetospheric model applies to SS Cyg, the inner edge of the disk is at  $r_0 = 5.6 \times 10^8 \text{ cm} \approx 1.5 \text{ white dwarf radii}$  at the peak of the outburst. The resulting fastness parameter  $\omega_s \equiv \nu_*/\nu(r_0) \approx 0.09$ . This value is significantly less than the equilibrium fastness parameter  $\omega_c = 0.7\text{--}0.95$  (Li & Wang 1996), but it is unlikely that the white dwarf is in spin equilibrium during outburst—it is much more likely that it is being spun up. The implied rotation velocity of the white dwarf is  $v = 2\pi R_*\nu_* \approx 300 \text{ km s}^{-1}$ . This compares with  $v \sin i < 200 \text{ km s}^{-1}$  for U Gem and  $\approx 600 \text{ km s}^{-1}$  for VW Hyi (Sion et al. 1994; 1995). These values are more meaningfully expressed as a fraction of the breakup velocity of the white dwarf,  $v_{\text{break}} = (GM_*/R_*)^{1/2}$ :  $v/v_{\text{break}} < 4\%$  for U Gem,  $\approx 5\%$  for SS Cyg, and  $\approx 20\%$  for VW Hyi. The corresponding ratio of the boundary layer to accretion disk luminosity is  $\zeta = [1 - (v/v_{\text{break}})]^2 > 0.92$  for U Gem,  $\approx 0.90$  for SS Cyg, and  $\approx 0.64$  for VW Hyi. The measured values of these ratios are  $\zeta \approx 0.45$  for U Gem (Long et al. 1996),  $\lesssim 0.07$  for SS Cyg (Mauche, Raymond, & Mattei 1995), and  $\sim 0.04$  for VW Hyi (Mauche et al. 1991). Apparently, some other mechanism beyond rotation of the white dwarf is responsible for the low boundary layer luminosities of non-magnetic CVs.

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## Discussion

*P. Stockman:* Can you tell us what temperature you observed in the EUVE flux and could you measure the temperature at low count rates? Could the low dependence of the period on count rate be due to the count rate being a strong function of the accretion rate? (A variable bolometric correction).

*C. Mauche:* The EUVE spectrum can be parameterised as a blackhole with an effective temperature  $kT = 20 - 30$  eV absorbed by a neutral hydrogen column density of  $7.4 \times 10^{19} \text{ cm}^{-2}$ . Amazingly, the EUV spectrum does not change as the EUV flux increases by a factor of nearly 1000 as the system enters outburst. Hence, whatever the bolometric correction is, it is fixed during the outburst, and the shallow dependence of oscillation period with EUV intensity cannot be due to a time-variable bolometric correction. For more information see Mauche, Raymond & Mattei 1995 ApJ 446, 872.