THE EXTREME ULTRAVIOLET SPECTRUM OF THE QUASI-COHERENT OSCILLATIONS OF THE DWARF NOVA SS CYGNI

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ABSTRACT

Data obtained by the Extreme Ultraviolet Explorer satellite are used to determine the EUV spectrum of the quasi-coherent oscillations of the dwarf nova SS Cygni. It is found that the spectrum of the oscillations is neither blue nor red nor gray relative to the net (oscillation-phase-integrated) spectrum and hence that the oscillations cannot be explained by variations in the effective temperature, absorbing column density, or effective area, respectively. Instead, it is found that the amplitude of the oscillations is high at the relative maxima of the net spectrum and low to zero at the relative minima of the net spectrum. This behavior can be explained either by variations in the emission line flux atop a constant underlying continuum or by variations in the optical depth of a haze of overlapping absorption lines, in which case the optical depths must be \( \tau \approx 1 \) at the relative maxima of the net spectrum and \( \tau \gg 1 \) at the relative minima.

Subject headings: novae, cataclysmic variables — stars: individual (SS Cygni) — stars: oscillations — ultraviolet: stars

1. INTRODUCTION

In a recent Letter (Mauche 1996b, hereafter Paper II), we described Extreme Ultraviolet Explorer (EUV; Bowyer & Malina 1991; Bowyer et al. 1994) observations of the 7–9 s quasi-coherent oscillations (“dwarf nova oscillations”; Patterson 1981; Warner 1995a; Warner 1995b) in the EUV flux of the dwarf nova SS Cyg during an anomalous outburst in 1993 August and a normal outburst in 1994 June/July. For both outbursts, the period \( P \) of the oscillation was observed to correlate with the EUV intensity \( I_{\text{EUV}} \) according to \( P \propto I_{\text{EUV}}^{-0.04} \). For a magnetospheric model to produce this variation, an effective high-order multipole field is required with a strength at the surface of the white dwarf of 0.1–1 MG.

Having determined the periods of the EUV oscillations of SS Cyg from the power spectra of the events recorded by the EUV Deep Survey (DS) instrument, we now are in a position to determine the spectrum of the oscillations from the events recorded simultaneously by the EUVE short wavelength (SW) spectrometer. The spectrum of the oscillations is of interest for at least two reasons. First, one might hope to learn something about the cause of the oscillations from the nature of their spectrum. For example, the spectrum of the oscillations will be blue if the oscillations are due to variations in the effective temperature, red if due to variations in the column density, or gray if simply due to variations in the effective area. At present, all that is known about the spectrum of the oscillations is that the optical colors are bluer than the disk (Hildebrand, Spiller, & Steining 1981; Middleditch & Córdoa 1982). Second, one might hope to learn something about the net (oscillation-phase–integrated) spectrum by studying its temporal variations. Mauche, Raymond, & Mattei (1995, hereafter Paper I) identified many of the emission features in the net EUV spectrum of the 1993 August outburst of SS Cyg with strong transitions of 5–7 times ionized Ne, Mg, and Si and parameterized the continuum with a blackbody with a temperature of \( kT \approx 20–30 \) eV absorbed by a neutral hydrogen column density of \( N_{\text{H}} \approx 7–4 \times 10^{21} \) cm\(^{-2}\). Failing a complete understanding of this spectrum, any clues from its temporal variations are welcome. Is it the case, for example, that the EUV continuum varies but that the lines do not? Such a situation applies in U Gem, where many of the emission lines are affected much less than the continuum by the dips in the EUV flux at orbital phases \( \phi \approx 0.6–0.8 \) (Long et al. 1996; Mauche 1997).

Motivated by these hopes, we determined the spectrum of the EUV oscillations of the 1993 and 1994 outbursts of SS Cyg. With an SW count rate of \( \lesssim 0.3 \) counts s\(^{-1}\), an oscillation amplitude of \( \lesssim 16\% \), and \( \lesssim 100 \) independent spectral elements of 0.5 Å, we need to employ nearly every photon recorded by the SW instrument during the \( \approx 100 \) ks observations to construct oscillation spectra with sufficient signal-to-noise ratio. To accomplish this task, we need to take careful account of the varying period and phase of the oscillation throughout the observations and verify as best we can that other factors (e.g., secular variations in the net spectrum) do not strongly affect the result.

2. OBSERVATIONS AND ANALYSIS

Target-of-opportunity observations of SS Cyg in outburst were made with EUVE in 1993 August (MJD 9216.58–9223.12; MJD = JD – 2,440,000) and 1994 June/July (MJD 9526.67–9529.78 and 9532.54–9536.94). The optical and DS count rate light curves of the outbursts are shown in Figure 1 of Mauche (1996a). On both occasions, the optical flux was above \( V = 10 \) for \( \approx 16 \) days, but the 1993 outburst was anomalous in that it took \( \approx 5 \) days for the light curve to reach maximum, whereas typical outbursts (such as the 1994 outburst) reach maximum in 1–2 days.

As described in Paper II, we determined the period of the oscillation of the EUV flux of SS Cyg during each valid interval by calculating the power spectrum of DS count rate light curves with 1 s time resolution. The period \( P \) of the oscillation as a function of time and of the log of the 75–120 Å SW count rate is shown in Figures 1 and 2 of Paper II. The
phase $\phi_0$ and amplitude of the oscillation during each valid time interval was calculated by phase-folding the DS data on the period appropriate to that interval and by fitting a function of the form

$$f(t) = A + B \sin \left(2\pi(t - \phi_0)/P\right)$$

where $\phi = t/P$. The relative amplitudes $B/A$ of the oscillation are shown as a function of the log of the 75–120 Å SW count rate in Figure 1. The weighted mean of these amplitudes is $16.1\% \pm 0.3\%$ ($\chi^2$/dof = 129/60) for the 1993 outburst and $14.7\% \pm 0.2\%$ ($\chi^2$/dof = 609/72) for the 1994 outburst. Note, however, that the amplitudes during the 1994 outburst are often low when the SW count rates are above $10.6$ counts s$^{-1}$; in a plot of the amplitude as a function of the period, the amplitudes are systematically low when the period is below $7.5$ s. Above $7.5$ s, the weighted mean of the amplitudes is $17.7\% \pm 0.2\%$ ($\chi^2$/dof = 194/58); below $7.5$ s, it is $10.8\% \pm 0.3\%$ ($\chi^2$/dof = 54.0/13). This magic period of $7.5$ s is (perhaps not coincidentally) the same as the minimum asymptotic period reached during the plateau of the 1993 outburst. Apparently, the oscillation can be driven below this magic period but only for a short time (see Fig. 1 of Paper II) and only at the expense of its amplitude. Below this magic period, the amplitude of the oscillation is reasonably constant with count rate at $16\%$, but the large reduced $\chi^2$ values demonstrate the orbit-to-orbit variability about this value.

To investigate possible spectral variability during the observations, we divided the 75–120 Å SW bandpass at 90 Å, determined the count rate during each valid interval in the 75–90 Å ("hard") and 90–120 Å ("soft") channels, and calculated the ratio of the hard-over-soft count rates; these count rate ratios are shown as a function of the total 75–120 Å count rate in Figure 2. The weighted mean of these ratios is $0.654 \pm 0.007$ ($\chi^2$/dof = 70.8/60) for the 1993 outburst and $0.629 \pm 0.006$ ($\chi^2$/dof = 105/72) for the 1994 outburst, and the difference between these values is $0.025 \pm 0.009$. These results demonstrate that the ratio of the hard/soft count rates are reasonably constant with time and count rate, that the spectrum, unlike the amplitude, is not affected when the period of the oscillation is below $7.5$ s, and that the ratio of the hard-over-soft count rates of the 1993 and 1994 outbursts differs by less than $3\sigma$. Evidently, the EUV spectrum of SS Cyg is independent of total intensity, oscillation period, oscillation amplitude, or even outburst type; the spectrum might as well be cut out of titanium for all it changes.

Encouraged by the fact that the spectrum of the EUV oscillations of SS Cyg is reasonably constant with time, we used the periods and phases determined from the DS data to accumulate SW spectra during the high and low portions of the oscillation. Specifically, photons satisfying $\sin 2\pi(t - \phi_0)/P > 0.5$ were accumulated in one array, and those satisfying $\sin 2\pi(t - \phi_0)/P \leq 0.5$ where accumulated in another. We also tried accumulating only those photons from near the peak and valley of the oscillation, specifically those photons satisfying $\sin 2\pi(t - \phi_0)/P > +0.5$ and $\sin 2\pi(t - \phi_0)/P < -0.5$, but this procedure wasted nearly one-third of the photons and produced a result which was the same within the errors. The spectrum of the high and low portions of the oscillation of the 1993 (1994) outburst of SS Cyg is shown in the top panel of Figure 3 (Figure 4). The spectrum of the oscillations is the difference between these two spectra shown as filled squares with error.
bars in the middle panel of the figure. For comparison, we also show the sum (net; oscillation-phase–integrated) spectrum after scaling by a factor of $s = 0.1064$ (0.1059). This scale factor corresponds to an oscillation amplitude of $B/A = \pi s/2 = 16.7\%$ (16.6%), which reproduces reasonably well the count-weighted mean oscillation amplitude measured by the DS instrument of 16.8\% (16.2\%). The ratio of the high-phase spectrum to the low-phase spectrum is shown in the bottom panel of the figure as residuals about the weighted mean ratio of 1.218. With $\chi^2$/dof of 139/115 (182/115), the hypothesis that the EUV oscillations are produced by variations in the absorbing column density can be rejected with $\approx 99.9\%$ confidence. Next, consider variations in the effective temperature: as the variation in $kT$ increases from zero, the amplitude of the oscillation increases, but the ratio spectrum becomes increasingly blue. Assuming that $N_H(\phi) = N_{H0} - N_{H1} \sin 2\pi \phi$, $\chi^2$ is minimized for $N_{H0} = 4 \times 10^{18}$ cm$^{-2}$, but $\chi^2$/dof = 171/115 (183/115), so the hypothesis that the EUV oscillations are produced by variations in the absorbing column density can be rejected with $\approx 99.9\%$ confidence. In both instances, the hypothesis that the EUV oscillations are produced by variations in the effective temperature can be rejected with $\approx 95\%$ ($\approx 99.9\%$) confidence.

3. DISCUSSION

Having shown formally that the spectrum of the EUV oscillations of SS Cyg is neither blue nor red nor gray relative to the oscillation-phase–integrated spectrum, it is useful to refer to Figures 3 and 4 to get a qualitative sense of the wavelength dependence of the oscillations. First, consider those bins in the difference spectra which are $\leq 0$ within the
errors: with only a few exceptions, they invariably lie at relative minima in the sum spectra, e.g., at \( \approx 74, 82, 87, 96, 105 \) Å. In contrast, those bins in the difference spectra which exceed the (scaled) sum spectra invariably lie at the relative maxima in the sum spectra, e.g., at \( \approx 86, 92, 100 \) Å. Overall, it is clear that the flux at the relative minima in the sum spectra is constant with oscillation phase and that it is the flux at the relative maxima which oscillates.

How does this result constrain the cause of the oscillations? Unfortunately, the answer is as uncertain as the processes responsible for the shape of the oscillation-phase integrated spectrum. In the simplest interpretation, the net spectrum is composed of emission lines superposed on a weak continuum. In that case, the lines oscillate and the continuum does not. This interpretation is favored by our success in identifying numerous emission lines in the net spectrum with strong transitions of 5–7 times ionized Ne, Mg, and Si (Paper I). On the other hand, we cannot yet rule out the possibility that the net spectrum is formed by complex radiation transfer effects in the outflowing wind known from IUE observations to exist when SS Cyg is in outburst (Heap et al. 1978). In that case, the supposed emission lines in the net spectrum are instead regions of relative transparency in a haze of overlapping absorption lines. Then variations in the optical depth of the haze will most strongly affect those regions of the spectrum where \( \tau \approx 1 \), the relative maxima, and least strongly affect those regions where \( \tau \gg 1 \), the relative minima. Since the spectrum of the EUV oscillations does not distinguish between these alternatives, we defer further analysis of the EUV spectrum of SS Cyg to a later work.

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