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

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ABSTRACT

Quasi-coherent oscillations have been detected in the extreme ultraviolet flux of the dwarf nova SS Cygni during observations with the Extreme Ultraviolet Explorer satellite of the rise and plateau phases of an anomalous outburst in 1993 August and a normal outburst in 1994 June/July. On both occasions, the oscillation turned on during the rise to outburst and persisted throughout the observation. During the 1993 outburst, the period of the oscillation fell from 9.3 s to 7.5 s over an interval of 4.4 days; during the 1994 outburst, the period fell from 8.9 s to 7.19 s (the shortest period ever observed in SS Cyg, or any other dwarf nova) within less than a day, and then rose to 8.0 s over an interval of 8.0 days. For both outbursts, the period $P$ of the oscillation was observed to correlate with the 75–120 Å count rate $I_{EUV}$ according to $P \propto I_{EUV}^{-0.094}$. A magnetospheric model is considered to reproduce this variation. It is found that an effective high-order multipole field is required, and that the field strength at the surface of the white dwarf is 0.1–1 MG. Such a field strength is at the lower extreme of those measured or inferred for bona fide magnetic cataclysmic variables.

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

1. INTRODUCTION

Rapid periodic oscillations are observed in the optical flux of high accretion rate ("high-$M$") cataclysmic variables (CVs; nova-like variables and dwarf novae in outburst) (Patterson 1981; Warner 1995a, 1995b). These oscillations have high coherence ($Q \approx 10^4–10^6$), periods $P \approx 10–30$ s, amplitudes of less than 0.5%, and are sinusoidal to within the limits of measurement. They are referred to as "dwarf nova oscillations" (DNOs) to distinguish them from the apparently distinct longer period, low-coherence ($Q \approx 1–10$) quasi-periodic oscillations (QPOs) of high-$M$ CVs, and the longer period, high-coherence ($Q \approx 10^{10}–10^{12}$) oscillations of DQ Her stars. 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 decreases on the rising branch and increases on the declining branch, but because the period reaches a minimum about 1 day after maximum optical flux, dwarf novae describe a loop in a plot of period versus optical flux.

The dwarf nova SS Cygni routinely exhibits DNOs during outburst. Optical oscillations have been detected at various times with periods ranging from 8.2 s to 10.9 s (Patterson, Robinson, & Kiplinger 1978; Horne & Gomer 1980; Patterson 1981). During one outburst, the period was observed over an interval of $\approx 6$ days to fall from 7.5 s to 7.3 s and then rise to 8.5 s (Hildebrand, Spillar, & Stiening 1981). At soft X-ray energies ($E \approx 0.1–0.5$ keV), oscillations have been detected in HEAO 1 LE 1 data at periods of $\approx 9$ s and 11 s (Côrdova et al. 1980, 1984) and in EXOSAT LE data at periods between 7.4 s and 10.4 s (Jones & Watson 1992). In this Letter, we describe observations with the Extreme Ultraviolet Explorer satellite (EUVE; Bowyer & Malina 1991; Bowyer et al. 1994) of the EUV oscillations of SS Cyg.

2. OBSERVATIONS

Target-of-opportunity observations of SS Cyg in outburst were made with EUVE in 1993 August (MJD 9216.58 to 9223.12; MJD = JD – 2,440,000) and 1994 June/July (MJD 9526.67 to 9532.54 to 9536.94). On both occasions, SS Cyg was detected with the EUVE Deep Survey (DS) photometer and Short Wavelength (SW) spectrometer. 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 to 2 days. The EUV light curve of the 1993 outburst rose more quickly than the optical, and the rise of the EUV light curve of the 1994 outburst was delayed by $\approx 1$ day relative to the optical. On both occasions, the EUV spectrum evolved homologously over roughly 2 orders of magnitude in luminosity. The EUV spectrum is very complex, but it can be very crudely approximated by a blackbody with a temperature of $kT \approx 20–30$ eV absorbed by a neutral hydrogen column density of $N_H \approx 7–4 \times 10^{19} \, \text{cm}^{-2}$ (Mauche, Raymond, & Mattei 1995).

To detect oscillations in the EUV flux of SS Cyg, we proceeded as follows. First, we selected valid intervals when the source was above Earth's limb and both the DS and SW instruments were in operation. Only those intervals longer than 600 s were retained for further consideration. For the 1993 (1994) observations, 89 (75) valid intervals were defined with a net time of 155 (103) ks. Second, we calculated the background-subtracted count rate in the DS and SW instruments for each of the valid time intervals. For the SW instrument, only those photons between 75 and 120 Å were included in the sum; above and below these limits, the spectrum is dominated by noise (Mauche et al. 1995). Third, for each of the valid time intervals, we constructed background-subtracted DS count rate light curves with 1 s time resolution.
resolution. Fourth, we calculated the power spectra of these light curves using the XRONOS software package. As with the HEAO 1 (Córdova et al. 1980) and EXOSAT (Jones & Watson 1992) soft X-ray power spectra, typical EUVE power spectra consist of a single line in a single frequency bin, with no power above the noise at any of the harmonics (Mauche 1996a). From this result, we understand that the EUV oscillation is (a) sinusoidal and (b) essentially coherent (\(Q = |\Delta P_{D}|^{2} > 6 \times 10^{4}\)) over the \(\sim 30\) minute valid time intervals. The period of the oscillation is then simply the inverse of the frequency of the bin of the power spectrum with the peak power, and its error is less than the bin width of \(P^{2}/2048 \approx 0.03\) s. Fifth, we calculated the amplitude of the oscillation during each valid time interval by phase-folding the data on the period appropriate to that interval and fitting a function of the form \(f(\phi) = A + B \sin(\phi + \phi_{0})\), where \(\phi = 2\pi t/P\). The relative amplitude \(B/A\) was 14\% during the 1993 outburst and 16\% during the 1994 outburst, with a tendency in the 1994 data for the relative amplitude to decrease as the count rate increased. These amplitudes are comparable to those of the soft X-ray oscillations measured by HEAO 1 (Córdova et al. 1980) and EXOSAT (Jones & Watson 1992).

The period of the EUV oscillation of SS Cyg detected by the above means is plotted as a function of time in Figure 1. For the 1993 outburst, the oscillation turned on during the rise to outburst on MJD 9218.77; its period was initially 9.31 s, fell over the next \(\approx 1.6\) days to \(\approx 7.6\) s, and then asymptotically approached \(\approx 7.5\) s over the next few days. For the 1994 outburst, the oscillation turned on during the fast rise to outburst on MJD 9528.06; its period was initially 8.90 s, fell to 7.19 s (the shortest period ever observed in SS Cyg, or in any other dwarf nova) within less than a day, and rebounded to 7.42 s by the end of the observation on MJD 9529.77. When observations resumed 2.8 days later, the period of the oscillation was 7.59 s and rose slowly over the next few days to \(\approx 8.0\) s. On both occasions, the oscillations switched on when the SW count rate was \(\approx 0.1\) counts s\(^{-1}\) or when the DS count rate was \(\sim 1\) counts s\(^{-1}\) (Mauche 1996a). For a coherent oscillation to be detected below this count rate, its amplitude must be \(\approx 5\%\).

Superposed on Figure 1 is the log of the 75–120 Å SW count rate as a function of time for the (a) 1993 August and (b) 1994 June/July outbursts of SS Cyg. The dotted line is an unweighted fit to the combined data: \(P = 7.08 I_{\text{EUV}}^{0.094} \) s.

First, despite the vastly different rate at which the period evolved in this diagram during the 1993 and 1994 outbursts, the slope and normalization of the trend of period with SW count rate are to first order the same. Using a function of the form \(P = P_{0} I_{\text{EUV}}^{a}\), where \(I_{\text{EUV}}\) is the 75–120 Å SW count rate, the combined data is fitted with parameters \(P_{0} = 7.08 \pm 0.03\) s and \(a = 0.09385 \pm 0.00003\) if the errors on the period are set to produce \(\chi^{2} = 1\), but a more realistic estimate for the exponent is \(a = 0.094 \pm 0.030\).

Second, there is no “hysteresis” in the trajectory of the 1994 outburst—it doubles back on itself instead of “looping,” as do plots of the period of optical DNOs versus optical flux (see, e.g., Patterson 1981). This figure makes clear that to first order...
the period of the EUV DNOs of SS Cyg is determined solely by the SW count rate. Because the SW spectrum does not change during the observations, the bolometric correction for the EUV flux is fixed. We conclude that the period of the EUV DNOs of SS Cyg is determined by the EUV/soft X-ray luminosity, and, by inference, by the mass-accretion rate onto the white dwarf.

Yet another conclusion that follows from the above result is that the period of the EUV DNOs of SS Cyg is a single-valued function of the EUV flux. Optical and EUV light curves of SS Cyg (Mauche 1996a), U Gem (Long et al. 1996), and VW Hya (Mauche 1996b) demonstrate not only the well-known result that the optical flux leads the EUV flux by ~1 day on the rise to outburst, but also that the optical flux lags the EUV flux on the decline from outburst. With the (as-yet unproved?) assumption that the period of the optical and EUV DNOs are equal, the looping trajectory of the period of optical DNOs versus optical flux is understood to be simply due to the time-dependent lead/lag of the optical flux relative to the EUV flux, and, by extension, the mass-accretion rate onto the white dwarf. (Quite happily, just such an effect is predicted by the accretion disk limit cycle mechanism for dwarf nova outbursts [see, e.g., Fig. 13 of Cannizzo 1993].) This result, combined with the high coherence, amplitude, and luminosity of the EUV DNOs, strongly supports the long-held belief that the optical DNOs are produced by reprocessing of the EUV DNOs.

3. DISCUSSION

Many models have been considered to explain the DNOs of high-\(M\) CVs (Warner 1995a). The low period stability of the oscillations rules out the rotating white dwarf (the DQ Her mechanism) as well as nonradial pulsations of the white dwarf as the cause of the oscillations; pulsations are observed in high inclination systems, ruling out the eclipse by the white dwarf of luminous blobs of material in the inner disk and boundary layer; \(r\)-modes and trapped \(g\)-modes fail because more than one mode would be excited; oscillations of the accretion disk fail because they are not confined to a particular annulus and hence to a particular period. Viable mechanisms are more difficult to construct. Molteni, Sponholz, & Chakrabarti (1996) argue that shocks are an inevitable consequence of gas flow near the inner edge of an accretion disk, and that shock oscillations lead to a cycling of the accretion luminosity when the cooling time of the shocked gas is comparable to the radial infall time. Warner & Livio (1996) propose that the oscillations are due to the combined action of the differentially rotating surface layers of the white dwarf and magnetically controlled accretion.

Despite any other direct evidence that the white dwarf in SS Cyg is magnetic, we consider the requirements of a magnetospheric model for the DNOs of SS Cyg. Such a model has been recently applied by Finger, Wilson, & Harmon (1996) to the quasi-periodic oscillations of the hard X-ray flux of the X-ray transient A0535+262. The Burst and Transient Source Experiment on board the Compton Gamma Ray Observatory observed a “giant” outburst of A0535 during 1994 February 3 through March 20. Finger et al. applied a magnetospheric model to the pulsar in A0535 to explain the observed variations in the QPO frequency \(\nu_{\text{QPO}}\) and spin-up rate of the neutron star. The rationale is as follows: the neutron star accretes through a disk; the disk will be disrupted by the magnetic field of the pulsar at some radius \(r_0\); the observed QPOs will be generated by some mechanism at either (a) the Keplerian frequency \(2\nu_{K}(r_0) = (GM_*/r_0^3)^{1/2}\) at \(r_0\) or (b) the beat frequency \(\nu_{\text{beat}}(r_0) = \nu_{K}(r_0) - \nu_0\) between the Keplerian frequency at \(r_0\) and the spin frequency of the neutron star \(\nu_0\); and torques on the magnetosphere interior and exterior to the corotation radius \(r_0 = (GM_*/(2\nu_{K}))^{1/3}\). Will spin the neutron star up or down as \(r_0\) varies with the mass-accretion rate. Assuming a dipole magnetic field \(B(r) = \mu/r^3\) where \(\mu = B(R_*) R_*^2\) is the dipole moment, and determining \(r_0\) by conservation of angular momentum for a Keplerian flow (Ghosh & Lamb 1991),

\[
r_0 = K(GM_*)^{-1/7} \mu^{4/7} M^{-2/7},
\]

where \(K\) is a constant of order unity. Hence, \(\nu_{K}(r_0) \propto M^{-3/7}\). With these relationships and a simple estimate for the accretion torque, Finger et al. could fit the observed variations in the QPO frequency and neutron star spin-up rate as a function of the measured 20–100 keV flux by identifying the QPO frequency with either \(\nu_{K}(r_0)\) or \(\nu_{\text{beat}}(r_0)\). Specifically, \(\nu_{\text{QPO}} \propto \nu_{\text{K}}^{1/3}\), over a variation of a factor of \(\approx10\) in the observed 20–100 keV hard X-ray flux \(I_{\text{X}}\). For subsequent reference, we note here that for the parameters derived by Finger et al., \(\mu \approx 1 \times 10^{32} \text{ G cm}^3\) and, at the peak of the outburst, \(M \approx 4 \times 10^{-7} M_\odot \text{ yr}^{-1}\). With these values, the above equation gives \(r_0 \approx 1 \times 10^9 \text{ cm} \approx 1 \times 10^4 \text{ neutron star radii}\). The strength of the magnetic field on the surface of the star is \(B(R_*) \approx 1 \times 10^{13} \text{ G}\) and its value at \(r_0 = B(R_*) \approx 1 \times 10^4 \text{ G}\).

Whereas \(\nu_{\text{QPO}} \propto \nu_{\text{K}}^{1/3}\) for A0535, \(\nu_{\text{DNO}} \propto I_{\text{EUV}}^{1/3}\) for SS Cyg. If a magnetospheric model applies to SS Cyg as it does to A0535, why is the variation of the DNO frequency such a weak function of the EUV flux? Variations in the bolometric correction relating the observed EUV flux to the EUV/soft X-ray luminosity and hence to \(M\) are ruled out because the EUV spectrum does not change throughout the outburst. Two alternatives exist, both of which appeal to different scalings of \(r_0\) with \(M\) than shown above: \(r_0 \propto M^{-\alpha}\), where \(\alpha \approx 0.29\). The first alternative involves the accretion disk. Ghosh (1996) considered four standard disk models and found \(\alpha = 0.15\) for a one-temperature, optically thick, radiation pressure dominated disk; \(\alpha = 0.25\) for a one-temperature, optically thick, gas pressure dominated disk; and larger values of \(\alpha\) for more exotic two-temperature optically thin disks. The data for A0535 are well fitted by the scaling for the one-temperature, optically thick, gas pressure dominated disk; \(r_0 \propto M^{-0.25}\), hence \(\nu_{K}(r_0) \propto M^{0.38}\). Although a one-temperature, optically thick, radiation pressure dominated disk gives a weaker scaling for \(\nu_{K}(r_0)\) with \(M\), it is very unlikely that such a model describes the disks of high-\(M\) CVs.

If the structure of the inner disk of SS Cyg does not differ significantly from that of A0535, perhaps the structure of its magnetosphere does. The weak dependence of the frequency of the DNOs of SS Cyg on EUV flux suggests that the magnetosphere of SS Cyg is “stiffer” than the dipole magnetosphere of A0535. Assuming instead of a dipole magnetic field a single star-centered multipole field \(B(r) = m_l/r^{l+2}\) where \(m_l = B(R_*) R_*^{l+2}\) is the multipole moment (Arons 1993),

\[
r_0 = K'(GM_*)^{-1/(4l + 3)} m_l^{1/(4l + 3)} M^{-2/(4l + 3)},
\]

hence, \(\nu_{K}(r_0) \propto M^{3/(4l + 3)}\). To match the observed behavior of SS Cyg, we require \(l = 7/2\). At the peak of the outburst, the
EUV/soft X-ray luminosity of SS Cyg is $L \approx 2 \times 10^{33}$ ergs s$^{-1}$ for $kT = 20$ eV (Mauche et al. 1995); hence $M = 4R_0L/GM_0 \approx 3 \times 10^{-10}$ $M_\odot$ yr$^{-1}$, where we have used $M_\odot = 1.2 M_\odot$ and $R_\odot = 3.9 \times 10^6$ cm. Identifying $\nu_{\text{ono}}$ with $\nu_k(r_0)$, $r_0 = 5.9 \times 10^8$ cm $\approx 1.5$ white dwarf radii (if instead we had used $M_\odot = 1.0 M_\odot$, for which $R_\odot = 5.5 \times 10^6$ cm, $r_0 = 5.6 \times 10^6$ cm $\approx 1.0$ white dwarf radii; the magnetosphere is crushed to the surface of the white dwarf). With these values and the above equation, the strength of the magnetic field at $r_0$ is $B(r_0) \approx (GM_\odot)^{1/2}M^{7/2} r_0^{-5/4} \approx 5 \times 10^8$ G (independent of $l$) and its value on the surface of the white dwarf is $B(R_\odot) = B(r_0)(r_0/R_\odot)^{7/2} \approx 1 \times 10^6(1.5)^2 G \approx 2 \times 10^8 G$.

A surface magnetic field strength of 0.1–1 MG is sufficiently low to be impossible to detect directly. In the presence of the light from the disk and secondary, field strengths below $\approx 3–5$ MG are undetectable via circular polarization measurements in the optical or infrared (Stockman et al. 1992).

Direct detection of the cyclotron harmonics is difficult because the cyclotron fundamental is at $\nu = 0.54(B/0.2$ MG) mm. Zeeman splitting broadens spectral lines by a measurable $\Delta \nu/\nu = 1.2 \times 10^{-5} (\nu/6563 \ A)(B/0.2$ MG), but Stark broadening is significant in the high-temperature, high-density photosphere of the white dwarf, and the disk contributes lines with Doppler widths $\Delta \nu/\nu = 8.4 \times 10^{-4} (r/10^{10}$ cm) $^{-1/2}$ sin $i$. Furthermore, unlike some other dwarf novae (e.g., U Gem, VW Hyi), the white dwarf in SS Cyg is not observed above the disk and secondary during quiescence, even in the UV.

Of more concern is the high order required of the multipole magnetic field. This comes about because of the weak dependence of the frequency of the DNOs of SS Cyg on EUV flux and, by inference, the slow variation of $r_0$ with $M$. We have produced this slow variation by increasing the sensitivity of the magnetic field strength on radius: $B(r) = m_i/r^{l+2}$ with $l \sim 7$ instead of the usual expression with $l = 1$. In general, the magnetic field can be expressed as an infinite sum of multipoles: $B(r) = \sum_{l=0}^{\infty} m_i/r^{l+2} = \sum_{l=0}^{\infty} B_l(r)$. The behavior of SS Cyg requires that at $r_0$, the strength of the $l \sim 7$ multipole component of the magnetic field be significantly greater than the sum of all other components: $B_l(r_0) \gg B_l(r_0)$ for $l \neq 7$. This condition is quite restrictive, as it requires that the corresponding surface fields $B_l(R_\odot) \ll (R_\odot/r_0)^{7-l}B_l(r_0) \sim (1.5)^{7-l}B_l(R_\odot)$. It is unlikely that such a strong inversion in the distribution of multipole components arises naturally—the topology of the currents required to produce such a field would be complex, to say the least.

It is much more likely that the intrinsic magnetic field of the white dwarf of SS Cyg is a low-order multipole. The magnetic fields of AM Her stars are predominantly dipolar, although often the field strengths at the two poles are not equal, indicating that the dipole is off-center or equivalently that a few higher order terms enter into the expansion of the field. If the intrinsic magnetic field of SS Cyg is similarly predominantly dipolar, we need to explain why its magnetosphere behaves so much more "stiffly" than a dipole. A clue comes from the relative sizes of the magnetospheres of SS Cyg and A0535. In the latter, the magnetosphere extends to $\approx 1000$ stellar radii at the peak of the outburst, while in the former it extends to only $\approx 1.5$ stellar radii. Suppose that the accretion disk of SS Cyg is sufficiently diamagnetic as to exclude a significant fraction of the magnetic field of the white dwarf. During the outburst, the magnetosphere will be pinched inward by the accretion disk as the mass-accretion rate increases and the inner edge of the disk moves inward. Trapped in the orbital plane between the inner edge of the disk at $r_0$ and the surface of the white dwarf at $R_\odot$, the magnetosphere will become significantly distorted if the ratio $r_0/R_\odot$ approaches unity as it does in SS Cyg. Expressing the distorted field as a sum of multipoles, it is clear that higher order terms will become more and more important as the field is increasingly distorted. We do not imagine that the $l \sim 7$ term ever actually dominates the multipole expansion of the field, but that the magnetosphere comes to behave as if it did. In the context of the simply theory behind equation (1), we require simply that conditions conspire to produce $B(r_0) \propto r_0^{-l+2}$ with $l \sim 7$. Our derived value of $B(r_0) \approx 5 \times 10^8$ G should still be a reasonable estimate, but the extrapolation of the strength of the field from $r_0$ to the surface of the white dwarf is very uncertain. The simply scaling gives $B(R_\odot) \approx B(r_0)(r_0/R_\odot)^{7/2} \approx 1 \times 10^6(1.5)^2 G \sim 2 \times 10^7 G$ for $l = 7/2$, but this can be considered only an order-of-magnitude estimate.

4. CONCLUSIONS

If a magnetospheric model applies to SS Cyg, it appears likely that the surface magnetic field strength of its white dwarf is 0.1–1 MG. This range of values is orders of magnitude lower than the field strengths of AM Her stars ($B \approx 10–80$ MG; Cropper 1990; Beuermann & Burwitz 1995), but may overlap with the field strengths of DQ Her stars (very uncertain, by $B \sim 0.1–10$ MG; Patterson 1994). With such a field strength, it is a challenge for SS Cyg in quiescence not to manifest the photometric variations associated with DQ Her stars; the limit on such variations in the optical is 0.001 mag ($\approx 0.01\%$) near 0.1 Hz (Patterson 1995). In outburst, the accretion flow should be channeled down to the footpoints of the magnetic field and produce hard and soft X-rays in the manner of AM Her and DQ Her stars. However, neither the eponymous DQ Her nor V533 Her are hard X-ray sources (Cordova, Mason, & Nelson 1981), demonstrating that magnetic accretion can take place without the production of hard X-rays. While SS Cyg in outburst is a known hard X-ray source (Jones & Watson 1992; Nousek et al. 1994; Ponomar et al. 1995), it is not known to oscillate in hard X-rays; the limit is 6% when soft X-ray oscillations were observed by HEAO 1 (Swank 1979). To produce a more stringent upper limit, XTE observations are required. Planned simultaneous observations of SS Cyg in outburst with XTE and EUVE will determine the shapes of the hard and soft X-ray light curves, the correlations between the soft and hard X-ray fluxes, and the extent to which the oscillations in the soft X-ray flux are manifest in the hard X-ray flux.

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