ANALYSIS OF THE SOFT X-RAY PULSATIONS OF DWARF NOVAE

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Both SS Cyg and U Gem show enhanced soft X-ray emission (0.1-0.5 keV) during optical outbursts. In extended HEAO-1 pointings, it was discovered that a large fraction of this emission is pulsed (see Fig. 1). This confirms the general expectation that high energy pulsations are the ultimate source of the optical pulsations observed during outbursts of dwarf novae. For SS Cyg the average soft X-ray pulsation amplitude is 30%; this is to be contrasted with the upper limit of 10% to a hard X-ray (2-25 keV) pulsed component for the same observation (Swank 1979). Thus the origin of the oscillation is in soft X-rays, and the direct implication of such a large pulsed amplitude is that the oscillation itself must be an intrinsic part of the X-ray production mechanism.

Power spectra of relatively short stretches of the data for both systems are shown in Figs. 2 and 3. Most of the power in SS Cyg's signal lies in a narrow frequency interval, while for U Gem the power

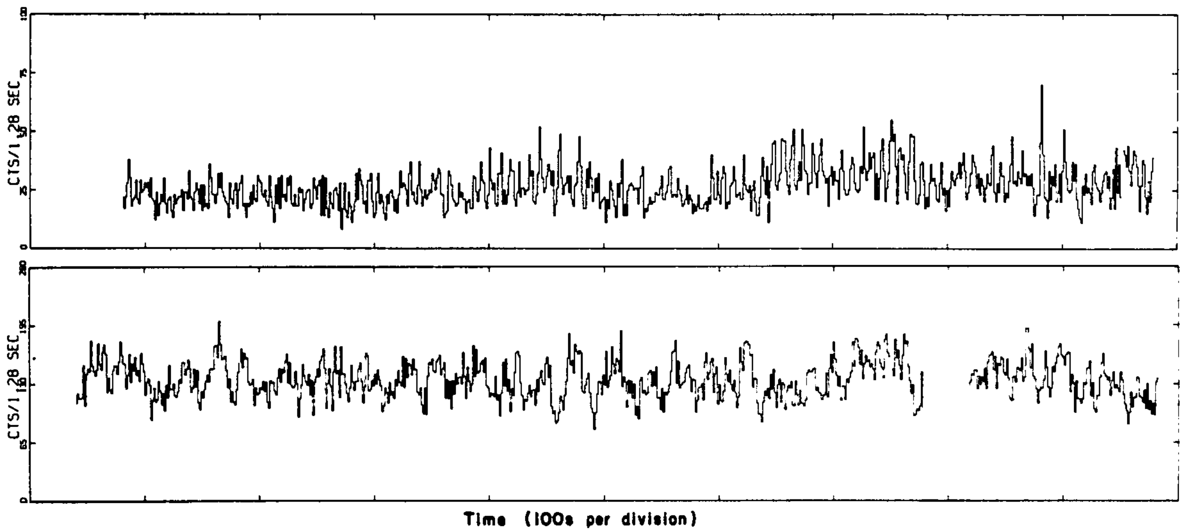

Fig. 1 - A portion of the soft X-ray light curves of both dwarf novae. Aside from amplitude modulation, the pulsations of SS Cyg look fairly regular. U Gem's pulsations look chaotic by comparison, having no well-defined period.

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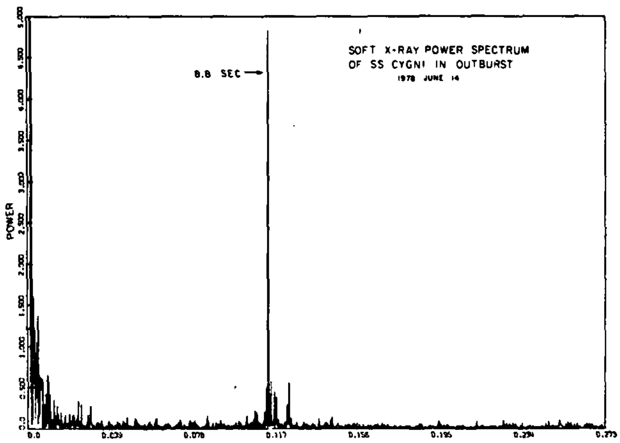

Fig.2

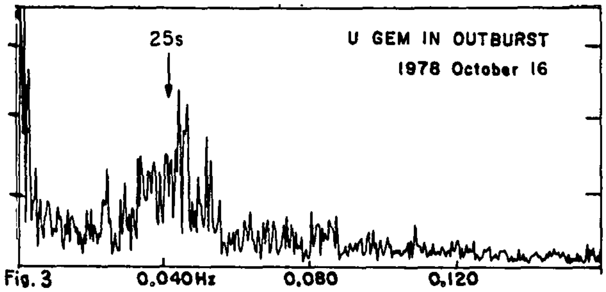

Fig.3

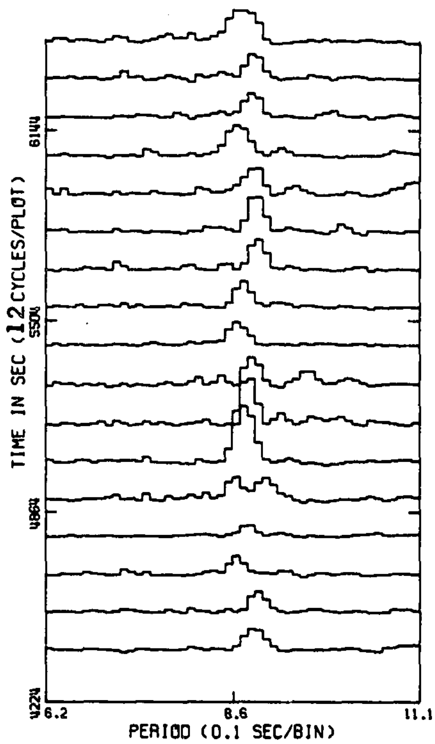

Fig. 4 - SS Cyg periodogram

is broadly distributed around a mean period of 25 s. It is difficult to look for changes on short timescales using the Fourier transform technique. If frequency or phase noise is present, it is also not possible to meaningfully search for harmonics.

Conventional analysis of the optical oscillations from cataclysmic variables make use of the "periodogram" technique; that is, short segments of continuous data are folded on a mean period and the amplitudes are plotted versus period. Such a technique applied to SS Cyg's soft X-ray pulsations, and illustrated for a portion of the data in Fig. 4, show that the X-ray pulsations have the same characteristics as the optical pulsations observed in many dwarf novae: large amplitude variability, period excursions on short timescales, and the occasional presence of multiple periods. When this technique is applied to all the SS Cyg X-ray data, a long term period drift amounting to -1×10^{-5} $s\ s^{-1}$ is evident. The problem with this type of analysis is that an apparent change in period, such as the small shifts observed from one periodogram to the next in Fig. 4, can be produced by variations in either phase or amplitude, or both; it is not possible to distinguish the true nature of the noise component.

The technique we eventually settled on to analyze the pulsations was the following.* We determined the pulse arrival times by cross-correlating individual pulses or groups of pulses with a master pulse profile (for SS Cyg a sinusoid was used because it best approximated the pulse shape observed in foldings of the data). We thus obtained

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*A detailed analysis of the pulsations is described in Córdova et al. (1979a,b).

both the amplitude and phase of the pulsation as a function of time. We found that the amplitude can change by a factor of six within fifteen pulses with no effect on the pulse phase. The phase itself exhibits both slow variations and rapid jumps. In Fig. 5 these results are illustrated for a portion of the SS Cyg data.

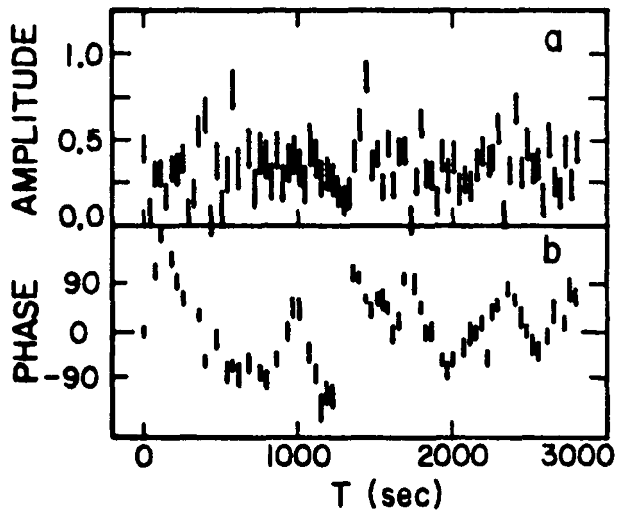

Fig. 5

By superposing each pulse so that the maxima coincide, we were able to sensitively search for harmonics. The pulsation is remarkably sinusoidal, with an upper limit of 12% for the first harmonic and ~ 7% for other harmonics.

Our chief intention was to investigate the noise properties of the oscillation, that is, to determine whether the pulsed signal was dominated by "phase noise," "frequency noise," or "slowing-down noise" (see Groth 1971). We did this by examining how the variance of the phase about a constant period depends on time. Figure 6 shows the result, namely that the variance increases approximately linearly with time. This is consistent with a random walk in phase caused by white noise in the period of the oscillation.

The slope of the phase variance versus time would give us the strength of the random walk <u>if</u> we knew the underlying pulsation period. Since we do not have this knowledge we, instead, simulate the data by generating arrival times T_N such that $T_N = T_{N-1} + P$, where $P = P_0 + P_1 x$, P_0 and P_1 are fixed numbers, and x is a normally distributed random variable with a mean of zero and unit standard deviation. For $P_0 = 8.77_s$ (chosen somewhat arbitrarily), we find that $P_1 = 0.04 \pm 0.06$ s produces a curve consistent with Fig. 6.

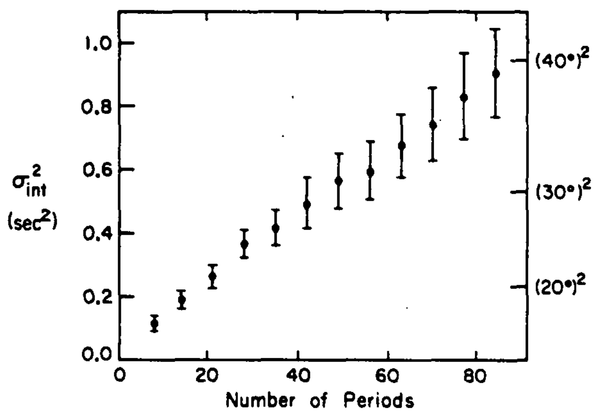

Fig. 6

Although we know that phase steps must occur at least as often as once per cycle, we do not know the true frequency of the steps. Thus, instead of specific values of P_0 and P_1, our simulation gives us the strength of the random walk, which is defined as a rate of phase steps times the mean square phase step:

$$S = R <(\Delta\phi)^2> = \frac{1}{P_0}\left(\frac{2\pi P_1}{P_0}\right)^2 = 0.011 \pm 0.003 \ s^{-1} \quad (1)$$

In a random walk of this strength, the phase of the oscillation changes by 90° on the average every 25 ± 7 pulses!

In a similar analysis performed on U Gem's oscillations we find that the intrinsic variance of the phase also grows linearly with time, and that P_0 = 25 s, P_1 = 5±1 s reproduces the variance in slope. Although superficially the quasi-coherent pulsation from U Gem seems qualitatively different from the more coherent soft X-ray pulsation of SS Cygni, it appears that a change in only the strength of the random walk in phase can account for the difference between the two stars; our analysis shows that the phase noise in U Gem is ~ 10-30 times greater than in SS Cyg.

To demonstrate in a simple way the characteristics of a pulsed signal subject to phase noise, we have generated artificial data sets showing what happens to a pulsation when the strength of the random walk is increased. Figure 7 shows three power spectra generated by

$$f(t) = 100 + 20 \cos(\omega t + \phi_t) + 20 \cos(2\omega(t + \phi_t)), \quad (2)$$

where ϕ_t is a step function which changes its value every cycle:

$$\phi_t = \phi_{t-P_0} + \frac{2\pi P_1}{P_0} x. \quad (3)$$

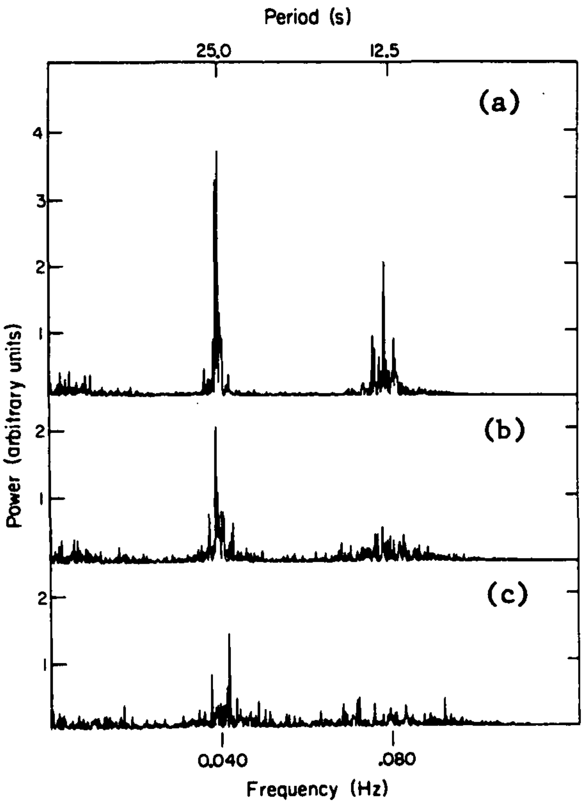

Fig. 7

P_0 is the basic pulsation period, chosen to be 25 s.

We have chosen values for P_1, the standard deviation of P_0, equal to 1.5, 3, and 5 in Fig. 7a, b, and c, respectively. Our artificial data set consisted of 256 pulses. The figure illustrates several important points:

1. A variation in the strength of the random walk can change the "coherent" pulsation of SS Cyg to the "incoherent" pulsation of U Gem. Fig. 7a shows a strong pulsation at 25 s with an appearance similar to that for SS Cyg. Fig. 7c, on

the other hand, shows only an enhancement in the power spectrum at periods clustering around 25 s, a profile similar to that for U Gem.

2. Harmonics will be even more strongly affected by phase noise than the fundamental is affected. In (c) the harmonic that showed up strongly in (a) has completely disappeared even though it has an amplitude equal to that of the fundamental! This could explain the absence of harmonics in the observed dwarf novae pulsations.

3. The phase noise produces random period shifts. In (a), where the phase noise was weak, the peak is 0.1 s away from the true pulse period. In (b) it is shifted by 0.2 s.

4. The random walk can produce multiple pseudo-periodicities. (see the two spikes in Fig. 7c).

Thus the behavior of the so-called "coherent" visual oscillations (Patterson, Robinson, and Nather 1977; Patterson, Robinson, and Kiplinger 1978) can be explained by intrinsic phase instability; these pulsations resemble the X-ray pulsations in SS Cyg. The "quasi-coherent" visual oscillations observed for several dwarf novae on the decline from maximum brightness (Robinson and Nather 1979) have a behavior similar to the X-ray pulsation in U Gem. Figure 7 shows that the difference between the "coherent" and "quasi-coherent" pulsations may be only in the strength of the random walk in phase. It is possible that <u>all</u> of the optical and X-ray oscillations are produced by the same mechanism.

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