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Letter to the Editor

A 2.8-second quasi-coherent oscillation in the soft X-ray flux of the dwarf nova SS Cygni

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Abstract. During maximum optical brightness of a wide outburst, the soft X-ray flux of the dwarf nova SS Cyg was measured with the ROSAT satellite. The soft X-ray flux is modulated with a highly coherent sinusoidal oscillation with a period near 2.8 s. This is, by more than a factor of 2.5, the shortest period measured in a dwarf nova and, if identified with the Kepler period, provides a lower limit for the mass of the white dwarf in SS Cyg of 1.24 solar masses. Except for the much shorter period and the higher phase stability, the properties of the oscillation are reminiscent of oscillations observed previously in SS Cyg, which suggests a similar physical origin. The shorter period may be due to a significantly faster rotation, near break-up, of the white-dwarf surface layers or a location in the accretion disk much closer to the white dwarf than before.

Key words: accretion disks – stars: individual: SS Cygni – cataclysmic variables – oscillations – white dwarfs – X-rays: stars

1. Introduction

Cataclysmic variables are interacting binary stars in which a white dwarf accretes matter from a Roche-lobe filling main-sequence star. A subclass of cataclysmic variables, the dwarf novae, show outbursts during which the optical brightness increases by a factor of 10–100 due to a dramatic increase in the mass-transfer rate in the accretion disk and onto the white dwarf. Highly coherent periodic oscillations (also called dwarf-nova oscillations) have been observed in the extreme-ultraviolet and soft X-ray flux of a few dwarf novae in outburst (consult Warner 1995 for an extensive review of cataclysmic variables, dwarf novae and dwarf-nova oscillations). Optical dwarf-nova oscillations, which are most likely soft X-ray oscillations reprocessed by the accretion disk, have been observed in several other dwarf novae in outburst (Patterson 1981). Dwarf-nova oscillations typically have periods of 10–30 seconds. The shortest periods, in the range of 7–12 seconds, have been observed in the dwarf nova SS Cyg (Córdova et al. 1980, 1984; Jones & Watson 1992; Mauche 1996).

Though we do not have a convincing model for these dwarf-nova oscillations, it is likely that the extreme-ultraviolet and soft X-ray radiation is produced in the boundary layer between the white dwarf and the accretion disk, where the accreting matter decelerates from the Keplerian velocity to the rotation velocity of the white dwarf (Pringle 1977). The physical mechanism for the quasi-coherent oscillations must be closely connected is some way with the soft X-ray production in this boundary layer. An existing explanation for the oscillations invokes differential rotation of the white-dwarf surface layers and a weak white-dwarf magnetic field, where the observed period would be the rotation period of the surface layers (Paczyński 1978). During an outburst, the surface layers would spin up as a result of the accretion of angular momentum from the inner accretion disk. After outburst maximum, when the accretion rate decreases, magnetic viscosity in the white-dwarf envelope would transfer angular momentum inwards and the rotational period of the surface layers would increase again. Independent of the physical details, the observed period should be longer than the Kepler period at the white-dwarf surface and gives, therefore, a lower limit to the white-dwarf mass.

In this *Letter*, I present the discovery of a quasi-coherent oscillation in the soft X-ray flux of SS Cyg with an unprecedentedly short period of 2.8 s. Section 2 describes the observations and the properties of the oscillation. Section 3 briefly compares the results with previous observations and discusses the implications for the white dwarf in SS Cyg.

2. Observations and results

During the December 1996 outburst, the ROSAT X-ray satellite (Trümper 1982) observed SS Cyg with the High Resolution Imager (HRI), which is sensitive to photons in the energy range of 0.1–2 keV. The top panel of Fig. 1 shows the optical light curve of the outburst observed by members of the American Associa-

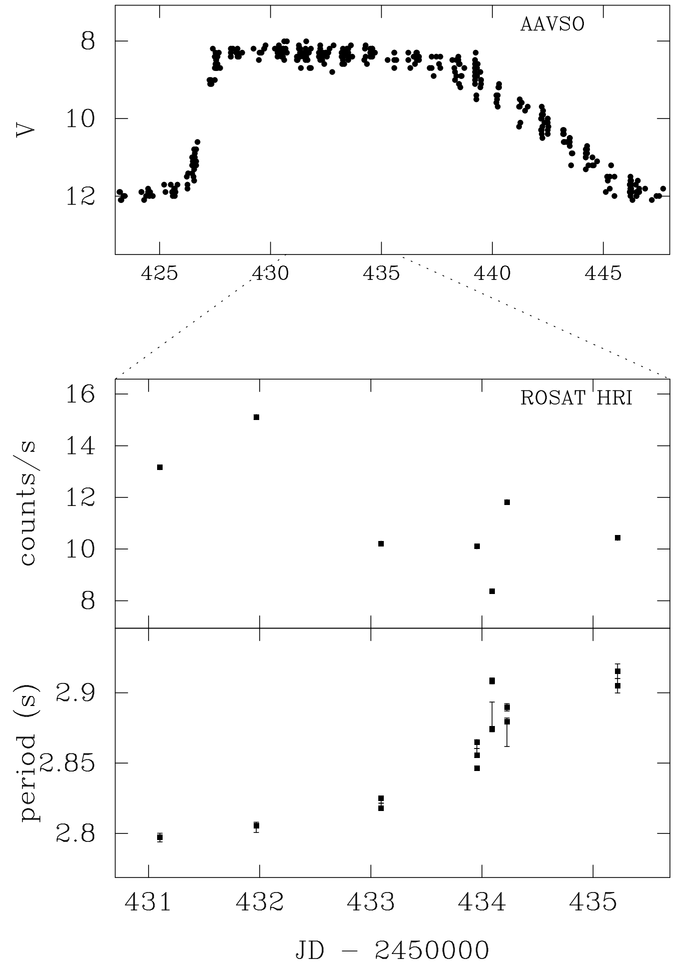

Fig. 1. The top panel shows the optical light curve (in visual magnitudes) of the December 1996 wide outburst of SS Cyg as observed by members of the American Association of Variable Star Observers. The lower panels, which cover only part of the outburst, show the average ROSAT HRI X-ray count rates and the period of the quasi-coherent oscillation in the count rate. In the bottom panel, each peak in the power spectrum is shown by a separate point.

tion of Variable Star Observers (Mattei 1997). The outburst was a normal wide outburst, since the source stayed at optical maximum for about 12 days. The X-ray observations, with a total exposure of 15 818 s, were obtained in seven observation intervals (*obi*'s) from Dec 13, 14:05 UTC to Dec 17, 17:31 UTC, in the middle of the outburst plateau phase.

The data were reduced using the EXSAS software package (Zimmermann et al. 1994). Source counts were extracted from a circle with a radius of 25" and centered on the position of SS Cyg. The resulting X-ray count rates were corrected for detector vignetting and dead time. The count rate of SS Cyg was strongly variable with minima of < 5 counts s^{-1} in the fifth *obi* and flares reaching > 30 counts s^{-1} in the first two *obi*'s. Part of the light curve during the first *obi*, binned into 2.797-s bins, is shown in Fig. 2. The average count rate in the seven *obi*'s shows a decreasing trend, which is not seen in the optical light curve (Fig. 1). Because the HRI possesses only a very modest spectral resolution, it is not possible to determine an accurate X-ray flux from the observed count rates. However, because practically all counts were detected in pulse-height-analyzer channels 1–5, the spectrum was probably very similar to the spectrum observed with the *Extreme Ultraviolet Explorer* satellite during the anomalous outburst of August 1993 (Mauche et al. 1995). Using the same absorbing column density $N_{\mathrm{H}} = 3.5 - 7 \times 10^{19}\ \mathrm{cm}^{-2}$ and blackbody temperature $kT = 37-20$ eV, the observed count rates correspond to a blackbody luminosity of 10^{32}–$10^{34}\ \mathrm{erg\ s}^{-1}$ for a distance of 75 pc. The average count rate of 15 counts s^{-1} in the second *obi* corresponds to a blackbody luminosity of 5×10^{32}–$5 \times 10^{33}\ \mathrm{erg\ s}^{-1}$

The raw source counts, corrected to barycentric arrival times, were searched for periods in the range of 0.1–100 s by calculating power spectra. The power spectra of the seven *obi*'s, from 0 to 0.7 Hz, are plotted all together in Fig. 3. In all power spectra, there is a highly significant period at 2.8–2.9 s. There is no significant power at any of the harmonics, which implies that the oscillation is strikingly sinusoidal. Within an *obi*, the period coherence of the oscillation, defined as $Q \equiv |\Delta P/\Delta t|^{-1}$, is $Q > 10^5$. Between the first two *obi*'s, the period coherence is even $Q > 10^7$. In the later *obi*'s, however, the coherence was significantly lower. As shown in Fig. 1, the period of the oscillation increases slowly from 2.797 s in the first *obi* to 2.917 s in the last *obi*.

Figure 4 illustrates the perfectly sinusoidal pulse profile and the high coherence of the oscillation, where the first *obi* with a length of 2 594 s has been folded with the 2.797-s period. The flickering shown in Fig. 2 has been completely averaged away in the folded light curve. Figure 4 also illustrates the high phase stability of the oscillation, which is at least ~ 900 cycles. This is much higher than during the longer-period oscillations observed before in SS Cyg (Córdova et al. 1980). Both the absolute and relative amplitude of the oscillation correlate with the measured count rate with 99.8% significance: the oscillation is more prominent when the count rate is higher. The relative amplitude of the oscillation varies between 9% and 18% of the average count rate. Although the average count rate shows a decreasing trend and the period an increasing trend, the anti-correlation between the two is not significant.

3. Discussion

The coherence and amplitude of the 2.8-s oscillation are similar to those of previously detected quasi-coherent oscillations in the extreme-ultraviolet and soft X-ray flux of SS Cyg. The absence of any harmonics, the correlation between the amplitude and the count rate, and the suggestive relation between the period and the count rate are also reminiscent of the usual dwarf-nova oscillations. The period, however, is at least a factor of 2.5 shorter than any period detected so far in SS Cyg, or in fact any reliable period in any other cataclysmic variable (except for the much less coherent $Q \sim 250$ quasi-periodic oscillations in polars; Larsson 1992). The resemblance between the 2.8-s oscillation and the previously reported longer-period quasi-coherent oscil-

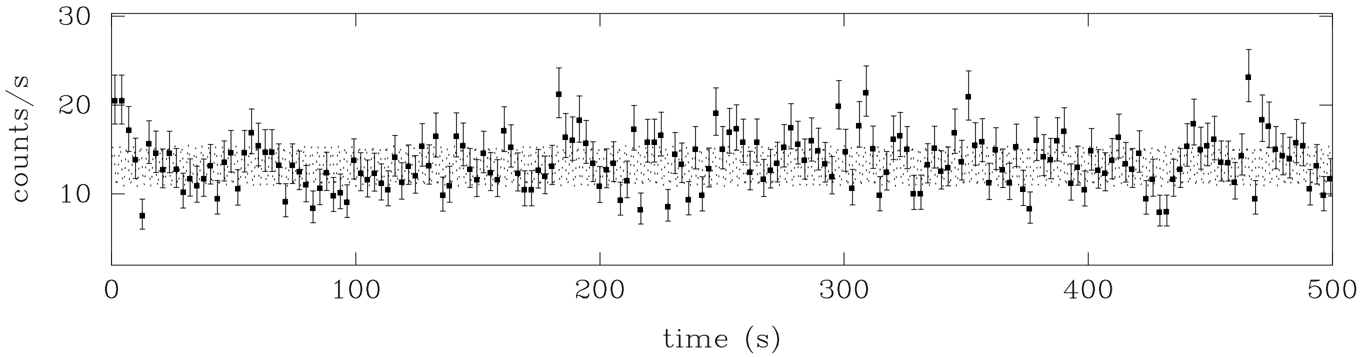

Fig. 2. Part of the X-ray light curve during the first observation interval binned into 2.797-s bins. The dotted band shows the peak-to-peak amplitude of the average 2.797-s oscillation

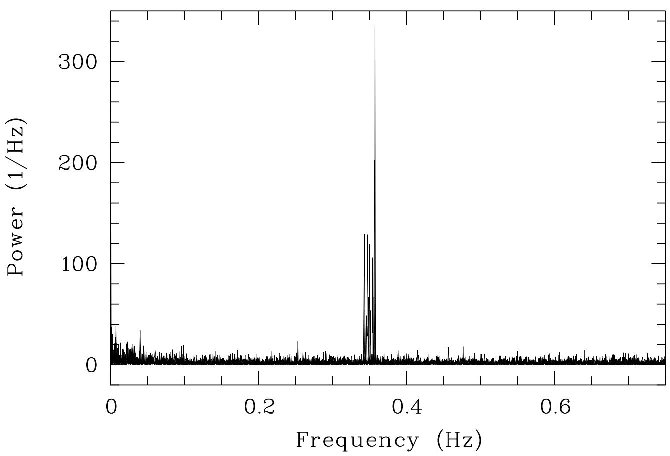

Fig. 3. Superimposed power spectra of the seven observation intervals. The peaks in the individual power spectra at 0.35 Hz move to lower frequencies with increasing interval number.

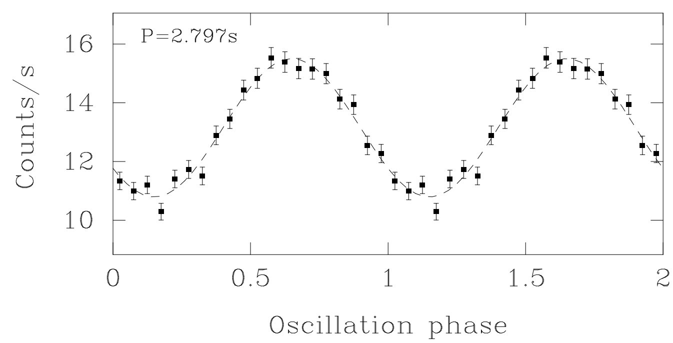

Fig. 4. ROSAT HRI X-ray light curve of the first observation interval folded on the 2.797-s period of the oscillation. The total interval covers more than 900 oscillation periods. The dashed line is a χ^2 fit with $A + B\sin(\phi + \phi_0)$, where $\phi = 2\pi t/2.797$. The derived value for the relative amplitude is $B/A = 17.9 \pm 0.8\,\%$

lations suggests that both are produced by the same physical mechanism. In the context of existing models, the longer periods observed in previous observations would correspond to a significantly slower rotation of the white-dwarf surface layers or a location in the accretion disk much further away from the white-dwarf surface.

The lack of harmonics suggests that the $\sim$ 2.8-s period is the fundamental period of the oscillation. This again implies that the oscillation must be due to a very basic pulsation or rotation deep inside the gravitational potential well of the accreting white dwarf. The typical time scale of most revolutionary and pulsational phenomena near the white dwarf is of the order of a few seconds. The low Q rules out the rotation or non-radial pulsation of the white dwarf, unless we observe the differential rotation or pulsation of surface layers which are only loosely coupled to the interior. Rossby-type r-modes (Papaloizou & Pringle 1978), trapped g-modes, and radial modes (Saio et al. 1983), all have the correct range of periods, but it is not yet clear whether and how only a single mode could be excited. The same may be true for oscillations in the inner part of the accretion disk, which could be confined to a particular radial range (cf. Glatzel & Mehren 1996), and where, due to possible radial coupling, it is not *a priori* true that each radius has its own frequency.

The fundamental period of the boundary layer is the Kepler period in which the X-ray emitting gas orbits the white dwarf. For instance, a pulsation of the boundary layer, in resonance with the Kepler period, might sinusoidally modulate the soft X-ray flux by periodically changing its optical thickness. This would be consistent with the observed extreme-ultraviolet spectrum of the oscillations (Mauche 1997). On the other hand, numerical calculations have shown that the boundary-layer luminosity may either oscillate on time scales of the Kepler period with much less coherence and with a much less sinusoidal pulse profile than observed (Kley 1991) or sinusoidally with a period which is an order of magnitude too large (Hujeirat 1995). If the 2.8-s oscillation in SS Cyg is identified with the Keplerian rotation of the inner disk or with the rotation of the white-dwarf surface layers, the minimum observed period provides a lower limit on the white-dwarf mass. The Kepler period at the white-dwarf surface is given by

$$P_{\rm K} = 2\pi\sqrt{\frac{R^3}{GM}} \tag{1}$$

where R is the white-dwarf radius and M the white-dwarf mass. Using the Hamada & Salpeter (1961) mass-radius relation for zero-temperature white dwarfs, the observed minimum period of 2.8 s gives a lower limit for the mass of the white dwarf in SS Cyg of $1.26 M_\odot$ for a carbon white dwarf and $1.24 M_\odot$ for a neon/magnesium white dwarf. These values are consistent with the measured radial velocities of SS Cyg (Hessman et al. 1984; Friend et al. 1990) if the inclination is $\sim 37°$ and the secondary star is a near-main-sequence star with a mass of ~ 0.7–$0.8 M_\odot$, which in turn is consistent with the K5 V spectral type of the secondary star.

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