

## Rapid Variability as a Diagnostic of Accretion and Nuclear Burning in Symbiotic Stars and Supersoft X-ray Sources

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**Abstract.** Accretion disks and nuclear shell burning are present in some symbiotic stars (SS) and probably all supersoft X-ray binaries (SSXBs). Both the disk and burning shell may be involved in the production of dramatic outbursts and, in some cases, collimated jets. A strong magnetic field may also affect the accretion flow and activity in some systems. Rapid-variability studies can probe the interesting region close to the accreting white dwarf (WD) in both SS and SSXBs. I describe fast photometric observations of several individual systems in detail, and review the results of a photometric variability survey of 35 SS. These timing studies reveal the first clearly magnetic SS (Z And), and suggest that an accretion disk is involved in jet production in CH Cyg as well as in the outbursts of both CH Cyg and Z And. They also support the notion that the fundamental power source in most SS is nuclear burning on the surface of a WD, and raise questions about the structure of disks in the SSXBs. Finally, spectroscopic observations of RS Oph reveal minute-time-scale line-strength variations, probably due to a hot boundary layer. Taken together, the rapid timing observations explore the connections between jet-producing WDs and X-ray binaries, as well as SS, SSXBs, and CVs.

### 1. Introduction

Accretion onto a white dwarf (WD) and nuclear shell burning probably power the observed activity in supersoft X-ray binaries (SSXBs) and many symbiotic stars (SS). Besides the hallmark high-excitation-state emission lines (for SS) and soft X-ray spectra (for SSXBs), this activity can include outbursts and collimated jets. But in SS, emission and absorption by the nebula can hide the spectroscopic signatures of a disk and absorb the soft X-rays from the nuclear-burning shell. In SSXBs, the disk is optically visible, but the optical emission is dominated by reflected nuclear-burning light, and the disk is significantly heated (e.g., Popham & Di Stefano 1996). One way to examine the region close to the accreting WD despite these complications is to look for rapid variations.

In the context of this work, ‘rapid’ or ‘fast’ variations are those which could be associated with WD-disk phenomena. Stochastic variations from a disk, termed “flickering”, generally occur on either a dynamical time

$$t_{dyn} \sim \frac{1}{\Omega_k} \sim 4 \text{ s} \left( \frac{r}{10^9 \text{ cm}} \right)^{3/2} \left( \frac{M_{WD}}{0.6 M_{\odot}} \right)^{-1/2}$$

(where  $\Omega_k = \Omega_k(r)$  is the Keplerian angular velocity,  $r$  is the radial position in the disk, and  $M_{WD}$  is the mass of the WD), or a viscous time

$$t_{visc} \sim \frac{1}{\alpha} \left( \frac{r}{H} \right)^2 \frac{1}{\Omega_k} \sim 8 \text{ hr} \left( \frac{\alpha}{0.1} \right)^{-4/5} \left( \frac{\dot{M}}{10^{-8} M_\odot \text{ yr}^{-1}} \right)^{-3/10} \left( \frac{r}{10^9 \text{ cm}} \right)^{5/4}$$

(where  $H$  is the disk height,  $\alpha$  is the viscosity parameter, and  $\dot{M}$  is the accretion rate onto the WD; Frank, King, and Raine 1992). Disk flickering therefore depends on the size and properties of the disk, and the location of the emitting region within the disk. In WD disks, fluctuations occur with time scales of roughly a day or less, and observations verify that the fastest stochastic variations come from the inner disk (e.g., Bruch 2000).

Brightness oscillations due to magnetic accretion should also have time scales ranging from minutes to hours. When a WD is in spin equilibrium (neither being spun up nor spun down by torques from the disk material), it rotates with the Keplerian frequency at the radius where the ram pressure from in-falling material balances the pressure in the magnetic field. For fields typically measured in intermediate polars (IPs;  $B_S \sim 10^5 - 10^6$  G) and accretion rates that are reasonable for SS or SSXBs ( $\dot{M} \sim 10^{-9} - 10^{-7} M_\odot \text{ yr}^{-1}$ ), the equilibrium spin periods are tens of minutes.

Changes in the luminosity from a burning shell occur on the nuclear time,  $t_{nuc}$ , which is roughly the time to accrete the envelope scaled by the fraction of the envelope that must be burned to heat the entire envelope to temperature  $T$ :

$$\begin{aligned} t_{nuc} &\sim \left( \frac{C_P T}{E_{nuc}} \right) \left( \frac{\Delta M}{\dot{M}} \right) \\ &\sim 3 \text{ yr} \left( \frac{T}{3 \times 10^7 \text{ K}} \right) \left( \frac{\Delta M}{6 \times 10^{-5} M_\odot} \right) \left( \frac{\dot{M}}{4 \times 10^{-8} M_\odot \text{ yr}^{-1}} \right)^{-1}, \end{aligned}$$

where  $C_P$  is the specific heat at constant pressure,  $E_{nuc}$  is the energy released per gram from nuclear burning of H, and  $\Delta M$  is the mass of the envelope, which is dependent on  $M_{WD}$  and  $\dot{M}$  (Fujimoto 1982). Therefore, fast variations cannot be due to fundamental changes in the nuclear burning emission (changes due to obscuration or reflection of this emission, however, could happen quickly).

Even though the nuclear burning luminosity cannot change quickly, it is still an important consideration in rapid-variability studies. Since  $E_{nuc}/E_{grav} \approx 40$  (where  $E_{grav}$  is the energy released per gram from accretion onto the WD), quasi-steady nuclear shell burning dominates the energetics of the hot component when present. Nuclear burning can therefore hide or diminish rapid variations that are directly associated with accretion. The maximum and minimum accretion rates to produce quasi-steady shell burning are

$$\begin{aligned} \dot{M}_{steady,max} &= 2.8 \times 10^{-7} + 5.9 \times 10^{-7} \left( \frac{M_{WD}}{M_\odot} - 1.0 \right) M_\odot \text{ yr}^{-1} \\ \dot{M}_{steady,min} &= 1.32 \times 10^{-7} M_{WD}^{3.57} M_\odot \text{ yr}^{-1}. \end{aligned}$$

(Paczynski & Rudak 1980; Iben 1982). If  $\dot{M} > \dot{M}_{steady,max}$ , the fuel cannot be burned as fast as it is accreted, and the envelope could expand or be ejected. If

$\dot{M} < \dot{M}_{steady,min}$ , material burns unstably in nova explosions, although a period of residual burning may follow. If the hot-component luminosity ( $L_{hot}$ ) is greater than approximately  $100 L_{\odot}$ , significant nuclear burning must be present, since such high luminosities cannot be produced by accretion with  $\dot{M} < \dot{M}_{steady,min}$ .

One final time scale of interest is the recombination time in a SS nebula,

$$t_{rec} \sim \frac{1}{n_s \alpha_B} \sim 1 \text{ hr} \left( \frac{n_s}{10^9 \text{ cm}^{-3}} \right)^{-1} \left( \frac{\alpha_B}{2.59 \times 10^{-13} \text{ cm}^3/\text{s}} \right)^{-1} \text{ at } 10^4 \text{ K}$$

(where  $n_s$  is the density at the outer edge of the ionized region and  $\alpha_B$  is the case-B recombination coefficient; Fernández-Castro et al. 1995). Any high-energy (far-UV or soft X-ray) variations faster than  $t_{rec}$  will be smeared out when the nebula reprocesses them into the optical.

In §2, I discuss the first known case of a WD with both magnetically channeled accretion and surface nuclear burning (Z And). I describe photometric evidence for changes in an accretion disk associated with the production of a jet in a WD accretor (CH Cyg) in §3, and discuss how high-time-resolution studies can reveal the relative importance of nuclear burning vs. viscous dissipation in §4. Disk flickering from the supersoft source MR Vel is described in §5, and minute-time-scale spectral line variability that can act as a diagnostic for the physical conditions in the line-emitting regions (RS Oph) is shown in §6. I discuss the overall results from these variability studies in §7.

## 2. Magnetic Accretion in Z Andromedae

In IPs, the WD magnetic field is strong enough to truncate the inner accretion disk, channel material onto the WD polar caps, and produce an X-ray and/or optical oscillation at the WD spin period (see e.g., Warner 1995). If strong WD fields are fossil fields of magnetic Ap and Bp stars (see Wickramasinghe & Ferrario 2000), then the fraction of magnetic WDs in interacting binaries should be higher than the fraction of single WDs with strong fields<sup>1</sup>. A higher fraction of WDs in CVs do appear to be magnetic (25% vs. 5% in the field; Wickramasinghe & Ferrario 2000). But selection effects could bias this comparison, since CVs are often discovered because of their X-ray pulsations. It is therefore useful to examine different classes of WD accretors. Until recently, however, no IP-like oscillations had been found in either a SS or SSXB.

In 1997 and 1998, Sokoloski & Bildsten (1999) observed the prototypical symbiotic Z And on 8 occasions, with the 1-m telescope at Lick Observatory, and found a 28-minute oscillation each time. Figure 1 shows example *B*-band light curves and the corresponding power spectra. Taking reasonable values for the WD mass, radius, and accretion rate, a spin period of 28 m implies a WD surface magnetic field strength of at least  $B_S = 3 \times 10^4$  G, and if the WD is in spin equilibrium,  $B_S = 6 \times 10^6$  G (Sokoloski & Bildsten 1999). This field is comparable to fields found in magnetic CVs. The amplitude of the optical oscillation ( $< 2$  mmag, or  $< 0.2\%$  in quiescence), however, is roughly 10 to 100

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<sup>1</sup>Because the accreting WD in a CV-like interacting binary was originally the more massive of the pair, the progenitor population of these WDs contains relatively more Ap and Bp stars.

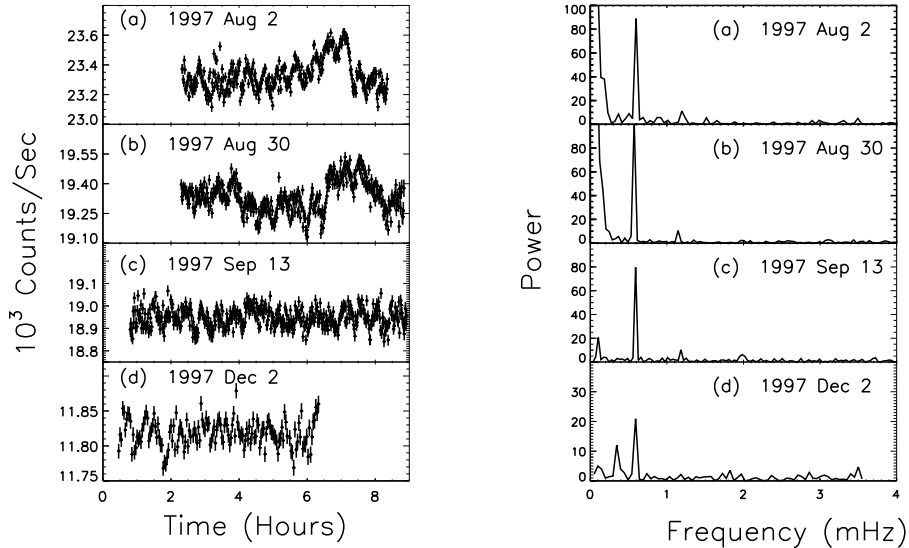


Figure 1. Example Z And *B*-band light curves and corresponding power spectra (from Sokoloski & Bildsten 1999). The power is plotted in units of mean high frequency power. The feature at 0.6 mHz corresponds to an oscillation period of 28 m.

times smaller than the optical spin modulations seen in magnetic CVs. If such low oscillation amplitudes are typical of magnetic SS, then they were probably not discovered earlier because past observations were not sufficiently sensitive.

Mürset et al. (1991) estimate a WD luminosity for Z And of  $L_{hot} \approx 600 - 1600L_{\odot}$ , so Z And is probably experiencing some nuclear shell burning. Two important points follow: 1) magnetic accretion can produce an optical modulation at the WD spin period even in a WD with quasi-steady nuclear burning (and Z And is the first example), and 2) the presence of nuclear shell burning and a nebula that can reprocess high-energy emission into the optical may reduce the amplitude of the optical modulation.

Osborne et al. (2001) found what may be the first X-ray oscillation due to magnetic accretion onto a WD with surface nuclear burning - in the super-soft source M31PSS. The X-ray modulation amplitude was roughly 50%. King, Osborne, & Schenker (2002) argue that the X-ray flux varies at the WD spin period because the nuclear burning rate is higher near the poles, where the burning shell is preferentially supplied with fresh fuel. In contrast, the X-ray flux of Z And was constant to within the errors in an XMM observation on 2001 28 January (A. Kong, private communication). The amplitude of any sinusoidal spin modulation was less than roughly 10%. The small X-ray oscillation amplitude compared to M31PSS could mean that the high WD luminosity in Z And is due to residual burning from a previous nova rather than accretion with  $\dot{M} > \dot{M}_{steady,min}$ . Alternatively, the X-ray oscillation amplitude could be reduced by the presence of an additional source of X-ray flux, such as emission from shock-heated colliding winds.

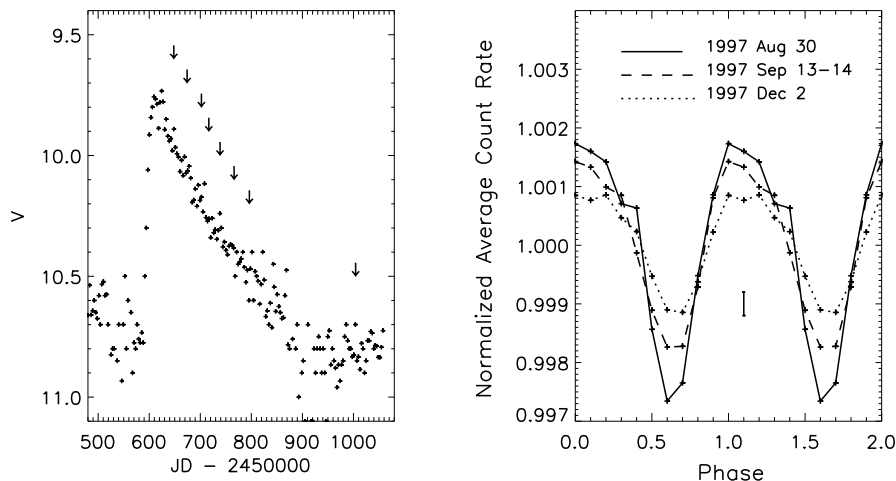


Figure 2. Z And long-term V-band light curve with the times of the 8 fast photometric observations marked with arrows (left), and the pulse profile evolution (right; from Sokoloski & Bildsten 1999). The size of a typical  $1\sigma$  error is shown in the center of the pulse profile plot.

The behavior of the 28-m optical oscillation amplitude during two recent outbursts of Z And has implications for the nature of these events. In 1997, the oscillation amplitude was highest near the optical peak of the outburst, and decreased as the outburst faded (see Figure 2). The hot spots near the WD surface were therefore not hidden by an expanded photosphere. Instead, the oscillation-amplitude evolution is consistent with an increase in  $\dot{M}$  during outburst, such as from a dwarf-nova-like disk instability. Near the optical peak of the larger outburst in 2000-2002, on the other hand, the optical oscillation was not detected, and FUV observations indicate that a shell of material was ejected (Sokoloski et al. 2002). The 2000 outburst may have also been triggered by an disk instability, but with a more dramatic response by the burning layer.

### 3. Disk-Jet Connection in CH Cygni

In CH Cyg, both the optical flickering amplitude and power-spectrum shape can change. Figure 3 shows some example high-speed light curves, and Figure 4 (top) shows the long-term light curve with the times of the fast photometric observations marked. In 1996 and 1997, CH Cyg dropped to a very low optical state, and low amplitude, rolling (hour-time-scale) variations were present, with little to no minute-time-scale variability (see also Rodgers et al. 1997). This type of smooth light curve is unusual for CH Cyg, which more commonly shows CV-like fluctuations on time scales from seconds to hours. In 1997 August, when the optical flux began to rise again, the minute-time-scale variations returned, although the overall flickering amplitude was still low ( $\lesssim 0.1$  mag). In 1998 August, when CH Cyg returned to an optical high state, the peak-to-peak flickering amplitude increased to  $\lesssim 0.5$  mag. In 1999 July, the optical flux was constant

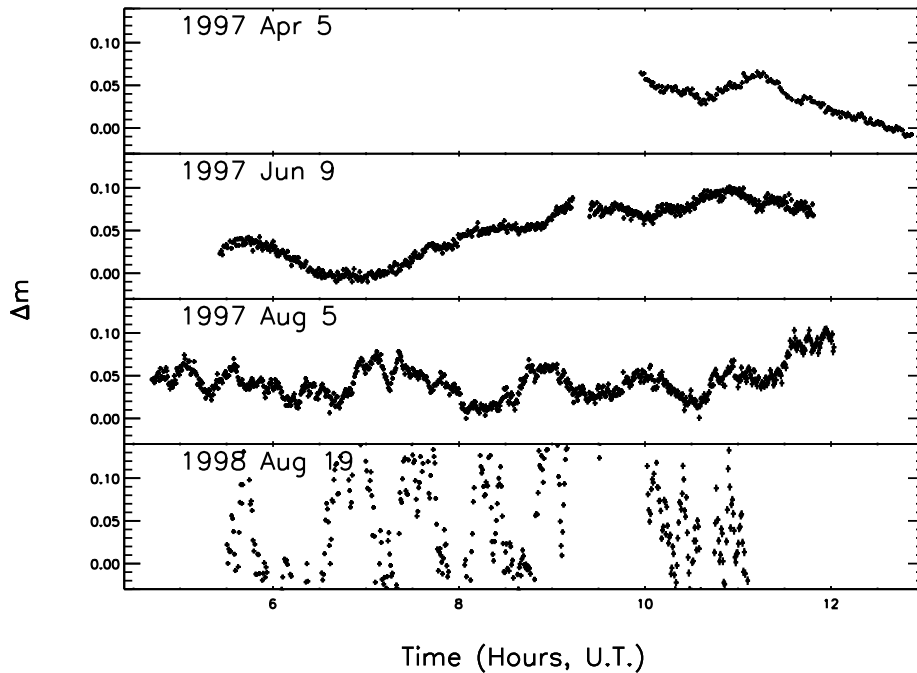


Figure 3. Example CH Cyg light curves from 1997 and 1998. The fluctuations evolve from smooth, low-amplitude variations after the jet ejection (estimated to have occurred in mid-1996; Sokoloski & Kenyon 2003a), to full CV-like flickering. The light curve from the 4th observation is off scale, since it has peak-to-peak variations of  $\sim 0.5$  mag.

to within the detection limit of a few mmag, presumably due to an eclipse of the accreting WD by a companion orbiting with a period of roughly 14 yr (e.g., Crocker et al. 2001). High-speed photometric observations from between 1997 and 2000 are described in detail by Sokoloski & Kenyon (2003a,b).

The unusual, smooth light curves from 1996 and 1997 were obtained right after material was ejected from the system and during the development of a radio jet (Karovska, Carilli, and Mattei 1998; Sokoloski & Kenyon 2003a). The bottom panel of Figure 4 shows the times of the fast photometric observations in the context of the rising radio flux densities. Since both the dynamical and viscous time scales increase with radius in the disk, and flickering is likely to be associated with dynamical or viscous processes, the fastest variations generally come from the innermost portion of the disk. In fact, observations of stochastic and quasi-periodic oscillations originating at different distances from the central object in X-ray binaries, CVs, and pre-main-sequence stars support a radial dependence of fluctuation speeds (e.g., Revnivtsev et al. 2000; Kenyon et al. 2000; Mauche 2002). Sokoloski & Kenyon (2003a) therefore interpret the absence of minute-time-scale variations in 1996 and 1997 as due to the disruption of the inner accretion disk. CH Cyg may therefore reveal a connection between jet-

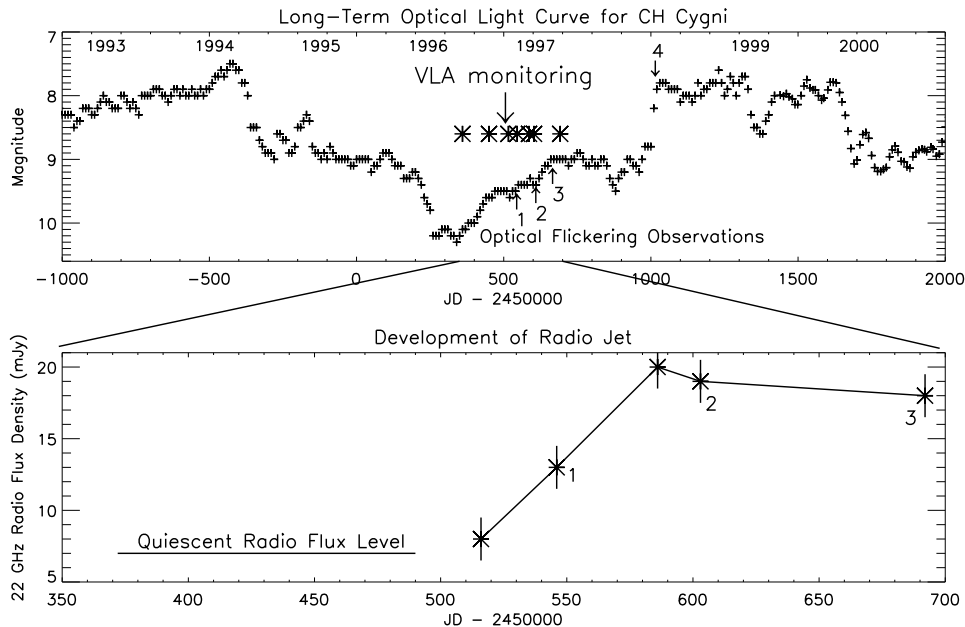


Figure 4. Top panel: long-term optical light curve of CH Cyg, from the AAVSO. The times of the four flickering observations shown in Fig. 5 are marked with arrows, and the period of radio monitoring by Karovska et al. (1998) is marked with stars. Bottom panel: 22 GHz radio flux densities, from Karovska et al. (1998). The rise in the radio emission was due to the production of a radio jet.

producing WD accretors and jet-producing X-ray binaries, since some X-ray binaries have also shown evidence for a disruption of the inner accretion disk with jet production (e.g., Feroci et al. 1999; Belloni et al. 1997). A link between WD systems and LMXBs with neutron-star or black-hole accretors is intriguing, since the energetics are quite different, and the accretion flow in CH Cyg is unlikely to be advection dominated.

To explain the jet activity and brightness changes in CH Cyg, Mikołajewski & Mikołajewska (1988) proposed that the WD in CH Cyg has a strong magnetic field, and that optical brightness changes, flickering changes, and transient collimated jets occur when the system moves between accretor and propeller states (see also Mikołajewski et al. 1990a,b; Panferov & Mikołajewski 2000; Tomov, this volume). In magnetic CVs, however, the optical and X-ray emission generally oscillates at the WD spin period. Optical quasi-period oscillations (QPOs) have been claimed for CH Cyg (e.g., Mikołajewski et al 1990a; Rodgers et al. 1997), but the putative QPO frequencies are not consistent with each other, and the significance of the claimed detections is difficult to evaluate due to the presence of 'red noise' in the power spectrum. To determine the statistical significance of a peak in a power spectrum with broad-band power, one can assume that the noise powers are distributed like  $\chi^2$  about the best-fit power law (van der Klis 1989; Deeter & Boynton 1982). Dividing the power spectrum by the best-

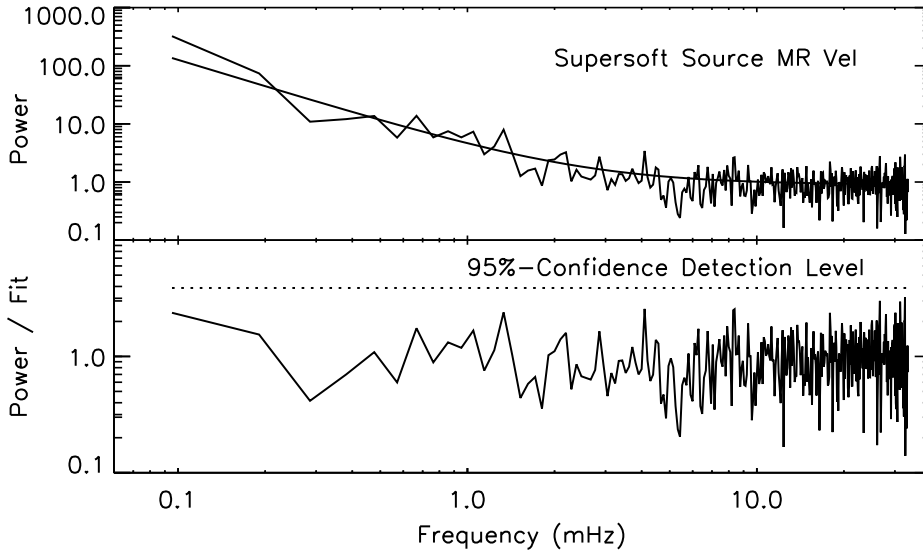


Figure 5. Example of searching for an oscillation against a background of broad-band power. Top: Average power spectrum of SSXB MR Vel in 1995 (see §5), and the best-fit power-law model. Bottom: When the power spectrum is divided by the model, standard detection statistics can be applied, and no significant peaks are found.

fit model then recovers the familiar statistical properties of white noise, e.g.,  $\Pr(P_{noise} > P) = e^{-P}$  (for unbinned and non-averaged power spectra, where  $\Pr(P_{noise} > P)$  is the probability that a statistical fluctuation will produce a peak greater than  $P$ ; see also Fig. 5). Sokoloski & Kenyon (2003b) applied this technique to CH Cyg light curves from both the high and low states, and did not find any significant oscillations. They thus concluded that alternatives to the magnetic propeller model for CH Cyg should be considered.

As one alternative, Sokoloski & Kenyon (2003b) suggest that the activity in CH Cyg is driven by an unstable disk, as in dwarf novae. The flickering amplitude in CH Cyg tends to be low when it is in an optical low state, and high when it is in an optical high state. Assuming that the flickering is from an accretion disk (almost all systems with disk accretion produce stochastic brightness variations), the correlation between flickering amplitude and optical brightness state implies that increased mass flow through the disk is responsible for the high states in CH Cyg. Since jets are generally observed after a decline in optical brightness, an unstable disk could also be associated with (e.g., trigger or be triggered by) the outflow of material in collimated jets.

#### 4. Survey of 35 SS and the Prevalence of Nuclear Shell Burning

As discussed in §3, accretion through a disk generally produces stochastic variations in interacting binaries. But early flickering studies of SS found many

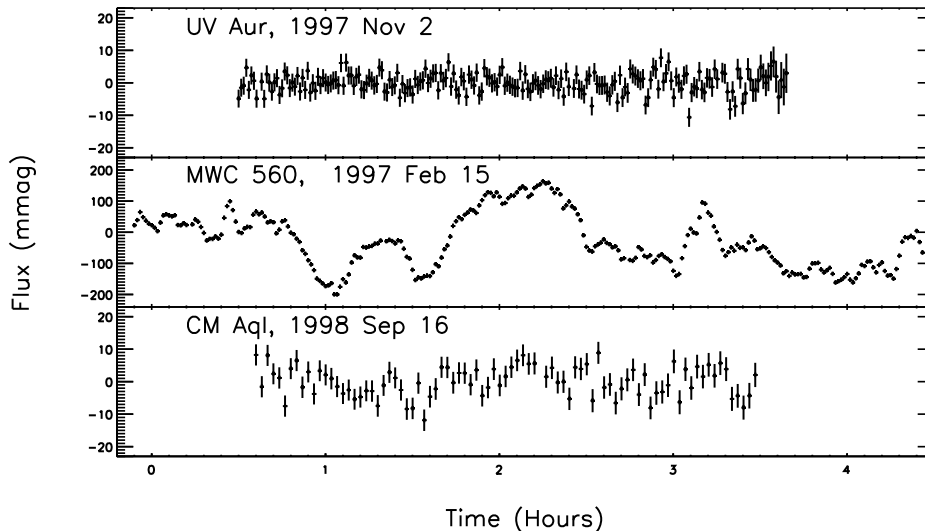


Figure 6. In the survey of SBH, 25 objects had optical light curves like UV Aur (top panel), 5 had light curves similar to MWC 560 (middle panel), and 4 had light curves similar to CM Aql (bottom panel).

systems that do not flicker (Walker 1977; Dobrzycka, Kenyon, & Milone 1996). Because it is not clear whether most SS have disks, additional observations may help to determine whether the prevalence of flickering is related to disk formation, or, as I argue below, disk flickering in many SS could be hidden by emission from nuclear burning material on the surface of the WD.

To address these questions, as well as to search for magnetic SS, Sokoloski, Bildsten, & Ho (1999; hereafter SBH) obtained high-time-resolution differential CCD light curves for 35 SS, more than doubling the number of SS observed in this way. The light curves generally fall into three categories (excluding Z And); Figure 6 shows examples of each type. Twenty-five of the 35 survey objects did not vary. In these systems, aperiodic (e.g., stochastic) variations were constrained to be less than just a few mmag, and sinusoidal oscillation amplitudes were constrained to be less than 2 - 10 mmag ( $\sim 0.2 - 1\%$  fractional variation). Strong stochastic variations were confirmed in five well-known flickering systems - RS Oph, T CrB, CH Cyg, MWC 560, and Mira. The four final systems (EG And, BX Mon, CM Aql, and BF Cyg) varied at a low level ( $\lesssim$  tens of mmag), but need additional observations to be considered high-confidence detections. Thus, despite the dramatic fast variability of a few well-studied systems like CH Cyg, and the presence of magnetism in at least one SS (Z And), most SS do not show either aperiodic or periodic rapid variations at a level greater than roughly 1%. Furthermore, the distribution of flickering amplitudes is bi-modal; although a few systems flicker with variations on the order of tenths of a mag, the flickering in most systems is constrained to less than roughly 10 mmag.

There are several possible reasons why optical flickering is absent in most SS. Accretion disks could be absent, or the flickering could be hidden by emission

from the red giant or luminous WD. Because direct evidence for an accretion disk, such as double-peaked emission lines, has been difficult to find in SS, the hypothesis that the presence of flickering reflects the presence of a disk is hard to test. Optical flickering is unlikely to be hidden by light from the red giant in most SS because there is no systematic difference between the red giants in the large-amplitude flickerers and the non-flickering systems. There is, however, a systematic difference in the WD luminosities,  $L_{hot}$ . The few low- $L_{hot}$  systems are much more likely to flicker (as first noted by Dobrzycka et al. 1996), whereas the high- $L_{hot}$  systems generally do not flicker. Much of the WD luminosity is radiated at high energies, but the nebula absorbs some of this light and re-radiates it in the optical. Since  $E_{nuc} \gg E_{grav}$ , this nebular emission could easily hide the optical disk flickering. A high  $L_{hot}$  indicates nuclear burning, so the flickering amplitude seems to be related to the fundamental power source - nuclear shell burning vs. accretion alone. The lack of flickering in most SS thus indicates that most SS may be powered by nuclear shell burning on the WD.

## 5. Disk Flickering from Supersoft Source MR Velorum

As discussed in the previous section, reprocessed nuclear shell burning can overwhelm optical disk flickering in SS. Some SSXBs may also be powered by WD nuclear shell burning, so it is natural to ask whether disk flickering is also hidden in SSXBs. In the standard picture, the mass-donor star in SSXBs transfers material via Roche-lobe overflow. An accretion disk almost certainly forms. These disks may be quite flared; models with high rims can reproduce eclipse profiles in some edge-on SSXBs (Schandl, Meyer-Hofmeister, & Meyer 1997; Meyer-Hofmeister, Schandl, & Meyer 1997). Dubus et al. (1999), however, claim that an extremely flared structure is unphysical for an illuminated disk, and that a thick inner region should shield the outer disk.

In 2001 January, Sokoloski, Charles, and Clarkson (2003) observed the Galactic transient-jet SSXB MR Vel (= RX J0925.7-4758) with the 1.9-m telescope at SAAO. They repeatedly found what is almost never seen in SS - flickering with a moderate amplitude of  $\sim 60 - 80$  mmag. Figure 7 shows one MR Vel differential white light CCD light curve. The power spectrum is well-represented by a power-law-plus-constant model, with a power-law slope of 1.5. The power law drops below the white-noise at around 4 mHz, indicating that variations with time scales as short as 4 m were present. Simultaneous *BVR* light curves are shown in Figure 8. The overall variability amplitude was slightly larger in *B* ( $\sigma_B = 22.1$  mmag,  $\sigma_V = 16.3$  mmag, and  $\sigma_R = 17.9$  mmag), and the fastest flare was significantly stronger in *B* compared to *V* and *R*.

Meyer-Hofmeister et al. (1997) suggested that alterations in the size of a reflecting disk rim (on the dynamical time at the edge of the disk) could introduce variations into the optical emission. If  $R_{disk} \approx 0.3a$  (where  $R_{disk}$  is the disk radius, and  $a$  is the binary separation), as in CVs (Warner 1995), the disk in MR Vel has a radius of roughly  $3 \times 10^{11} (P_{orb}/4 \text{ d})^{2/3} (M_{tot}/2 M_{\odot})^{1/3}$  cm. The dynamical time at this radius (taking  $M_{WD} = 1 M_{\odot}$ ) is roughly 4 h. But the MR Vel light curves reveal variations as fast as minutes. Therefore, either the changing disk-rim model may not account for all the observed variations, or the disk is smaller than a scaled-up CV disk (i.e.,  $R_{disk} < 0.3a$ ).

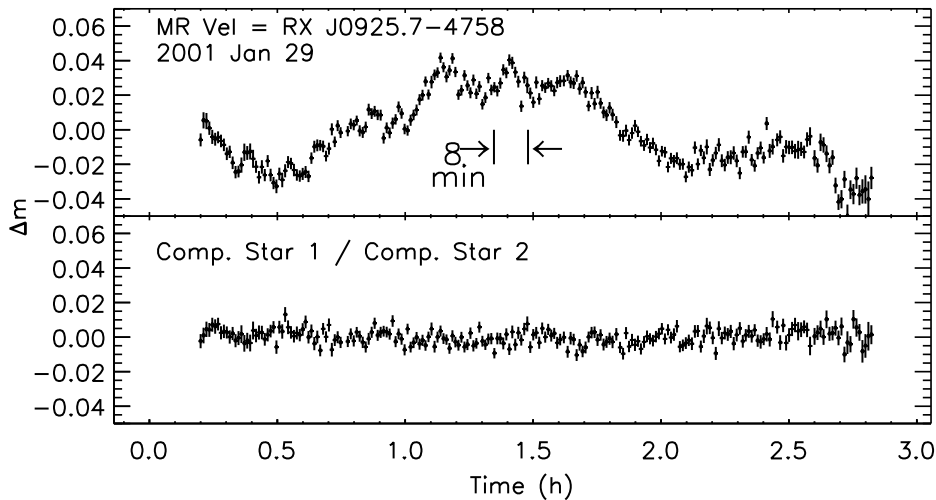


Figure 7. Variations in the white-light flux of MR Vel with respect to constant comparison stars, and ratio of comparison-star fluxes.

Another possible explanation for the visible flickering is that disks in SSXBs convert less of the high-energy photons to optical photons than are converted by the nebulae in SS. In this case, the ratio  $L_{opt,acc}/L_{opt,nuc}$  (where  $L_{opt,acc}$  is the component of the optical luminosity from viscous dissipation in a disk and  $L_{opt,nuc}$  is the component of optical luminosity due to reflected nuclear-burning light) could be larger in SSXBs than SS, allowing some of the disk flickering to show through. On the other hand, the fractional variability in SSXBs is less than in CVs, so there appears to be at least some reduction in amplitude due to the nuclear burning. The multi-color light curves in Figure 8 support the idea that at least some of the variable optical light in MR Vel is due to CV-like viscous dissipation in the disk. The bluer color of the fast flare marked with a box in Fig. 8 compared to similar-sized slower flares implies that the fastest flares could be due to a different physical process (perhaps more directly related to accretion) or originate in a different (hotter) physical region than the hour-time-scale variations. If they are from the inner disk, they provide a diagnostic of the region that, as in CH Cyg, could be associated with jet production.

## 6. Fast Emission-Line Variations from RS Ophiuchi

Rapid spectral changes can in principle give us the spectral energy distribution (SED) of the variable source, and also probe the properties of the intervening material. In practice, determining the SED of the underlying flickering source is complicated by the need to separate intrinsic source variations from Poisson variations. Because of the relatively lower Poisson contribution, measuring changing line fluxes is more straight-forward. Sokoloski et al. (2003) performed simultaneous optical differential photometric observations and spectroscopic observations of RS Oph on the 1- and 3-m telescopes at UCO/Lick Observatory.

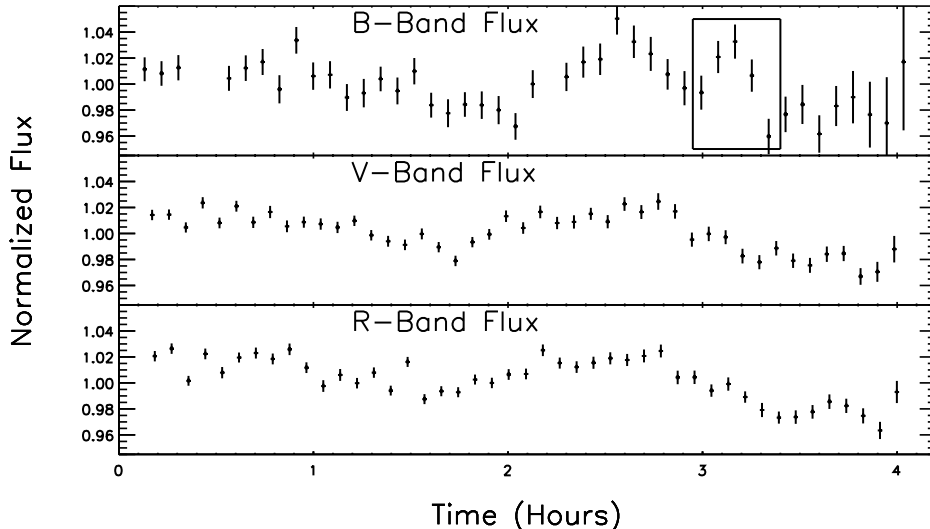


Figure 8. Cyclic *BVR* observations of SSXB MR Vel reveal that fast flares might have bluer colors than hour-time-scale variations.

The KAST dual-armed spectrograph covered 3200 - 5300 Å on the blue side, and 5300 - 6750 Å on the red side. Assuming that the red giant does not vary on a time scale of minutes, they used normalizations from fits of a template red giant plus a power law to the red end of each spectrum to correct for losses due to guiding errors and seeing changes. Figure 9 shows example plots of the flux density (above the continuum) in several lines.

The spectral flux-density variations in RS Oph prove that the red giant was an effective internal calibration source, and they reveal new aspects of the well-known flickering. The light curves produced from the featureless portions of the normalized spectra (Fig. 9, top two panels) agree well with the simultaneous differential photometry. The calibration technique was therefore considered reliable. The He II  $\lambda 4686$  line varied as fast as the blue-side observing cadence of approximately one spectrum every 4 minutes (two red-side spectra were taken per blue-side spectrum), and the changes were roughly correlated with the spectral continuum and photometric fluctuations. Thus, there must exist a source of photons that have energies greater than 55 eV (i.e., a source with  $T \gtrsim 50,000$  K), such as an optically thick accretion-disk boundary layer, that varies on a time scale of minutes. Furthermore, the He II line variations appear to lead the featureless continuum variations, suggesting that the region which produces the He II emission could drive the flickering variability. Alternatively, some of the variable continuum flux may be recombination radiation from the nebula (instead of, or in addition to, optical light directly from the disk). In this case, the light-travel-time delay between the He II-line and continuum changes would imply that the He II emission region is closer to the hot WD than the continuum emission region. The lower-ionization-state He I and Balmer lines varied more slowly than the He II line (see Fig. 9, bottom two panels), possibly due to the

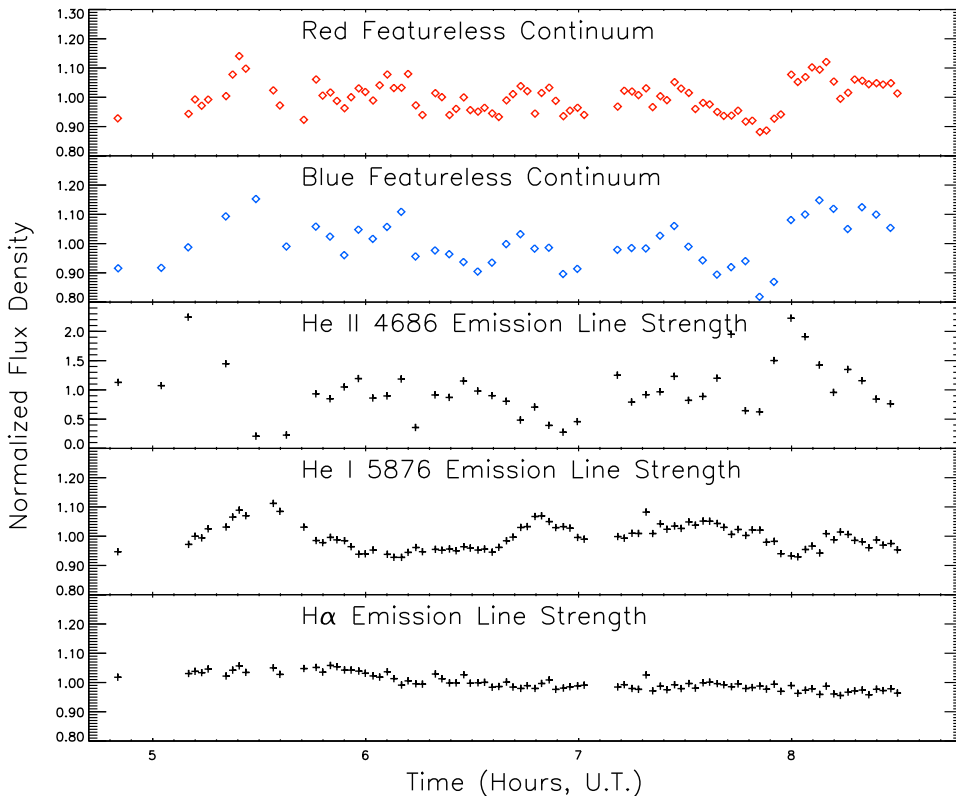


Figure 9. Top two panels: flux densities from the continuum spectral regions not contaminated by lines. They look similar to the photometric light curve. Middle panel: the He II  $\lambda 4686$  line strength changes in minutes, and may lead the featureless-continuum variability. Bottom two panels: the fastest variations seen in the featureless-continuum flux density are not present in the He I- and Balmer-line light curves.

emission regions being farther from the hot WD, longer recombination times, or a larger optical depth in these lines.

### 7. Discussion

Rapid-variability studies suggest that the strength of aperiodic variations in SS is related to the power source (nuclear shell burning or accretion alone). Systems with high  $L_{hot}$  generally do not show large-amplitude flickering, whereas SS with low  $L_{hot}$  almost always do (Walker 1977; Dobrzycka et al. 1996; SBH and references therein). The luminosity ratio of a typical high- $L_{hot}$  system ( $\sim 100 - 1000 L_{\odot}$ ) to a typical low- $L_{hot}$  system ( $\sim 1 - 10 L_{\odot}$ ) is close to the ratio of the energy released per nucleon in the nuclear burning of hydrogen-rich material to that from accretion onto a WD. Therefore, if nebular emission in a symbiotic is powered by quasi-steady nuclear shell burning on the surface of a WD, flickering

or oscillations from accretion are often hidden or reduced. In many SSXBs, on the other hand, nuclear-burning emission is probably reprocessed into the optical by the accretion disk, and the ratio of reprocessed light to direct disk emission may be low enough that some CV-like disk flickering is detectable. Since symbiotic recurrent novae are preferentially low- $L_{hot}$  systems, the presence of flickering may also be related to the type of outburst a SS experiences.

Whether a symbiotic burns material quasi-steadily or not, observations described in §2 and §3 suggest that accretion-disk instabilities may play a role in the more common, classical SS outbursts. Furthermore, Mikołajewska (this volume) found that SS with ellipsoidal variations (in which the red giant is closer to filling its Roche lobe, and a disk is more likely to form due to focusing of the red giant wind) have more outburst activity. So the presence of disks could be broadly associated with outbursts in classical SS. In CH Cyg and also possibly in Z And (Brocksopp et al. 2003), collimated jets are sometimes produced during or after outbursts, so disks may also be related to the production of jets in SS. As discussed in §3, there is evidence that the disk in CH Cyg was disrupted when a jet was produced. Similar behavior has been reported for some transient-jet X-ray binaries, so, as suggested by Zamanov & Marziani (2002), disks and jets may provide a link between symbiotic and black-hole jet sources.

Finally, periodic variations provide information about magnetism. Given the very low oscillation amplitude in Z And, however, SBH could not rule out strong magnetic fields in any of their survey objects. The detection fraction for magnetic WDs of 3% is therefore only a crude lower limit. More sensitive observations are needed to determine the magnetic fraction in SS, and thereby test theories of the origin of magnetism in WDs and binary stellar evolution. Identification of additional magnetic SS is also needed to clarify whether a strong WD field helps produce collimated jets (as suggested by Panferov & Mikołajewski 2000 and references therein; Tomov, this volume) or inhibits their formation by truncating the inner accretion disk where the jet is launched (as may be the case in NS X-ray binaries; Fender & Hendry 2000). Finally, since magnetically channeled accretion with  $\dot{M} \gtrsim \dot{M}_{steady,min}$  produces a large soft X-ray spin modulation, whereas residual burning on a magnetic WD does not (King et al. 2002), comparison between the X-ray oscillation amplitudes in magnetic SS and magnetic SSXBs may provide information about the different (or similar) causes of nuclear shell burning in these two classes of systems.

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